

Deep-sea observation equipment and exploration technology

Edited by

Shaowei Zhang, JongJin Park and
Zhiqun Daniel Deng

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Deep-sea observation equipment and exploration technology

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Editorial: Deep-sea observation equipment and exploration technology

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KEYWORDS

hadal zone, ocean observation, AUV, network, buoy

Editorial on the Research Topic

Deep-sea observation equipment and exploration technology

The increasing interest in deep-sea exploration is a crucial catalyst for driving advancements in deep-sea observation technology research. Numerous sophisticated sensors have been developed to facilitate comprehensive studies of deep-sea physics, chemistry, and geology. For example, cutting-edge small and compact seabed samplers are now employed on various platforms, such as Autonomous Underwater Vehicles (AUVs), Remotely Operated Vehicles (ROVs), and Human-Operated Vehicles (HOVs), enabling observation of the hadal zone. Additionally, Micro-electromechanical Systems (MEMS) sensors are routinely utilized for ocean wave observation. This Research Topic aims to foster new insights into ocean exploration and observation technology, including ocean sensor technology, ocean observation platforms, and ocean observation reliability technology.

With respect to ocean sensor technology, the works included in this Research Topic cover communication and navigation technology, opto-electronic MEMS sensors, deep-sea samplers, and specialized equipment for oil and gas exploration. Unlike traditional electromagnetic communication technology, atmospheric evaporation waveguide communication technology facilitates long-distance transmission by utilizing surface water vapor as a transmission medium. Additionally, the dual-axis rotary modulation inertial navigation system (INS) introduces a gravity disturbance compensation method to enhance the positioning accuracy of the INS. With the advancement of MEMS technology, the design of wave sensors and sound velocity profiles has become more miniaturized and modular, allowing marine scientists and engineers to design sensors based on their specific research needs. In the research of specialized instruments for marine geology, the developed deep-sea seabed sampler can directly reach the abyssal zone.

Qiu et al. studied the evaporation duct properties in the East China Sea. The evaporation duct is an abnormal phenomenon that occurs at an extremely high frequency in the marine atmospheric boundary layer and directly affects the propagation of electromagnetic waves. Therefore, it is necessary to investigate the various characteristics of the evaporation duct. Large-scale observations at sea are difficult, so reanalysis data are usually utilized for evaporation duct property studies.

Zhang et al. presented gravity disturbance compensation for a dual-axis rotary modulation INS. The error and frequency characteristics of the INS caused by gravity disturbances is investigated. And the gravity disturbance is introduced into the INS initial alignment and calculation to implement the INS gravity compensation. As INSs are widely employed to establish autonomous navigation systems, this work provides an effective method to enhance the long-endurance positioning capability of underwater or other autonomous passive navigation.

Zhou et al. described the design and application of the miniaturized strap-down inertial wave sensor DWS19-2, which is mainly utilized for ocean air-sea buoys and surface drifting buoys. A 9-axis MEMS inertial module was integrated into an STM32F446 embedded controller to measure buoy pitch angle, roll angle, yaw angle, and 3-axis accelerations.

Zhang et al. designed and calibrated a low-cost underwater sound velocity profiler consisting of three parts: the control unit, the storage module, and the ultrasonic measurement module. This can be integrated into the profilers and platforms or utilized as a sound velocity sensor. The low cost of the sound velocity profiler can enable large-scale deployment.

Chen et al. designed an underwater free-space optical communication module to be used between AUVs and seafloor junction boxes. They characterized underwater optical transmission, established photoelectric signal processing and modulation and demodulation algorithms, and designed a prototype including a free-space optical transmitter and a receiver. They reported that a communication rate of 1 Mbps could be achieved with a transmitter power of 10W.

He et al. presented a submersible-mounted sampler capable of collecting pressure-retained samples at full ocean depth to obtain seabed sediments. The submersible-mounted sampler was fixed on the HOV and coordinated sampling with the manipulator. This sampler has a compact structure, is small in size, and is lightweight, making it convenient to operate with ROVs and HOVs.

Li et al. conducted a sensitivity analysis of seismic attributes and oil reservoir predictions based on jointing wells and seismic data to identify the location of gravelly sandstone. The well analysis and core data were utilized to establish the geological model of mudstone and sandstone and to identify the electrical characteristics of the lithology.

Ocean observation and exploration platforms mainly involve ocean buoys, underwater gliders, AUVs, etc. The profile thermal buoy captures the thermal energy of the ocean and converts it into electrical energy, thus improving the endurance of the profile buoy. Oceanographic buoys are the traditional and mainstream means of observation, while the development of Electro-Optical Mechanical (EOM) mooring cables takes on the role of buoy mooring lines, extending the observation from the sea surface to the sea floor. As a long-range autonomous observation platform, the streamlined design and wing shape of underwater gliders have a crucial impact on their energy consumption. Compared to human-operated ROVs, AUVs' underwater target detection algorithms require strong real-time performance and the ability to cope with issues such as poor underwater light conditions and buried targets.

Chen et al. developed an energy conversion system for ocean thermal profilers that has great potential for application in underwater gliders and profilers. The authors analyzed the performance of the energy conversion system and established an experimental platform to study the system's performance and verify the validity and accuracy of the established mechanical model. They reported that the experiment for mechanical efficiency was close to the simulation, and the energy conversion system can meet the engineering application.

Zhang et al. presented the design of a mooring buoy observation system with a mooring EOM cable. The cable connects the sea surface buoy and the benthic observation node as a transmission link for information and power. The paper also provides detailed design concepts for the buoy nodes and seabed nodes.

The EOM cable plays the role of buoy mooring tether and is also the crucial link to ensure long-term and effective system operation and energy/data transmission. Zhang et al. presented the mooring dynamic characteristics of the EOM cable of the cable-moored buoy observation technology. They analyzed the static mooring loads and dynamic characteristics of the mooring line under different external environments. They also added a rubber snubber to the mooring line to reduce the influence of the sea surface.

Wang et al. reported on a swept-wing strategy to optimize the wing shape and position of underwater gliders. They conducted hydrodynamic numerical simulations of different wing sweep angles and found the optimal sweep angle. They also established a dynamic model of the underwater glider with the hydrodynamic simulation results. This study can improve the optimal capabilities of underwater gliders, such as gliding duration and trajectory accuracy.

Xu et al. described a vision-based real-time underwater target detection method for AUV subsea exploration in poor lighting conditions and deep-sea sediment burial. They integrated the proposed method into the AUV control system for online target detection. They expected this technology to be utilized in the marine archaeological survey field.

Ocean observation is a long-term and sustained effort that requires addressing various issues, such as the overall deployment of the observation system, improving the quality of the observation data, and improving system reliability. This is particularly evident for underwater observation networks and ocean buoy observation networks. Because many of the observations are for the near-shore sea surface, the locations and number of buoys are particularly important in terms of how to cover the observed area with as few buoys as possible. The design life of the seabed observation network is generally more than 20 years, so the watertight connectors should have good reliability and the seabed sensors can self-calibrate and suppress data drift. At the same time, new technologies for seabed observation networks, such as the Internet of Underwater Things, are gradually making underwater observation more intelligent.

Liu et al. optimized buoy deployment in Bohai Bay, China. It was a crucial and core issue to optimize the buoys' effectiveness by using as few of them as possible for the ocean buoy network and to optimize the buoy location to reflect the changing characteristics of the target observation area. The optimization method provides

ideas for the selection of buoy deployment locations for regional ocean buoy observation networks.

Skålvik et al. developed measurement strategies to ensure data quality in deep-sea sensors. The paper discusses how sensors can be affected by the specific environment and the correlations between different variables that influence the measurement results. Their research focused on fixed-platform sensors on the ocean floor, which can be deployed for several years in remote deep-sea locations.

Duan et al. developed a non-contact wet-mateable connector for optical communications and power transmission. The inductive coupling for power transmission and optical communication is separated to cope with power transmission and communication issues. They also designed the docking structure of the sockets and plugs to facilitate the operation of the ROVs.

Duan et al. presented the system design of the Xiangshan Internet of Underwater Things (XIoUT). The XIoUT is China's first multi-node constant current cable observation network, which is utilized for collecting and transmitting ocean environmental data. The development of the IoUT has benefited from the rapid development of current intelligent technologies, such as artificial intelligence technology and the Internet of Things technology. In addition, the XIoUT provides a testing system for the research of Internet of Things technologies in the ocean.

The Guest Associate Editors thank all the authors and reviewers for their dedicated work on this Research Topic. We hope that this can inspire further research for deep-sea observation equipment and exploration technology.

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New approach for designing an underwater free-space optical communication system

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Ocean observation system that involves multiple underwater vehicles and seafloor nodes plays an important role in better learning the ocean, where underwater wireless communication is mandatory for massive data interaction. Optical communication that has wide bandwidth and comprehensive working distance is the preferred method compared to acoustic and other methods. However, the presence of directionality makes the optical method difficult to use especially when the transceiver is equipped on a motive vehicle. In this study, an underwater free-space optical communication method of transmitting information is proposed. Characteristics of underwater optical transmission, as well as the photoelectric signal processing and modulation and demodulation algorithms, are studied and modeled. New approach for realizing underwater free-space optical communication is proposed and simulated. A prototype including a free-space optical transmitter and a receiver is developed; tests in different scenarios were carried out, and the results were observed: (1) by using the minimum number of LEDs, the effect of uniform lighting in space is achieved, and the transmitter coverage reaches 160°. (2) When the power of the transmitter is 10 W and the communication rate is 1 Mbps, the maximum communication distance reaches 13 m.

KEYWORDS

seabed observation platform, free-space optical communication, underwater wireless communication, space luminescence array, pulse modulation and demodulation

Introduction

The ocean is rich in resources. The exploration, development, and utilization of the ocean are of great significance to the future development of mankind. Seabed observation platforms can provide diversified, comprehensive, and instantaneous marine information (Sherlock et al., 2014; Liu et al., 2019). The platforms are laid at the bottom of the ocean. Collecting marine information through a variety of underwater sensors mounted on the platforms can help researchers instantaneously obtain physical and chemical marine

data, as well as earthquake and tsunami data and other relevant information, which is very helpful for scientific observations.

After obtaining the corresponding observation information, a seabed observation system must send the information back to an observation station on the shore. The most convenient information transmission method is to use submarine cable communication. However, submarine cable communication has distance limitations and is not suitable for seabed observation systems located in the deep sea or far away from the shore. In these cases, information transmission must be conducted using mobile platforms, such as autonomous underwater vehicles (AUVs) (Yoon et al., 2012; Su et al., 2019). The information interaction between a mobile platform and a fixed platform is very important. During the information interaction process, a mobile platform AUV can not only replace the communication cable and remove the communication distance limitation, but can also conduct two-way communication with multiple fixed platforms. After obtaining data, an AUV will sail to the sea surface and then send the information back to a coastal observation station *via* a satellite (Zhang et al., 2020a). The core problem with this information handling mode is achieving stable communication between an AUV and a seabed base station. Underwater communication modes can be divided into contact communication and non-contact communication groups. Traditional contact communication needs a connection technology based on direct coupling or electromagnetic coupling. This relies on high-precision physical positioning of the underwater vehicle (Zhang et al., 2020a; N'Doye et al., 2021). Non-contact communication has lower requirements than contact communication for AUV positioning accuracy and control and can achieve one-to-one, one-to-many, and many-to-many information transmissions. Therefore, the goal of this study was

to design a general and stable underwater contactless communication system.

Underwater non-contact communication methods primarily include acoustic communication (Cao et al., 2018; Han et al., 2019b), radio frequency (RF) communication (Che et al., 2010), and optical communication (Sahoo et al., 2019; Zhu et al., 2020). Acoustic communication uses sound waves as the information transmission medium. Seabed observations have high-security requirements, so underwater acoustic communication cannot be used because underwater acoustic information can be easily stolen. RF communication uses high-frequency electromagnetic waves as the communication medium. RF communication has shorter communication distances and higher power requirements than optical communication. Therefore, underwater optical communication was chosen in this study to achieve non-contact communication, as shown in Figure 1.

Since the beginning of the twenty-first century, the development of photoelectric technology and communication technology has promoted progress in underwater optical communication technology. Optical communication may use Gbps or even Tbps bandwidths (Zhang et al., 2020b). However, most underwater optical communication devices use concentrated light beams for communication. AquaOptical II is an underwater point-to-point optical communication device (Doniec and Rus, 2010). At a distance of 21 m, the two ends could conduct stable two-way communication at a rate of 5 Mbps. The disadvantage of this equipment is that it can only conduct point-to-point communication. It can only be applied to underwater information handling media that can conduct accurate position control, so its use scenarios are limited.

To achieve uniform optical coverage over the whole space, free-space optical communication (FSOC) technology was

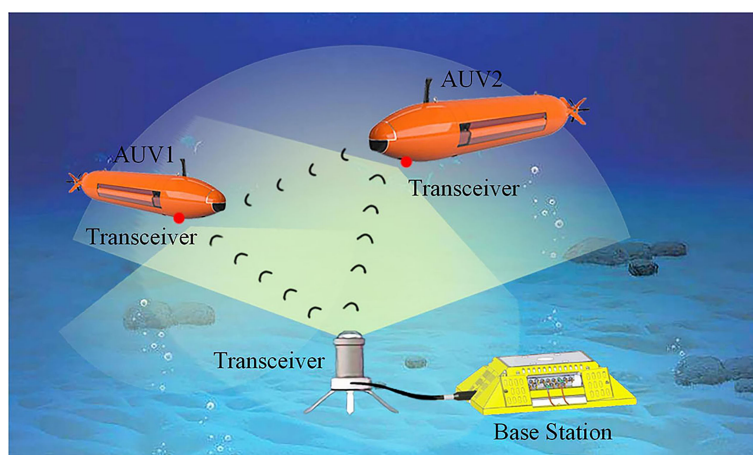


FIGURE 1
Schematic diagram of the seabed communication of AUV.

developed (Abrahamsen et al., 2021; Alexander et al., 2021; Zafar and Khalid, 2021). LED light is uniform and is not costly, so it is often used in FSOC (Huang et al., 2019; Abrahamsen et al., 2021). The Woods Hole Institute (Farr et al., 2006; Pontbriand et al., 2008; Pontbriand et al., 2016) has made outstanding research achievements in long-distance underwater optical communication. Their long-distance optical communication products use six 470 nm blue LEDs at the light-emitting end to form an evenly distributed light field. At the light-receiving end, a hemispherical photomultiplier tube (PMT) is used for optical signal acquisition. A sea trial of communication between a deep-sea seabed optical communication node and an AUV was performed for the products, and full duplex communication for distances of 0–125 m and rates of 5–20 Mbps was achieved at a depth of 2,400 m.

Some commercial products also exist, such as Sonardyne's BlueComm modems and Aquatec's AQUA modems. Studies regarding these products have achieved good communication results, but they rarely discuss how to design the spatial arrangements of the light-emitting devices. In fact, the structural designs of the emitters are also very important because they determine the distribution effects of the light in space. If the emitting end emits light unevenly, it can no longer conduct stable and efficient communication in space. To make the transmitter emit light evenly, a spherical transmitter with a 360° light emission range was designed (Baiden et al., 2009; Baiden and Bissiri, 2011). The light-emitting devices used were LEDs. Communication at a distance of 11 m and with a speed of 20 Mbps was achieved in a laboratory. A lake trial was completed for communication at a speed of 10 Mbps. Additionally, a new LED packaging structure was proposed (Han et al., 2019a). The light emitted by the LED with the improved structure was nearly evenly distributed in the space, a result which laid a solid foundation for optical communication in the entire space. The optical communication experiment was conducted with seven LEDs as optical transmitters. It was found that the bit error rate was very low in the range of 160°, which meets the needs of all space communication. There is still much room for improvement in FSOC light utilization and distribution uniformity, which depend on the optimization of transmitter structure. Optimizing the transmitter structure can also further improve the communication distance.

During this study, the following primary work was completed:

- A luminous model for underwater LEDs was developed and a transmitter structural design approach is proposed.
- A set of transmitter models with hemispherical coverage, high light utilization, and uniform luminescence was designed, and its luminous effect was verified.
- Through the modulation and demodulation of the photoelectric signal, a set of free-space optical communication equipment suitable for underwater use

was manufactured. Experiments indicated that the communication of this system is stable and reliable.

The paper structure is described next. The approaches and corresponding simulation results are described in Sections 2–4. The experimental results are presented in Section 5. Finally, the conclusions drawn during the study are given in Section 6.

Underwater light diffusion model

The blue–green visible light band is located in the minimum attenuation window of the underwater visible light absorption spectrum. Therefore, the light in this band (wavelength between 400 and 480 nm) can be used for communication in seawater. To achieve the effect of full coverage and uniform luminescence at the transmitter, a new underwater LED blue–green light diffusion model was developed.

Underwater transmission characteristics of blue–green light

As is shown in Figure 2A, when a beam of light hits a particle underwater, three effects may occur. First, part of the light is absorbed by the particle, resulting in attenuation. Second, part of the light is scattered by the particle, which changes the transmission direction. Third, part of the light is emitted in the original direction. Through this analysis, the influences of particles on light can be approximately divided into absorption and scattering effects. These two effects weaken the light and attenuate its energy.

If the energy of the incident light is represented by $\varnothing_0$, the light energy absorbed by the seawater is $\varnothing_a$, the light energy scattered by the seawater is $\varnothing_b$, and the transmitted light energy is $\varnothing_t$, their relationship can be expressed by Eq. (1):

$$\varnothing_0 = \varnothing_a + \varnothing_b + \varnothing_t \quad (1)$$

To evaluate the effect of seawater on light, some parameters must be defined. a is defined as the absorption coefficient of seawater with respect to light, and it is primarily related to various particles in seawater. b is defined as the scattering coefficient of seawater with respect to light. Scattering causes irregular light transmission, leading to a pulse broadening effect and improving the bit error rate of the communication. c is defined as the extinction coefficient of seawater with respect to light.

$$c = a + b \quad (2)$$

These three coefficients are generally used to evaluate the total impact of seawater on optical transmission. The composition of seawater is complex, and the seawater quality in different sea areas is different. To facilitate the research, it is

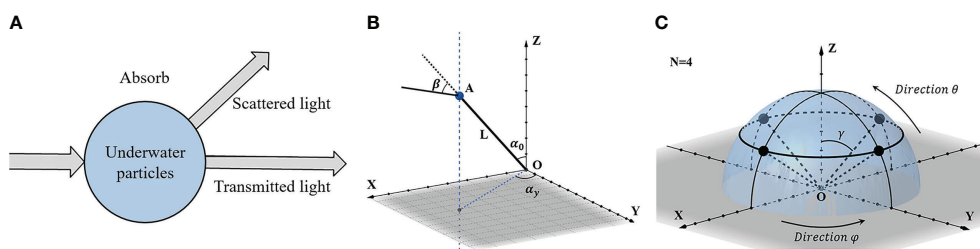


FIGURE 2

Physical model of (A) light colliding with an underwater particle, (B) photon emission, (C) LED spatial layout coordinate system.

necessary to clearly define and classify different types of seawater quality.

Jerlov classified sea areas according to the spectral transmission coefficient of light per meter of sea water. Scientists then classified Jerlov's water types in more detail (Cochenour et al., 2008). In this study, as is shown in Table 1, three types of water bodies and related parameters are cited, which provides support for the optical modeling described next.

LED photon-free motion model

LEDs were chosen as the light source at the transmitting end for this study. The primary advantages of LED light are simple circuitry, long service life, low heat production, reliable performance, and large light-emitting range. These characteristics ensure that the light can work stably underwater for a long time, and that there are low requirements for the positioning of the receiving end.

The motion of photons generated by the LEDs was modeled based on the Monte Carlo method (Song et al., 2013). Taking the motion of a single photon as the research object, through the analysis and statistics for the motions of a large number of photons, a macroscopic light distribution result was obtained.

(1) Photon emission direction

The probabilities of photon emission in each direction are not equal. As is shown in Figure 2B, the initial photon motion direction, OA, is generated by a probability equation. The probability equation was modeled to randomly generate the initial motion conditions of the photons.

The Lambert radiation formula is a theoretical formula used to describe the relationship between the LED luminous intensity and the emission angle. According to the Lambert radiation formula, the LED radiation model can be expressed by Eq. (3):

$$\varphi(\alpha) = \frac{m_0 + 1}{2\pi} \cos^{m_0}(\alpha) \quad (3)$$

where α represents the LED emission angle, $\varphi(\alpha)$ is the unit angle relative light intensity, and m_0 is a coefficient related to the half power angle of the LED light. Eq. (3) meets both Eqs. (4) and (5):

$$\int_0^{\pi/2} \varphi(\alpha) \sin \alpha d\alpha = \frac{1}{2\pi} \quad (4)$$

$$m_0 = -\frac{\ln 2}{\ln(\cos \alpha_{1/2})} \quad (5)$$

In Eq. (5), $\alpha_{1/2}$ is the half power angle. The most common LED half power angles are 30° and 60°. Section 2.3 focuses on the simulation of these two types of LEDs.

To describe the random emission directions of the photons, an equal probability random number, $\epsilon \in [0, 1]$, was constructed:

$$\epsilon = 2\pi \int_0^{\alpha_0} \frac{m_0 + 1}{2\pi} \cos^{m_0}(\alpha) \sin \alpha d\alpha \quad (6)$$

Eq. (7) was obtained by combining Eqs. (4) and (6):

$$\alpha_0 = \arccos(1 - \epsilon)^{\frac{1}{m_0+1}} \quad (7)$$

By constructing the random number, the required random emission angle can be generated. α_0 represents the angle between the exit direction and the z-axis, and $\alpha_0 \in [0, \pi/2]$. To obtain the

TABLE 1 Characteristic parameters of different types of seawater.

Type of water	a (m ⁻¹)	b (m ⁻¹)	c (m ⁻¹)
Pure sea	0.053	0.003	0.056
Clear sea	0.069	0.08	0.15
Coastal	0.088	0.216	0.305

initial photon emission direction, the included angle with the y -axis is also required. Similarly, the angle with the y -axis (α_y) is also a random value, and α_y has equal probability in $[-\pi, \pi]$. Another random number, μ , was also constructed.

$$\alpha_y = (\mu - 0.5) * 2\pi \quad (8)$$

$\alpha_y \in [-\pi, \pi]$. If the photon emission velocity is U_0 , the initial photon emission direction is expressed by Eq. (9):

$$\begin{cases} U_x = U_0 \sin \alpha_0 \sin \alpha_y \\ U_y = U_0 \sin \alpha_0 \cos \alpha_y \\ U_z = U_0 \cos \alpha_0 \end{cases} \quad (9)$$

(2) Free motion distance and energy

The free motion distance of the photons refers to the distance the photons travel before colliding with particles, and it is calculated using Eq. (10):

$$L = -\frac{1}{c} \ln \tau \quad (10)$$

In Eq. (10), τ represents a random number evenly distributed between 0 and 1, and c is the extinction coefficient of seawater with respect to light, which was introduced in Section 2.1. After scattering or absorption, the photon energy decays:

$$e_{out} = \left(1 - \frac{a}{c}\right) e_{in} \quad (11)$$

where e_{out} and e_{in} represent the energy before and after particle collisions, respectively, and a is the light absorption coefficient.

(3) Scattering

As shown in Figure 2B, light scattered in water changes the direction of photon motion and forms a scattering angle (β). The H-G phase function was used in this study for the scattering analysis, and its expression is given in Eq. (12):

$$p_{HG}(\beta) = \frac{1 - g^2}{4\pi(1 + g^2 - 2g\cos\beta)^{\frac{3}{2}}} \quad (12)$$

In Eq. (12), $g = \langle \cos\beta \rangle$, which is not only the scattering asymmetry factor, but also the average value of the cosine of the scattering angle. When $g = -1$, all the light is backscattered. $g = 0$ indicates isotropic light scattering. When $g = 1$, all the light is forward-scattered. According to Eq. (12), the random function for the scattering angle is given by Eq. (13):

$$\beta = \arccos \left\{ \frac{1}{2g \left[1 + g^2 - \left(\frac{1-g^2}{1-g+2g\mu} \right)^2 \right]} \right\} \quad (13)$$

where μ is a random number evenly distributed between 0 and 1. σ represents the scattering pitch angle, which is a random value:

$$\sigma = 2\pi\mu \quad (14)$$

If (U_x, U_y, U_z) is the photon motion vector before the last collision and (U_{x1}, U_{y1}, U_{z1}) is the photon motion vector after that, when $U_z \geq 0.999$, Eq. (15) applies:

$$\begin{cases} U_{x1} = \sin \beta \cdot \cos \sigma \\ U_{y1} = \sin \beta \cdot \sin \sigma \\ U_{z1} = \sin \beta \cdot \cos \beta \end{cases} \quad (15)$$

Otherwise, Eq. (16) is used for calculations:

$$\begin{cases} U_{x1} = \frac{\sin \beta (U_x \cdot U_z \cos \sigma - U_y \cdot \sin \sigma)}{\sqrt{1 - U_z^2}} + U_x \cdot \cos \beta \\ U_{y1} = \frac{\sin \beta (U_y \cdot U_z \cos \sigma + U_x \cdot \sin \sigma)}{\sqrt{1 - U_z^2}} + U_y \cdot \cos \beta \\ U_{z1} = -\sin \beta \cdot \cos \sigma \cdot \sqrt{1 - U_z^2} + U_z \cdot \cos \beta \end{cases} \quad (16)$$

The equations presented above comprise the underwater light diffusion model developed during this study.

LED luminous simulation

To test this model, the luminescence of two common LEDs was simulated: LEDs with a half power angle of 30° and LEDs with a half power angle of 60° . The asymmetry coefficient, g , was taken as 0.924, and the results are shown in Figure 3.

In pure sea water, the theoretical results of the two LEDs are approximately consistent with the actual results, but there are also some differences. The reason for the differences is that the absorption of light by the water makes the intensity in the transmission direction (an angle of 180°) lower than the theoretical value. Light scattering also makes the light intensity extend to both sides. Comparing the transmission results of single LEDs in different water qualities indicates that a worse water quality leads to a greater difference between the actual and theoretical light intensity distributions and more obvious absorption and scattering effects. Overall, the simulation results for the single LEDs are consistent with the theoretical predictions.

LED array layout

The placement of the LEDs in the space was designed to achieve the effect of uniform light coverage in the space. Figure 2C shows the coordinate system of the light-emitting end. It is assumed that the LEDs are distributed on a sphere with radius r , and that the luminous direction is consistent with the normal direction. N LEDs emit K photons in total, and some

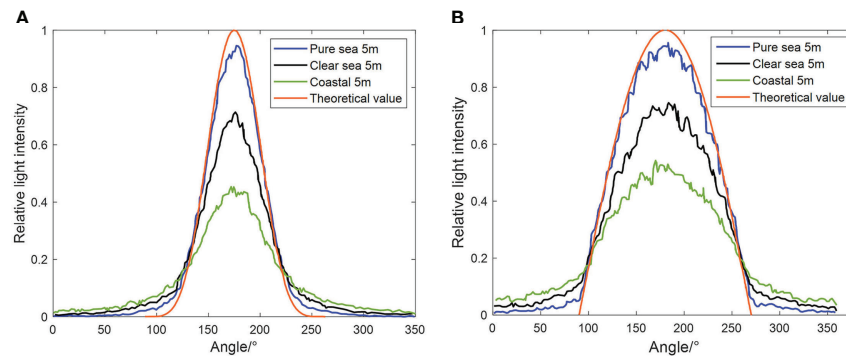


FIGURE 3
Luminous effects of single LEDs with half power angles of (A) 30° and (B) 60°.

photons reach the sphere at a distance L from the center. The spatial luminous effect of each LED can be described by two directions, φ and θ , in spherical coordinates. The influences of the two factors on the light intensity distribution do not interfere with each other, so they were studied separately.

φ direction

First, the change in light intensity caused by the arrangement of LEDs in the φ direction was studied. For the convenience of design, N was set as a number that can be divided by 360, that is, $N = 1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 15, \dots$. If V_1 is the emitting direction of the LED numbered 1 and V_i is the emitting direction of the LED numbered i , then $i \in [1, N]$ and Eq. (17) applies:

$$V_i = R_{i1} V_1 \quad (17)$$

In Eq. (17), R_{i1} represents the rotation matrix around the z -axis:

$$R_{i1} = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 & 0 \\ \sin \alpha & \cos \alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (18)$$

$$\alpha = \frac{360}{N} \times (i - 1) \quad (19)$$

The distribution of photons in the φ direction reaching the sphere is measured. There are two indicators to evaluate the effect of spatially distributed light: the minimum photon number in space and the luminous uniformity.

(1) Minimum photon number

The range of φ is $[0^\circ, 360^\circ]$ and is divided into 360 intervals, where each interval is 1° . The total number, m_i , of photons

reaching this interval is calculated and its minimum value is found. This minimum value is defined as M_i :

$$M_i = \min(m_i) \quad (20)$$

M_i can show the influence of the number of LEDs on the minimum photon number when the LEDs are evenly arranged.

(2) Luminous uniformity

The standard deviation of the number of photons reaching these intervals is defined as the luminous uniformity, ρ_i :

$$\rho_i = \sqrt{\frac{\sum_{i=0}^n (m_i - \bar{m})^2}{n - 1}} \quad (21)$$

In Eq. (21), $\bar{m}$ represents the average value of the photons and $n = 360$.

To obtain the best design scheme for the transmitter LED array, the luminescence of the LED array in the φ direction was analyzed using the mathematical model described above. When the total number of photons is the same, different numbers of LED groups are evenly distributed along the circumference in the φ direction. The photon distributions in space are compared. As shown in Figure 4, with increases in the number of LED groups, the light intensity fluctuations become smaller and the luminous uniformity improves.

Then, the minimum photon number and the standard deviation along the circumferential direction are used to compare the luminous uniformity, as shown in Figure 5. For different water qualities, when the half power angle is 30° and six or more groups of LEDs are distributed along the circumference, the minimum photon number and the standard deviation remain nearly unchanged, indicating that the light distribution is uniform.

Similarly, when the half power angle is 60° and three or more groups of LEDs are distributed along the circumference, the light distribution is uniform. Comparing the luminous effects of the two LEDs indicates that the LEDs with a half power angle of 60°

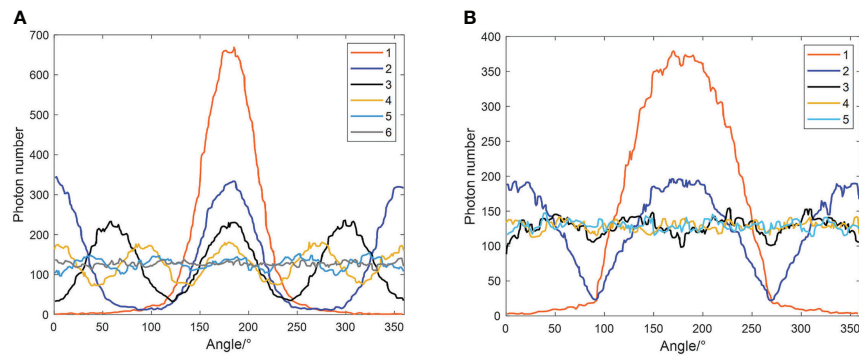


FIGURE 4

Photon distributions in the ϕ direction of the LED array with half power angles of (A) 30° and (B) 60°.

achieve a more uniform luminous effect with a smaller quantity of LEDs. Therefore, four groups of LEDs with a half power angle of 60° were used for the next analysis.

θ direction

The analysis methods for the θ and ϕ directions are the same. Since the AUV will have depth control when sinking, it

will not be at a large angle with the base station. Therefore, it is sufficient for the LED to cover an angle of 160° in the θ direction. The included angle between the LED and the z-axis is represented by γ . Since the photons in the area below the hemisphere are useless, the light effective utilization, ω , was used to quantify the useful light.

$$\gamma = \frac{\theta}{2} \quad (22)$$

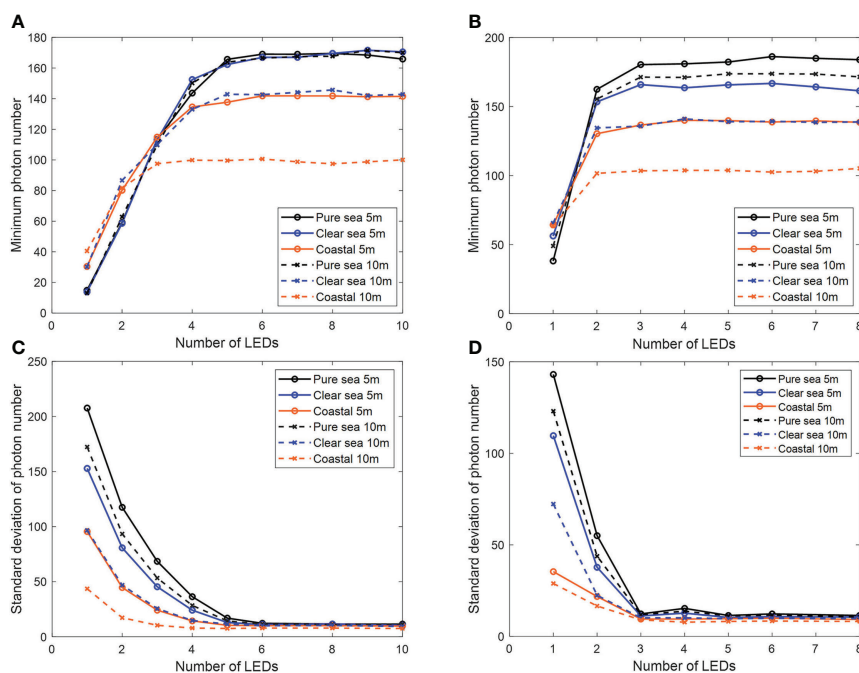


FIGURE 5

Minimum number of photons in the ϕ direction for LED arrays with half power angles of (A) 30° and (B) 60°. Standard deviation of the photon number in the ϕ direction for LED arrays with half power angles of (C) 30° and (D) 60°.

$$\omega = \frac{n_1}{n_0} \quad (23)$$

In Eq. (23), n_0 represents the number of photons emitted and n_1 is the number of photons in the upper hemisphere. When the number of LEDs is odd, to ensure light symmetry, the direction of one LED is vertically upward. When the number of LEDs is even, the LEDs are symmetrically distributed around the z-axis.

The luminescence in the θ direction was then simulated and analyzed. As shown in Figure 6, when $\gamma \in (60^\circ, 65^\circ)$, the photon standard deviation is small and the minimum photon density is large. A smaller included angle leads to a greater effective light utilization rate. Considering these three factors comprehensively, $\gamma = 60^\circ$ was taken as the design criterion.

Transmitter luminous simulation

Combined with the analyses in the φ and θ directions, the structural design of the transmitter was completed. The design consists of four groups of LEDs with a half power angle of 60° that are evenly distributed along the φ direction, with an included angle between these LEDs and the z-axis of 60° .

The transmitter model was imported into the optical simulation software Trace Pro for testing. As shown in Figure 7, the light is evenly distributed in the φ directions, and the coverage angle of the light in the θ direction increased to 83° . This model ensures uniform light distribution over a large range, which shows that the design is reasonable.

Photoelectric signal processing

Avalanche diodes can detect weak light with a high response frequency. An avalanche diode was chosen as the receiving

device when designing the system. To achieve stable communication, photoelectric signal processing is needed at the receiving end.

Noise filtering

The photocurrent of an avalanche diode must be amplified and shaped by an operational amplifier circuit. This process requires a high bias voltage and generates a large amount of noise, so it must be denoised before output.

Blue light band communication with a wavelength of approximately 400–480 nm was used. According to this characteristic, the blue light filter can be used to filter out most of the light with wavelengths not in this band. In this work, two different types of interference must also be eliminated: various noise interferences generated in the circuit and ambient light interference. In this work, a second-order Butterworth low-pass filter was used to filter the circuit noise. This filter has a good suppression effect on high-frequency signals and can be used to filter out high-frequency noise. A finite length unit impulse response digital filter (FIR) was used to filter the ambient light interference. The FIR filter ensures arbitrary amplitude frequency characteristics and strict linear phase frequency characteristics simultaneously, which can effectively filter out low-frequency sinusoidal ambient noise.

Improved 16-PPM algorithm

To avoid the interference of the environment and reduce the bit error rate, it is necessary to modulate and demodulate the optical signal. Pulse modulation is generally used for long-distance underwater optical communication, that is, optical pulses are used to transmit optical information. The pulse

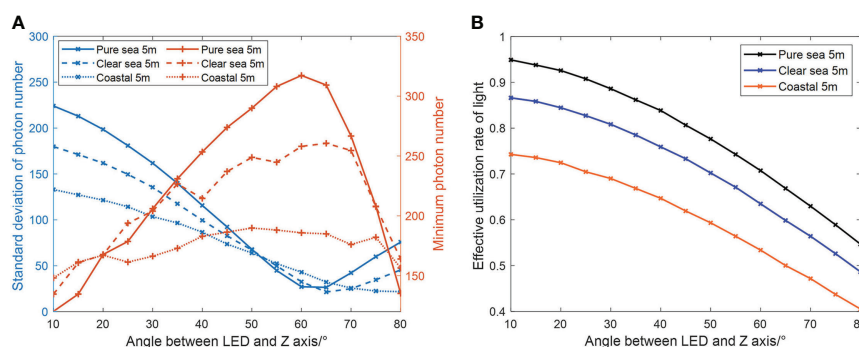


FIGURE 6
(A) Minimum photon number and standard deviation, (B) effective utilization of light in the θ direction of the LED array with a half power angle of 60° .

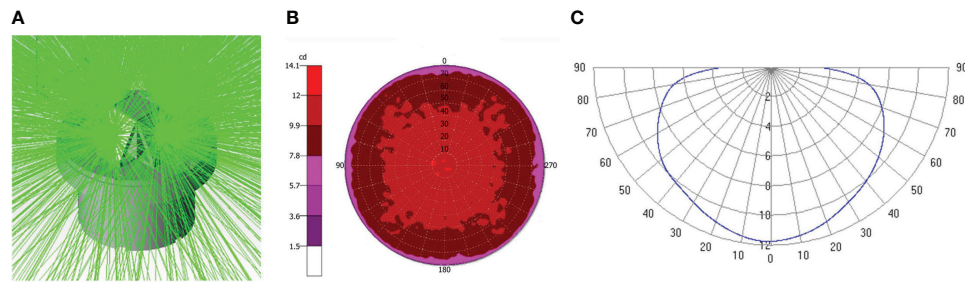


FIGURE 7
Luminous effect of (A) the transmitter and (B) the transmitter in the ϕ direction and (C) in the θ direction.

position modulation (PPM) method has the lowest bit error rate for long-distance underwater optical communication. Considering the transmission efficiency, the 16-PPM method was finally selected for information transmission.

The traditional PPM method has some defects. Owing to the limited production process and the influence of temperature, there are irregular errors in the clock frequency of the hardware system at the transmitter and receiver. This problem leads to continuous changes in the clock phase between the receiver and the transmitter, resulting in some misjudgments. For example, when the rising edge of a pulse reaches the receiving end, the clock at the receiving end is in the low state and the information cannot be effectively collected. Instead, it must wait until the high state of the next clock, so the arrival time is misjudged.

The solution to this problem is described next. The time between receiving the rising edge of one pulse and receiving the rising edge of the next pulse is measured. This time interval is used to accurately judge the distance between two adjacent pulses, so as to ensure the accuracy of demodulation. As is shown in Figure 8, two additional measures are also taken to increase the stability of communication.

(1) Increase the initial reference pulse

The length of the reference pulse is set to twice that of an ordinary pulse to indicate the beginning of communication. This is done to avoid misjudging the reference pulse due to short-term interference and to achieve frame synchronization.

(2) Add a protection slot

A blank time slot is placed after each pulse to prevent the front and rear pulses from interfering with each other. Although this change takes up time, it improves the communication stability.

Experimental results

Prototype

A system prototype was manufactured according to the method described above. The prototype was divided into two primary parts, a transmitter and a receiver, as shown in Figure 9. The transmitter used LEDs with a half power angle of 60° as the light-emitting device. Four groups of LEDs were evenly distributed along the circumference with an inclination of 60° .

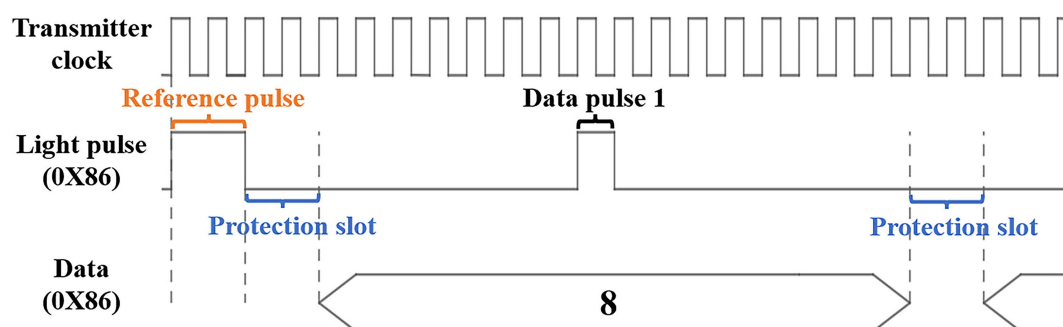


FIGURE 8
Schematic diagram of the improved 16-PPM method.

Avalanche diodes were used as signal receiving devices. An FPGA processing board was used for photoelectric signal modulation and demodulation, information caching, and processing. The devices were located in a mechanical pressure housing with a glass observation window that was sealed with an O-ring and a rubber gasket. We test the application reliability of the prototype through a heat dissipation simulation and pressure response experiment.

When an LED is emitting light, only 20%–30% of the energy is converted into light energy, and the rest is converted into heat energy. If the heat energy cannot be dispersed well, the temperature of the LED will rise rapidly. This will lead to a rapid decline in the luminous efficiency and will ultimately affect the communication effect. The maximum power of the system is 14 W; we simulate the heat dissipation of the transmitter, and

the results are shown in Figure 10. When the system is turned on at full power, high temperatures are concentrated at the luminous LED (approximately 35°C). At this temperature, the LED operation will not be significantly affected. This proves that the design presented in this paper is feasible.

To test the reliability of the equipment for deep-sea applications, we use the software ANSYS to conduct a withstand pressure analysis of the pressure housing. Because the housing is centrosymmetric, the simulation model can be simplified to a two-dimensional model as shown in Figure 11A. The housing is made of 6061-T6 aluminum alloy with a yield strength of 275 MPa. We add 30-MPa pressure to the outer surface of the housing in all directions, and the results are shown in Figure 11B. The simulation shows that there are stress concentration points at some corners that exceed the yield



FIGURE 9
Prototype: receiver on the left and transmitter on the right.

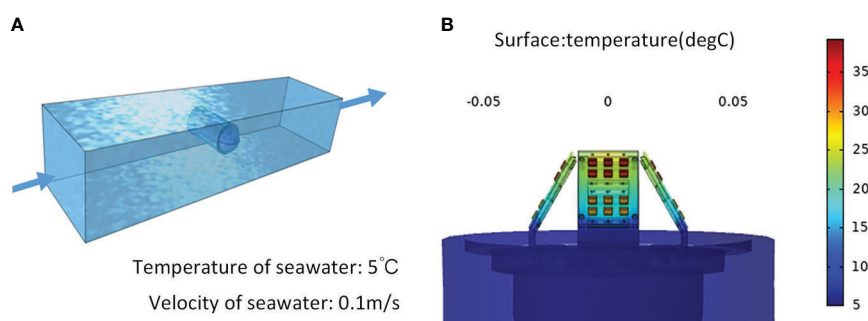


FIGURE 10
Heat dissipation simulation: (A) simulation model, (B) heat dissipation diagram of the transmitter when the thermal power is 14 W.

strength, so we add chamfers at the corners. As shown in Figure 11C, D, the pressure test is carried out on the prototype using a high-pressure experimental chamber. Since the target application depth of the prototype is 1500 m, the test pressure is set to 15 MPa. The prototype can withstand high pressure without water leakage and can be used in the deep sea normally.

Basic function test

As shown in Figure 12A, C, the basic function of the system was tested in the air. First, the light intensity of the transmitter was tested in all directions. A comparison between Figure 12B and Figure 7C shows that the measured light intensity curve was approximately the same as that from the simulation results. The difference is that the actual curve lies closer to the central axis than the curve from the simulation results. It was speculated that the reason for the difference is that the observation window outside the LED impacted the light distribution, causing the light to converge more toward the central axis. Then, the performance of the receiver was tested when receiving optical pulses of different frequencies. As shown in Figure 12D, the receiver successfully received optical pulses of different frequencies.

Although the square wave signal was slightly distorted, the communication quality was not affected.

Underwater communication experiment

Experiments on the underwater communication effect of the optical communication system were conducted, as shown in Figure 12E. The reception of square wave signals in the optical communication system was tested. On this basis, the bit error rate of the communication between the transmitter and the receiver at different distances was measured.

First, a 3.5 m short-range communication experiment was performed. During the test, the instantaneous power of the transmitter was 10 W and the square wave frequency was 2.5 MHz. The shape of the received pulse is shown in Figure 12F. The received pulse was a relatively regular square wave. Owing to the small distance, it differed slightly from the waveform in the air, only the falling edge was relatively slow and had a certain lag phenomenon. The rising edges of the driven and received signals coincided, while the shapes of the falling edges were different. Therefore, it is feasible to use the rising edge as a benchmark.

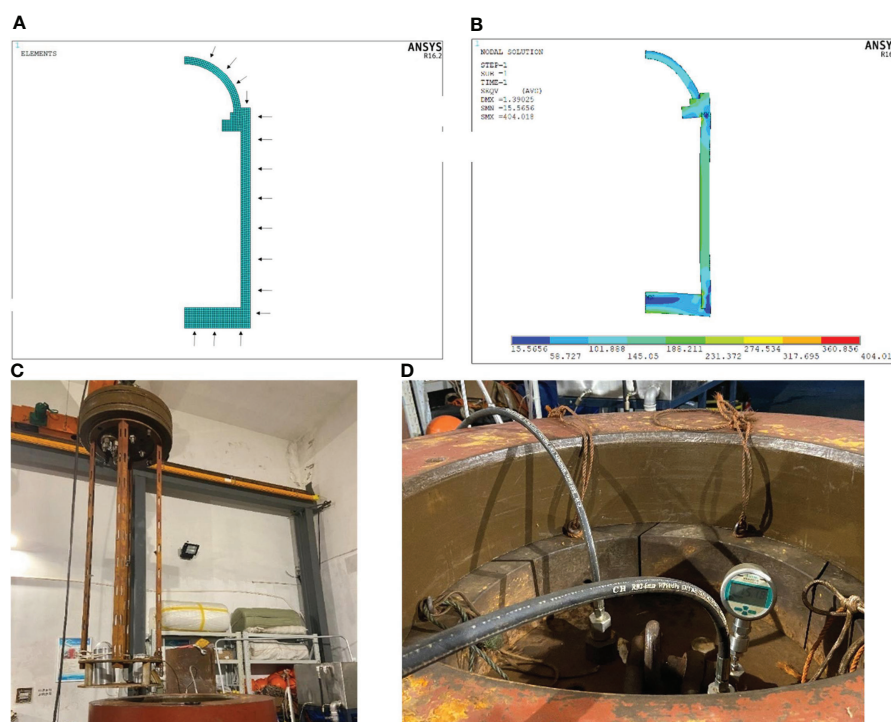


FIGURE 11
The pressure withstand experiment: (A) load model, (B) stress diagram of housing, (C) test in high-pressure experimental chamber, (D) pressure value.

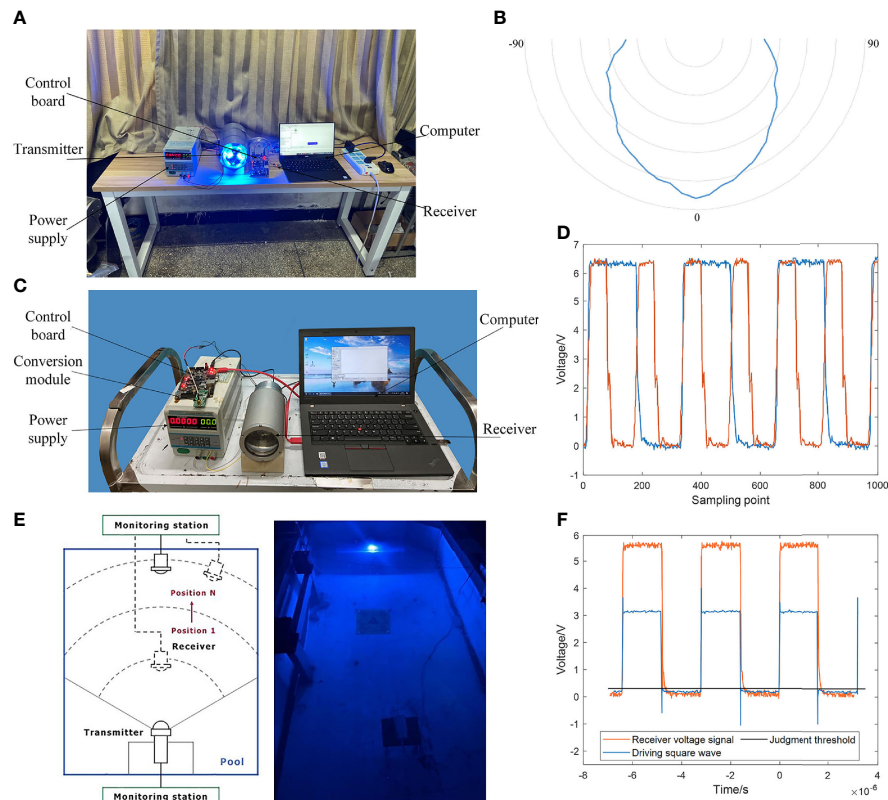


FIGURE 12

(A) Transmitter test system. (B) Actual luminous effect of the transmitter. (C) Receiver test system. (D) Receiving effect of the receiver on 2.5-MHz and 5-MHz optical pulses. (E) Underwater experiment. (F) Diagram comparing the received optical pulse signal and the driving signal.

The bit error rates for three different communication rates are shown in Table 2. The bit error rate of a certain communication distance is the maximum value of the bit error rate of three randomly sampled points when $\gamma \in [-30^\circ, 30^\circ]$. The data in this table demonstrate that the short-distance communication quality of the new equipment is very good.

Then, a long-distance communication experiment was conducted. The bit error rates for the long-distance communication are shown in Table 3 (NVI = no valid information). When the distance is greater than 12 m, the bit error rate begins to rise rapidly from 0. Demodulation cannot be performed at 15 m, a situation which applies to all three rates. Therefore, when the transmitter power is 10 W, the maximum underwater communication distance is 12–13 m. For larger distances, the bit error rate rises rapidly, and communication cannot continue.

To explain this phenomenon, the optical pulse signal at a distance of 13 m was measured. Figure 13 shows that the received optical pulse is seriously deformed. Although the photovoltage was still above 0.5 V at the beginning,

the voltage becomes increasingly smaller after that. When the distance continues to rise, it is predicted that part of the optical pulse voltage will be lower than the critical voltage, so that the pulse time for judgment will be shorter. This situation does not meet the conditions of demodulation, and the bit error rate will increase rapidly.

The experiments described above indicate that this new system achieved the expected goal better. When the transmitter power is 10 W, the maximum communication distance is 12–13 m. Theoretically, when the power of the transmitting end is 20 W, the communication distance will increase to approximately $\sqrt{2}x$, that is, the communication distance will be 17–18.5 m. This is not the distance limit. The communication distance can be further improved by reducing the judgment threshold.

Conclusions

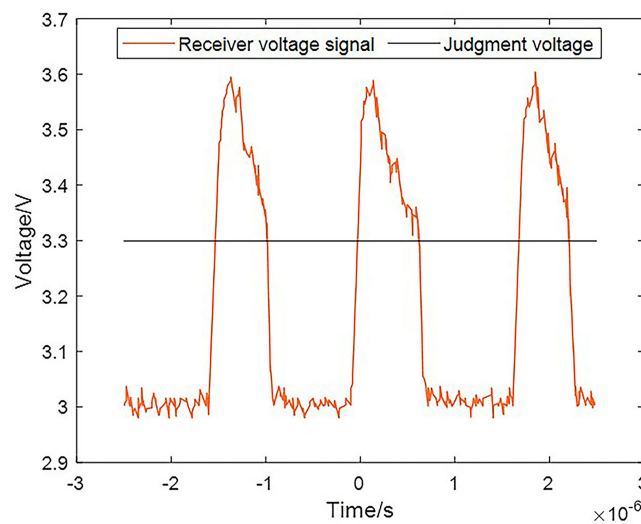
In this study, based on the research background of the information communication modes between a seabed

TABLE 2 Statistical table of communication bit error rates at a distance of 3.5 m.

Communication rate (Mbps)	Data size (kB)	Error number (Bit)	Error rate
0.25	1000	0	0
0.5	1000	0	0
1	1000	0	0

TABLE 3 Bit error rates for different distances and communication rates.

Distance (m)	0.25 Mbps	0.5 Mbps	1 Mbps
≤11	0	0	0
12	0	6.2×10^{-3}	3.4×10^{-3}
13	7.6×10^{-3}	2.6×10^{-2}	2.9×10^{-2}
14	1.12×10^{-1}	9.4×10^{-2}	1.37×10^{-1}
15	NVI	NVI	NVI

FIGURE 13
Optical pulse signal at a distance of 13 m.

observation base station and an information transmission medium, a space optical communication method suitable for the deep sea was proposed. Through research regarding the underwater luminescence mechanism of light-emitting elements, a transmitter was designed. By analyzing the transmission characteristics of underwater optical pulses and exploring photoelectric noise filtering methods, a receiver was designed. Existing pulse modulation and demodulation methods were improved to achieve better results. Finally, a complete set of space free optical communication prototypes was developed that can be used underwater. The simulations and basic function tests show that the prototype has good heat dissipation and high-

pressure resistance, and the prototype can be used in the deep sea. The communication experiments demonstrate that our system has good communication performance. The reliability and applicability of the system verify that our method is feasible and practical.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

YC: Methodology, Project administration, Investigation. LZ: Writing - Original Draft, Visualization, Validation. YL: Data Curation, Software. All authors contributed to the article and approved the submitted version.

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References

- Abrahamsen, F. E., Ai, Y., Wold, K., and Mohamed, M. (2021). Free-space optical communication: From space to ground and ocean. *IEEE Potentials*. 40, 18–23. doi: 10.1109/MPOT.2020.2979057
- Alexander, B., Felix, S., and Igor, M. (2021). "Practical applications of free-space optical underwater communication," in *2021 Fifth Underwater Communications and Networking Conference (UComms)*, Vol. 2021. (Lerici, Italy: IEEE), 2–6.
- Baiden, G., and Bissiri, Y. (2011). "High bandwidth spherical optical wireless communication for subsea telerobotic mining," in *OCEANS'11 MTS/IEEE KONA*. (Waikoloa, HI, US: IEEE), 1–4. doi: 10.23919/oceans.2011.6106950
- Baiden, G., Bissiri, Y., and Masoti, A. (2009). Paving the way for a future underwater omni-directional wireless optical communication systems. *Ocean Eng.* 152, 633–640. doi: 10.1016/j.oceaneng.2009.03.007
- Cao, X.-L., Jiang, W., and Tong, F. (2018). Time reversal MFSK acoustic communication in underwater channel with large multipath spread. *Ocean Eng.* 152, 203–209. doi: 10.1016/j.oceaneng.2018.01.035
- Che, X., Wells, I., Dickens, G., Kear, P., and Gong, X. (2010). Re-evaluation of RF electromagnetic communication in underwater sensor networks. *IEEE Commun. Mag.* 48, 143–151. doi: 10.1109/MCOM.2010.5673085
- Coenenour, B. M., Mullen, L. J., and Laux, A. E. (2008). Characterization of the beam-spread function for underwater wireless optical communications links. *IEEE J. Ocean. Eng.* 33, 513–521. doi: 10.1109/OJE.2008.2005341
- Donic, M., and Rus, D. (2010). "BiDirectional optical communication with AquaOptical II," in *12th IEEE Int. Conf. Commun. Syst. 2010, ICCS*, Vol. 2010. 2010 *IEEE International Conference on Communication Systems*. (Singapore: IEEE) 390–394. doi: 10.1109/ICCS.2010.5686513
- Farr, N., Chave, A. D., Freitag, L., Preisig, J., White, S. N., Yoerger, D., et al. (2006). Optical modem technology for seafloor observatories. *Ocean* 2006, 1–7. doi: 10.1109/OCEANS.2006.306806
- Han, X., Yin, J., Tian, Y., and Sheng, X. (2019b). Underwater acoustic communication to an unmanned underwater vehicle with a compact vector sensor array. *Ocean Eng.* 184, 85–90. doi: 10.1016/j.oceaneng.2019.03.024
- Han, B., Zhao, W., Zheng, Y., Meng, J., Wang, T., Han, Y., et al. (2019a). Experimental demonstration of quasi-omni-directional transmitter for underwater wireless optical communication based on blue LED array and freeform lens. *Opt. Commun.* 434, 184–190. doi: 10.1016/j.optcom.2018.10.037
- Huang, X., Yang, F., and Song, J. (2019). Hybrid LD and LED-based underwater optical communication: State-of-the-art, opportunities, challenges, and trends [Invited]. *Chin. Opt. Lett.* 17, 100002. doi: 10.3788/col201917.100002
- Liu, L., Liao, Z., Chen, C., Chen, J., Niu, J., Jia, Y., et al. (2019). A seabed real-time sensing system for *in-situ* long-term multi-parameter observation applications. *Sensors (Switzerland)*. 19. doi: 10.3390/s19051255
- N'Doye, I., Zhang, D., Alouini, M. S., and Laleg-Kirati, T. M. (2021). Establishing and maintaining a reliable optical wireless communication in underwater environment. *IEEE Access* 9, 62519–62531. doi: 10.1109/ACCESS.2021.3073461
- Pontbriand, C., Farr, N., Hansen, J., Kinsey, J. C., Pelletier, L. P., Ware, J., et al. (2016). "Wireless data harvesting using the AUV sentry and WHOI optical modem," in *Ocean. OCEANS 2015 - MTS/IEEE Washington*. (Washington, DC, USA: IEEE).. doi: 10.23919/oceans.2015.7401985
- Pontbriand, C., Farr, N., Ware, J., Preisig, J., and Popenoe, H. (2008). *Diffuse high-bandwidth optical communications*. (Quebec City, QC, Canada: IEEE).
- Sahoo, A., Dwivedy, S. K., and Robi, P. S. (2019). Advancements in the field of autonomous underwater vehicle. *Ocean Eng.* 181, 145–160. doi: 10.1016/j.oceaneng.2019.04.011
- Sherlock, M., Marouchos, A., and Williams, A. (2014). "An instrumented corer platform for seabed sampling and water column characterisation," in *Ocean. OCEANS 2014 - TAIPEI*. (Taipei, Taiwan: IEEE). doi: 10.1109/OCEANS-TAIPEI.2014.6964367
- Song, S., Kobayashi, Y., and Fujie, M. G. (2013). Monte-Carlo simulation of light propagation considering characteristic of near-infrared LED and evaluation on tissue phantom. *Proc. CIRP*. 5, 25–30. doi: 10.1016/j.procir.2013.01.005
- Su, R., Zhang, D., Li, C., Gong, Z., Venkatesan, R., and Jiang, F. (2019). Localization and data collection in AUV-aided underwater sensor networks: Challenges and opportunities. *IEEE Netw.* 33, 86–93. doi: 10.1109/MNET.2019.1800425
- Yoon, S., Azad, A. K., Oh, H., and Kim, S. (2012). AURP: An AUV-aided underwater routing protocol for underwater acoustic sensor networks. *Sensors* 12, 1827–1845. doi: 10.3390/s120201827
- Zafar, S., and Khalid, H. (2021). Free space optical networks: Applications, challenges and research directions. *Wirel. Pers. Commun.* 121, 429–457. doi: 10.1007/s11277-021-08644-4
- Zhang, D., N'doye, I., Ballal, T., Al-Naffouri, T. Y., Alouini, M. S., and Laleg-Kirati, T. M. (2020a). Localization and tracking control using hybrid acoustic-optical communication for autonomous underwater vehicles. *IEEE Internet Things. J.* 7, 10048–10060. doi: 10.1109/JIOT.2020.2995799
- Zhang, S., Yang, X., Wang, Y., Zhao, Z., Liu, J., Liu, Y., et al. (2020b). Automatic fish population counting by machine vision and a hybrid deep neural network model. *Animals* 10, 1–17. doi: 10.3390/ani10020364
- Zhu, S., Chen, X., Liu, X., Zhang, G., and Tian, P. (2020). Recent progress in and perspectives of underwater wireless optical communication. *Prog. Quantum. Electron.* 73, 100274. doi: 10.1016/j.pquantelec.2020.100274

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Performance study of energy conversion system for ocean thermal profiler

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With the increasing scarcity of energy in the world, energy has become an important part of restricting the development and application of traditional ocean profilers. The method of converting ocean thermal energy (OTE) into electrical energy through an energy conversion system is a solution. The model establishment and performance analysis of the energy conversion system are the basis of the ocean thermal profiler (OTP) design. The model and performance are affected by the coupling of multiple parameters, especially rotational speed and pressure. In this study, a universal parameterized model for multi-parameter coupling was proposed. System performance analysis based on experiments including load current, speed, mechanical efficiency and total efficiency was presented. After model parameter identification, the error of mechanical efficiency was within 5%; the total efficiency error was less than 12.8%, and the maximum efficiency point error didn't exceed 2.21%. The results indicated that the parameterized model was satisfactory for the engineering applications and could guide the design of OTP.

KEYWORDS

ocean thermal profiler, energy conversion system, mathematical modelling, efficiency, performance analysis

1 Introduction

Profiler used for monitoring ocean profile elements are important platforms for marine scientific research. Traditional ocean profilers, such as ARGO buoys and underwater gliders, usually include many batteries. Owing to the limitations of battery capacity, they can only perform simple and short-term missions, which greatly restricts their long-term and complex applications in the ocean. In the face of energy constraints, harnessing marine renewable energy with energy conversion system is an effective solution (Khan et al., 2017; Wilberforce et al., 2019). Considering the pattern of profile motion, wave energy and tidal energy are mainly concentrated in shallow waters

(Townsend, 2016; Townsend and Sheno, 2016; Song et al., 2018); wind energy and solar energy are limited to the ocean surface and are significantly affected by weather (Tian and Yu, 2019); ocean pressure energy is related to the working depth of the profiler, which can only compensate for energy consumption (Xue et al., 2020); however, ocean thermal energy (OTE) reserves are abundant. At present, the large-scale ocean thermal energy conversion (OTEC) technology is mature, which can be generally distinguished as closed-cycle, open-cycle and hybrid cycle (Huang et al., 2003). In the closed-cycle structure, the ejector refrigeration cycle and spray flash evaporation desalination unit realize desalination and refrigeration (Zhou et al., 2021). The OTEC has been effectively applied in the energy and freshwater supply of the island (Osorio et al., 2016). The researches of large-scale OTEC indicate that OTE is widely distributed and has a stable structure. Compared to other types of marine renewable energy sources, OTE is more suitable for ocean profilers.

An ocean thermal profiler (OTP) can capture and utilize OTE. Compared with direct driving by OTE, the method of converting OTE into electrical energy through an energy conversion system to drive is safer and more reliable. Two categories of energy conversion system can be classified according to the power generation principles. (1) Using thermoelectric generators (TEGs) to convert OTE into electrical energy directly (Buckle et al., 2013; Falcão Carneiro and Gomes de Almeida, 2018); (2) using solid-liquid phase change materials (PCMs) to capture OTE, and then convert it into electrical energy through an energy conversion system. The energy conversion system is mainly composed of a hydraulic motor and a generator. Owing to its compact structure and high energy-density ratio, it more suitable for OTP and has been widely applied. SOLO-TREC (Chao, 2016), Slocum-TREC (Haldeman et al., 2015) and SL1 (15) are equipped with energy conversion system to provide energy supply, which greatly increased the voyage and sampling frequency.

The performance study of the energy conversion system through modelling can provide important support for the design, motion control, and energy optimization of the OTP. Currently, most studies have concentrated on the conversion system of wind energy, wave energy, tidal energy, and hydraulic energy (Chen et al., 2020; He et al., 2020). Fan et al. studied the modelling and control of a hybrid wind-tidal turbine with an accumulator. A hydraulic transmission device was used to integrate and transmit the captured energy. The hydraulic accumulator balanced output power and demand by storing and releasing excess energy. Finally, they developed and integrated a mathematical model of the system (Fan et al., 2016). Walter Gil-González et al. established a dynamic model for small hydro-power plant, and designed a controller based on passivity theory which better than PI controller (Gil-González et al., 2020). Wei et al. proposed a new type of closed hydraulic wind turbine with an energy storage system and demonstrated

the parametric design and modelling of a 600 kW hydraulic wind turbine using a Micon 600 kW wind turbine as an example (Wei et al., 2018). Chan Roh et al. established a mathematical model for the hydraulic system of floating wave energy converters, which included an accumulator, hydraulic motor, and generator. The proposed maximum power control algorithm based on the model increased the output power by 18% (Roh et al., 2021). Wang et al. established a mathematical model for the key components of the hydraulic energy storage and conversion system of a wave energy converter, which provided theoretical guidance for optimizing the energy conversion efficiency (Wang and Lu, 2018). Jónsdóttir et al. proposed a stochastic models of the short-term variability for wave energy and tidal energy based on the Irish system, which indicated that tidal generation leads to larger frequency variations than those that are caused by wind generation (Jónsdóttir and Milano, 2020). Zhang et al. proposed an electro-hydraulic energy collection damper for off-road vehicles, which could convert the vibration of a reciprocating suspension into one-way rotation of the generator, and they mathematically deduced the dynamic model of the system. Simultaneously, an experimental test proved the effectiveness of its energy collection capacity (Zhang et al., 2017). Ho et al. proposed a new hydraulic closed-loop hydrostatic transmission energy-saving system and developed a hydraulic pump/motor efficiency model for speed, displacement, and differential pressure. The maximum energy recovery efficiency was 66% (Ho and Ahn, 2010).

However, research on the modelling of energy conversion systems for the OTP has been scarce. Owing to the nonlinear characteristics, Xia et al. applied the neural network method to identify and model the energy conversion system of the OTP and obtained the curved surface of the efficiency on the inlet pressure of the hydraulic motor and the load current of the generator (Xia et al., 2020). Wang et al. established a comprehensive energy conversion efficiency model of the OTP, developed a system prototype OTEC, and successfully completed a sea trial. The converted energy initially met the energy requirements of the OTEC (Wang et al., 2019).

Above research has mostly ignored the actual working conditions of energy conversion systems for OTP, especially the change in the mechanical efficiency and the total efficiency with the rotation speed and pressure; thus, performance study is not comprehensive. In this paper, the factors affecting the performance of energy conversion system are analyzed according to the operation principle of OTP. A universal parameterized model of the total efficiency for the energy conversion system are proposed. The performance analysis is presented by establishing an experimental platform. Simultaneously, experimental data are used to identify parameters of the parameterized model and verify the accuracy.

The remainder of this paper is organized as follows. Section 2 introduces the operation principle of OTP, analyses the

affecting factors of performance and presents an experimental platform. In Section 3, the parameterized model of the energy conversion system is established. In Section 4, performance analysis and experimental verification are presented. Section 5 provides a brief conclusion.

2 System overview and experimental platform

2.1 System overview

The OTP collects data of the ocean's vertical profile by moving up and down while capturing OTE and generating electricity to power sensors, controllers, GPS, and other electronic equipment. The OTP is mainly composed of a thermal engine, energy conversion system, buoyancy adjustment system, data acquisition and communication systems, control system, and a pressure hull. The thermal engine, buoyancy adjustment system, and energy conversion system jointly realize OTP movement and power generation. The thermal engine was encapsulated with PCM to capture the OTE. When the OTP is in warm water, the volume of the PCM increases and external work is performed to convert OTE into potential energy and store it in the accumulator. The energy conversion system is mainly composed of a hydraulic motor, generator, and battery, which can convert the potential energy of the accumulator into electrical energy.

Figure 1 shows the energy conversion and operation principle of the OTP, which is mainly divided into four stages. (1) The water surface stage: the OTP stays on warm water, the PCM melts and expands, and the oil in the thermal engine is pumped into the accumulator to realize OTE capture. (2) The sinking stage: the buoyancy adjustment system regulates oil return from the external bladder to the internal bladder so that the buoyancy decreases and the OTP sinks. (3) The deep water stage: the OTP is located in cold water, the PCM solidifies and shrinks, and the oil in the internal bladder is sucked into the thermal engine. (4) The rising stage: the oil in the accumulator enters the external bladder through the hydraulic motor so that the buoyancy becomes larger and the OTP rises. Simultaneously, the hydraulic motor drives the generator to generate electricity and store electric energy in the battery.

The energy conversion system adopts an energy storage power generation mode. According to the operation principle of the OTP, the energy conversion system is characterized by the following. (1) In a single profile, the total amount of OTE stored by the accumulator is certain; (2) the hydraulic motor inlet pressure follows the accumulator pressure and gradually decreases; and (3) the outlet pressure of the hydraulic motor changes with the pressure of the external bladder, which is the water pressure during power generation. Therefore, the performance of energy conversion system is affected by the coupling of multiple parameters. The parameters of the hydraulic motor include inlet pressure, outlet pressure, displacement, and speed. The parameters of the generator include the power, voltage, armature resistance, speed constant, torque constant, and reducer.

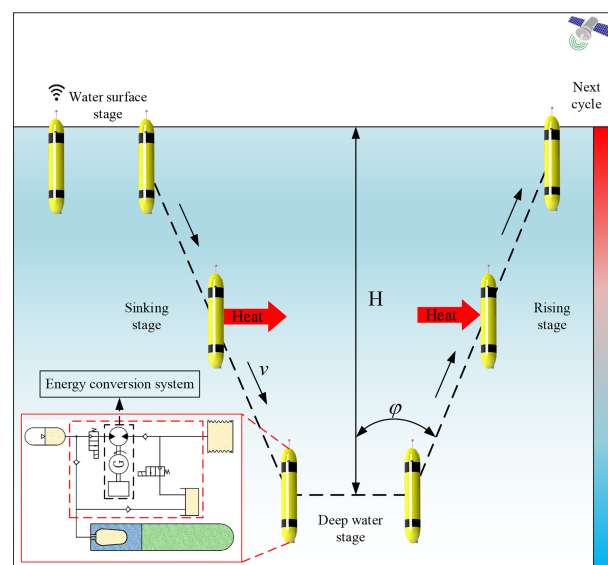


FIGURE 1
The principle of the operation and the energy conversion for the OTP.

In practical applications, it was found that the mechanical efficiency of the hydraulic motor was significantly affected by the speed, and the traditional mechanical efficiency model was not suitable for the energy conversion system of the OTP. When the hydraulic motor and generator are determined, the performance of energy conversion system is mainly affected by the pressure, speed and load current.

2.2 Experimental platform

According to system overview of the OTP, the experimental platform for the energy conversion system is designed and shown in Figure 2. The pump station provides a pressure source for the energy conversion system and can adjust the inlet pressure of the hydraulic motor to maintain stable pressure. A relief valve was set between the outlet of the hydraulic motor and the oil return port of the pump station to form the outlet pressure and simulate the seawater pressure. The hydraulic motor and generator were connected through torque and speed sensors to monitor the changes in torque and speed during power generation. Flow meters and pressure sensors were installed at the inlet and outlet of the hydraulic motor to collect the pressure and flow. The output of the generator is connected to a programmable electronic load that adopts the constant-current mode to adjust the load current of the generator. The computer controlled the electronic load to change the load current of the generator to adjust the speed of the hydraulic motor.

The component parameters used in the experimental platform of the energy conversion system are listed in Table 1. The outlet pressure of the hydraulic motor was set at 5 MPa to

simulate the seawater pressure. Under each fixed pressure during the experiment, the controller controlled the speed of the hydraulic motor rising from 300 rpm to 2000 rpm while controlling and collecting data every 50 rpm.

3 Mathematical modelling

3.1 Hydraulic motor model

A hydraulic motor is a hydraulic actuator that converts hydraulic energy into rotational mechanical energy. It is one of the core components of energy conversion systems. The swashplate axial piston hydraulic motor has the advantages of a high working pressure, high working speed, and compact structure. It is suitable for the highly integrated energy conversion system of the OTP.

The working principle and force analysis of the swashplate axial piston hydraulic motor are shown in Figure 3. The high-pressure oil with an inlet pressure P_1 enters the bottom of the plunger through the flow distribution window of the port plate to push the plunger outwards and cause the slippers to press against the swash plate. The acting force F_N is decomposed into the axial component force F_z balanced with the hydraulic pressure of the plunger and the force F_y perpendicular to the axis of the plunger. F_y forms torque on the axis of the cylinder block and drives the cylinder block to rotate against the load. The effect of the outlet pressure P_2 is similar to that of the inlet pressure, but it acts as a hindrance.

The number of plungers Z of the hydraulic motor is mostly odd, which reduces the flow non-uniformity coefficient. Therefore, there are two scenarios for the number of plungers

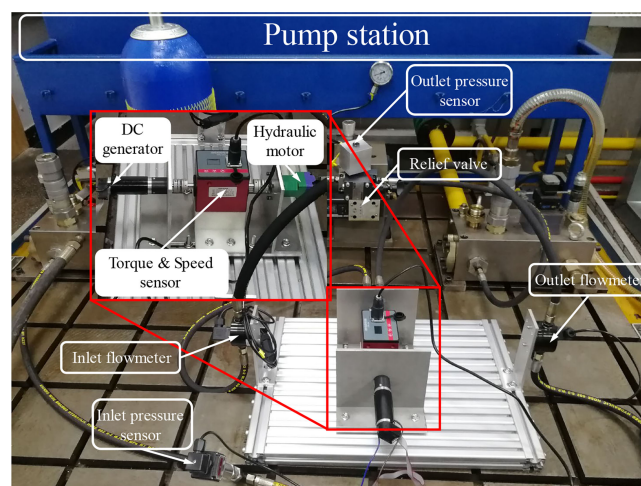


FIGURE 2
The experimental platform of the energy conversion system.

TABLE 1 The component parameters used in the experimental platform of energy conversion system.

Item	Parameter	Value
Hydraulic motor	D	0.4 cc/rev
	P_2	5 MPa
Reducer	I	4
DC generator	Max. speed	8000 rpm
	K_A	0.0292 N■m/A
	K_V	328 rpm/V
	ΔT	0.013 N■m
	R	0.583 Ω
	ΔR	0.47 Ω

connecting the high-pressure oil of the port plate.

$$\begin{cases} \frac{Z+1}{2}, & 0 \leq \varphi \leq \frac{\alpha}{2} \\ \frac{Z-1}{2}, & \frac{\alpha}{2} < \varphi \leq \alpha \end{cases} \quad (1)$$

where φ is the rotation angle of the deepest plunger embedded in the cylinder block relative to the bottom dead centre and α is the angle between two adjacent plungers.

$$\alpha = \frac{2\pi}{Z} \quad (2)$$

3.1.1 The mechanical efficiency model

Mechanical efficiency is a parameter used to evaluate the degree of mechanical loss in a hydraulic motor. The friction loss of the swashplate axial piston hydraulic motor is mainly caused by the relative motion of the friction pair between the bottom surface of the cylinder block and port plate, between the plungers

and swashplate, and between the plunger and plunger cavity. The mechanical efficiency of the hydraulic motor is expressed as follows:

$$\eta_M = \frac{T_p}{T_t} = 1 - \frac{T_{loss}}{T_t} \quad (3)$$

where T_t is the theoretical torque, T_p is the practical torque, and T_{loss} is the friction-loss torque.

According to the force analysis shown in Figure 2, T_t and T_{loss} can be deduced (Ke et al., 2006; Yongqiang, 2008; Tianliang and Yueying, 2012).

(1) The force of the inlet and outlet pressure oil is transmitted to the swash plate through the plunger and slipper, and the average torque is produced by the reaction force generated by the swash plate on the output shaft. The average torque is T_t .

$$\begin{aligned} T_t &= \frac{1}{\alpha} \int_0^\alpha M_0 d\varphi \\ &= \frac{1}{\alpha} \left\{ \int_0^{\frac{\alpha}{2}} \left[\sum_{i=0}^{\frac{z-1}{2}} AP_1 \tan \gamma r_0 \sin(\varphi + i\alpha) - \sum_{i=\frac{z-1}{2}}^{z-1} AP_2 \tan \gamma r_0 \sin(\varphi + i\alpha) \right] d\varphi \right. \\ &\quad \left. + \int_{\frac{\alpha}{2}}^\alpha \left[\sum_{i=0}^{\frac{z-3}{2}} AP_1 \tan \gamma r_0 \sin(\varphi + i\alpha) - \sum_{i=\frac{z-1}{2}}^{z-1} AP_2 \tan \gamma r_0 \sin(\varphi + i\alpha) \right] d\varphi \right\} \\ &= \frac{ZAr_0 \tan \gamma}{\pi} (P_1 - P_2) \times 10^6 = \frac{\Delta P \cdot D}{2\pi} \end{aligned} \quad (4)$$

where M_0 is the instantaneous friction torque on the output shaft caused by the reaction force generated by the inlet and outlet pressure oil transmitted to the swash plate, A is the cross-sectional area of the plunger, γ is the inclination angle of the swash plate, r_0 is the radius of the plunger distribution circle, P_1 is the inlet pressure of the hydraulic motor, P_2 is the outlet pressure of the hydraulic motor, ΔP is the pressure difference

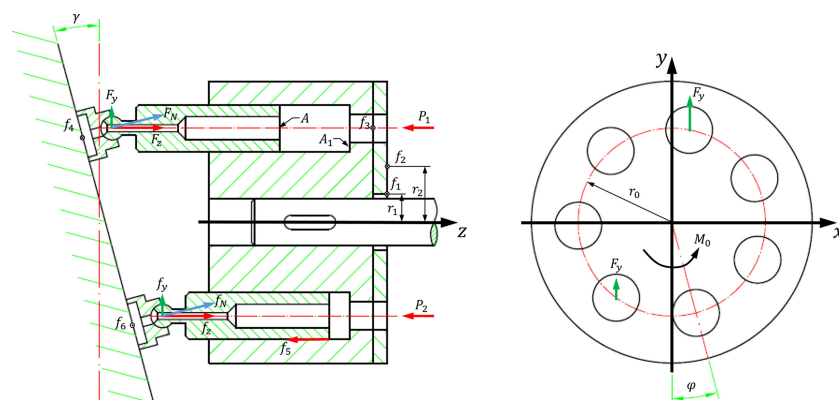


FIGURE 3 The working principle and force analysis of the swashplate axial piston hydraulic motor.

between the inlet and outlet of the hydraulic motor, and D is the displacement of the hydraulic motor.

(2) Average friction torque T_1 of the output shaft owing to friction generated by the radial force of the bearing

$$\begin{aligned} T_1 &= \frac{1}{\alpha} \int_0^\alpha M_1 d\varphi \\ &= \frac{1}{\alpha} \left\{ \int_0^{\frac{\alpha}{2}} \left[\sum_{i=0}^{\frac{z-1}{2}} \mu_1 A P_1 \tan \gamma r_1 + \sum_{i=\frac{z+1}{2}}^{z-1} \mu_1 A P_2 \tan \gamma r_1 \right] d\varphi \right. \\ &\quad \left. + \int_{\frac{\alpha}{2}}^\alpha \left[\sum_{i=0}^{\frac{z-3}{2}} \mu_1 A P_1 \tan \gamma r_1 + \sum_{i=\frac{z-1}{2}}^{z-1} \mu_1 A P_2 \tan \gamma r_1 \right] d\varphi \right\} \\ &= \frac{\mu_1 Z A r_1 \tan \gamma \times 10^6}{2} (P_1 + P_2) \end{aligned} \quad (5)$$

where M_1 is the instantaneous friction torque produced by the friction generated by the radial force of the bearing on the output shaft, r_1 is the action radius of friction f_1 , and μ_1 is the friction factor of the action surface of friction f_1 .

(3) The average friction torque T_2 of the friction generated by the axial force of the bearing on the output shaft is

$$\begin{aligned} T_2 &= \frac{1}{\alpha} \int_0^\alpha M_2 d\varphi \\ &= \frac{1}{\alpha} \left\{ \int_0^{\frac{\alpha}{2}} \left[\sum_{i=0}^{\frac{z-1}{2}} \mu_2 A P_1 \tan \gamma r_2 + \sum_{i=\frac{z+1}{2}}^{z-1} \mu_2 A P_2 \tan \gamma r_2 \right] d\varphi \right. \\ &\quad \left. + \int_{\frac{\alpha}{2}}^\alpha \left[\sum_{i=0}^{\frac{z-3}{2}} \mu_2 A P_1 \tan \gamma r_2 + \sum_{i=\frac{z-1}{2}}^{z-1} \mu_2 A P_2 \tan \gamma r_2 \right] d\varphi \right\} \\ &= \frac{\mu_2 Z A r_2 \tan \gamma \times 10^6}{2} (P_1 + P_2) \end{aligned} \quad (6)$$

where M_2 denotes the instantaneous friction torque produced by the friction generated by the axial force of the bearing on the output shaft, r_2 denotes the action radius of friction f_2 , and μ_2 denotes the friction factor of the action surface of friction f_2 .

(4) The average friction torque T_3 of the output shaft caused by the friction between the bottom surface of the cylinder block and the port plate is given by

$$\begin{aligned} T_3 &= \frac{1}{\alpha} \int_0^\alpha M_3 d\varphi \\ &= \frac{1}{\alpha} \left\{ \int_0^{\frac{\alpha}{2}} \left[\sum_{i=0}^{\frac{z-1}{2}} \mu_3 A_1 P_1 r_0 + \sum_{i=\frac{z+1}{2}}^{z-1} \mu_3 A_1 P_2 r_0 \right] d\varphi \right. \\ &\quad \left. + \int_{\frac{\alpha}{2}}^\alpha \left[\sum_{i=0}^{\frac{z-3}{2}} \mu_3 A_1 P_1 r_0 + \sum_{i=\frac{z-1}{2}}^{z-1} \mu_3 A_1 P_2 r_0 \right] d\varphi \right\} = \frac{\mu_3 Z A_1 r_0 \times 10^6}{2} (P_1 + P_2) \end{aligned} \quad (7)$$

where M_3 is the instantaneous friction torque transmitted to the output shaft by the friction generated between the bottom surface of the cylinder block and port plate, μ_3 is the friction

factor of the friction f_3 action surface, and A_1 is the action area of the pressure oil in the cylinder bore.

(5) The average friction torque T_4 of the output shaft caused by friction between the swash plate and sliding shoe is given as follows.

$$\begin{aligned} T_4 &= \frac{1}{\alpha} \int_0^\alpha M_4 d\varphi \\ &= \frac{1}{\alpha} \left\{ \int_0^{\frac{\alpha}{2}} \left[\sum_{i=0}^{\frac{z-1}{2}} c_1 \mu_4 \frac{A P_1}{\cos \gamma} \frac{r_0}{\cos \gamma} + \sum_{i=\frac{z+1}{2}}^{z-1} c_1 \mu_4 \frac{A P_2}{\cos \gamma} \frac{r_0}{\cos \gamma} \right] d\varphi \right. \\ &\quad \left. + \int_{\frac{\alpha}{2}}^\alpha \left[\sum_{i=0}^{\frac{z-3}{2}} c_1 \mu_4 \frac{A P_1}{\cos \gamma} \frac{r_0}{\cos \gamma} + \sum_{i=\frac{z-1}{2}}^{z-1} c_1 \mu_4 \frac{A P_2}{\cos \gamma} \frac{r_0}{\cos \gamma} \right] d\varphi \right\} \\ &= \frac{c_1 \mu_4 Z A r_0 \times 10^6}{2 (\cos \gamma)^2} (P_1 + P_2) \end{aligned} \quad (8)$$

where M_4 is the instantaneous friction torque transmitted to the output shaft by the friction generated between the swash plate and slipper, μ_4 is the friction factor between the swashplate and slipper, and c_1 is the transmission coefficient of the friction torque generated by friction f_4 to the output shaft.

(6) The average friction torque T_5 of the friction generated by the centrifugal force of the plunger acting on the cylinder block to the output shaft is given by

$$\begin{aligned} T_5 &= \frac{1}{\pi} \int_0^\alpha M_5 d\varphi = \frac{1}{\pi} \int_0^\pi Z \mu_5 m r_0 \omega^2 \tan \gamma r_0 \sin \varphi d\varphi \\ &= \frac{2 Z \mu_5 m \tan \gamma r_0^2 \times 10^6}{\pi} \left(\frac{2 \pi n}{60} \right)^2 \end{aligned} \quad (9)$$

where M_5 denotes the instantaneous friction torque of the output shaft caused by the friction force generated by the centrifugal force of the plunger acting on the cylinder, μ_5 denotes the friction factor of the action surface of the friction force f_5 , m denotes the plunger mass, and n denotes the hydraulic motor speed.

Therefore, T_{loss} can be expressed as follows.

$$T_{loss} = T_1 + T_2 + T_3 + T_4 + T_5 \quad (10)$$

From equations (5)–(9), it can be seen that the friction loss of the hydraulic motor is related to the inlet pressure P_1 , outlet pressure P_2 , displacement D , and speed n because

$$P_1 + P_2 = \Delta P + P_2 \quad (11)$$

Thus, T_{loss} can be rewritten as

$$T_{loss} = C_1 n^2 + C_2 n + C_3 D (\Delta P + 2 P_2) \quad (12)$$

where C_1 , C_2 , and C_3 are undetermined parameters. Substituting Equations (4) and (12) into Equation (3) to obtain the mechanical efficiency model of the hydraulic motor, we obtain the following.

$$\eta_M = \frac{-2\pi C_1}{\Delta P \cdot D} n^2 + \frac{-2\pi C_2}{\Delta P \cdot D} n + 1 - 2\pi k_3 + \frac{-4\pi C_3 P_2}{\Delta P} \quad (13)$$

3.1.2 The volumetric efficiency model

The power loss caused by the internal and external leakage of the liquid, including the internal leakage of the working chamber volume due to the compressibility of the liquid, is expressed in terms of volumetric efficiency as follows.

$$\eta_V = \frac{q_{Vt}}{q_V} = \frac{q_{Vt}}{q_{Vt} + \Delta q} = \frac{1}{1 + \frac{\Delta q}{q_{Vt}}} \quad (14)$$

where q_V is the actual flow, q_{Vt} is the theoretical flow, and Δq is the internal leakage flow of liquid in the hydraulic motor.

$$\Delta q = C_V \frac{\Delta P \cdot D}{\mu_{oil}} \quad (15)$$

Substituting Equation (16) into Equation (15) to obtain the volumetric efficiency model of the hydraulic motor, we obtain

$$\eta_V = \frac{1}{1 + C_V \frac{\Delta P}{\mu_{oil} \cdot n}} \quad (16)$$

where C_V is the differential pressure leakage coefficient of the hydraulic motor and μ_{oil} is the dynamic viscosity of the hydraulic oil.

3.2 The energy conversion system model

Q_t is the theoretical input flow of the hydraulic motor, and the theoretical input power P_{in} of the hydraulic motor is given as follows.

$$P_{in} = (P_1 - P_2)Q_t = (P_1 - P_2) \frac{nD}{60\eta_V} \quad (17)$$

where T_{drive} is the driving torque output of the hydraulic motor and is calculated using the following equation.

$$T_{drive} = \frac{(P_1 - P_2)D}{2\pi} \eta_M \quad (18)$$

The hydraulic motor was connected to the DC generator through the reducer. The mechanical resistance torque ΔT and electromagnetic resistance torque T_{em} generated by the generator form a dynamic balance with the hydraulic motor driving torque. The torque balance equation is as follows:

$$T_{drive} = i(T_{em} + \Delta T) \quad (19)$$

$$T_{em} = \frac{K_A I}{1000} \quad (20)$$

where i is the transmission ratio of the reducer, K_A is the torque

coefficient of the generator, and I is the generator output current. Substituting Equation (20) into Equation (19), we obtain the output current of the generator as follows.

$$I = \frac{1000(P_1 - P_2)D}{2\pi i K_A} \eta_M - \frac{1000\Delta T}{K_A} \quad (21)$$

The output voltage of the DC generator U is calculated as follows.

$$U = \frac{i \cdot n}{K_V} - I(R + \Delta R) \quad (22)$$

where K_V is the speed constant of the generator, R is the armature resistance of the generator and ΔR is the contact resistance of the generator. Therefore, the power of generator P_{out} is given as follows.

$$P_{out} = UI = \left[\frac{in}{K_V} - I(R + \Delta R) \right] I \quad (23)$$

The efficiency model of energy conversion system η_{total} can be obtained as follows.

$$\eta_{total} = \frac{P_{out}}{P_{in}} = \frac{60\eta_V \left[\frac{in}{K_V} - I(R + \Delta R) \right] I}{(P_1 - P_2)nD} \quad (24)$$

4 Performance analysis and parameters identification

The performance analysis of the energy conversion system based on the experiment complements the parameterized model. Due to the nonlinearity of the parameterized model, the relationships of the intermediate variables after parameter identification are difficult to obtain directly, such as the load current. However, the speed is controlled by the load current. Therefore, analyzing the performances of load current, speed, and efficiency contributes to the original design of the OTP.

4.1 Performance analysis

4.1.1 Load current and speed

Figure 4 shows the results of the load current varies with inlet pressure of hydraulic motor. The maximum and minimum load current increase with the inlet pressure. The slope of the minimum load current is much gentler than that of maximum load current, thereby narrowing the variation range of load current. More obviously, the range of load current is 0-2.26 A when the inlet pressure is 15 MPa, while it is 7.61-8.04 A when the inlet pressure is 28 MPa.

The speed and load current are not independent. Figure 5 shows the relationship between speed and load current. The

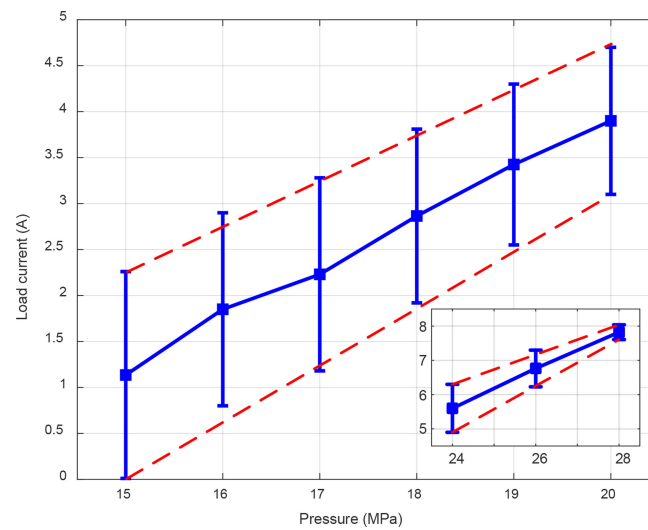


FIGURE 4
Load current varies with inlet pressure of hydraulic motor.

results show that the load current is inversely related to the speed under the same inlet pressure. From equation (20), it can be concluded that the larger the load current, the higher the electromagnetic resistance torque; in turn, the speed decreases. When the speed is fixed, the load current increases with the inlet pressure. The reason for the performance is the large inlet pressure makes the hydraulic motor output more torque, in order to achieve the same speed, a larger current is required to generate electromagnetic resistance torque. The initial value of

the speed also shows a trend with the increase of the inlet pressure. The possible cause is insufficient electromagnetic resistance torque provided by the generator.

4.1.2 Mechanical efficiency

Figure 6 shows the results of the mechanical efficiency of hydraulic motor in the energy conversion system. The results show that the larger the speed, the lower the mechanical efficiency under the same inlet pressure. The essential reason

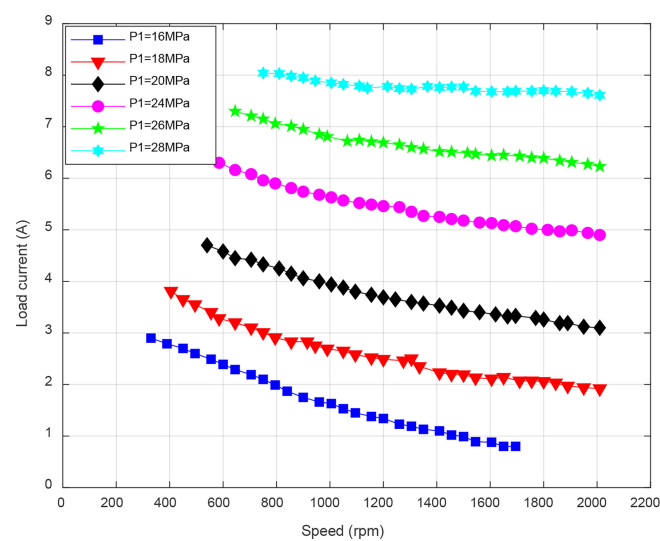


FIGURE 5
The relationship between speed and load current.

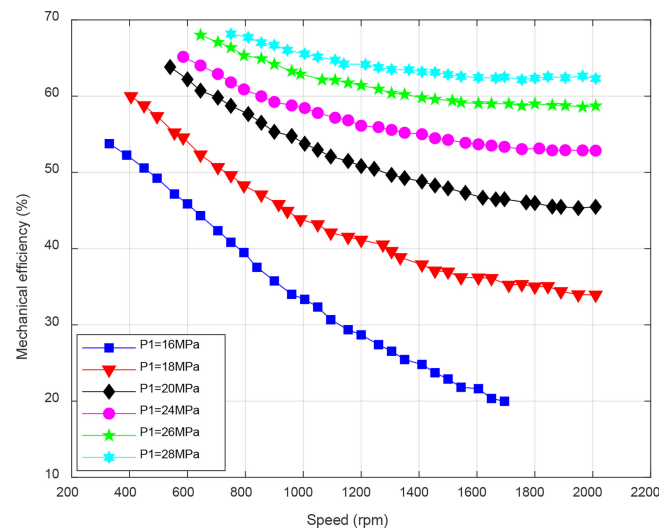


FIGURE 6
The mechanical efficiency of hydraulic motor in the energy conversion system.

is the same as the analysis of load current and speed in the previous part. From equation (18) to equation (20), it can be concluded that the larger the speed, the lower the torque at dynamic balance; in turn, the mechanical efficiency decreases. The mechanical efficiency increases with the inlet pressure, and the improvement is more pronounced when the inlet pressure is lower. The variation range of mechanical efficiency is inversely related to the inlet pressure, which is consistent with the conclusion of load current.

4.1.3 Total efficiency

Figure 7 shows the total efficiency of the energy conversion system. When the inlet pressure is low, the total efficiency increases first and then decreases with the load current. As the inlet pressure increases, the total efficiency decreases with the load current, and the maximum point appears in the initial stage of power generation. The reason for the phenomenon is the limitation of the maximum speed of the generator. The maximum efficiency point of the energy conversion system

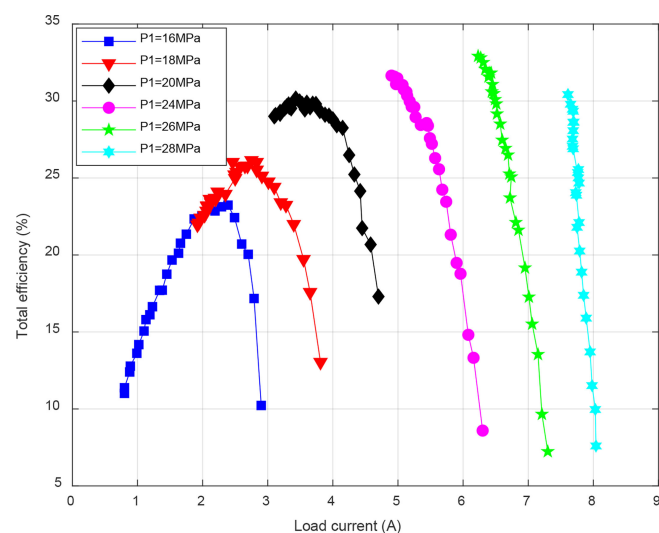


FIGURE 7
The total efficiency of the energy conversion system.

also shows a rising trend with the increase of the inlet pressure. Therefore, using high-speed generator in energy conversion system can achieve maximum efficiency under high pressure.

4.2 Parameters identification

4.2.1 Parameter identification of mechanical efficiency

The mathematical model of the mechanical efficiency of a hydraulic motor contains three undetermined parameters, and Equation (13) can be simplified as follows.

$$\eta_M = \frac{A_1}{D \cdot \Delta P} n^2 + \frac{A_2}{D \cdot \Delta P} n + \frac{A_3 P_2}{\Delta P} + B_1 \quad (25)$$

where A_1 , A_2 , A_3 , and B_1 are undetermined parameters.

The pressure difference ΔP was 10–15 MPa, and the pressure difference increment was 1 MPa. The mechanical efficiency data at different speeds under these six working conditions were obtained experimentally, and the Levenberg-Marquardt method in the nonlinear least-squares problem was used to fit Equation (25). The experimental data and fitting results are shown in Figure 8. The goodness-of-fit R^2 was 0.97402, which yielded good results. The relationship between the mechanical efficiency, differential pressure, and speed is as follows.

$$\eta_M = \frac{1}{100} \left(\frac{1.41139 \times 10^{-4}}{\Delta P} n^2 - \frac{0.54645}{\Delta P} n - \frac{347.26418}{\Delta P} + 100.74141 \right) \quad (26)$$

Experiments with differential pressures of 19, 21, and 23 MPa were performed to verify the accuracy of Equation (26) for other pressure and speed ranges of the hydraulic motor. A comparison between the simulation and experimental results of mechanical efficiency is shown in Figure 9. Under the three verified working conditions, the average relative error between the simulated and experimental data was less than 5%, and the maximum relative error was 5.6%, verifying the effectiveness and accuracy of the mechanical efficiency parameterized model.

During the experiment, there was less leakage of the hydraulic motor. Therefore, to simplify the model and calculation, it is considered that the volumetric efficiency of the hydraulic motor does not change with the pressure difference and speed.

4.2.2 Parameter identification of total efficiency

The total efficiency of energy conversion system can be derived using two methods based on the mechanical efficiency model of the hydraulic motor: (1) indirect method based on the mechanical efficiency model after parameter identification and (2) direct method based on the mechanical efficiency model before parameter identification. The indirect method can identify the unknown parameters of the intermediate variables and can be applied in the fields of dynamic modeling and control algorithm design of energy conversion system. The direct method implicitly includes unknown parameters of intermediate variables and can be applied in static modeling and energy efficiency analysis of energy conversion system.

The indirect method involves substituting Equations (26) and (21) into Equation (24). Figure 10 shows the simulation and

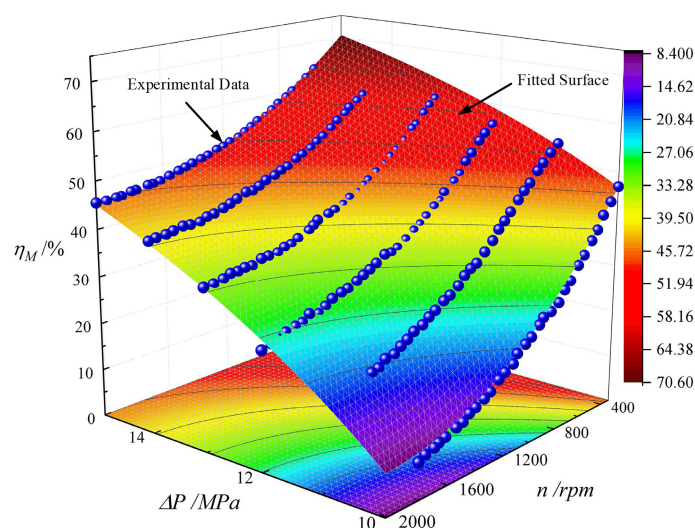


FIGURE 8
The experimental data and fitting results for mechanical efficiency of hydraulic motor.

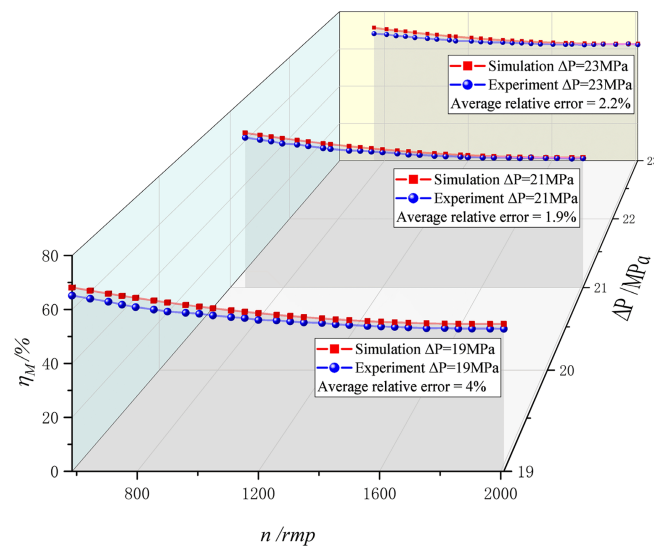


FIGURE 9

The comparison between the simulation and experimental results of the mechanical efficiency model.

experimental comparison of indirect method. Differential pressures of 13, 15, 19, and 21 MPa were selected for model verification. From Figure 10, it is observed that the results obtained by the model are in good agreement with the experimental results at low speeds, but they are generally greater than the experimental results at high speeds. A possible reason for this is that there is a deviation between the

internal parameters of the generator and the theoretical reference value, resulting in increased frictional resistance and reduced efficiency. Furthermore, it is observed that the changing trend of the simulation results is consistent with the experimental data, and the simulation average errors are 5.7%, 4%, 12.8%, and 11.3%, respectively. Therefore, the model is valid and accurate.

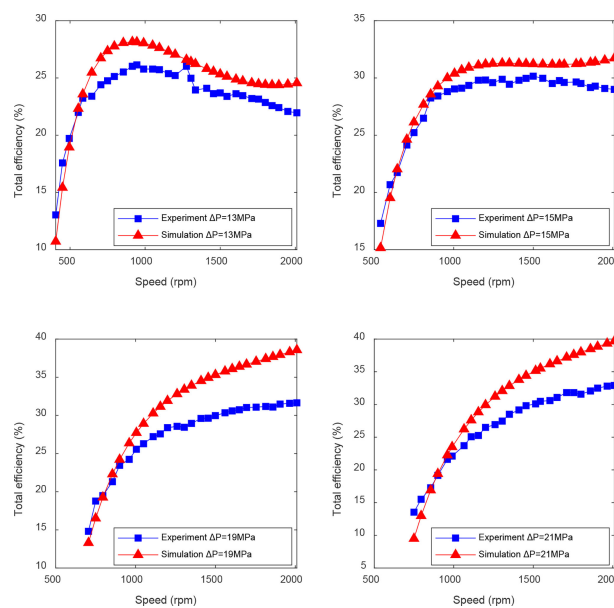


FIGURE 10

The simulation and experimental comparison of indirect method.

The direct method involves bringing Equations (25) and (21) into Equation (24) and simplifying them to obtain a parameterized model of the total efficiency as follows.

$$\eta_{total} = k_1' n^4 + k_2' n^3 + b_1 n^2 + b_2 n + b_3 \quad (27)$$

where

b_1 , b_2 and b_3 should be separated by three lines. " ΔP_2 " is modified to " ΔP^2 ". " D_2 " is modified to " D^2 ".

$$\begin{aligned} \{b_1 &= k_3' DP_2 + k_4' \Delta PD + k_5' \\ b_2 &= k_6' DP_2 + k_7' \Delta PD + k_8' \\ b_3 &= k_9' \Delta P^2 D^2 + k_{10}' \Delta PP_2 D^2 + k_{11}' DP_2 + k_{12}' \Delta PD + k_{13}' \end{aligned} \quad (28)$$

Here, k_1' to k_{13}' are undetermined parameters. When the displacement and outlet pressure of the hydraulic motor remain constant, Equation (27) can be further simplified as follows.

$$\eta_{total} = k_1 n^4 + k_2 n^3 + (k_3 \Delta PD + k_4) n^2 + (k_5 \Delta PD + k_6) n + b_4 \quad (29)$$

where

$$b_4 = k_7 \Delta P^2 + k_8 \Delta P + k_9 \quad (30)$$

k_1 to k_9 in the equation are undetermined parameters.

Parameter identification in the total efficiency was similar to the mechanical efficiency of the hydraulic motor. The experimental data and fitting results are shown in Figure 11. The goodness-of-fit R^2 was 0.93927, indicating a good fitting result. The parameters of Equation (29) are listed in Table 2.

The experimental data for differential pressures of 19, 21, and 23 MPa were selected to verify the parameterized model of total efficiency established by the direct method. Figure 12 shows

TABLE 2 The parameters in parameterized model of total efficiency.

Undetermined parameters	Fitting value	Standard error
k_1	-9.18156E-12	2.92082E-12
k_2	6.27942E-8	1.4227E-8
k_3	-2.62316E-6	1.74247E-7
k_4	-1.15067E-4	2.40286E-5
k_5	0.00953	4.57568E-4
k_6	0.018	0.01656
k_7	-0.34921	0.0078
k_8	4.60104	0.36058
k_9	-21.62071	4.62731

the simulation and experimental comparison of direct method. The experimental results show that the relative error between the simulation and experiment is relatively large at the initial speed of each pressure, the relative error at other speeds is within 10%, and the average relative error between the simulation and experiment at pressure differences of 19, 21, and 23 MPa are 9%, 0.41%, and 6.75%, respectively, which verifies the validity and accuracy of the total efficiency parameterized model.

The accuracy of maximum efficiency point prediction of energy conversion system is a significant criterion for judging the rationality of the proposed parameterized model. The maximum efficiency point is the optimal load current and optimal speed when the total efficiency is maximum. The load current in the direct method is an intermediate variable, which is difficult to obtain accurate parameters; therefore, the simulation and experimental comparison of the optimal load current only applies to the indirect method, while the direct method can be explained by the optimal speed indirectly. Figures 13, 14 show the experimental and simulation comparison of optimal load

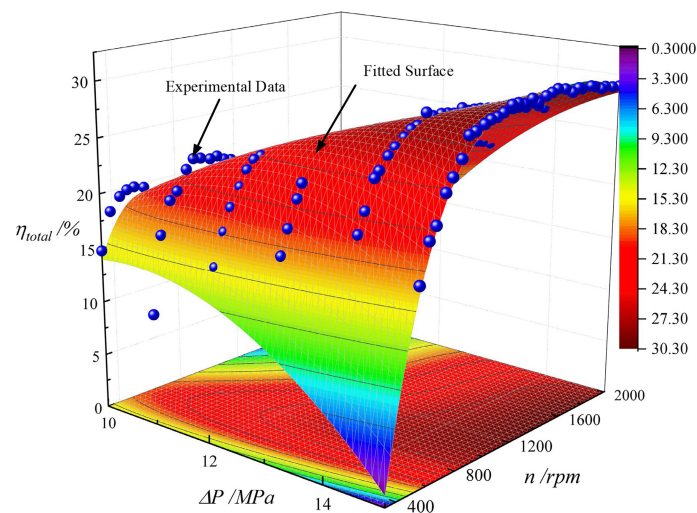


FIGURE 11

The experimental data and fitting results for the total efficiency of energy conversion system.

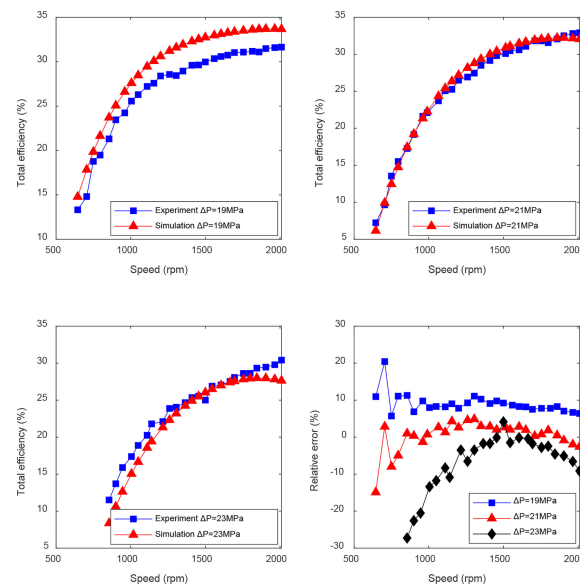


FIGURE 12

The simulation and experimental comparison of direct method.

current and speed. In the prediction of optimal load current, the average relative error of the indirect method is 2.21%. In the prediction of optimal speed, the average relative error of indirect method is 0.45%, while that of direct method is 0.8%. The results indicate that the parameterized model of energy conversion system has a satisfactory prediction effect and meets the engineering application.

5 Conclusion

In this study, the factors affecting the performance of energy conversion system are analyzed according to the operation principle of OTP. A force analysis of a swashplate axial piston hydraulic motor was performed, and a parameterized model for establishing the mechanical

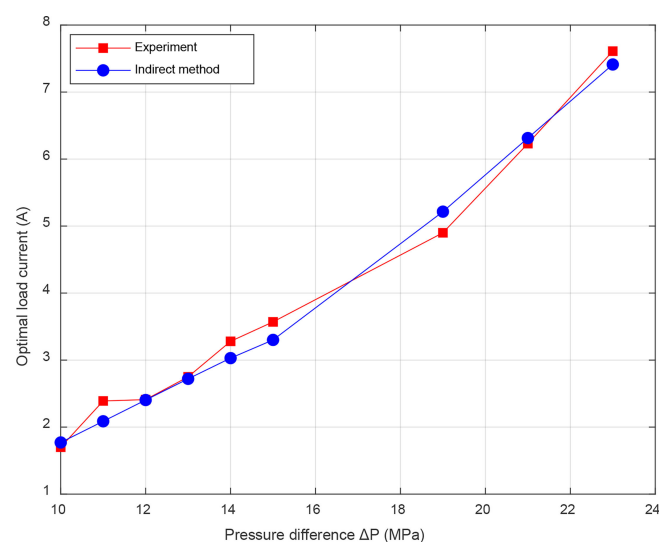


FIGURE 13

The simulation and experimental comparison of the optimal load current.

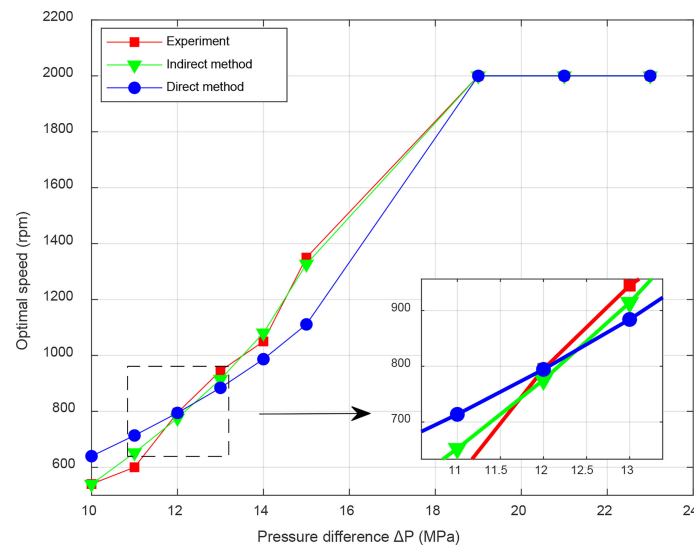


FIGURE 14
The simulation and experimental comparison of the optimal speed.

efficiency of the hydraulic motor was established. Direct method and indirect method were proposed for establishing the universal parameterized model of total efficiency for energy conversion system. An experimental platform was established to study system performance and verify the accuracy of the proposed parameterized model.

In the energy conversion system of OTP, the maximum and minimum load current increased with the inlet pressure, but the variation range decreased. The load current was inversely related to the speed, while positively related to the inlet pressure. The mechanical efficiency of hydraulic motor increased with inlet pressure, but decreased with speed. The total efficiency increased with the load current, and decreased after reaching the maximum point at low inlet pressure, whereas the total efficiency decreased with the load current at high inlet pressure. The maximum efficiency point showed a rising trend with inlet pressure.

In the parameterized model identification, the average relative error between the simulation and experiment for the mechanical efficiency of the hydraulic motor was less than 5%, and the maximum relative error was 5.6%, verifying the validity and accuracy of the established mechanical efficiency parameterized model. For the total efficiency model established by the indirect method, the minimum average relative error was 4%, and the maximum average relative error was 12.8%. For the direct method, except for the large error at the initial speed, the average relative error in the other speed ranges was within 10%, the maximum was 9%, and the minimum was 0.41%. In the prediction of optimal load current, the average relative error of the indirect method was 2.21%. In predicting the optimal speed, the average relative errors of the indirect method and

the direct method were 0.45% and 0.8%, respectively. The parameterized model of energy conversion system met the engineering application.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

YC, BC, QX, and CY contributed to conception and design of the study. YC provided methodology and performed the statistical analysis. BC conducted experiments, organized the database, and wrote the first draft of the manuscript. MH provided data visualization. LZ carried out the preliminary investigation. QX provided resources and supervision. CY provided project administration and funding acquisition. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Available at: <https://seatec.com/news>.
- Buckle, J. R., Knox, A., Siviter, J., and Montecucco, A. (2013). Autonomous underwater vehicle thermoelectric power generation. *J. Electron Mater.* 42 (7), 2214–2220. doi: 10.1007/s11664-013-2584-1
- Chao, Y. (2016). *Autonomous underwater vehicles and sensors powered by ocean thermal energy* Vol. 1 (Oceans 2016 - Shanghai, IEEE).
- Chen, W., Wang, X., Zhang, F., Liu, H., and Lin, Y. (2020). Review of the application of hydraulic technology in wind turbine. *Wind Energy (Chichester England)* 23 (7), 1495–1522. doi: 10.1002/we.2506
- Falcão Carneiro, J., and Gomes de Almeida, F. (2018). Model and simulation of the energy retrieved by thermoelectric generators in an underwater glider. *Energy Convers Manage.* 163, 38–49. doi: 10.1016/j.enconman.2018.02.031
- Fan, Y., Mu, A., and Ma, T. (2016). Modeling and control of a hybrid wind-tidal turbine with hydraulic accumulator. *Energy (Oxford)* 112, 188–199. doi: 10.1016/j.energy.2016.06.072
- Gil-González, W., Montoya, O. D., and Garcés, A. (2020). Modeling and control of a small hydro-power plant for a DC microgrid. *Electric Power Syst. Res.* 180, 106104. doi: 10.1016/j.epsr.2019.106104
- Haldeman, C. D., Schofield, O., Webb, D. C., Valdez, T. I., and Jones, J. A. (2015). Implementation of energy harvesting system for powering thermal gliders for long duration ocean research. *MTS* 1, 1–5. doi: 10.23919/OCEANS.2015.7404559
- He, X., Xiao, G., Hu, B., Tan, L., Tang, H., He, S., et al. (2020). The applications of energy regeneration and conversion technologies based on hydraulic transmission systems: A review. *Energy Convers Manage.* 205, 112413. doi: 10.1016/j.enconman.2019.112413
- Ho, T. H., and Ahn, K. K. (2010). Modeling and simulation of hydrostatic transmission system with energy regeneration using hydraulic accumulator. *J. Mech Sci. Technol.* 24 (5), 1163–1175. doi: 10.1007/s12206-010-0313-8
- Huang, J. C., Krock, H. J., and Oney, S. K. (2003). Revisit ocean thermal energy conversion system. *Mitigation Adaptation Strat Global Change* 8 (2), 157–175. doi: 10.1023/A:1026062531405
- Jónsdóttir, G. M., and Milano, F. (2020). Stochastic modeling of tidal generation for transient stability analysis: A case study based on the all-island Irish transmission system. *Electric Power Syst. Res.* 189, 106673. doi: 10.1016/j.epsr.2020.106673
- Ke, M., Ding, F., Li, B., and Chen, Z. (2006). Exploration of the influence of backing pressure on the efficiency of hydraulic motor. *Nongye Jixie Xuebao (Transact Chin. Soc. Agric. Machinery)* 37 (10), 127–131. doi: 10.3969/j.issn.1000-1298.2006.10.034
- Khan, N., Kalair, A., Abas, N., and Haider, A. (2017). Review of ocean tidal, wave and thermal energy technologies. *Renewable Sustain. Energy Rev.* 72, 590–604. doi: 10.1016/j.rser.2017.01.079
- Orosio, A. F., Arias-Gaviria, J., Devis-Morales, A., Acevedo, D., Velasquez, H. I., and Arango-Aramburo, S. (2016). Beyond electricity: The potential of ocean thermal energy and ocean technology ecoparks in small tropical islands. *Energy Policy* 98, 713–724. doi: 10.1016/j.enpol.2016.05.008
- Roh, C., Ha, Y., Shin, S., Kim, K., and Park, J. (2021). Advanced maximum power control algorithm based on a hydraulic system for floating wave energy converters. *Processes* 9 (10), 1712. doi: 10.3390/pr9101712
- Song, R., Dai, Y. M., and Qian, X. (2018). Intermittent wave energy generation system with hydraulic energy storage and pressure control for stable power output. *J. Mar. Sci. Technol.* 23 (4), 802–813. doi: 10.1007/s00773-017-0512-4
- Tianliang, L., and Yueying, Y. (2012). Research on the efficiency of bent axis hydraulic piston motor. *Fluid Power Transm. Control* 6, 18–23.
- Tian, B., and Yu, J. (2019). Current status and prospects of marine renewable energy applied in ocean robots. *Int. J. Energy Res.* 43 (6), 2016–2031. doi: 10.1002/er.4371
- Townsend, N. (2016). *In situ results from a new energy scavenging system for an autonomous underwater vehicle* Vol. 1 (Oceans 2016 mts/ieee Monterey, IEEE).
- Townsend, N. C., and Sheno, R. A. (2016). Feasibility study of a new energy scavenging system for an autonomous underwater vehicle. *Auton Robots* 40 (6), 973–985. doi: 10.1007/s10514-015-9506-4
- Wang, D., and Lu, K. (2018). Design optimization of hydraulic energy storage and conversion system for wave energy converters. *Prot. Control Modern Power Syst.* 3 (1), 1–9. doi: 10.1186/s41601-018-0080-6
- Wang, G., Yang, Y., Wang, S., Zhang, H., and Wang, Y. (2019). Efficiency analysis and experimental validation of the ocean thermal energy conversion with phase change material for underwater vehicle. *Appl. Energy* 248, 475–488. doi: 10.1016/j.apenergy.2019.04.146
- Wei, L., Liu, Z., Zhao, Y., Wang, G., and Tao, Y. (2018). Modeling and control of a 600 kW closed hydraulic wind turbine with an energy storage system. *Appl. Sci.* 8 (8), 1314. doi: 10.3390/app8081314
- Wilberforce, T., El Hassan, Z., Durrant, A., Thompson, J., Soudan, B., and Olabi, A. G. (2019). Overview of ocean power technology. *Energy (Oxford)* 175, 165–181. doi: 10.1016/j.energy.2019.03.068
- Xia, Q., Chen, Y., Yang, C., Chen, B., Muhammad, G., and Ma, X. (2020). Maximum efficiency point tracking for an ocean thermal energy harvesting system. *Int. J. Energy Res.* 44 (4), 2693–2703. doi: 10.1002/er.5055
- Xue, G., Liu, Y., Si, W., Ji, C., Guo, F., and Li, Z. (2020). Energy recovery and conservation utilizing seawater pressure in the working process of deep-argo profiling float. *Energy (Oxford)* 195, 116845. doi: 10.1016/j.energy.2019.116845
- Yongqiang, G. (2008). Analysis on efficiency of axial piston motor. *Hoisting Conveying Machinery* 2008 (7), 51–54. doi: 10.3969/j.issn.1001-0785.2008.07.017
- Zhang, Y., Chen, H., Guo, K., Zhang, X., and Eben Li, S. (2017). Electro-hydraulic damper for energy harvesting suspension: Modeling, prototyping and experimental validation. *Appl. Energy* 199, 1–12. doi: 10.1016/j.apenergy.2017.04.085
- Zhou, S., Liu, X., Zhang, K., Yue, Q., Bian, Y., and Shen, S. (2021). Evaluation of a novel ammonia-water based combined cooling, desalination and power system based on thermodynamic and exergoeconomic analyses. *Energy Convers Manage.* 239, 114176. doi: 10.1016/j.enconman.2021.114176

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Ocean observation system design of mooring buoy and benthic node with electro-optical-mechanical cable

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We designed a hybrid system named Mooring Buoys Observation System with Benthic Electro-optical-mechanical Cable (MBOSBC) for long-term seafloor and sea surface multi-parameter ocean observation. The electro-optical-mechanical (EOM) cable connects a sea surface buoy and a seafloor junction box so as to establish a transmission link of information and power between the sea surface and the seafloor. The EOM cable also plays the role of mooring tether to the MBOSBC and has to withstand the rigorous marine environment—experiencing mooring loads under complex marine environmental conditions for long periods of time. The data transmission of the system includes the EOM, satellite communication, wireless radio, and acoustic communication. The system power is generated by a wind turbine and solar panels and is transmitted to the seafloor junction box. An acoustic communication instrument is used to gather the sample data from other benthic nodes, such as seafloor landers, AUVs, and underwater gliders. MBOSBC is designed to operate from shallow water to deep sea, and to simultaneously monitor sea surface hydrology, meteorology, and water quality, as well as benthic temperature, pressure, salinity, currents, and seafloor video. We provide the MBOSBC architecture design, including the mechanical design, control, power, data transmission, and EOM cable. Finally, we describe the launch and recovery process of MBOSBC, as well as experimental results.

KEYWORDS

electro-optical-mechanical (EOM) cable, seafloor junction box, Buoy, ocean observation, mooring

Introduction

Seafloor observatories provide a method to understand physical, chemical, and geological seafloor processes. Seafloor observatories can monitor the environment as well, including ocean climate predictions, ocean upwelling, eddies, seismicity, geomagnetic variation, temperature, salinity, currents, and gas occurrence over long

periods, offering many multidisciplinary ocean data for scientists in real time. The NEPTUNE Canada project in Ref (Delaney et al., 2000). is the most representative example of state-of-the-art marine technology. Also, seafloor observatories have potential applications in the offshore operations of the oil and gas industry. Finally, seafloor observatories are utilized for supporting maritime security; specifically, seafloor observatories with seafloor hydrophone arrays can track and identify surface vessels, AUVs, and cetaceans.

Cabled seafloor observatories have been developed in Canada, USA, and Japan. This kind of system transmits power to an underwater junction box through an EOM cable from the shore station. By using the EOM cable and junction box, cabled seafloor observatories establish a connection to shore stations, benthic nodes, and sensors. However, the EOM cable, launching the system, and maintaining the system involve huge costs. Also, it is difficult to change or adjust the position of the seafloor junction box once the system is completely launched. Therefore, cabled seafloor observatory systems are difficult to move. These properties limit the application of surface and seafloor observation for areas far from the shore. In addition, seafloor observatories are difficult to relocate in response to emergencies events.

Moored buoy seafloor observatories offer a strategy to cope with these challenges, which combine renewable energy, an EOM cable, and satellite communication to establish power and communication transmission links, so as to construct a system that can provide real-time synchronized three-dimensional observations of the sea surface and the seafloor. Renewable energy, such as from wind turbines and solar panels, makes it possible to offer renewable power for the seafloor observatories. The EOM cable offers power and data transmission capability between the seafloor and the sea surface. Moored buoy seafloor observatories provide a supplementary observation method for cabled seafloor observatories; they are a reusable and portable system because they can be recovered and relocated as required once deployed. This kind of system is suitable for ocean area, whereas a shore station is difficult to establish or may be undesirable. Finally, this kind of transferable-fixed regional ocean observatory system is suitable for emergencies events, especially for maritime security using seafloor hydrophone arrays from surrounding offshore islands. Ocean buoys mainly collect the data, which include the temperature, salinity, ocean current, waves, and oceanographic meteorology. Buoys provide support for ocean climate prediction and research on physical ocean processes, and seafloor nodes are used for geophysical and environmental monitoring.

The MBARI Ocean Observatory System (MOOS) prototype in Refs (Chaffey et al., 2001; Chaffey et al., 2005; Hamilton and Chaffey, 2005). use an EOM cable to deliver power and communication to seafloor instruments, and it can be deployed in the deep ocean at depths reaching 4000 m. The system includes a 2.3-m-diameter buoy, an ocean benthic

platform, and an EOM cable. The surface buoy collects as much as 40 W of solar and wind energy. The EOM cable connects the buoy and the ocean benthic instrument, so as to establish the power and data link between surface and seafloor. The EOM cable and the seafloor junction box are connected by ROV with a wet-mate electro-optical connector.

The Cabled Underwater Module for Acquisition of Seismological data (CUMAS) in Refs (Iannaccone et al., 2009; Martino et al., 2014). is designed to extend the land surveillance network toward the wide marine sector of the caldera system. CUMAS is the first marine network that integrates volcanic monitoring with the coastal observation system. The buoy has a weight of 17T, and the total weight of the seafloor module is 430 kg. The EOM cable that connects the buoy and the seafloor node has a diameter of 23 mm. The buoy is moored by another anchor chain at a depth of 97 m. The system was launched in the Campi Flegrei caldera (southern Italy), one of the most hazardous and populated volcanic areas in the world; it is generally undesirable to set up a shore station in these areas. The scientific sensor includes a seismometer and a hydrophone, and it can detect current and water temperature. Signal transmission occurs through the network protocol and the RS485 protocol through the cable, and the power supply on the cable is 48 VDC.

CSnet's Offshore Communications Backbone (OCB) in Refs (Clark et al., 2009; Georgiou et al., 2010; Clark and Kocak, 2011). is a hybrid buoy/cabled observatory. The CSnet consists of a buoy, a buoy riser cable (mooring/power and communications), an anchor, a seafloor cable, and four seafloor nodes. The Cyprus-TWERC (Tsunami Warning and Early Response system of Cyprus) initially served as the CSnet prototype system for the Tsunami Warning and Early Response system of Cyprus and was first deployed at a depth of 2400 m in 2010. The buoy provides 5 kW of power for the seafloor node and communication at 3 Mbps via a satellite link. CSnet was selected to measure seafloor pressure to analyze the onshore destruction caused by seismically generated tsunamis. The Cyprus-TWERC project developed the framework to forecast marine disasters.

The OOI (Ocean Observatories Initiative) Coastal Surface Mooring Buoy System, which is maintained as part of the Regional Cable Array, is introduced in Refs (Smith et al., 2018; Trowbridge et al., 2019). The maximum launching depth is 450 m. The Coastal Surface Mooring Buoy System includes a surface buoy with a 3-m-tall tower, a near-surface instrument frame located at a depth of 7 m, and a multifunction node at the sea bottom. These three components are connected by the EOM cable for information and power transmission between the sea bottom and the sea surface. Due to the Coastal Surface Mooring Buoy System, the buoy has to offer enough buoyancy for the moored armored metal cable. Therefore, at present, this kind of system is rarely applied in deep waters.

Satellite communication offers a low-bandwidth path for the buoys, whereas optical fiber communication provides a high-bandwidth path from the seafloor to the sea surface through the

EOM cable. Currently, the transmission rate of the iridium (9522 modular) used in a traditional buoy is 2.4 kbps, which is mainly used for the transmission of instrument observation data. The surface buoy of CSnet is equipped with a VSAT modular, so that it can offer a data bandwidth in excess of 2 Mbps and transmit the data through the C-Band satellite, as shown in Ref (Sekino and Clark, 2003).

The cable used in MOOS is net-buoyant, as shown in Refs (Han and Grosenbaugh, 2006; Grosenbaugh et al., 2006), which is different from the seafloor observation network. The traditional EOM cable used in the seafloor network is a steel wire armored EOM cable, lying statically on the seafloor. This kind of EOM cable is a steel wire armored cable. Steel wire armored EOM cables are utilized in near-shore areas with shallow depths, but they are not suitable for deep-sea buoy mooring. Because the net buoyancy of the buoy is limited, the EOM cable has to have sufficient net buoyancy to hang in the water for long term, or else many floats may be needed to balance the weight of the cable. Vectran-fiber, nylon, and polyester are selected as strengthening materials. This kind of net-buoyancy EOM cable requires high strength, excellent bending properties, watertight performance, and wear resistance. The properties of EOM cables with different strength materials are compared in Ref (Mellinger et al., 2003), especially the static and dynamic responses of the mooring EOM cable.

Tethering technology is used in Shallow Ocean, as shown in Refs (Iannaccone et al., 2009; Makris et al., 2014), where the anchoring rope and coaxial cable are roped together as the mooring component, so the coaxial cable does not need experience the moored force. The analog signals transmit on the coaxial cable, which is converted to a digital signal by an A/D converter at the buoy and seafloor. This kind of mooring method is difficult to utilize in deep sea because it is hard to launch and recover the system while the anchor chain and cable are entangled together.

In this paper, we design the Mooring Buoys Observation System for Benthic with Electro-optical-mechanical Cable (MBOSBC) for seafloor and sea surface observation of the South China Sea for ocean meteorology, ocean physical processes, and water quality. MBOSBC includes a mooring buoy and a benthic observation node, and these two components are connected by an EOM cable. The mooring buoy plays the role of observation and relay platform for power generation and data transmission. The benthic observation node is designed for monitoring ocean physical processes and seafloor image acquisition, as well as anchoring the mooring buoy. We established the cable and the acoustic communication linked between the mooring buoy, the seafloor moored node, and an independent node. The acoustic communication is used to collect seafloor sample information from other seafloor observation nodes, such as glider and seafloor lander. MBOSBC can be relocated or deployed rapidly for transient observation or long-term observation. Especially, the sea surface

buoy, as the power generator and data transmitter, has a mixture of capabilities for long-term observation and real-time data transmission for ocean observation. This paper gives a description of the architecture, function, design, and experiments of the system, which is organized as follows. First, we give the concept design of the MBOSBC system. Second, we give a detailed description of the mooring buoys and the benthic observation node. Third, we introduce the EOM cable and mooring technology. Fourth, we provide experimental results, including the launch and recovery processes. Finally, we conclude the paper and discuss future works.

System design

MBOSBC is aimed to work with the coastal observatories of the South China Sea, as shown in Figure 1. Using the surface buoy and seabed observation system with an EOM cable, we provide an open test platform to verify the reliability of various communication modes, renewable energy, and integration of data acquisition/transmission technology. Through this research, we hope to provide technical reference for buoy modular integration, underwater networking technology, and industrial application of this system, especially for the solution of real-time transmission technology of isolated observation nodes with an EOM cable.

MBOSBC integrates seafloor and sea-surface instruments for a broad spectrum of environmental, meteorological, and hydrological observatory data, including water temperature, pressure, salinity, current, wind speed/direction, air temperature, relative humidity, barometric pressure, and water chemistry. We integrate a seafloor video module, including a light, camera, and a PTZ, to verify the power capacity of MBOSBC and its wireless radio transmission. In the future, MBOSBC will be equipped with a geomagnetic sensor, a hydrophone, and a seismometer for extreme environmental monitoring.

MBOSBC communication integrates an optical fiber, acoustic, Ethernet network, wireless radio, and satellite as a communication network system of regional ocean observatories. MBOSBC obtains its seafloor data from the EOM cable and collects seafloor lander/glider data with acoustic communication. MBOSBC transmits the data in real time or near-real-time to the shore control center to construct a closed loop of the “ocean observatories data stream.”

The overall system architecture is shown in Figure 2, including three modules: the mooring buoy, the benthic node, and the EOM cable. The mooring buoys play the role of sea surface observation, data communication, and energy supply. The benthic node contains the junction box, the oceanographic instruments, the seafloor video module, and the buoy anchor block. The junction box contains three modules for power management, control and data acquisition, and seafloor

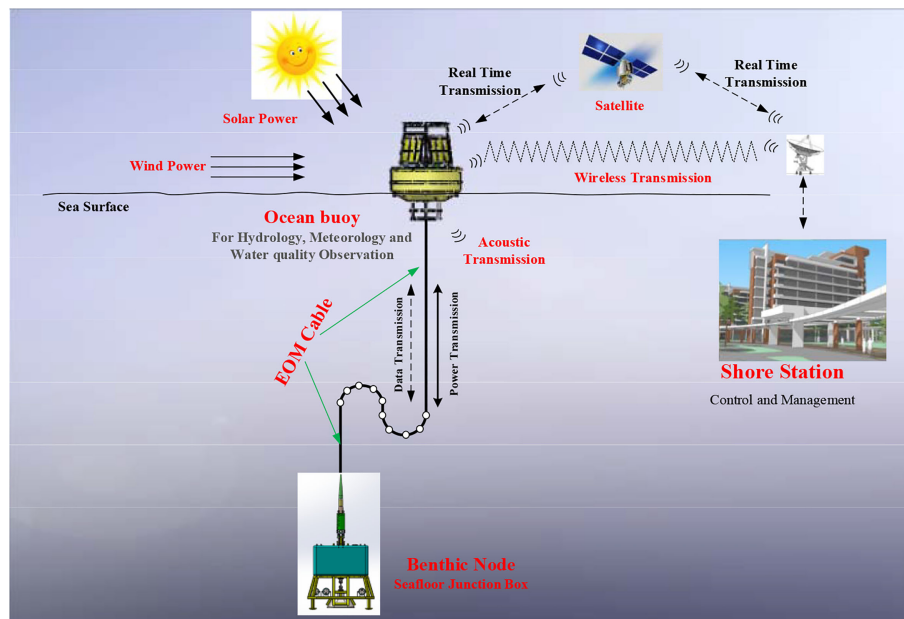


FIGURE 1
Concept design of Mooring Buoys Observation System for Benthic with Electro-Optical-Mechanical Cable (MBOSBC).

junction box status monitoring. Detailed information is given in the following sections.

The control and data management module integrates the power module, the communications module, the sample instruments of the buoys and benthic observation node, and EOM cable, as shown in Figure 2. We monitor the voltage and current of the battery, the wind turbine, and the solar panel in real time. With this information, we adjust the acquisition frequency of the instruments to optimize the energy consumption.

The embedded computer and the DC/DC converter connect the mooring buoys and the benthic observation node. Data are transmitted between the mooring buoys and the benthic observation node through the EOM cable and the optical Ethernet hub. The embedded computer on the mooring buoy integrates the heterogeneous data stream of the mooring buoys and the benthic observation node. Data are stored on the buoy as a redundant backup module, which includes an SD card and a 2-T data recording disk. The data recording disk mainly stores the sea surface mini camera images and seafloor videos, and other sample data are stored on the SD card.

The control and data management module is the control core of the system, integrating the embedded computer, data acquisition and storage, power supply, communication. Therefore, it requires excellent stability and scalability, and we design this module with the following guidelines:

1. Realize data storage, exchange, and transmission.

2. Manage various kinds of sensors for data sampling, recording, packing, and uploading.
3. Adjustable sampling frequency.
4. Convenient for maintenance and expansibility. The hardware should have excellent expansion capability, including storage capacity and interface expansion, and the software should be easily maintained and upgraded.

Observation platform design

Mooring buoys

The mooring buoy has a rigid structure and is made of 304 steel. The main diameter of the buoy is 3 m, and the bottom diameter of the buoy is 1.5 m, as shown in Figure 3A. The displacement of the buoy is 4.2 Tons. The buoy body is divided into two parts: a watertight tank in the center, and four buoyancy cabins, which are arranged around the watertight tank. The electronic instruments are held in the watertight tank.

The buoy is equipped with 24 rechargeable batteries (2 V, 500 Ah each). The power supply includes eight solar panels and a wind turbine. Each solar panel is nominally 100 W with dimensions of 1200 mm × 540 mm, and the wind turbine is nominally 150 W.

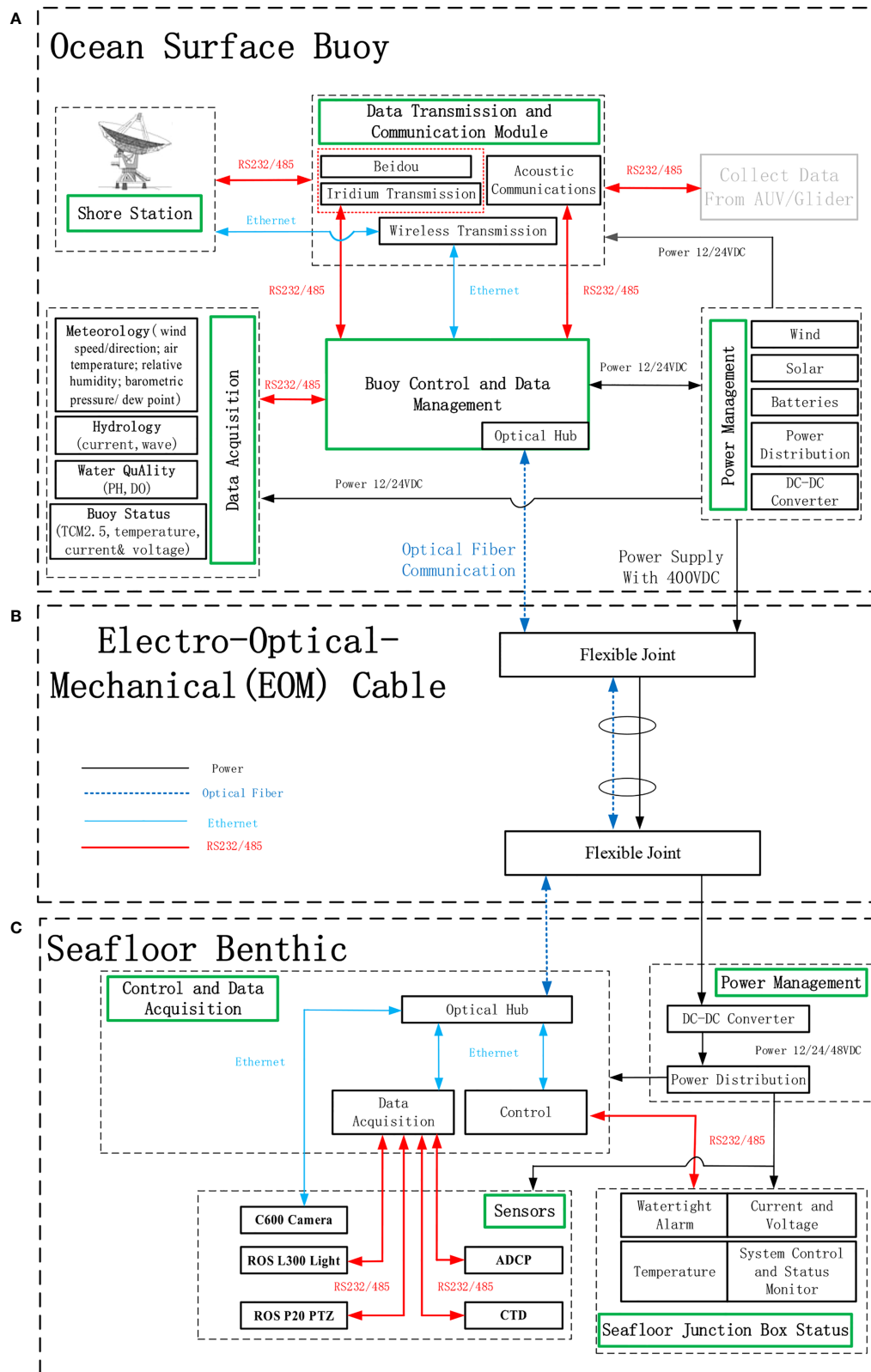
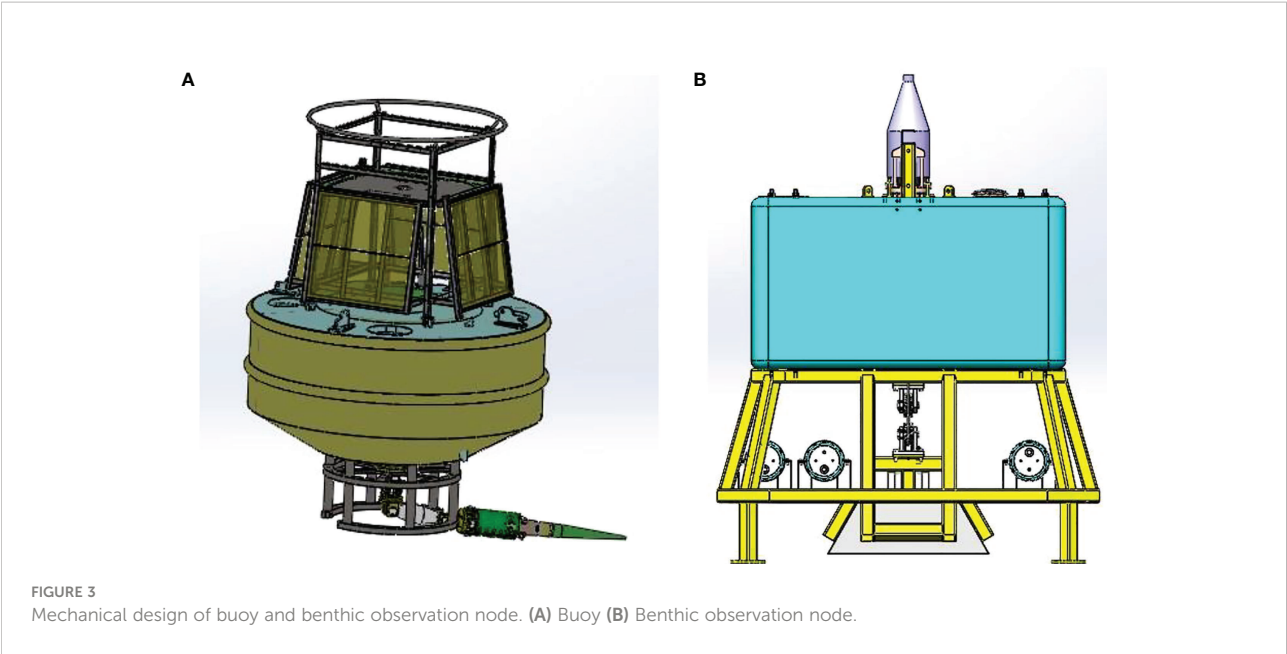


FIGURE 2

Detailed architecture of MBOSBC: (A) mooring buoy; (B) seafloor junction box; (C) EOM cable for mooring and power and data transmission.



The mooring buoy is used for the observation of meteorological, hydrological, and water-quality data. Detailed information about the scientific sensors and status sensors is given in [Table 1](#). The sampling frequency is set to satisfy the needs of marine science research. Specifically, we put a miniature camera on the buoy instrument frame for near-shore monitoring and verification of the wireless radio communication.

The status sensors provide information on the state of the buoy. TCM3 and GPS devices embedded with iridium provide the attitude and position of the buoy. The total power generation and daily power consumption are determined by the wind and solar controller and DC/DC converter, respectively.

Benthic observation node

For the benthic observation node, the junction box includes a titanium cylinder for power supply, and another titanium cylinder for data communication and control. The weight of the junction box is approximately 150 kg, which is surrounded by a cage with a weight of 1 ton. The cage has a length, width, and height of 2.25 m, 2.25 m, and 2.53 m respectively, as shown in [Figure 3B](#). The seafloor junction box and the video module are fixed on the grid of the cage. The titanium cylinder of the junction box has a diameter of 320 mm and a length of 1060 mm. The DC/DC converter and data sampling and transmission module are fixed in the two

TABLE 1 Scientific and status sensors on the mooring buoy.

Type	Sensor	Sampling rate	Measurement Elements
Scientific sensors	Hikvision camera	1 min/hour	Coastal monitoring
	MetPark	1 sample/hour	a)Wind speed, b)Wind direction, c)Air temperature, d)Relative humidity, e)Barometric pressure, f) Dew point
	AXYS wave NW2	1 sample/hour	a)Wave height, b)Wave direction, c)Wave cycle time
	SeaPROFILER ADCP	1 sample/hour	Ocean current of x components and y components
Status sensors	HydroCAT-EP	1 sample/hour	a)Temperature Salty, b)pH Pressure, c)Dissolved oxygen Chlorophyll, d)Turbidity
	TCM3	1 sample/min	Attitude angle as Roll, Pitch, and Yaw
	GPS	1 sample/hour	Buoy position as latitude and longitude
	Wind and solar controller	1 sample/hour	Power generation Power consumption
	24VDC/375VDC-DC/DC Converter	1 sample/hour	Voltage and current monitor of the system

titanium cylinders separately. The benthic observation node also plays the role of a seafloor anchor. The cage weighs 1 ton and contains the scientific instruments. The anchor block at the bottom center of the cage is 3 tons, so as to offer enough weight to moor the buoy. The anchor block can be released by the acoustic releaser when we recover the MBOSBC.

The junction box converts the 375 VDC from the EOM cable to 12 VDC, 24 VDC, and 48 VDC for the seafloor instruments. The junction box accepts input control commands *via* RS232, RS422, and RS485. The junction box offers 8-pin watertight connectors (SubConn MCBH8F) for the sensors for power supply and data transition. Ethernet communication connects the optical fiber from the EOM cable and the ARM embedded system with the TCP/IP protocols. The ARM embedded system facilitates data acquisition from the instruments and data transmission to the Ethernet.

The junction box hosts several instruments, including a seafloor video imaging system, a CTD, and an ADCP. Detailed information about the instruments is given in Table 2. The video module includes a C600 ROS camera, two L300 led lights, and a P20 Pan and Tilt Positioner. The video format of the C600 HD camera is 1080i/720p, and the coaxial signal output from the C600HD camera is transformed to TCP/IP protocols by a video server; thus, video protocols are able to be transmitted to the sea surface buoys with the EOM cable. The Ethernet (10/100 Mbps) is used to transform the video data. Finally, the seafloor video is transmitted to the shore station *via* wireless communication. Considering the limitation of the power supply, we set the camera and light to start and stop regularly, or they are intermittently turned on *via* wireless radio control from the shore station.

Communications module

The communication module is equipped with satellite communication, wireless radio communication ST5801GB-M1,

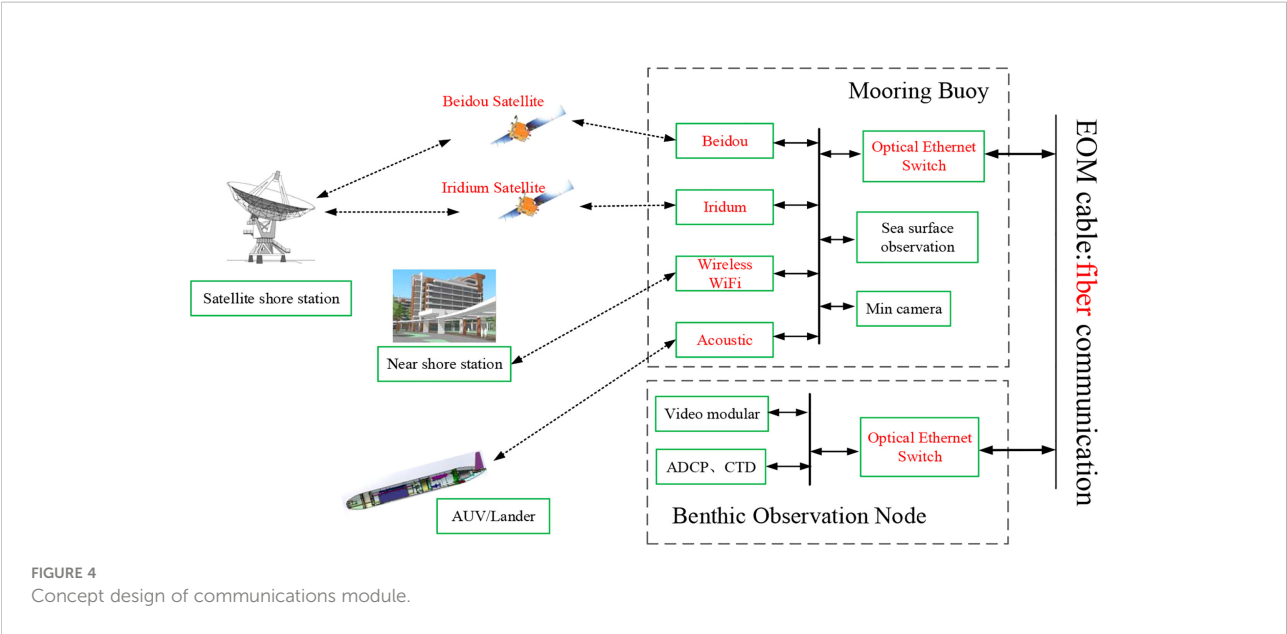
and Evologics S2C acoustic communication, as shown in Figure 4. We establish the communication between the buoy and the benthic observation node with the optical fiber and Ethernet of the EOM cable. Detailed information about the communication instruments are given in Table 3.

The Evologics S2C device is utilized to collect sample data from the AUV, lander, and other seafloor observational platforms. Wireless radio communication is used to transmit the videos to the shore station when we launch the MBOSBC near the coast. The nameplate power supply of wireless radio ST5801GB-M1 is 50 W/24 VDC, and the data transmission rate is 10 Mb/s within 5 km. The communication link for the seafloor video module to the buoy is established as “coaxial signal (C600 HD)-Ethernet (underwater junction box)-Ethernet/Optical Switch-EOM cable-Optical/Ethernet Switch-Ethernet(buoy)-wireless radio communication(buoy).” Satellite communication, including Beidou and Iridium, is utilized to transmit all data except the video data. When the MBOSBC is launched far from the coast, we find it difficult to transmit the video data. As a result, we select HIKVISION DS-7104HGH-F1/N as the video serve, shortened the recording time of the camera, and then store the video data in the server. The power consumption is 8W with 12VDC and weight less than 0.8kg. Details of the video serve design idea is shown in Figure 2.

We tested the transmission rate of the ST5801GB-M1 wireless radios that are located in our institute and boat, separately. We then moved the boat away from the coast gradually. The transmission distance varied from 1 km to 5 km. Detail information is shown in Ref (Zhang et al., 2018). When the distance was less than 1 km, the wireless transmission signal was strong and stable, with a transmission rate of 50 Mb/s. When the distance was from 1 km to 2.5 km, the transmission was unstable because of the mismatched settings of the wireless transceiver mode. At distances of 2.5 km to 3 km, we changed the transceiver mode, and as the distance increased, the transmission rate dropped sharply, as the wireless signal

TABLE 2 Scientific and status sensors for the benthic observation node.

Type	Sensor	Sampling rate	Measurement Elements
Scientific sensors	ROS C600 Camera	1 min/hour	Resolution:1080i HD; Size:91.44 mm × 256.54 mm Video; Depth Rating:6000 m; Control: RS-232, Voltage: 10~36 VDC
	PTZ(P20 Pan and Tilt Positioner)	1 sample/3hours	Payload:20 lbs (9 kg); Torque:10 lb/ft; Scan Range:0~360°(both axes); Power:24 VDC, 1.7 A; Control: RS485
	ROS L300	1 sample/3hours	Light type: LED; Voltage:24 VDC; Power: 79 W, 3.3A; Size:127 mm× 66mm× 84mm; Weight in water:0.7 kg; Control: RS485.
	SeaPROFILER ADCP	1 sample/hour	Ocean current of x components and y components
	CTD	1 sample/hour	Temperature, Salinity, and Pressure
Status sensors	DC/DC Converter	1 sample/min	Voltage and current from the EOM cable
	Temperature of DC/DC cylinder	1 sample/hour	Temperature of the cylinder electronic cabin
	Leakage monitoring	1 sample/hour	Short circuit if water leaks in the cylinder electronic cabin



strength became weak. At distances of 3 km to 4 km, we increased the power supply (>24 W), and the transmission rate increased to 30 Mb/s. At distances of 4 km to 5 km, the transmission rate remained stable at 30 Mb/s at a supplied power of 24 W.

Power module

The power module is designed to collect and store wind and solar energy and then distribute the energy to the seafloor and sea surface instruments; it also transmits power to the seafloor *via* a standardized 375 VDC power bus. The overall system is described in Figure 5. The power module includes the solar panels, the wind turbine, and the battery blocks. We chose 24 blocks of 2-V 500-Ah AGM lead-acid batteries. As a result, the batteries offer a nameplate capacity of 1000 Ah with 24 VDC.

Through the DC/DC converter, the sea surface instruments are powered by a 12 VDC bus, and the seafloor load is powered by a 375 VDC bus. For energy management and control, we give priority to ensure that power is supplied to the critical load, which mainly includes the communication instruments. Energy is then distributed to the observation instruments. When the system is located more than 10-km away from the coast, it is impossible control the camera through the wireless radio, so we have to start the seafloor video and the wireless radio in a preset intermittent mode.

The above-mentioned mode greatly reduces the energy consumption of the system. The sea surface observation costs 2.41 Ah at 12 VDC per day, whereas the seafloor observation costs 23.6Ah at 12 VDC per day. The buoy communications module costs 23.4 Ah at 12 VDC per day. The total energy consumption per day reaches 592.9 Wh. The actual instantaneous power consumption is 24.7 W. The

TABLE 3 Types and technical characteristics of communication module.

Communication mode	Instruments	Technical characteristics
Wireless radio communication	ST5801GB-M1	Control: TCP/IP; Voltage:12~24 VDC, 50 W; Work mode: Base Station, CPE, P2P (Bridge); Frequency:2.5~52 MHz; Transmission rate:10 Mb/s (distance<5 km).
Satellite communication	Beidou	Transmission rate: 600 bps; Control: RS232; Power:12~28 VDC, 5 W.
	Iridium	Transmission rate: 9600 bps; Control : RS232; Power:12~28 VDC, 5 W.
Acoustic communication	Evologics S2CR 18/34	Transmission rate:13.9 kbit/s; Control : RS232; Power:12 VDC, 1.3 W.
Optical communication	Optical fiber	Optical fiber of EOM cable

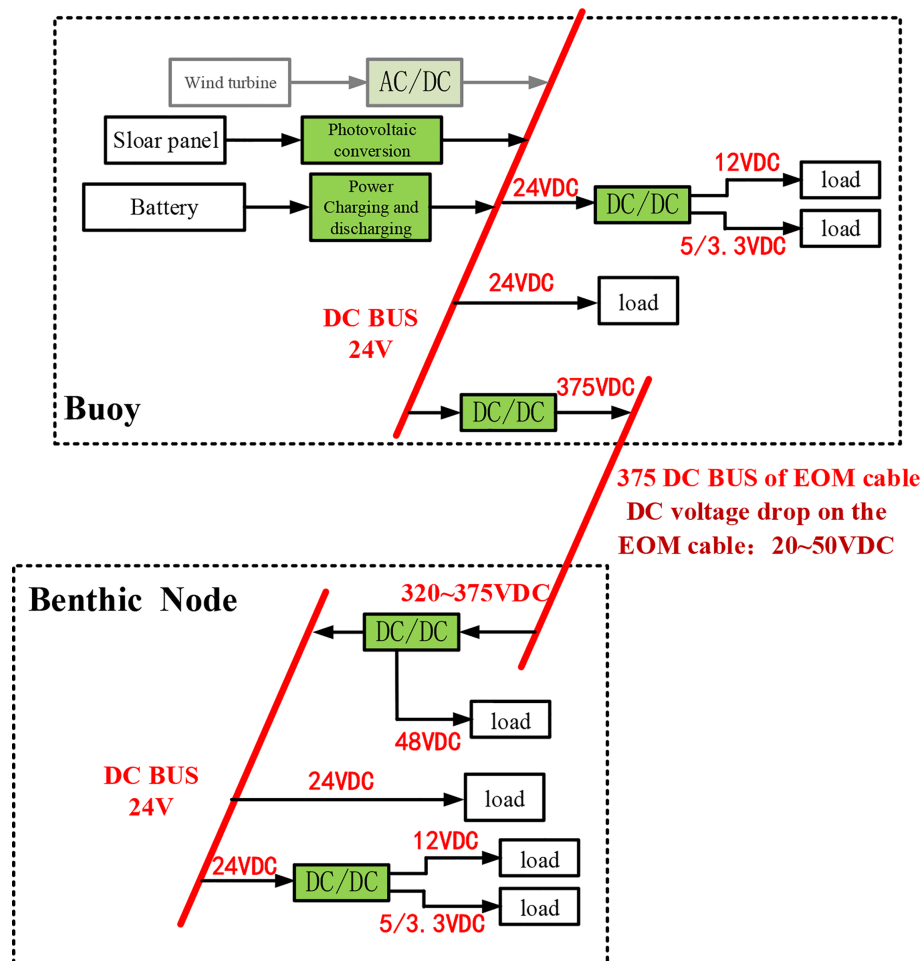


FIGURE 5
Power supply of MBOSBC.

photoelectric conversion efficiency of the solar panels reaches 10%, so the solar panels provide approximately 80 W of power for the system, which offer enough power for MBOSBC.

Ocean mooring technology with EOM cable

EOM cable

Two kinds of cables are utilized in the buoy mooring as are shown in Figure 6. First, we select Rochester Engineered Cable NO.A302351, with three optical fibers and three 11[#] AWG wires, as shown in Figure 6A. Two optical fibers are utilized for data transmission, and two copper wires are utilized for power transmission. The diameter of the EOM cable is 17.30 mm.

The breaking strength of the EOM cable is 204.6 kN, and its weight in the water is 905 kg/km. The voltage rating @ 123 volts/mil is 2800 VDC, and the insulation resistance is 3000 MΩ·km. The cable is armored with three layers of steel wires. At the benthic node, the optical core and the electric core are separated and connected to the junction box through a watertight connector. A load bearing is designed and vulcanized with the EOM cable and the watertight connector, which is fixed on the buoy and seafloor node, and the mooring force of the buoy is transferred to the EOM cable through the load-bearing. We used this cable for initial experiments and testing. Because it is finished product, and it is worth considering for it relatively low-cost option.

We select the vectran-fiber cable in the later stage to try the application of the neutral buoyancy cable in the system. The weight of metal cable is large, the buoy should offer reserve

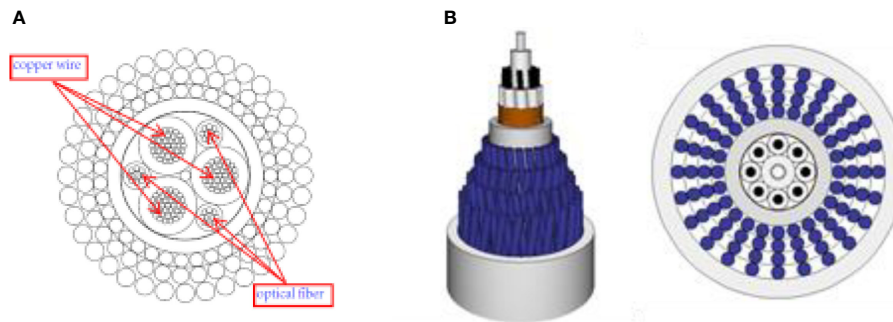


FIGURE 6

Section view of steel-wire armored EOM cable and vectran-fiber EOM cable. (A) Rochester Engineered Cable NO.A302351. (B) Vectran fibers cable.

buoyancy for different depth. At the same time, if we select the metal cable, it makes the system recovery complex. We have to lift the metal cable with hydraulic winch. If we select the vectran-fiber cable, and when we release the anchor block, the benthic node and the neutral buoyancy cable can automatically rise to the surface. We designed a net-buoyant EOM cable to replace the mooring armored cable. The EOM cable is utilized as the single-point mooring for MBOSBC. The EOM cable is composed of four optical fibers and eight 18[#] AWG wires. Two optical fibers are used for data transmission, and eight copper wires are used for power transmission. The diameter of the EOM cable is 30 mm, its breaking strength is 200 kN, and its weight in the water is 0~2.0 N/m. We did tensile tests on the EOM cable to verify its strength, so as to making sure that it can moor the buoy. We first tested the EOM cable with a nominal safe working load of 7 tons for approximately one hour, and then we tested the EOM cable with a minimum breaking load of 20 tons for approximately 10 minutes. The test results showed that the EOM cable could withstand the working load and the minimum breaking load. Detailed information about the testing is given in Ref (Yu et al., 2020). The weight of this kind of cable is relatively light, and the buoy is not required to provide additional reserve buoyancy. Compared with metal armored cable, vectran-fiber cable provides a good choice for the system launch and recovery in deep water.

In Ref (Yu et al., 2020), we establish the buoy mooring model and give the simulation result. The total mooring force of the buoy bottom is 32.6kN. And the safety factor is selected as 6, so the expected loads of the EOM cable is 200kN. We designed a cable load-bearing joint so as to connect the buoy and the cable. The EOM cable is designed with vectran-fiber as strengthening materials. The conducting and optical fibers are in the core, and the vectran-fiber are outside them. The vectran-fiber have four layers and are reverse-spiral braided doubly around the core to

reduce the torque of the cable. Polyester is selected as the outer bedding braid layer to protect the vectran-fiber from abrasion. Because the EOM cable is replaced with the traditional buoy anchor chain, it is made to be net-buoyant in water by configuring the thickness of the polyester and the vectran-fiber. Detailed information is given in Table 4.

Flexible connection joints

Considering the torque imparted by buoy rotation to the EOM cable, a slip ring is used to connect the EOM cable and the buoy. The cost of a photoelectric slip ring that can bear the mooring force and is custom-made would be too high. Therefore, we have to use an electric slip ring with 13 wires as a replacement, as shown in Figure 7. As a result, the optical signals need to be converted into electrical signals. The frequent swinging of the buoy also has a great influence on the cable at the joint. This kind of frequent vibration may lead to fatigue damage of the optical fiber; therefore, we had to design a universal joint to eliminate this vibration influence.

We designed a flexible connection, as shown in Figure 8, where the buoy connects with the universal joint, and then the electric slip ring, and lastly the E/O electronic cabin. The load-bearing joint is vulcanized with the EOM cable, and the E/O electronic cabin is fixed on the load-bearing joint. The flexible connection of the benthic node is the same as the buoy, but the slip ring is not installed on the benthic node. The E/O electronic cabin is powered by the 375 VDC bus of the cable. At the benthic node, the E/O electronic cabin separates from the EOM cable as an 8-pin Ethernet connector for data transmission and a 3-pin copper-wire connector for power supply. Sea surface data transmission and power supply are integrated in the 13-wire watertight connector of the slip ring.

TABLE 4 Properties of the EOM cable.

Cable properties	Unit	Nominal value
Diameter	mm	30
Air weight	kg/m	0.9 ± 0.1
Weight in sea water	N/m	0 ± 2.0
Minimum breaking strength	kN	200
Maximum working load	kN	100
Safe working load	kN	50
Working voltage	V	DC, 1000
Current of each copper conductor	A	≤ 5

The advantages of this flexible connection joints are as follows:

1. The swing angle of the universal joint is $0\sim 30^\circ$, which reduces the fatigue damage caused by the buoy swing to EOM cable, and realizes the flexible transition and connection.
2. Electric slip ring is utilized in the design to transmit signals and power. Affected by wind, wave and ocean current, the buoy will rotate irregularly on the sea surface. If the torsional torque generated by the buoy rotation is transferred to the mooring EOM cable, the mooring EOM cable will be knotted or twisted, which will easily cause the attenuation and failure of optical signal of the EOM cable.
3. The E/O electronic cabin converts optical signals into network signals. In this way, it is unnecessary to choose the optical fiber slip ring, especially the optical fiber slip ring have to bear tethering force. The design of the E/O electronic cabin reduces the cost and the risk of system failure; while it can also transmit video signals from benthic to the sea surface.
4. For the design of benthic node, in order to avoid underwater ROV plugging, we design the E/O electronic cabin and the universal joint for connection. For the system launch, we can connect the above

component and modules, and deploy the benthic node, EOM cables and buoys in proper order.

Experiments and challenges

Experiments

In this section, we discuss experiments performed with the system. We do not utilize the ROV to perform the connection with the wet-mate connector because both the ROV tether and buoy EOM cable are hanging in the seawater, and these two cables may intertwine together under the influence of sea current. For the system design, we have considering the acoustic releaser and the buoyancy materials (above the benthic node), as shown in Figure 3B. So when we recovery the system, the mooring and the benthic node can float out to surface. But in the near shore experiment, we do not utilize it, mainly considering the following aspect:

1. While the anchor block (3 ton) and the buoyancy material (1.7 ton) is installed on the benthic node (1 ton), the total weight of the seabed node is close to 5.7 ton. Gross Registered Tonnage of the ship is 300 tons and the ship has a “A” Frame with the max 2.5 ton

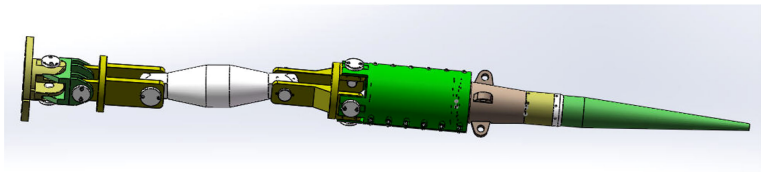


FIGURE 7 Flexible connection joints including the universal joint, slip ring and E/O electronic cabin.

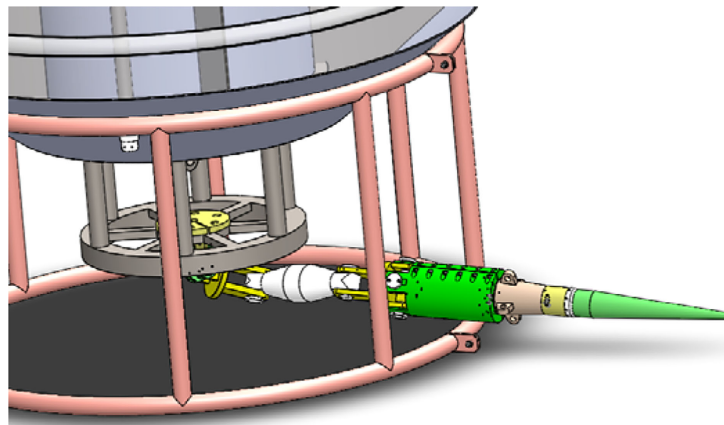


FIGURE 8
Connection of buoy and the flexible connection joints.

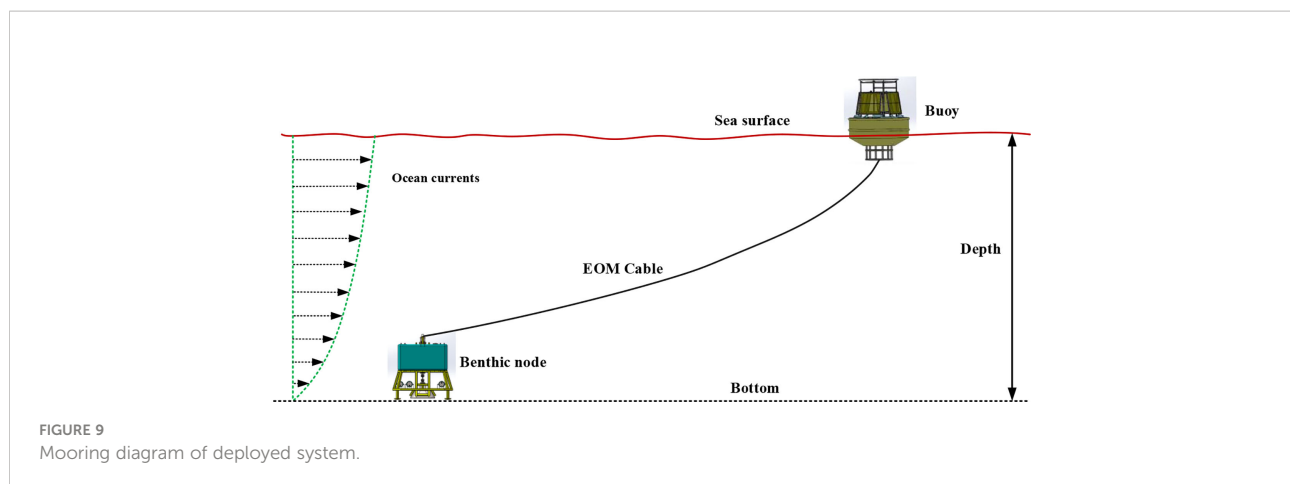
Lifting weight. So it is impossible to launch the benthic node with the anchor block, while the cost of large scientific research ships is huge.

2. The location of the near shore launch experiment is selected where the water depth less the 30 meter. So that, when recover the benthic, the diver can dive into the seafloor to hook the benthic node. Then we can pull the benthic node to the ship by the ship wire rope winch. We give the mooring diagram of deployed system as shown in [Figure 9](#).

In 2017, a Rochester Engineered Cable was utilized in the experimental testing of the system. The system only integrated the ST5801GB-M1 wireless radio, acoustic communication, the benthic camera, and the sea surface camera at first, and the benthic node had a simple structural frame with a weight less than 300 kg. We had to use the anchor chain to moor the buoy, which is similar to Ref ([Iannaccone et al., 2009](#)), but we also bound the EOM cable and the anchor chain together with Kevlar rope (5 m each). The length of the anchor chain was approximately 1 m shorter than the EOM cable at each bundled section, so the optical fiber of the EOM cable would not be pulled off while the anchor chain was bearing the pull force from the seafloor anchor block. At the seafloor, there was a ~2 T anchor chain playing the role of anchor block to moor the buoy. Another ~50-m EOM cable on the seafloor was deployed far from the anchor block, so as to avoid the influence of the drifting of the anchor block and buoy. For near-shore experiments, we connected the buoy and the benthic node with the EOM cable from the harbor. The lifting capacity and height of the “A” frame of the mother ship was limited, so it was difficult to lift the buoy from the mother ship to the sea surface. We had to use a crane to lift the buoy into the water in the

harbor, and then lifted the benthic node onto the mother ship. We then towed the buoy to a predetermined location and launched the benthic node to the seafloor with the “A” frame. We recovered the system in the opposite order, but we also had to let divers hook the seafloor junction box with Kevlar rope to bring it to the sea surface. Through the experiment, we achieved seafloor video transmission to the shore in real time and verified the acoustic communication with the underwater lander. The solar panels provided enough power for the system. The efficiency of the wind turbine was not high due to the low wind speed. The experimental results are given in Ref ([Zhang et al., 2018](#)). For prototype system design in Ref ([Zhang et al., 2018](#)), the cable terminal are fixed on the buoy bottom bracket. This rigid connection method is not applicable for the buoy launch and recovery. The rigid connection make the fiber of the EOM cable easily invalid. So we choose the universal joint as a replace for the flexible connection. The flexible connection brings great convenience to the system launch and recovery.

In 2018, we designed and manufactured the benthic node and the vectran-fiber cable, as shown in [Figure 6B](#). Flexible connection joints and the vectran-fiber cable were first applied in experiments. The shore control interface is shown in [Figure 10B](#) and the buoy towing process is shown in [Figure 10A](#). The benthic node had a weight as high as 4 tons, which could provide enough mooring force for the buoy. All the sensors and communication instruments were carried on the system. The EOM cable was 200 m in length, and the system was launched at a depth of 20 m. The power loss in the 200m cable length is about 0.35W. The launch and recovery method is similar with the experiment in 2017, but the experiment in 2018 has exposed some design and application problems. Firstly, we did not preset the on/off state of the seafloor video instruments with the software, and these instruments were normally on. The total power consumption is 230W, and the large



power consumption modular including wireless radio, light, and camera. The system last four days. If the large power consumption modular are powered intermittently (10 minutes per 3 hours), the average power consumption of the system is about 80W. We improved the control software in 2019, and make the design of the control software more reasonable. The wireless radio also comprised high-power-consumption instruments, which led to a shortage of energy supply to the system several days after it was launched. Thus, the software should be optimized to preset the startup and shutdown of the instruments. Secondly, the EOM cable was too long for the system at a depth of 20 m. When we recovered the system after a month, superfluous cable was entangled on the cage of the benthic node. We also found that the outer bedding braid layer of the cable became worn, cracked, and wrinkled. Therefore, we had to choose a harder outer bedding braid layer for the EOM cable.

In 2019, we launched the system again at a depth of 20 m with 60 m of remanufactured EOM cable. The location of the system is N18.285, E109.4723, and the shore center locate at E109.485601, N18.215604. So the transmission distance of the wireless radio is 7.8km. During the experiment, the sample data from the instruments of the sea surface and the sea benthic node were transmitted to the shore *via* iridium communication and Beidou communication continuously. Detailed information about the sample data is given in Ref (Wang et al., 2019). The observation data can be transmitted through Beidou and Iridium. The video data from the benthic node can be stored in the junction box, and it can be transmitted in real time through wireless radio. However, considering the large power consumption of seabed light, camera, and wireless radio, we verify the benthic image acquisition and transmission link, and we do not carry out continuous video data acquisition. In order to utilize this kind of cable in Deep Ocean, it required a special hydraulic winch for cable project construction. Compared with the steel-wire armored cable, the manufacturing technology of the selected vectran-fiber cable is not mature. Furthermore, the

EOM cable is squeezed after winding on a hydraulic winch when it is tested at the factory, which will lead to the failure of optical fiber communication. Therefore, we delayed experimenting with this kind of application.

We have verified the technology of the whole system through the above experiments. In the mechanical structure design of surface buoy and the benthic node, universal joint is designed to realize the connection between cable and buoy. At the same time, the risk and cost of offshore experiments are reduced by means of towing buoys, offshore wharf installation, etc. The transmission of power flow and data flow from the sea surface to the benthic has been established. We build optical fiber communication, Ethernet communication wireless communication links to realize video data transmission. This provides a possibility for underwater acoustic observation in the future. Through many tests, the control module of the system is gradually stabilized. For the design of the EOM cables, we compare the metal armored cable and the vectran-fiber cable through the experiments, especially vectran-fiber cable, it provides a great possibility for the application of the systems in the deep sea. We have verified the reliability of the vectran-fiber cable in the near shore. For the buoy mooring, we design E/O electronic cabin and load-bearing electric slip ring, so as to eliminate the influence of the torque generated by the rotation of the buoy on the mooring EOM cable. These above optimizations solve the problems we meet in the experiments. And through the near shore experiments, we verify the reliability of the system.

Challenges

In this section, we discuss the challenges of the system and potential improvements.

First, whether the system can work for a long time depends largely on the working state of the EOM cable, which creates

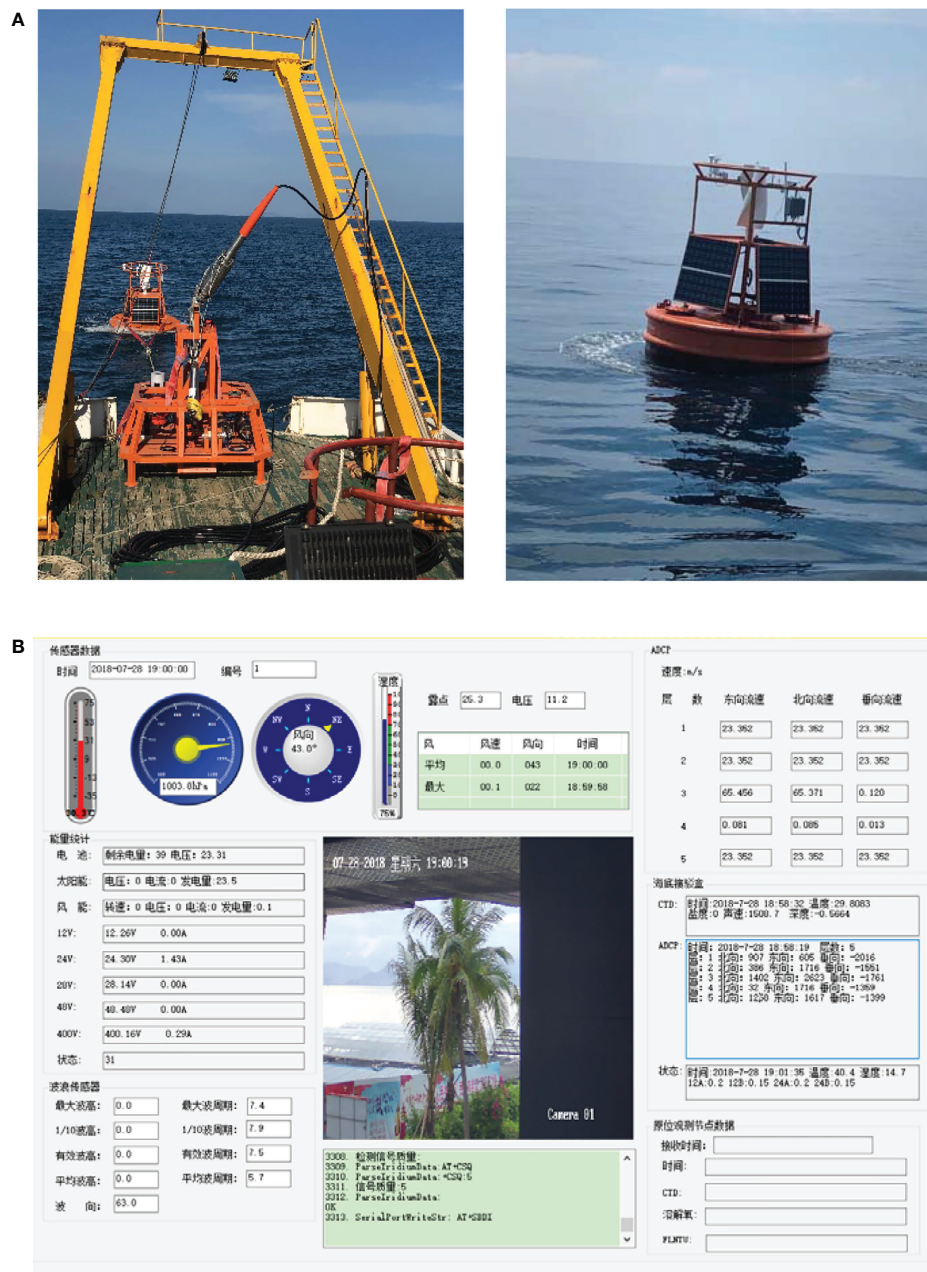


FIGURE 10

Recovery of the system and the shore control interface. (A) Towing and launch of the buoy. (B) The shore control interface.

high requirements for its technology and utilization. Optical fiber communication is utilized for the MOOS prototype in Refs (Chaffey et al., 2001; Chaffey et al., 2005; Hamilton and Chaffey, 2005). at a depth of 4000 m, when the cable is suspended in water. Further, the fiber is affected by various external forces and vibrations under long-term continuous operation. These application scenarios bring more stringent requirements for the manufacturing of the EOM cable. As shown in Ref

(Palanza et al., 2017). Ethernet (CATV) cables can be used for data transmission, but this method will lead to a reduction of transmission rate as the cable length becomes longer. Coaxial cables are another option for underwater long-distance communication. As shown in Ref (Makris et al., 2014), a real-time on/offshore seismic and tsunami network with coaxial cables was established based on seismic and tsunami telemetry buoys.

Secondly, both a steel armored cable and a net buoyancy cable (Nylon and Vectran fibers) are used in this kind of system. However, the manufacturing of net buoyancy cables is not as mature as that of steel armored cables. Furthermore, the coordination of the cable and winch is also a difficulty, and improper operation will lead to cable extrusion and damage. As shown in Ref (Chaffey et al., 2005). ROV and wet-plug technology are selected for launching this kind of system, which significantly increases costs. The problem with steel armored cables is their weight; therefore, we should design underwater float balls to balance the gravity of steel armored cables. Of course, this will increase the difficulty of system launch and recovery.

Thirdly, rubber hoses Ref (Mellinger et al., 2003). are useful for reducing the impact of buoy vibration on the cable, especially for the instantaneous impact of mooring force. This was a key point of the EOM cable in Ref (Frye et al., 2004), where the elongation of the nylon at break was between 15%~28%, whereas the copper and optical elements stretched in the cable no more than 0.5%. Thus, the fiber may break before the nylon cable reaches its maximum elongation. As a result, communication *via* the cable is interrupted. A nylon-cord reinforced rubber hose can provide additional compliance during mooring and decrease dynamic tension under wave action. At the moment, we do not carry out long-term observations in the deep sea, so we have not added rubber hosing in the flexible connection joints.

Fourth, a slip ring is necessary in the flexible connection joints. We use a slip ring to eliminate the torque on the EOM cable that is caused by the rotation of the buoy. However, we have to carefully consider the torsion resistance of the EOM cable if we do not add the slip ring to the flexible connection joints. The EOM cable is made of even armoring layers so as to avoid the residual torque existing on the cable; especially, buoy rotation may increase the residual torsion on the cable.

Fifth, the renewable energy provided by the solar panels is limited. The efficiency of photovoltaic power generation is ~10%, and the power supply depends on how many solar panels can be equipped on the buoy. For observation systems with a high power consumption, additional solar panels are needed, which may require the manufacturing of a buoy with a larger size. As the buoy's structural size increases, the difficulty of launching and recovery will gradually increase, which is also an aspect we need to consider before such a system is designed.

Sixth, the launch and recovery of the system are difficult compared to traditional buoys. We have to utilize a gravity anchor to moor the buoy, but not a grip anchor. As a result, the gravity anchor is too heavy to launch from the mother ship. The "A" frame must have sufficient lifting capacity and height for the launch of the buoy. In addition, a hydraulic winch is needed to launch the EOM cable. These requirements make it difficult to

choose a suitable mother ship. As shown in Ref (Clark and Kocak, 2011). Cyprus-TWERC uses three vessels and an ROV to work together to deploy the anchor, the buoy, and the riser cable. The buoy and riser cable plug into the anchor interface through ROV wet-mate connectors. While meeting the requirements, we should consider the modular design from the view of system launch and recovery.

Discussion and conclusion

The Mooring Buoys Observation System for Benthic with Electro-Optical-Mechanical Cable, also known as MBOSBC, is designed for ocean observation and communication networks of the South China Sea. The system records signals from the seafloor and sea surface. We fully integrate the sea surface and seafloor platforms, including mechanical design, control and data management, power supply, communication, and system launch and recovery. We developed this system and technology as a supplemental mode for traditional buoy observation and seabed observation networks. We integrate Beidou, wireless, and iridium communication, as well as an optical fiber communication link, so as to realize real-time communication for three-dimensional ocean observation and real-time transmission of underwater video from the ship or the coast. We utilize acoustic communication to collect sample data from other benthic observation platforms, such as other isolated benthic observation nodes and AUVs. Through experiments, we verified the effectiveness of the mooring buoy system for seafloor observation. At present, MBOSBC is the subject of a feasibility study of communication networks of regional ocean observation; in the future, it will be integrated into the seafloor observation systems of the South China Sea for application.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

SZ contributed to conception and design of system and the manuscript preparation. CT and FZ contributed to the experiment. All authors contributed to manuscript revision, read, and approved the submitted version.

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References

- Chaffey, M., Bird, L., Erickson, J., Graybeal, J., Hamilton, A., Headley, K., et al. (2005). MBARI's buoy-based seafloor observatory design. *MTS/IEEE Techno-Ocean 4*, 1975–1984. doi: 10.1109/OCEANS.2004.1406447
- Chaffey, M., Mellinger, E., and Paul, W. (2001). "Communications and power to the seafloor: MBARI's ocean observing system mooring concept," in *MTS/IEEE oceans 2001. an ocean odyssey. conference proceedings*. (Honolulu, HI, USA: IEEE Oceans) 2001, 2473–2481. doi: 10.1109/OCEANS.2001.968389
- Clark, A. M., and Kocak, D. M. (2011). *Installing undersea networks and ocean observatories: The CSnet offshore communications backbone (OCB)* (Waikoloa, HI), 1–9. OCEANS '11 MTS/IEEE KONA. doi: 10.23919/OCEANS.2011.6107087
- Clark, A. M., Kocak, D. M., Martindale, K., and Woodroffe, A. (2009). "Numerical modeling and hardware-in-the-loop simulation of undersea networks, ocean observatories and offshore communications backbones," in *Proc. MTS/IEEE OCEANS 2009 conference*. (Biloxi: IEEE Oceans), 2009, 1–11.
- Delaney, J., Heath, G. R., Chave, A. D., Howe, B. M., Kirkham, H., et al. (2000). NEPTUNE: real-time ocean and earth sciences at the scale of a tectonic plate. *Oceanography* 13 (2), 71–79. doi: 10.5670/oceanog.2000.37
- Frye, D., Hamilton, A., Grosenbaugh, M., and Paul, W. (2004). Deepwater mooring designs for ocean observatory science. *Mar. Technol. Soc. J.* 38 (2), 7–20. doi: 10.4031/002533204787522857
- Georgiou, G., Clark, A. M., Zodiatis, G., Hayes, D., and Glekas, D. (2010). "Design of a prototype Tsunami Warning and Early Response system for Cyprus -TWERC". 2010 in OCEANS '10 IEEE SYDNEY. Sydney, NSW, Australia: IEEE Oceans, 2010, 1–5. OCEANS '10 IEEE SYDNEY. doi: 10.1109/OCEANSSYD.2010.5603936
- Grosenbaugh, M., Walter, P., Frye, D., and Farr, N. (2006). Development of synthetic fiber-reinforced electro-optical-mechanical cables for use with moored buoy observatories. *IEEE J. Ocean. Eng.* 31, 574–584. doi: 10.1109/OE.2005.850937
- Hamilton, A., and Chaffey, M. (2005). "Use of an electro-optical-mechanical mooring cable for oceanographic buoys: Modeling and validation," in *International conference on ocean, offshore and Arctic engineering*. Halkidiki, Greece: Ocean, Offshore and Arctic Engineering Division, 2, 897–903.
- Han, S. M., and Grosenbaugh, M. A. (2006). On the design of single-point cable-linked moorings for ocean observatories. *IEEE J. Ocean. Eng.* 31 (3), 585–598. doi: 10.1109/OE.2005.850917
- Iannaccone, G., Guardato, S., Vassallo, M., Elia, L., Beranzoli, L., et al. (2009). A new multidisciplinary marine monitoring system for the surveillance of volcanic and seismic areas. *Seism. Res. Lett.* 80, 203–213. doi: 10.1785/gssrl.80.2.203
- Makris, J., Papoulia, J., and Tsambas, A. (2014). *A real-time seismic and tsunami network in the kyparissiakos gulf, Greece, bollettino di geofisica teorica ed applicata*, 55(2)561–587.
- Martino, P. D., Guardato, S., Tammara, U., Vassallo, M., Iannaccone, G., et al. (2014). A first GPS measurement of vertical seafloor displacement in the campi flegrei caldera (Italy). *J. Volcanol. Geotherm. Res.* 276, 145–151. doi: 10.1016/j.jvolgeores.2014.03.003
- Mellinger, E., Erickson, J., Hamilton, J. A., Chaffey, M., and McBride, L. (2003). "Dynamic modeling and actual performance of the moos test mooring," in *Proceedings of the IEEE/MTS OCEANS conference*. (San Diego, CA: IEEE Oceans), 2003, 2574–2581.
- Palanza, M., Petillo, S., and Matthias, P. (2017). Ocean observatories initiative coastal surface mooring technology. *IEEE Conf. Oceans*, 2003, 1–4. doi: 10.1109/OCEANSE.2017.8085008. Aberdeen.
- Sekino, H., and Clark, A. M. (2003). A near real-time buoy telemetry system for observation of marine earthquake/crustal deformation in Japan. *IEEE Int. Workshop Sci. Use Submarine Cables Related Technol.* 2003, 266–271. doi: 10.1109/SSC.2003.1224159
- Smith, L. M., Barth, J. A., Kelley, D. S., Plueddemann, A., Roderio, I., Ulses, G. A., et al. (2018). The ocean observatories initiative. *Oceanography* 31 (1), 16–35. doi: 10.5670/oceanog.2018.105
- Trowbridge, J., Weller, R., Kelley, D., Dever, E., Plueddemann, A., Barth, J. A., et al. (2019). The ocean observatories initiative. *Front. Mar. Sci.* 6, 1–22. doi: 10.3389/fmars.2019.00074
- Wang, H., Yang, W., Xin, Y., and Zhang, S. (2019). A data management method for remote and long-term seafloor observation system. *Mar. Geod.* 43 (1), 1–22. doi: 10.1080/01490419.2019.1673265
- Yu, J., Zhang, S., Yang, W., Xin, Y., and Gao, H. (2020). Design and application of buoy single point mooring system with electro-optical-mechanical (EOM) cable. *J. Mar. Sci. Eng.* 8 (672), 1–25. doi: 10.3390/jmse8090672
- Zhang, S., Yang, W., Xin, Y., Wang, R., Li, C., Cai, D., et al. (2018). Prototype system design of mooring buoy for seafloor observation and construction of its communication link. *J. Coast. Res.* 83, 41–49. doi: 10.2112/SI83-008.1

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The design and calibration of a low-cost underwater sound velocity profiler

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The sound velocity profile is the base of various underwater acoustic equipment. In this paper, a low-cost sound velocity profiler is designed based on the time difference method. It mainly includes three parts: the control unit, the storage module and the ultrasonic measurement module. Its overall volume is small, and the standby power consumption is low. It can be integrated into various underwater measurement platforms and profilers to realize the sound velocity measurement, and it also could be used as a self-contained sound velocity sensor. Furthermore, according to the sound velocity measurement principle and response characteristics, a calibration algorithm based on Recurrent Neural Network (RNN) and Discrete Wavelet Transformation (DWT) is proposed, which can improve the accuracy and adapt to the nonlinear response of the system by using multiple sets of time data obtained from the measurements. It is verified by calibration experiments that the neural network calibration algorithm can effectively reduce the nonlinear system error in the measurement, and its effect is better than the traditional linear regression method. The designed system prototype can achieve measurement accuracy of 0.05m/s after calibration, which can meet the needs of low-cost and high-precision underwater sound velocity measurement.

KEYWORDS

calibration, discrete wavelet transform, ranging, recurrent neural network, sound velocity profiler

Introduction

According to the different measurement applications and methods, the mainstream methods of obtaining sound velocity profiles can be roughly divided into inversion methods (Bela Santos et al., 2017; Huang et al., 2021) and measurement methods (Didier et al., 2019). Among them, the inversion method usually uses underwater acoustic equipment to directly perform acoustic detection on a large range of seawater. One

method is to use high-power underwater acoustic transceiver equipment to form an underwater acoustic network, measure the time delay of sound propagation on all paths, then estimate sound velocity profile. It is also possible to use a multi-beam echo sounder to measure the time delay of sound wave reflection in waters with known depths, and then use mathematical tools to model and invert the actual sound speed profile. The inversion method does not require any the traditional sensor in process of obtaining the sonic speed, and its measurement accuracy and efficiency are usually related to the algorithm used in the inversion. The other measurement method is to measure the sonic speed of water samples directly at a specific location. According to the measurement principle, it can be divided into indirect measurement method and direct measurement method. The indirect measurement method does not directly measure the propagation rate of sound waves in water. The sensor used is mainly the Conductivity-Temperature-Depth Profiler (CTD) (Shi, 2006). Based on the obtained temperature and salinity data, the formula is used to estimate sound velocity value of the corresponding point, where empirical formula algorithms include Del Grosso algorithm (Del Grosso and Made, 1973), Wilson algorithm (Wilson, 1959) and so on (Liu et al., 2020). In practical measurement applications, indirect measurement methods using empirical formulas usually have significant limitations (Talib et al., 2011). Since the data measured by the temperature and salinity sensor also has errors, these errors may be further amplified by the empirical formula, and the accuracy of the empirical formula itself is limited, so the calculated sound velocity value may have a large error with the real value. The direct measurement method is a more intuitive measurement method (Xue et al., 2018). Its main principle is to use an acoustic sensor to measure the wavelength or propagation time of sound waves in water to calculate the sonic speed. According to the different measurement methods, it can be divided into phase comparison method, resonance sound spectrum method and time difference method. The three methods measure the wavelength, spectrum and propagation time of sound waves respectively. The phase comparison method is to determine the wavelength by comparing the phase difference of a sound wave with a fixed frequency at two points (Chen et al., 2011; Yang et al., 2021; Cheng and Lou, 2022). Resonance spectrometry uses an excitation signal to induce the resonance of seawater in a certain space (Akbar et al., 2019; Siyu et al., 2020). The frequency of the resonance is independent of the excitation function used, but an inherent property of seawater as an elastic body. According to the change of the resonant sound spectrum of the object, the parameters such as the density, elastic coefficient, acoustic impedance and sonic speed of the object can be studied. The time difference method is to directly measure the time required for the sound wave to propagate a fixed length in the seawater to be measured. Compared with other sonic speed measurement methods, the time difference method has a faster response speed. The sensor

using the time difference method is small in size and low in power consumption, hence the time difference method is very suitable for field measurements (Ko et al., 2012; Sun et al., 2020; Liu et al., 2021; Sun et al., 2021; Zhang et al., 2021). Most underwater sound velocity measurement sensors and profilers on the market use the time difference method. The most critical step in the time difference method is to measure time. The smaller the volume of the sound velocity probe, the higher the accuracy of time measurement is required. With the rapid development of various radar, ultrasonic or laser-based ranging sensor technologies in recent years, the design process of Time to Digital Converter (TDC), the core component used to measure time, has also become more and more mature. There are a large number of TDC chips that can meet the requirements of low-cost and high-precision time measurement, and their time resolution is usually in the picosecond level, which can also meet the needs of small transit-time sound velocity measurement sensors (Rostami et al., 2020; Garzetti et al., 2021).

In this paper, a low-cost, low-power, miniaturized time-difference sound velocity profiler is designed, and a dedicated calibration algorithm for the system is proposed based on RNN and DWT. In order to reduce the system's demand for hardware computing power as much as possible, the measurement system adopts a marginal design. The main control module in the sound velocity profiler is only responsible for process control and data interaction, and all computing processes are completed by the data processing terminal. The calibration algorithm of the measurement data is based on the RNN framework, which can calibrate the nonlinear error in the sensor response curve to adapt to the low-cost probe with poor acoustic performance, and can fuse multiple measurement data at the same time to utilize the repeated information in the measurement data to improve the measurement precision.

The principle of time difference sound velocity measurement sensor

According to the types of measurement circuits, the time-difference sound velocity sensor can be divided into ring-sound type (Yang et al., 2021) and transit time type (Kalisz, 2003). The ring-sound method, also known as the cyclic pulse method, is a very classic time difference measurement circuit. The basic idea is to connect the water to be tested and the transceiver transducer in series as a delay device in a self-excited circuit, and then measure the period or frequency of the pulse excitation signal in the circuit to obtain the specific time delay of sound propagation. The ring-sound sensor will continuously repeat the measurement process during the working process, and through a reasonable calculation method, the effect similar to the averaging of repeated measurements can be achieved to improve the accuracy of the measurement results. The disadvantage is that the ring-sound sensor needs to repeat the measurement

continuously, which will inevitably greatly improve the overall power consumption and response time of the system, and because the signal generation and detection depend on the analog circuit, it is difficult to accurately analyze the noise and other disturbances in the circuit. Time of Flight (TOF) sensor can measure the propagation time of a single sonic speed. Due to the high demand for hardware in principle, its appearance and development are later than the ring-sound type. The transit time measurement method using the reflective structure is also called the pulse echo method. The circuit will directly measure the time required for the sound wave to be sent to the echo signal to be received, thereby obtaining the sonic speed in the water. The accuracy of TOF measurement is related to the time resolution and propagation distance of the measurement system. When the sonic speed in the water to be measured does not change much, the longer the distance of the sound propagation path and the more accurate the time resolution, the more accurate the measured sonic speed.

The design of system

The sound velocity profiler designed in this paper is intended to be used as a general-purpose sound velocity sensor module to be applied to various small underwater observation platforms. In order to adapt to different platforms and facilitate secondary development, the designed software and hardware system can be used as a lower module. The serial port receives commands and sends data, and it can also be used independently as a self-capacitive sensor when only the power supply battery is connected. Some parameters of the system are shown in Table 1.

Hardware design

The designed sound velocity profiler is integrated on a small PCB board, and the overall hardware architecture is shown in Figure 1. The circuit can be divided into four parts: power supply module, ultrasonic measurement module, data storage module and main control.

In the process of hardware development and debugging, three versions of PCB boards have been designed successively, and the corresponding PCB is shown in Figure 2. The first version of the PCB (left) uses two layers of wiring, with a length of 74mm and a width of 52mm. The main signal lines on the board have terminals for easy debugging, which are mainly used to verify the working principle of the hardware; the second version of the circuit (upper right) with a high-precision oscillator is used as a synchronous clock signal, and the regulated power supply circuit and common terminal layout are optimized; the PCB adopts four-layer wiring, and the length and width are reduced to 38mm and 18mm, which are mainly used for system performance testing. The third version of the circuit (bottom right) adds a memory module on the base of the second version, including a flash chip and an SPI interface for an external SD card; the PCB is 40mm long and 15mm wide, the layout of components has been further optimized, and the spacing and arrangement of some signal lines are adjusted to reduce crosstalk.

In order to meet the long-term work needs of the system on various underwater observation platforms and the low-cost design characteristics, MSP430G2XX Series MCU produced by Texas Instruments is selected as the main control chip, with an area only half of that of other conventional MCU of MSP430 series, which is suitable for the hardware system design with limited space. In this design, about 32 bytes of data from the TDC chip need to be recorded for each measurement, and the storage in the MCU is very limited, so an external storage device is required to store the measurement results to meet the non-real-time measurement requirements of self-capacitance sensor data. The circuit supports two kinds of storage devices, micro SD multimedia memory card (MMC, Multimedia Memory Card) and W25QXX series chips. Among them, the W25QXX memory chip is integrated on the PCB, and the micro SD card is externally connected. In the sensor platform containing the SD card storage device, the reserved SPI bus interface can be directly connected to the SD card to realize centralized data storage. The ultrasonic measurement module is the core device of the whole system, which includes two time-to-digital conversion chips TDC7200 and TDC1000. The TDC7200 undertakes the task of high-precision timing in the circuit, and can precisely measure the time interval between the start signal and up to five end signals. The chip contains a high-frequency oscillator and is equipped with a calibration function, which can compensate for the timing deviation caused by factors such as temperature changes according to the external clock time base, so as to obtain picosecond-level accuracy. The TDC7200 also supports multi-cycle measurements, where results from up to 128 measurement cycles can be added for averaging for higher measurement accuracy. Therefore, it is suitable for the design of sensor calibration algorithm based on neural network for this system. TDC1000 is an analog front-end for ultrasonic induction, which is directly connected to the transducer probe.

TABLE 1 Parameters of the system.

Parameters	Value
Supply voltage	4.5-5.5V
Standby power consumption	<1mW
Storage capacity	8MB/16MB
Serial communication rate	9600-115200bps
Sampling interval	0.5~10s (configurable)
Single measurement error	< ± 0.1m/s
Measurement response time	<5ms
Range	1440-1550m/s

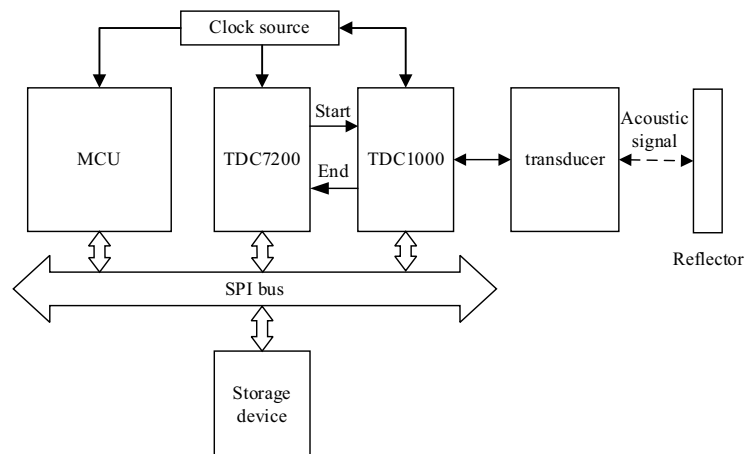


FIGURE 1
System hardware structure.

The pulse frequency of the transmitted signal, the amplification gains of the received signal and the detection threshold can be adjusted according to the configuration. The internal amplifier has low noise and interference, so as to meet the requirements of high precision ultrasonic testing.

The design of software control process

In this sound velocity profiler, the MCU is only responsible for the enabling and data transmission of each chip on the control board, and it does not receive the analog signal generated during the measurement process. The processing of the ultrasonic signal and the precise timing are realized by two time-to-digital conversion chips respectively. The program running on the measurement system mainly includes the main loop, measurement program, data recording and serial port services.

The main loop is shown in Figure 3. The main program is responsible for receiving the timing interrupt from the timer and the receiving interrupt of the UCA0 serial port under the UART configuration. The interrupt service corresponds to the timing measurement program and the serial port control program respectively. In the running cycle, the MCU can be divided into two states: work and sleep. When waiting for the measurement, the MCU enters the low-power mode to reduce power consumption. At this time, the global interrupt is enabled, and the MCU will be woken up by waiting for the timer or serial port interrupt. When the system receives the interrupt message, it determines the program to be run according to the current interrupt type, and it enters the sleep mode again after executing the target program to save power consumption. During the

execution of one interrupt, the MCU will shield other interrupts to avoid data conflicts. In a measurement cycle, the time required to measure data and communicate is very short, and the MCU does not need to perform operations most of the time, and is in a dormant state, which can greatly reduce the average power consumption of the main control module.

The measurement program is mainly responsible for controlling the TDC chip to perform a measurement and reading the measurement results into the memory. It also updates the system time and TDC measurement configuration before the measurement starts. After the serial port transmission is enabled, the data will be sent directly through the UART serial port.

The data logging system supports two storage devices, SD card and flash memory chip, which can be selectively used according to actual needs. If one of the storage devices is not connected or the writing fails, it will skip and continue. Some SD cards do not support the reading and writing of data of any size, so it is necessary to set a buffer in the program, and it writes all the data in the buffer to the SD card after the amount of data reaches a certain level. When the serial port receives data, the serial port receiving interrupt will be generated. At this time, the serial port service program is opened, and the received data is read one byte at a time. When the end character is received, or the serial port has not received data for a certain period of time, the corresponding received instruction will run.

Echo signal modelling

In the narrowband ultrasonic ranging system, the time domain waveform of the ultrasonic echo signal can be expressed as a mixed exponential model as shown in Equation 1.

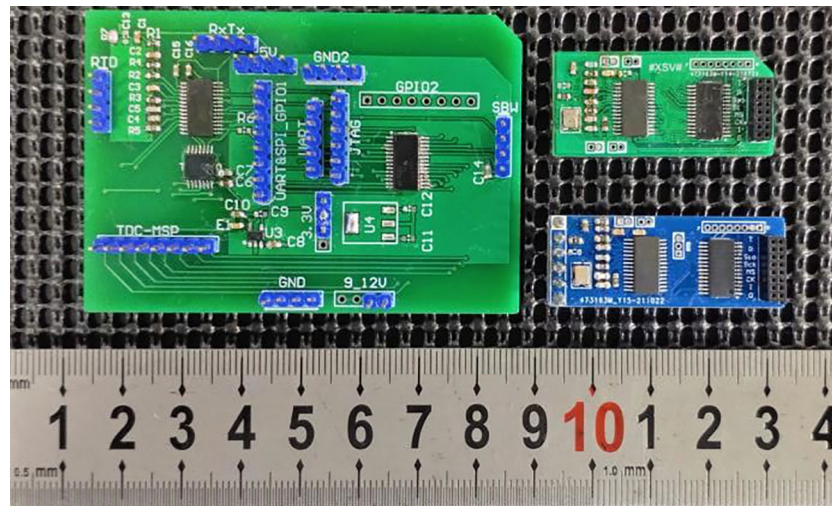


FIGURE 2
Physical diagram of circuit board for test.

$$s(t) = A(t - \tau)^m \cos(2\pi f(t - \tau) + \theta) e^{(\tau-t)/T} \quad (1)$$

where A is the amplitude of the signal; m is an integer, usually 1, 2 or 3 depending on the system parameters; f is the center frequency of the signal, which is 1MHz in this system; φ is the initial phase, generally 0. In the parameters of the simulated echo signal, the larger the value of m , the slower the envelope attenuation of the echo signal. According to the actual situation, $m=2$ is selected as the simulation parameter, and the simulation image is shown in [Supplementary Figure 1](#).

The echo waveform actually measured when the water temperature is 25°C is shown in [Supplementary Figure 2](#). It can be seen that the measured waveform is quite different from the single-channel echo signal under the mixed exponential model in [Supplementary Figure 1](#). Considering the overall small size of the sensor, the transducer and the reflective surface cannot be equivalent to an ideal sound source during the sound propagation process, and multipath effects may occur during the propagation process. After adjustment by the simulation experiment, the response of the multipath channel is shown in [Supplementary Figure 3](#), i.e., the channel model after combining the multipath effect and the mixed exponential model is similar to the actual response of the transducer. The simulated waveform after adding the multipath effect is shown in [Supplementary Figure 4](#).

Response performance test of sound velocimeter

Because the calculated TOF contains the systematic error caused by the characteristics of circuit components and sensor structure, it cannot be directly used as the ultrasonic propagation

time, which will result in the low sound velocity value, thus the data need to be calibrated. Under the condition of fixed distance, the sound velocity is inversely proportional to time, so after selecting the reciprocal of any timing result as the reading of the sensor, the calibration curve of the sensor can be linearly fitted by the least square method. Under the ideal condition without any interference factors, the echo signal waveform received by the transducer during each measurement is identical, and the distance between each detected zero crossing point is equal to the period of the ultrasonic signal, so the distance between each zero-crossing point is fixed. When there is only additive white Gaussian noise, the five zero crossing moments can be approximately regarded as five measurements of the same TOF value. Theoretically, using the average value of the five time points as the measurement result of the sensor can improve the measurement accuracy. However, due to the multi-path fading effect and frequency selective characteristics in the sound propagation process, the phase difference of each signal may not be fixed, resulting in the position of the five zero crossings detected in the echo being affected to some extent.

In order to verify whether the actual performance after averaging the five time points measured by the sensor meets the needs of sound velocity measurement, a principle verification experiment was carried out in a laboratory water tank. Place the sensor to be tested in the water tank, control the water temperature to change continuously within about 8°C ~32°C, and the sensor samples every 1 second. MATLAB is used to read and process the collected data through the serial port. [Figure 4](#) shows that five zero crossing times collected by the sensor and the change of water temperature with time. In order to more clearly display the response of the sensor, take the temperature in the water tank as the abscissa and the measured five time points as the

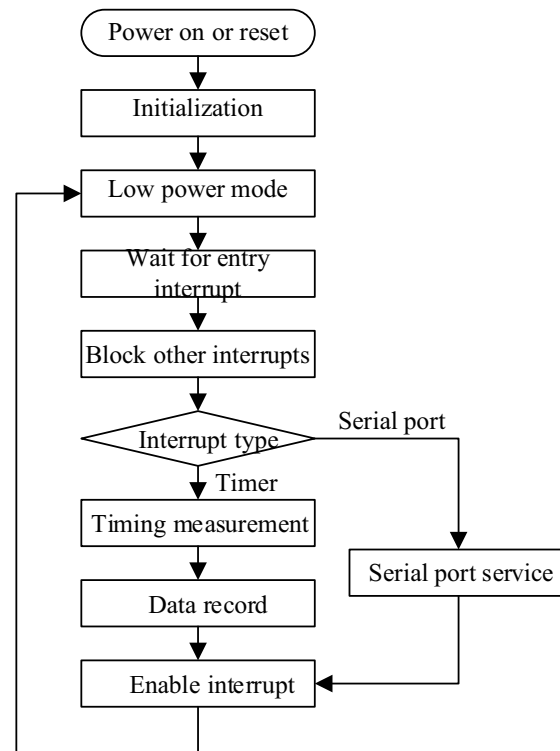


FIGURE 3
Main program flow.

ordinate, and only select the image drawn by the experimental data whose temperature is within the range of 15 to 20°C during the process of temperature rise and fall, as shown in Figure 5.

The trends of the measured values in Figures 4, 5 shows that there is a small nonlinear error related to temperature changes in the fitting results, and the five measurement points are affected to different degrees, and the nonlinear characteristic of t_3 is the most obvious. The sound velocity measurement equipment requires very high accuracy for time measurement, and the results of the response test show that there is a certain nonlinear error in the measurement results of the sensor, and the averaging method cannot completely solve the nonlinear error. The accuracy is difficult to meet the needs of practical applications under specific conditions. Designing and developing a data calibration algorithm for the data receiving end is an optimal solution to further improve the measurement accuracy.

Design of sensor calibration algorithm based on RNN and discrete wavelet decomposition

Neural network (Abiodun et al., 2018) is an artificial intelligence algorithm whose structure is similar to the way

of neural connections in living organisms. The network consists of an input layer, an output layer and a hidden layer. Each layer has several neurons, and its input can be a scalar, a vector or a higher-order tensor. This structure is also called a multi-layer perceptron (Multi-Layer Perceptron, MLP). Neural networks with multiple hidden layers are called deep neural networks. Through the training process, deep neural networks can simulate the input-output relationship of any function, or learn the abstract rules between input and output, and are widely used in data fusion and compression, curve fitting (Shao et al., 2016) and pattern recognition (Mikheev et al., 2020; Li et al., 2021). Generally speaking, the more layers a neural network has, the stronger its ability to learn details and abstract information, and the longer the training process will take. The number of layers of the hidden layer can be adjusted according to the needs. The selection of the number of neurons in each layer in the layer has no theoretical guidance and needs to be determined by experimental comparison. The neurons of two adjacent layers are connected to each other, and the input vector X_k of the k -th layer can be regarded as the sum of the vector b_k after multiplying the output vector Y_{k-1} of the $k-1$ th layer by the matrix W_k . This matrix is called the weight matrix and the

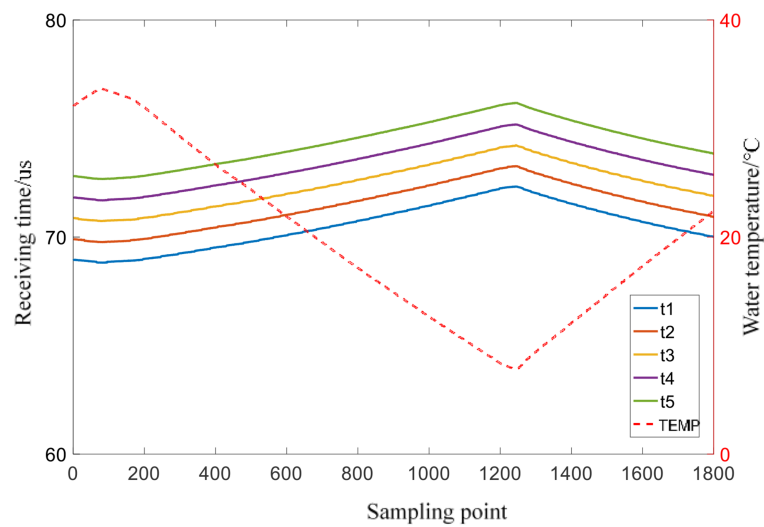


FIGURE 4
Curve of TOF measured value and water temperature with time.

vector is called the bias vector. Then this process can be expressed in the form shown in Equation 2.

$$\mathbf{X}_k = \mathbf{Y}_{k-1} \mathbf{W}_k + \mathbf{b}_k \quad (2)$$

In order to correct the nonlinear error in the sensor response curve and further improve the measurement accuracy and

usability of the designed low-cost sound velocity profiler, a sensor calibration algorithm based on RNN (Lv et al., 2021) and Discrete Wavelet Transform (DWT) (Chaubey and Atre, 2017) is designed in this paper, which can calculate the sound velocity value by combining the available information from the five zero-crossing measurements. RNN is used to process time-

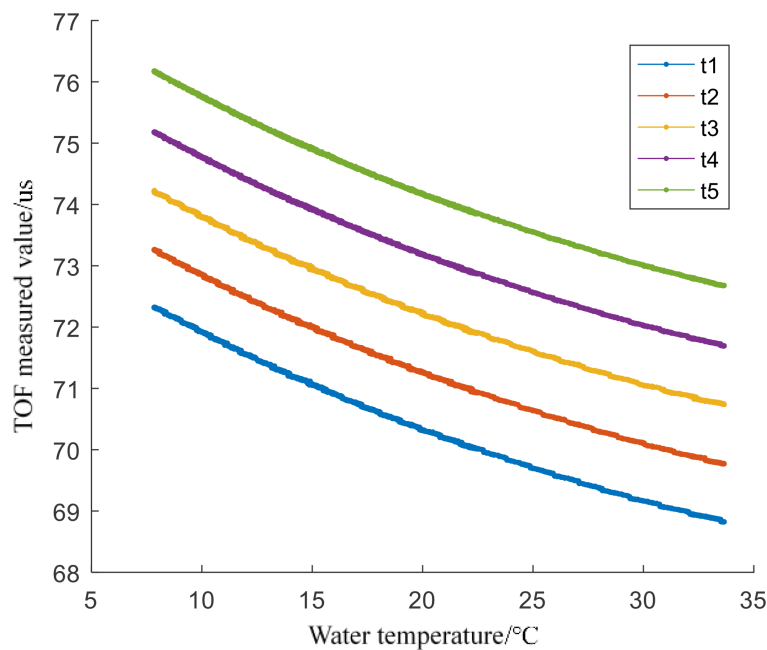


FIGURE 5
Relation curve between TOF measured value and water temperature.

serial signal which is similar with sequential received measurement signal. Specifically, RNN can predict future signal with past information, it has good performance in the prediction and analysis of nonlinear time series signal. The RNN can be represented by

$$y_j(t+1) = f\left(\sum_{i=1}^{m+n} \omega_{ji} z_i(t)\right)$$

$$z_i(t) = \begin{cases} y_i(t), & i \leq n \\ x_{i-n}, & i > n \end{cases} \quad (3)$$

where y_j is the output of j -th neuron, $f(\cdot)$ is the activate function, ω_{ji} denotes connection weight between j -th neuron and i -th neuron, $z_i(t)$ represents recurrent input y_i or external input x_i .

Discrete Wavelet Transform (DWT) can decompose signal into a series of lower resolution components with filtering and decimating operations. Specifically, high-pass and low-pass filters are used to get corresponding components and coefficients which are consisted with approximation (cA) and detail (cD) coefficients, as in shown in Figure 6. In order to get robust relationship between predicted results and inputs, the input signal is decomposed with DWT into four component coefficients (cD_1 , cD_2 , cD_3 , cA_3), and then the four coefficients are sent to RNN block_1 to get more refined temporal correlation and output high-dimension result. Meanwhile, the original signal is processed with RNN block_2 to get rough predicted result. At last, the outputs of RNN block_1 and RNN block_2 are concatenated with a Full Connection (FC) layer, and the result will be gotten.

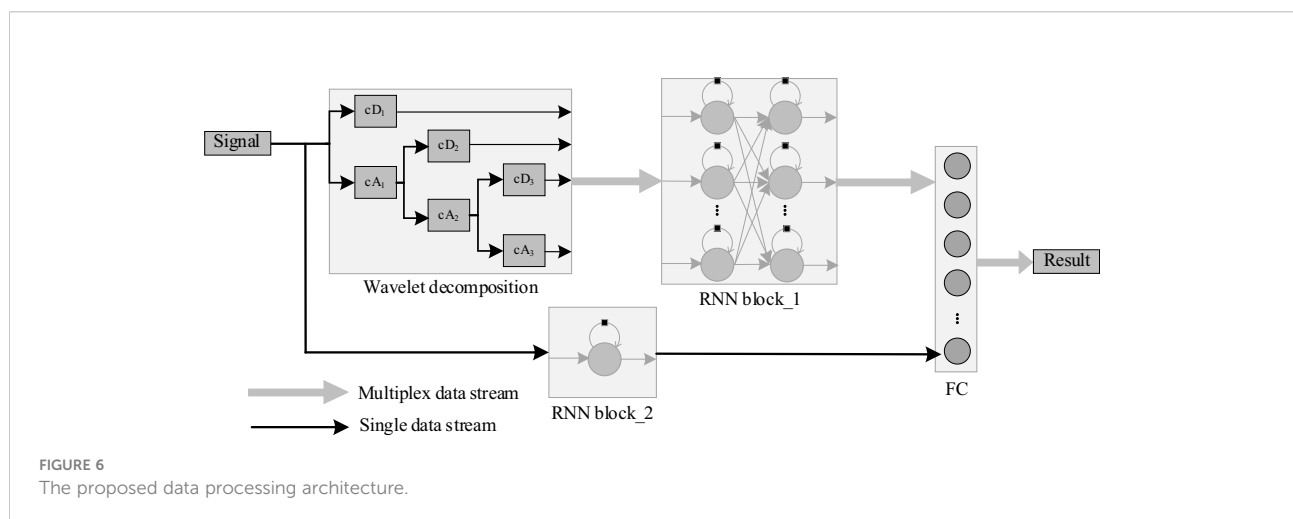
RNN is suitable for processing sequence data using historical information, and since the measurement data are sequential and are interrelated, RNN can be used to improve the fitting accuracy and give stable results compared with direct calculation results. At the same time, DWT decomposes the data into a series of components with different frequencies so that the RNN can use rich fitting features. Therefore, stable

sonic speed prediction can be achieved by combining the characteristics of RNN and DWT.

The commercial SVP as a reference and the probe of the sound velocity measurement device designed in this paper were placed adjacent to the water tank, and the measurement experiment was repeated to collect enough data as a dataset for training the neural network. The sampling interval of each sensor is set to 0.25 seconds, and the water temperature in the water tank is controlled to change from 35°C to 7°C within three hours and then return to 30°C. After that, 54,000 groups of continuous sensor measurement data were collected. In contrast, the SVP sensor used will return a blank value when the sound velocity data cannot be collected. The point where the blank value is located needs to be replaced by the average of the two nearest valid points to complete the measurement data.

Take the reciprocal of the five TOF time values as the ordinate, and the sound velocity value measured by the SVP as the abscissa, draw a relationship curve. The least squares method was used to linearly fit the measured data, and outliers with residual values greater than three times the standard deviation were eliminated from the data. The final data are shown in Figure 7.

Due to the uneven temperature change, the measurement densities of the two sound velocity sensors in different temperature ranges are different during the experiment i.e., the measurement points in the range close to the highest temperature and the lowest temperature are denser, while the measurement points in the middle area are sparse. In addition, there is a certain amount of noise in the measurement results, so using noisy data as a training set will affect the performance of neural network training. In order to make the points in the data set continuous and evenly distributed, and to suppress random errors in the measurement data to a certain extent. First, use the joint interpolation method to increase the resolution of the measured data to 0.001m/s, so that the measured data is evenly distributed along the abscissa, and then perform an average downsampling with a step size of 8 on the



interpolated data, and finally use the interpolation method to bring the resolution back to 0.001m/s. Taking the processed ordinate vector and abscissa as the input value and the target value, respectively, the training data set is obtained.

The neural network used for data calibration and fitting is built by MATLAB, and the activation function is the hyperbolic tangent function. The performance of data fitting is poor when the network structure is simple, and the excessive number of layers and neurons in the network will increase the computational complexity and lead to over-fitting. In order to determine the number of layers and neurons of the neural network, a continuous section is intercepted from the data set obtained in the previous section to test the relationship between the performance of the neural network and the parameters of the network construction, and finally the number of hidden layers in the built network is determined to be 2, each layer contains 20 neurons. 15% of the collected datasets were selected as test set and validation set, and the rest were used as training data. Set the number of training times to 5000 times. During the training process, the loss function of the neural network on the test set, training set and validation set varies with the number of training times as shown in Figure 8. The final mean square error of the network on the training data set is 7.5853×10^{-6} , the fitting accuracy is calculated by three times the standard deviation, the result is about ± 0.00826 m/s, which can meet the needs of sound velocity measurement calibration. However, the noise in the measurement data is removed in the data processing process, and there may be

overfitting. The actual measurement accuracy of the neural network needs further experimental verification.

System software and hardware testing

First, connect the system to the 5V power supply and disconnect all other connections. The measured current of the system in the standby state is about 190 μ A. Then connect the UART serial port of the system to the PC to verify its basic functions. Use an oscilloscope to connect both ends of the transducer, and place the probe in water at room temperature. The waveform on the oscilloscope during measurement is shown in Figure 9. The two waveforms are the transmit signal and the echo signal. Use the oscilloscope to measure the time between the two signals. The interval, about 68 μ s, corresponds to the actual measurement of the sensor.

Use an oscilloscope to connect the start signal line and the transducer signal line of the TDC1000. The signal waveform measured at the beginning of the measurement is shown in Figure 10. The upper and lower signal waveforms are the 1MHz ultrasonic pulse signal and the start signal respectively. It can be seen that the two signals are sent out synchronously, but there is still a level change on the transducer after the ultrasonic pulse signal is emitted, which may be related to the frequency response characteristics of the transducer.

Connect the end signal line and the transducer signal line of the TDC7200. The signal waveform at the arrival time of the echo

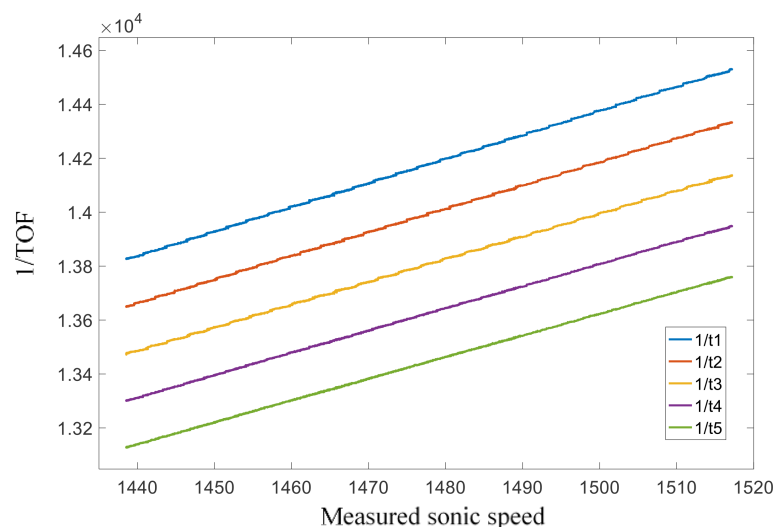


FIGURE 7
Measured data fit results.

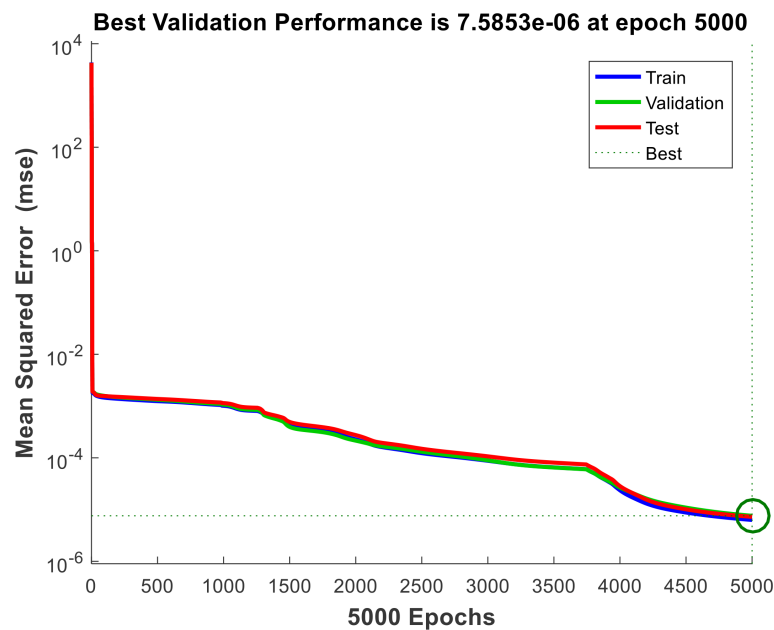


FIGURE 8
Loss curves.

is shown in Figure 11. The upper and lower signal waveforms are the ultrasonic echo signal and the end signal respectively. It can be seen from the figure that the envelope change of the echo signal caused by the multipath effect has no obvious impact on the signal detection process, and the TDC7200 chip can correctly detect the zero-crossing point of the echo signal.

In order to measure the accuracy of the sensor, a sensor calibration experiment was carried out in a constant temperature water tank. From the introduction of the sonic speed in seawater in Chapter 1, we can see that the sonic speed in water tends to increase with temperature. When the salinity and pressure are constant, the sonic speed in water is only related to temperature. Therefore, temperature is selected as the variable to control the change of sonic speed to calibrate the sensor. Using the SVP2 temperature-salt-depth sound velocity profiler produced by VALEPORT Company as a reference, its nominal sound velocity measurement error is $\pm 0.02\text{m/s}$.

Select 30°C , 25°C , 20°C , 15°C , and 10°C as the measurement temperature. After the temperature of the water tank drops to the measurement temperature point and stabilizes, read 100 sets of readings from the two sensors through the serial port through MATLAB, and then control the water temperature to drop to the next measured temperature. Finally, the readings of the two sensors at each point are shown in Figure 12, where the sonic speed is the

sound speed value (right Y-axis) measured by VALEPORT SPV2, and t_1 to t_5 are the five TOF moments (left Y-axis) measured by the sensor to be calibrated.

Run the neural network trained in the previous chapter by MATLAB, and calculate the sound velocity value output by the time difference measured by the sensor after being calibrated by the neural network. As a control, the regression line of the reciprocal of the sound velocity value measured by the SVP2 profiler and the average value of the five zero-crossing points was calculated using the least squares method. The fitting results are shown in Equation 4, where V_{cf} is the output result of the linear fitting.

$$V_{cf} = 1.16997 \times \frac{5}{t_1 + t_2 + t_3 + t_4 + t_5} + 136.51134 \quad (4)$$

Taking the mean value of 100 times the sonic speed measured by SVP as the reference value, the 100 sets of data measured at each temperature are brought into the neural network and Equation 3 for calculation. The error between the neural network output result and the linear regression fitting result is shown in Figure 13. The averages of the results of neural network calibration and linear regression calibration at each temperature point are compared, as shown in Table 2. Combining Figure 13 and Table 2, it can be seen that the output of the neural network is closer to the SVP at the five

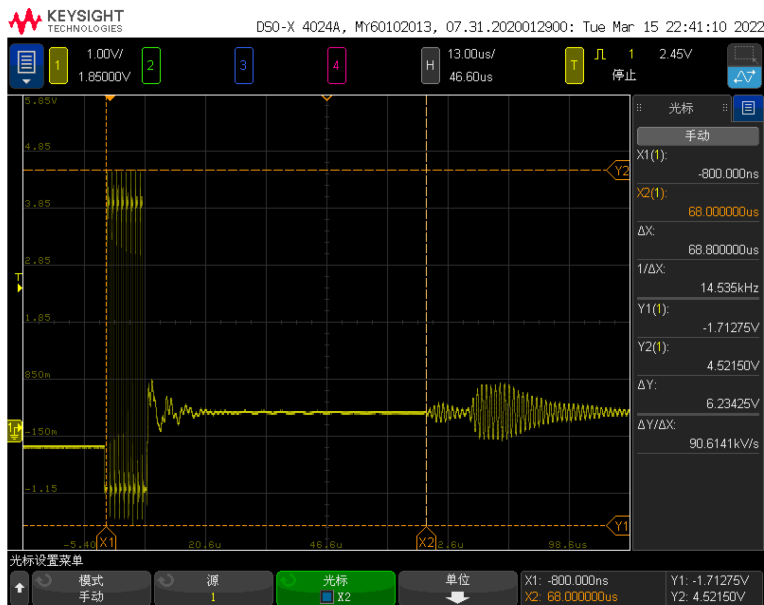


FIGURE 9
Transducer signal waveform during measurement.

measured temperature points, and the errors are concentrated around the zero point, and the error range is about $\pm 0.047\text{m/s}$. It is calculated that the mean square error of the linear regression results at each measurement temperature point is 0.0553, and the standard deviation is 0.235; the mean square error of the output result after using the neural network

calibration and the reference value is 0.00025, and the standard deviation is 0.0157. To sum up, the neural network method designed in this paper effectively reduces the error of the sound velocity profiler, and the final error range measured in the laboratory environment is less than $\pm 0.05\text{m/s}$, which can meet the design requirements of the system.

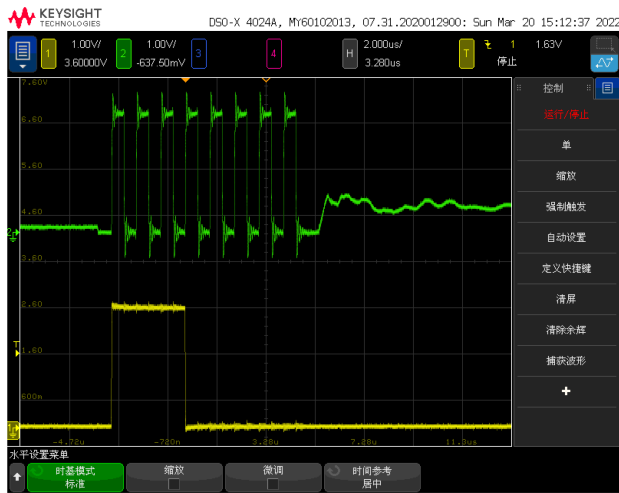


FIGURE 10
Measurement start signal and emission pulse waveform.

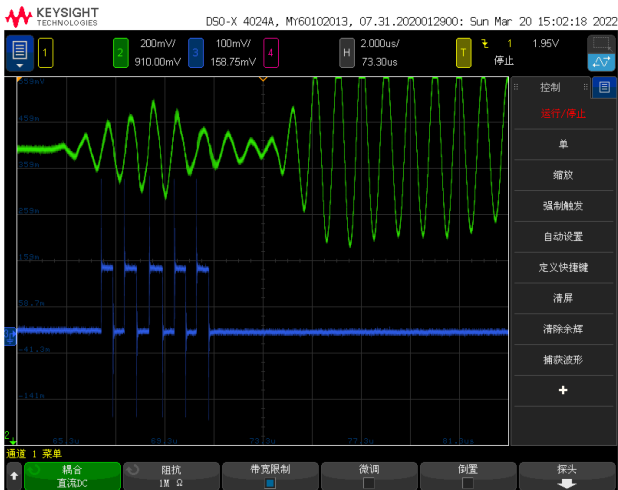


FIGURE 11
Measurement end signal and echo signal waveform.

As shown in the [Supplementary Table 1](#), compared with our design, most underwater sound velocity profilers are more expensive, and the corresponding accuracy improvement is not significant. It verifies that our designs enable high prediction accuracy with lower cost.

Conclusion

In this paper, a low-cost underwater sound velocity profiler is designed, and a calibration algorithm is proposed based on the sound velocity measurement principle and response

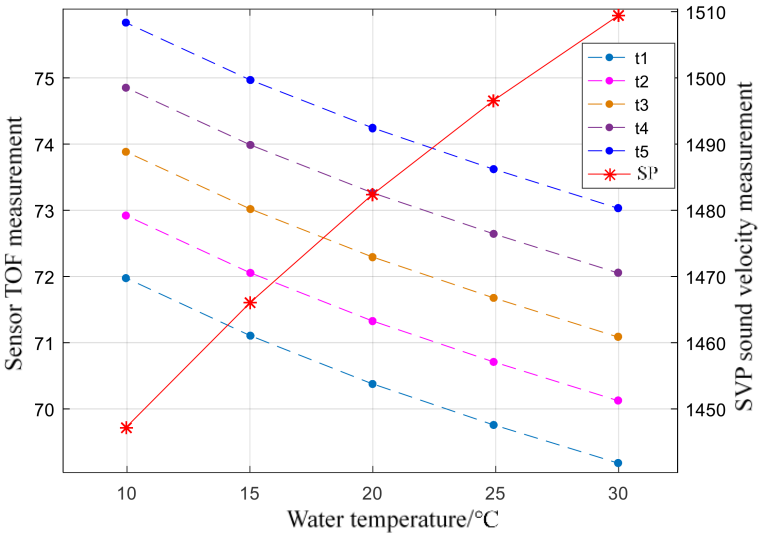


FIGURE 12
Two sensor readings at different temperatures.

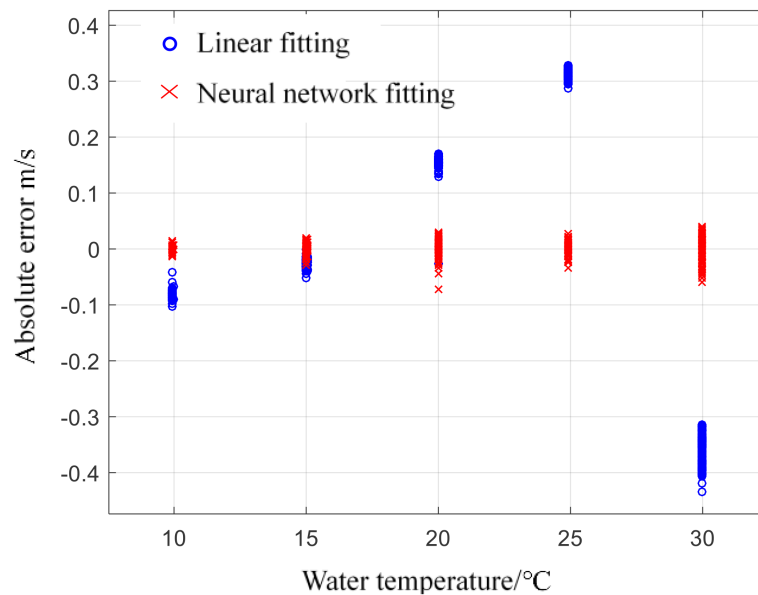


FIGURE 13
Error distribution of measurement results.

TABLE 2 Experimental measurement results.

Temperature °C	SVP reading (m/s)	Neural network (m/s)	Linear fitting (m/s)
30.00	1509.389	1509.387	1509.748
25.00	1496.603	1496.603	1496.291
20.00	1482.4	1482.394	1482.248
15.00	1466.094	1466.097	1466.123
10.00	1447.178	1447.177	1447.259

characteristics of the system. The hardware system adopts a low-cost marginal design. The main control module is only responsible for data collection, interaction and storage, and does not perform data processing work, which can greatly reduce the system's demand for hardware computing power and is suitable for large-scale deployment scenarios. Compared with the traditional linear fitting, the designed neural network calibration algorithm has better fitting and data fusion capabilities for nonlinear response curves, and can obtain measurement data with higher accuracy. In the future, the design of the probe will be improved, and the performance of the system can be further improved.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#). Further inquiries can be directed to the corresponding authors.

Author contributions

SZ: Conceptualization, methodology, formal analysis, investigation, visualization. XX: Methodology, formal analysis, investigation. DX: Formal analysis, investigation, visualization. KL: writing-review & editing, software, visualization. CS: Supervision, data curation, project administration and funding acquisition. CT: Conceptualization, methodology, formal analysis, investigation, visualization. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Abiodun, O. I., Jantan, A., Omolara, A. E., Dada, K. V., Mohamed, N. A., and Arshad, H. (2018). State-of-the-art in artificial neural network applications: A survey. *Heliyon* 4 (11), e00938. doi: 10.1016/j.heliyon.2018.e00938
- Akbar, S. A., Shah, A. S. M., Abdullah, A. S., Yusof, N. A.T., Khatun, S., Shaharum, S. M., et al. (2019). An accurate characterization of different water properties using resonant method for underwater. *Proc. 10th Natl. Tech. Sem. Underwater Syst. Technol.* (Singapore) 538, 113–120. doi: 10.1007/978-981-13-3708-6_10
- Bela Santos, A., Felisberto, P., and Jesus, S. M. (2017). Using shipping noise for sound speed inversion in coastal areas. *OCEANS* (Aberdeen, UK), 1–5. doi: 10.1109/OCEANSE.2017.8085009
- Chaubey, A., and Atri, A. (2017). “A hybrid DWT-DCLAHE method for enhancement of low contrast underwater images,” in *2017 International Conference of Electronics, Communication and Aerospace Technology (ICECA)* (Coimbatore, India), 196–201.
- Cheng, H., and Lou, W. (2022). PD-FMCW: Push the limit of device-free acoustic sensing using phase difference in FMCW. *IEEE Trans. Mobile Comput.* doi: 10.1109/TMC.2022.3162631
- Chen, J., Zhao, S., Huang, Z., and Qiao, C. (2011). “Acoustic velocity measurement in seawater based on phase difference of signal,” in *IEEE 2011 10th International Conference on Electronic Measurement & Instruments*. (Chengdu China: Institute of Electrical and Electronics Engineers (IEEE)) 181–184. doi: 10.1109/ICEMI.2011.6037883
- Del Grosso, V. A., and Made, C. W. (1973). Another search for anomalies in the temperature dependence of the speed of sound in pure water. *J. Acoust. Soc. America* 53 (23), 561–563. doi: 10.1121/1.1913358
- Didier, C., Jaouad, E., Gaspard, G., and Michel, L. (2019). Real-time correction of sound refraction errors in bathymetric measurements using multibeam echosounder. *OCEANS* (Marseille, France), 1–7. doi: 10.1109/OCEANSE.2019.8867076
- Garzetti, F., Corna, N., Lusardi, N., and Geraci, A. (2021). Time-to-Digital converter IP-core for FPGA at state of the art. *IEEE Access* 9, 85515–85528. doi: 10.1109/ACCESS.2021.3088448
- Huang, W., Liu, M., Li, D., Yin, F., Chen, H., Zhou, J., et al. (2021). Collaborating ray tracing and AI model for AUV-assisted 3-d underwater sound-speed inversion. *IEEE J. Ocean. Eng.* 46 (4), 1372–1390. doi: 10.1109/JOE.2021.3066780
- Kalisz, J. (2003). Review of methods for time interval measurements with picosecond resolution. *Metrologia* 41 (1), 17–32.
- Ko, N. Y., Kim, T. G., and Moon, Y. S. (2012). Particle filter approach for localization of an underwater robot using time difference of arrival. *2012 Ocean. (Yeosu Korea)*, 1–7. doi: 10.1109/OCEANS-Yeosu.2012.6263573
- Liu, F., Chen, H., Zhang, L., and Xie, L. (2021). Time-Difference-of-Arrival-Based localization methods of underwater mobile nodes using multiple surface beacons. *IEEE Access* 9, 31712–31725. doi: 10.1109/ACCESS.2021.3060565
- Liu, C., Han, K., Zhang, W., and Chen, W. (2020). “An optimization method for sound speed profile inversion using empirical orthogonal function analysis,” in *2020 IEEE 3rd International Conference on Information Communication and Signal Processing (ICICSP)* (Shanghai, China: Institute of Electrical and Electronics Engineers (IEEE)). 104–107.
- Li, H., and Zhang, L. (2021). And algorithm for self-organizing feed-forward neural networks for pattern classification. *IEEE Trans. Neural Networks Learn. Syst.* 32 (11), 4901–4915. doi: 10.1109/TNNLS.2020.3026114
- Lv, P. F., He, B., and Guo, J. (2021). Position correction model based on gated hybrid RNN for AUV navigation. *IEEE Trans. Veh. Technol.* 70 (6), 5648–5657. doi: 10.1109/TVT.2021.3080134
- Mikheev, M. Y., Gusynina, Y. S., and Shornikova, T. A. (2020). “Building neural network for pattern recognition,” in *2020 International Russian Automation Conference (RusAutoCon)* (Sochi, Russia: Institute of Electrical and Electronics Engineers (IEEE)). 357–361. doi: 10.1109/RusAutoCon49822.2020.9208207
- Rostami, M. S., Saberi, M., Maymandi-Nejad, M., and Sawan, M. (2020). A low-power time-to-Digital converter for sensor interface circuits. *IEEE Trans. Circuits Syst. II: Express Briefs* 67 (12), 2853–2857. doi: 10.1109/TCSII.2020.2996505
- Shao, K., Chen, J., Zhao, Z., and Zhang, D. H. (2016). Communication: Fitting potential energy surfaces with fundamental invariant neural network. *J. Chem. Phys.* 145 (7), 071101. doi: 10.1063/1.4961454
- Shi, S. (2006). “Ad hoc wireless network based oceanic CTD measurement,” in *IEEE International Conference on Information Acquisition* (Vehai, China: Institute of Electrical and Electronics Engineers (IEEE)). 11–15.
- Siyu, E., Zhang, Y. N., Han, B., Zheng, W., Wu, Q., and Zheng, H. (2020). Two-channel surface plasmon resonance sensor for simultaneous measurement of seawater salinity and temperature. *IEEE Trans. Instrum. Meas.* 69 (9), 7191–7199. doi: 10.1109/TIM.2020.2976405
- Sun, S., Qin, S., Hao, Y., Zhang, G., and Zhao, C. (2021). Underwater acoustic localization of the black box based on generalized second-order time difference of arrival (GSTDOA). *IEEE Trans. Geosci. Remote Sens.* 59 (9), 7245–7255. doi: 10.1109/TGRS.2020.3032982
- Sun, S., Zhang, X., Zheng, C., Fu, J., and Zhao, C. (2020). Underwater acoustical localization of the black box utilizing single autonomous underwater vehicle based on the second-order time difference of arrival. *IEEE J. Ocean. Eng.* 45 (4), 1268–1279. doi: 10.1109/JOE.2019.2950954
- Talib, K. H., Othman, M. Y., Sulaiman, S. A. H., Wazir, M. A.M., and Azizan, A. (2011). Determination of speed of sound using empirical equations and SVP. *IEEE 7th Int. Colloq. Signal Process. its Appl.* (Penang, Malaysia), 252–256. doi: 10.1109/CSPA.2011.5759882
- Wilson, W. D. (1959). Speed of sound in distilled water as a function of temperature and pressure. *J. Acoust. Soc. America* 31 (8), 1067–1072. doi: 10.1121/1.1907828
- Xue, B., Wang, Z., Zhang, K., Zhang, H., Chen, Y., Jia, et al. (2018). Direct measurement of the sound velocity in seawater based on the pulsed acousto-optic effect between the frequency comb and the ultrasonic pulse. *Optics Express*, 26 (17), 21849–21860.
- Yang, L., Zhang, J., and Wang, J. (2021). Sound speed measurement using phase estimation method of pulse signal in water. *OES China Ocean. Acoust. (COA)* (Harbin, China), 267–271. doi: 10.1109/COA50123.2021.9519875
- Zhang, L., Zhang, T., Shin, H. S., and Xu, X. (2021). Efficient underwater acoustical localization method based on time difference and bearing measurements. *IEEE Trans. Instrum. Meas.* 70, 1–16. doi: 10.1109/TIM.2021.3127641

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Glide performance analysis of underwater glider with sweep wings inspired by swift

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Underwater glider (UG) is one of the most promising autonomous observation platforms for long-term ocean observation, which can glide through seawater columns by adjusting its buoyancy and attitude. Hydrodynamic shape, especially the wing parameters, has an important influence on the glide performance of UG. In this paper, a sweep wing strategy inspired by the swift wings is proposed to apply pre-adjustable sweep wings for UGs, so as to improve the glide performance in different glide conditions. The approximate model that describes the relationship between the hydrodynamic coefficients of UG and the wing sweep angles is established with computational fluid dynamics method. By importing the approximate models into the dynamic model, the glide performance analysis, including endurance ability and trajectory accuracy, is performed to analyze the effect of the various sweep wings. The analysis results indicate that different sweep angles of wings are required by UG to obtain the optimal ability in gliding range, gliding duration, turn and resisting current, and the sweep wing strategy is useful for UG to improve its performance in observation mission due to the uncertainty of ocean environment.

KEYWORDS

underwater glider, sweep wing strategy, glide performance, computational fluid dynamics, approximate model

Introduction

Animals have been the bio-inspirational source for some novel concepts of locomotion (Triantafyllou and Triantafyllou, 1995), sensing (Yang et al., 2010; Miller, 2018) and the intelligent control (Low and Willy, 2006) of underwater vehicles, which have the adaptability to changes in the environment and the ability for self-repair of the system. Thus, bionic underwater robots have become one of the focuses of robotics in

recent years because of their high flexibility and intelligence (Zeng et al., 2006). However, there may exist a certain difference between the human-made systems and the biological systems in design space.

Instead of proving general benefits of biological systems, this paper aims to investigate the usefulness of the wings with various sweep angles (various sweep wings for short) based on bio-inspired for underwater gliders (UGs). In fact, nature's flyers have been excellent inspirations of various air vehicles. A lot of efforts have been made to mimic bio-flight mechanisms in order to achieve similar aerodynamic performances, such as lift and thrust enhancement and high stability with minimal power consumption (Rojratsirikul, 2013).

The morphing wings generally have a variable shape or structure. According to their morphing strategies and objectives, morphing wings are classified into different categories, mainly involving variable camber (Pendleton et al., 2000), variable thickness (Popov et al., 2010), twist morphing (Raither et al., 2013), span morphing (Vale et al., 2011), variable sweep (Powers et al., 1992) and folding wing (Wang and Dowell, 2011). From smaller air vehicles to larger unmanned aerial vehicles and human-powered hang gliders, many attempts have been made to improve the vehicle performance using concepts found in nature. The concept of variable sweep wing was adopted for military fighter aircraft from the 1950s, primarily to achieve higher supersonic cruising speeds (Li et al., 2018). Kilgore (1971) measured aerodynamic damping and oscillatory stability in pitch and in yaw and the effective-dihedral parameter for two configurations of a model of a variable-sweep-wing multimission military airplane by using a small-amplitude forced-oscillation mechanism. Bulekov and Teryev (1972) investigated the dynamics of variable sweep wings aircraft in the course of changing geometry. Dobbs et al. (1985) tested the two dynamically scaled 0.1 scale composite semispan variable sweep wing models. Gursul et al. (2006) investigated spectral features of separated flows over various low-sweep wings, their relation to the observed optimum frequencies, and the effect of wing sweep angle.

The influence of bird wings on artificial vehicles was firstly reflected in Leonardo da Vinci's studies of a fluid and aerodynamic forces over a bird wing (Videler, 2006), based on which Otto Lilienthal built a large glider and flew it successfully (Jones and Platzer, 2009). A great number of flapping-wing micro air vehicles (Krashanitsa et al., 2009) have been designed and developed inspired by the flapping flights of birds. Besides flapping, bird wings can also sweep back, as can be seen on a swift (Lentink et al., 2007), based on which (Summers and Mahannah, 2008) studied what airplane designers could learn from the shape-changing wings of birds. In addition, flight mechanism of insects has greatly motivated air vehicle designers, especially when the size of the vehicle is the main concern. Ellington (1999) presented the detailed aerodynamic characteristics of an insect-based flying machine in an attempt to

provide a design for flapping wing micro air vehicles. Van Breugel et al. (2008) designed a flapping hovering micro air vehicle taking advantage of the clap and fling mechanisms of insects, which considered four pairs of wings. Wood (2008) designed an insect-sized micro air vehicle inspired by dipteran insects capable of vertical liftoff with external control and power. The research team at Harvard Microrobotics Laboratory developed another insect-sized flapping wing micro air vehicle inspired by the biology of a bee and the insect's hive behavior (Wood et al., 2012). Tanaka et al. (2011) investigated the effect of wing flexibility on lift generation using an at-scale model to develop an artificial hoverfly wing.

As a kind of ocean observation platform, UG is widely applied in oceanographic sensing and data collection, due to its advantages of low cost and long gliding range (Rudnick et al., 2004; Rudnick, 2016; Sánchez et al., 2020; Petritoli et al., 2021). UG can dive or climb in the seawater column by adjusting its buoyancy, and the horizontal motion can be realized with the lift generated by its wings (Yang et al., 2022). The hydrodynamic shape, especially the wing shape, has a major impact on the glide performance of UG. The investigations in recent years have provided numerous results related to the wing shape design.

Lyu et al. (2019) investigated the impact of winglet on hydrodynamic performance and gliding trajectory of a blended-wing-body UG. Javaid et al. (2017) investigated the effect of two different wing shapes, rectangular and tapered wings, on the hydrodynamic characteristics and dynamic stability of UG to determine the optimal shape. Sun et al. (2019) proposed a kind of controllable wing mechanism for a hybrid-driven underwater glider, which can be deployed and stowed like a cicada wing to improve the maneuverability in propulsion mode. Wang et al. (2017) designed controllable wings for the hybrid UG, which have adjustable/variable angle of attack, sweep angle and aspect ratio to adapt to different motion modes.

The above investigations have provided some designs related to the wing shape or controllable wing mechanism, but there still exist the following problems. (1) When the wing sweep angle changes, the hydrodynamic coefficients of UG will be variable. To analyze the glide performance of UG with various sweep wings, the relationship between the hydrodynamic coefficients and the wing sweep angles needs to be expressed, which is rarely researched. (2) Due to the variety of ocean observation mission, different glide performance, such as endurance, turn ability and ability of resisting current, are required to execute mission in the complicated and variational ocean environment. However, few studies have analyzed the change of glide performance with the altering of sweep wings.

This paper introduces a sweep wing strategy inspired by the swift wings, which is proposed to apply pre-adjustable sweep wings before the deployment of UGs, so as to improve the glide performance in different glide conditions. The approximate model technology is applied to express the relationship

between the hydrodynamic coefficients and the wing sweep angles, by importing which into the dynamic model the glide performance analysis of UG with various sweep wings is performed. This paper investigates the usefulness of the sweep wing strategy for UGs, which provides a reference for design and selection of wing sweep angle to improve UG performance.

Sweep wing strategy

Gliding birds continually change the shape and size of their wings, presumably to exploit the profound effect of wing morphology on aerodynamic performance (Tucker, 1987; Rosen and Hedenstrom, 2001). Swift wings can realize the change of shape due to the articulated skeleton under muscular control, and the changing overlap between feathers allows continuous changes in wing shape and wing size. As shown in Figure 1, the swift can increase sweep angle of its wings from 5° to 50°, which decreases wing area and aspect ratio by roughly one-third (Lentink et al., 2007). The swift can control the force coefficient by altering wing shape, angle of attack and speed. It sweeps the wings back at high flight speeds, and spread the wings at low speeds.

In this study, the bio-inspired strategy mainly refers to flight modes realized by swift based on variable sweep wing, which belongs to the bionics of flight mode. Similar to the swift, the UG also has two glide modes according to the specific observation mission, including the regular low-speed glide and the high-speed glide when passing through a current. To obtain a smooth high-density dataset (Benoit-Bird et al., 2018) and sample turbulent waters for longer duration (Fer et al., 2014), the UG generally adopts the wings with a small sweep angle to realize low-speed glide, which is the better appropriate glide mode in certain situations. According to Leonard et al. (2007), slow, high-endurance vehicles might be more useful for larger scales,

whereas fast, low-endurance vehicles might serve better collecting data over smaller scales. However, when passing a strong eddy boundary (Jones et al., 2014) and high currents (Claus et al., 2010; Carneiro et al., 2021), the UG needs to adopt the wings with a large sweep angle to obtain a high speed. Therefore, by simulating the flight modes of swift with variable sweep angle, the UG can be equipped with pre-adjustable sweep wings to realize different motion modes and carry out different observation missions more perfectly.

In this paper, a sweep wing strategy inspired by the actual swift wings is established, as shown in Figure 2. The wings are articulated with the body of UG, L is the wing span. Figure 2B shows the relationship between the wing area and the aspect ratio with sweep angle θ_s , which can change from 7° to 60°. The area of single wing S_{wing} is described rectangle $OA_iB_iD_i$ at arbitrary sweep angle θ_{si} , which can be calculated as

$$S_{wing} = (b_1 + b_0)l_0 \cos \theta_{s0} - b_0^2 \tan(\theta_{si} - \theta_{s0}) \quad (1)$$

where b_0 and b_1 are chord of the wing root and tip, respectively, and l_0 is the length of wing leading edge.

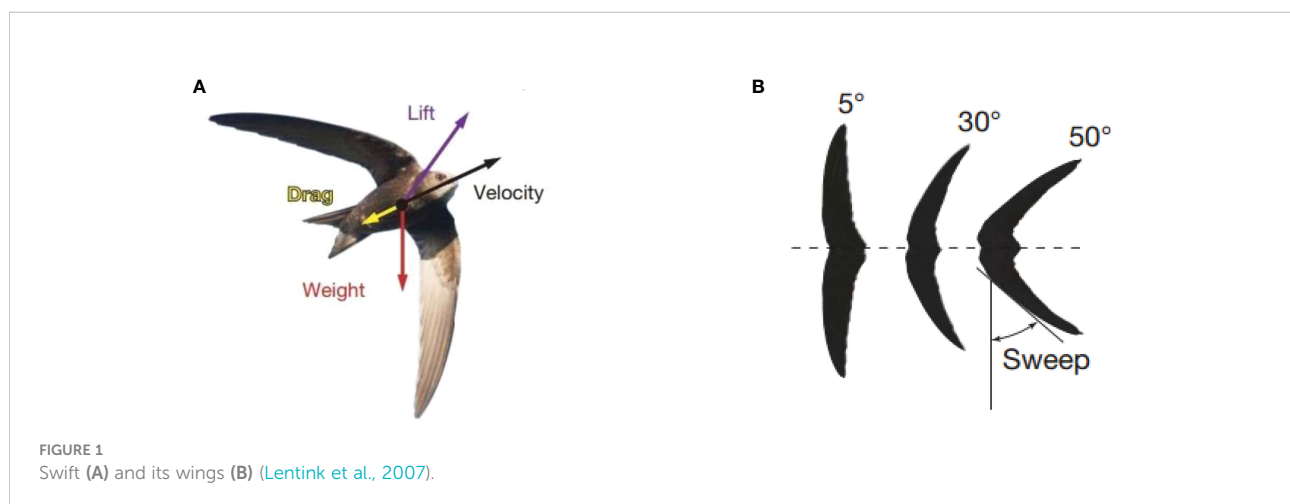
The wing aspect ratio λ is described with the average chord b_{av} simple because that is not a standard rectangle.

$$b_{av} = \frac{2S_{wing}}{2l_0 \cos \theta_{si} + D} \quad (2)$$

$$\lambda = \frac{(2l_0 \cos \theta_{si} + D)^2}{2S_{wing}} \quad (3)$$

where D is the glider diameter.

The corresponding variations of the wing area and the aspect ratio are shown in Figure 3, which indicates that the wing area and the aspect ratio decrease from 0.183 m² and 4.8 to 0.138 m² and 2.8 respectively when the sweep angle increases from 7° to 60°.



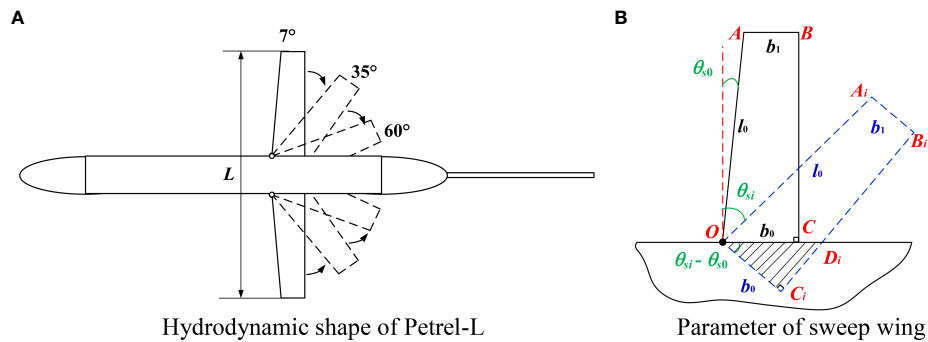


FIGURE 2
Hydrodynamic shape of Petrel-L with various sweep wings. (A) Hydrodynamic shape of Petrel-L (B) Parameter of sweep wing.

Dynamic modeling of UG

This paper takes Petrel-L underwater glider (Yang et al., 2019), developed by Tianjin University, China, as the research object, and the structure of the glider is shown in Figure 4. Petrel-L can adjust its buoyancy by transferring the oil between the internal oil tank and the external bladder, which leads to its vertical motion. The horizontal motion is realized by the lift generated by its wings. Thus, UG moves follow the zigzag trajectory. By translating and rotating the movable internal mass block, the attitude of UG can be adjusted. To analyze the glide performance of UG with various sweep wings, a dynamic model is established in this paper.

Coordinate frames and kinematic equations

To facilitate the subsequent deduction, three coordinate frames are established firstly, including the inertial frame E -

XYZ , body frame O - xyz and velocity frame O' - $x'y'z'$ shown in Figure 5. The origin of inertial frame is fixed to the initial location of UG on the sea surface, in which the motion trajectory of UG can be expressed. The direction of the X -axis is same as the initial heading of UG on the sea surface, and the direction of the Z -axis is vertically downward with the sea surface. The origin of the body frame is fixed to the center of buoyancy. The direction of the x -axis is coincident with that of the axis of UG, and the direction of the z -axis is vertically downward with the x -axis. As for the velocity frame, the origin of it coincides with the body frame and the O' - x' axis points to the velocity direction of UG. The O' - z' axis is vertically downward with the O' - x' axis, which is in the plane O - xz . Other axes are determined by right-hand rule.

The position and the attitude of UG in the inertial frame can be expressed by position vector $\mathbf{b} = [X, Y, Z]^T$ and $\boldsymbol{\eta} = [\varphi, \theta, \psi]^T$. The φ , θ and ψ respectively denote the angles that the body frame rotates along the X -axis, Y -axis and Z -axis from the attitude coinciding with the internal frame, which are called roll angle, pitch angle and yaw angle, respectively. The inertial

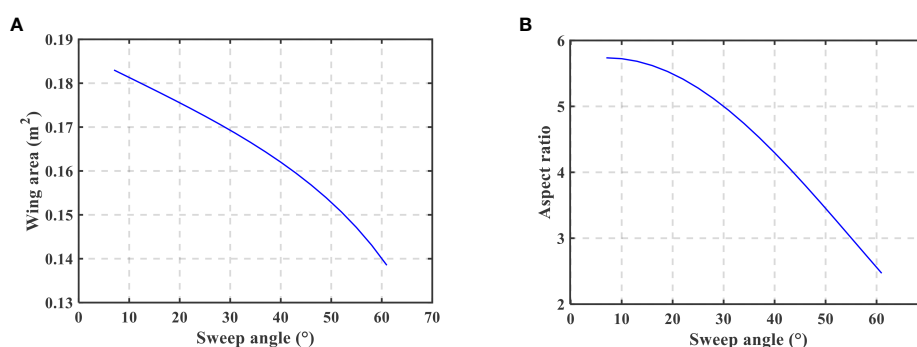


FIGURE 3
Variations of the wing area (A) and the aspect ratio (B).

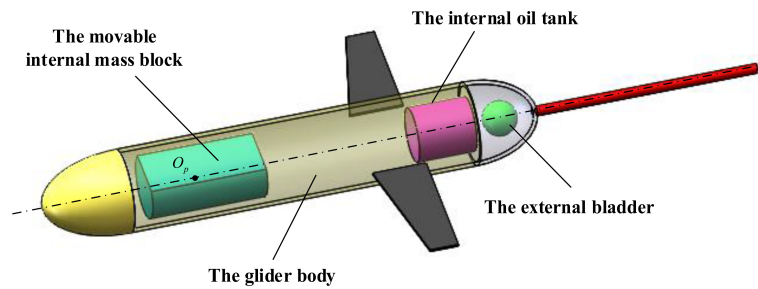


FIGURE 4
Structure diagram of Petrel-L.

frame E -XYZ can be coincident with the body frame O -xyz after rotating, the rotation matrix between which can be expressed as (Fossen, 2011)

$$\mathbf{R}_B^E = \begin{bmatrix} \cos \psi \cos \theta & \sin \psi \cos \theta & \sin \theta \\ \cos \psi \sin \theta \sin \varphi - \sin \psi \cos \varphi & \sin \psi \sin \theta \sin \varphi + \cos \psi \cos \varphi & \cos \theta \sin \varphi \\ \cos \psi \sin \theta \cos \varphi + \sin \psi \sin \varphi & \sin \psi \sin \theta \cos \varphi - \cos \psi \sin \varphi & \cos \theta \cos \varphi \end{bmatrix} \quad (4)$$

The rotation matrix from the body frame to the inertial frame $\mathbf{R}_E^B$ is the transpose of $\mathbf{R}_B^E$. The velocity and the angular velocity of UG in the body frame are defined as velocity vector $\mathbf{V} = [u, v, w]^T$ and angular velocity vector $\boldsymbol{\Omega} = [p, q, r]^T$, which are the velocities and angular velocities along the x -axis, y -axis and z -axis respectively. The rotation matrix from the body frame to the velocity frame can be expressed as

$$\mathbf{R}_V^B = \begin{bmatrix} \cos \alpha \cos \beta & \sin \beta & \cos \beta \sin \alpha \\ -\cos \alpha \sin \beta & \cos \beta & -\sin \alpha \sin \beta \\ -\sin \alpha & 0 & \cos \alpha \end{bmatrix} \quad (5)$$

Similarly, the rotation matrix from body frame to inertial frame $\mathbf{R}_B^V$ is the transpose of $\mathbf{R}_V^B$. The velocity V of UG can be calculated as

$$V = \sqrt{u^2 + v^2 + w^2} \quad (6)$$

According to the (Fossen, 2011), the angle of attack α and the sideslip angle β can be expressed as

$$\alpha = \arctan\left(\frac{w}{u}\right) \quad (7)$$

$$\beta = \arcsin\left(\frac{v}{V}\right) \quad (8)$$

According to the (Fossen, 2011), the kinematic differential equations of the UG are as follows

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = \mathbf{R}_E^B \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin \varphi \tan \theta & \cos \varphi \tan \theta \\ 0 & \cos \varphi & -\sin \varphi \\ 0 & \sin \varphi / \cos \theta & \cos \varphi / \cos \theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (10)$$

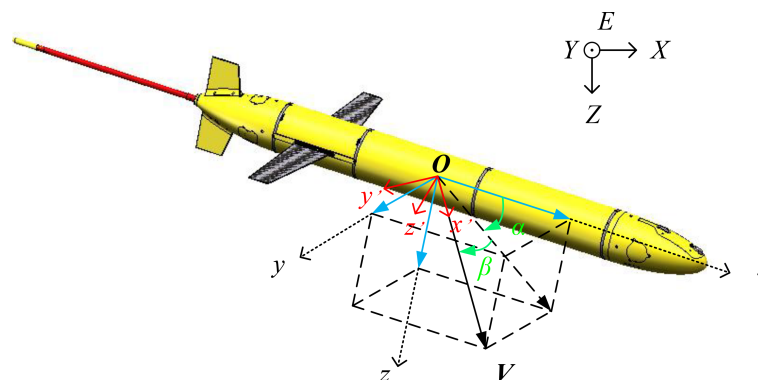


FIGURE 5
Coordinate frames of UG.

Force analysis

Usually, the buoyancy of the whole UG $\mathbf{B}_0$ can be equivalent to a concentrated exerted on its buoyancy center O . The net buoyancy is denoted as $\Delta\mathbf{B}$. In the motion process, the UG is also subjected to the gravity $\mathbf{G}_h$, the gravity of the movable internal mass block $\mathbf{G}_p$, the inertial hydrodynamic force $\mathbf{F}_m$, and the viscous hydrodynamic force $\mathbf{F}_s$. The additional moments may be generated when the above forces are moved to O , which are defined as $\mathbf{M}_b$, $\mathbf{M}_h$, $\mathbf{M}_p$, $\mathbf{M}_m$ and $\mathbf{M}_s$ respectively (Wu et al., 2020).

In addition, the position vector of the barycenter relative to the origin of the body frame is denoted as $\mathbf{r}_h$. The position vector of the buoyancy center of the external bladder relative to O is denoted as $\mathbf{r}_b$. Under the standard state, the position vector of the movable internal mass block barycenter relative to O is denoted as $\mathbf{r}_p$. Then the position change vector of O_p is denoted as $\Delta\mathbf{r}$. Here $\mathbf{r}_h$, $\mathbf{r}_b$, $\mathbf{r}_p$ and $\Delta\mathbf{r}$ are all expressed in the body frame. Since the directions of both gravity and buoyancy are always parallel to the Z -axis of the inertial frame, in the body frame, the expressions of $\mathbf{G}_h$, $\mathbf{G}_p$, $\mathbf{B}_0$, $\Delta\mathbf{B}$, $\mathbf{M}_h$, $\mathbf{M}_p$ and $\mathbf{M}_b$ are (Wu et al., 2020)

$$\begin{bmatrix} \mathbf{G}_h \\ \mathbf{M}_h \end{bmatrix} = \begin{bmatrix} \mathbf{R}_B^E (0 \ 0 \ m_h g)^T \\ \mathbf{r}_h \times \mathbf{G}_h \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} \mathbf{G}_p \\ \mathbf{M}_p \end{bmatrix} = \begin{bmatrix} \mathbf{R}_B^E (0 \ 0 \ m_p g)^T \\ (\mathbf{r}_p + \Delta\mathbf{r}) \times \mathbf{G}_p \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} \Delta\mathbf{B} \\ \mathbf{M}_b \end{bmatrix} = \begin{bmatrix} \mathbf{R}_B^E (0 \ 0 \ -\rho g V_b)^T \\ \mathbf{r}_b \times \Delta\mathbf{B} \end{bmatrix} \quad (13)$$

$$\mathbf{B}_0 = \mathbf{R}_B^E (0 \ 0 \ -(m_h + m_p)g)^T \quad (14)$$

where g represents the acceleration of gravity, ρ is the density of seawater, V_b is the volume change amount of the external bladder, m_p is the movable internal mass and m_h is the mass of the glider excluding m_p .

Since Petrel-L is symmetrical relative to the O - xz plane in the body frame, the expressions of the inertial hydrodynamic force and inertial hydrodynamic moment can be expressed as

$$\begin{bmatrix} \mathbf{F}_m \\ \mathbf{M}_m \end{bmatrix} = - \begin{bmatrix} \lambda_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_{22} & 0 & 0 & 0 & \lambda_{26} \\ 0 & 0 & \lambda_{33} & 0 & \lambda_{35} & 0 \\ 0 & 0 & 0 & \lambda_{44} & 0 & 0 \\ 0 & 0 & \lambda_{35} & 0 & \lambda_{55} & 0 \\ 0 & \lambda_{26} & 0 & 0 & 0 & \lambda_{66} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{V}} \\ \dot{\boldsymbol{\Omega}} \end{bmatrix} \quad (15)$$

where λ_{11} , λ_{22} and λ_{33} represent the added mass; λ_{44} , λ_{55} and λ_{66} represent the added moment of inertia; λ_{26} , λ_{35} , λ_{53} and λ_{62} represent the added static moment.

According to (Jones et al., 2002; Fossen, 2011), the viscous hydrodynamic force $\mathbf{F}_s = [D, SF, L]^T$ and viscous hydrodynamic moment $\mathbf{M}_s = [M_{x'}, M_{y'}, M_{z'}]^T$ can be expressed as

$$\begin{bmatrix} \mathbf{F}_s \\ \mathbf{M}_s \end{bmatrix} = \begin{bmatrix} D \\ SF \\ L \\ M_{x'} \\ M_{y'} \\ M_{z'} \end{bmatrix} = \begin{bmatrix} 0.5\rho_0 \|V\|^2 AC_D \\ 0.5\rho_0 \|V\|^2 AC_{SF} \\ 0.5\rho_0 \|V\|^2 AC_L \\ 0.5\rho_0 \|V\|^2 AC_{x'} \\ 0.5\rho_0 \|V\|^2 AC_{y'} \\ 0.5\rho_0 \|V\|^2 AC_{z'} \end{bmatrix} \quad (16)$$

where D , SF and L are the hydrodynamic forces in the velocity frame along with the x' -axis, y' -axis and z' -axis respectively, $M_{x'}$, $M_{y'}$ and $M_{z'}$ are the hydrodynamic moments in the velocity frame along with the x' -axis, y' -axis and z' -axis respectively, ρ_0 is the in-situ density, A is the cross sectional area of UG, C_D , C_{SF} and C_L are hydrodynamic force coefficients and $C_{x'}$, $C_{y'}$ and $C_{z'}$ hydrodynamic moment coefficients, which can be obtained by experimental and computational fluid dynamics method.

Dynamic modeling

The dynamic model of UG is established by the linear momentum theorem and angular momentum theorem. Due to the neglect of the changing process of control parameters values, the dynamics modeling omits the mutual movement process between the movable internal mass block and the glider body.

In the inertial frame, the linear momentum and the angular momentum of UG relative to E are defined as $\mathbf{P}_E$ and $\mathbf{L}_E$. In the body frame, the linear momentum and the angular momentum of UG relative to O are defined as $\mathbf{P}_B$ and $\mathbf{L}_B$. Since the barycenter of the whole UG does not coincide with O , $\mathbf{P}_B$ and $\mathbf{L}_B$ can be expressed as

$$\begin{bmatrix} \mathbf{P}_B \\ \mathbf{L}_B \end{bmatrix} = \begin{bmatrix} (m_h + m_p)(\mathbf{V} + \boldsymbol{\Omega} \times \mathbf{r}_g) \\ \mathbf{J}_o \boldsymbol{\Omega} + (m_h + m_p)\mathbf{r}_g \times \mathbf{V} \end{bmatrix} \quad (17)$$

where $\mathbf{J}_o$ represents the inertia tensor of UG relative to the body frame, which is obtained based on the inertia tensor $\mathbf{J}_p$ of the movable internal mass block relative to its barycenter, the inertia tensor $\mathbf{J}_h$ of UG relative to its barycenter and the parallel axis theorem, $\mathbf{r}_g$ represents the position vector of the whole glider barycenter relative to O shown as

$$\mathbf{r}_g = (m_h \mathbf{r}_h + m_p (\mathbf{r}_p + \Delta\mathbf{r})) / (m_h + m_p) \quad (18)$$

According to the kinematic relation, there are

$$\begin{cases} \dot{\mathbf{b}} = \mathbf{R}_E^B \mathbf{V} \\ \dot{\mathbf{R}}_E^B = \mathbf{R}_E^B \hat{\boldsymbol{\Omega}} \end{cases} \quad (19)$$

$$\begin{cases} \mathbf{P}_E = \mathbf{R}_E^B \mathbf{P}_B \\ \mathbf{L}_E = \mathbf{R}_E^B \mathbf{L}_B + \mathbf{b} \times \mathbf{P}_E \end{cases} \quad (20)$$

where the operators $\wedge$ maps a vector to the matrix representation of the vector cross product operator (Leonard and Graver, 2001).

According to the Newton's second law, there is

$$\begin{cases} \dot{\mathbf{P}}_E = \mathbf{f} \\ \dot{\mathbf{L}}_E = \boldsymbol{\tau} + \mathbf{b} \times \mathbf{f} \end{cases} \quad (21)$$

where $\mathbf{f}$ and $\boldsymbol{\tau}$ are the resultant force and resultant moment in the inertial frame, respectively. According to the Eq. (18) and Eq. (21), there is

$$\begin{cases} \mathbf{f} = \mathbf{R}_E^B \hat{\boldsymbol{\Omega}} \mathbf{P}_B + \dot{\mathbf{R}}_E^B \mathbf{P}_B \\ \boldsymbol{\tau} + \mathbf{b} \times \mathbf{f} = \mathbf{R}_E^B \hat{\boldsymbol{\Omega}} \mathbf{L}_B + \mathbf{R}_E^B \dot{\mathbf{L}}_B + \mathbf{b} \times \dot{\mathbf{P}}_E + \mathbf{R}_E^B \mathbf{V} \times \mathbf{R}_E^B \mathbf{P}_B \end{cases} \quad (22)$$

The resultant force $\mathbf{F}$ and resultant moment $\mathbf{M}$ in the body frame can be ascertained by sum of Eq. (11) to Eq. (16).

$$\begin{cases} \dot{\mathbf{P}}_B = \mathbf{P}_B \times \boldsymbol{\Omega} + \mathbf{F} \\ \dot{\mathbf{L}}_B = \mathbf{L}_B \times \boldsymbol{\Omega} + \mathbf{P}_B \times \mathbf{V} + \mathbf{M} \end{cases} \quad (23)$$

Substituting Eq. (14) into Eq. (20), Eq. (21) can be obtained as

$$\begin{cases} (m_h + m_p)(\dot{\mathbf{V}} + \hat{\boldsymbol{\Omega}} \times \mathbf{r}_g) = (m_h + m_p)(\mathbf{V} + \boldsymbol{\Omega} \times \mathbf{r}_g) \times \boldsymbol{\Omega} + \mathbf{F} \\ \mathbf{J}_o \hat{\boldsymbol{\Omega}} + (m_h + m_p) \mathbf{r}_g \times \dot{\mathbf{V}} = (\mathbf{J}_o \boldsymbol{\Omega} + (m_h + m_p) \mathbf{r}_g \times \mathbf{V}) \times \boldsymbol{\Omega} + (m_h + m_p)(\mathbf{V} + \boldsymbol{\Omega} \times \mathbf{r}_g) \times \mathbf{V} + \mathbf{M} \end{cases} \quad (24)$$

Combining Eq. (9), Eq. (10) and Eq. (24), the dynamic model of UG is established.

Viscous hydrodynamic coefficients of UG with various sweep wings

The correctness of the dynamic model established above has been verified by Petrel-L glider in our previous work (Yang et al., 2021). However, it cannot be directly used in the motion simulation of UG with various sweep wings due to its variable hydrodynamic coefficients, including C_D , C_{SF} , C_L , C_x , C_y , and C_z . Usually, these hydrodynamic coefficients of a constant hydrodynamic shape can be obtained by computational fluid dynamics (CFD) method. For a variable hydrodynamic shape of UG with various sweep wings, it will lead to low efficiency, large time consumption, and huge amount of data to carry out performance analysis by directing combing hydrodynamic numerical simulation. In this paper, an approximate model is

applied to replace the fluid computation, which is commonly used in complex engineering design to minimize the computational expense of running complex and high-fidelity simulations (Sobester et al., 2008).

Approximate model, established by a few sample points, is based on the mathematical statistics, which can replace the complex engineering model and be used in optimization with the premise of ensuring reasonable accuracy. Compared with the traditional engineering model, the optimization with the approximate model has the advantages of low computation and high computational efficiency, which can effectively relieve the calculation pressure, shorten the development cycle, reduce the cost, and improve the hydrodynamic performance. It is a common technical method for engineering optimization problems with many design variables and high test cost.

In this study, the establishment process of approximate model can be summarized as follows.

Numerical experimental design

Experimental design is an important branch of mathematical statistics, which studies how to arrange the test scheme and improve the rationality of test sample distribution to reduce the impact of test error, and make the experimental results used in reasonable statistical analysis. Experimental design can be divided into two categories according to the design idea: classical experimental design and experimental design based on space filling.

Classical experimental design, developed from traditional physical experimental design, usually distributes most sample points on the boundary of design space to reduce random error, such as factorial designs, central composite designs and orthogonal designs. With the continuous improvement of computing power and the development of numerical simulation software, the main object of experimental design has changed from traditional physical experiment to numerical experiment. In order to reduce the system error and improve the space exploration of the test scheme, the sampling points should be evenly covered throughout the design space, based on which the experimental design based on space filling developed, such as uniform designs, Latin hypercube designs and optimal Latin hypercube designs.

In this study, the hydrodynamic coefficients are calculated by CFD method, including the flume and the rotating arm pool numerical experiment. The flume experiment is used to obtain the hydrodynamic coefficients related to the velocity direction of UG, the design space of which is shown in Table 1. The rotating arm pool experiment is used to obtain the hydrodynamic coefficients related to the angular velocities, and the design space is shown in Table 2.

TABLE 1 Design space in flume experiment.

Parameter	Value range	Parameter type
Angle of attack α	$-10^\circ \sim 10^\circ$	Integer
Sideslip angle β	$-10^\circ \sim 10^\circ$	Integer
Sweep angle θ_s	$7^\circ \sim 60^\circ$	Integer

TABLE 2 Design space in rotating arm pool experiment.

Parameter	Value range	Parameter type
Turning radius R	10 m~100 m	Integer
Sweep angle θ_s	$7^\circ \sim 60^\circ$	Integer

Due to the characteristic of less design variables, this paper adopts optimal Latin hypercube designs to sample from the design space. In this paper, the initial number of sample points is set as 200. As shown in Figure 6, the sample points in the two tests uniformly distribute in the design spaces.

Based on the sample points in the experimental design, the CFD is adopted to obtain the relevant hydrodynamic coefficients for establishment of approximate models. Firstly, a parameterized 3D hydrodynamic shape of Petrel-L with pre-adjustable sweep wings is established, as shown in Figure 7, which can change the wing shape according to sweep angle in the sample data.

Then, the model is imported into the software ICEM to generate the mesh. The computation domain further away from the glider hull uses unstructured meshes, and the computational domain closer to the glider hull uses prism meshes to enhance the mesh quality near the glider surface. The number of grid boundary layer nodes is 10, and the distance of the first layer grid is adjusted to ensure $y^+ < 5$. The mesh map of computational domain and surface for Petrel-L is shown in Figure 8.

Then, to validate the independence of the mesh for obtaining accurate results, the drag of the case (velocity 1 m/s, angle of attack 0° , sideslip angle 0° and sweep angle 7°) with four types of mesh quantities have been calculated, and the results are listed in Table 3. Considering the trade-off between simulation accuracy and efficiency, the grid quantity of 3.343 million is finally imported into the software ANSYS Fluent to calculate the hydrodynamic coefficients of all cases.

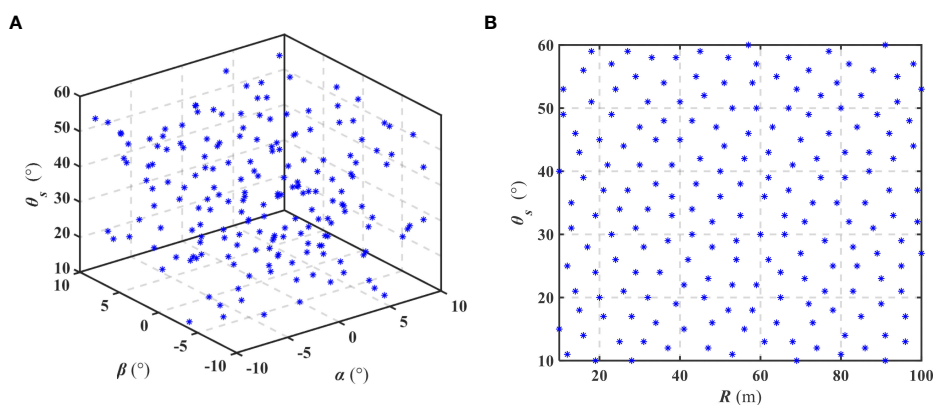


FIGURE 6
Sample points of the flume experiment (A) and rotating arm pool experiment (B).

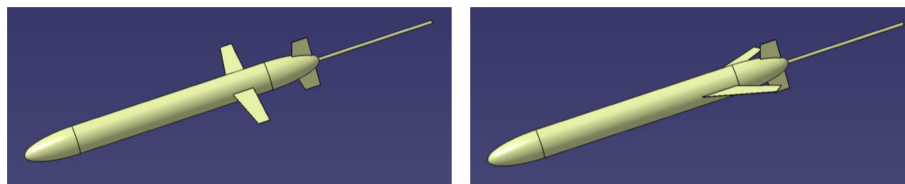


FIGURE 7
Parameterized model of hydrodynamic shape.

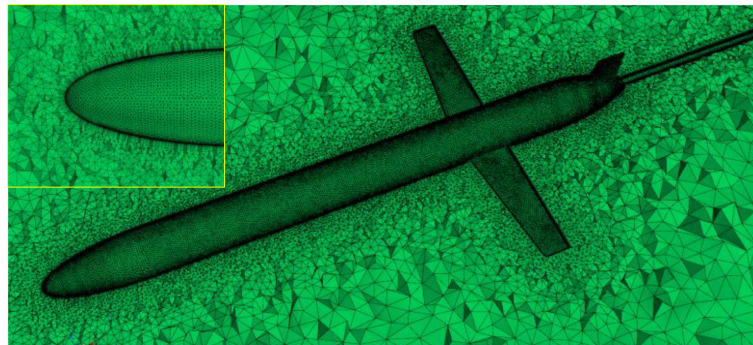


FIGURE 8
Mesh map of computational domain and surface for Petrel-L.

In terms of outflow field simulation, the computational domain should be set large enough to avoid the influence of domain boundary (Fu et al., 2018; Sun et al., 2021). Referring to the above research and considering our practical situation, computational domain of flume experiment is set as $3L_{\text{glider}} \times 3L_{\text{glider}} \times 7L_{\text{glider}}$ (L_{glider} is the total length of the glider) in this study, as shown in Figure 9. In addition, the computational domain of rotating arm pool experiment is ring-shaped and set as $6L_{\text{glider}} \times 1.5L_{\text{glider}} \times 1.5L_{\text{glider}}$. The total arc length of the centerline of the ring is $6L_{\text{glider}}$, and the arc length along the centerline from the buoyancy center of glider to the inlet is $2L_{\text{glider}}$. Other boundary conditions of computational domain are the same as flume experiment. In the CFD solver, $k-\omega$ shear stress transport turbulence model is employed because it not only provides the best prediction of vortex distribution around underwater vehicles but also strikes a good balance between computational cost and convergence stability (Jagadeesh et al., 2009).

Figure 10 show the velocity contours in the flume and rotating arm pool numerical experiment respectively, in which the velocity is uniformly set as 0.5 m/s.

Although the application of approximate model can reduce the calculating amount for obtaining the hydrodynamic coefficients of UG with various sweep wings, it will still consume a lot of manpower to repeat the process of calculation with CFD for 200 times. Thus, we construct an automatic solution platform in software iSight by command

streams of CATIA, ICEM and ANSYS Fluent, which can automatically update the 3D model, divide the mesh and calculate the coefficients according to the sample points.

Establishment of approximate model

The approximate mode is an effective tool that describes arbitrary nonlinear system of inputs and the corresponding outputs. The method of establishing it mainly including polynomial fitting method, Kriging interpolation method and neural network interpolation method. Among them, the polynomial fitting method has a unique superiority with relatively computational convenient and acceptable accuracy. Therefore, the polynomial fitting method is employed to establish approximate models in this paper based on 1stOpt which is a general nonlinear fitting software platforms.

Before establishing the approximate models, the correlation analysis is firstly performed with the collected data to determine the influence rule between the design variables and the hydrodynamic coefficients, by which we know that each hydrodynamic coefficient shall be fitted by which variables. The hydrodynamic coefficients obtained in flume and rotating arm pool numerical experiment, and their relevant variables are shown in Figures 11 and 12 respectively.

In this study, the derivative of angular velocity p in the coefficient C_x is set as a constant (-0.62) due to its negligible effect. The approximate models of hydrodynamic coefficients, shown in Eq. (22), can be obtained with randomly selected 75% of data points. The other 25% of the points are used to verify the accuracy of the approximate models by contrasting the calculation results. All of the multiple correlation coefficient (R^2) between the CFD simulations and the approximate models are more than 0.99, which indicated that we don't need increase the number of sample points and the approximate models can be imported into the dynamic model to analyze the performance of UG with various sweep wings.

TABLE 3 Grid independence verification results.

Type	Mesh quantity (million)	Drag (N)	Numerical error
1	1.171	9.0352	~
2	1.595	9.2534	2.41%
3	2.271	9.3856	1.43%
4	3.343	9.4554	0.74%
5	4.715	9.4581	-0.03%

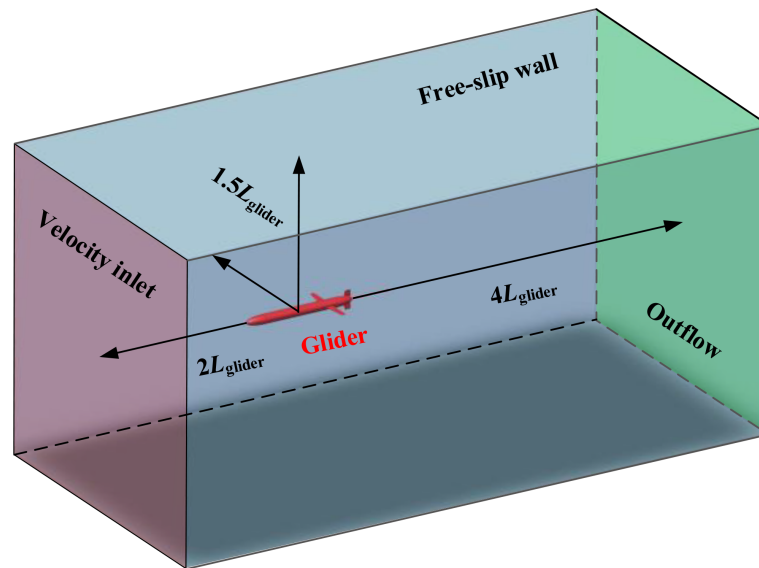


FIGURE 9
Boundary conditions of numerical simulation in flume experiment.

$$\begin{aligned}
 C_D &= 0.418 + (24.7 - 0.14\theta_s - 4.76 \times 10^{-4}\theta_s^2)\alpha^2 + 6.19\beta^2 + 1.69 \times 10^{-4}\theta_s - 1.97 \times 10^{-5}\theta_s^2 \\
 C_{SF} &= 6.87\beta \\
 C_L &= (-29.05 + 0.21\theta_s)\alpha \\
 C_{x'} &= -10.76\alpha\beta - 0.62p \\
 C_{y'} &= (-11.98 - 0.044\theta_s + 1.84 \times 10^{-3}\theta_s^2)\alpha - (22.85 + 0.45\theta_s - 7.06 \times 10^{-3}\theta_s^2)q \\
 C_{z'} &= (-1.83 + 5.82\alpha^2)\beta - 18.34r
 \end{aligned}
 \quad (22)$$

In Eq. (22), the unit of angle is radian. To identify the influence of design variables on hydrodynamic coefficients, the Sobol' method (Sobol', 1990) is applied, the process of which mainly includes the following four steps. Step 1: Select parameters. Step 2: Confirm the ranges and distributions of parameters. Step 3: Generate samples. Step 4: Calculate the sensitivity indexes. The sensitivity indexes can be calculated by (Sobol', 2001). According to sensitivity analysis results, the sweep angle θ_s has an influence on the drag coefficient C_D , lift

coefficient C_L , and moment coefficient C_y . Obviously, the C_D is mainly determined by the α and β , and θ_s has no significant effect on it. Because the change of sweep angle θ_s directly affects the wet-surface of wing. The C_{SF} and β meet the linear relationship after ignoring the high-order infinitesimal. The influence of α and θ_s on C_L is opposite. The increase of θ_s will directly reduce the wing area and aspect ratio of wing, shown in Figure 3, which will reduce the lift coefficient C_L of UG.

Performance analysis of UG with various sweep wings

With the demand increase of ocean observation mission in time and space, endurance ability is gradually becoming one of the most important factors for UGs. In addition, a high

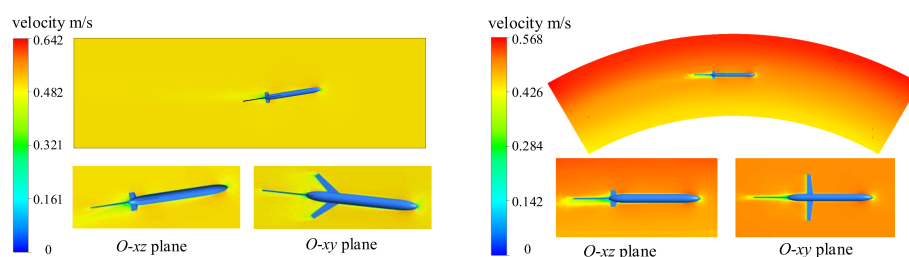


FIGURE 10
Velocity contours in the CFD simulation.

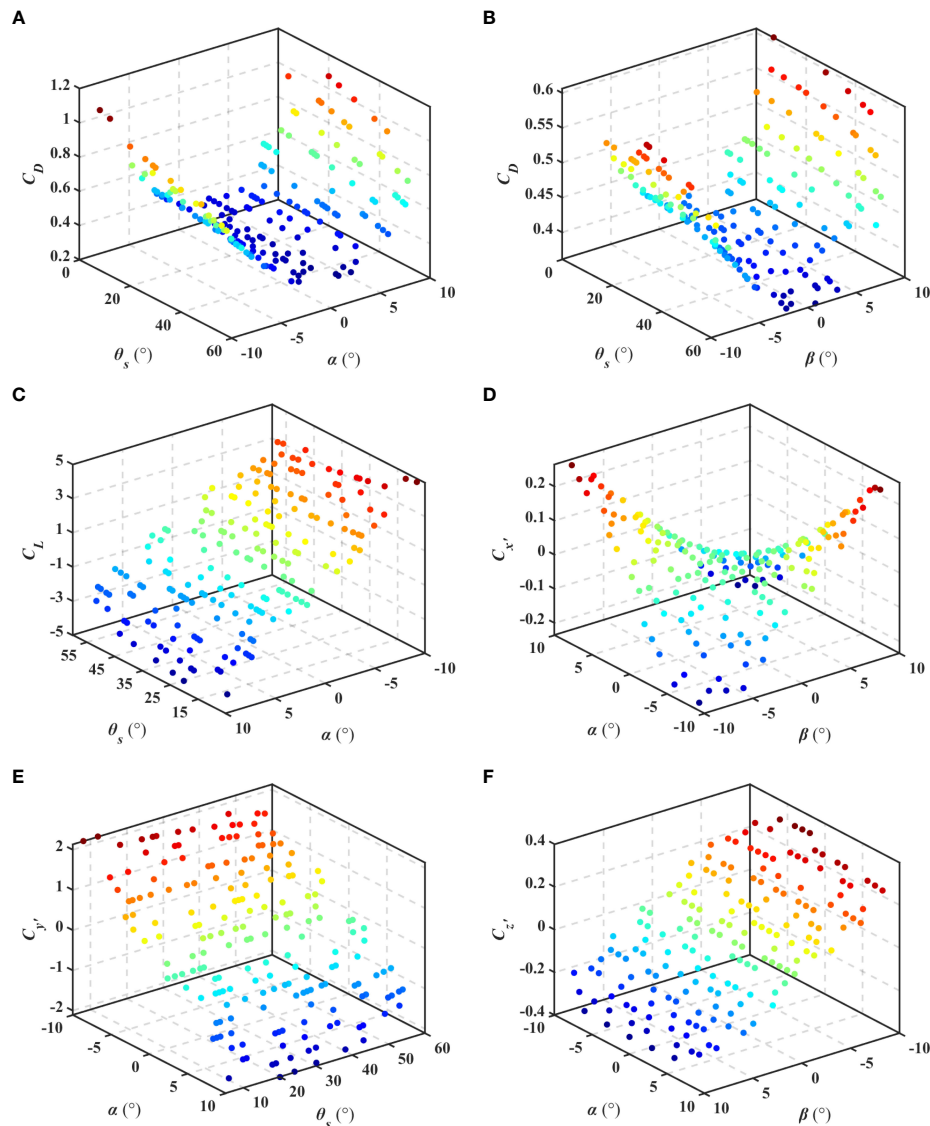


FIGURE 11
Hydrodynamic coefficients obtained in flume numerical experiment.

trajectory accuracy of UG is also required in some observation missions to reduce the observation error. Thus, the endurance ability and trajectory accuracy are referred to as the indexes to analyze the performance of UG with various sweep wings. Three indexes related to the endurance ability are: (1) gliding range (expressed as the maximum glide ratio), (2) gliding duration, and (3) turn angle (variation of heading angle) for a given depth loss. By maximizing range or time spent gliding, UG can satisfy the demand of some observation mission in space and time respectively. The high trajectory accuracy requires (4) fast turns (high angular velocity) with (5) a small turn radius, and (6) high horizontal velocity to avoid drift in ocean currents.

By importing the hydrodynamic coefficients into the dynamic model, the above indexes can be obtained to analyze the performance of Petrel-L with various sweep wings. The net buoyancy is set as different values due to the buoyancy loss of UG. Thus, by giving the different net buoyancy (1–8 N) and sweep angle (7–60°), the six indexes can be calculated, as shown in Figures 13A–F. Figures 13A, B indicate that UG with extended wings ($\theta_s=7^\circ$) has a larger glide ratio and duration than that with variable sweep angle for the constant angle of attack. Figures 13C–E indicate that there exist the optimal sweep angles for turning, with which UG has the largest turn angle for a depth loss ($\theta_s=35.12^\circ$), the smallest turn radius ($\theta_s=35.12^\circ$) and the largest angular velocity ($\theta_s=36.45^\circ$). Figure 13F shows

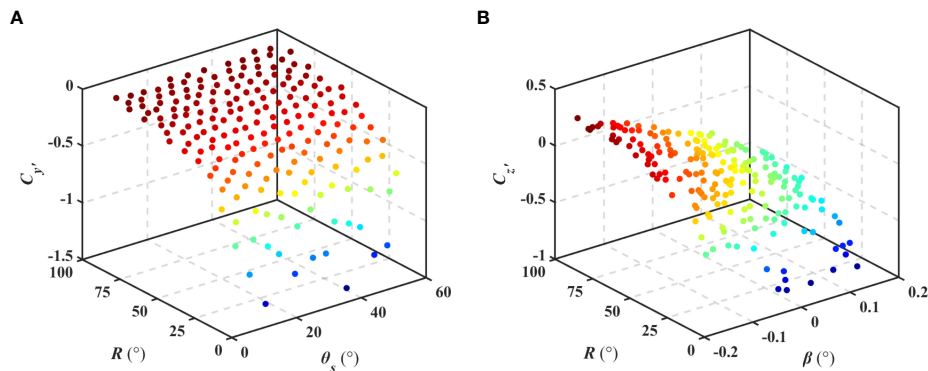


FIGURE 12
Hydrodynamic coefficients obtained in rotating arm pool numerical experiment.

that UG with sweep wings has a larger horizontal velocity than that with extended wings.

Petrel-L with extended and sweep wings provided the largest glide ratio and the best ability of resisting ocean currents respectively. Petrel-L with a sweep angle (around 35°) of wings has the best turn ability, which can reduce the trajectory error caused by heading adjustment of Petrel-L.

Glide ratio and duration analyzed above can represent the gliding range and gliding duration of swifts due to their negligible hotel load when gliding. However, unlike the swifts, the hotel load of UG, varying with the type of carried sensors and sampling frequency, is an important component of energy consumption of UG, which may have an influence on the gliding range and duration. Thus, the gliding range and gliding time per energy consumption unit are referred as to the indexes to analyze the gliding range and gliding duration of Petrel-L.

Figure 14 shows the gliding range per energy consumption unit, denoted by e , with the different hotel loads (0.5–2 W), in which the black points represent the maximum value with a given net buoyancy. Figure 14 indicates that the optimal sweep angle for largest gliding range transforms from the 60° to the 7° with the net buoyancy for a given hotel load, where the net buoyancy is defined as B_t . Petrel-L with sweep wings or extended wings has larger gliding range when its net buoyancy is smaller or larger than B_t . As shown in Figure 15, the net buoyancy B_t increases with the hotel load.

Figure 16 shows the gliding duration per energy consumption unit, denoted by η , with the different hotel loads (0.5–2 W), in which the black points represent the maximum value with a given net buoyancy. The optimal sweep angle for gliding duration is invariable (6°) with the hotel load and net buoyancy, which indicates that Petrel-L with extended wings has a larger gliding duration than that with sweep wings.

To sum up, the relationship between the performance demand of UG and its sweep angle can be obtained. (1)

Gliding range demand. To obtain the largest gliding range, Petrel-L need sweep back wings (60°) when the net buoyancy is smaller than B_t , and extend wings (7°) when it is larger than B_t . (2) Gliding duration demand. Petrel-L with extended wings (7°) is more suitable to obtain the largest gliding duration. (3) Trajectory accuracy demand. Petrel-L with wings (around 35°) has a better turn ability. (4) Resisting current demand. Petrel-L with sweep wings (60°) has a larger horizontal velocity to avoid drift in ocean currents.

This study aims to adopt pre-adjustable sweep wings for UGs with different glide modes in specific observation missions to obtain better performances, which also has a great economic value. In comparison, the wing structure with a variable sweep angle is not an appropriate way to improve the performance of UG, due to the complexity, weight penalty, and maintenance requirements, concluded as follows. 1) Variable sweep wings have the complexity of design, manufacturing and maintenance, resulting in a high cost. 2) The driving system of variable sweep wings will increase energy consumption and reduce the reliability of UG which is a low-power and high-reliability platform for long-term ocean observation. 3) It generally takes a long time for the UG to complete an observation mission which requires the glider to work in a relatively fixed glide mode. Therefore, compared with variable sweep angle, the strategy proposed in this paper of pre-adjustable sweep wings depending on task-orientation before the deployment is an optimal individualized design, which can balance performance and reliability of underwater glider at the current stage.

Verification

The reliability verification of CFD method by circulating flume test is significant and widely applied in ship and ocean engineering fields (Wang et al., 2018; Bie and Li, 2022). To verify the correctness of the CFD method and the performance analysis

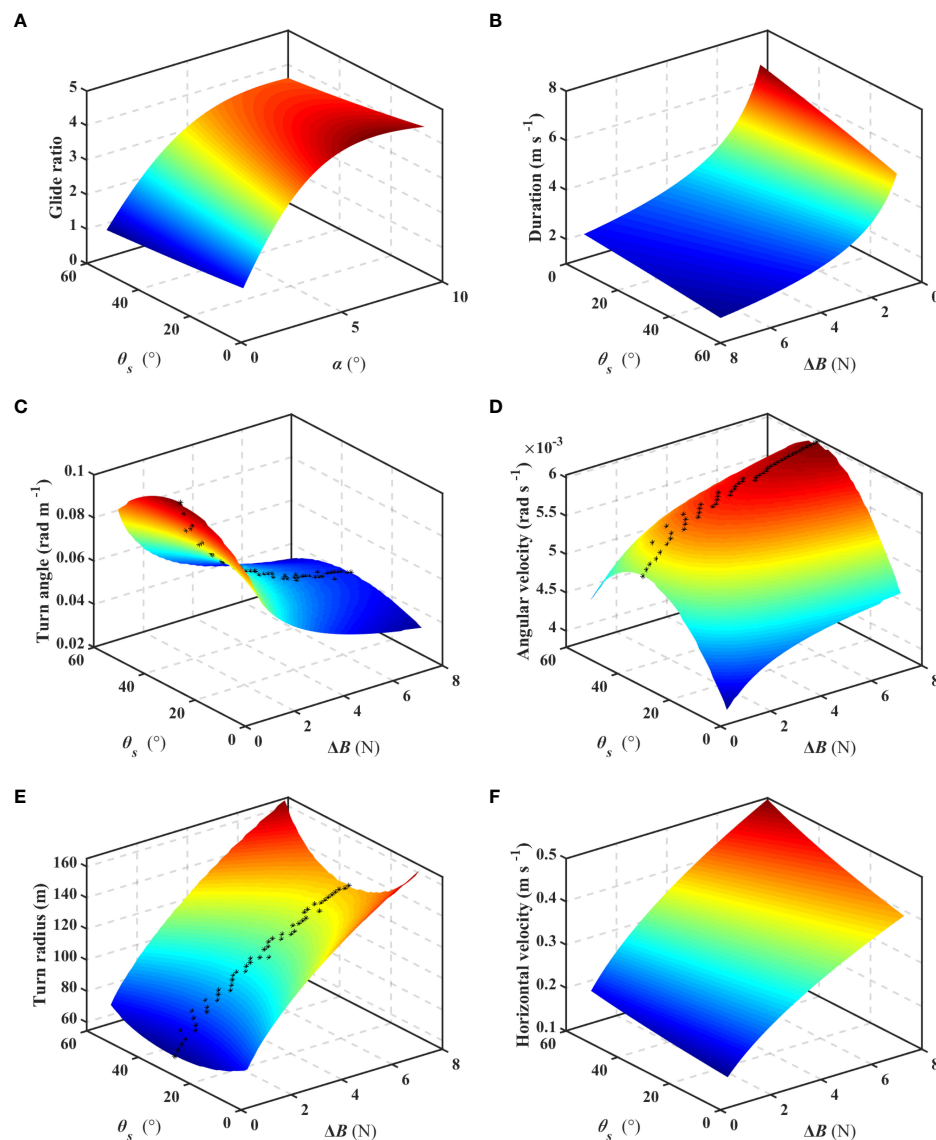


FIGURE 13
The indexes of UG with pre-adjustable sweep wings.

of Petrel-L, a circulating flume test is carried out by Petrel-L with extended wings (7°), which can be expended to cover more of the range of sweep angles. In the circulating flume test, the oblique towing motion of vertical plane and horizontal plane of Petrel-L are performed to obtain the relevant hydrodynamic coefficients. The vertical plane measurement of Petrel-L in circulating flume are shown in Figure 17.

In the circulating flume test, the directions of O - x axis, O - y axis and O - z axis of the forces are directly measured. To facilitate comparison with CFD simulation, the results of circulating flume tests are transformed from body frame to velocity frame. Figures 18A–F show the comparison of CFD simulation

results and circulating flume test results measured in horizontal plane and vertical plane. In the figures, the fitted curve of the experimental results is indicated with red dotted line, and the multiple correlation coefficient R^2 of fitted curve is presented. Meanwhile, the correlation coefficient ρ between CFD simulation results and flume test results is marked with red triangles. According to analysis of R^2 and ρ , the CFD simulation results are basically in accordance with the flume test results.

To further analyze distribution of the error data, the absolute error between CFD simulation and flume test is calculated, as shown in Figure 19. The absolute error of all case is dispersed in the interval $[-2, 2]$, and the absolute error of

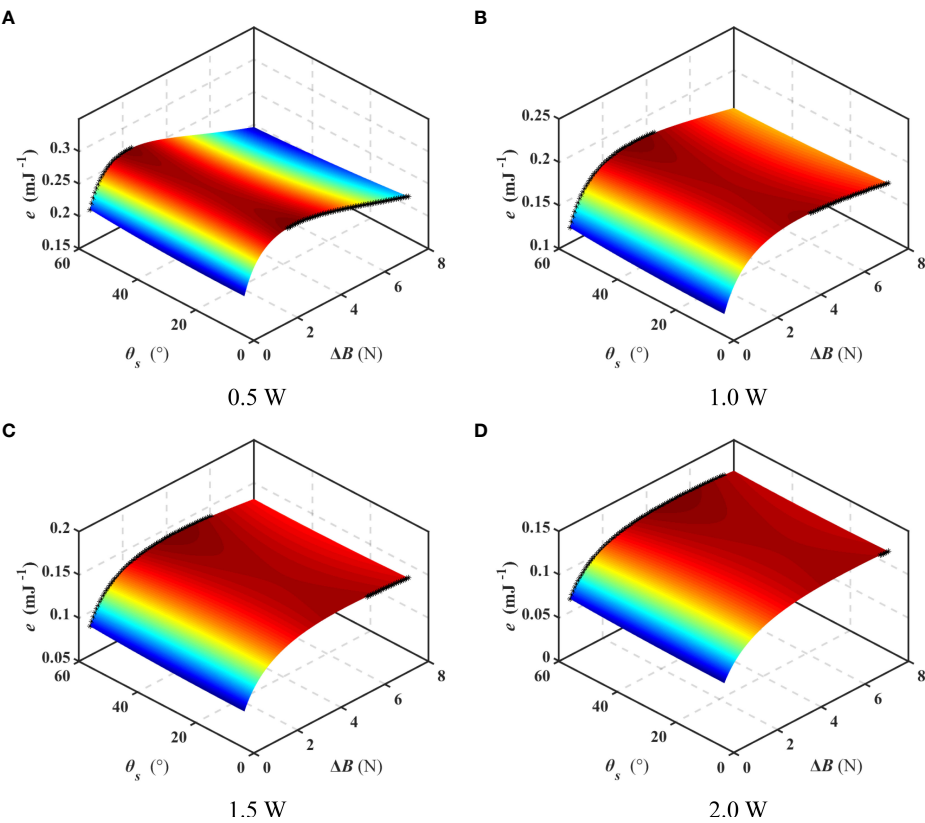


FIGURE 14
Gliding range per energy consumption unit. (A) 0.5 W (B) 1.0 W (C) 1.5 W (D) 2.0 W.

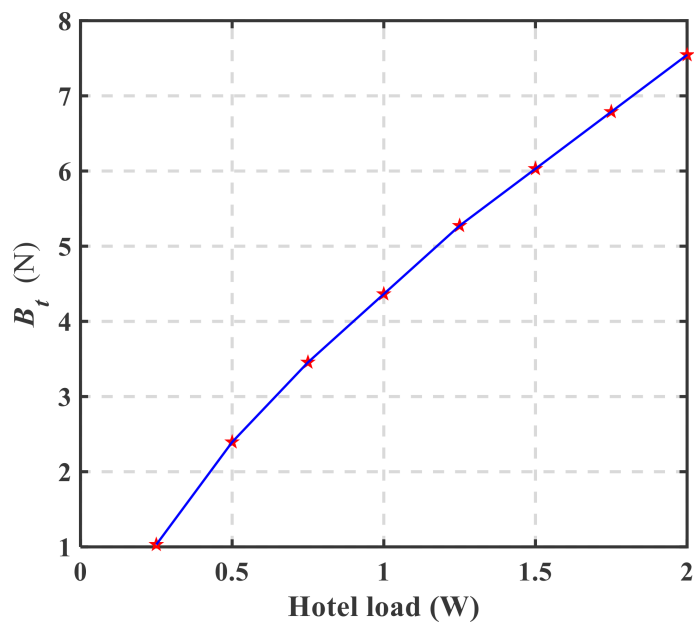


FIGURE 15
Variation of B_t with hotel load.

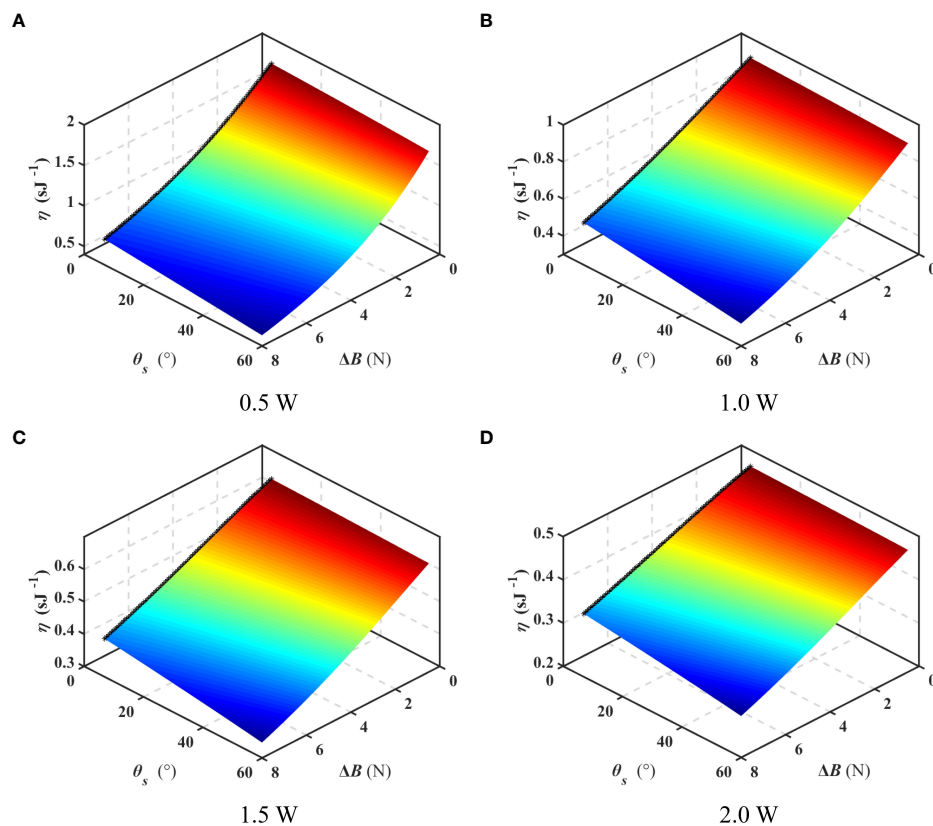


FIGURE 16
Gliding duration per energy consumption unit. (A) 0.5 W (B) 1.0 W (C) 1.5 W (D) 2.0 W.

L - α and SF - β has obvious bias. The error between CFD simulation and flume test results is analyzed, which can be attributed to the following aspects. 1) The support frames of UG in the flume test have a slight vibration due to water flow.

2) The viscosity and density of water in simulation are inconsistent with those in the test. 3) Due to the limitation of the size of the flume, the walls may affect hydrodynamic force of the UG model in the test.



FIGURE 17
Equipment and glider in circulating flume test.

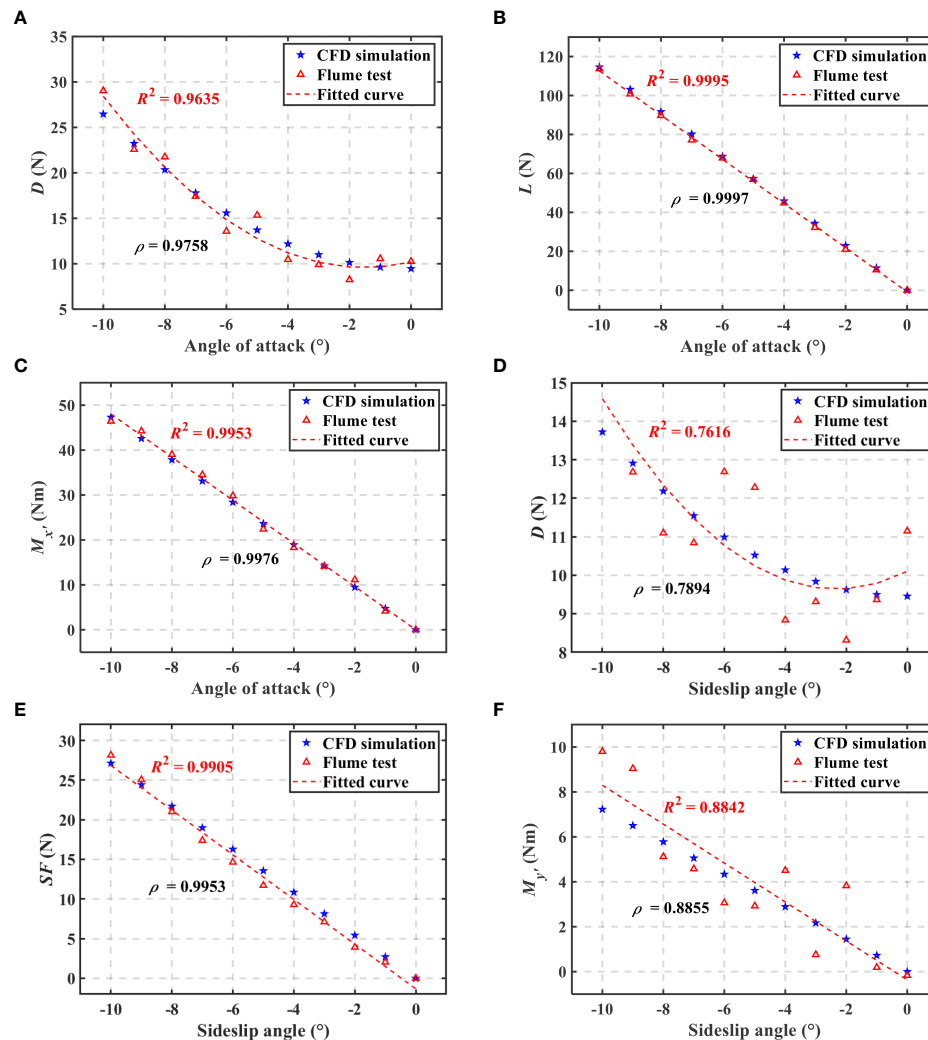


FIGURE 18
Results of circulating flume test and CFD simulation.

Conclusions

Inspired by the flight modes of swift, a sweep wing strategy is proposed to apply pre-adjustable sweep wings before the deployment of UGs, so as to improve the glide performance in different glide conditions. To facilitate the performance analysis of UG with various sweep wings, the approximate models of the hydrodynamic coefficients are established based CFD method to express the relationship between hydrodynamic coefficients and wing sweep angles. By importing the approximate models into the dynamic model of UG, the performance analysis of UG with various sweep wings related to endurance ability and trajectory accuracy are performed. The circulating flume test verifies the validity of the CFD method and the following conclusions can be drawn.

- (1) The sweep angle of wings has obviously influence on motion performance of Petrel-L. Petrel-L with a sweep angle of 7° , 35° and 60° can obtain the largest gliding time, the best turn ability and the best resisting current ability respectively.
- (2) To obtain the largest gliding range, Petrel-L need transform the sweep angle from 60° to 7° when the variable net buoyancy is larger than B_p , which is determined by the hotel load of Petrel-L.
- (3) The sweep wing strategy of UG proposed in this paper is useful for UG to obtain the optimal ability in some aspects, such as gliding range, gliding duration, trajectory accuracy and resisting current.

In the practical engineering, the specific ability demand of UG, such as gliding range, gliding duration, trajectory accuracy and resisting current ability, can be obtained from the

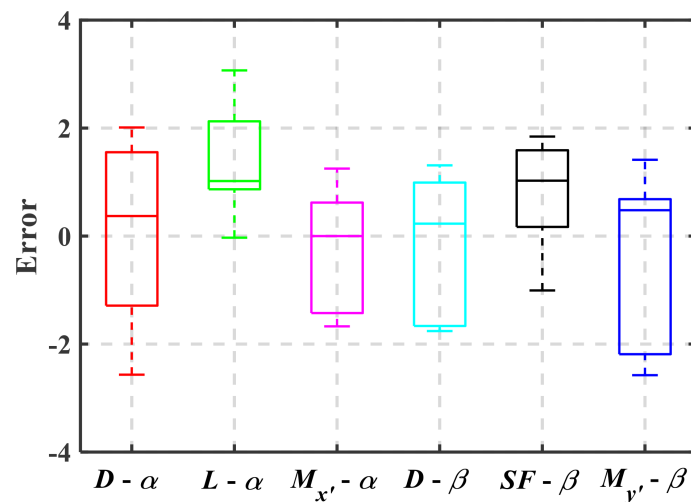


FIGURE 19
The absolute error of CFD simulation and flume test.

observation missions, and the motion strategy of UG can be determined to obtain the optimum performance. In addition, the strategy need be adjusted in real time due to uncertainty of ocean environment in the process of ocean observation. Therefore, the design and application of wing mechanism of a variable sweep angle with lightweight, low power consumption and high reliability will be considered to further improve the task observation efficiency of UG in the future work.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YW: Funding acquisition, Project administration, Conceptualization. CW: Methodology, Software, Data Curation, Writing - original draft. MY: Conceptualization, Writing - original draft, Validation, Investigation. YL: Investigation. WH: Experiment, Data curation. SY: Supervision, Funding acquisition. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Benoit-Bird, K. J., Patrick Welch, T., Waluk, C. M., Barth, J. A., Wangen, I., McGill, P., et al. (2018). Equipping an underwater glider with a new echosounder to explore ocean ecosystems: Echosounder equipped glider. *Limnol. Oceanogr. Methods* 16, 734–749. doi: 10.1002/lom3.10278
- Bie, D., and Li, D. (2022). Numerical analysis of the wing-wake interaction of tandem flapping wings in forward flight. *Aerosp. Sci. Technol.* 121, 107389. doi: 10.1016/j.ast.2022.107389
- Bulekov, V. P., and Teryev, E. D. (1972). Dynamics of variable sweep wing aircraft in the course of changing geometry. *IFAC Proc.* 5, 153–162. doi: 10.1016/S1474-6670(17)68464-7
- Carneiro, J. F., Pinto, J. B., Gomes de Almeida, F., and Cruz, N. A. (2021). Variable buoyancy or propeller-based systems for hovering capable vehicles: An energetic comparison. *IEEE J. Ocean. Eng.* 46, 414–433. doi: 10.1109/JOE.2020.3000703
- Claus, B., Bachmayer, R., and Williams, C. D. (2010). Experimental flight stability tests for the horizontal flight mode of a hybrid glider. *2010 IEEE/OES Autonomous Underwater Vehicles*, 1–6. doi: 10.1109/AUV.2010.5779680
- Dobbs, S. K., Miller, G. D., and Stevenson, J. R. (1985). Self-induced oscillation wind tunnel test of a variable sweep wing. *26th Structures Struct. Dynamics Materials Conf.* 739:1–16. doi: 10.2514/6.1985-739
- Ellington, C. P. (1999). The novel aerodynamics of insect flight: applications to micro-air vehicles. *J. Exp. Biol.* 202, 3439–3448. doi: 10.1242/jeb.202.23.3439
- Fer, I., Peterson, A. K., and Ullgren, J. E. (2014). Microstructure measurements from an underwater glider in the turbulent faroe bank channel overflow. *J. Atmospheric Ocean. Technol.* 31, 1128–1150. doi: 10.1175/JTECH-D-13-00221.1
- Fossen, T. I. (2011). *Handbook of marine craft hydrodynamics and motion control* (UK: Wiley).
- Fu, X., Lei, L., Yang, G., and Li, B. (2018). Multi-objective shape optimization of autonomous underwater glider based on fast elitist non-dominated sorting genetic algorithm. *Ocean Eng.* 157, 339–349. doi: 10.1016/j.oceaneng.2018.03.055
- Gursul, I., Vardaki, E., and Wang, Z. (2006). Active and passive control of reattachment on various low-sweep wings. *44th AIAA Aerospace Sci. Meeting Exhibit* 506:1–21. doi: 10.2514/6.2006-506
- Jagadeesh, P., Murali, K., and Idichandy, V. (2009). Experimental investigation of hydrodynamic force coefficients over AUV hull form. *Ocean Eng.* 36, 113–118. doi: 10.1016/j.oceaneng.2008.11.008
- Javadi, M. Y., Ovinis, M., Hashim, F. B. M., Maimun, A., Ahmed, Y. M., and Ullah, B. (2017). Effect of wing form on the hydrodynamic characteristics and dynamic stability of an underwater glider. *Int. J. Nav. Archit. Ocean Eng.* 9, 382–389. doi: 10.1016/j.jnaoe.2016.09.010
- Jones, C., Allsup, B., and DeCollibus, C. (2014). “Slocum Glider: Expanding our understanding of the oceans,” in *OCEANS*, 2014. 1–10, IEEE.
- Jones, D. A., Clarke, D. B., Brayshaw, I. B., Barillon, J. L., and Anderson, B. (2002). The Calculation of Hydrodynamic Coefficients for Underwater Vehicles. (Australia: Technical report DSTO Platforms Sciences Laboratory).
- Jones, K. D., and Platzer, M. F. (2009). Design and development considerations for biologically inspired flapping-wing micro air vehicles. *Exp. Fluids* 46, 799–810. doi: 10.1007/s00348-009-0654-1
- Kilgore, R. A. (1971). Some transonic and supersonic dynamic stability characteristics of a variable-sweep-wing tactical fighter model. *NASA Langley Research Center*, 1–44.
- Krashnitsa, R., Silin, D., Shkarayev, S., and Abate, G. (2009). Flight dynamics of a flapping-wing air vehicle. *Int. J. Micro Air Veh.* 1, 35–49. doi: 10.1260/1756-8293.1.1.35
- Lentink, D., Muller, U. K., Stamhuis, E. J., de Kat, R., van Gestel, W., Veldhuis, L. L. M., et al. (2007). How swifts control their glide performance with morphing wings. *NATURE* 446, 1082–1085. doi: 10.1038/nature05733
- Leonard, N. E., and Graver, J. G. (2001). Model-based feedback control of autonomous underwater gliders. *IEEE J. Ocean. Eng.* 26, 633–645. doi: 10.1109/48.972106
- Leonard, N. E., Paley, D. A., Lekien, F., Sepulchre, R., Fratantoni, D. M., and Davis, R. E. (2007). Collective motion, sensor networks, and ocean sampling. *Proc. IEEE* 95, 48–74. doi: 10.1109/PROC.2006.887295
- Li, D., Zhao, S., Da Ronch, A., Xiang, J., Drofelnik, J., Li, Y., et al. (2018). A review of modelling and analysis of morphing wings. *Prog. Aerosp. Sci.* 100, 46–62. doi: 10.1016/j.paerosci.2018.06.002
- Low, K. H., and Willy, A. (2006). Biomimetic motion planning of an undulating robotic fish fin. *J. Vib. Control* 12, 1337–1359. doi: 10.1177/1077546306070597
- Lyu, D., Song, B., Pan, G., Yuan, Z., and Li, J. (2019). Winglet effect on hydrodynamic performance and trajectory of a blended-wing-body underwater glider. *Ocean Eng.* 188, 106303. doi: 10.1016/j.oceaneng.2019.106303
- Miller, T. F. (2018). A bio-inspired climb and glide energy utilization strategy for undersea vehicle transit. *Ocean Eng.* 149, 78–94. doi: 10.1016/j.oceaneng.2017.11.048
- Pendleton, E. W., Besette, D., Field, P. B., Miller, G. D., and Griffin, K. E. (2000). Active aeroelastic wing flight research program: Technical program and model analytical development. *J. Aircr.* 37, 554–561. doi: 10.2514/2.2654
- Petriloti, E., Bartoletti, C., and Leccese, F. (2021). Preliminary study for AUV: Longitudinal stabilization method based on takagi-sugeno fuzzy inference system. *Sensors* 21, 1866. doi: 10.3390/s21051866
- Popov, A. V., Grigorie, L. T., Botez, R., Mamou, M., and Mebarki, Y. (2010). Real time morphing wing optimization validation using wind-tunnel tests. *J. Aircr.* 47, 1346–1355. doi: 10.2514/1.47431
- Powers, S., Webb, L., Friend, E., and Lokos, W. (1992). “Flight test results from a supercritical mission adaptive wing with smooth variable camber,” in *6th AIAA Biennial Flight Test Conference*.
- Raither, W., Heymanns, M., Bergamini, A., and Ermanni, P. (2013). Morphing wing structure with controllable twist based on adaptive bending-twist coupling. *Smart Mater. Struct.* 22, 065017. doi: 10.1088/0964-1726/22/6/065017
- Rojratsirikul, P. (2013). Bio-inspiration in the wings of man-made flyers. *J. Res. Appl. Mech. Eng.* 1, 1–7.
- Rosen, M., and Hedenstrom, A. (2001). Gliding flight in a jackdaw: A wind tunnel study. *J. Exp. Biol.* 204, 1153–1166. doi: 10.1242/jeb.204.6.1153
- Rudnick, D. L. (2016). Ocean research enabled by underwater gliders. *Annu. Rev. Mar. Sci.* 8, 519–541. doi: 10.1146/annurev-marine-122414-033913
- Rudnick, D. L., Davis, R. E., Eriksen, C. C., Fratantoni, D. M., and Perry, M. J. (2004). Underwater gliders for ocean research. *Mar. Technol. Soc. J.* 38, 73–84. doi: 10.4031/002533204787522703
- Sánchez, P. J. B., Papaelias, M., and Márquez, F. P. G. (2020). Autonomous underwater vehicles: Instrumentation and measurements. *IEEE Instrum. Meas. Mag.* 23, 105–114. doi: 10.1109/MIM.2020.9062680
- Sobester, A., Forrester, A., and Keane, A. (2008). *Engineering design via surrogate modelling: a practical guide* (New York, USA: John Wiley & Sons).
- Sobol', I. M. (1990). On sensitivity estimation for nonlinear mathematical models. *Mat. Model.* 2, 112–118.
- Sobol', I. M. (2001). Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Math. Comput. Simul.* 55, 271–280. doi: 10.1016/S0378-4754(00)00270-6
- Summers, A., and Mahannah, J. (2008). On swift wings: What airplane designers could learn from the shape-changing wings of birds. *Nat. Hist.* 117, 42–43.
- Sun, T., Chen, G., Yang, S., Wang, Y., Wang, Y., Tan, H., et al. (2021). Design and optimization of a bio-inspired hull shape for AUV by surrogate model technology. *Eng. Appl. Comput. Fluid Mech.* 15, 1057–1074. doi: 10.1080/19942060.2021.1940287
- Sun, T., Yang, M., Wang, Y., Wang, S., and Chen, Y. (2019). “Parametric design and experimental verification of cicada-wing-inspired controllable wing mechanism for underwater glider,” in *IFTOMM world congress on mechanism and machine science* (Cham: Springer) 73. Available at: https://gfbfg1b13095ec5284139swqxu6bowffqc6fkbfgcc.eds.tju.edu.cn/10.1007/978-3-030-20131-9_3.
- Tanaka, H., Whitney, J. P., and Wood, R. J. (2011). Effect of flexural and torsional wing flexibility on lift generation in hoverfly flight. *Integr. Comp. Biol.* 51, 142–150. doi: 10.1093/icb/ict051
- Triantafyllou, M. S., and Triantafyllou, G. S. (1995). An efficient swimming machine. *Sci. Am.* 272, 64–70. doi: 10.1038/scientificamerican0395-64
- Tucker, V. A. (1987). Gliding birds: the effect of variable wing span. *J. Exp. Biol.* 133, 33–58. doi: 10.1242/jeb.133.1.33
- Vale, J., Leite, A., Lau, F., and Suleman, A. (2011). Aero-structural optimization and performance evaluation of a morphing wing with variable span and camber. *J. Intell. Mater. Syst. Struct.* 22, 1057–1073. doi: 10.1177/1045389X11416031
- Van Breugel, F., Regan, W., and Lipson, H. (2008). From insects to machines demonstration of a passively stable, untethered flapping-hovering micro-air vehicle. *IEEE Robot. Autom. Mag.* 15, 68–74. doi: 10.1109/MRA.2008.929923
- Videler, J. J. (2006). *Avian flight* (Great Clarendon Street: Oxford University Press: Great Clarendon Street in Oxford).

- Wang, I., and Dowell, E. H. (2011). Structural dynamics model of multisegmented folding wings: theory and experiment. *J. Aircr.* 48, 2149–2160. doi: 10.2514/1.C031509
- Wang, X., Song, B., Wang, P., and Sun, C. (2018). Hydrofoil optimization of underwater glider using free-form deformation and surrogate-based optimization. *Int. J. Nav. Archit. Ocean Eng.* 10, 730–740. doi: 10.1016/j.ijnaoe.2017.12.005
- Wang, Y., Zhang, Y., Zhang, M., Yang, Z., and Wu, Z. (2017). Design and flight performance of hybrid underwater glider with controllable wings. *Int. J. Adv. Robot. Syst.* 14:1–12. doi: 10.1177/1729881417703566
- Wood, R. (2008). The first takeoff of a biologically inspired at-scale robotic insect. *IEEE Trans. Robot.* 24, 341–347. doi: 10.1109/TRO.2008.916997
- Wood, R. J., Finio, B., Karpelson, M., Ma, K., Pérez-Arancibia, N. O., Sreetharan, P. S., et al. (2012). Progress on ‘pico’air vehicles. *Int. J. Robot. Res.* 31, 1292–1302. doi: 10.1177/0278364912455073
- Wu, H., Niu, W., Wang, S., Yan, S., and Liu, T. (2020). Sensitivity analysis of input errors to motion deviations of underwater glider based on optimized response surface methodology. *Ocean Eng.* 209, 107400. doi: 10.1016/j.oceaneng.2020.107400
- Yang, Y., Nguyen, N., Chen, N., Lockwood, M., Tucker, C., Hu, H., et al. (2010). Artificial lateral line with biomimetic neuromasts to emulate fish sensing. *Bioinspir. Biomim.* 5, 016001. doi: 10.1088/1748-3182/5/1/016001
- Yang, M., Wang, Y., Liang, Y., and Wang, C. (2022). A new approach to system design optimization of underwater gliders. *IEEEASME Trans. Mechatron.* 27, 3494–3505. doi: 10.1109/TMECH.2022.3143125
- Yang, M., Wang, Y., Wang, S., Yang, S., Song, Y., and Zhang, L. (2019). Motion parameter optimization for gliding strategy analysis of underwater gliders. *Ocean Eng.* 191, 106502. doi: 10.1016/j.oceaneng.2019.106502
- Yang, M., Wang, Y., Yang, S., Zhang, L., and Deng, J. (2021). Shape optimization of underwater glider based on approximate model technology. *Appl. Ocean Res.* 110, 102580. doi: 10.1016/j.apor.2021.102580
- Zeng, N., Hang, G., Cao, G., and Wang, Z. (2006). Present state and tendency of bionic underwater robot. *Mech. Eng.*, 18–21. doi: 10.3969/j.issn.1002-2333.2006.04.014



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Measurement principle and technology of miniaturized strapdown inertial wave sensor

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This paper presents the design and implementation of a low-cost directional inertial wave sensor, DWS19-2, which is suitable for installation on ocean air-sea coupling buoys, offshore environmental monitoring buoys and surface drifting buoys. DWS19-2 integrates an STM32F446 embedded controller with a 9-axis MEMS inertial module QZ901 to measure buoy pitch, roll, heading and accelerations. These parameters are further used to calculate wave parameters and estimate directional and non-directional wave spectra. These wave parameters and spectral information are then reported to the buoy data logger for real-time transmission to shore-based data centers. Details of the electrical design and onboard wave processing algorithm (coordinate projection, numerical integration in the frequency domain, time-based wave parameters, frequency-based wave parameters, directional wave spectrum), in addition to turntable tests, field marine comparison with DWR-MKIII wave buoy and related ocean observation applications enabled by this device, are described in this paper.

KEYWORDS

inertial wave sensors, strap-down accelerometers, coordinate projection, numerical integration, directional wave spectra

Introduction

In the field of ocean wave observations, inertial wave measurements have been a major method for observing ocean waves ever since their invention. Its advantages over pressure gauges, acoustic sensors, and laser remote sensors are made possible by not being affected by water depth and field mounting environment (Doong et al., 2011; Qi et al., 2019). Wave sensors have gradually developed toward miniaturization, low power consumption, and low-cost to meet the increasing requirements of mobile and portable observations (Datawell; TRIAXYSy). The South China Sea Institute of Oceanology (SCSIO),

Chinese Academy of Sciences (CAS), has developed the DWS19-2 miniature strap-down inertial wave sensor, whose hardware components and onboard data processing, such as coordinate projection (digital stabilization platform), numerical integration in the frequency domain, wave parameter calculation (time based, frequency based), and directional wave spectrum estimation, as well as the observations and applications of the DWS19-2-boarded buoy platform, are introduced in this paper. The digital stabilization platform enables wave sensors to fully eliminate their reliance on external mechanical/electrical stabilization platforms, thus allowing them to be installed independently and to make precise observations in the dynamic wave environment. DWS19-2, with its small size and low power consumption, has been subjected to the laboratory turntable test and used in many marine observation experiments. Because of its high-precision measurement and stable and reliable performance, DWS19-2 is suitable for mass deployment in the marine environment observation network. Because DWS19 uses mathematical processing methods such as coordinate projection and numerical integration to replace hardware to realize the functions of stable platform and hardware integration circuit, the cost is reduced and the hardware component cost of DWS19 is less than 1000 US dollars.

Details of DWS19-2

DWS19-2 (Figure 1) is a miniature strap-down inertial wave sensor with a power supply voltage of 5–20 VDC and power consumption of less than 20 mA@5 VDC. It can output wave parameters via RS232, including H_{max} , H_{avr} , $H_{1/3}$, T_{avr} , H_{m0} , T_p , D_{meam} , D_{main} , $Spr(f)$, $DSpr(f, d)$. These wave parameters are

defined in Table 1. Additionally, DWS19-2 contains an integrated inertial navigation module (IINM), namely, QZ901 (Figure 2). QZ901, with its low power consumption (10 mA5VDC), contains a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer. The attitude angle (roll, pitch, heading) were calculated by the on-board Kalman filter algorithm) and acceleration signals are directly output through a serial peripheral interface (SPI). The acceleration measurement ranges from -8g to +8g, and the sampling frequency reaches 200 Hz. According to the Longuet-Higgins (1985) method in, most stable waves seldom produce an acceleration of greater than +0.30g at the wave trough and an acceleration of less than -0.39g at the wave peak, so all these parameters are within QZ901's measurement ranges.

The high-performance embedded processing chip, namely, STM32F446, was adopted to meet the stringent requirements of the calculations on real-time coordinate projection and fast Fourier transform (FFT), among others. The chip has a 4-channel USART interface, a 3-channel SPI interface, a 2-channel inter integrated circuit (IIC) interface, and two secure digital input/output (SDIO) interfaces. Functions from the official digital signal processing (DSP) library can be invoked to rapidly finish the FFT calculation during wave signal processing. Conducting FFT for 2,048 sets of acceleration data takes no more than 10 ms, a speed that satisfies the demands of real-time wave calculation. The circuit schematic diagram of DWS19-2 wave sensor is shown in Figure 3. The algorithm process of a DWS19-2 measurement consists of the following steps shown as Figure 4. First, the software and hardware are initialized after the sensor had been powered on, and then 2 s later, the 9-axis data are sampled at a frequency of 4 Hz; moreover, the coordinate projection is conducted in every

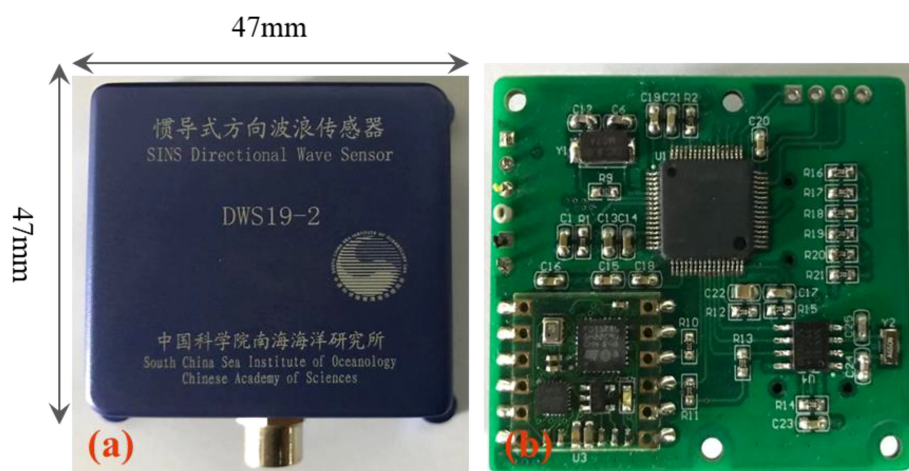


FIGURE 1
DWS19-2 directional wave sensor: (A) physical picture; (B) signal processing board.

TABLE 1 Definition of the wave parameters.

Name	Symbol	Definition
Maximum wave height	$H_{\max}$	Maximum height of the wave record by zero-crossing
Maximum wave period	$T_{\max}$	Wave period at $H_{\max}$
Theoretical significant wave height	$H_{1/3}$	Average height of the highest one-third waves by zero-crossing
Theoretical significant wave period	$T_{1/3}$	Average period of the highest one-third waves by zero-crossing
Average wave height	H_{avr}	Average height of a wave record by zero-crossing
Average wave period	T_{avr}	Average period of a wave record by zero-crossing
Mean wave direction	D_{mean}	$D_{\text{mean}} = \arctan(B_1/A_1)^a$
Domain wave direction	D_{main}	$D_{\text{main}} = \arctan(B_2/A_2)/2^a$
Maximum directional spectral density	$DSpr_{\max}$	$DSpr_{\max}(f_p, d_p) = \text{MAX}(DSpr(f, d))^b$
Wave period at $DSpr_{\max}$ peak	F_p	$F_p = 1/f_p @ DSpr_{\max}(f_p, d_p)$
Wave direction at $DSpr_{\max}$ peak	D_p	$D_p = d_p @ DSpr_{\max}(f_p, d_p)$
Significant wave height	H_{m0}	$H_{m0} = 4.0 \sqrt{m_0^c}$
Peak wave period	T_p	$T_p = 1/f_p @ Spr_{\max}(f_p)^d$
Average wave height by spectral integration	H_{avr_s}	$H_{\text{avr}_s} = \sqrt{2\pi m_0}$
Average wave period by spectral integration	T_{avr_s}	$T_{\text{avr}_s} = 2\pi \sqrt{m_0/m_2^e}$

^a A_1, B_1, A_2, B_2 : Fourier coefficients of $DSpr(f, d)$ ^b $DSpr(f, d)$: directional spectrum^c m_0 : zero moment is the summation over all angular frequency bands of the nondirectional spectra^d $Spr(f)$: nondirectional spectrum^e m_2 : second-order moment is the summation over all second-order angular frequency bands of the nondirectional spectra

9-axis data sample. When the sample number reaches 2048, in succession, the wave calculation procedure starts to conduct the frequency-domain numerical integration, the time-based wave parameter statistical analysis, the frequency-based parameter calculation, and the estimation of directional wave spectra. Each sample's raw data, such as the acceleration of the body coordinate system (BCS), the attitude information (pitch, roll, heading), and the acceleration of the geographic coordinate

system (GCS), are recorded in the SD card. It takes approximately 8 min and 50 s to output the wave parameters through the RS232 interface after the sensor is powered up. The reported wave parameters is as follows:

\$wave, yyyyymmddhhmmss, < $H_{\max}$ > < $T_{\max}$ > < $H_{1/3}$ > < $T_{1/3}$ > < H_{avr} > < T_{avr} > < D_{mean} > < D_{main} > < $DSpr_{\max}$ > < F_p > < D_p > < H_{avr_s} > < T_{avr_s} > <cr> <if>

The definitions of each wave parameter are given in Table 1.

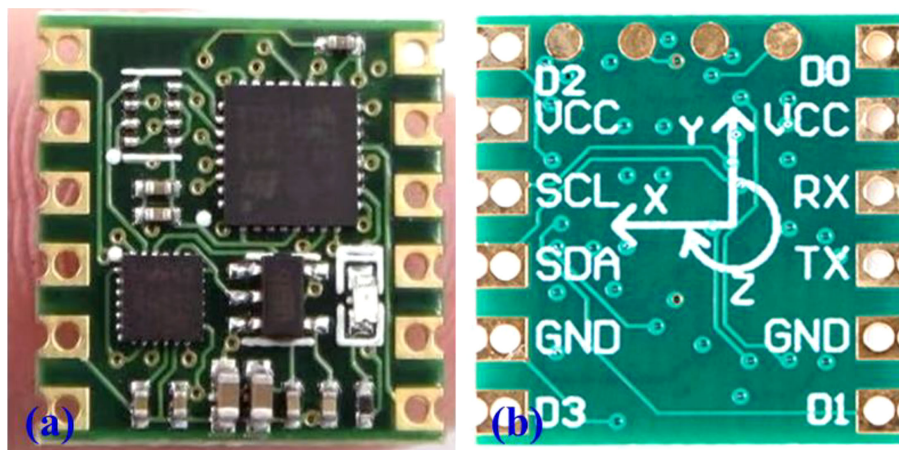


FIGURE 2
QZ901 IINM: (A) front side; (B) back side.

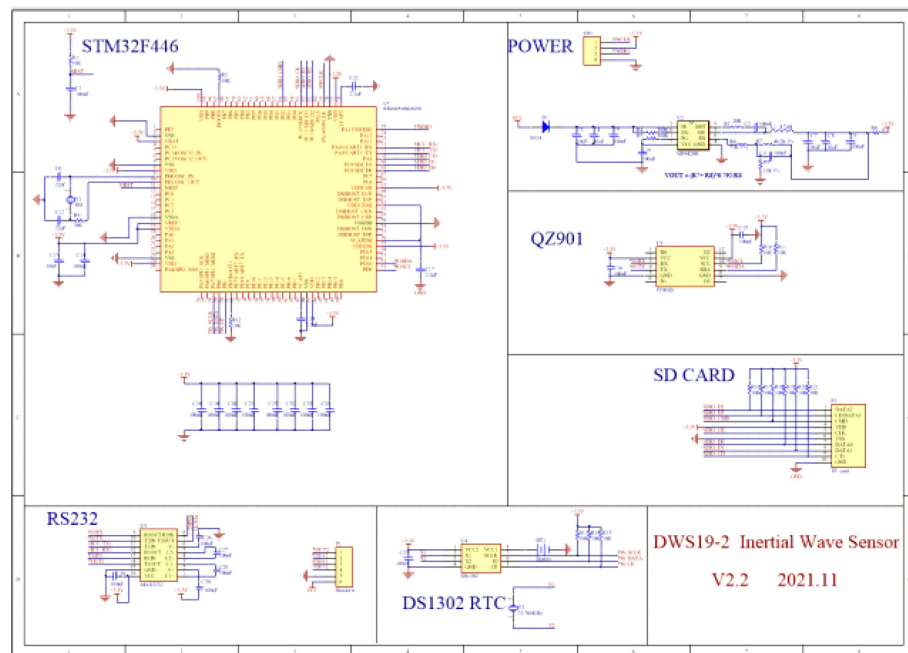


FIGURE 3
Circuit schematic diagram of DWS19-2 wave sensor.

On board signal processing

Coordinate projection

Because buoys fluctuate and swing with waves, whether the inertial sensing components of the sensor can remain horizontally stable in a dynamic wave environment directly affects the precision of the wave measurement (Fong et al., 2008; Marin-Perianu et al., 2008). The vertical accelerometer is used to calculate the wave height of the sensor. Because the wave sensor floats continuously changing attitude, coordinate projection is a necessary step to compute the real vertical acceleration relative to the Earth plane. In DWS19-2, the 3-axis accelerations of the BCS can be projected to the GCS by the coordinate projection matrix, the coordinate projection matrix realizing the function of the “digital stabilization platform”.

The coordinate rotation matrix (C_b^n) is calculated by the 3-axis attitude angle,

$$C_b^n = C(\psi)C(\theta)C(\phi)$$

$$= \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi) & \cos(\phi) \end{bmatrix}$$

where ψ , Φ , and θ stand for the roll, pitch, and heading, respectively. The 3-axis accelerations of the BCS are projected to the GCS via the formula $a_n = a_b C_b^n$.

In Figure 3, the Z-axis acceleration is sampled by DWS19-2 in a 0.9 m diameter circular buoy in the offshore sea area of Jiangmen City, Guangdong province. The sampling number is 2048 and the sampling frequency is 4Hz, and the Z-axis acceleration (A_Z) between the BCS and the GCS is compared. The Z-axis acceleration and the calculated displacement (D_Z) after the coordinate projection differ prominently from the BCS values, where the average displacement error reaches 15% (Figure 5).

Numerical integration of acceleration

The goal of this part is to develop a reliable process from which the wave displacement signal can be derived from the measured acceleration data via a double integration process. Integration errors must be minimized so that the calculated displacement is very close to the actual displacement.

To date, three integration techniques have been used to determine displacement by measured acceleration: analog integration, time-domain numerical integration, and frequency-domain numerical integration (Lee and Lee, 1996; Pang and Liu, 2001). In principle, the process of double integration can be done electronically with an RC amplification circuit (Ribeiro et al., 1999). Because the circuit components are set at the very beginning of the design, the filter

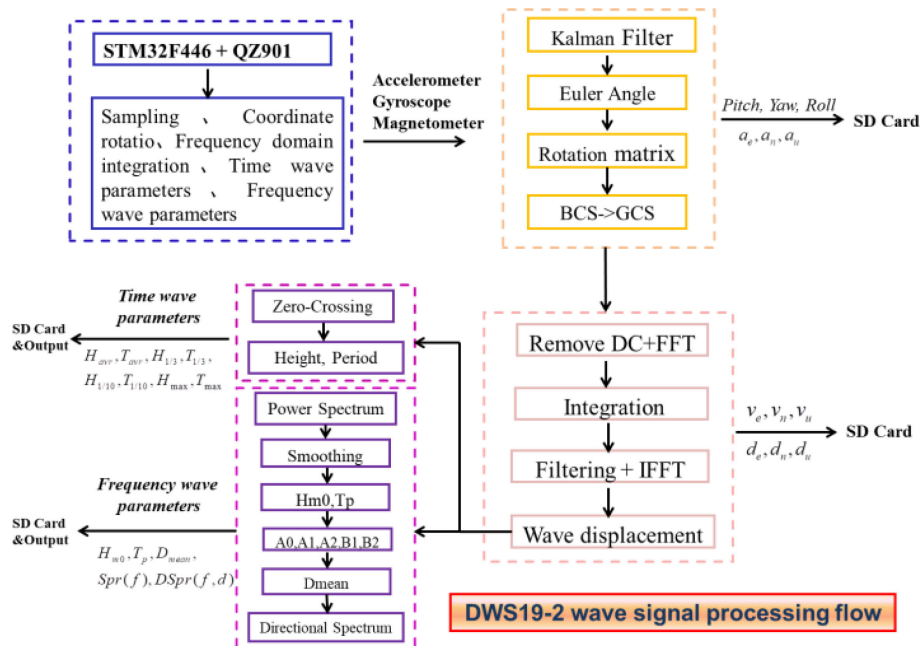


FIGURE 4
DWS19-2 wave signal processing flow.

performance of the integration circuit is fixed. For the random wave that occurred in the ocean, the hardware integration does not have filter self-adaptability. Therefore, the analog double integrator is reliable only to measure sinusoidal steady-state displacements. In addition, an unbounded displacement drift can arise after two integrations in the time domain caused by a

small DC bias in the acceleration signals. Consequently, an empirical digital filter should be designed to extract the real displacement signal (Rong et al., 2000). By filtering after integration, drift errors are eliminated.

Frequency-domain integration applies the FFT to acceleration first, converting the time-domain acceleration

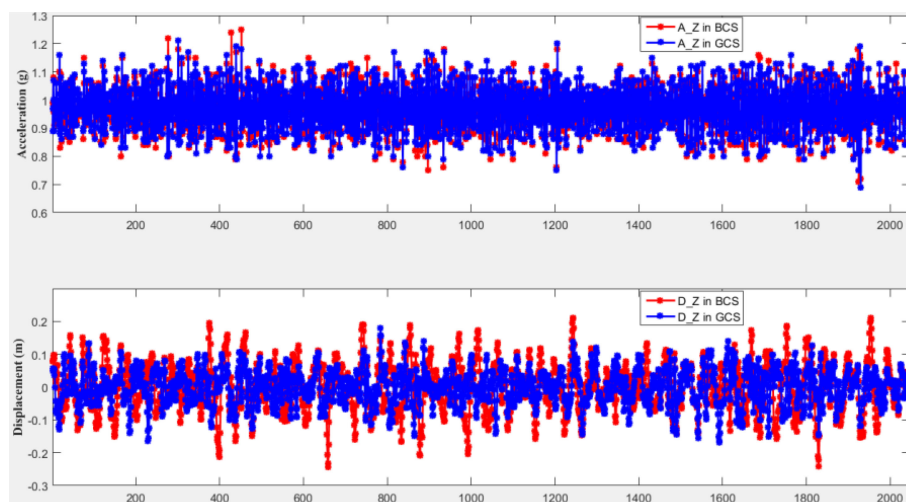


FIGURE 5
Comparison of accelerations and displacements before and after coordinate projection.

signal to the frequency domain. The inverse FFT (IFFT) is conducted to change the integrated results to time-domain displacement signals. In contrast to the time-domain numerical integration, the frequency-domain integration can effectively restrict the cumulative amplification effect of the low-frequency DC error signals after two integrations, thereby obtaining a more precise and reliable displacement result. As the calculation ability of the high-performance ARM/DSP chip is greatly improved, FFT and IFFT calculations in an embedded chip are feasible. DWS19-2 adopts the frequency-domain numerical integration method, and the calculation process is shown below. In accordance with Formula (1), the FFT is carried out on projected Z-axis accelerations a_n to achieve the real and imaginary components.

$$A(k) = \sum_{n=0}^{N-1} a_n e^{-j2\pi k \frac{n}{N}}, \quad k = 0, 1, \dots, N-1 \quad (1)$$

According to the integral transformation properties of the FFT, the displacements are calculated by Formula (2), followed by bandpass filtering of 0.04–0.67 Hz to the displacement signals. Finally, the time-domain displacement signals are achieved through IFFT.

$$S(n) = \sum_{k=0}^{N-1} \frac{1}{-(2\pi k \Delta f)^2} H(k) a_n e^{-j2\pi k \frac{n}{N}} \quad (2)$$

where $H(k) = \begin{cases} 1, & f_d \leq kf \leq f_u \\ 0, & \text{otherwise} \end{cases}$; Δf stands for the frequency resolution; and f_u and f_d represent the upper and lower cutoff frequencies of the bandpass filter, respectively, which are set as 0.67 (corresponding to 1.5 s) and 0.04 (corresponding to 25 s), respectively, in this paper.

From Figure 6, a series of projected Z-axis accelerations are integrated by two methods in the time domain and frequency domain to obtain the two displacement series. The displacement result of the time-domain displacement displays notable drifting, and an empirical signal filter processing method is needed later to extract the real displacement signals. Although there is phase shift in the FDI, the obvious drift error does not exist in the results of the frequency-domain integration. This phase shift only affects the real-time wave displacement series by FDI, but has no effect on the time wave parameters statistics by the zero-crossing method and the frequency wave parameters by spectral integration method.

Time wave parameters

The DWS19-2 wave sensor's onboard program contains two methods for calculating wave parameters, the zero-crossing method (Figure 7) and the energy spectrum method, and the corresponding calculation results are time wave parameters and frequency wave parameters, respectively.

For a wave displacement series, the zero-crossing method can be used to conduct wave characteristic statistics. The first step is to determine the average value for the reference zero line and take the first intersection between the downward movement position of the buoy and the zero line as a zero-crossing starting point. Then, the next crossing point is searched as the second zero-crossing end point. The time difference and the vertical displacement difference between the two downward zero-crossing points are the observed wave period and wave height,

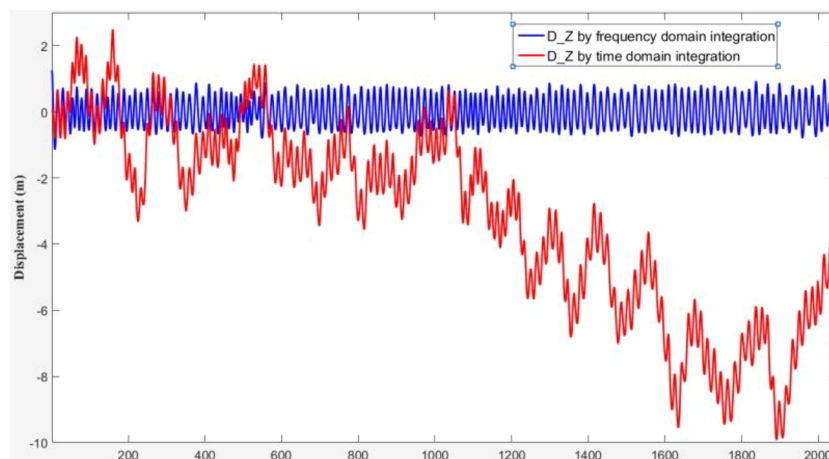


FIGURE 6
Comparison of displacement obtained by time and frequency domain integration.

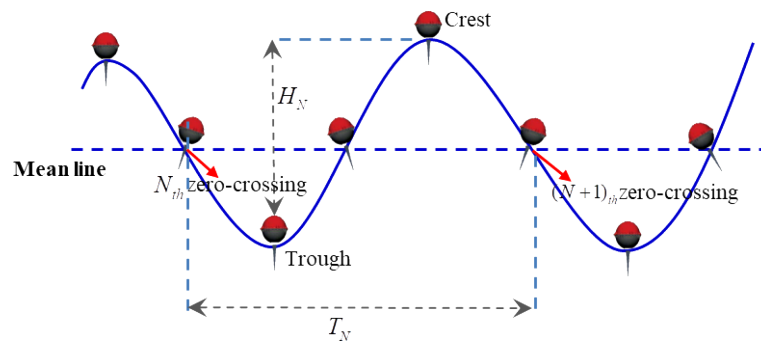


FIGURE 7
Downward zero-crossing method.

respectively. Subsequently, all the observed wave heights and wave periods are ranked in descending order to obtain statistical wave parameters, including H_{max} , T_{max} , $H_{1/3}$, $T_{1/3}$, $H_{1/10}$, $T_{1/10}$, H_{avr} , and T_{avr} .

Frequency wave parameters

The power spectrum method can be used to obtain the frequency wave parameters. The non-directional power spectrum can be calculated as follows:

$$Spr(w_k) = \frac{\Delta t}{2\pi N} |A_k|^2, \quad w_k = k\Delta w, \quad k = 0, 1, 2, \dots, N/2 \quad (3)$$

where A_k is the FFT of the displacement time series $S(n)$. The power spectrum is further smoothed according to the following equation:

$$\overline{Spr(w_k)} = \frac{1}{4} Spr(w_{k-1}) + \frac{1}{2} Spr(w_k) + \frac{1}{4} Spr(w_{k+1}) \quad (4)$$

Then, the wave spectral moments are calculated. The calculation equations for the zero-order momentum m_0 and the second-order momentum m_2 are as follows:

$$m_0 = \left[\frac{1}{2} Spr(w_0) + \sum_{k=1}^{N/2-1} Spr(w_k) + \frac{1}{2} Spr(w_{N/2}) \right] \Delta w \quad (5)$$

$$m_2 = \left[\frac{1}{2} Spr(w_0)w_0^2 + \sum_{k=1}^{N/2-1} Spr(w_k)w_k^2 + \frac{1}{2} Spr(w_{N/2})w_{N/2}^2 \right] \Delta w \quad (6)$$

Then, the frequency wave parameters, including $H_{avr,s}$, $T_{avr,s}$, H_{m0} , and T_p , are calculated according to the equations defined in Table 1.

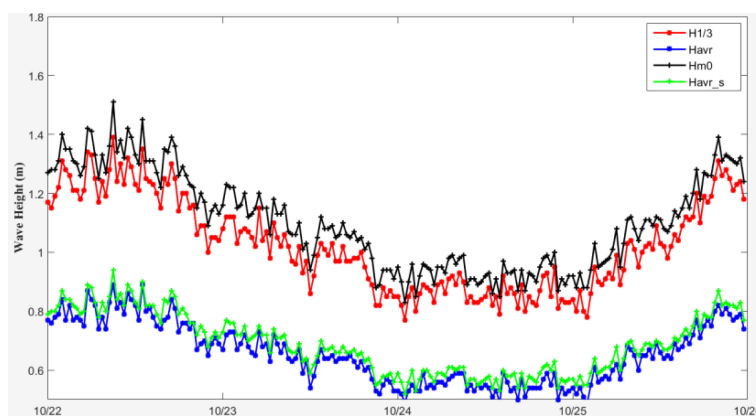


FIGURE 8
Comparison of time and frequency wave height.

A four-day observed wave height time series from a mooring buoy in the Indian Ocean in 2021 is shown in Figure 8. The time parameters (H_{avr} , $H_{1/3}$) obtained by the zero-crossing method are highly consistent with the frequency wave parameters (H_{avr_s} , H_{m0}) obtained by the power spectra method. The average error between H_{avr} and H_{avr_s} is 0.02 m. The H_{m0} is approximately 8% higher than $H_{1/3}$. Reasons for the deviation between the time and frequency parameters were explained by Longuet-Higgins (1952). An assumption for approximating significant wave height by H_{m0} is that wave spectra are narrow banded. In Longuet-Higgins (1980), the finite spectral width is the likely explanation for the differences between $H_{1/3}$ and H_{m0} , with H_{m0} values typically being approximately 5 to 10 percent greater than $H_{1/3}$ values, which is consistent with the studies in this paper.

Directional wave spectrum

The directional wave spectrum $DSpr(f, \theta)$ is the energy spectrum reflecting the internal directional structure of the wave and represents the energy distribution of wave components in different directions with respect to the frequency.

Directional wave spectra provide the distribution of wave elevation variance as a function of both wave frequency (f) and wave direction (θ). A directional wave spectrum can be written as

$$DSpr(f, \theta) = \frac{A_0}{2} + \sum_{n=1}^2 [A_n \cos(n\theta) + B_n \sin(n\theta)] \quad (7)$$

The first five Fourier coefficients A_0 , A_1 , A_2 , B_1 , B_2 are given by $A_0 = \frac{C_{11}}{\pi}$, $A_1 = \frac{Q_{12}}{k\pi}$, $B_1 = \frac{Q_{13}}{k\pi}$, $A_2 = \frac{C_{22}-C_{33}}{k^2\pi}$, $B_2 = \frac{2C_{23}}{k^2\pi}$. D_{mean} and D_{main} are calculated by

$$D_{mean} = \arctan\left(\frac{B_1}{A_1}\right), D_{main} = \frac{1}{2} \arctan\left(\frac{B_2}{A_2}\right) \quad (8)$$

DWS19-2 measures buoy heave, pitch, roll, and heading, and the subscripts of Q_{xy} and C_{xy} are defined as follows:

- 1 = displacement along the Z-axis, which corresponds to buoy heave after coordinate projection, which can be obtained by integrating the acceleration twice in the frequency domain.
- 2 = wave slope along east–west, which corresponds to buoy tilt in this direction.
- 3 = wave slope along south–north, which corresponds to buoy tilt in this direction

For each measured data point by DWS19-2, heading is used to convert pitch and roll to wave slopes along the east–west and south–north directions, respectively.

Here, C_{xy} is the cospectrum, and Q_{xy} is the quadrature spectrum, which can be given by

$$C_{xy} = (Re[X] * Re[Y] + Im[X] * Im[Y]) / N \quad (9)$$

$$Q_{xy} = (Im[X] * Re[Y] - Im[X] * Im[Y]) / N \quad (10)$$

where X and Y are frequency domain representations of the time series x and y , respectively.

DWS19-2 can report power spectra by query command “? MNMD<lr>” after every wave measurement (2048 data4Hz). The output format of directional spectrum is

```
$TSPMA, yyyymmddhhmmss,<FreNum>,<FreStart>,<df>,<FreEnd>
<Fre_1>,<1*5>,<DirSpec>
...
<Fre_1>,<72*5>,<DirSpec>
<Fre_2>,<1*5>,<DirSpec>
...
<Fre_2>,<72*5>,<DirSpec>
...
<Fre_100>,<1*5>,<DirSpec>
...
<Fre_100>,<72*5>,<DirSpec>
```

DWS19-2 outputs 7,200 directional spectrum values, which are obtained by 100 frequency intervals multiplied by 72 direction intervals. $FreNum$ is defined as 100, $FreStart$ is the starting frequency defined as 0.041 Hz, df refers to the frequency interval of 0.006 Hz, and $FreEnd$ represents the cutoff frequency of 0.627 Hz.

Laboratory and filed testing

Laboratory turntable testing

A buoy floating in a wave is generally assumed to motion in a circular orbit, in which the buoy itself maintains an approximately upright position in the sea without rotating (Dean and Dalrymple, 1991; Boccotti, 2000). To evaluate the measurement validity of wave sensors from different manufacturers, a mechanical wave motion simulation laboratory was established in the National Center of Ocean Standards and Metrology (NCOSM). A circular motion turntable with an adjustable period and height is the key simulation device, which is very similar to the ferris wheel in an amusement park. The turntable wave simulator (TWS) is shown in Figure 9. From April 21–23, 2021, three wave height simulation tests were conducted on DWS19-2 at 1 m, 3 m and 6 m on the TWS. With each simulated wave height, seven different periods of measurement were carried out. The average wave height (H_{avr}) and wave period (T_{avr}) output by

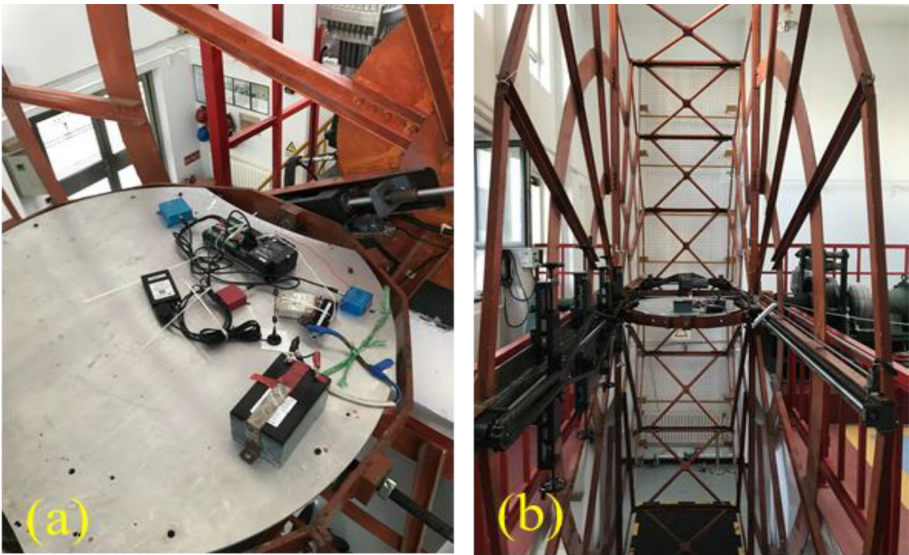


FIGURE 9
Wave simulation turntable: (A) Installation of DWS19-2 and data acquisition system (B) Turntable simulator device.

DWS19-2 obtained by zero-crossing were compared with the standard height and periods, respectively.

At a height of 1 m, simulation measurements were conducted in seven periods of 25.0 s, 17.6 s, 10.3 s, 8.3 s, 6.4 s, 4.7 s, and 3.7 s. At a height of 3 m, simulation measurements were conducted in seven periods of 14.2 s, 9.9

s, 7.6 s, 6.2 s, 5.2 s, and 4.5 s. At a height of 6 m, simulation measurements were conducted in seven periods of 25.0 s, 16.8 s, 12.7 s, 10.2 s, 8.5 s, 7.3 s, and 6.4 s. The test results are listed in [Tables 2–4](#).

Overall, for DWS19-2, at a height of 1 m, the errors in height measurement were within 1% (except for the

TABLE 2 Measurement at a height of 1 m (height unit: m; period unit: s).

Turntable standard	Height	1.00						
	Period	25.00	17.60	10.30	8.30	6.40	4.70	3.70
DWS19-2measurement	H _{avr}	1.04	1.01	1.00	1.00	1.00	1.00	1.01
	T _{avr}	25.00	17.63	10.33	8.32	6.40	4.72	3.73
Error	ΔH	0.04	0.01	0.00	0.00	0.00	0.00	0.01
	ΔT	0.00	0.03	0.03	0.02	0.00	0.02	0.03

TABLE 3 Measurement at a height of 3 m (height unit: m; period unit: s).

Turntable standard	Height	3.00						
	Period	25.00	14.20	9.90	7.60	6.20	5.20	4.50
DWS19-2measurement	H _{avr}	3.06	3.03	3.01	3.00	3.00	3.00	2.99
	T _{avr}	25.00	17.46	9.95	7.66	6.25	5.25	4.54
Error	ΔH	0.06	0.03	0.01	0.00	0.00	0.00	-0.01
	ΔT	0.00	0.26	0.05	0.06	0.05	0.05	0.04

TABLE 4 Measurement at a height of 6 m (height unit: m; period unit: s).

Turntable standard	Height	6.00						
	Period	25.00	16.80	12.70	10.20	8.50	7.30	6.40
DWS19-2measurement	H_{avr}	6.08	6.05	6.03	6.01	6.01	5.99	5.99
	T_{avr}	25.00	17.02	12.76	10.26	8.55	7.34	6.40
Error	ΔH	0.08	0.05	0.03	0.01	0.01	-0.01	-0.01
	ΔT	0.00	0.22	0.06	0.06	0.05	0.04	0.00

measurement at 25.00 s), and those for period measurement were within 0.05 s. At heights of 3 m and 6 m, the errors in height measurement were within $\pm 2\%$. Those in the period measurement were basically within 0.06 s (except for 14.2 s at 3 m and 16.8 s at 6 m).

Field comparison

For the purpose of filed comparison, a DWS19-2 was mounted on a spherical wave buoy deployed in Haimen Bay (22.93° N, 116.52°E) in the Northern South China Sea, hereinafter referred to as DWS19 Wave Buoy. The diameter of the wave buoy was 0.9m, powered by solar energy. The collected wave data was transmitted back to shore based data center in every half hour by 4G (fourth generation) link. The water depth of the buoy site is about 15 m. There is a gravity-acceleration-type DWR-MKIII Waverider buoy was deployed by the South China Sea Branch of the State Oceanic Administration, the straight-line distance between the two buoys was about 150m (Figure 10). DWS19 Wave buoy used the same mooring system as DWR-MKIII, which was composed of a buoyancy ball, an elastic cable, a nylon rope, and a grip anchor. The control cabin had a serious leakage ten days later because of a water tightness issue, so comparison test

was only carried out from 11 January to 21 January 2022 for about 10 days with a wave measurement interval of 30 min. A total of 473 simultaneous wave data were collected by two buoys. The significant wave height H_{m0} , the peak wave period T_p and the mean wave direction D_{mean} were used for the comparison purposes.

A time series and scatter plots of H_{m0} , T_p , D_{mean} were shown in Figures 11 and 12. Statistics of mean deviation and standard deviation of each parameter are shown in the Table 5. The wave height of DWR-MKIII Waverider is about 5% higher than DWS19 wave buoy, this bias may be due to that the DWR-MKIII Waverider has a better wave tracking performance in short waves. We have analyzed the hydrodynamic response of the DWS19 buoy using ANSYS AQWA software (Version 18.2) prior to the deployment. The response amplitude operator of heave can reach 1 only when the incident wave period is greater than 3 s, which means the current designed DWS19 wave buoy is not ideal for short-wave (< 3 s) measurement. The user manual of DWR-MKIII indicates that waves with a period of 1.5–30 s can be measured, so it is better than DWS19 buoy in short wave component measurement. Therefore, the wave height measurement of DWS19 may be slightly smaller than that of DWR-MKIII because the contribution of short waves is excluded. A review of the period series shows that the overall trend is almost the

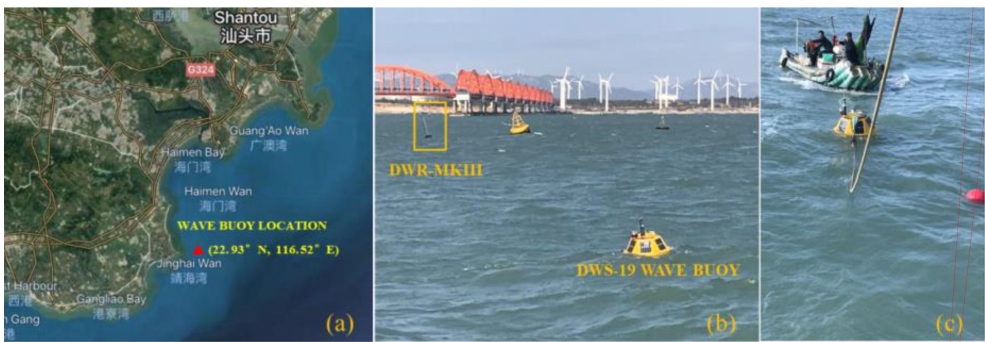


FIGURE 10 Filed comparison with DWR-MKIII wave buoy: (A) Filed comparison location. (B) Offshore comparison site. (C) Deployment of DWS19 Wave Buoy.

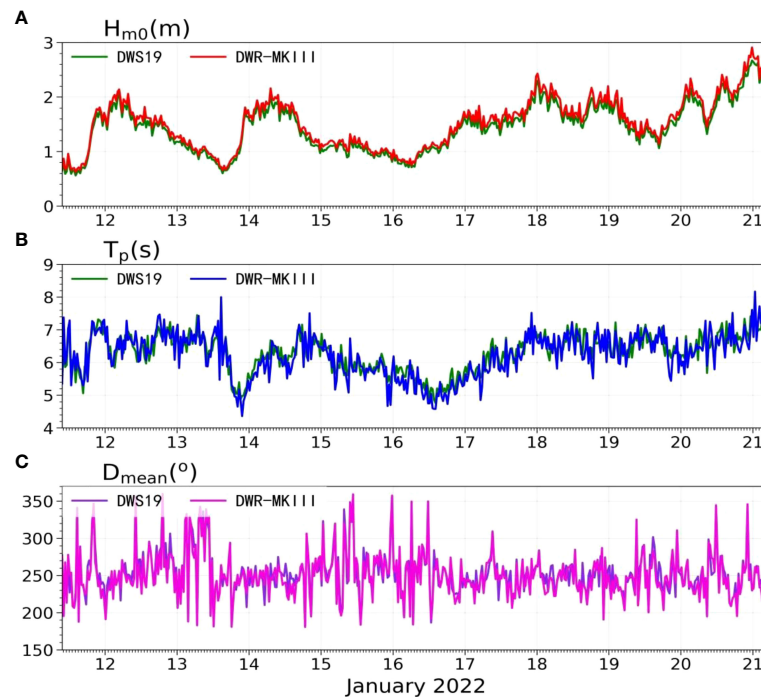


FIGURE 11
Time series of H_{m0} , T_p , D_{mean} observed by DWS19 buoy and DWR-MKIII.

same as the wave height, the overall mean deviation between DWS19 buoy and DWR-MKIII is 0.07s. The wave period increases or decrease with the wave height. Therefore, we can conclude that this sea area is dominated by wind wave during the comparison period. For the direction series reveals that the overall trend of DWS19 is in overall agreement with the DWR-MKIII with a mean deviation of 2° and standard deviation of 10° , the wave is coming from the southwest. But

during low wave height period, especially when the wave height is less than 1m, relatively larger direction differences are observed. We speculated that when the wave height is small, the DWS19 buoy with large mass has poor wave tracking performance, the pitch, roll and heavy of the buoy are correspondingly small. Therefore, the accuracy of wave direction calculated by these three parameters is poor during small wave height period.

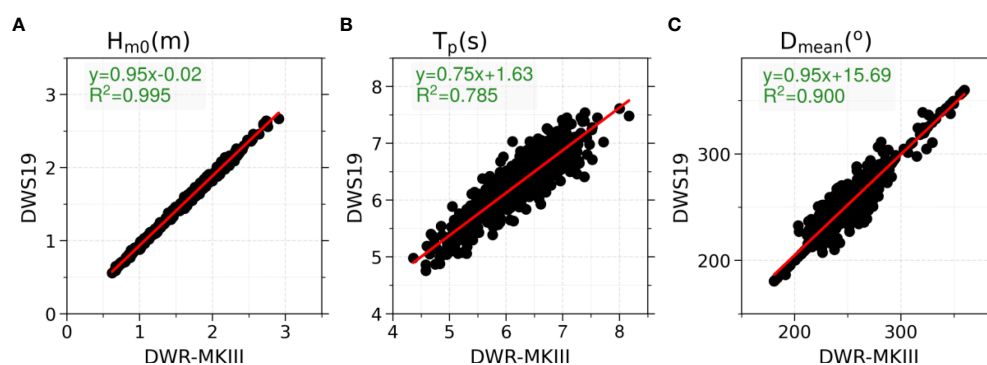


FIGURE 12
Scatter plots of H_{m0} , T_p , D_{mean} observed by DWS19 buoy and DWR-MKIII.

TABLE 5 Statistics of mean deviation(MD) and standard deviation (SD).

	$H_{m0}(m)$	$T_p(s)$	$D_{mean}(^{\circ})$
MD	-0.09	0.07	2.08
SD	0.10	0.32	10.21

Applications

Wave observation in the equatorial Indian Ocean

On October 16, 2020, researchers from the SCSIO deployed an air-sea coupling observation buoy (ASCOB_EIO) in the equatorial Indian Ocean (79.0°E, 2.0°N) at a depth of 4,100 m. The buoy was 3 m in diameter and equipped with a DWS19-2

wave sensor with a wave observation interval of 30 min. The real-time data were transmitted to the data center of the SCSIO with the Iridium and Bei Dou satellite communication link. By May 30, 2021, a total of 10,848 wave data sets, including wave height, period, and wave direction, had been obtained. The time series of $H_{1/3}$, H_{m0} , H_{avr} , $T_{1/3}$, T_{avr} and D_{mean} from ASCOB_EIO are given in Figure 13.

Wave observation in the South China Sea

On July 6, 2021, a 3 m diameter marine environment monitoring buoy (MEMB_ZH) was deployed by researchers from Sun Yat-sen University (SYU) at a water depth of 12 m in coastal Zhuhai (113.20°E, 21.55°N). The buoy transmits real-time data back to the SYU shore-based data center by a 4G link. The buoy was equipped with DWS19-2, with a wave sampling

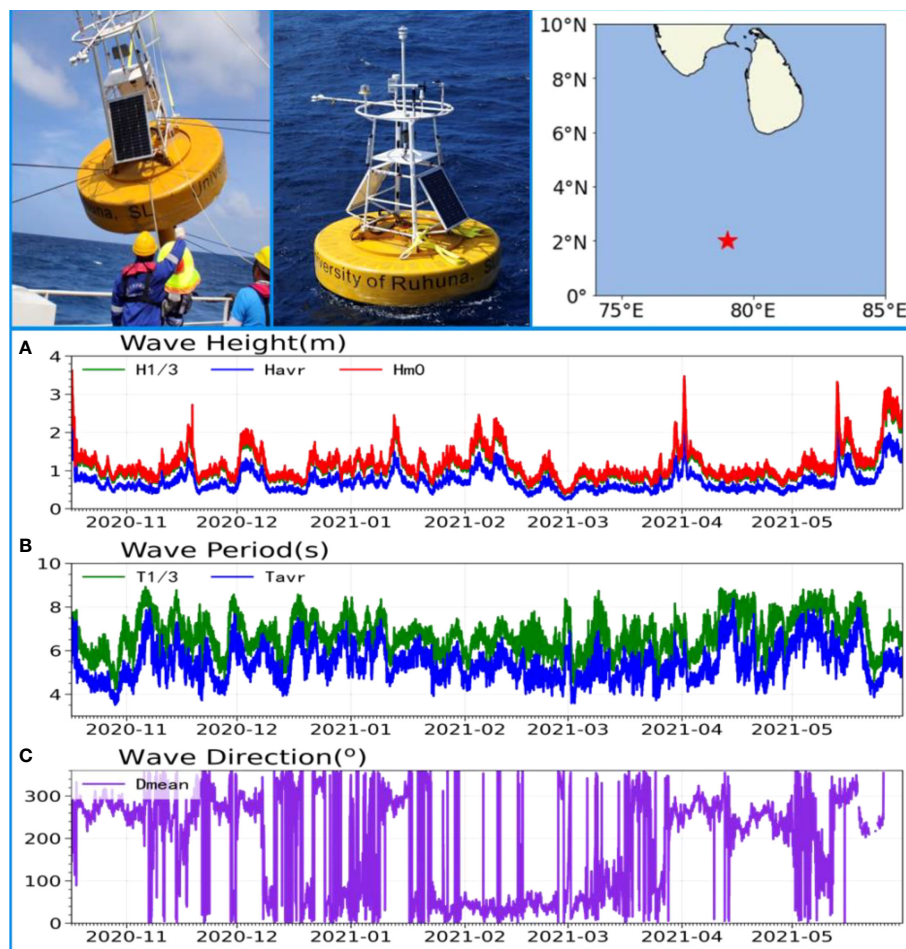


FIGURE 13
Wave observation in the Equatorial Indian Ocean.

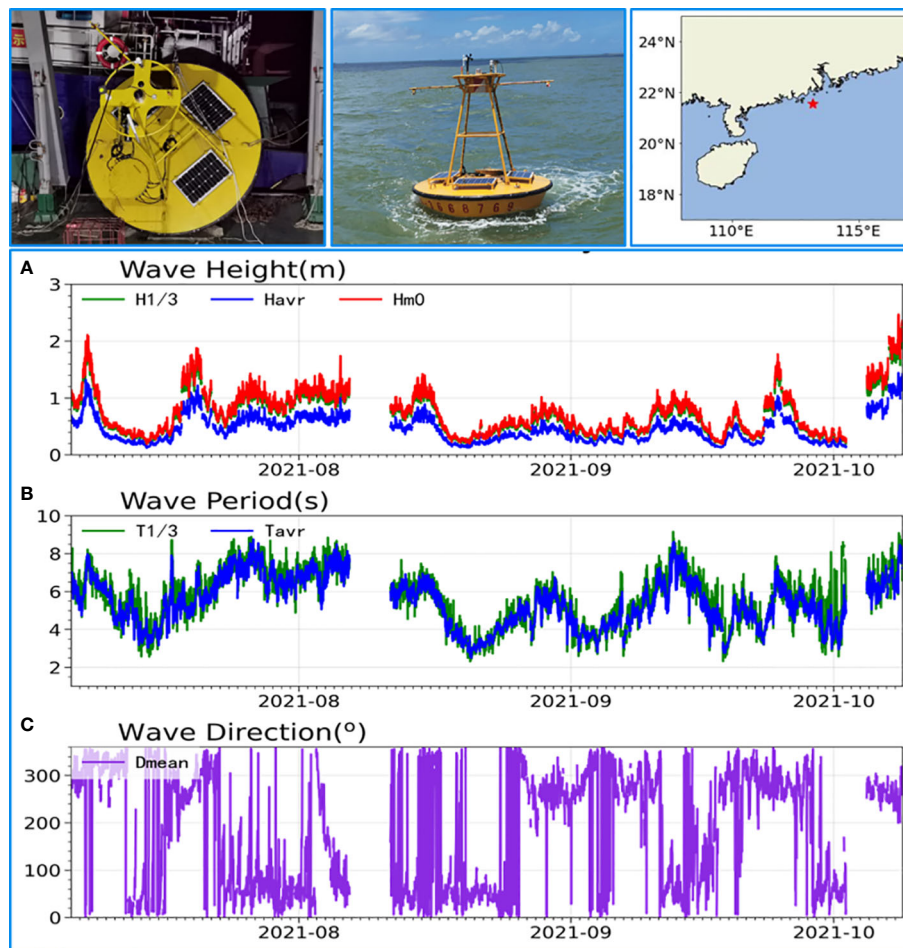


FIGURE 14
Wave observation in Zhuhai.

interval of 30 min. Notably, data were missing for approximately 5 days, from August 7 to 12, because of the failure of buoy control system. By October 8, 2021, 3,710 wave data sets, including wave height, period, and wave direction, had been obtained. The time series of $H_{1/3}$, H_{m0} , H_{avr} , $T_{1/3}$, T_{avr} , and D_{mean} from MEMB_ZH are given in Figure 14.

On June 23, 2021, 1.5 m diameter ocean dynamic observation buoys (ODOB_ZJ) were deployed by Guangdong Ocean University (GOU) at a depth of 10 m in coastal Zhanjiang (109.0°E, 20.0°N). The buoy was equipped with DWS19-2 and transmits real-time data to the GOU shore-based data center. The wave sampling interval was 10 min. By November 8, 2021, a total of 20,016 wave data sets, including wave height, period, and wave direction, had been obtained. The time series of $H_{1/3}$, H_{m0} , H_{avr} , $T_{1/3}$, T_{avr} , and D_{mean} from ODOB_ZJ are given in Figure 15.

On September 22, 2021, a 0.6 m diameter surface drifter equipped with DWS19-2 was dropped by researchers from the

SCSIO at a depth of 3,700 m in the northern South China Sea (115.08°E, 17.34°N). The wave sampling interval was 1 h. The real-time data were sent back to the SCSIO data center by the Bei Dou communication link. By November 9, the buoy had drifted to coastal southern Vietnam, and a total of 925 wave data sets had been collected. The time series of $H_{1/3}$, H_{m0} , H_{avr} , $T_{1/3}$, T_{avr} , and D_{mean} are given in Figure 16. Notably, data were missing for approximately 3 days, from October 16 to 19, because of the failure of the satellite communication link. At 11:00 a.m. on October 16, the drifter was located in the influence wind circle of the Kompas typhoon, and the 6.94 m significant wave height was measured.

Conclusions

DWS19-2 is a small-sized inertial wave sensor with low power consumption developed by SCSIO, CAS. The onboard

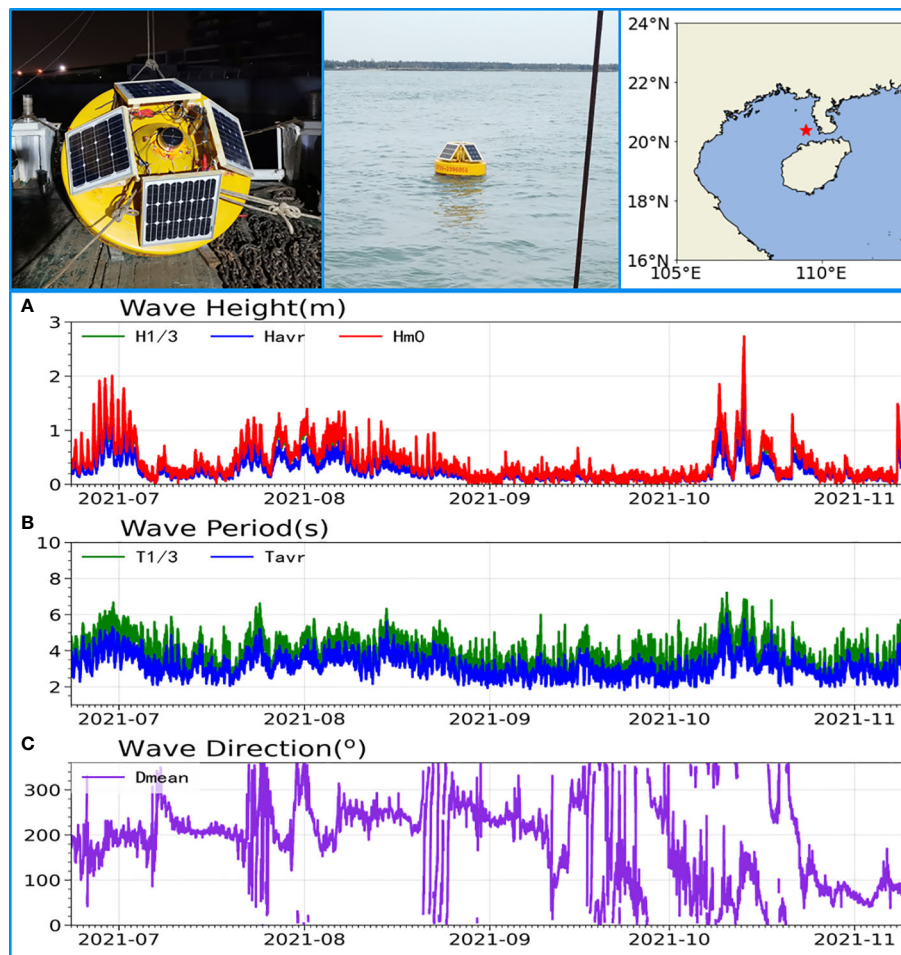


FIGURE 15
Wave observation in Zhanjiang.

data processing algorithms include coordinate projection, acceleration-displacement numerical integration, time wave parameters by the zero-crossing method, frequency wave parameters by the power spectrum method, and the estimation of the directional wave spectrum. Seven different periods of testing at heights of 1 m, 3 m, and 6 m were performed on the wave simulation turntable of NCOSM. In addition, the on-site comparison with the wave rider DWR-MKIII buoy was also completed at the beginning of 2022. Based on the results of the turntable test and filed comparison, DWS19-2 featured high measurement accuracy, a small size, low power consumption, and reliability in marine environments. It offered an innovative method for wave measurement in some mobile and portable applications. Following are the author's conclusions:

1. Digital stabilization technology was applied for real-time coordinate projection, thus eliminating the dependence on mechanical/electrical stabilization mechanisms. DWS19-2 is small in size and easy to install, which could effectively increase the measurement accuracy in dynamic wave environments.
2. In terms of acceleration-displacement integration, compared with time-domain numerical integration, frequency-domain integration performed better in suppressing the integral drifting errors caused by DC acceleration deviation.
3. The significant wave height obtained by the power spectrum method was 5% to 8% larger than that obtained by the zero-crossing method, which is also consistent with previous research.

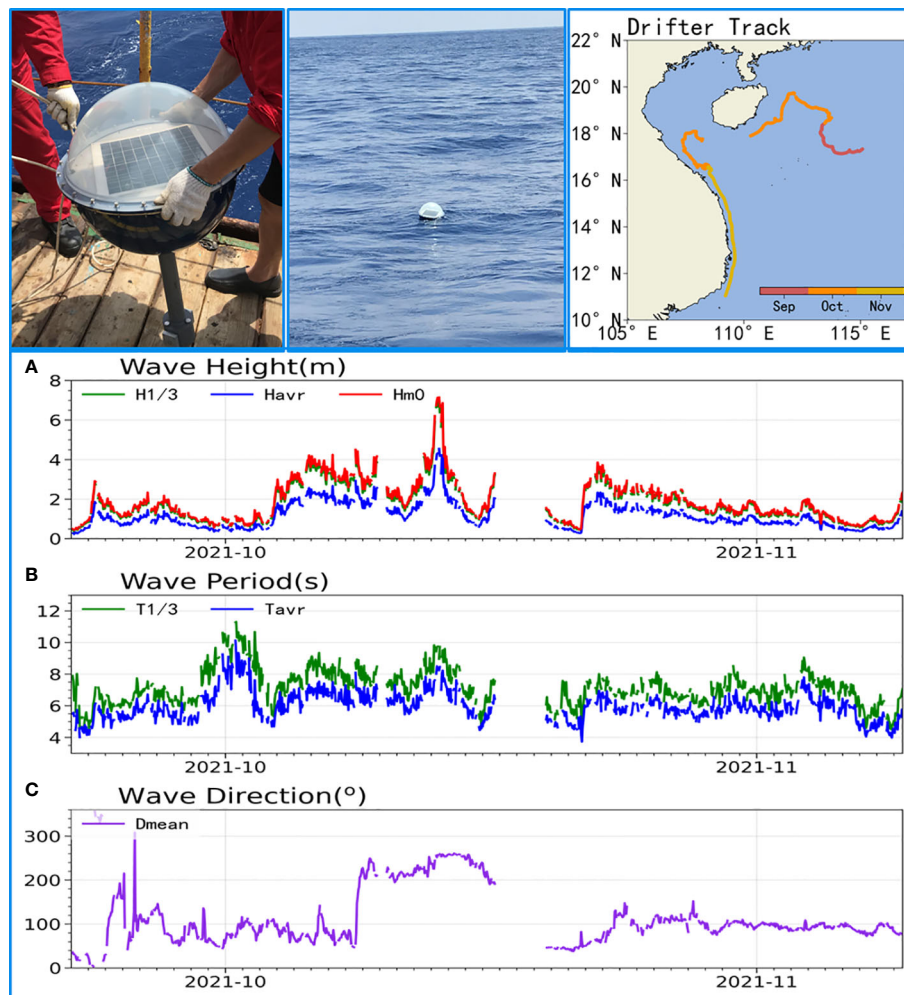


FIGURE 16
Wave observation by a drifter in the South China Sea.

4. According to the wave simulation test on the standard turntable, high measurement accuracy of the wave height ($< \pm 2\%$) and wave period ($< \pm 0.05$ s) was obtained by DWS19-2, reaching the excellent measurement index level. The results of filed comparison with DWR-MKIII wave buoy show that the mean deviation of H_{m0} and T_p are -0.09 m and 0.07 s respectively. The mean deviation and standard deviation of wave direction is 2.08° and 10.21° respectively.
5. Wave observations from anchored buoys in the Equatorial Indian Ocean, coastal Zhuhai, coastal Zhanjiang, and drifters in the South China Sea revealed that DWS19-2 is suitable for various types of marine platforms with stable and reliable performance in harsh marine environments.

Data availability statement

All the data used in the article can be obtained by email to zhoufh@scsio.ac.cn. We will also post all the data in this paper on the data center website of SCSIO (South China Sea Institute of Oceanology, Chinese Academy of Sciences, <http://data.scsio.ac.cn/>).

Author contributions

Conceptualization: FZ. Methodology: FZ and SZ. Hardware design: FZ. Algorithm design and simulation: FZ and RZ. Software coding: FZ and RZ. Turntable test: SZ. Filed comparison: FZ, SZ and RZ. Writing-review and editing: FZ, SZ and RZ. Project administration: FZ. Funding acquisition: FZ. All authors have read and agreed to the published version of the

manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Boccotti, P. (2000). *Wave mechanics for ocean engineering* (Amsterdam; New York: Elsevier Science).
- Datawell, B. V. *Home of the waverider*. Available at: <http://www.datawell.nl/> (Accessed 29 November 2021).
- Dean, R. G., and Dalrymple, R. A. (1991). *Water wave mechanics for engineers and scientists* (Singapore: World Scientific).
- Doong, D. J., Lee, B. C., and Kao, C. C. (2011). Wave measurements using GPS velocity signals. *Sensors. (Basel)*. 11, 1043–1058. doi: 10.3390/s110101043
- Fong, W. T., Ong, S. K., and Nee, A. Y. C. (2008). Methods for in-field user calibration of an inertial measurement unit without external equipment. *Meas. Sci. Technol.* 19, 85202. doi: 10.1088/0957-0233/19/8/085202
- Lee, S. G., and Lee, M. T. (1996). Integration of measured acceleration to determine the vibration characteristics of bridges. *Comput. Struct. Eng.* 9, 107–115.
- Longuet-Higgins, M. S. (1952). On the statistical distribution of the height of sea waves. *J. Mar. Res.* 11, 245–266.
- Longuet-Higgins, M. S. (1980). On the distribution of the heights of sea waves: Some effects of nonlinearity and finite band width. *J. Geophys. Res. Oceans*. 85, 1519–1523. doi: 10.1029/JC085iC03p01519
- Longuet-Higgins, M. S. (1985). Accelerations in steep gravity waves. *J. Phys. Oceanogr.* 15, 1570–1579. doi: 10.1175/1520-0485(1985)015<1570:AISGW>2.0.CO;2
- Marin-Perianu, M., Chatterjea, S., Marin-Perianu, R., Bosch, S., Dulman, S., Kininmonth, S., et al. (2008). “Wave monitoring with wireless sensor networks,” in *2008 international conference on intelligent sensors, sensor networks and information processing* (Sydney, NSW, Australia: IEEE), 611–616.
- Pang, G., and Liu, H. (2001). Evaluation of a low-cost MEMS accelerometer for distance measurement. *J. Intell. Robot. Syst.* 30, 249–265. doi: 10.1023/A:1008113324758
- Qi, Z., Li, S., Li, M., Dang, C., Sun, D., Zhang, D., et al. (2019). Research on the algorithm model for measuring ocean waves based on satellite GPS signals in China. *Sensors. (Basel)*. 19, 541. doi: 10.3390/s19030541
- Ribeiro, J. G. T., Freire, J. L. F., and Castro, J. T. P. (1999). Some comments on digital integration to measure displacements using accelerometers. *Shock Vib. Dig.* 32, 52.
- Rong, T., Shen, C., Yuan, Z., and Xu, S. (2000). Principle of measuring the displacement with accelerometer and the error analysis. *Huazhong. Ligong. Daxue. Xuebao/J. Huazhong. (Cent. China)*. 28, 58–60.
- TRIAXYS Directional wave buoy. Available at: https://axystech.wpengine.com/?page_id=5314/ (Accessed 22 November 2021).



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Sensitivity analysis of seismic attributes and oil reservoir predictions based on jointing wells and seismic data – A case study in the Taoerhe Sag, China

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It is important to identify the location of gravelly sandstone in Taoerhe Sag, an oil target area in the Chezhen Depression. To date, most attention has focused on sedimentary characteristics; hence, information regarding a clear sensitivity analysis of seismic attributes is incomplete. To address this, we used well analysis and seismic attribute interpretation to find sensitive seismic attributes and sand bodies. Based on the well analysis and core data, a geological model of mudstone and sandstone was established, and the electrical characteristics of three kinds of lithology were identified. We used correlation analysis to select the optimal logging parameters and seismic attributes to identify sandstone. We used multi-attribute fusion technology and stratigraphic slices to characterize the spatial distribution characteristics of gravelly sandstone in the target area and used genetic algorithm inversion volume to evaluate the prediction results. The results indicate that the three main lithologies of the lower submember of Shahejie Formation 3 ($P_2S_3^X$) in the Taoerhe Sag can be distinguished by natural gamma (GR), acoustic time difference (AC) and saturated hydrocarbon content (SH) logging curves. The seismic attribute characteristics of gravelly sandstone of $P_2S_3^X$ are high root mean square amplitude (RMS) values, high instantaneous bandwidth (BW) values, low 3D curvature (Curv) values, medium-high instantaneous phase (Phase) values and high instantaneous frequency (Freq) values. In this study, we found two nearshore underwater fans in $P_2S_3^X$. Gravelly sandstone is located along the slope zone and the lake bottom, with a total sedimentary area of 57.9 km². The method summarized in this paper can be applied to other similar deep-water basins.

KEYWORDS

sensitive attribute, attribute fusion, genetic algorithm inversion, lithology recognition, heatmap analysis

1 Introduction

Most oil and gas reserves in deep-sea basins are stored in sandstones. We can determine the lithological characteristics of a point through drilling. However, drilling cannot accurately depict the horizontal distribution of sandstone. A variety of methods, however, have been proposed to determine this distribution (Simon et al., 2018). In some cases, geochemical methods such as the diagenesis of sandstone in the early stage of oil and gas exploration provide guidance (Primmer et al., 1997). Additionally, with the development of seismic exploration technology, sequence methods, such as sequence analysis (Galloway, 2012) and sequence stratigraphy (Edwards, 1994; Johannessen et al., 1995), have been regularly applied to sandstone prediction. For instance, Galloway (2012) and others applied the sedimentary system and sequence analysis of clastic rocks to reservoir prediction (Galloway, 2012). Sequence stratigraphy has played a great role in sandstone prediction in the “Brent Delta” and the Gulf Coast Basin (Edwards, 1994; Johannessen et al., 1995). Computer technology promotes the application of imaging technology and geophysical inversion in reservoir prediction (Nisar et al., 2022). Using interlayer and window seismic attribute technology, the geometric structure of gas-bearing deep-water sandstone and other reservoirs in the Veracruz Basin, Mexico, can be clearly displayed (Fouad et al., 2002). Furthermore, a variety of inversion methods have improved the vertical resolution of sandstone prediction, such as band-limited inversion (Ferguson and Margrave, 1996), geostatistical inversion (Lamy et al., 1999) and waveform phase-controlled inversion (Xu and Greenhalgh, 2010). The seismic sedimentation method (Zeng et al., 2007), neural network analysis method (Abdullatif and Sitouah, 2011), RGB fusion analysis method (Zhang et al., 2011), and fuzzy logic method (Baouche and Nabawy, 2021) offer a theoretical basis for horizontal sand-body prediction. Seismic sedimentology is the main method discussed in this paper. This method has been successfully applied to other basins (Ge et al., 2018). For instance, the application of seismic sedimentology to sandstone prediction in the Pearl River Mouth Basin has achieved good prediction results (Ge et al., 2018).

It is not difficult to find that with the development of imaging technology, the methods of predicting sandstone in paleostrata are constantly updated. This paper utilizes seismic sedimentology, especially the seismic attribute method. It is worth mentioning that the types of predicted seismic attributes of sandstone are increasing. A variety of seismic attributes allows for different perspectives in observing underground rocks. However, this variety lead to multiple interpretations of the results. How to choose the appropriate seismic attributes is a challenge that needs to be addressed. This paper takes the Taoerhe Sag as an example to study how

to choose the appropriate seismic attributes to predict sandstone locations.

Taoerhe Sag belongs to the secondary geological unit of the Chezhen Depression. The exploration results in recent years show that the third member of the Shahejie Formation of Paleogene age has oil and gas resources, but it is not rich (Du et al., 2021). Defining the distribution of reservoirs and deploying new wells is the key to discovering new reserves. The sand body in the Taoerhe Sag has rapid, lateral changes; sandstone and mudstone are alternately distributed; and the sandstone thickness is thin (Zhang et al., 2010), creating substantial challenges for sandstone characterization and reservoir prediction. Most previous studies on sand-body and reservoir prediction have drawn conclusions based predominantly on drilling data (Yang et al., 2020; Jfa et al., 2021); few seismic prediction methods have also applied experience to describe sand bodies and have not provided a clear sensitivity analysis of seismic attributes. Therefore, prediction accuracy remains to be examined.

To accelerate the exploration process of the Taoerhe Sag and increase its reserves, the author carried out sandstone and reservoir prediction research on the third member of the Shahejie Formation (P_2S_3) in this area. To address sandstone and reservoir prediction challenges faced by P_2S_3 in the Taoerhe Sag, the sensitive parameters for predicting thin sandstone, including logging parameters and seismic attributes, were optimized *via* log analysis and correlation analysis. Seismic sedimentology theory was used to guide the spatial distribution of sandstone and reservoirs in the lower submember of Shahejie Formation 3 ($P_2S_3^X$) of the Taoerhe Sag. Two nearshore underground fans and five gravelly sandstone distribution areas in $P_2S_3^X$ of the Taoerhe Sag were predicted. This research achieved good exploration results and application effectiveness and is applicable to the whole Chezhen Depression.

In the following sections, we introduce the geological setting in the Taoerhe Sag in section 2, including the location, area and strata. In section 3, we describe the data and methods used in this paper. In section 4, we summarize the logging characteristics of rocks and conduct correlation analysis, extract 10 types of seismic attributes and conduct correlation analysis. Then, we interpret the seismic attributes by slices. In section 5, we discuss the results from section 4 with the help of multi-attribute fusion technology and genetic algorithm inversion. These two technologies are explained in section 3 and section 5. Finally, we obtain reliable conclusions based on seismic attribute interpretation and well analysis.

2 Geological overview of the study area

Taoerhe Sag (Figure 1), located in the middle of the Chezhen Depression and north of the Jiyang Depression (Zeng et al., 2008), is our target spot. It comprises approximately 450 km² (Wang et al., 2007). The study area in this paper is approximately 212.24

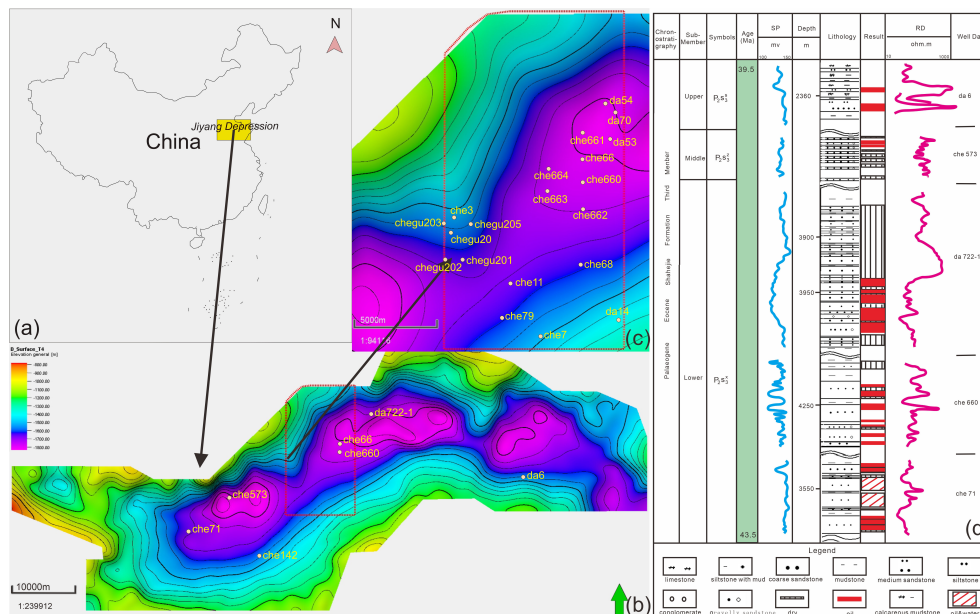


FIGURE 1

Geographic location of the study area. (A) Map of China. The yellow box is the Jiyang Depression. The Chezheng Depression is a part of the Jiyang Depression. (B) Structural map of the Chezheng Depression. The red dotted box is the location of the Taoerhe Sag. (C) Structural map of the Taoerhe Sag. There are 20 wells on the picture. (D) Stratigraphic and lithologic histogram of the third member of the Shahejie Formation in the Taoerhe Sag.

km². The depression presents as an ellipse on the plane. Drilling results in 2005 indicated abundant oil and gas in the third member of the Shahejie Formation, represented by Well Che 66 (Zeng et al., 2010). However, there was no oil or gas in the same layer in Well Che 661 near Well Che 66 (Zeng et al., 2010). This indicates that the geological conditions in this area are complex and that the distribution of oil and gas is characterized by strong heterogeneity.

Structurally, normal faults are developed in the southern part of the depression, and small northwest–southwest-trending faults are locally developed. In general, faults in the depression are not developed, and only faults around the depression are developed (Wang et al., 2007). Stratigraphically, the Cenozoic strata of the Taoerhe Sag include Quaternary, Neogene and Paleogene strata (Li et al., 2018). The target horizon is the third member of the Shahejie Formation of Eocene age. The sediment thickness of the Shahejie Formation is generally more than 200–1000 m (Du et al., 2021). The lithologies of the third member of the Shahejie Formation include dark gray to gray black oil mudstone, oil shale and siltstone, which can be divided into upper ($P_2S_3^S$), middle ($P_2S_3^Z$) and lower members ($P_2S_3^X$) (Zeng et al., 2008; Zhang et al., 2010; Yang et al., 2020; Jfa et al., 2021). In this study, the attribute sensitivity is examined by taking $P_2S_3^X$ as an example. The main lithologies of the lower part of the third member of the Shahejie Formation are mudstone, calcareous oil mudstone and gravelly sandstone; the sediments in the middle part are mainly clay rock, pure mudstone, shale and oil shale; and the sediments in upper part

are oil mudstone, oil shale, siltstone and carbonate rock (Zhang et al., 2010; Yang et al., 2020; Jfa et al., 2021). In terms of sedimentation, the gravelly sandstone body in the study area is thin and widely distributed (Zeng et al., 2008; Zhang et al., 2010; Yang et al., 2020; Jfa et al., 2021). The third member of the Shahejie Formation represents the peak of the development of the faulted lake basin. The climate is humid, and gravelly sandstone fans have developed along the lake bank (Yang et al., 2020).

3 Data and methods

3.1 Data

The study area is 212.24 km², covering seismic data, and there are 22 wells in the study area. All data are from the Shengli oil field in China. Seismic data were collected in 2014. The bin grid is 15 m*30 m, the number of coverages is 288, and the horizontal to vertical ratio is 0.54 (Zhao, 2017). The main frequency range of the processed seismic data is 10–35 Hz (Figure 2). The average velocity of the formation below 3000 m in the study area is 3247 m/s (Zhao, 2017), and the seismic resolution is approximately 40 m. The applied logging curves include the natural gamma curve (GR), acoustic time difference curve (AC), density curve (DEN), spontaneous potential curve (SP) and saturated hydrocarbon content (SH).

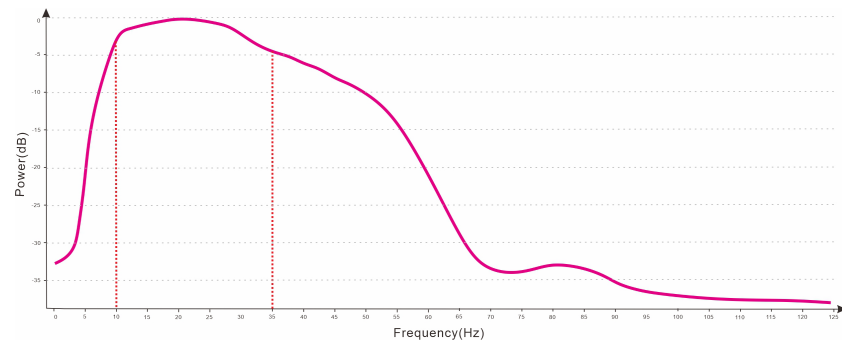


FIGURE 2

Spectral analysis of the seismic data volume in the Taoerhe Sag. The main frequency range is 10~35 Hz. The high frequency range is 70~85 Hz.

The target stratum of the study is the lower submember of Shahejie Formation 3 ($P_2S_3^X$).

3.2 Methods

As indicated in the introduction, there are two problems that must be solved in this paper. The first problem is the selection of the appropriate seismic attributes. The second problem is the prediction of the thin sandstone of $P_2S_3^X$ in the Taoerhe Sag. The two problems are progressive. Only by selecting the appropriate seismic attributes can we accurately determine the distribution of sandstone in the study area. The research steps can be divided into six steps to solve these two problems (Figure 3). The most critical step is Step 4. We will describe Step 4 in detail.

Step 4 contains three processes, of which Step a means to extract appropriate seismic attributes. Extracting seismic attributes for the first time requires the “expert optimization method” (Zhao, 2016), that is, extracting seismic attributes according to the experience of geophysical experts. In this paper, sand-body prediction is needed. Therefore, 10 seismic attributes related to sand bodies are extracted based on experience, such as the root mean square amplitude attribute (RMS), instantaneous phase attribute (Phase), and instantaneous frequency attribute (Freq) (Dongjun et al., 2006). However, all of these 10 seismic attributes will not necessarily be used for the final sand-body prediction. These attributes need to be screened, which occurs during Step c, when the seismic attributes are filtered. Step b summarizes the characteristics of sandstone on the logging data and its sensitive parameters. Generally, the characteristics of sandstone based on the loggings are as follows: “bell shaped” or “box shaped”, low GR, and medium - high AC. In addition, when compared with the surrounding rocks, sandstone is mainly characterized by low velocity and low DEN (Collett et al., 2011).

In this paper, the crossplot of the logs and rocks are made, and the logging curves with obvious differentiation are selected for further research.

Choosing the appropriate seismic attribute (Step c) is a primary focus of this paper. In the process of seismic reservoir prediction, various seismic attributes related to the reservoir are usually introduced. However, more attributes are not better, as they lead to data redundancy and multiple solutions. Hence, for the specific problem of reservoir prediction, it is very important to select the one attribute that can best express the reservoir characteristics. Seismic attribute optimization (Step c) in this paper includes two secondary steps. The first step is to analyze the correlation between attributes. We next introduce how to analyze the correlation between attributes.

The correlation between two attributes is measured by the correlation coefficient. The correlation coefficient is a digital expression of the degree of correlation between two variables (Barnes, 2007). It is an index used to express the strength of the correlation relationship (Barnes, 2007). The sample correlation coefficient is expressed in R , and the value is generally between -1 and 1 (Barnes, 2007). 1 is the largest positive correlation, 0 is irrelevant, and -1 is the largest negative correlation. In the optimization of seismic attributes, the greater the absolute value of the correlation coefficient between the two is, the higher the degree of correlation; the smaller this value is, the lower the degree of correlation (Barnes, 2007). If the reservoir characteristics expressed by the two seismic attributes are similar, information redundancy and interference occurs in the seismic attribute analysis. Therefore, we can select one of the seismic attributes with a correlation greater than 0.7. The correlation coefficient calculation formula (Barnes, 2007) is as follows:

$$R = \frac{\sum (X - \bar{X})(Y - \bar{Y})}{\sqrt{\sum (X - \bar{X})^2 \sum (Y - \bar{Y})^2}} = \frac{l_{xy}}{\sqrt{l_{xx}l_{yy}}} \quad (1)$$

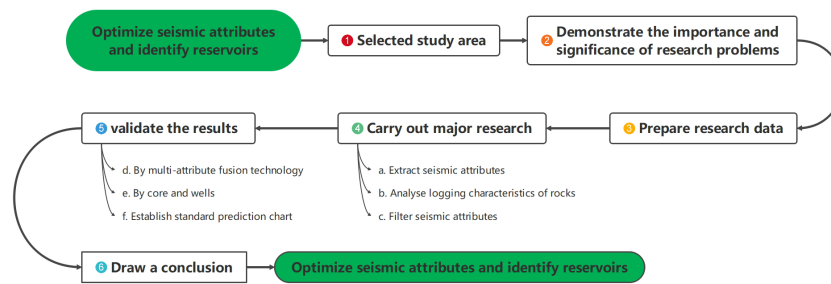


FIGURE 3
Research flow chart.

where X and Y are the values of the two seismic attributes and $\bar{X}$ and $\bar{Y}$ are the average values of X and Y , respectively. The correlation degree is found in Table 1 (Barnes, 2007).

The second step of Step c is to use the seismic attributes selected in the previous step and the logging parameters to implement crossplot analysis; the seismic attributes with good correlation are left. Seismic attributes with good correlation are used for sandstone and reservoir prediction. Among them, the logging parameters sensitive to sandstone are obtained in Step b.

We can find some information by interpreting seismic attribute slices. However, if we confirm that the results are correct, we need to provide more evidence. Hence, we should validate the results *via* Step 5, including Step d and Step e. For Step d, we use multi-attribute fusion technology to interpret gravelly sandstone. Multi-attribute fusion technology in this paper can be carried out using the following workflow. First, we take a certain attribute slice as the background. Then, we set the transparency of the slice. In addition, we overlay other attribute slices to display more information. This slice is also set to transparency. The transparency is approximately 30% - 50%. Step e involves comparing the results to cores and wells. In this step, we apply genetic algorithm inversion to improve accuracy. When we process genetic algorithm inversion, the input data are issued. Step b indicates which logging parameters can be inverted. We realize genetic algorithm inversion *via* software named Petrel. Step f in Step 5 refers to the establishment of a comparison chart based on the selected

seismic attributes and logging parameters, including seismic attributes, logging curves, and reservoir parameters. The chart can be used for reservoir predictions of other blocks in the work area. This part is explained in the Discussion.

4 Results

4.1 Log analysis (logging characteristics of rocks)

Using the data from 22 wells in the Taoerhe Sag, the lithologic, electrical and logging characteristics of $P_2S_3^X$ are analyzed. There are three main lithologies in $P_2S_3^X$ in the Taoerhe Sag: medium conglomerate, mudstone and calcareous oil mudstone.

Taking Well Che 66 as an example, the depth of calcareous oil mudstone in Figure 4 is 4323.9~4329.0 m, and the thickness is 5.1 m. The GR value of calcareous oil mudstone is 45.4~67.0 API, with an average of 53.0 API. The AC of calcareous oil mudstone is 59.3~67.5 μ S/ft (1 ft = 30.48 cm), with an average of 61.7 μ s/ft. The saturated hydrocarbon content (SH) of calcareous oil mudstone ranges from 4.7 to 24.4, with an average value of 10.1. The resistivity (RD) ranges from 168.7 to 268.6 ohm.m, with an average of 226.9 ohm.m (Table 2).

The thicknesses of the gravelly sandstone in the two sections are 3.4 m and 6 m (Figure 4). The average GR value of gravelly sandstone is 27.1 API. The average value of AC is 57.9 μ s/ft. The average SH is 4.6. The average RD range is 211.3 ohm.m (Table 2).

The depth of the mudstone is 4357.3~4359.4, and the thickness is 2.1 m. The average GR value of mudstone is 87.7 API. The average value of AC is 80.6 μ s/ft. The average SH of gravelly sandstone is 78.1. The average RD range is 74.5 ohm.m (Table 2).

We counted the data from 22 well logs and found that the lithologic and electrical characteristics of the lower Sha 3

TABLE 1 Classification standard of correlation degree (Barnes, 2007).

Absolute value of R	Degree of relevance
0~0.2	Extremely low correlation
0.2~0.4	Low correlation
0.4~0.7	Moderate correlation
0.7~0.9	Height correlation
0.9~1.0	Polar height correlation

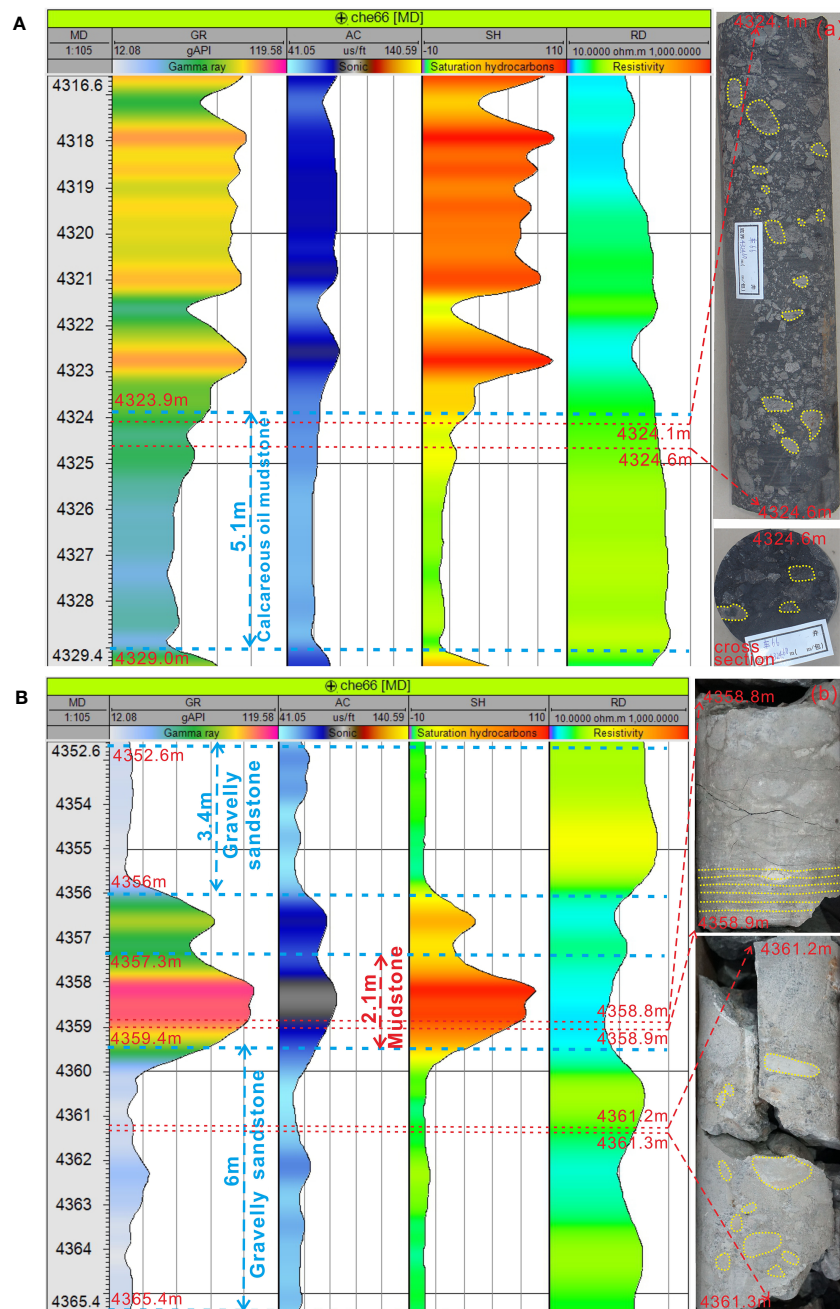


FIGURE 4

Logging curve characteristics and core characteristics of Well Che 66. (A) Calcareous oil mudstone of Well Che66 is at 4323.9–4329.0 m. The core is calcareous oil mudstone, which is dark. The yellow dotted circle on the core picture is the calcite mud crystal. The core depth is 4324.1–4324.6 m. The core can be related to the logs by depth. (B) Gravelly sandstone of Well Che66 is 4352.6–4356.0 m and 4359.4–4365.4 m. Mudstone of Well Che66 is in 4357.3–4359.4 m. The core depth is 4358.8–4358.9 m (mudstone) and 4361.2–4361.3 m (gravelly sandstone). The core can be related to the logs by depth. The yellow dotted line on the core picture is the horizontal texture during mudstone deposition. The lithology is used as the intersection background. The crossplot indicates that for the Taoyerhe Sag, GR can only be selected if gray oil mudstone and gravelly sandstone are to be distinguished. If we want to distinguish calcareous oil mudstone and mudstone, we can choose GR, AC, or SH. If we want to distinguish mudstone from gravelly sandstone, we can choose GR, AC, or SH. In conclusion, GR can better distinguish lithology.

TABLE 2 Lithology and electricity comparison data of the lower Sha 3 subsection of Well Che 66.

Logging parameters lithology	Depth (m)	GR (API)		AC ($\mu\text{s}/\text{ft}$)		SH		RD (ohm.m)	
		value	average	value	average	value	average	value	average
gravelly sandstone	4351~4355.4	21.9~30.5	25.6	52.7~64.6	57.6	2.6~6.4	4.3	175.7~356.8	259.3
gravelly sandstone	4360~4365	22.2~37.3	28.4	52.6~66	58.4	2.7~8.4	4.8	95.3~232.3	169.0
mudstone	4317.6~4320.9	82.6~95.0	87.7	72.5~78.9	76.9	64.4~100	77.9	60.1~160.4	105.0
mudstone	4332.5~4333.9	82.3~96.4	90.6	72.1~83.4	80.1	65.5~100	86.6	72.8~93.7	79.3
mudstone	4340.9~4343.0	75.4~92.2	84.2	79.5~88.0	82.8	53.6~91.1	71.3	72.6~191.3	116.1
mudstone	4357.3~4359.4	77.2~104.5	95.7	72.7~85.7	80.6	44.1~98.5	78.1	62.5~102.2	74.5
calcareous oil mudstone	4323.9~4329.0	45.4~67.0	53.0	59.3~67.5	61.7	4.7~24.4	10.1	168.7~268.6	226.9

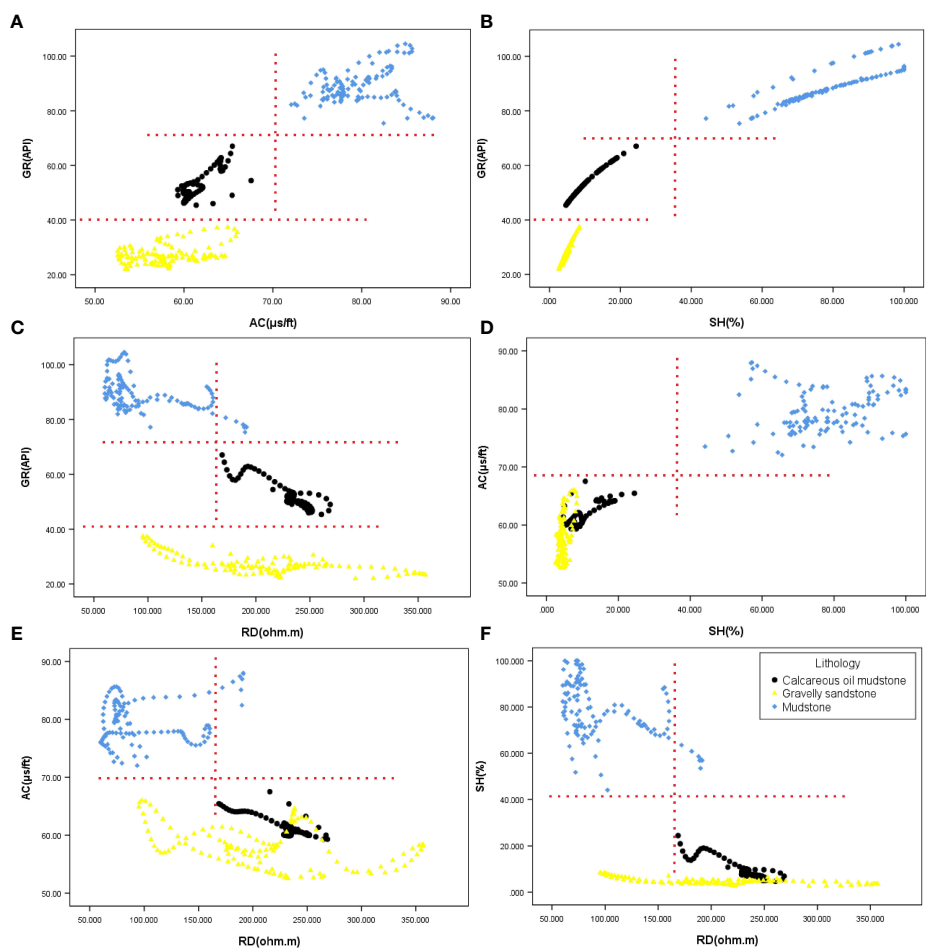


FIGURE 5 Well Che66 crossplot. (A) GR-AC crossplot; (B) GR-SH crossplot; (C) GR-RD crossplot; (D) AC-SH crossplot; (E) AC-RD crossplot; and (F) SH-RD crossplot. Figures (A–C) show that GR can effectively distinguish mudstone, calcareous oil mudstone and gravelly sandstone. Figure (A), Figure (D) and Figure (E) show that AC can distinguish between mudstone and calcareous oil mudstone and between mudstone and gravelly sandstone, but calcareous oil mudstone and gravelly sandstone overlap greatly in value range. Figure (B), Figure (D) and Figure (F) show that SH can distinguish between mudstone and calcareous oil mudstone and between mudstone and gravelly sandstone, but calcareous oil mudstone and gravelly sandstone overlap greatly in value range. Figure (C), Figure (E) and Figure (F) show that RD can only distinguish mudstone and calcareous oil mudstone. There are overlapping parts between 150 and 200 ohm.m. RD cannot distinguish mudstone from gravelly sandstone. RD cannot distinguish between calcareous oil mudstone and gravelly sandstone.

submember are consistent. Calcareous oil mudstone has medium gamma rays, low acoustic wave time difference, low SH and high RD. Gravelly sandstone is characterized by low GR, low AC, low SH and high RD. Mudstone is characterized by high natural gamma rays, high acoustic transit time, high SH and medium low RD.

The crossplot can clarify the differentiation of the above four electrical characteristics for lithology. Taking the well-logging data of $P_2S_3^X$ from Well Che 66 as an example, we completed the production of six kinds of crossplots: GR and AC, GR and SH, GR and RD, AC and SH, AC and RD, and SH and RD (Figure 5). Lithology is used as the intersection background. The crossplot indicates that for the Taorhe Sag, GR can only be selected if gray oil mudstone and gravelly sandstone are to be distinguished. If we want to distinguish calcareous oil

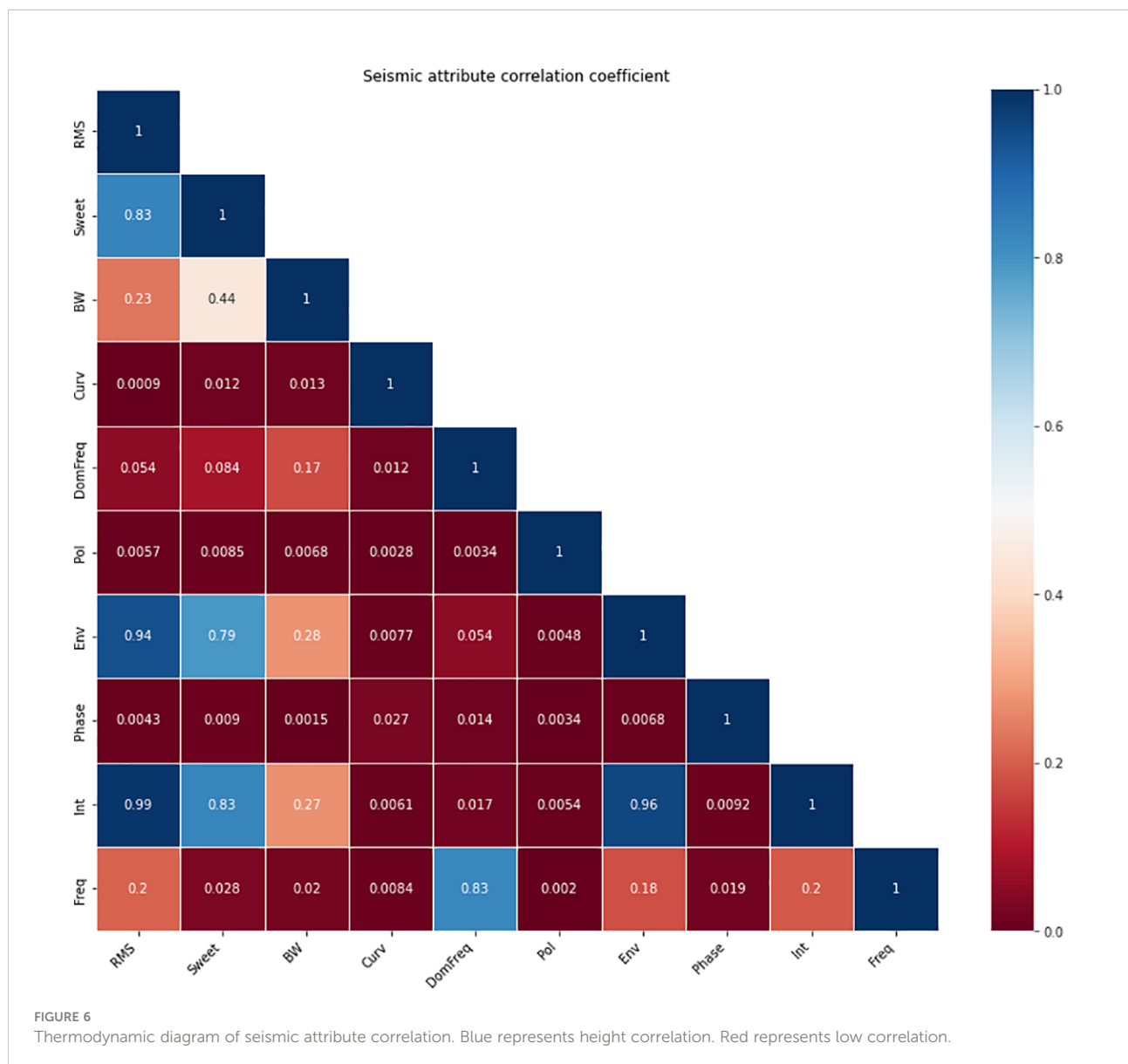
mudstone and mudstone, we can choose GR, AC, or SH. If we want to distinguish mudstone from gravelly sandstone, we can choose GR, AC, or SH. In conclusion, GR can better distinguish lithology.

4.2 Sensitivity analysis of seismic attributes

4.2.1 Correlation analysis of attributes

Three kinds of lithologies are distinguished by seismic attributes: gravelly sandstone, mudstone and calcareous oil mudstone.

Taking the lower segment of Sha 3 as an example, we calculated 10 volume attributes, including amplitude, energy



and frequency. These 10 seismic attributes are RMS, sweetness (Sweet), instantaneous bandwidth (BW), 3D curvature (Curv), dominant frequency (Domfreq), approximate polarity (Pol), envelope (Env), phase, reflection intensity (Int), and Freq.

Figure 6 shows the thermodynamic diagram of the correlation coefficient between seismic attributes; for example, the correlation coefficient of RMS and int is 0.99. According to Table 1, the two are highly correlated. One seismic attribute can be obtained by simple mathematical transformation, and the other can be retained. Similarly, referring to Table 1, if the

correlation of two attributes reaches 0.7, it is regarded as highly correlated, and only one of them is retained.

According to this method, four seismic attributes are removed, namely, Sweet, Env, Int and DomFreq. Six seismic attributes are retained, namely, RMS, BW, Curv, Pol, Phase and Freq.

4.2.2 GR crossplot of attributes and logging

The six seismic attributes are data bodies. We extracted the seismic attribute data from the well at the same sampling rate

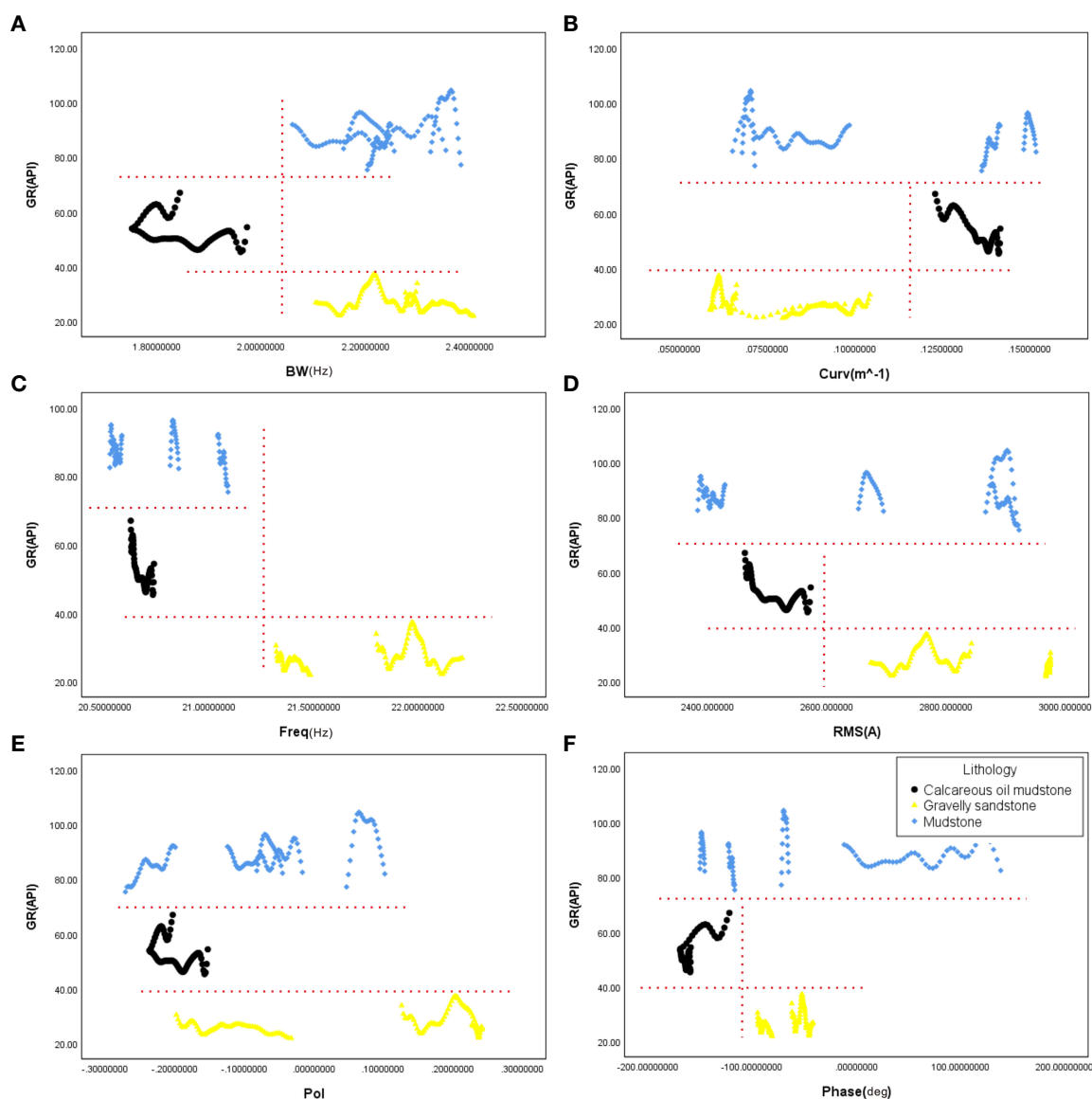


FIGURE 7

Well Che66 GR-Seismic attribute crossplot. (A) GR-BW crossplot; (B) GR-Curv crossplot; (C) GR-Freq crossplot; (D) GR-RMS crossplot; (E) GR-Pol crossplot; (F) GR-Phase crossplot.

(0.076 m) as the logging data. We used Petrel software to perform resampling. To verify the sensitivity of the retained six seismic attributes to lithology, GR data at the same depth and six seismic datasets were selected for intersection analysis (Figure 7). The intersection map shows that except for the pol attribute, the attributes have a certain degree of differentiation for lithology.

Among them, BW can recognize calcareous oil mudstone. The low value (<2.0 Hz) represents calcareous oil mudstone. The Curv can distinguish between calcareous oil mudstone and gravelly sandstone. Gravelly sandstone has a low value ($0.05\sim0.125$ m⁻¹), and calcareous oil mudstone has a high value ($0.125\sim0.15$ m⁻¹). Freq can recognize gravelly sandstone. High values (>21.5 Hz) represent gravelly sandstone. RMS can distinguish between calcareous oil mudstone and gravelly sandstone. Gravelly sandstone has a high value (>2600 a), and calcareous oil mudstone has a low value (<2600 a). The Pol attribute cannot distinguish the three lithologies in the study area, and the data coincidence degree is high. Phase can distinguish between calcareous oil mudstone and gravelly sandstone. Gravelly sandstone has a medium-high value ($-100\sim0$ deg), and calcareous oil mudstone has a low value (<-100 deg). In summary, high BW, Freq and RMS values represent gravelly sandstone; high BW and RMS values represent mudstone; and low Curv values represent both gravelly sandstone and mudstone. Therefore, when identifying gravelly sandstone, we can compare the above five attributes to obtain its distribution range.

4.2.3 Seismic attribute interpretation

The five attributes, RMS, BW, Curv, Phase and Freq, have a certain lithological differentiation. We first extract five stratigraphic attribute slices of the lower submember of Sha 3. On the RMS slice, the red and yellow areas with values greater than 2600 a (Figure 7D) are divided into gravelly sandstone. In the Curv attribute map, the brown area between 0.05 and ~0.125 m⁻¹ is divided into gravelly sandstone (Figure 7B). In the Freq plan, the high value area (red and yellow) greater than 21.5 Hz (Figure 7C) is divided into gravelly sandstone. In the phase diagram, the yellow and green parts of the $-100\sim0$ deg (Figure 7F) area are divided into gravelly sandstone. The TWT map (Figure 8F) shows that there is a river valley in the northern part of the work area, and the river carries sediment into the low-lying area in the middle part of the work area. It is difficult to see obvious valleys in the southern highland area of the work area, and whether there is an alluvial deposit needs to be determined in the discussion part.

Comparing the reflection results of the lithology on the five attribute maps, combined with the structural map of the study area, we believe that the nearshore underground fan (Figures 8A, B, D) was deposited in the northern part of the study area. The RMS, BW and Freq attributes can clearly distinguish the boundary of the fan. Gravelly sandstone is mainly distributed in the middle part of the fan and deep lake bottom of the slope zone, with a total area of

approximately 39.5 km². Curv and Phase can only recognize gravelly sandstone, but the sedimentary boundary of the fan is not obvious. In the Curv attribute graph, three gravelly sandstone blocks can be depicted. Units 1~3 (Figure 8C) are within the range of the nearshore underwater fan. Six gravelly sandstone blocks are identified in the phase attribute map. However, after comparison with the Freq attribute map, blocks 5 and 6 (Figure 8E) are ultimately not recognized as gravelly sandstone.

5 Discussion

To verify the correctness of the above attribute analysis results, we use multi-attribute fusion technology and genetic algorithm inversion.

When we use a single attribute to identify sandstone, there will be multiple results. In this way, multi-attribute fusion technology should be considered. In recent years, scholars have made significant progress in exploring multi-attribute fusion technologies or methods (Mcardle and Ackers, 2012; Maleki et al., 2019). RGB color blending is one method of multi-attribute fusion technology, which has been used to show subtle lithological changes (Mcardle and Ackers, 2012). In this paper, fusion is easy to achieve. We overlay two slices, and we set different transparencies to show more information from the two slices (Figures 9A, B).

The genetic algorithm (GA) was proposed by Professor J.H. Holland at the University of Michigan (Holland, 1992). GA is a randomized search method based on the evolutionary laws of the biological world (Holland, 1992). This algorithm can solve the optimal value (Holland, 1992). Genetic algorithm inversion has frequently been applied to deep-sea basin reservoir prediction. Chinese scholars took a central paddy sandstone reservoir in a deep-water area as an example and predicted the distribution characteristics of favorable reservoirs using the GA method, which greatly reduced the exploration risk (Huang, A. M., Li, L., 2011). GA can also be applied to calculate rock compressive strength (Xiong et al., 2021).

GR data and original seismic data are used as input for the genetic algorithm. The inverted data volume is then obtained. The GR curve and AC curve are projected on the seismic profile after inversion, and the coincidence between the two curves and the seismic inversion volume data is counted (Figure 9C). Both GR and AC of gravelly sandstone are low values. The GR and AC data from 22 well logs in the study area are compared. The coincidence between the borehole data and the inversion profile is more than 90%, thus, the reliability of the inversion body is high.

For the nearshore underwater fan in the study area, the distribution range of gravelly sandstone shown by the stratigraphic inversion volume slice of $P_2S_3^X$ is consistent with the conclusion obtained in Figure 8. The superimposed map of stratigraphic slices and structures (Figure 9A) clearly shows that

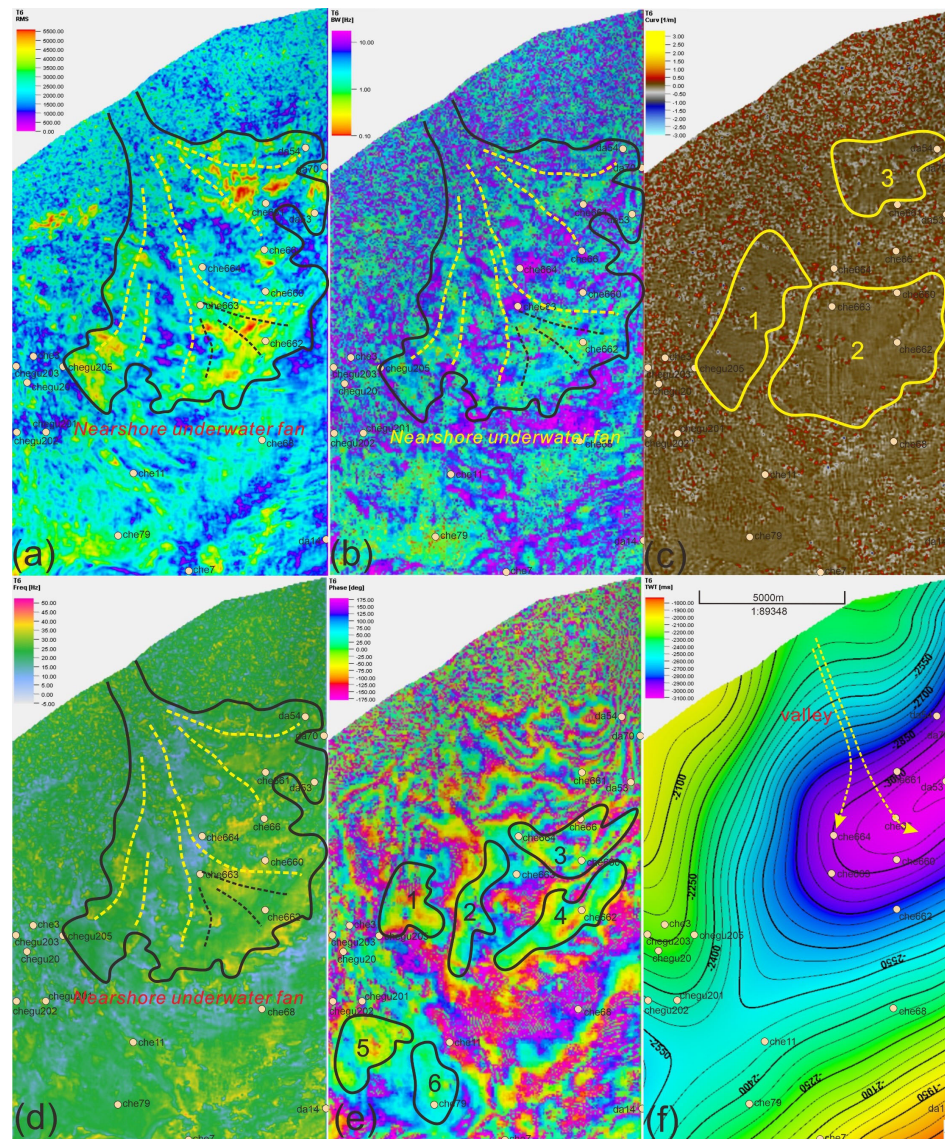


FIGURE 8

Plan of five attributes of P_2S_3X . (A) RMS attribute. The black curve is the boundary of the nearshore area under the fan, and the yellow and black dotted lines are river channels. (B) BW attribute. The black curve is the boundary of the nearshore area under the fan, and the yellow and black dotted lines are river channels. (C) Curv attribute. The yellow curve is the boundary of gravely sandstone deposition. (D) Freq attribute. The black curve is the nearshore boundary under the fan, and the yellow and black dotted lines are river channels. (E) Phase attribute. The black curve is the predicted boundary of gravely sandstone deposition. (F) The two-way-time contour map. The terrain in the northern area is high, and the terrain in the southern area is high, and the terrain in the middle area is low. Therefore, there is a depression in the middle. Sediments were transported from high to low along the river channel and deposited on the slope zone and lake bottom.

a part of the nearshore underwater fan is also developed in the southern part of the work area. Due to the scope limitation of the work area, we cannot examine all sedimentary boundaries of the fan. Obviously, a relatively thick gravely sandstone was deposited on the front edge of the fan. After adding this fan, the total distribution area of gravely sandstone in the study area is approximately 57.9 km² (Figure 9D).

In addition to the Taoerhe Sag, there are also three subdepressions: the Dawangzhuang Sag, Chexi Sag and Guojuzi Sag in the Chezhen Depression. The attribute optimization scheme discussed in this paper can be extended to these three depressions to depict the distribution range of gravely sandstone or other rocks. We will explore this engineering problem in the future.

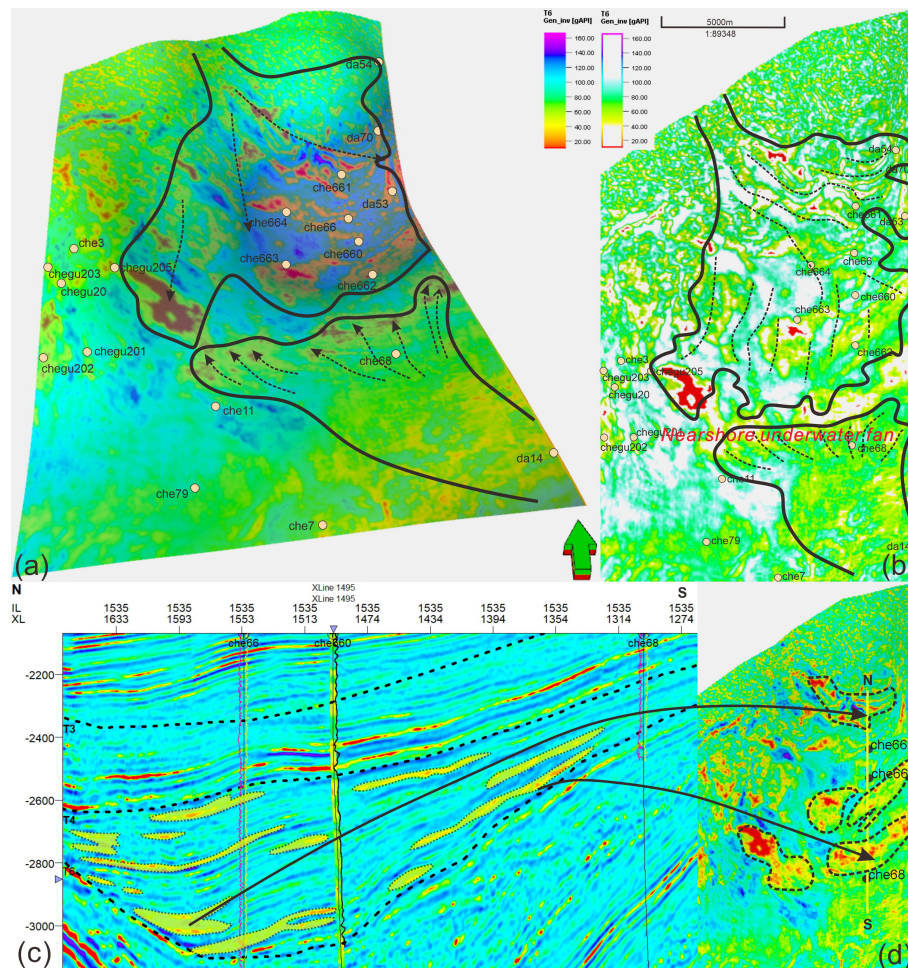


FIGURE 9

Inversion stratigraphic slice and profile of $P_2S_3^X$. (A) Multiattribute fusion technology - superposition map from GR genetic inversion stratigraphic slice and structural map. The black curve represents a fan. Red and yellow represent GR low values, representing gravelly sandstone. Based on the 3D structural map, it is inferred that two fans were developed in this area: one was from the northern mountainous area, and the other was from the southern mountainous area. (B) GR genetic inversion stratigraphic slices after filtering high and very low values. This figure can depict the fan more clearly. The black curve represents a fan. (C) GR genetic inversion profile. T3 is the top of $P_2S_3^X$. T4 is the top of $P_2S_3^Z$. T6 is the bottom of $P_2S_3^X$. The red curve on the left side of Well che66 is the GR curve (the curve protruding to the right indicates a low GR value), and the yellow curve on the right is the AC curve (the curve protruding to the left indicates a low AC value). The middle axis of the che660 well is the extracted above-well Freq attribute, and red and yellow are high values, representing gravelly sandstone. The black curve on the right is the AC curve (the curve highlighted to the left indicates that the AC value is low). The red curve on the left of Well che68 is the GR curve (the curve protruding to the right indicates a low GR value), and the yellow curve on the right is the AC curve (the curve protruding to the left indicates a low AC value). The yellow area circled by the dotted point is gravelly sandstone delineated from the profile. (D) Unfiltered GR genetic inversion stratigraphic slices with high and very low values. The black dotted line is the distribution range of gravelly sandstone finally delineated on the plane. The yellow straight line is the location of Section (C).

6 Conclusion

In this paper, through the methods of sensitive attribute optimization and attribute fusion, three logging attributes and five seismic attributes that can distinguish gravelly sandstone are selected in the Taoyerhe Sag. The prediction results of seismic attributes are explained. Finally, the correctness of the interpretation results is evaluated through GR genetic inversion

data volume, and a set of gravelly sandstone prediction parameters and methods suitable for the Taoyerhe Sag are formed. The main conclusions are as follows. The results of log analysis show that for the Taoyerhe Sag, GR can only be selected if calcareous oil mudstone and gravelly sandstone are distinguishable. If we want to distinguish calcareous oil mudstone and mudstone, we can choose GR, AC, or SH. If we want to distinguish mudstone from gravelly sandstone, we can choose GR, AC, or SH. GR has the most obvious distinction for

lithology. The sensitivity analysis results of the seismic attributes show that the five primary attributes are RMS, BW, Curv, Phase and Freq, which have a certain degree of lithological differentiation in the study area. The results of seismic attribute interpretation show that there is a nearshore underwater fan in the northern and southern parts of the study area, and gravelly sandstone is distributed in the slope zone and the lake bottom. The distribution range of gravelly sandstone in the study area is 57.9 km².

The research methods of logging attribute optimization, seismic attribute sensitivity analysis, genetic algorithm inversion, and quality control can both identify lithologic characteristics in the deep Earth and provide a basis for planning drilling locations. In future research work, this method can be applied to other deep-sea depressions.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, JZ and JM. Methodology, NL. Software, NL and MD. Validation, NL and XL. Formal analysis, NL and TC. Investigation, XL and LW. Resources, JZ and JM. Data curation, NL. Writing-original draft preparation, NL and XL. Writing-review and editing, JZ and JM. Visualization, XL. Supervision, JZ and JM. Project administration, JZ. Funding acquisition, JZ. All authors contributed to the article and approved the submitted version.

References

- Abdullatif, O. M., and Sitouah, M. (2011). "Reservoir porosity and permeability prediction from petrographic data using artificial neural network: a case study from Saudi Arabia," in *9th middle east geosciences conference geo 2010. Georabia*, European Association of Geoscientists & Engineers. doi: 10.3997/2214-4609-pdb.248.103
- Baouche, R., and Nabawy, B. S. (2021). Permeability prediction in argillaceous sandstone reservoirs using fuzzy logic analysis: a case study of triassic sequences, southern hassi r'mel gas field, algeria. *J. Afr. Earth Sci.* 173, 104049. doi: 10.1016/j.jafrearsci.2020.104049
- Barnes, A. E. (2007). Redundant and useless seismic attributes. *Geophysics* 72 (3), 978. doi: 10.1190/1.2716717
- Collett, T. S., Lewis, R. E., Winters, W. J., Lee, M. W., Rose, K. K., and Boswell, R. M. (2011). Downhole well log and core montages from the mount Elbert gas hydrate stratigraphic test well, Alaska north slope. *Mar. Petroleum Geology* 28 (2), 561–577. doi: 10.1016/j.marpetgeo.2010.03.016
- Dongjun, T., Fu, E., Sullivan, C., and Kurt, J. M. (2006). Rock property- and seismic-attribute analysis of a chert reservoir in the devonian thirty-one formation, west texas, U.S.A. *Geophysics* 71 (5), B151–B158. doi: 10.1190/1.2335636
- Du, P., Cai, J., Liu, Q., Zhang, X., and Wang, J. (2021). A comparative study of source rocks and soluble organic matter of four sags in the jiyang depression, bohai bay basin, ne china. *J. Asian Earth Sci.* 216, 104822. doi: 10.1016/j.jseae.2021.104822
- Edwards, M. B. (1994). "Enhancing sandstone reservoir prediction by mapping erosion surfaces, lower miocene deltas, southwest louisiana, gulf coast basin," in *Gulf coast association of geological societies transactions*, (Austin, TX, United States: OSTI.GOV) vol. 44., 205–215. Available at: <https://archives.datapages.com/data/gcags/data/044/044001/0205.htm#purchaseoptions>.
- Ferguson, R. J., and Margrave, G. F. (1996). A simple algorithm for band-limited impedance inversion. *CREWES Res. Rep.* 8, 1–11. doi: 10.1.1.578.3383
- Fouad,, Khaled,, Jennette,, David, C., Soto-Cuervo,, and Arturo, (2002). "Fluid prediction from 3-d seismic data in deepwater sandstone reservoirs: applications

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Conflict of interest

Author MD was employed by Shengli Oilfield Dongsheng Jinggong Petroleum Development Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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from cocuite gas field, veracruz basin, southeastern mexico," in Gulf Coast Association of Geological Societies Transactions, vol. 52. , 291–300. Available at: <https://archives.datapages.com/data/gcags/data/052/052001/0291.htm>.

Galloway, W. E. (2012). Clastic depositional systems and sequences: applications to reservoir prediction, delineation, and characterization. *Leading Edge* 17 (2), 173–180. doi: 10.1190/1.1437934

Ge, J., Zhu, X., Jones, B. G., Zhang, Y., Huang, H., and Shu, Y. (2018). Facies delineation and sandstone prediction using seismic sedimentology and seismic inversion in the eocene huizhou depression, pearl river mouth basin, china. *Interpretation*, 6 (2), 1–51. doi: 10.1190/int-2017-0155.1

Holland, J. H. (1975). Adaption in natural and adaptive systems. *Appl. Radiat. isotopes*. doi: 10.1021/ja211220r

Holland, J. H. (1992). Adaption in natural and adaptive systems. (MIT Press, Massachusetts), 35–66. doi: 10.7551/mitpress/1090.001.0001

Jfa, B., Jq, A., Hw, C., and Qr, A. (2021). Quantitative prediction of multiperiod fracture distributions in the cambrian-ordovician buried hill within the futai oilfield, jiyang depression, east china. *J. Struct. Geology* 148, 104359. doi: 10.1016/j.jsg.2021.104359

Johannessen, E. R., Mjs, R., Renshaw, D., Dalland, A., and Jacobsen, T. (1995). Northern limit of the "brent delta" at the tampan spur -a sequence stratigraphic approach for sandstone prediction. *Norwegian Petroleum Society Special Publications* 5, 213–223, 229–256. doi: 10.1016/S0928-8937(06)80070-6

Lamy, P., Swaby, P. A., Rowbotham, P. S., Dubrule, O., and Haas, A. (1999). From seismic to reservoir properties with geostatistical inversion. *Spe Reservoir Eval. Eng.* 2 (4), 334–340. doi: 10.2118/57476-PA

Li, J., Ma, Y., Huang, K., Zhang, Y., Wang, W., Liu, J., et al. (2018). Quantitative characterization of organic acid generation, decarboxylation, and dissolution in a shale reservoir and the corresponding applications—a case study of the bohai bay basin. *Fuel* 214 (FEB.15), 538–545. doi: 10.1016/j.fuel.2017.11.034

Maleki, M., Davolio, A., and Denis, J. S. (2019). Quantitative integration of 3d and 4d seismic impedance into reservoir simulation model updating in the norne field. *Geophysical Prospecting* 67 (1), 167–187. doi: 10.1111/1365-2478.12717

Mcardle, N. J., and Ackers, M. A. (2012). Understanding seismic thin-bed responses using frequency decomposition and rgb blending. *First Break* 30, (1956). doi: 10.3997/1365-2397.2012022

Nisar, A., Wiktor, W. W., and Dario, G. (2022). Constrained non-linear AVO inversion based on the adjoint-state optimization. *Comput. Geosci.* 168, 105214. doi: 10.1016/j.cageo.2022.105214

Primmer, T. J., Cade, C. A., Evans, J., Gluyas, J. G., Mark, S. H., , Norman, H. O., et al. (1997). Global patterns in sandstone diagenesis: their application to reservoir

quality prediction for petroleum exploration. *Am Assoc. Petrol. Geol.* 69, 61–78. doi: 10.1306/M69613C5

Simon, M., Lutz, R., Dieter, F., Christoph, G., and Jutta, W. (2018). Shallow gas accumulations in the German north Sea. *Mar. Petroleum Geology* 91, 139–151. doi: 10.1016/j.marpetgeo.2017.12.016

Wang, R. L., Sun, J., and Li, J. G. (2007). The recognition on oil-gas reservoir of glutinite body of sha 3 sub-inter of CH 66 block in taorhe shallow depression. *Mud Logging Eng.* 02, 62–68+78.

Xiong, X., Gao, F., Zhou, K., Gao, Y., and Yang, C. (2021). Intelligent prediction model of the triaxial compressive strength of rock subjected to freeze-thaw cycles based on a genetic algorithm and artificial neural network. *Geofluids* 2021 (7), 1–12.. doi: 10.1155/2021/1250083

Xu, K., and Greenhalgh, S. (2010). Ore-body imaging by crosswell seismic waveform inversion: a case study from kambalda, western australia. *J. Appl. Geophysics* 70 (1), 38–45. doi: 10.1016/j.jappgeo.2009.11.001

Yang, T., Cao, Y., Friis, H., Liu, K., and Zhang, S. (2020). Diagenesis and reservoir quality of lacustrine deep-water gravity-flow sandstones in the eocene shahejie formation in the dongying sag, jiyang depression, eastern China. *AAPG Bull.* 104 (5), 1045–1073. doi: 10.1306/1016191619917211

Zeng, Z., Fang, H., Song, G., Sui, F., et al. (2010). Palaeo-formation pressure evolution and episodic hydrocarbon accumulation in tao'erhe depression, chezheng sag. *Oil Gas Geology* 31 (2), 193–197+205. doi: 10.11743/ogg20100209

Zeng, H. L., Robert, G., Loucks, L., and Frank, B. (2007). Mapping sediment dispersal patterns and associated systems tracts in fourth- and fifth-order sequences using seismic sedimentology: example from corpus christi bay, Texas. *AAPG Bull.* 91 (7), 981–1003. doi: 10.1306/02060706048

Zeng, Z. P., Song, G. Q., and Liu, K. Y. (2008). Overpressure mechanisms in taoerhe sag of chezheng depression. *Bull. Geological Sci. Technol.* 06, 71–75.

Zhang, Y., Xia, B., Wan, N., Wan, Z., Shi, Q., and Song, C. (2010). Tectonic controls on the hydrocarbon accumulations in the chexi sag. *Geotectonica Et Metallogenia* 34 (4), 593–598. doi: 10.1145/1836845.1836984

Zhang, J. H., Zhen, L., Zhu, B. H., Feng, D. Y., Zhang, M. Z., and Zhang, X. F. (2011). Fluvial reservoir characterization and identification: a case study from laohekou oilfield. *Appl. Geophysics* 8 (003), 181–188. doi: 10.1007/s11770-011-0288-y

Zhao, W. P. (2016). The application of well-seismic joint attribute analysis technique to the prediction of deep-water turbidite sand reservoir. *J. Eng. Geophysics* 13 (02), 213–220.

Zhao, Z. H. (2017). *Study on high-precision seismic acquisition method in gentle slope zone of chezheng depression* (Qingdao: China University of Petroleum (East China)). doi: 10.27644/d.cnki.gsydu.2017.000184

Appendix

Root mean square amplitude computes RMS on instantaneous trace samples over a specified window (default 9 samples).

Sweetness is defined as $\text{envelope}/\sqrt{\text{Instantaneous frequency}}$. For numerical reasons, a lower threshold of frequency is set at 1 Hz.

The instantaneous bandwidth is the absolute value of the time derivative of the envelope.

3D curvature is the curvature of the reflectors/seismic structure of a volume.

The dominant frequency is from the measure of the hypotenuse between the instantaneous frequency and instantaneous bandwidth.

Apparent polarity is the polarity of the instantaneous phase. It is calculated at the local amplitude extrema.

The envelope is also known as the instantaneous amplitude, magnitude or reflection strength. It is the instantaneous magnitude of the analytic signal (the complex trace), independent of phase: $\text{env} = \sqrt{\text{sqr}(f) + \text{sqr}(g)}$.

The instantaneous phase is an argument of the analytic signal. $\text{phase} = \arctan(g/f)$, where $f(t)$ is the real part and $g(t)$ is the imaginary.

Reflection intensity integrates the instantaneous amplitude along the trace (using the trapezoidal rule).

Instantaneous frequency is the time derivative of phase ($d(\text{phase})/dt$). The time derivative of the instantaneous phase is often referred to as 'phase acceleration'.



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Design and optimization of buoy mooring with single-point cable for seafloor observatories

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For long-term mooring buoy observatories in the deep sea far from the coasts, we design the hybrid system, named Mooring Buoys Observation System with Benthic Electro-optical-mechanical Cable (MBOSBC). The Electro Optical Mechanical (EOM) cable connects the sea surface buoy, and benthic observation node, as the transmission link of information and power. Different from the traditional buoy mooring, Mooring Buoys Observation System needs to accomplish the energy and data transmission between the seabed and the sea surface. The EOM cable is utilized for mooring, and it is the crucial link to ensure the long-term and effective work of the system and energy / data transmission. EOM cable plays the role of mooring tether of MBOSBC. Since the EOM cable has to experience higher loads under most environmental conditions for long terms. It is often happened that, the EOM cable is not broken, but the power supply core wire and signal wire have broken or failed, while the buoy is subjected to wind, wave and current load. This puts forward the requirements for the design of bearing load and mooring style for the mooring EOM cable. This paper gives the idea of mooring design of buoy, and this paper provide the design criteria of the single point mooring buoy with EOM cable. We compare the dynamics properties and mooring line type under different external environmental load, and the mooring style is optimized. Finally, the dynamic properties and mooring line type during the system deployment process is discussed.

KEYWORDS

ocean buoy mooring, EOM cable, single point mooring, oceanographic moorings, snubber rubber cable

1 Introduction

Seafloor observatories are used to gather information about the physical, chemical, and geological processes that occur on the seafloor. They can monitor environmental processes, including changes to the ocean climate, ocean upwelling, eddies, seismicity, geomagnetic variations, temperature, salinity, currents, and gas over the long term. First,

these observatories produce a large amount of multidisciplinary ocean data for scientists in real time. The NEPTUNE Ocean Observatory in Canada is the most representative example of such state-of-the-art marine technology. Second, seafloor observatories have potential applications for the offshore operations of the oil and gas industry. Third, seafloor observatories support maritime security. For example, seafloor observatories with seafloor hydrophone arrays can track and identify surface vessels, autonomous underwater vehicles, and cetaceans.

Cabled seafloor observatories have been developed by Canada, USA, and Japan. These systems transmit power to an underwater junction box from a shore station through an electro-optical-mechanical (EOM) cable. Thus, the EOM cable and junction box connect the shore station with the sensors and instruments. However, there are huge costs for manufacturing the EOM cable and launching and maintaining the system. Also, it is difficult to change or adjust the position of the seafloor junction box once the system has been completely constructed. So, a cabled seafloor observatory is not easily moved, for example, in response to an emergency event. Such surface and seafloor observatories are restricted to regions close to the coast rather than in the deep sea far from the shore.

However, renewable energy generators, such as wind turbines and solar panels, make it possible to deploy seafloor observatories far from the coast. The data can be transferred from the seabed *via* an EOM cable and relayed to a satellite. The EOM cable is used to transfer data and power between a benthic node and a moored buoy. Such moored-buoy seafloor observatories can provide real-time, synchronized, three-dimensional data from observations of the sea surface and the seafloor (Smith et al., 2018; Trowbridge et al., 2019). There are, however, several problems with moored-buoy seafloor observatories. The EOM cable hangs in the water due to its net buoyancy. Thus, it has to endure dynamic conditions for a long time. It is difficult to get continuous high-bandwidth communications. A very-small-aperture terminal can provide a bandwidth of up to 1 Mbps. Finally, the power supply is limited by how many solar panels and wind turbines can be equipped on the buoy, which depends on the size of and available space on the buoy.

It would be useful to establish a regional system of ocean observatories that can be relocated in response to an emergency event. We developed the Moored-Buoy Observation System with a Benthic Electro-optical-mechanical Cable (MBOSBC). This system can be used to make supplementary observations that complement those made by traditional buoys or a seafloor observation network. MBOSBC has a surface buoy, mooring cable, and benthic node to realize three-dimensional observations of the sea surface and seabed. The system connects the observation nodes through the mooring cable. The mooring cable transfers energy and data while also mooring the sea surface buoy. Acoustic communication is

used to supplement the cable communication from the benthic node to the sea surface. Such ocean buoys mainly collect data on temperature, salinity, ocean currents, waves, and oceanographic meteorology. They are deployed in regions with a depth of less than 1000 m. The data collected provide support for research into the ocean climate and physical ocean processes, such as ocean circulation, internal isolation waves, upwelling, and other ocean phenomena. The buoy in MBOSBC not only makes sea surface observations but also transfers energy to the seabed and information from it. The data collected are transmitted back to the shore base *via* a satellite. For example, a buoy has been designed as a communication intermediary. It collects data from an autonomous underwater vehicle and seafloor benthic platform through acoustic communication (Detrick et al., 2000; Favali et al., 2006).

CUMAS (Cabled Underwater Module for Acquisition of Seismological data) has been deployed in Campi Flegrei caldera (Pozzuoli, southern Italy) at a depth of 100 m (Iannaccone et al., 2009; De Martino et al., 2014). It extends the land surveillance network into the large marine sector of the caldera. CUMAS, developed for monitoring a volcano in shallow water, adopts a mixed solution. It has an elastic-beacon buoy consisting of a pole (of about 40 m in length) with a linear polyethylene float, which contains polyurethane foam for buoyancy. The buoy weighs 7 tons. A purely mechanical anti-torsion wire connects the buoy to a concrete boulder on the seabed, which acts as ballast (17 tons). A multidisciplinary observatory installed on the seafloor is connected to the buoy *via* a separate electromechanical (EM) cable, which is used for deployment and recovery and transferring power and data. Data with GPS locations are sent to the shore monitoring site *via* a Wi-Fi link operating at 5 GHz. This mooring method is suitable for shallow water applications up to depths of about 400–500 m. If this method is utilized for mooring in the deep sea, the optical cable and anchor chain can easily become entangled, which may lead to fracturing of the optical core and system failure.

The prototype MBARI Ocean Observatory System (MOOS) (Chaffey et al., 2001; Chaffey et al., 2005; Hamilton and Chaffey, 2005) has a 3-m-diameter buoy, an ocean benthic platform, and EOM cable. It has been deployed in the deep ocean in depths of up to 4000 m. The EOM cable transmits power and data between seafloor instruments and the buoy. The surface buoy can generate up to 40 W of power with a horizontal-axis wind turbine and a solar panel. The EOM cable and the seafloor junction box are connected to a remotely operated underwater vehicle with a wet-mateable electro-optical connector.

The Dynamics of Earth and Ocean Systems observatory (DEOS) (Detrick et al., 2000) has a moored discus buoy connected by an electro-optic cable to instruments on the seafloor. C-Band satellite telemetry is utilized in DEOS for continuous high-bandwidth communication (64–128 kbps or higher). The buoy has a diesel generator, which supplies enough power (up to 1000 W) for the benthic node.

An acoustic link between the sea surface and the seafloor is less complicated than a cable but has lower data rates and an inability to provide power to the seafloor. CSnet's Offshore Communication Backbone (OCB) will initially serve as the Tsunami Warning and Early Response system of Cyprus (TWEREC). OCB can operate at depths of 3000 m. It is designed to support a modular architecture, linking together several buoys (Clark et al., 2009; Clark, 2010; Georgiou et al., 2010; Clark and Kocak, 2011). The OCB consists of a buoy, a buoy riser cable (for mooring, power, and communications), anchor, seafloor cable, and four seafloor nodes. The surface buoy has a C-band satellite antenna, which provides a data bandwidth in excess of 2 Mbps. The buoy is powered by a diesel electrical generator that produces 1000 W of power for the seafloor equipment. The seafloor junction box has wet-mateable "plug-in" ports.

The Coastal Surface Mooring Buoy System developed by the Ocean Observatories Initiative (OOI) is maintained as part of the Regional Cable Array (Smith et al., 2018). The maximum launch depth is 588 m. This system has a surface buoy with a 3-m-tall tower, a near-surface instrument frame (NSIF), which is at a depth of 7 m, and a multifunction node on the sea bottom. These three components are connected by an EM cable, which transfers information and power between the sea bottom and surface. The buoy is moored to a metal-armored EM cable instead of an EOM cable. The data transmission technology between the seafloor and the surface is based on DSL. The EM stretch hose used is designed to stretch 2.5 times its length in a typhoon without disrupting its ability to transfer data or power. It is suitable for mooring, as the stretching decreases the dynamic tension.

Satellite communication offers a low-bandwidth communications path for the buoys, whereas the optical fiber in the EOM cable provides high-bandwidth communications from the seafloor to the sea surface. The cable utilized in MOOS is different from that used for a cabled seafloor observation network. The traditional EOM cable in a seafloor network is armored with steel wire and lies static on the sea bottom. However, an armored EOM cable is not suitable for mooring a buoy in the deep sea. Because the net buoyancy of the buoy is limited, the EOM cable has to have net buoyancy, so that it will hang in the water for a long time. This kind of EOM cable requires high strength, excellent bending ability, watertight performance, and good wear resistance. Vectran fibers, nylon, and polyester are selected as the strength member of the cable. The properties of EOM cables with different strength materials are compared in the literature (Hamilton et al., 2003; Paul et al., 2003; Han and Grosenbaugh, 2006; Grosenbaugh et al., 2006), especially the static and dynamic responses of a mooring EOM cable.

Tethering is simpler in shallow seas (Iannaccone et al., 2009; De Martino et al., 2014). The anchoring rope and coaxial cable are linked together as the mooring component

(Makris et al., 2014). However, it is difficult to utilize this kind of mooring method in the deep sea since it is hard to launch and recover the system because the anchor chain and cable are entangled together.

The cables used in MOOS have Vectran fibers as the load-bearing layer. These have neutral buoyancy. Optical fibers are used for communication. Thus, neutral-buoyancy EOM cables are used for mooring. To reduce the effect of loads generated by waves and winds at the sea surface, a 24-m-long retractable rubber snubber connects the MOOS buoy and the Vectran cable as a buffer link (Hamilton and Chaffey, 2005). For data and power transmission, electric wire is spirally wound around a rubber tube at a certain spiral angle. Tests have demonstrated that the snubber absorbs the bearing tension in the EOM cable. EOM Offshore has designed a special retractable snubber for the cables in the OOI moored-buoy observation system. The snubber can extend up to twice its original length. Thus, it buffers the load from the buoy to the mooring cable. The cable in a moored-buoy observation system has to be different from that used for a traditional buoy, which is moored with a chain, nylon rope, or polyurethane rope. The extension ratio of nylon rope is about 20%, which has a significant buffering effect on the load induced by the heaving movement of the buoy. When an EOM cable is pulled by an external load, its maximum extension and contraction should not exceed 0.5% (Frye et al., 2004). Otherwise, the external load will break the electric wire or optical fiber, causing system failure.

When we deploy MBOSBC, the buoy is generally deployed first, then we lay the mooring cable with a winch, and finally we deploy the benthic node. When the benthic node is deployed from a scientific research ship, it drops to the seafloor quickly, and the tension is quickly transmitted to the sea surface buoy. Driven by the drag force from the mooring cable, the sea surface buoy will move rapidly in the horizontal plane. As a result, the mooring tension and the shape of the mooring line will also change fast. The dynamic tension during deployment increases with the deployment depth and, correspondingly, as the distance between the buoy and the benthic node increases. Moreover, the horizontal speed of the scientific research ship will also increase the dynamic tension. Thus, deployment is a fast and unstable process. The buoy may be pulled under the surface and sink.

In this paper, we design MBOSBC as a seafloor and sea surface observatory in the South China Sea. It can make observations of ocean meteorology, physical processes in the ocean, and the water quality at the sea surface and seafloor. MBOSBC has a moored buoy and a benthic node connected by an EOM cable. The moored buoy makes observations, generates power, and transmits data. The benthic node collects information about ocean physical processes and video images of the seafloor. Furthermore, the benthic node is the anchor for the moored buoy. Therefore, this paper first describes the background in the design of MBOSBC system. We then design the mooring approach. We analyze static mooring loads under

different external environments. The influence of the length and position of a rubber snubber on the mooring force is discussed. Moreover, we assess the dynamic load under the influence of winds, waves, and currents. We also analyze the dynamic characteristics of the buoy during deep-sea deployment, especially the shape of the mooring line and the horizontal speed of the buoy after the benthic node is launched from a scientific research ship. The research results may provide guidance in the deployment of the system.

2 Background information about moored-buoy observatories

2.1 Description of a moored-buoy observation system

MBOSBC is designed for regional observatories off the coast in the South China Sea. It combines seafloor and sea surface instruments to provide a broad spectrum of environmental, meteorological, and hydrological measurements, including water temperature, pressure, salinity, current, wind speed and direction, air temperature, relative humidity, barometric pressure, and chemistry. We integrated a seafloor video module, which has an LED light for camera illumination, camera, CTD, and acoustic Doppler current profiler, to verify the power capacity of MBOSBC and its radio transmission capability (Zhang et al., 2018). The overall system architecture is shown in Figure 1A). It has three main parts: moored buoy, benthic node, and EOM cable. The moored buoy makes observations of the sea surface, transfers data, and generates energy. The benthic node contains a junction box, the oceanographic instruments, the seafloor video module, and the

buoy anchor block. The junction box contains systems for power management, control, data acquisition, and monitoring the status of the seafloor junction box. The EOM cable moors the sea surface buoy to the benthic node.

Initially, we used a metal-armored EOM cable and a Vectran cable in experiments with the prototype system in shallow water, as shown in Figure 1A). To resolve the problems identified in the experiments, we optimized the system, as shown in Figure 1B). We discuss the mooring design in this paper.

2.2 Prototype system design

2.2.1 Moored buoy and benthic observation node

The moored buoy is a rigid structure made of AISI-304 stainless steel. Its main diameter is 3 m, and its weight in air is 4.2 tons. It is shown in Figure 1A). A watertight tank surrounds the center of the buoy. The electronic instruments are mounted in the watertight tank. The buoy has 24 rechargeable batteries (2 V and 500 Ah each), which are connected to eight solar panels and a wind turbine. Since the watertight tank is cylindrical, we arranged the batteries in a cube with four rows and five columns. Another four batteries were placed at the centers of the four vertical sides of the cube. Twelve of these batteries were connected in series to offer 24 V as the bus voltage. Then, the two groups were connected in parallel to offer 24 V 1000 Ah storage for the whole buoy system. A DC/DC converter connected the batteries and buoy control module to offer 12V, 24V, 5V, and 3.3 V (DC) for the sensors. Each solar panel produced a nominal 100 W and had dimensions 1200 mm × 540 mm.

The benthic observation node is also shown in Figure 1A). Its maximum working depth is 1000 m. The junction box has a

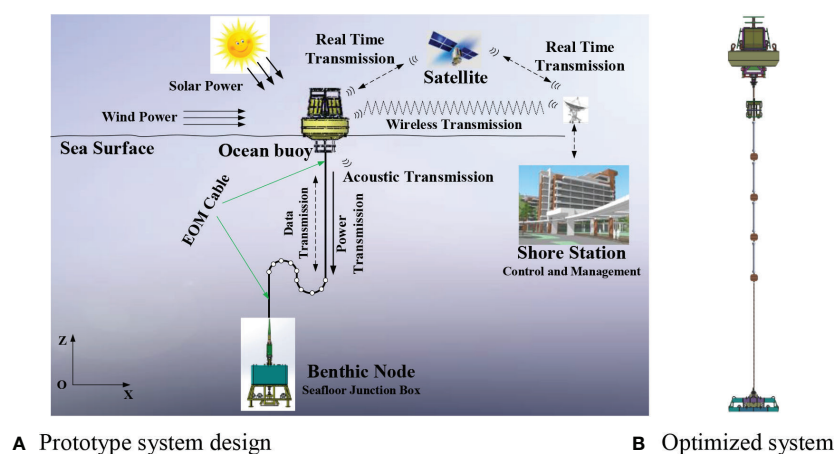


FIGURE 1
Design of MBOSBC. (A) Prototype system design (B) Optimized system.

titanium cylinder that holds the power supply. A second titanium cylinder holds the data communication and control equipment. The mass of the junction box is less than 150 kg in air, and it is surrounded by a cage. The junction box hosts several instruments, including a seafloor video imaging module, CTD, and acoustic Doppler current profiler.

The base area of the cage is $2.25 \text{ m} \times 2.25 \text{ m}$, and it has a height of 2.53 m. The seafloor junction box and the video module are fixed to the grid of the cage. The diameter of the two titanium cylinders holding the junction box is 320 mm, and their length is 1060 mm. The DC/DC converter, data sampler, and transmission module are fixed separately into the two titanium cylinders.

The benthic observation node is the seafloor anchor. The cage used to hold the scientific instruments has a mass of 1 ton in air. The anchor block at the bottom center of the cage has a mass of 3 tons in air, which is sufficient to moor the buoy. To recover the MBOSBC, the anchor block can be released by an acoustic release.

2.2.2 Mooring cable design

Our goal is to moor the system at a depth of 1000 m with an EOM cable. A traditional EOM cable is armored with metal (A302351, Rochester Engineered EOM Cable; Figure 2). The EOM cable has a diameter of 17.30 mm, and a breaking strength of 204.6 kN. Its weight in water is 9.050 kN/km. We deployed the system in shallow coastal water to test the communications. It is composed of three optical fibers and three #11 AWG copper wires, as shown in Figure 2A).

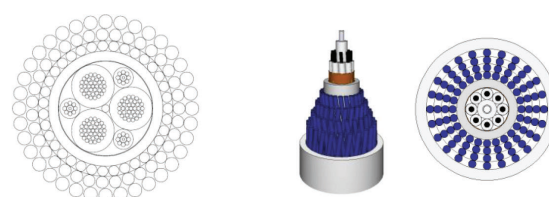
If we replace the mooring chain with the A302351 cable, then the 1400 m of cable will have a mass of 1267 kg in air, which will have a significant effect on the stability of the buoy. The weight of the armored cable may drag the buoy under the water surface, which may lead to loss of the buoy. Thus, it is not suitable to deploy the system at a depth of 1000 m. For a deep-sea buoy, we have to select an EOM cable with net buoyancy rather than this armored mooring cable. Thus, an EOM cable with net buoyancy is utilized for single-point mooring in MBOSBC.

We designed a net buoyancy EOM cable that has four optical fibers with watertight connectors and eight #18 AWG copper wires, as shown in Figure 2B). Two optical fibers are utilized for data transmission, and two copper wires are utilized for power transmission. The diameter of the EOM cable is 30 mm, its breaking strength is 200 kN, and its weight in water is $0 \pm 2.0 \text{ N/m}$.

It has Vectran fibers as the strength member. The conductors and optical fibers are in the core and surrounded by Vectran fibers. The Vectran fibers [blue circles in Figure 2B)] are arranged in four layers. The outer bedding braid layer is made from polyester, which protects the Vectran fibers from abrasion.

In the initial design of the prototype system, we utilized hybrid mooring methods with the A302351 cable and an anchor chain twisted together. We laid out the system near the shore and recovered it to verify the feasibility of the system. Then, we designed the deep-sea single-point mooring mode. We used Vectran fibers as the bearing layer, as shown in Figure 2B). The tension in the cable was measured to be as high as 280 kN. However, during the test, we found that the cable has poor scalability. Moreover, the manufacturing process is complex. We also discovered that the Vectran-fiber material has poor seawater corrosion resistance. The outer sheath of the optical cable is hard and wears quickly. When the outer sheath breaks, the Vectran fibers become corroded by seawater. As a result, the tethering force is greatly reduced and no longer meets the mooring requirements. Communications *via* the optical fibers in the EOM cable failed in each test. Thus, considering the problems we found in the near shore experiments, we decided to analyze the mooring dynamics and to redesign the mooring system with a rubber snubber and EM cable.

In addition, for the initial design, the frame for the benthic node was made of AISI-316 stainless steel. It was too heavy, so we added a huge amount of buoyant material to the top of the frame. Thus, the benthic node would rise to the sea surface with the buoyancy force if the anchor block were released from the benthic node. However, in this design, the weight of the seafloor node is still too high. Therefore, in our subsequent optimized



A Rochester cable A302351

B Cross-sectional view of EOM cable made with Vectran fibers

FIGURE 2

Design of mooring EOM cable. (A) Rochester cable A302351 (B) Cross-sectional view of EOM cable made with Vectran fibers.

design, a cylinder made from an aluminum alloy was used as the frame for the benthic node. This reduces the weight of the system, since the density of the aluminum alloy is much less than that of stainless steel. Moreover, the aluminum alloy cylinder can be utilized as a buoyancy compartment. It provides enough buoyancy for the benthic node to rise to the surface, which avoids the need to include additional buoyancy material.

Table 1 gives the specifications of buoy-moored seafloor observatory systems. Overall, the tensile strength of Vectran-fiber EOM cable is sufficient for mooring, as shown by Yu et al. (2020). However, in our actual tests, the performance of the Vectran-fiber EOM cable was not as good as we expected, mainly in the following aspects:

1. The elasticity of Vectran-fiber EOM cable is poor, which may lead to loss of communications due to failure of the optical fibers.
2. The outer sheath of Vectran-fiber EOM cable is relatively soft, and it is easily scratched by the seabed.
3. Vectran-fiber EOM cable is not sufficiently waterproof. The tensile strength of Vectran fiber decreases if it is immersed in seawater, which can occur if the cable sheath becomes scratched.
4. The slip ring can cause a short circuit. So, we need a flexible connection between the buoy and the cable.

Thus, we decided to use a combination of nylon EM cable and Nilspin EM cable for buoy mooring in our subsequent designs. We optimized the mooring components and carried out a dynamic simulation of the mooring system as follows:

1. We choose nylon EM cable and Nilspin EM cable for mooring, as they were sufficiently waterproof. Optical

fiber was no longer utilized for the cabled communications.

2. To increase the flexibility of the mooring system, we connected the buoy and the EM cable with a snubber. We analyzed the dynamic properties of the mooring system under the influence of wind, waves, and currents.
3. We optimized the length of the snubber by measuring the cable tension in the mooring system with different lengths of snubber.
4. During a deep deployment, the mooring cable and benthic node pull on the surface buoy. Thus, we theoretically analyzed the speed of the surface buoy during deployment and identified the maximum and when this occurred. This information allows us to understand the movement of the buoy during deployment. Thus, we can use small boats to counter the pull on the buoy.

2.3 Mooring design and optimal configuration

The properties of the components of a mooring cable are listed in Table 2. The dynamics of the mooring cable for a buoy closely depends on deployment depth. Thus, the diameter, mooring tension, and self-weight of the mooring cable need to be analyzed for the deployment depth. Moreover, the snubber is an important component for mitigating the impact of the external environmental load on the mooring cable. Thus, it is necessary to determine the best position and length of the EM cable and the snubber based on the results for different deployment depths and mooring dynamics. This will ensure that the EM cable meets the requirements for a moored buoy and for energy and data transmission. We evaluated mooring

TABLE 1 Specifications of buoy-moored seafloor observatory systems.

Property	MBARI moored buoy	OOI coastal surface mooring buoy	Seismic and tsunami telemetry buoy	CUMAS	Cyprus-TWERC buoy
Diameter (m)	2.3	3	–	–	5
Volume	–	–	$2.5 \times 2.5 \times 1 \text{ m}^3$		
Weight	1.5 t	4.6 t	400 kg Net buoyancy 2.5 t	17 t	–
Depth (m)	1500	450	–	100	2400
Cable	Vectran-fiber EOM cable	Nilspin EM cable	Coaxial cable and anchoring rope	EM cable	Steel EOM cable
Data transmission	Fiber	Ethernet	Coaxial signal	RS485	Fiber
Lifespan of the system	6 months	1.5 years	1 month	25 years, for the buoy; 18 months for the seabed module	6 months without refueling

TABLE 2 Properties of mooring cable components.

Component	Diameter (m)	Length (m)	Mass	Wet weight	Equivalent stiffness, EA (N)
7/16" EM Nilspin cable	0.0143	–	0.548 kg/m	4.1 N/m	6.7×10^6
Snubber	0.078	–	3.94 kg/m	15 N/m	3×10^4
Hose interface buoyancy unit (HIB)	0.61	0.61	68 kg	–525 N	6.7×10^7
Near-surface instrument frame (NSIF)	1	1	100 kg	778 N	7×10^7
EM chain	0.1	–	14.6 kg/m	29.1 N/m	6×10^7
Nylon EM cable	0.039	–	0.97 kg/m	3.28 N/m	$\sim 3.7 \times 10^5$

under tension. The external boundary conditions for the wind and waves are listed in Table 3. The current profile utilized is the maximum expected current, as given in Table 4.

In the mooring system, there is an EM chain near the buoy. It is connected to the NSIF. The mooring system then has four groups of a snubber and a hose interface buoyancy unit (HIB). Finally, an EM cable is connected to the benthic node. The length and buoyancy of each section are listed in Table 5.

The mooring simulations are obtained with Woods Hole Oceanographic Institution (WHOI) cable, a software that is developed for calculating the static and dynamic response of moored oceanographic systems (Gobat and Grosenbaugh, 2000). The software utilizes the finite-difference time-domain (FDTD) method for the mathematical model of cable dynamics.

3 Steady-state analysis and comparison of mooring systems under the influence of winds, waves, and currents

3.1 Comparison of nylon EM cable and Nilspin EM cable

In the steady-state tension analysis, the whole system is considered to be deployed at a water depth of 1000 m. It needs to be able to withstand a 100-year storm. Both nylon EM cable and Nilspin EM cable are utilized for mooring traditional buoys. The difference between the two kinds of cable is that the equivalent stiffness (EA) of nylon rope is low and its extension ratio is large. The EA of the Nilspin EM cable is about ten times that of the nylon

EM cable. The manufacturing process for nylon EM cable is more complex and more difficult. These tests allowed us to assess the influence of the material used to make the cable for a moored buoy.

In addition, the location of the snubber in the mooring system also has a great impact on the mooring tension. Since the buoy is the first node, it must bear external loads due to waves and winds. The tension load is transmitted to the seafloor. If the snubber is near the seafloor node (snubber down), the tension load is transmitted to the EM cable without being absorbed. In contrast, if the snubber is near the buoy (snubber up), some of the mooring load will be absorbed by the rubber snubber, so that changes in the mooring tension in the EM cable are more stable. Thus, we ran four steady-state stress analysis tests with either the nylon EM cable or the Nilspin EM cable and with the snubber near the buoy or above the benthic node, as shown in Table 6.

Figure 3 shows that the mooring lines with the Nilspin EM cable have steeper slopes, mainly because the extension ratio of Nilspin is smaller than that of a nylon EM cable. The location of the snubber also has an impact on the mooring line. For the nylon EM cable, if the snubber is near the seafloor, the slope is steeper near the seafloor than near the sea surface. The length of each mooring line is different. How much they stretch depends on the stiffness of the cable material. However, if the snubber is near the buoy, the mooring tension transmitted to the EM cable is absorbed, for both kinds of EM cable, so the overall mooring line stretches more, mainly due to the extension of the snubber. Table 7 and Figure 4 show that, in the steady-state tension analysis, although both types of cable are connected to the snubber, the mooring force with the Nilspin EM cable is obviously greater than that with the nylon EM cable. The maximum tension with the Nilspin EM cable is about 2 tons, while for the nylon EM cable it is less than 1.3 tons. The variation

TABLE 3 Storm conditions: Wave height and period defines a modified Pierson–Moskowitz spectrum.

Weather conditions	Wind speed (m/s)	Significant wave height (m)	Peak wave period (s)
10-year storm	25.6	11	14.6
30-year storm	27.7	12.4	15.5
100-year storm	30.1	14.0	16.6

TABLE 4 Current profile.

Depth (m)	Current speed (m/s)
0	1
5	1
10	0.9
20	0.45
50	0.3
150	0.2
600	0.05
1000	0

in the tension in the nylon EM cable with depth is very small, as its elasticity absorbs the resistance generated by the ocean current. Moreover, the nylon EM cable has a low retraction rate but a long length. The rubber snubber has twice the retraction rate but is shorter. The mooring tension in the Nilspin EM cable decreases gradually from the sea surface to the benthic node, but the ability of the Nilspin EM cable to cope with the ocean current is worse.

Introducing snubbers and HIBs reduces the mooring tension. The mooring tension has a small bend in the HIB section because the HIB is a rigid connection in the buoy block. Both ends of each HIB are connected to a snubber. This explains the influence of the stiffness of the mooring material.

In conclusion, the snubber should be close to the buoy, so that the mooring tension generated by the external load can be

absorbed by the snubber before it is transmitted to the EM cable. This reduces the mooring tension in the cable. In particular, the load-bearing tension in the Nilspin EM cable is greatly reduced. Comparing nylon and Nilspin, it seems that nylon is more suitable for the EM cable due to its stiffness and flexibility (extension ratio 20%). A traditional buoy is moored with nylon rope because of its high extension ratio, which means that the mooring tension is basically constant with respect to depth. However, this is a drawback for the optical core and electric core wire (extension ratio less than 0.5%), which are the media for energy and information transmission. Another advantage of the Nilspin EM cable is its mature manufacturing process. Thus, the Nilspin EM cable is a good choice for the moored buoy in our application.

3.2 Mooring tension with and without a snubber

In the next set of simulations, we compare the EM mooring cable with and without a snubber. The snubber is installed near the buoy. For the tests without the snubber, the snubber is replaced by EM cable. [Figure 5](#) compares the shape of the mooring line and the mooring tension for mooring lines with and without a snubber. The ranges for the mooring tension are given in [Table 7](#).

For the combined mooring method with the nylon EM cable and snubber, in the steady state, the overall change in the mooring tension is small compared with no snubber. For the Nilspin EM cable, the combined mooring method reduces the mooring

TABLE 5 Components of the mooring system in order with the snubber near the buoy.

Component	Diameter (m)	Length (m)	Depth (m)	Wet weight	EA (N)	Mass
Buoy	3	–	0	–	–	–
EM chain	0.1	5	5	29.1 N/m	6×10^7	14.6 kg/m
NSIF	1	1	6	778 N	7×10^7	100 kg
Snubber	0.078	30	36	15 N/m	3×10^4	3.94 kg/m
HIB	0.61	0.61	36.61	–525 N	6.7×10^7	68 kg
Snubber	0.078	30	66.61	15 N/m	3×10^4	3.94 kg/m
HIB	0.61	0.61	67.22	–525 N	6.7×10^7	68 kg
Snubber	0.078	30	97.22	15 N/m	3×10^4	3.94 kg/m
HIB	0.61	0.61	97.83	–525 N	6.7×10^7	68 kg
Snubber	0.078	30	127.83	15 N/m	3×10^4	3.94 kg/m
HIB	0.61	0.61	128.44	–525 N	6.7×10^7	68 kg
Nilspin (nylon EM cable)	0.0143 (0.022)	871	999.44	4.1 N/m (0.28 N/m)	6.7×10^6 ($\sim 3.7 \times 10^5$)	0.548 kg/m (0.29 kg/m)
Benthic node	–	0.6	1000.04	–	–	–

TABLE 6 Location of each component in the mooring system.

Index	Abbreviated name in simulation	Mooring position and connection sequence
1	Nilspin, snubber up	Buoy → EM chain → NSIF → snubber and HIB (four groups) → Nilspin cable → benthic node
2	Nylon, snubber up	Buoy → EM chain → NSIF → snubber and HIB (four groups) → nylon cable → benthic node
3	Nilspin, snubber down	Buoy → EM chain → NSIF → Nilspin cable → snubber and HIB (four groups) → benthic node
4	Nylon, snubber down	Buoy → EM chain → NSIF → nylon cable → snubber and HIB (four groups) → benthic node

tension by 50% compared with no snubber. From the tests described here and in Section 3.1, we conclude that the best mooring components are the Nilspin EM cable and a snubber and that the snubber should be near the buoy. In the following section, we discuss the dynamic properties of the mooring system.

3.3 Variation of mooring tension in different external environments

3.3.1 Variation of mooring tension with and without winds or waves

The shape of the mooring line is shown in Figure 6 for different weather conditions for a Nilspin cable with the snubber up. The current and wind are continuous loads, so the slope of the mooring line is steeper when there is no wind or ocean current. It is obvious that the wind increases the mooring tension, as also indicated by Table 8. However, waves are a periodic load. So, the steady-state mooring tension is the same with or without waves if the wind and current are the same, as shown in Figure 7. Therefore, the influence of waves is not reflected in this steady-state mooring tension analysis.

3.3.2 Variation of mooring tension with the severity of the storm

Table 8 lists the wave height and period and also the wind speed for different storms. The next set of tests used the combined mooring method with the Nilspin EM cable and snubber. The mooring tension increases as the wind speed increases, as shown in Figure 8. Comparing a 10-year storm with a 100-year storm, the maximum mooring tension in the Nilspin EM cable increases by about $(2.06 - 1.78)/1.78 = 15.7\%$. In contrast, the maximum mooring tension of the snubber increases by $(2.56 - 2.33)/2.33 = 9.9\%$.

4 Dynamic analysis of the mooring system in a storm for different mooring-line configurations

4.1 Mooring with the Nilspin EM cable when the snubber is near the buoy

A steady-state analysis can study only the influence of wind and current on the mooring system, as these two kinds of

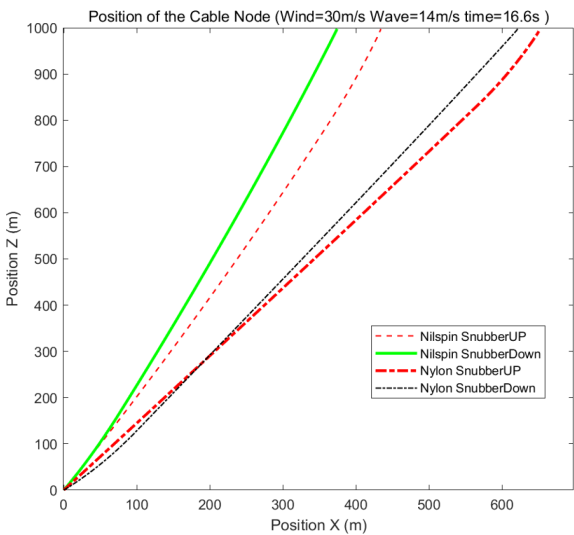


FIGURE 3 Shape of the mooring line for a wind speed of 30 m/s, wave speed of 14 m/s, and peak wave period of 16.6 s for different configurations of the mooring line.

TABLE 7 Comparison of the mooring tension for different cable materials and snubber locations.

EM cable	Snubber location	Tension range of EM cable (tons)	Tension range of snubber cable (tons)
Nylon	Up (near the buoy)	1.06–1.28	1.06–1.76
Nylon	Down (near the benthic node)	1.29–1.36	0.93–1.29
Nilspin	Up	1.73–2.06	2.06–2.56
Nilspin	Down	1.87–2.28	1.45–1.87
Nylon	–	1.29–1.32	–
Nilspin	–	3.5–3.95	–

external load are continuous rather than dynamic. However, the external load for waves is periodic. Thus, a dynamic analysis of the mooring system is very important for selecting the best configuration of the mooring segments.

Regular waves can be simplified as sine waves. The parameters of the waveform include the height and period. The acceleration and velocity of water particles in a wave vary with time. Thus, there are dynamic changes in the tension and position of the mooring system. The purpose of the snubber is just to absorb this dynamic load. Therefore, this section studies the dynamic characteristics of mooring tension. The characteristic parameters of the external load are a wind speed of 30.1 m/s, a wave height of 14.0 m, and a wave period of 16.6 s. The simulations are carried out with the assumption that the system is deployed with a depth of 1000 m. The mooring-line configuration is shown in Table 5.

Figure 9 shows that the tension at the buoy is basically the same as that at the NSIF. The maximum tension at the buoy is 3.02 tons, and the maximum tension in the EM cable is 2.22 tons.

Each snubber acts as a buffer by absorbing some of the mooring tension from the buoy.

For the dynamic tension load, Table 9 gives the mean, maximum, and standard deviation of the mooring tension for each main component with the snubber up or down. The table also shows an approximate linear relation between the three tensions.

4.2 Mooring with Nilspin EM cable when the snubber is near the benthic node

When there are waves, the dynamic load varies over time. The maximum dynamic load determines the maximum bearing capacity required by the Nilspin EM cable. However, changing the position of the snubbers in the mooring system changes the maximum tension in the EM cable, as found by the steady-state analysis. Therefore, in this section, we use the mooring-line configuration of Table 5 except that the snubbers are near the

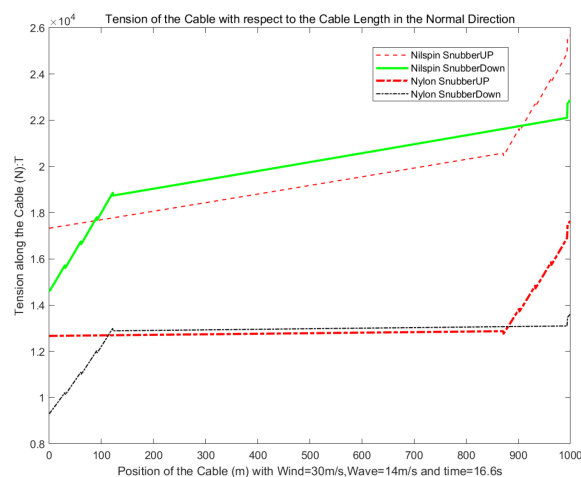
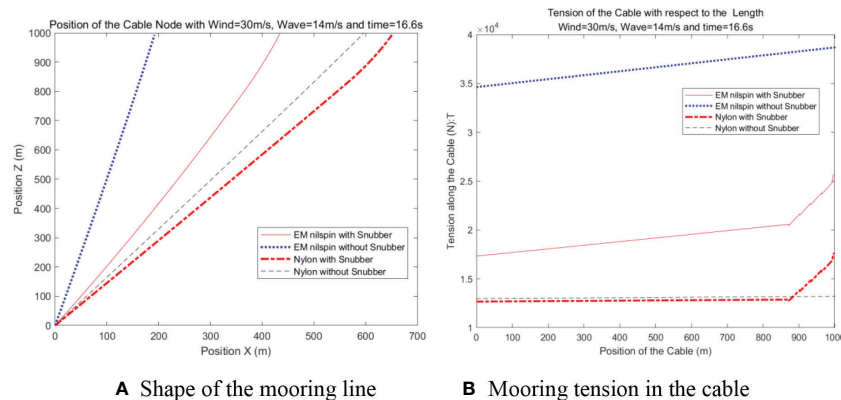


FIGURE 4

Steady-state tension along the cable for a wind speed of 30 m/s, wave speed of 14 m/s, and peak wave period of 16.6 s for different configurations of the mooring line.



FIGURES

Steady-state tension analysis for a wind speed of 30 m/s, wave speed of 14 m/s, and peak wave period of 16.6 s for mooring lines with and without a snubber. (A) Shape of the mooring line (B) Mooring tension in the cable.

benthic node. The other parameters are the same as those in Section 4.1.

Figure 10 shows that in this mooring-line configuration, the maximum load on the buoy is 2.77 tons and the maximum load on the Nilspin EM cable is 1.57 tons. The expected load on the Nilspin EM cable is basically the same as that on the buoy. The load on the Nilspin EM cable is much larger than that in Section 4.1. The snubber can absorb the tension, but it reduces the tension load only on the benthic node. The impact load on the buoy is directly transmitted to the Nilspin EM cable. The snubber does not absorb the dynamic tension from the buoy, because the Nilspin EM cable is directly connected to the buoy whereas the snubber is near the seafloor. It is not between the buoy and the EM cable. This dynamic analysis again indicates that each snubber

absorbs some of the tension load. The tension in the EM cable can be significantly reduced if the snubber is near the buoy.

4.3 Dynamic analysis of the mooring system with different lengths of snubber

The function of the snubber is described above. In this section, we compare mooring-line configurations with different lengths of snubber: 40, 120, 240, or 360 m. The basic mooring-line configuration is given in Table 5. We also analyze a mooring-line configuration with Nilspin EM cable of length 1200 m, but without a snubber, as the snubber in Table 5 is replaced by the Nilspin EM cable. The external load is for a 100-year storm.

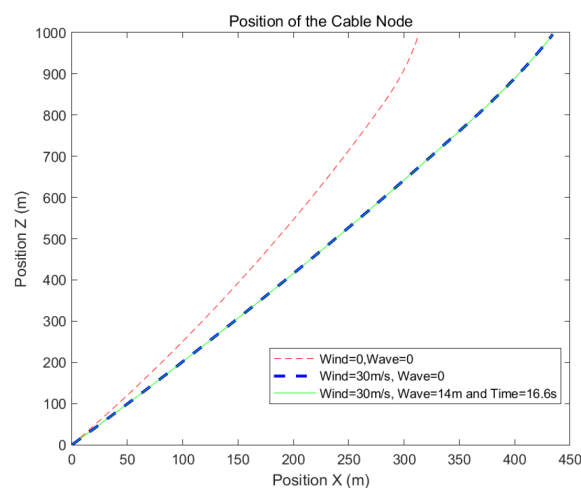


FIGURE 6

Shape of the mooring line for different weather conditions for a Nilspin cable with the snubber up.

TABLE 8 Comparison of the mooring tension in a Nilspin EM cable with the snubber up for different weather conditions .

Weather conditions	Tension range of EM cable (tons)	Tension range of snubber cable (tons)
10-year storm	1.45–1.78	1.78–2.33
30-year storm	1.55–1.89	1.89–2.43
100-year storm	1.73–2.06	2.06–2.56
Wind = 0 Wave = 0	0.67–1.01	1.01–1.55
Wind = 30 m/s Wave = 0	1.70–2.03	2.03–2.54

The shape of the mooring line is shown in Figure 11, and the mooring tension is plotted in Figure 12. As the snubber becomes longer, the slope of the mooring line becomes less steep and the mooring tension in the Nilspin EM cable falls and becomes smoother. Table 10 gives the mean, maximum, and standard deviation of the tension for the main components for different lengths of snubber. The table also gives approximate linear relations between the three tensions.

With an increase of the length of the snubber, the difference between the mean tension and the maximum tension becomes smaller. This confirms the results in Figure 4, which indicates that the mooring tension is basically constant for a nylon EM mooring cable. A snubber with a length of 30 m has a low elastic stiffness. Moreover, it is more difficult to install and recover the mooring system if the snubber is too long.

The approximate relations among the mean, maximum, and standard deviation of the tension are important in our choice of the Nilspin EM cable. The maximum operating tension of the cable should be greater than the maximum obtained in the dynamic analysis. This maximum usually lasts for a short time and is related to the wave period. The normal working tension is roughly the mean obtained by the dynamic analysis. The standard deviation of the tension verifies the results of vibration tests of the EM cable carried out by the manufacturer.

4.4 Summary

We simulated the steady state of the mooring system for the working depth of water. The snubber is an elastic buffer in the mooring module. It reduces the tension in the mooring cable from the buoy. It can be seen from Figure 4 that the snubber does not have a particularly large impact on the mooring force in the steady state. We had to decide whether to utilize Nilspin cable or nylon cable in the main mooring module. We chose Nilspin cable because nylon cable undergoes too much elastic deformation so that it is not suitable as an EM tether. Moreover, the nylon EM cable is difficult to manufacture.

We next analyzed the dynamic properties of a mooring tether made from Nilspin cable with a load due to ocean winds, waves, and currents. We had to decide whether the snubber should be near the sea surface buoy or near the benthic node, based on minimizing the tension in the snubber. Lastly, we had to consider the length of the snubber. Theoretically, the longer the snubber is, the better. However, the diameter of the snubber is relatively large. If the snubber is too long, it would be difficult to deploy the buoy and mooring system. Based on all these factors, we chose a suitable snubber and a suitable configuration, which can satisfy the dynamic mooring load.

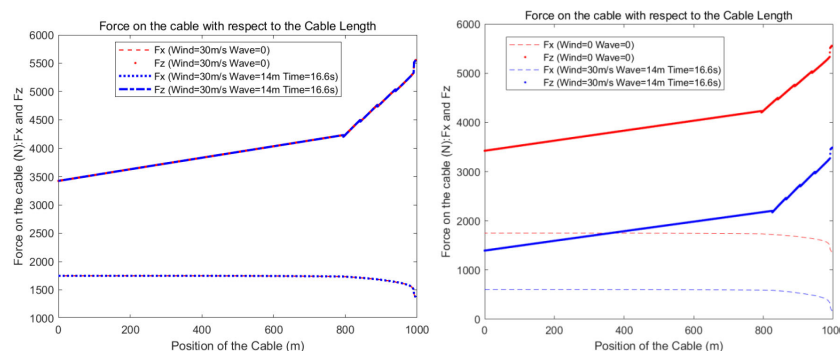


FIGURE 7

Mooring tension along the vertical direction F_z and horizontal direction F_x for different weather conditions for a Nilspin cable with the snubber up.

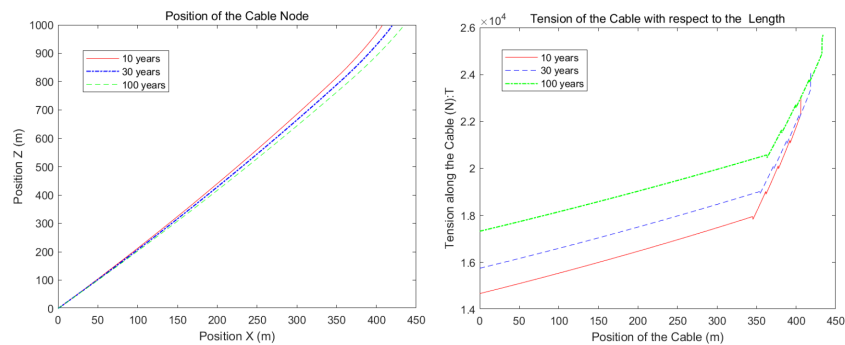


FIGURE 8

Shape of the mooring line and mooring tension for a Nilsipin EM cable with the snubber up for different storms.

5 Dynamic analysis of the mooring system when deploying the system

In this section, we simulate and analyze the dynamic properties during deployment. We usually adopt the method “buoy first, benthic node last” (Figure 13). Thus, we deploy the buoy with a frame and then the mooring line, and lastly, we deploy the benthic node from a ship into the sea. The difference between gravity and buoyancy is large, because the buoy is moored with a gravity anchor not a gripping anchor. Thus, the wet weight of the benthic node is 3 tons. When the benthic node is released from the A frame, its downward acceleration is due to the difference between gravity and buoyancy. It accelerates until the wet weight of the benthic node, the tension in the mooring cable, and the drag force of the benthic node become balanced. Since the shape of the mooring line varies continuously until the benthic reaches the seafloor, such a balance may not be achieved. However, as the downward speed of the benthic node increases, the drag force also increases, so the

maximum mooring tension may not be reached before the benthic node reaches the seafloor. This depends on the deployment depth, so we have to simulate these conditions to find the maximum mooring tension. Since the shape of the mooring line changes as the benthic node descends, the buoy will move rapidly on the sea surface toward the benthic node. Thus, we have to find the threshold mooring tension at which the buoyancy is insufficient and the buoy will sink into the water. Note that the mooring tension is not vertical, so that the buoy is inclined backward as it moves across the water surface. The deck of the buoy may be submerged in water, which may reduce its stability.

When the benthic node is released from the scientific research ship, it is assumed that the buoy and the ship are stationary. When it is first dropped, the benthic node has its maximum acceleration but zero velocity. At this moment, the distance between the buoy and the benthic node is a maximum. The velocity of the benthic node in the horizontal and vertical directions increases due to its acceleration. However, the buoy

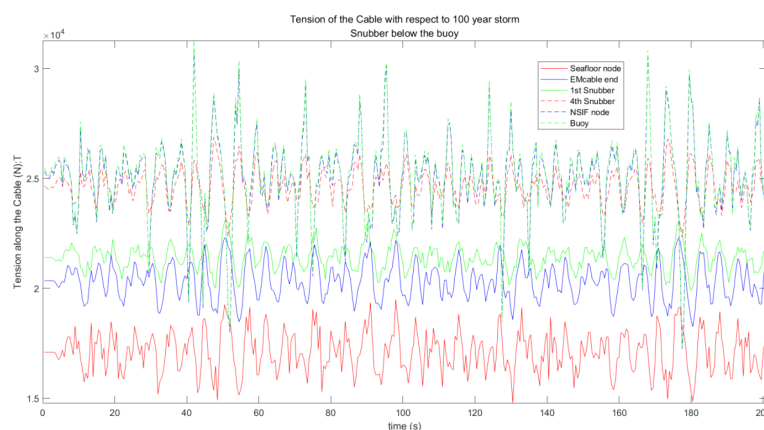


FIGURE 9

Dynamic tension for various components for a Nilsipin cable with the snubber up.

TABLE 9 Tension from the dynamic analysis for the snubber in different positions.

Tension	Benthic node	EM cable end	1st snubber	2nd snubber	3rd snubber	4th snubber	Buoy
Deployment at a depth of 1000 m with a 120-m snubber near the buoy							
$T_{mean}(N)$	17098.1	20344.1	21402.2	22464.4	23539.0	24622.9	25217.0
$T_{std}(N)$	714.99	664.046	452.55	326.542	458.088	621.38	1353.15
$T_{max}(N)$	19003.0	22201.2	22778.1	23365.5	24806.9	26488.1	30278.9
Deployment at a depth of 1000 m with a 120-m snubber: $T_{max} \approx T_{mean} + 3T_{std}$							
Deployment at a depth of 1000 m with a 120-m snubber near the benthic node							
$T_{mean}(N)$	13400.0	14522.2	15546.9	16588.9	17645.5	20887.4	21502.7
$T_{std}(N)$	702.054	501.33	360.907	462.701	653.471	1008.83	1794.66
$T_{max}(N)$	15164.9	16014.3	16504.7	17795.4	19496.1	23328.6	27767.0
Deployment at a depth of 1000 m with a 120-m snubber: $T_{max} \approx T_{mean} + 3T_{std}$							

moves toward the benthic node with horizontal velocity only, since the mooring tension along the vertical direction is absorbed by the reserve buoyancy of the buoy. In this chapter, we analyze the change in the shape of the mooring line and the velocities of the buoy and benthic node.

The shape of the mooring line during deployment is shown in Figure 14, and the velocities of the buoy and benthic node are plotted in Figure 15. Figure 15 indicates that it takes 3 min from being released for the benthic node to reach the seafloor. The maximum mooring force is 32.7 kN, which occurs at 101 s. When the benthic node reaches the seafloor, the mooring tension gradually falls. Finally, the mooring tension achieves a steady state due to the action of the ocean current, if there are no winds or waves. As the benthic node descends, the buoy moves 331 m in the horizontal direction and the benthic node 218 m. The maximum speed of the benthic node in the vertical direction is 9.26 m/s and the maximum speed in the horizontal direction is 2.05 m/s, which occurs about 10 s after

deployment. The maximum speed of the buoy in the horizontal direction is 1.68 m/s, which occurs after about 146 s.

This simulation suggests that if the buoy does not have enough buoyancy to balance the vertical component of the mooring tension, we will have to use an auxiliary boat to hold the buoy up and prevent it from sinking into the water.

6 Conclusion and future works

In this paper, we optimized the mooring EM cable for the future MBOSBC. Nylon rope is a good choice for a traditional buoy due to its low wet weight and high extension ratio (about 20%). The expansion can absorb the load from the surface buoy, which reduces the maximum mooring tension. However, it is not a good choice for an EM cable, since the extension ratio of the electric core and optical fiber core (0.5%) does not match

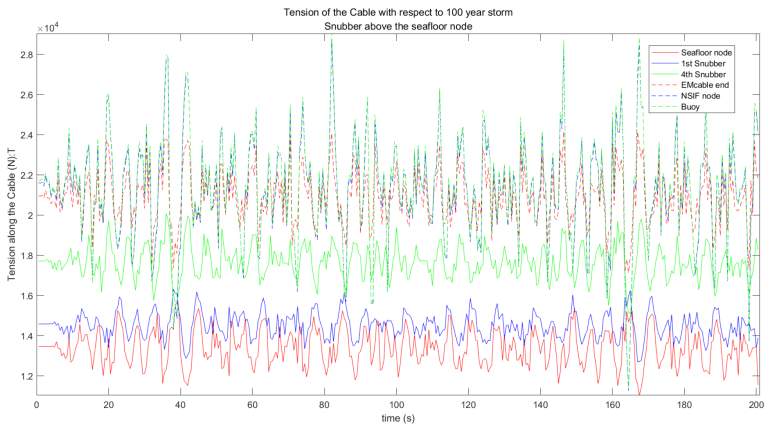


FIGURE 10
Dynamic tension for various components for a Nilsipin cable with the snubber down.

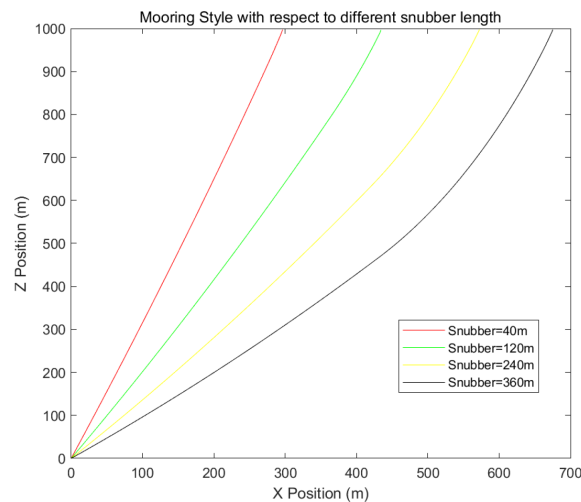


FIGURE 11

Shape of the mooring line for different lengths of snubber for a Nilspin cable with the snubber up.

that of the nylon material. Moreover, the manufacturing process for a nylon EM cable is too complex and difficult, so we adopted the Nilspin EM cable for mooring the buoy.

Then, we analyzed the combined mooring method with Nilspin EM cable and a snubber. The snubber has a low elastic stiffness, so that it absorbs the dynamic load generated by waves. This combination reduces the stiffness of the mooring line and improves its flexibility. The length of a single snubber is about 30 m. Considering the difficulty of system deployment, we selected four segments for the mooring line.

An analysis of the mooring tension for different mooring-line configurations and external environmental loads showed that winds and ocean currents are the main factors affecting the

steady-state mooring tension, which is important in designing an EM cable. The influence of ocean waves on the mooring system was assessed with a dynamic analysis. The periodic wave motion caused the buoy to move, putting a load on the mooring line. In the combined mooring method, the snubber absorbed some of the dynamic load. Once the load had dissipated, the stored tension due to elastic deformation was released and the snubber returned to its original state. The load due to wave motion was isolated by the snubber, which reduced the mooring tension in the Nilspin EM cable so that it remained within a relatively stable range. This tension is the working load on the Nilspin EM cable, and the snubber compensates for the poor flexibility of a Nilspin EM cable. From the dynamic analysis, we

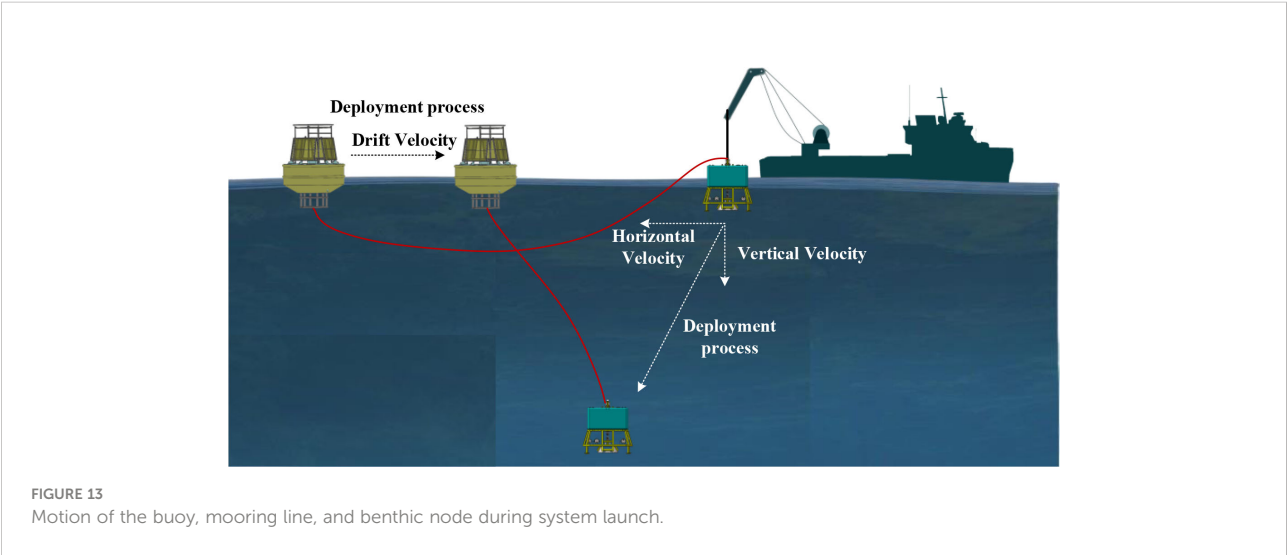


FIGURE 12

Dynamic tension for various components for different lengths of snubber for a Nilspin cable with the snubber up.

TABLE 10 Tension from the dynamic analysis for different lengths of snubber.

Tension	Benthic node	EM cable end	1st snubber	2nd snubber	3rd snubber	4th snubber	Buoy
Deployment at a depth of 1000 m with a 40-m snubber							
(N)	24929.3	28663.3	28945.2	29225.6	29504.8	29780.8	30390.5
(N)	793.474	667.167	593.085	525.147	507.655	501.148	1072.73
(N)	27126.1	30214.1	30374.0	30409.7	30687.8	30979.5	33251.2
Deployment at a depth of 1000 m with a 40-m snubber: $T_{max} \approx T_{mean} + 3.4T_{std}$							
Deployment at a depth of 1000 m with a 120-m snubber							
(N)	17098.1	20344.1	21402.2	22464.4	23539.0	24622.9	25217
(N)	714.99	664.046	452.55	326.542	458.088	621.38	1353.15
(N)	19003.0	22201.2	22778.1	23365.5	24806.9	26488.1	30278.9
Deployment at a depth of 1000 m with 120-m snubber: $T_{max} \approx T_{mean} + 3T_{std}$							
Deployment at a depth of 1000 m with a 240-m snubber							
(N)	13189.5	15752.0	17877.1	20066.6	22308.4	24590.2	25169.4
(N)	572.084	548.317	304.09	392.036	453.131	548.327	1307.67
(N)	14503.5	16969.7	18638.0	21097.3	23756.9	26200.3	29739.6
Deployment at a depth of 1000 m with a 240-m snubber: $T_{max} \approx T_{mean} + 2.5T_{std}$							
Deployment at a depth of 1000 m with a 360-m snubber							
(N)	11088.5	12986.9	16030.0	19298.5	22707.5	26204.9	26820.9
(N)	487.337	474.389	290.544	404.088	397.3	522.895	1293.94
(N)	12102.4	13976.0	16661.1	20278.	23796.7	27630.5	31756.5
Deployment at a depth of 1000 m with a 360-m snubber: $T_{max} \approx T_{mean} + 2.1T_{std}$							



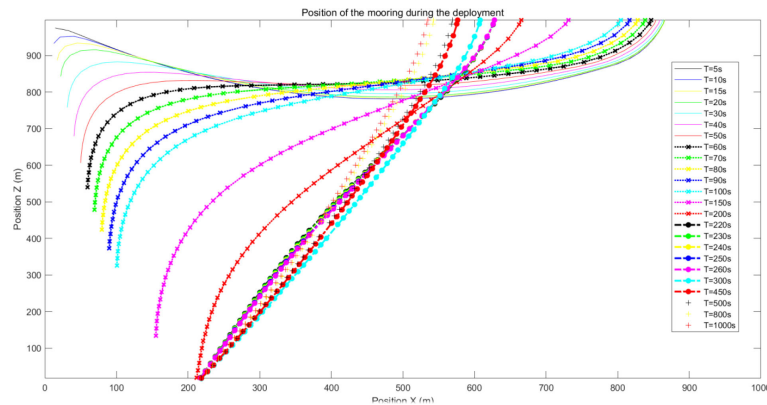


FIGURE 14
Change in the shape of the mooring line during deployment.

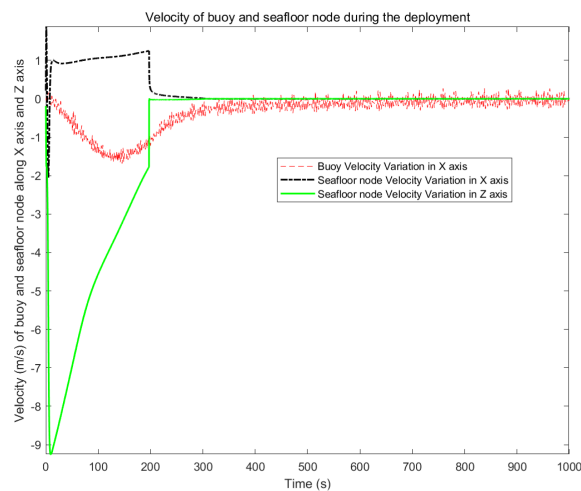


FIGURE 15
Velocities of the buoy and benthic node during system deployment.

inferred a relation among the mean, standard deviation, and maximum of the tension. Based on this, we chose the design values and requirements for the EM cable, especially the duration of the maximum tension. This may serve as a good reference for the duration of the maximum tension in an EM cable.

We analyzed the dynamics of the buoy during system deployment as the benthic node sinks from the water surface to the seabed. If the benthic node is too heavy, it will have an excessive vertical velocity. The mooring tension is transmitted to the buoy, which moves rapidly toward the benthic node in the horizontal plane. If the reserve buoyancy of the buoy is insufficient, we will need to pull the buoy up with an auxiliary ship to prevent it from being pulled into the sea.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization and Simulation, S.W. Zhang and F.H. Zhang writing-review and editing, S.W. Zhang and C. Tian. Application, F.H. Zhang and C. Tian. All authors contributed to the article and approved the submitted version.

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References

- Chaffey, M., Bird, L., Erikson, J., Graybeal, J., Hamilton, A., Headley, K., et al. (2005). "MBARI's buoy-based seafloor observatory design," in *Proceedings of IEEE OCEANS 2005*, Washington, DC, USA (18–23 Sept), *Proceedings of OCEANS 2005 MTS/IEEE - Project ENDEAVOR: Distributed Modeling for Advanced Marine Vehicle Performance Analysis*, 4, 1975–1984.
- Chaffey, M., Mellinger, E., and Walter, P. (2001). "Communications and power to the seafloor: MBARI's ocean observing system mooring concept," in *Proceedings of MTS/IEEE oceans 2001*, (Honolulu, HI, USA: An Ocean Odyssey), 2473–2481. doi: 10.1109/OCEANS.2001.968389
- Clark, A. M. (2010). CSnet's offshore communications backbone in Cyprus. *Touch Briefings Explor. Prod.* 9 (1), 1–4. doi: 10.23919/OCEANS.2011.6107087
- Clark, A. M., and Kocak, D. M. (2011). "Installing undersea networks and ocean observatories: The CSnet offshore communications backbone (OCB)," in *Proceedings of IEEE OCEANS 2011*, Waikoloa, HI (19–22 Sept), *OCEANS'11 MTS/IEEE KONA - Highlights of renewable energy studies and research in the bureau of ocean energy management, regulation and enforcement*, 1–9. doi: 10.23919/OCEANS.2011.6107087
- Clark, A. M., Kocak, D. M., Martindale, K., and Woodroffe, A. (2009). "Numerical modeling and hardware-in-the-loop simulation of undersea networks, ocean observatories and offshore communications backbones," in *Proceedings of MTS/IEEE oceans 2009 conference* (Bremen, Germany, IEEE OCEANS 2009 Conference Europe: Biloxi, MS), 26–29. doi: 10.23919/OCEANS.2009.5422204
- De Martino, P., Guardato, S., Tammara, U., Vassallo, M., and Iannaccone, G. (2014). A first GPS measurement of vertical seafloor displacement in the campi flegrei caldera (Italy). *J. Volcanol Geotherm Res.* 276, 145–151. doi: 10.1016/j.jvolgeores.2014.03.003
- Detrick, R., Frye, D., Collins, J., Gobat, J., Grosenbaugh, M., Petit, R., et al. (2000). *DEOS moored buoy observatory design study* (Arlington, VA: National Science Foundation/Ocean Sciences Division).
- Favali, P., Beranzoli, L., and D'anna, G. (2006). A fleet of multi parameter observatories for geophysical and environmental monitoring at seafloor. *Ann. Geophys.* 49, 659–680. doi: 10.4401/ag-3126
- Frye, D., Hamilton, A., Paul, W., Chaffey, M., et al. (2004). Deepwater mooring designs for ocean observatory science. *Mar. Technol. Soc. J.* 38 (2), 7–20. doi: 10.4031/002533204787522857
- Georgiou, G., Clark, A. M., Zodiatis, G., Hayes, D., and Glekas, D. (2010). "Design of a prototype tsunami warning and early response system for Cyprus – TWERC," in *IEEE OCEANS*, vol. 24–27. (Sydney), 1–5.
- Gobat, J. I., and Grosenbaugh, M. A. (2000). WHOI cable v2.0: Time domain numerical simulation of moored and towed oceanographic systems. *Woods Hole Oceanographic Inst., Woods Hole MA Tech Rep. WHOI 2000-08*, 2000.
- Grosenbaugh, M. A., Paul, W., Frye, D., and Farr, N. (2006). Development of synthetic fiber-reinforced electro-optical-mechanical cables for use with moored buoy observatories. *IEEE J. Oceanic Eng.* 31 (3), 574–583. doi: 10.1109/JOE.2005.850937
- Hamilton, A., and Chaffey, M. (2005). "Use of an electro-optical-mechanical mooring cable for oceanographic buoys: Modeling and validation," in *Proceedings of the 24th International Conference on Offshore Mechanics and Arctic Engineering*, Halkidiki, Greece (12–17, June), 24th International Conference on Offshore Mechanics and Arctic Engineering: Volume 1, 1–7.
- Hamilton, J. A., Chaffey, M., Mellinger, E., Erickson, J., and McBride, L. (2003). "Dynamic modeling and actual performance of the MOOS test mooring," in *Proceedings of OCEANS* (San Diego, CA), 2574–2581.
- Han, S. M., and Grosenbaugh, M. A. (2006). On the design of single-point cable-linked moorings for ocean observatories. *IEEE J. Oceanic Eng.* 31 (3), 585–597. doi: 10.1109/JOE.2005.850917
- Iannaccone, G., Guardato, S., Vassallo, M., Elia, L., and Beranzoli, L. (2009). A new multidisciplinary marine monitoring system for the surveillance of volcanic and seismic areas. *Seismol. Res. Lett.* 80 (2), 203–213. doi: 10.1785/gssrl.80.2.203
- Makris, J., Papoulia, J., and Tsambas, A. (2014). A real-time seismic and tsunami network in the kyparissiakos gulf, Greece. *Bollettino di Geofisica Teorica ed Applicata* 55 (2), 561–587. doi: 10.4430/bgta0120
- Paul, W., Bentley, D., Chaffey, M., Frye, D., and , D. (2003). "Electrical and electro-optical mooring links for buoy based ocean observatories," in *Proceedings of the 2003 International Conference on Physics and Control - Volume 3*, Saint Petersburg, Russia (20–22 Aug.), International Conference on Physics & Control IEEE Computer Society, 201–206. doi: 10.1109/SSC.2003.1224142
- Smith, L. M., Barth, J. A., Kelley, D. S., Plueddemann, A., Roderio, I., Ulses, G. A., et al. (2018). The ocean observatories initiative. *Oceanography* 31 (1), 16–35. doi: 10.5670/oceanog.2018.105
- Trowbridge, J., Weller, R., Kelley, D., Dever, E., Plueddemann, A., Barth, J. A., et al. (2019). The ocean observatories initiative. *Front. Mar. Sci.* 6, 1–23. doi: 10.3389/fmars.2019.00074
- Yu, J., Zhang, S., Yang, W., Xin, Y., and Gao, H. (2020). Design and application of buoy single point mooring system with electro-optical-mechanical (EOM) cable. *J. Mar. Sci. Eng.* 8 (672), 1–25. doi: 10.3390/jmse8090672
- Zhang, S., Yang, W., Xin, Y., Wang, R., Li, C., Cai, D., et al. (2018). Prototype system design of mooring buoy for seafloor observation and construction of its communication link. *J. Coast. Res.* 83, 41–49. doi: 10.2112/SI83-008.1



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Analysis of the accuracy of using ERA5 reanalysis data for diagnosis of evaporation ducts in the East China Sea

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Evaporation ducts are a phenomenon that occurs with extremely high frequency at the boundary between the atmosphere and the ocean. Because they directly affect the propagation of electromagnetic waves, it is necessary to study their various characteristics. Since it is difficult to conduct large-scale observations at sea, many researchers use reanalysis data for this task instead of observation data. However, there have been no studies verifying accuracy of this analysis method for the diagnosis of evaporation ducts. Therefore, in this work, observations of the low-altitude atmospheric refractivity profile were carried out over the East China Sea on board the research vessel *Xiangyanghong 18* in April 2021. First, the differences between different evaporation duct models were examined based on the meteorological and hydrological data obtained at different heights. It was concluded that the diagnostic accuracy of the evaporation duct model is low in stable conditions and a low-wind-speed environment. Under the same conditions, the Naval Postgraduate School (NPS) model showed high diagnostic accuracy when compared with other models. Second, Taylor plots were used to verify the accuracy of the reanalysis data and the observation data. It was concluded that the single-parameter precision of the reanalysis data is relatively high, and there were strong correlations with the observation data. Finally, the observation and reanalysis data were used to compare and analyze the false-report rate, the missing-report rate, and the accuracy of the diagnosed evaporation duct height using the NPS model. The false-report rate and missing-report rate were found to be 1.93% and 1.52%, respectively. The average diagnosis deviation was 3.34 m. The Pearson correlation coefficient was found to be close to 1. The results indicate that it is basically feasible to analyze the characteristics of evaporation ducts based on the NPS model using reanalysis data.

KEYWORDS

ocean observation, evaporation duct, atmospheric refractivity profile, boundary layer (B.L), air-sea interaction

1 Introduction

Evaporation ducts occur because of atmospheric stratification formed by the rapid decrease of water vapor with height near the sea surface; they are typically generated by ocean–atmosphere interactions. Research has shown that the probability of an evaporation duct occurring in the South China Sea exceeds 80% (Yang et al., 2017; Qiu et al., 2022). Evaporation ducts can cause anomalous propagation of electromagnetic (EM) waves, especially in the microwave band (Hitney and Vieth, 1990; Lentini and Hackett, 2015). On the one hand, trapped EM waves can propagate with lower loss in the ducting layer, which can realize beyond-the-horizon detection. On the other hand, an evaporation duct will allow EM waves of frequencies higher than the lowest trapped frequency and incident angle less than the critical angle to enter the ducting layer, causing a radar blind zone at a certain angle. As shown in Figure 1, the evaporation duct parameters—height (EDH) and strength (EDS)—directly affect the transmission path of EM waves on the sea surface (Wang et al., 2018). Therefore, accurate diagnosis of evaporation duct parameters is of great significance to maritime radio communications and radar target detection (Zhang et al., 2016a; Zaidi et al., 2018; Shi et al., 2019).

Refraction, the cause of the evaporation duct phenomenon, can be characterized by the vertical gradients in the atmospheric refractive index n . To more conveniently represent and account for the curvature of the Earth, n is usually replaced with a modified refractivity M , which is related to the atmospheric pressure AP (hPa), air temperature AT (K), partial pressure of water vapor e (hPa), and height above the sea surface z (m) through the equation:

$$M = 77.6 \frac{AP}{AT} - 5.6 \frac{e}{AT} + 3.73 \frac{e}{AT^2} + 0.157z \quad (1)$$

When using multiple meteorological observational data points from different heights to calculate the EDH, a least-squares fitting method is usually used to obtain the corresponding vertical profile of M (Babin et al., 1997). This profile is based on a log-linear function given by

$$M = f_0 z - f_1 \ln(z + 0.001) + f_2 \quad (2)$$

The constant 0.001 is added to prevent $\ln(0)$ from occurring at the sea surface. For each case, the coefficients f_0 , f_1 , and f_2 can be calculated for a least-squares best fit. The EDH is defined as the height at which $\partial M / \partial z$ is equal to 0, or, equivalently, the height at which M is a minimum (Almond and Clarke, 1983). As shown in Figure S1, the difference between the modified refractivity M at height 0 and the modified refractivity M at the EDH is the EDS.

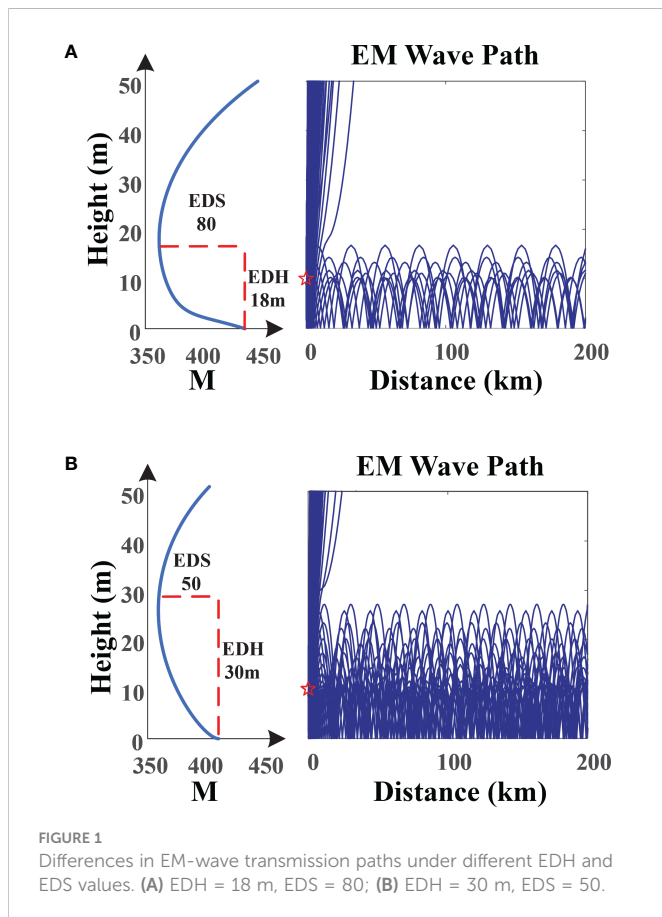
Currently, the main methods for obtaining the evaporation duct parameters are:

- Using a refractometer to directly measure the atmospheric refractivity at different heights (Chai et al., 2022);
- Using a radiosonde and meteorological observation towers to measure meteorological parameters at different heights and indirectly calculating the vertical distribution of atmospheric refractivity (Liu et al., 1979; Karimian et al., 2012);

- Using an evaporation duct model (EDM) based on meteorological and hydrological parameters (Sun et al., 2016; Zhang et al., 2017).

The basic principle of the last method is the Monin–Obukhov similarity theory. By measuring the wind speed (WS), air temperature (AT), relative humidity (RH), and air pressure (AP) at certain heights and the sea-surface temperature (SST), an empirical model can be developed to calculate the vertical distribution of atmospheric refractivity, and the evaporation duct parameters can then be obtained. Because of its convenient operation, this method has received extensive attention. Many EDMs have been proposed, including the Paulus–Jeske (Jeske, 1973), Babin–Young–Carton (BYC) (Babin et al., 1997), revised fifth-generation mesoscale (MM5REV) (Jiao and Zhang, 2015), Naval Postgraduate School (NPS) (Frederickson et al., 2000), Naval Warfare Assessment (NWA) (Liu and Blanc, 1984), Liu–Katsaros–Businger (LKB) (Babin and Dockery, 2002), and Coupled Ocean–Atmosphere Response Experiment (Fairall et al., 2003) models. These models all take atmospheric stratification into account. Atmospheric stratification is an important factor affecting an evaporation duct. In physical oceanography, the Richardson number (Ri) is usually used to characterize atmospheric stratification: $Ri > 0$, $= 0$, and < 0 respectively indicate that the atmosphere is in a stable, neutral, or unstable condition. In current boundary-layer parameterization schemes, Ri is usually set as a semi-empirical parameter, and different EDMs use different calculation methods for this. Although these EDMs are all based on the Monin–Obukhov similarity theory, they show different diagnostic results under different meteorological and hydrological environments. The uncertainty of the theoretical model is from the empirical parameters (the stability functions and roughness length parameterization) of the model, these parameters are derived from local observations. Which EDMs is more suitable for the East China Sea needs to be verified by actual ocean observation data.

To research the evolution rules and distribution characteristics of evaporation ducts, it is necessary to obtain real-time meteorological and hydrological data; however, this is very difficult at sea. Therefore, many researchers have started to use reanalysis data and apply EDMs to study the occurrence laws of evaporation ducts in particular areas. Since the 1980s, the US Navy has attempted to study atmospheric ducts using mesoscale weather models (Burk and Thompson, 1989). Since the mid-1990s, the US Naval Research Laboratory (NRL) has been developing a three-dimensional ocean–atmosphere coupled mesoscale forecast system (COAMPS). With continuous improvement of the data-assimilation system, wave parameterization, boundary-layer scheme, etc., this system has been deployed for many years in US Navy combat forecasts and applied to an evaporation duct numerical weather-prediction system (Hodur, 1997; Zhao et al., 2016). Zhu and Atkinson (2005) used the third-generation mesoscale (MM3) model to conduct one-year hindcasted predictors in the Persian Gulf and analyze the seasonal characteristics of evaporation ducts. Haack et al. (2010) used four mesoscale numerical weather-prediction models on the eastern coast of the United States to simulate the atmospheric refractive index and duct-layer structure; they found that the characteristics of evaporation



ducts are highly correlated with the SST, atmospheric stability, and underlying surface roughness.

The reanalysis data used in the above research assimilate a large amount of satellite and conventional observational data; this has the advantages of covering long time periods with high resolution. Since the 1990s, the United States, Europe, Japan, and other countries have successively developed reanalysis data products, including National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (American reanalysis data; ARD), National Centers for Environmental Prediction-Department of Energy (NCEP/DOE) (ARD), NCEP Climate Forecast System Reanalysis (CFSR) (ARD), Climate Forecast System version 2 (CFSv2) (ARD), Japanese 25-year Reanalysis project (JRA) (Japanese reanalysis data; JRD), Japanese 55-year Reanalysis (JRA55) (JRD) (Zhang et al., 2016b). The European Center for Medium-Range Weather Forecasts (ECMWF) was one of the early institutions to reanalyze data, and it developed the First Global Atmospheric Research Program Global Experiment (FGGE), ECMWF Reanalysis-40 years (ERA-40), and ERA-Interim datasets. In 2016, the ECMWF released the fifth-generation reanalysis product ERA5. Many researchers have analyzed the accuracy of different elements of reanalysis data, and they have generally concluded that the ERA5 data has higher accuracy than other available products (Shi et al., 2021). In 2015, the China Meteorological Administration (CMA) developed the Land Data Assimilation System (CLDAS-CMA), which includes high-precision WS, AT, RH, and AP data in the seas near China, but it does not include SST. Research has shown that the accuracy of reanalysis data is highly correlated with the

change trends of actual observation data (Luo et al., 2019). Tian et al. (2020) tried to analyze the influence of seasonal and nonreciprocal evaporation duct characteristics on EM wave propagation in the Gulf of Aden by using ERA5 to reanalyze the data. However, due to the difficulty of obtaining ocean-observation data, the accuracy of this kind of analysis needs to be further verified (Meng et al., 2018).

In summary, the environmental suitability of different EDMs to the East China Sea and the feasibility of using reanalysis data to study evaporation duct characteristics need to be verified. However, the above research needs to rely on the actual offshore evaporation duct observation data. In view of the lack of observational data relating to evaporation ducts at sea, an observation of the low-altitude atmospheric refractivity profile was carried out over the East China Sea. This was conducted on board the research vessel (R/V) *Xiangyanghong 18*. To obtain the atmospheric refractive index at different heights, five layers of meteorological and hydrological sensors were installed on the hull at different heights in the range 6–25 m, and a 25-day low-altitude atmospheric refractive-index-profile observation was carried out. Observation data, including WS, AT, RH, AP, and SST, were obtained under different time and space conditions, and these were analyzed and compared. First, the accuracy of the atmospheric refractive indexes obtained under different meteorological and hydrological conditions at different heights using different EDMs was analyzed and studied; second, the CLDAS and ERA5 reanalysis data were compared with the actual observation data; finally, the evaporation duct parameters obtained from the observations and from the ERA5 reanalysis data were examined and compared. The false-alarm rate, missing-report rate, and accuracy of the diagnosis results obtained using the reanalysis data were calculated. This study provides experimental verification for the subsequent use of reanalysis data to analyze the characteristics of evaporation ducts.

2 Data

The data used in this paper include the ocean-observation, ERA5 and CLDAS datasets.

2.1 Ocean-observation dataset

From the National Natural Science Foundation of China Open Research Voyage (Voyage No. NORC2021-02+NORC2021-301), different temporal and spatial meteorological and hydrological gradient observations in the East China Sea (as shown in Figure 2) were obtained from the 00:00:00 UTC+8 8 April 2021 to 23:59:59 UTC+8 24 April 2021. To obtain meteorological and hydrological parameters at different altitudes, as shown in Figure 3, five layers of high-precision HUMICAP sensors were installed on the bow deck (6.0 m), accommodation deck (8.3 m), compass deck (13.1 m), first-layer mast (14.8 m), and third-layer mast (22.3 m) of the R/V *Xiangyanghong 18* (IMO 9769506) to achieve layered measurements of AT and RH at different heights. An Airmar WeatherStation and a barometric pressure sensor were installed in the middle of the living deck to obtain observation data of WS and AP, respectively. A pair of infrared temperature sensors was installed on the port and starboard

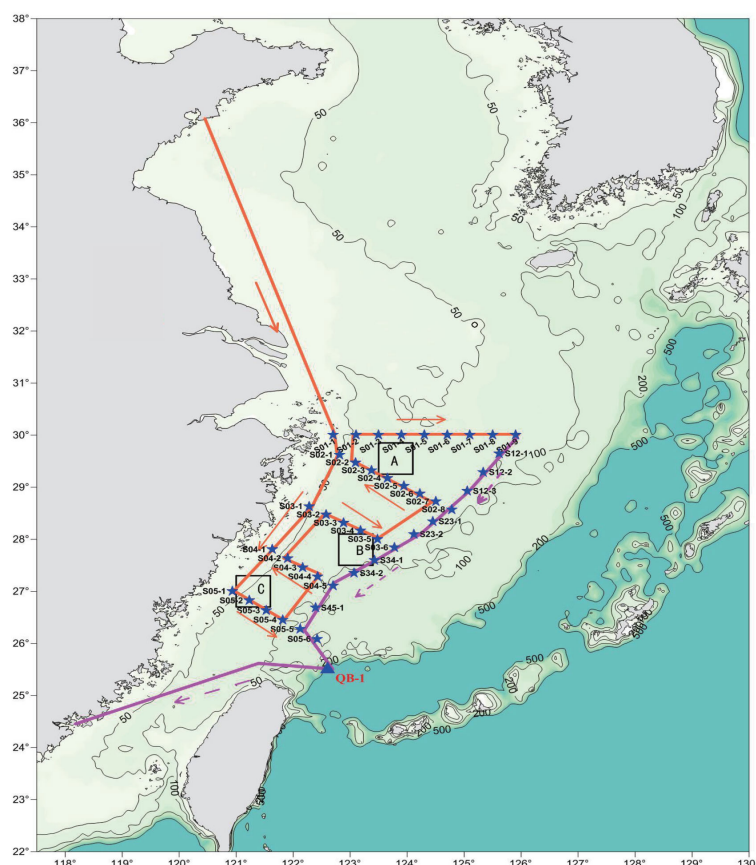


FIGURE 2

Station and route map of the voyage. Select three areas from north to south (areas A, B, and C in the figure), and the ship will sail back and forth in these areas.

to obtain the SST. All observation data were sent to a data collector in the ship's data center through communication cables. The collection frequency was set to 1 Hz.

To ensure the accuracy of the observed data, high-precision sensors were used and appropriate sensor calibrations were performed. The sensor parameters and their installation locations are shown in Table 1.

2.2 ERA5 dataset

The ERA5 reanalysis data is the latest generation of reanalysis data to be created by the ECMWF. It was first released in January 2019. These data can be used for tasks such as climate monitoring and numerical weather forecasting. The ERA5 product has been further upgraded on the basis of the previous series of reanalysis data products released by the ECMWF. More historical observation data, especially satellite data, have been applied to the advanced data assimilation and model system to estimate atmospheric conditions more accurately. ERA5 provides more variables, including AT, AP, wind force at different heights, rainfall, soil moisture content, wave height, and wave direction. In this work, only the 2-m temperature, 2-m dewpoint temperature d_{2m} , 10-m u and v wind components u_{10m} and v_{10m} , sea-surface pressure, and SST parameters of the sea area 24–32°N, 118–126°E in the previously noted period were used. The 10-m

WS is calculated using vector synthesis with the u and v wind components: $WS = \sqrt{u_{10m}^2 + v_{10m}^2}$. The parameters t_{2m} and d_{2m} are used as inputs for the Goff-Gratch equation to solve the actual water vapor pressure $e = \text{Goff_Gratch}(d_{2m})$ and the saturation water vapor pressure $E = \text{Goff_Gratch}(t_{2m})$. The 2-m RH is then expressed as $e/E \times 100\%$. The values of WS, AT, RH, AP, and SST, obtained from the ERA5 reanalysis dataset were compared with the ocean-observation data and the diagnostic values of the evaporation duct.

2.3 CLDAS dataset

The CLDAS (the China Meteorological Administration Land Data Assimilation System) uses multi-grid three-dimensional variational technology in a space and time multiple analysis system, and the National Centers for Environmental Prediction/Global Forecast System (NCEP/GFS) numerical model analysis/prediction products are used as the background field; these results were compared with the actual observation data at sea and from satellites. Multi-source fusion of observational data was performed to drive the Community Land Model Version 3.5 (CLM3.5) model to obtain high-quality grid datasets of elements such as AT, AP, RH, WS, precipitation, and radiation in offshore China. In this study, only the 2-m temperature, 2-m specific humidity, 10-m WS, and surface-pressure parameters of the 24–32°N, 118–126°E sea area in the



FIGURE 3
Schematic diagram of the sensor installation positions of the R/V Xiangyanghong 18 (IMO 9769506).

previously noted period were used. The RH values were obtained by calculation using the temperature, specific humidity, and surface pressure. The CLDAS dataset and the ocean-observation dataset were used for comparative analysis to verify the accuracy of the CLDAS reanalysis dataset. Unfortunately, the CLDAS dataset does not contain SST data. However, we can still compare the accuracy of the ERA5 and CLDAS datasets.

3 Data analysis

3.1 Ocean-observation dataset

Throughout the voyage, the AT and RH values from the five layers at different altitudes, and the AP, WS, and SST values from a single layer were obtained continuously. In addition, based on the obtained meteorological and hydrological observation data, the Ri calculation method was used in the process of solving the NPS model to obtain the atmospheric stratification.

Figure 4 shows plots of the meteorological and hydrological observation data in the time dimension. Figure 4A shows the

temperature data from the five layers. Here, AT-1, AT-2, AT-3, AT-4, and AT-5 represent the AT data from layers 1 to 5, respectively. It can be seen that the AT range during the whole voyage was 10°C to 28°C, and the AT values between each layer were constantly crossing. Figure 4B shows the RH data of the five layers at the same positions as the AT data. Similarly to the AT plots, RH-1, RH-2, RH-3, RH-4, and RH-5 represent the RH curves at the five respective heights. The RH varied from 42% to 100%. During certain periods of time, there were differences in the values of the layers. Figure 4C shows the AP data measured on the forecastle deck; its variation range was 1005–1026 hPa. Figure 4D shows the WS values measured on the compass deck; its variation range was 0–21 m/s. There were few WS values greater than 15 m/s, and the speeds were mostly concentrated below this value. Figure 4E shows the SST data acquired by infrared temperature sensors on the port and starboard sides of the compass deck. Due to changes in the angle between the ship's heading and the level of sunlight, the side of the ship away from the sun will be blocked to a certain extent. Therefore, the observation data from the left and right sides are different at certain moments, but their change trends are basically the same. Figure 4F shows the Ri number calculated using the AT and AP values from the forecastle

TABLE 1 Sensor parameters and installation location information.

Sensor	Type	Specification	Location	Height (m)
HUMICAP	Vaisala HMP155	RH: 15–25 °C: $\pm 1\%$ RH (0–90%RH); –20–40 °C: $\pm 1.7\%$ RH (90–100%RH)	Mast 3rd floor	22.3
			Mast 1st floor	14.8
			Compass deck	13.1
		AT: $\pm(0.055-0.0057 \times \text{AT}^\circ\text{C})$	Accommodation deck	8.3
			Forecastle deck	6.0
Barometric pressure	YOUNG 61302L	± 0.2 hPa (25 °C, ± 0.3 hPa (–40–60 °C)	Compass deck	13.7
WeatherStation	AIRMAR 150WXS	5% (10m/s)	Compass deck	13.7
Infrared thermometers	Optris CTLT20	$\pm 1^\circ\text{C}$	Compass deck	13.1

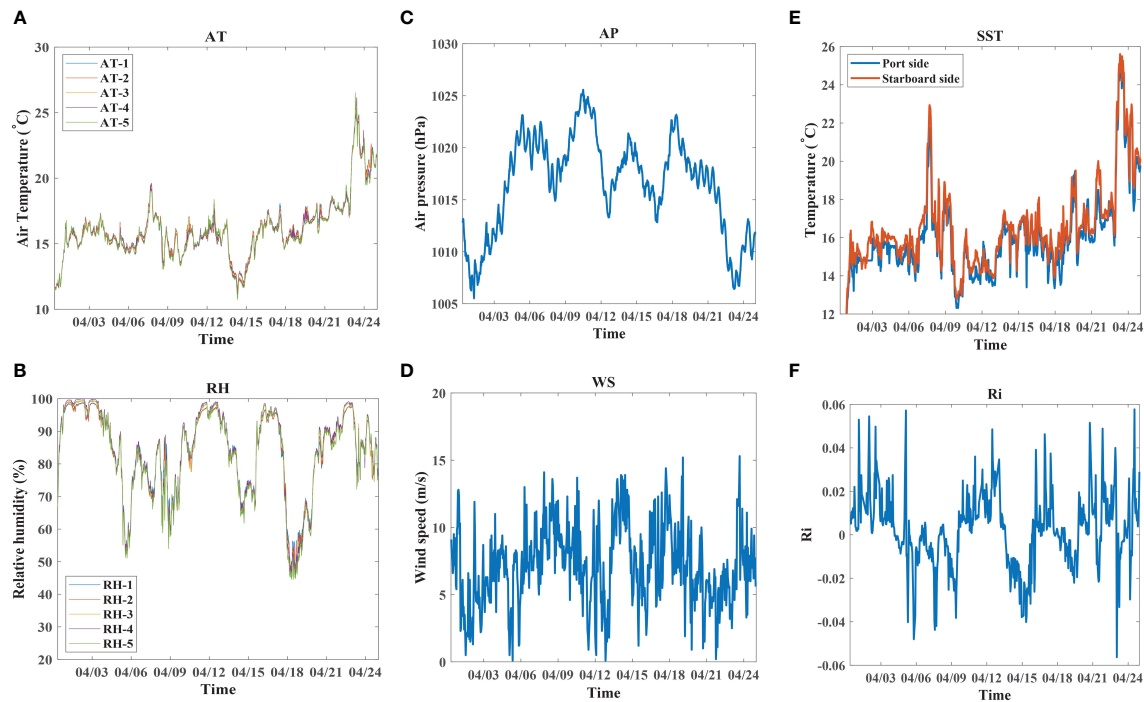


FIGURE 4
Variation curves of the acquired observation data in the time dimension. (A) AT; (B) RH; (C) AP; (D) WS; (E) SST; (F) Ri.

deck and the WS values from the compass deck. It can be seen that the Ri number changes with the fluctuations in the meteorological and hydrological environment. According to the statistics of these results, the ratio of stable to unstable conditions in the atmosphere was 9:5; there were thus more periods of stable than unstable atmospheric conditions during this voyage.

The profiles of AT and RH with height changed continuously over time. These changes are the main factor for the generation, development, and evolution of evaporation ducts. As shown in Figure 5, the RH profile was different on different days and at different times of the day. As shown in Figures 5A, B, the RH appears to decrease sharply at the highest level, and this change could easily cause the rapid generation of an evaporation duct. Figure 6 shows the change trend in the temperature profiles on different days and at different times of the day. The asterisk (“*”) at a height of 0 m indicates the SST. At some times, there were large variations in AT, up to 3° C. It can be seen from Figures 5, 6 that under different meteorological and hydrological environments, the AT and RH profiles are constantly changing, and this leads to constant changes in the evaporation duct.

A statistical analysis of the observation data in the spatial dimension is shown in Figure 7. Figure 7A shows that the AT is generally lower in the north and higher in the south. The AT is the highest in the northeastern waters of Taiwan, where the Kuroshio approaches the coast of China. Figure 7B shows the changes in RH in the spatial dimension. It can be seen that during the voyage along the coast of China, the RH was relatively high; however, it varied greatly during the voyage. Figure 7C shows the changes in AP in the spatial dimension. A relatively high AP appeared near 30°N, and the lowest AP appeared in the northeastern waters of Taiwan. Figure 7D shows the changes in WS in the spatial dimension. It can be seen that the WS

values in the areas far from the coast are obviously greater than those near the coast. Figure 7E shows the variation of SST in the spatial dimension. The distribution is random, but in the sea area of northeastern Taiwan, it is significantly higher than in other sea areas, which is consistent with the high-temperature characteristics of the Kuroshio (Ferrari, 2011). In addition, the SST values in the Taiwan Strait are also significantly higher than those in other sea areas. Figure 7F shows the variation of Ri in the spatial dimension. It can be seen that the unstable conditions mainly appear between 28°N and 30° N, and strong stable conditions appear in many places.

At different moments, the M profile will continue to change with changes in the meteorological environment. Figure S2 shows the changes in the M profile every 2 h during the whole day on 5 April 2021. Changes in the M profile will inevitably cause the height of the evaporation duct to change. Figure S3 shows the change curve of the EDH on 5 April 2021. The EDH is lower at night and peaks at noon.

3.2 Analysis of EDM

Using the EDM, it is possible to directly obtain the refractive-index profile of the atmosphere using the WS, AT, RH, AP, and SST parameters of a single layer; the EDH can then be obtained according to the profile change rate. In different meteorological and hydrological environments, the atmospheric refractive-index profiles obtained from different models result in different values from that found at the observation height. As shown in Figure S4, under different meteorological and hydrological conditions, there are differences between the atmospheric refractive-index profile obtained by the model and the observed profile.

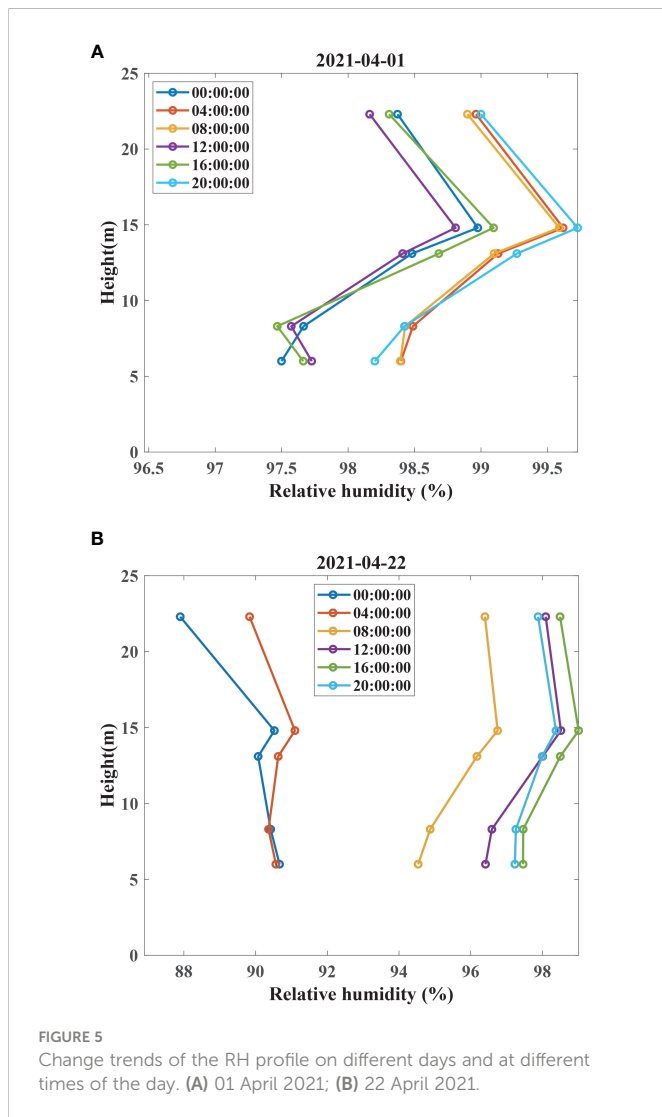


FIGURE 5
Change trends of the RH profile on different days and at different times of the day. (A) 01 April 2021; (B) 22 April 2021.

The differences in atmospheric refractive index in different layers and with different models in different environments were examined in terms of maximum absolute error (MAE), absolute average error (AAE), root-mean-square error (RMSE), and Pearson correlation coefficient (PCC). The results are shown in Table S1. The MAE values of NPS and NWA are better than those of other models. The AAE, RMSE, and PCC are all better, and the PCC in particular is close to 1, indicating that the overall trend predicted by the model is close to the observed value. It can also be seen that the deviations increase with increasing height. The NPS and NWA models showed better diagnostic results than the other models.

To further analyze the reason for the large values of MAE, the model diagnosis results were analyzed separately for different atmospheric stratifications. Tables S2, S3 show the analysis results under unstable and stable conditions, respectively. It can be seen from Table S2 that under unstable conditions, the deviations in atmospheric refractive index are small and the MAE values are relatively low. In contrast, Table S3 shows that the deviations in atmospheric refractive index are large under stable conditions. The large MAE values occur mainly under stable conditions.

To further analyze the factors affecting the accuracy of the model, the absolute deviations of the first-level M values were sorted in

ascending order, and the factors causing these large deviations were analyzed. The results of this are shown in Figure 8. It can be easily concluded that when the M deviation is large, the corresponding R_i value is large and the WS is small, that is, under the conditions of low WS and strong stable conditions, the model's diagnostic ability is poor.

Therefore, we further analyzed the influence of different models on the diagnosis accuracy in different WS intervals under stable conditions. Figure 9A shows the maximum absolute error (M_{max}), average absolute error (M_{mean}), and root-mean-square error (M_{rms}) under stable conditions under all values ($WS > 0$ m/s). According to M_{max} , it can be seen that the models BYC, NRL, and LKB have large diagnostic deviations in each layer. It can also be seen that the error increases with increasing layer height. Figure 9B shows the model diagnosis results when the atmosphere is under stable conditions and $WS \geq 3$ m/s. It can be seen that, aside from the large deviation of NRL, the other models have high diagnostic accuracy. Figure 9C shows the model diagnosis results when the atmosphere is under stable conditions and $WS \geq 5$ m/s. It can be seen that the prediction accuracy of each model is high, and there is almost no difference between this diagnostic accuracy and that under

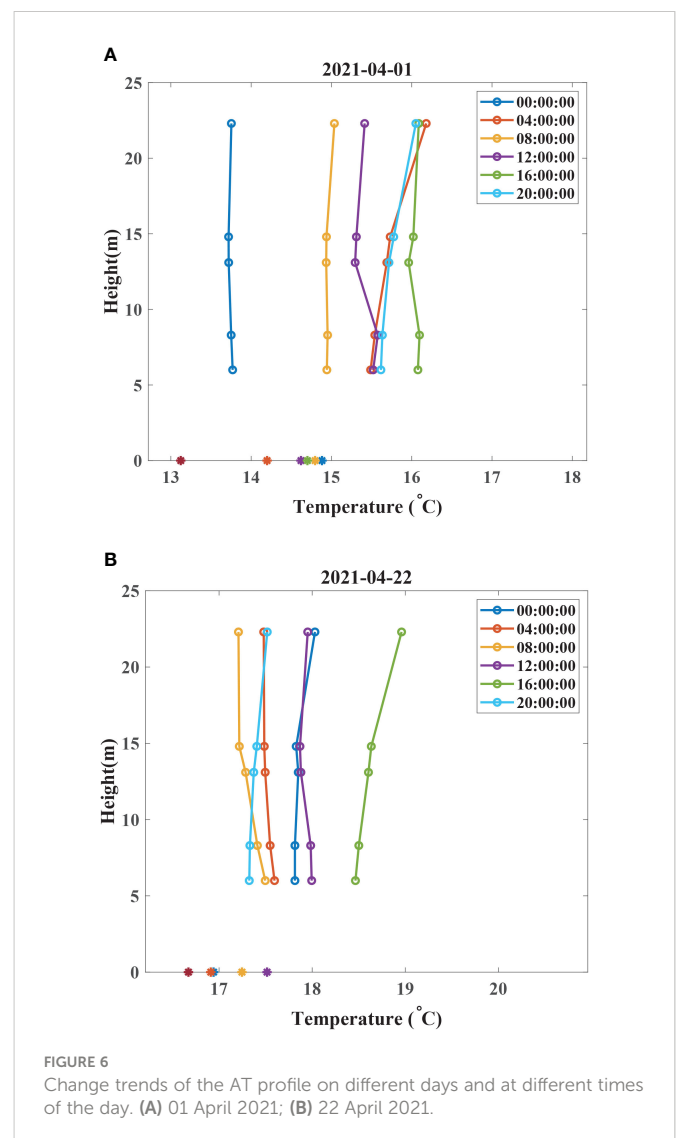


FIGURE 6
Change trends of the AT profile on different days and at different times of the day. (A) 01 April 2021; (B) 22 April 2021.

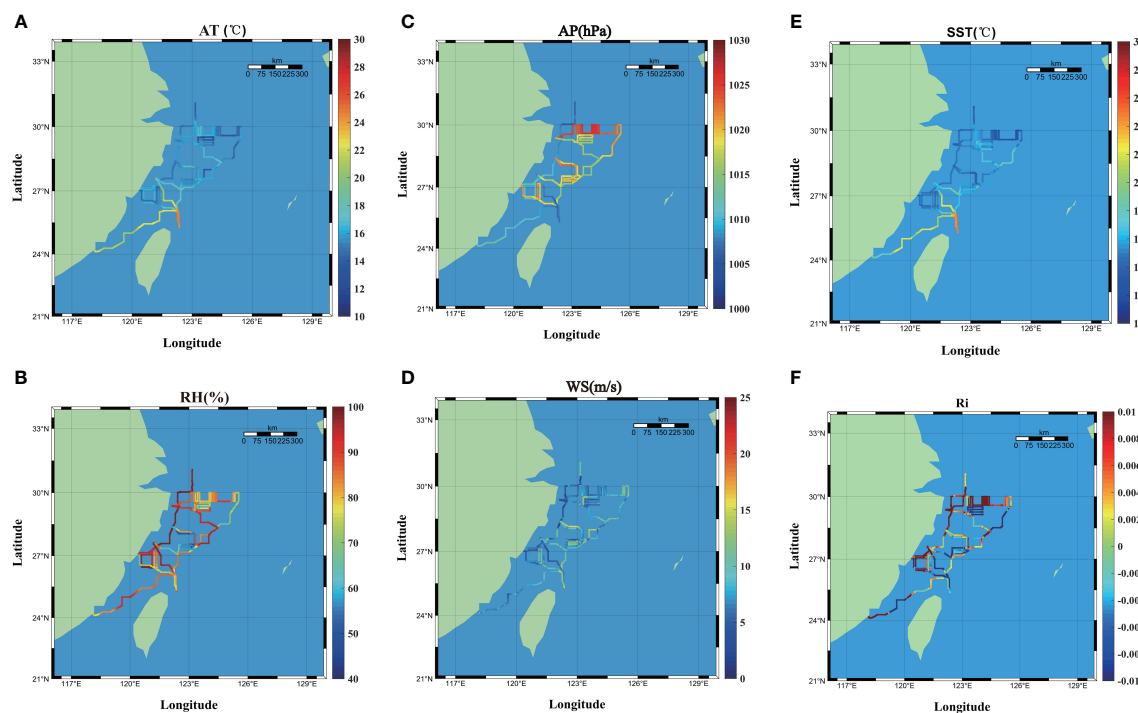


FIGURE 7
Statistical analysis of the observation data in the spatial dimension. (A) AT; (B) RH; (C) AP; (D) WS; (E) SST; (F) Ri.

unstable conditions. Furthermore, the accuracy is significantly higher than that for $WS \geq 3$ m/s.

From the above analysis, it can be concluded that each model has better diagnostic ability under unstable conditions, with almost no differences observed. However, under stable conditions, the diagnostic accuracy of the NPS and NWA models is better. Especially under strong stable conditions and low WS values, the prediction accuracy of the BYC, NRL, and LKB models is very low. However, when $WS \geq 5$ m/s, the prediction accuracy of each model increases. From this analysis of the observation data from the East China Sea on this voyage, it can be seen that the NPS and NWA models show better performance. Therefore, in Section 4, the NPS model is used to analyze the

difference between the observation data and the reanalysis data with regard to evaporation ducts.

3.3 Comparative analysis of meteorological and hydrological data

To analyze the feasibility of using the reanalysis data to study the regional characteristics of evaporation ducts, the data quality of the ERA5 reanalysis data has been evaluated for the East China Sea based on the voyage observation data. Since the heights of the shipborne sensors are inconsistent with the heights used in the reanalysis data, we used the near-surface similarity theory to convert the heights of

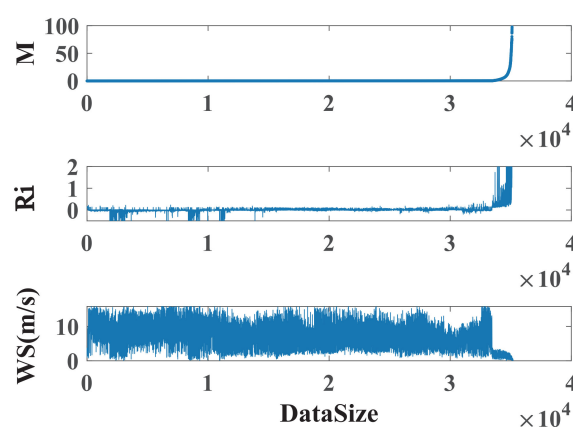


FIGURE 8
Relationship between the M deviation and Ri , as well as that between the M deviation and WS .

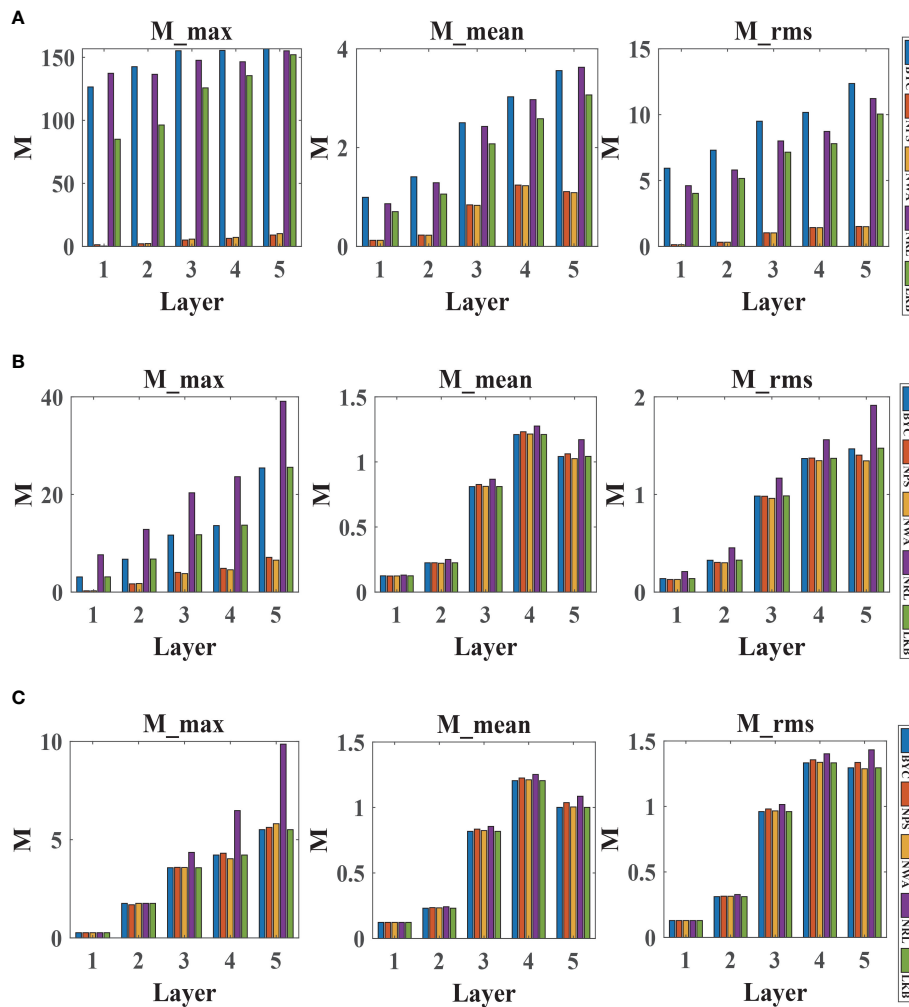


FIGURE 9
Model diagnosis results when the atmosphere is under stable conditions. (A) $WS > 0$ m/s. (B) $WS \geq 3$ m/s. (C) $WS \geq 5$ m/s.

the reanalysis data into the heights of the observation data. The reanalysis data is grid point data with a horizontal resolution of $0.25^\circ \times 0.25^\circ$, while the observation data is single point data. Therefore, we correspond to the grid point reanalysis data closest to the Euclidean distance from the single-point observation data.

A Taylor diagram was used to describe the standard error, RMSE, and correlations of the voyage observation data (WS, AT, RH, AP, and SST), and this is shown in Figure 10. Here, “Ship” represents the shipboard observation data, “ERA5” represents the ERA5 reanalysis data, and “CLDAS” represents the CLDAS reanalysis data. Figure 10A shows the WS comparison for ERA5, CLDAS, and the observation data. It can be seen that the values from ERA5 and CLDAS are close; the standard deviations are both greater than 2 m/s, the root-mean-square deviations (RMSD) are close to 2.5, and the correlations are 0.6. Figure 10B shows the AT data comparison. Overall, ERA5 is better than CLDAS, with a standard deviation of about 2°C . The correlation coefficients are both greater than 0.9. Figure 10C shows the RH data comparison. The accuracy of ERA5 and CLDAS is almost the same. Figure 10D shows the AP data comparison. CLDAS is better than ERA5, and the standard deviations are about 5 hPa. Since the CLDAS reanalysis data does not include SST, Figure 10E only compares ERA5 with the observation data in terms of SST. The

standard deviation of the SST data of ERA5 is less than 2.5°C , the RMSD is less than 1.5°C , and the correlation coefficients are greater than 0.8. Through this analysis, it can be seen that the single parameters of the reanalysis data have high accuracy, and there are strong correlations with the observed data.

4 Comparison and analysis of diagnosis results for evaporation ducts

As noted, meteorological and hydrological parameters at different heights were acquired through observations on this voyage. The height of the evaporation duct was diagnosed, and this was analyzed and compared with the values diagnosed by the NPS model using the ERA5 reanalysis data.

Using the EDM, the meteorological and hydrological parameters of the specified height were input. The EDH can then be calculated according to the Monin–Obukhov similarity theory. We used the 2-m AT, 2-m RH, 10-m WS, sea-surface AP, and the SST from the ERA5 datasets as the inputs of the EDM to obtain the EDH. Through the analysis in Section 3.2, it was found that the NPS model has strong applicability and high accuracy for the East China Sea; this model is

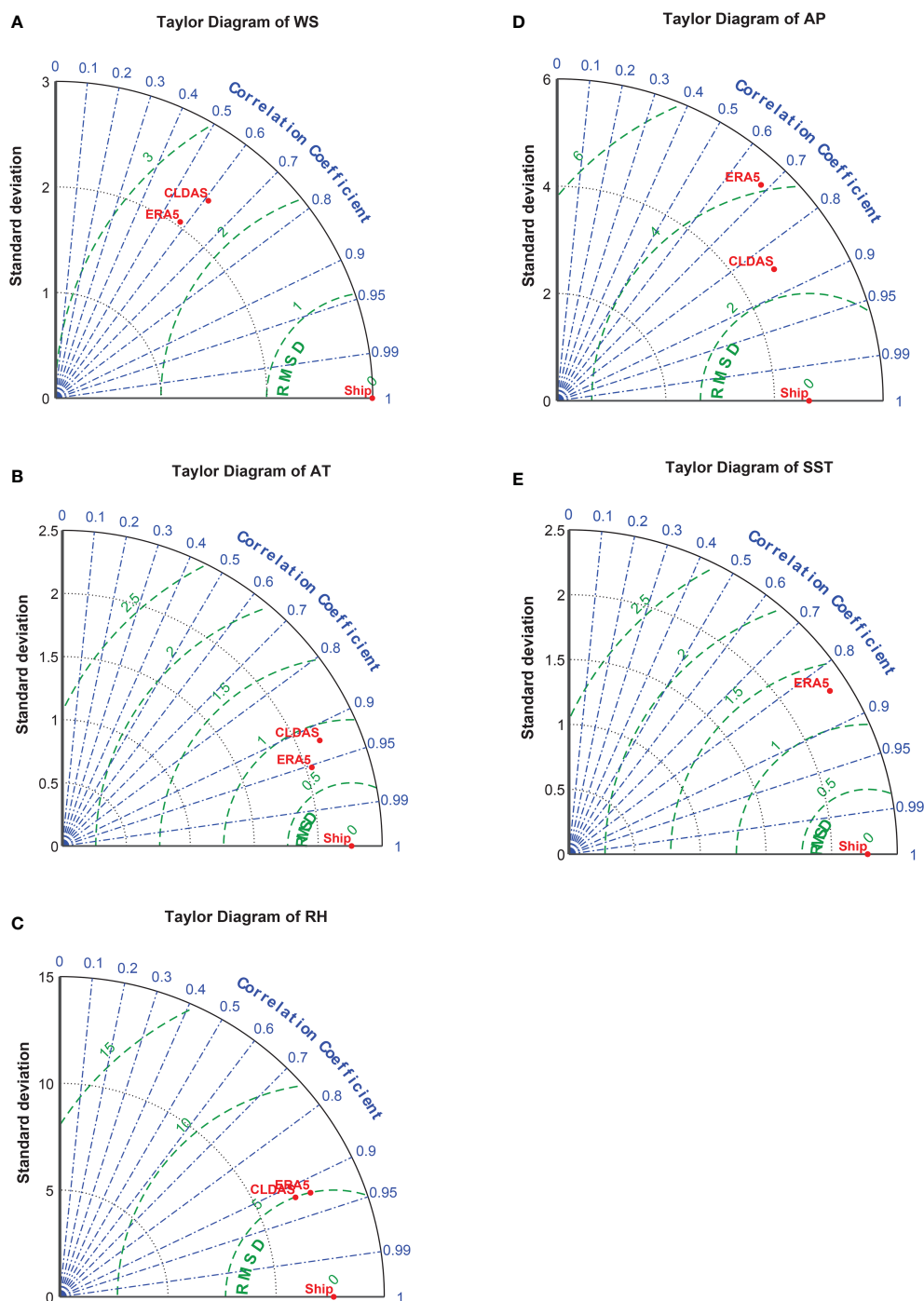


FIGURE 10
Accuracy of the reanalysis data: (A) WS; (B) AT; (C) RH; (D) AP; (E) SST.

thus adopted in this section. Therefore, the ERA5 reanalysis data was used as the input parameters for the NPS model, and the EDH was obtained. Then, a comparative analysis was made with the reference value of the EDH obtained from the voyage observation data. In this way, the feasibility of using the reanalysis data to examine the regional changes in evaporation ducts was obtained.

The analysis indicators in this paper were the false-report rate, the missing-report rate, the maximum diagnostic deviation, the average diagnostic deviation, the RMS of the diagnostic value, and the correlations under different atmospheric stratification. [Figure S5](#)

shows the change curves of the reference values of EDH obtained using the observation parameters during the voyage and the diagnostic values of EDH obtained by the NPS model using the reanalysis data. It can be seen that there is a strong correlation between the diagnostic values and the reference values, but there are also large deviations at some points in time.

False reports of evaporation ducts refer to a situation in which the reference value is 0 but the NPS diagnostic value is not 0. The false-report rate is the ratio of the number of false reports to the number of diagnoses. Missing reports refer to the situation in which the

TABLE 2 Evaporation duct false-report results.

Atmospheric stratification	Without evaporation duct of reference value	Total number of observations	Evaporation ducts of model diagnosis	False-report rate (%)
Stable and unstable	8795	35200	678	1.93
Unstable	465	14345	400	3.24
Stable	8330	20855	213	1.02

reference value is not 0 and the NPS diagnosis value is 0. Therefore, the missing-report rate is the ratio of the number of missing reports to the number of times the diagnostic reference value is not 0. The false- and missing-report results for evaporation ducts are shown in Tables 2, 3, respectively. It can be seen that the maximum false-report rate is only 3.24%, and the maximum missing-report rate is only 2.56% of the results obtained by reanalysis data, showing better diagnostic performance. At the same time, it can be seen that under the unstable conditions, the false-report rate is higher than that in other conditions, but under the unstable conditions, there is no missing report.

Excluding false and missing reports of evaporation ducts, the maximum diagnosis deviation, average diagnosis deviation, RMS, and correlation coefficients between the reference and the diagnosis values were analyzed. The results are shown in Table 4. There is a large diagnostic bias in both stable and unstable conditions. However, diagnostic bias was acceptable and strongly correlated, as seen by the average diagnosis deviation, RMS, and correlation coefficients.

Figure 11 shows the cumulative distribution functions (CDFs) of the deviation between the reference value and the diagnosis value. There are two kinds of input data for the EDH calculated by the NPS model: the meteorological parameters of each layer along with the sea-surface parameters obtained from the voyage, and the reanalysis data. Ship-true-1, 2, 3, 4, 5 represent the height difference between the reference value and diagnostic value by observation data of the 1, 2, 3, 4, and 5th floors of the ship, respectively. ERA5-true indicates the difference between the evaporative duct height diagnosed with the ERA5 dataset and the reference value. With increasing height, the deviations of the diagnosis results tend to gradually increase, but these deviations are slight. Regarding the reanalysis data, it can be seen that the results under unstable conditions are slightly better than those under stable conditions, although the differences are also small.

From the above analysis, it can be concluded that it is basically feasible to analyze the characteristics of evaporation ducts based on the NPS model using the reanalysis data. The diagnosis accuracy is similar to that of the observational data using the EDM. The EDM diagnosis accuracy when using reanalysis data is close to that of using observation data.

5 Discussion and conclusion

In this work, we first analyzed the accuracy of different models under different meteorological and hydrological environments through layered observations from an actual voyage. It is concluded that the NPS model is better than the other models examined, regardless of whether the stratification of the atmosphere is stable or unstable.

From further analysis of the factors affecting the diagnostic accuracy of the model, it is concluded that when the M deviation increases, the corresponding R_i value increases and the WS decreases. This means that under conditions of low WS and strong stable conditions, the EDM has poor diagnostic ability. Additional analysis found that in different WS ranges, each model has better diagnostic ability under unstable conditions, with almost no differences observed. However, under stable conditions, the diagnostic accuracy of NPS and NWA is better than that of other models. Therefore, by analyzing the actual observation data, it was found that the NPS and NWA models show better performance in the East China Sea.

The ERA5 and CLDAS reanalysis data were compared with the observation data. It was found that the reanalysis data had consistent correlations with the observation data, and the errors are reasonable. The ERA5 reanalysis data and the observation data were then used as the inputs of the NPS model to obtain the EDH. The results show that the false-report rate of the model was highest under unstable conditions, but it was still only 3.24%. Under stable conditions, the missing-report rate was higher than under unstable conditions, at 2.56%. Regardless of the atmospheric stratification, the average diagnostic error was about 3 m. According to this analysis, it was concluded that the model diagnostic error of using the reanalysis data is similar to that obtained using actual observation data. It is thus reasonable and feasible to use reanalysis data to analyze the characteristics of evaporation ducts.

The analysis of this work was based on observation data from the East China Sea obtained in April 2021. Due to the difficulty of making marine observations, the observation period of this dataset was relatively long. However, in terms of scientific analysis, this

TABLE 3 Evaporation duct missing-report results.

Atmospheric stratification	Evaporation duct of reference value	Total number of observations	Without evaporation ducts of model diagnosis	Missing-report rate (%)
Stable and unstable	26405	35200	535	1.52
Unstable	13880	14345	0	0
Stable	12525	20855	535	2.56

TABLE 4 Analysis of EDH diagnosis results.

Atmospheric stratification	Maximum diagnosis deviation (m)	Average diagnosis deviation (m)	RMS (m)	PCC
Stable and unstable	31.5	3.34	5.90	1
Unstable	31.5	3.40	5.70	1
Stable	29.0	3.26	6.12	1

quantity of data still leads to certain limitations. Therefore, in the future, more actual observational data from more sea areas and more seasons will continue to be obtained through more voyages. More buoys will be deployed, and platforms such as offshore observation towers will be applied to further verify our conclusions.

In addition, in combination with the existing observation data, we intend to analyze the underlying causes of the large deviations of the

model. In view of different meteorological and hydrological conditions, the parameterization schemes for the atmospheric stability function and roughness should be improved. Different methods to improve the model are proposed to further increase the accuracy of the EDM.

Based on the conclusions of this paper, we will further research the evolution of evaporation ducts and the processes of their

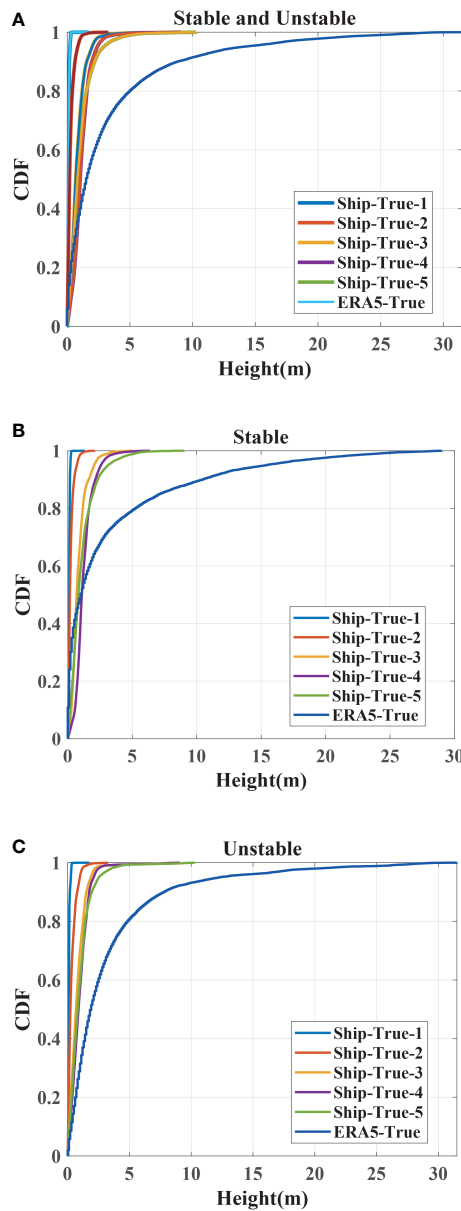


FIGURE 11 Diagnosis results showing the CDF of the EDH under different atmospheric stratifications: (A) stable and unstable conditions; (B) stable conditions; (C) unstable conditions.

formation, development, growth, and extinction based on the reanalysis data for the East China Sea. The purpose of this is to reveal the underlying causes of the formation and development of evaporation ducts. We will also use numerical prediction methods to achieve short-term predictions of the EDH, and we will verify the feasibility and accuracy of this prediction method using voyage observation data.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ZQ contributed to the conception and design of the study and the manuscript preparation. CZ performed the statistical analysis and wrote sections of the manuscript. BW, ZL, TH, JZ, SC, and SW contributed to the experiments. All authors contributed to manuscript revision, and they read and approved the submitted version.

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References

- Almond, T., and Clarke, J. (1983). Consideration of the usefulness of microwave propagation prediction methods on air-to-ground paths. *IEEE Proc. F* 130, 649–656. doi: 10.1049/ip-f-1.1983.0098
- Babin, S. M., and Dockery, G. D. (2002). Lkb-based evaporation duct model comparison with buoy data. *J. Appl. Meteorol. Clim.* 41, 434–446. doi: 10.1175/1520-0450(2002)041<0434:LBEDMC>2.0.CO;2
- Babin, S. M., Young, G. S., and Carton, J. A. (1997). A new model of the oceanic evaporation duct. *J. Appl. Meteorol. Climatol.* 36, 193–204. doi: 10.1175/1520-0450(1997)036<0193:ANMOTO>2.0.CO;2
- Burk, S. D., and Thompson, W. T. (1989). A vertically nested regional numerical weather prediction model with second-order closure physics. *Mon. Weather Rev.* 117, 2305–2324. doi: 10.1175/1520-0493(1989)117<2305:AVNRNW>2.0.CO;2
- Chai, X., Li, J., Zhao, J., Wang, W., and Zhao, X. (2022). Lgb-phy: An evaporation duct height prediction model based on physically constrained lightgbm algorithm. *Remote Sens.* 14, 3448. doi: 10.3390/rs14143448
- Fairall, C. W., Bradley, E. F., Hare, J. E., Grachev, A. A., and Edson, J. B. (2003). Bulk parameterization of air–sea fluxes: Updates and verification for the COARE algorithm. *J. Clim.* 16, 571–591. doi: 10.1175/1520-0442(2003)016<0571:BPOASF>2.0.CO;2
- Ferrari, R. (2011). A frontal challenge for climate models. *Science* 332, 316–317. doi: 10.1126/science.1203632
- Frederickson, P. A., Davidson, K. L., and Goroch, A. K. (2000). *Operational bulk evaporation duct model for MORIAH. tech. rep., naval postgraduate school. draft version.*
- Haack, T., Wang, C., Garrett, S., Glazer, A., Mailhot, J., and Marshall, R. (2010). Mesoscale modeling of boundary layer refractivity and atmospheric ducting. *J. Appl. Meteorol. Climatol.* 49, 2437–2457. doi: 10.1175/2010JAMC2415.1
- Hitney, H., and Vieth, R. (1990). Statistical assessment of evaporation duct propagation. *IEEE Trans. Antennas Propag.* 38, 794–799. doi: 10.1109/8.55574
- Hodur, R. M. (1997). The naval research laboratory's coupled ocean/atmosphere mesoscale prediction system (COAMPS). *Mon. Weather Rev.* 125, 1414–1430. doi: 10.1175/1520-0493(1997)125<1414:TNRLSC>2.0.CO;2
- Jeske, H. (1973). "State and limits of prediction methods, of radar wave propagation conditions over the sea," in *Modern topics in microwave propagation and air-sea interaction* (Dordrecht: Reidel Publishers), 131–148. doi: 10.1007/978-94-010-2681-9_13
- Jiao, L., and Zhang, Y. (2015). An evaporation duct prediction model coupled with the MM5. *Acta Oceanol. Sin.* 34, 46–50. doi: 10.1007/s13131-015-0666-z
- Karimian, A., Yardim, C., Gerstoft, P., Hodgkiss, W. S., and Barrios, A. E. (2012). Multiple grazing angle sea clutter modeling. *IEEE Trans. Antennas Propag.* 60, 4408–4417. doi: 10.1109/TAP.2012.2207033

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2022.1108600/full#supplementary-material>

- Lentini, N. E., and Hackett, E. E. (2015). Global sensitivity of parabolic equation radar wave propagation simulation to sea state and atmospheric refractivity structure. *Radio Sci.* 50, 1027–1049. doi: 10.1002/2015RS005742
- Liu, W. T., and Blanc, T. V. (1984). *The liu, katsaros, and businger, (1979) bulk atmospheric flux computational iteration program in FORTRAN and BASIC* (Washington, DC: Tech. rep., Naval Research Laboratory).
- Liu, W. T., Katsaros, K. B., and Businger, J. A. (1979). Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints at the interface. *J. Atmos. Sci.* 36, 1722–1735. doi: 10.1175/1520-0469(1979)036<1722:BPOASE>2.0.CO;2
- Luo, H., Ge, F., Yang, K., Zhu, S., Peng, T., Cai, W., et al. (2019). Assessment of ECMWF reanalysis data in complex terrain: Can the CERA-20C and ERA-interim data sets replicate the variation in surface air temperatures over sichuan, China? *Int. J. Climatol.* 39, 5619–5634. doi: 10.1002/joc.6175
- Meng, X., Guo, J., and Han, Y. (2018). Preliminary assessment of ERA5 reanalysis data. *J. Mar. Meteorol.* 38, 91–99. doi: 10.19513/j.cnki.issn2096-3599.2018.01.01110.19513/j.cnki.issn2096-3599.2018.01.011
- Qiu, Z., Hu, T., Wang, B., Zou, J., and Li, Z. (2022). Selection optimal method of evaporation duct model based on sensitivity analysis. *J. Atmos. Ocean. Technol.* 39, 941–957. doi: 10.1175/JTECH-D-21-0133.1
- Shi, H., Cao, X., Li, Q., Li, D., Sun, J., You, Z., et al. (2021). Evaluating the accuracy of ERA5 wave reanalysis in the water around china. *J. Ocean. Univ. China* 20, 1–9. doi: 10.1007/s11802-021-4496-7
- Shi, Y., Zhang, Q., Wang, S., Yang, K., Yang, Y., Yan, X., et al. (2019). A comprehensive study on maximum wavelength of electromagnetic propagation in different evaporation ducts. *IEEE Access* 7, 82308–82319. doi: 10.1109/ACCESS.2019.2923039
- Sun, Z., Ning, H., Tang, J., Xie, Y.-J., Shi, P.-F., Wang, J.-H., et al. (2016). Anomalous propagation conditions of electromagnetic wave observed over bosten lake, China in July and august 2014. *Chin. Phys. B* 25, 024101. doi: 10.1088/1674-1056/25/2/024101
- Tian, B., Liu, Q., Lu, J., He, X., Zeng, G., and Teng, L. (2020). The influence of seasonal and nonreciprocal evaporation duct on electromagnetic wave propagation in the gulf of aden. *Results Phys.* 18, 103181. doi: 10.1016/j.rinp.2020.103181
- Wang, J., Zhou, H., Li, Y., Sun, Q., Wu, Y., Jin, S., et al. (2018). Wireless channel models for maritime communications. *IEEE Access* 6, 68070–68088. doi: 10.1109/ACCESS.2018.2879902
- Yang, S., Li, X., Wu, C., He, X., and Zhong, Y. (2017). Application of the PJ and NPS evaporation duct models over the south China Sea (SCS) in winter. *PLoS One* 12, e0172284. doi: 10.1371/journal.pone.0172284
- Zaidi, K. S., Jeoti, V., Drieberg, M., Awang, A., and Iqbal, A. (2018). Fading characteristics in evaporation duct: Fade margin for a wireless link in the south China Sea. *IEEE Access* 6, 11038–11045. doi: 10.1109/ACCESS.2018.2810299
- Zhang, X., Liang, S., Wang, G., Yao, Y., Jiang, B., and Cheng, J. (2016b). Evaluation of the reanalysis surface incident shortwave radiation products from ncep, ecmwf, gsfc, and jma using satellite and surface observations. *Remote Sens.* 8, 225. doi: 10.3390/rs8030225
- Zhang, Q., Yang, K., Shi, Y., and Yan, X. (2016a). “Oceanic propagation measurement in the northern part of the south China Sea,” in *OCEANS 2016* (Shanghai: IEEE), 1–4.
- Zhang, Q., Yang, K., and Yang, Q. (2017). Statistical analysis of the quantified relationship between evaporation duct and oceanic evaporation for unstable conditions. *J. Atmos. Ocean. Technol.* 34, 2489–2497. doi: 10.1175/JTECH-D-17-0156.1
- Zhao, Q., Haack, T., McLay, J., and Reynolds, C. (2016). Ensemble prediction of atmospheric refractivity conditions for EM propagation. *J. Appl. Meteorol. Climatol.* 55, 2113–2130. doi: 10.1175/JAMC-D-16-0033.1
- Zhu, M., and Atkinson, B. W. (2005). Simulated climatology of atmospheric ducts over the Persian gulf. *Bound.-Layer Meteorol.* 115, 433–452. doi: 10.1007/s10546-004-1428-1



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Research on non-contact wet mateable connector for optical communication and power transmission

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At present, contact watertight connectors are commonly utilized for the connection between underwater electromechanical equipment and the seabed observation network. Such traditional watertight connectors are easy to be irreversibly worn when plugging and unplugging, however, they have complicated sealing structures and limited service life. This paper designs a Non-contact Wet Mateable connector for Optical Communication and Power Transmission (OCPT-NWMC), which is based on technology of Contactless Power Transmission (CLPT) and optical communication. Docking structure of the sockets and plugs are designed, facilitating Remotely Operated Vehicle (ROV) to operate. A prototype of the OCPT-NWMC was established. The experimental results show that the connector designed can achieve 200W power transmission, with a maximum power transmission efficiency of 94%. The communication bandwidth reaches 18MHz. The OCPT-NWMC can assist the rapid and safe deployment and operation of seabed observation network.

KEYWORDS

watertight connector, non-contact wet mateable connector, contactless power transmission, optical communication, seabed observation network

1 Introduction

With the rapid development of seabed observation technology, the development of deep sea has been improved (Mikada and Chave, 2004). The seabed observation network system provides a standard power supply and communication interface for seabed observation equipment, making long-term and continuous ocean observation possible (Favali et al., 2011; Best et al., 2014; Lin and Yang, 2020).

The construction of a large-scale seabed observation network is difficult, which is almost impossible to be deployed in a holistic manner. The underwater wet mateable connector can divide these engineering projects into different functional modules, which are deployed separately. Then Remotely Operated Vehicle (ROV) complete the connection of each module (Kawaguchi et al., 2008; Christ and Wernli, 2014). The operating principle of the commonly used wet mateable connector is isolated from the high-pressure seawater through the sealing

rubber (Painter and Flynn, 2006; Ré mouit et al., 2018), with complex structure, large plugging force and difficult operation process. The interface may be severely worn, causing a limited number of plugging and unplugging.

Contactless Power transmission (CLPT) can be utilized to replace the traditional contact wet mateable connector (Baer et al., 2009). Electromagnetic induction type CLPT has short transmission distance and high transmission efficiency, which is widely used in underwater electrical equipment, electric vehicles, biomedicine and robotics.

Baer C M et al. (Granger et al., 2013). developed a non-contact wet mateable connector based on CLPT, realizing 10W power transmission by coaxial nested coupling coils and signal rate of 600kbps by bidirectional optical communication. Li et al. proposed the coil turns optimization method and the coil structure design method of the loosely coupled CLPT coils in the marine environment (Li et al., 2017). The transmission of power and signal is jointly realized, with maximum 400W power transmission and 2Mbps data rate through WIFI. However, the communication bandwidth is low and the connector is large. Shi et al. designed a non-insert wet mateable connector based on mathematical modeling and numerical calculation (Shi et al., 2020). 130W power and 73Mbps full-duplex data through wireless router can be transmitted at the same time.

Optical communication has been applied underwater over small distance transmission (Khalighi et al., 2017). According to the electromagnetic wave characteristics, the blue-green light frequency band has an attenuation window in seawater (Li S et al., 2019). Compared with underwater acoustic communication and electromagnetic wave communication, optical communication is small, low in energy consumption and higher in communication rate (Kaushal and Kaddoum, 2016).

Doniec M W et al. developed an underwater point-to-point optical communication equipment and carried pool experiments (Doniec and Rus, 2015). Aqua Optical II is able to achieve a communication speed of 5.1Mbps within 50m (Doniec and Rus, 2010). Xu et al. used OFDM technology and a single LED to achieve underwater 2m transmission, and realized a data rate of 161Mbps (Xu et al., 2016). Chen et al. applied underwater laser communication to the positioning and navigation of underwater autonomous vehicles. The system achieved a data rate of 1 Mbit/s at 4 m (Chen et al., 2022).

Non-contact power transmission and optical communication technologies have been respectively applied in ocean observation projects (Li Y et al., 2019; Lin et al., 2019; Ali et al., 2020). This paper integrates the two technologies to design a non-contact wet mateable connector for optical communication and power transmission. Docking structure of the socket and plug is designed, ensuring high precision of the axial docking and facilitating ROV to operate. The OCPT-NWMC can assist the rapid and safe deployment and operation of seabed observation network.

2 Overall design of OCPT-NWMC

The OCPT-NWMC is mainly composed of input source, the primary side socket and the secondary side plug, watertight connectors. The external interfaces of power and communication

are realized through watertight cables and connectors. The schematic diagram of the OCPT-NWMC is shown in Figure 1A. The superior junction box of seabed observation network provides electric power and signals to the connector through the watertight connector. Since the current mainstream of the ocean observation network adopts direct current, the junction box here provides DC voltage. For power transmission, the AC voltage is generated by the inverter circuit. The high-frequency electromagnetic wave is emitted by the primary coils. On the secondary side, coils convert the received electromagnetic wave into AC voltage, which is then rectified and output.

For signal transmission, the laser driving circuit receives the signal, then the laser is driven. The signal is transmitted to seawater channel by the optical antenna of the transmitter. On the secondary side, the signal reaches the optical antenna of the receiver. The PIN tube converts the optical signal into electrical signal. And the signal is conditioned. Finally, the load receives power and signal through the watertight connector.

The exploded view of the mechanical structures of OCPT-NWMC shown in Figure 1B. The docking of the socket and plug is reliably achieved by the hook. The ROV operates the handle so that the locking hook is stuck on the groove of the primary cavity. Under the action of the guide cover and the hook, the two sides are closely connected. The seawater on the end face is squeezed, reducing the loss of optical signal. When separating two sides, the ROV pulls on the handle end. The locking hook is stretched, making the locking invalid. The assembled OCPT-NWMC is shown in Figure 1C.

3 Principles of OCPT-NWMC

3.1 Principle of CLPT system in seawater environment

The mutual inductance model of CLPT system in seawater is shown in Figure 2. L_p , L_s are respectively the self-inductances of the primary side and the secondary side. R_p , R_s are the respective internal resistances of the coils. The coupling of the two coils is described by mutual inductance M . The coupling coefficient k is used to express the degree of coupling between the two coils.

$$k = \frac{M}{L_p L_s} \quad (1)$$

According to the reflected impedance theory, the impedance reflected from the secondary side to the primary side can be calculated as:

$$Z_r = R_r + jX_r = \frac{\omega^2 M^2}{Z_s} \quad (2)$$

Z_r is called the reflection impedance, R_r , X_r are the reflection resistance and reflection reactance, respectively. The power absorbed by the reflection resistance represents the transmission capability of the coupling coil. The reflection reactance of the system generates reactive power, reducing the power factor. For the convenience of analysis, a two-port network model of the equivalent mutual inductance model of CLPT system in seawater is established. C_e is

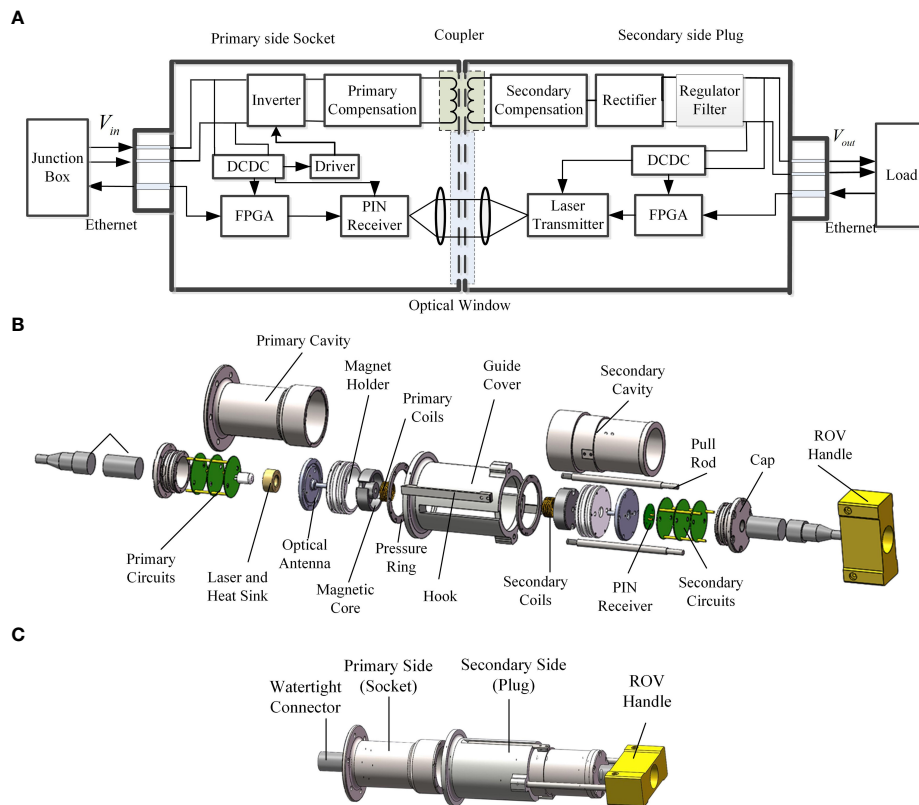


FIGURE 1
The OCPT-NWMC (A) schematic diagram (B) exploded view (C) assembled diagram of the mechanical structures.

the distributed capacitance of seawater between the loosely coupled coils caused by the high conductivity of seawater. The model is equivalent to the parallel connection of a mutual inductance model network in the air and a distributed capacitance network.

The transmission equation of the two-port network is defined as:

$$\begin{bmatrix} V_P \\ I_P \end{bmatrix} = T \begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} V_S \\ I_S \end{bmatrix} \quad (3)$$

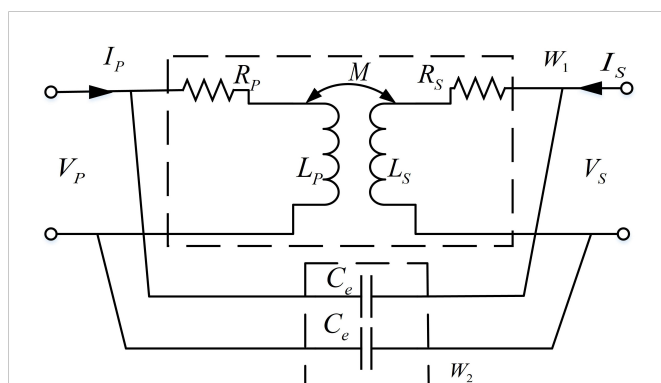


FIGURE 2
A two-port network model of the equivalent mutual inductance model of CLPT system in seawater.

Where T is the transmission matrix, which is converted to total admittance matrix:

$$T = \frac{1}{2j\omega M + j\kappa} \begin{bmatrix} 2Z_P + j\kappa & 2|Z_1| \\ 4Z_P Z_S + 2j\kappa(Z_P + Z_S) + 2\kappa\omega M & 2Z_S + j\kappa \end{bmatrix} \quad (4)$$

In the formula (4), T is the transmission matrix. Z_P and Z_S respectively represent open-circuit impedances on two sides, i.e. $Z_P = j\omega L_P + R_P$, $Z_S = j\omega L_S + R_S$. And $\kappa = \omega C_e |Z_1|$, where $|Z_1| = (j\omega L_P + R_P)(j\omega L_S + R_S) - (j\omega M)^2$.

The transmission equation of the equivalent mutual inductance model of CLPT system in seawater is:

$$\begin{cases} V_P = T_{11} V_S + T_{12} I_S \\ I_P = T_{21} V_S + T_{22} I_S \end{cases} \quad (5)$$

If the load is R_L , then the output voltage is, then the output voltage is:

$$V_S = -I_S R_L \quad (6)$$

The input impedance of the network for seawater is:

$$\begin{aligned} Z_{\text{water}} &= \frac{V_P}{I_P} = \frac{T_{12} - T_{11} R_L}{T_{22} - T_{21} R_L} \\ &= \frac{2|Z_1| - (2Z_P + j\kappa)R_L}{2Z_S + j\kappa - [4Z_P Z_S + 2j\kappa(Z_P + Z_S) + 2\kappa\omega M]R_L} \end{aligned} \quad (7)$$

The distributed capacitance C_e of the coil for length l , coil diameter d , inner radius r can be estimated

$$C_e = \frac{\pi \epsilon l}{\ln \frac{d-r}{r}} \quad (8)$$

Where ϵ is the dielectric constant of seawater.
The input impedance of the network for air is

$$\begin{aligned} Z_{air} &= j\omega L_P + R_P + \frac{\omega^2 M^2}{j\omega L_S + R_S + R_L} \\ &= \frac{\omega^2 M^2}{\omega^2 L_S^2 + (R_S + R_L)^2} (R_S + R_L) + R_P \\ &\quad - j \left(\frac{\omega^3 M^2 L_S}{\omega^2 L_S^2 + (R_S + R_L)^2} - \omega L_P \right) \end{aligned} \quad (9)$$

The equivalent mutual inductance model in seawater and in air are compared. The frequency characteristics of the impedance mode and impedance angle are shown in Figure 3.

It is shown that, under low operating frequency of the system, the system is hardly affected due to the large distributed capacitance and reactance of seawater. As the operating frequency of the system increases, the distributed capacitance and the inductance of the coils form an LC resonant circuit, causing a peak of the impedance mode of the system. The frequency of the CLPT system studied in this paper is between 10kHz and 100kHz, which belongs to the low frequency band. Therefore, the mutual inductance model can be simplified to the situation in the air, reducing the complexity of system design.

3.2 Modulation algorithm for underwater optical communication

In the actual system, optical communication is limited by power and bandwidth, so the modulation technology needs to consider power consumption, bandwidth and difficulty of implementation. On-Off Keying (OOK) modulation is used in this paper (Gayathri et al., 2015; Wang et al., 2016). In the OOK modulation system, the baseband rectangular pulse of digital “0” or “1” is used to control a continuous carrier. The carrier is output intermittently. The presence or absence of carrier output corresponds to sending 1 or 0. The OOK

signal can be considered as a unipolar rectangular pulse sequence multiplied by the carrier:

$$s(t) = m(t) \cos(\omega_c t + \theta_c) = \left[\sum_{k=-\infty}^{\infty} a_k g(t - kT_b) \right] \cos(\omega_c t + \theta_c) \quad (10)$$

Where $g(t)$ is a rectangular pulse with a duration of T_b , a_k represents the 01 sequence. ω_c is the carrier frequency, and θ_c is the initial phase of the carrier.

Since the spectrum of the rectangular pulse sequence of the baseband signal is infinitely wide, the pulse signal will expand in time, causing intersymbol interference and increasing the bit error rate at the receiving end. In order to use the channel effectively, it is necessary to compress the spectral bandwidth to improve the frequency band utilization. The most widely used filter that satisfies the Nyquist first criterion is the raised cosine roll-off filter, which is a finite impulse response (FIR) filter. The transfer function of FIR is:

$$H(f) = \begin{cases} T_s, & 0 \leq |f| \leq \frac{1+\alpha}{2T_s} \\ \frac{1}{2} \left\{ 1 + \cos \left[\frac{\pi T_s}{\alpha} (|f| - \frac{1-\alpha}{2T_s}) \right] \right\}, & \frac{1-\alpha}{2T_s} < |f| \leq \frac{1+\alpha}{2T_s} \\ 0, & |f| > \frac{1+\alpha}{2T_s} \end{cases} \quad (11)$$

Where α ($0 \leq \alpha \leq 1$) is the roll-off factor of shaping filter. The value of α determines the bandwidth of the system. In order to improve the frequency band utilization, the value of α should be as small as possible. However, when α gets smaller, synchronizing the bits at the receiving end becomes more difficult, and the system bit error rate becomes larger. To reduce the sampling pulse error, it is usually chosen as $\alpha \geq 0.2$.

Set the baseband signal rate $R_b = 1\text{Mbps}$, the carrier frequency $f_c = 50\text{MHz}$, the sampling frequency $f_s = 8R_b$, the shaping filter coefficients $f_s = 8R_b$, and shaping filter factor $\alpha = 0.35$. The spectrum of the OOK signal is shown in Figure 4.

It is shown that the frequency components of the OOK signal spectrum after the shaping filter other than the main lobe have been filtered out. Since the signal generated by MATLAB is a real signal, the signal spectrum is symmetrical about half of the sampling frequency (4MHz). According to the sampling theory, the sampled carrier frequency is $f_{as} = kf_s \pm f_c$, where k is an integer. When $k = 7$, the

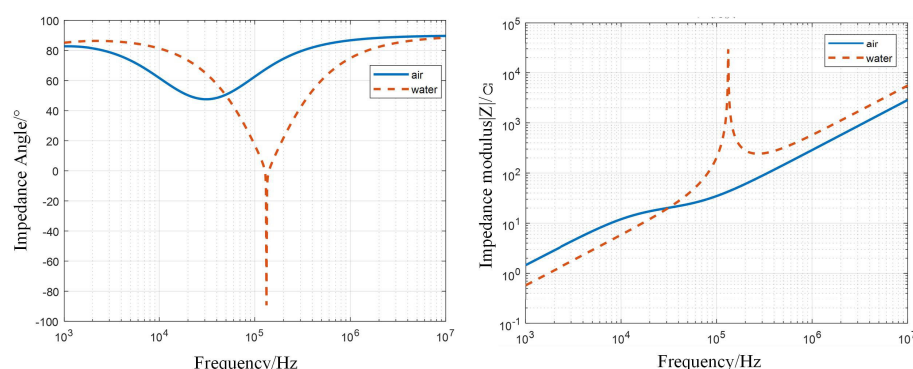


FIGURE 3
Frequency characteristics of the mutual inductance model in seawater and air.

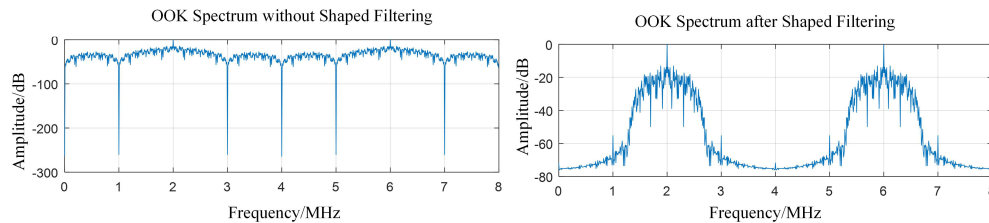


FIGURE 4
OOK signal spectrum in MATLAB.

sampled carrier frequency component is moved to 6MHz. It can be seen that after the shaping filter, the energy of the signal is more concentrated, making the decision more conducive.

OOK signal demodulation adopts non-coherent demodulation. It mainly uses envelope detection. The signal is first full-wave rectified then low-pass filtered. Sampling judgment is performed at the position where the eye diagram opens the most, to restore the original signal. The method is simple to implement, since the synchronous carrier does not need to extract.

4 System design of OCPT-NWMC

4.1 Structure of loosely coupled coils

The core of the design of CLPT system is the loosely coupled coils, which directly determines the output power and affects the transmission efficiency of the system. In this paper, the requirement of the axial positioning accuracy of the connector is low, and relative rotation of both sides is allowed. For small radial dimensions and high coupling coefficient, the coaxial and parallel coil structure is selected. GU-type magnetic core made of ferrite material is utilized. The magnetic core

covers almost all the coils, making the magnetic leakage small. The coil structure and magnetic field simulation are shown in. The coil and the magnetic core are exposed to seawater. High-frequency electromagnetic waves induce eddy currents in the seawater, resulting in a large power loss. As shown in Figure 5, the magnetic core window is potted with epoxy resin to prevent the infiltration of seawater.

4.2 Circuit design

The schematic diagram of the OPCT-NWMC circuit is shown in Figure 6. To improve the CLPT transmission performance, a compensation circuit is employed to eliminate reflected reactance (Gati et al., 2017). Compared to the four basic compensation methods, dual-LCC topology has better frequency characteristics and greater transmission power (Siqu Li et al., 2015). The dual-LCC topology compensation circuit adds additional compensation inductance, and additional compensation capacitance, to form a high-order resonant network. It has a higher power factor, less voltage and current stress on the switching device, and is easy to achieve soft switching.

The input currents of LCC circuits on both sides are $\dot{I}_{L_{f1}}$, $\dot{I}_{L_{f2}}$, and the current flowing through the primary and secondary coils are $\dot{I}_P$, $\dot{I}_S$.

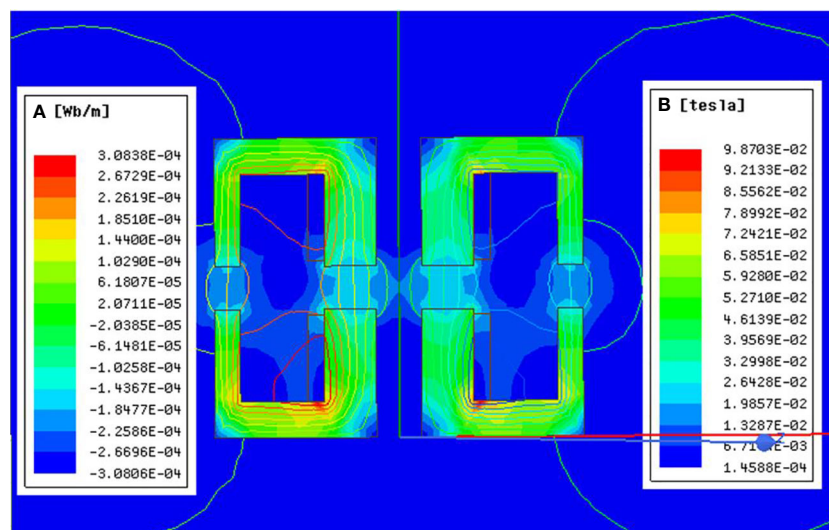


FIGURE 5
The magnetic field simulation of the coil.

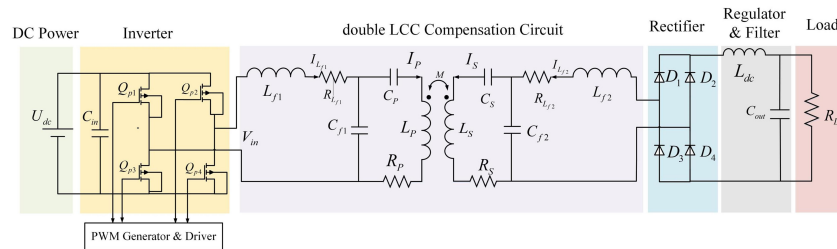


FIGURE 6
The schematic diagram of the OPCT-NWMC circuit.

The conditions for system resonance are:

$$\begin{cases} \frac{1}{\omega_0^2} = L_{f1}C_{f1} \\ \frac{1}{\omega_0^2} = L_{f2}C_{f2} \\ \frac{1}{\omega_0^2} = (L_p - L_{f1})C_p \\ \frac{1}{\omega_0^2} = (L_s - L_{f2})C_s \end{cases} \quad (12)$$

The system adopts a symmetrical design, i.e. $L_{f1} = L_{f2} = L_f$, $C_{f1} = C_{f2} = C_f$, self-inductances $L_p = L_s$, internal resistances of coils, $R_p = R_s$, internal resistances of compensation inductances $R_{f1} = R_{f2}$.

The primary side power conversion is realized by the full shifting bridge. After the full bridge rectification and filtering on the secondary side, the power is supplied to the secondary load. The zero-voltage zero-current switching (ZVZCS) is realized by using the parasitic capacitance of the circuit itself. IRFB4110 is chosen as the power switch tube. In order to drive the power switch tube, UCC3895Ns are used as the PWM signal generation chips, and IR2110s are used for current amplification. Fast recovery Schottky rectifier diodes MBR30100CT are selected as the rectifiers. A filter inductor and a large capacitor in parallel can reduce the voltage ripple.

4.3 Optical communication design

The optical communication system of OCPT-NWMC is mainly composed of three parts: transmitting device, receiving device, and seawater channel. The principle block diagram is shown in Figure 7. At the transmitting end, the information to be transmitted is encoded and modulation. The modulated wave containing the signal is coupled with

the DC source to drive the light source – laser. The light emitted is then collimated by the transmitting optical antenna. The receiving optical antenna receives the signal transmitted in the seawater channel. The optical detection device converts the optical signal into an electrical signal, and then restores the original signal through functional modules such as conditioning, demodulation, decoding, then sends it to the sink.

As for the implementation, at the transmitting end, the host computer communicates with the transmitting end FPGA chip. The transmitting end FPGA completes signal encoding and DA conversion, which is then connected to the laser tube that emits light. At the receiving end, the PIN tube is connected to the receiving end FPGA. The FPGA completes AD conversion and signal decoding, and then communicates with the host computer.

The connection between the host computer and OCPT-NWMC is realized by asynchronous transmission of UART. In order to solve the speed mismatch between the UART transmission and the modulation algorithm, a First Input First Output (FIFO) pair is used to connect the UART module and the modulation and demodulation module. At the transmitter side, the UART reads data from the host computer, and the OOK modulation algorithm reads the bit stream from the FIFO. “0111110” is selected as the frame header to encapsulate the data. In order to ensure that frame header data does not appear in the data, bit-fill processing is performed in the real data. The specific frame format of the sender is: 0111110 (sync header) + 32bit frame information (frame length, etc.) + data information. After the framed data is converted by DA, the laser tube is driven to emit light by the laser drive circuit. At the receiving end, the signal received by the PIN tube is converted by AD and input to the FPGA demodulation module. The demodulated data is then transmitted to the host computer through the UART. FIFO is also required for matching

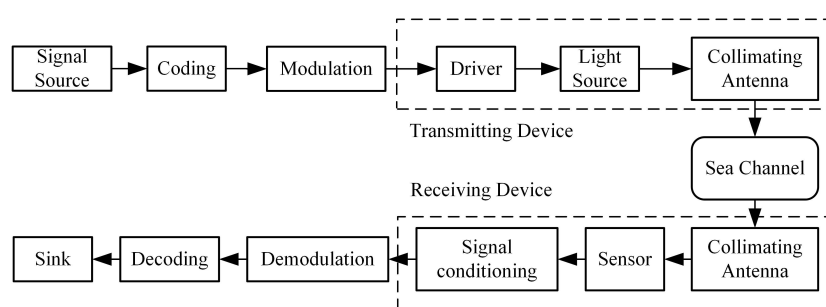


FIGURE 7
The principle block diagram of optical communication.

between the receiving end UART and the demodulation module. UART converts parallel data into serial and adopts asynchronous transmission, and sends the data in frames. A frame of data starts with a low-order start bit, followed by 6–8 data bits, 1 or several high-order stop bits, and finally a parity bit.

5 Prototype of OCPT-NWMC

A prototype of OPCT-NWMC is shown in Figure 8. The circuit board is designed to be circular. Mounting holes and wiring holes are processed. The primary cavity and secondary cavity lengths are both 120mm. The end cap and the cavity are made of aluminum alloy. The primary and secondary optical antennas need to be arranged on the end face of the connector. On the other hand, the magnet and coils for power transfer on both sides also need to be arranged on the end face in order to improve the coupling coefficient. Thus, a light transmitting acrylic plate is designed as an optical antenna. For reducing the radial dimension, the light transmission window is designed with the help of the through hole in the middle of the ferrite pot core. Considering that the laser is sensitive to temperature changes, copper is used to make the laser heat sink. The laser is fixed on the primary light transmitting

acrylic board through the heat sink block, and the secondary side receiving board is fixed on the secondary light transmitting acrylic board. If the magnetic cores of OCPT-NWMC are aligned, the laser is automatically aligned. The coils, combined with the optical antennas are fixed together in the nylon coil holder.

In addition, the insertion force of OCPT-NWMC is simulated. A speed of 10 mm/s is applied at the end of the handle, so that the plug is inserted into the socket along the axial direction. And the end face of the plug is 91mm away from the end face of the socket in the initial state. The force acting on the handle is measured during the insertion process, and the force curve is shown in Figure 9. It can be seen that the maximum insertion force does not exceed 150N, which meets the requirements of underwater insertion and extraction operations under the operation of ROV with gripper.

6 Experiments of OCPT-NWMC

6.1 Test of CLPT system

The test platform of CLPT system is shown in Figure 10. The programmable power supply is used as the primary side DC power

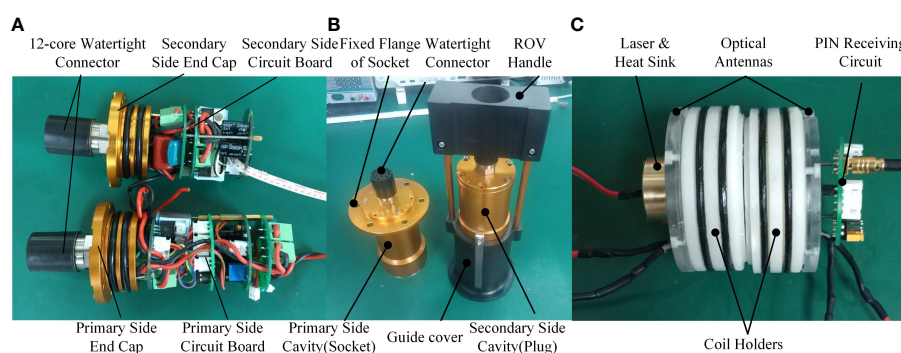


FIGURE 8
Assembled prototype of OCPT-NWMC [(A) Assembly of circuits and end caps (B) assembly of the connector (C) Assembly of Optical System and Loosely Coupled Coils].

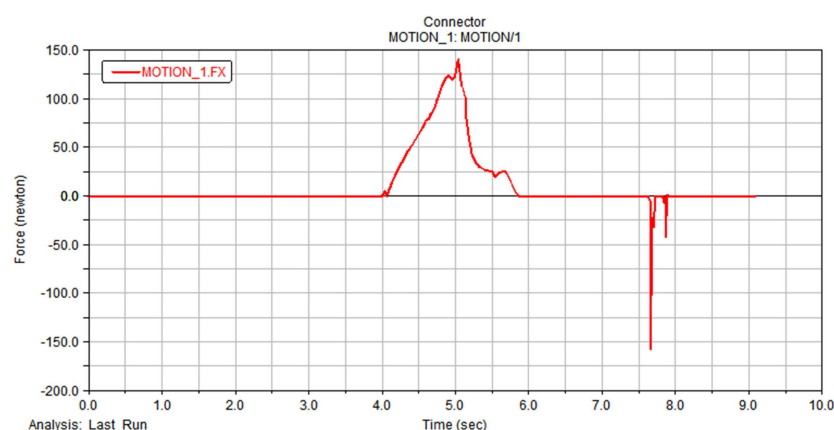


FIGURE 9
Force curve during insertion.

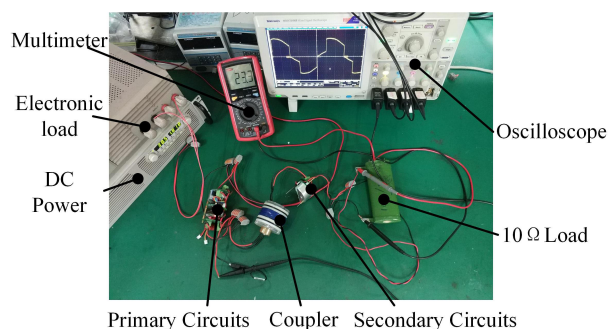


FIGURE 10
Test platform of CLPT system.

supply. The coils are wound with 22:22 turns. The gap between the two magnetic cores is 3mm.

The data curves tested under different operating frequencies when the output connected to a 10Ω resistor are shown in Figure 11. It can be seen that the system can achieve a maximum power transmission of 200W. In the range of 30~100kHz, the overall efficiency can reach more than 80%, and the highest reaches 94%.

The power transmission performance of CLPT system when an electronic load is connected to the output is tested under different load resistances. Figure 12 shows the power transmission performance of CLPT system. It is shown that when the system frequency is 35kHz, OCPT-NWMC has better constant voltage output characteristic. The system transmission frequency is basically greater than 0.8.

6.2 Test of OCPT-NWMC

After the assembly is completed, a tool experiment is performed on OCPT-NWMC. The signal of the transmitting side PC and the power of the power supply are transmitted to the OCPT-NWMC socket through the primary side watertight cable. And the OCPT-NWMC plug transmits the power and signal to the receiving side PC and electronic load through the secondary side watertight cable. The

configuration for the tool experiment of OCPT-NWMC is shown in Figure 13.

The tool is filled with simulated seawater(%3.5 salt water). Adjust the drive frequency of the inverter to 40kHz, the connector was connected to the electronic load. The tests of output performance are carried out in water and in air, respectively. The test results are shown in Figure 14. The results of the test in the air are almost consistent with the results of the test in simulated seawater. However, there exists an obvious difference with the results measured in CLPT test. The reason is that in order to facilitate assembly, a larger gap is left. The potting process also leads to an increase in the gap between two coils, resulting in a decrease of the coupling coefficient. Furthermore, the cavity is a metal shell. High-frequency electromagnetic waves induce eddy currents in the cavity, causing large losses. The solution is to fix the magnetic core, coil, and coil support first, and then potting, so as to reduce the axial spacing and assembly error of the magnetic core as much as possible. And a layer of copper foil can be added to the outer layer of the magnetic core for electromagnetic shielding, reducing the eddy current loss.

As for optical communication, use programmable power supply powers the FPGA and driver circuits. The drive current of the laser is set to 50mA. The test program is written by ISE software, and the square wave is output from the FPGA at the transmitting end. After DA conversion, it is loaded onto the laser through the driving circuit. An oscilloscope is used to observe the waveform output by the

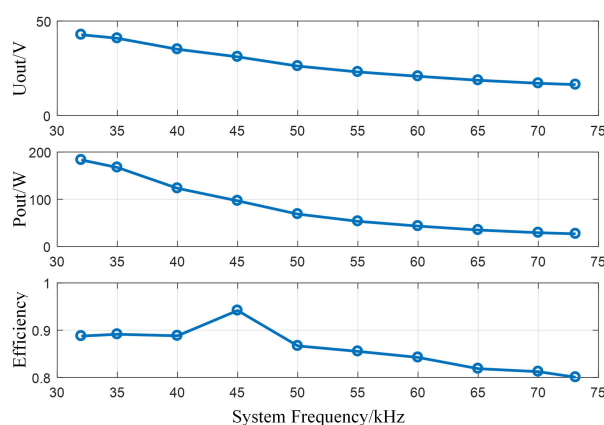


FIGURE 11
Output performance of 10Ω resistor under different operating frequencies.

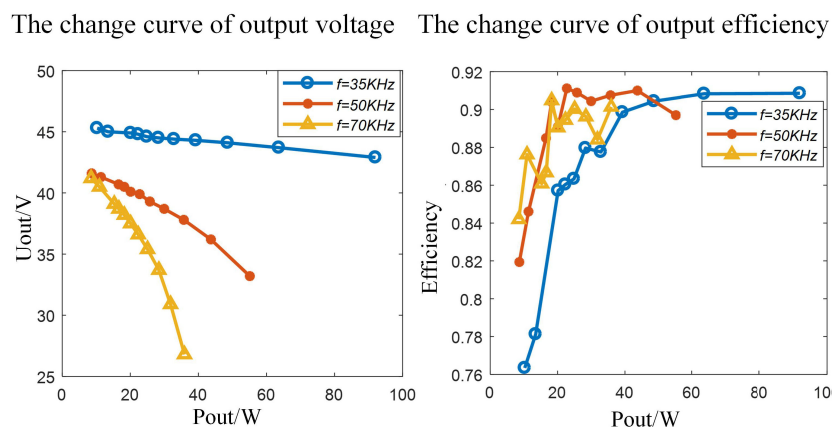


FIGURE 12
The power transmission performance of CLPT system.

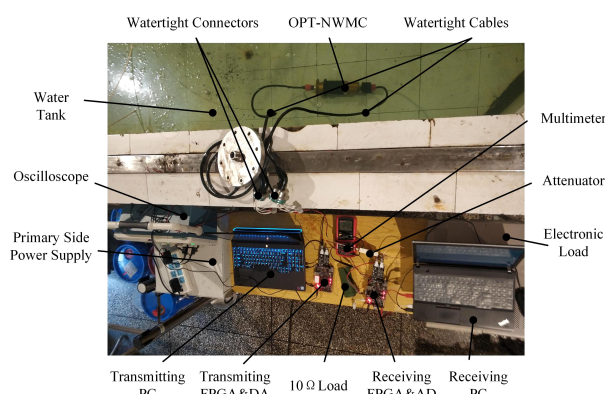


FIGURE 13
The configuration for the tool experiment of OCPT-NWMC.

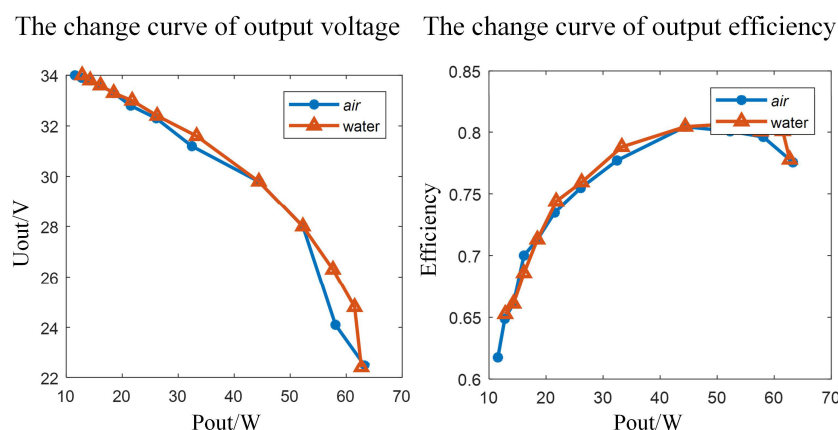


FIGURE 14
The power transmission performance of OCPT-NWMC in the water tool experiment.

receiver. In order to test the bandwidth of the communication system, square waves with an amplitude of 1Vp-p at different frequencies were sent at the transmitting side. And the output of the transimpedance amplifier at the receiving side was connected to an oscilloscope to check the amplitude and phase of the received signal. The amplitude-frequency response of the system obtained is shown in

Figure 15A. It can be seen that the bandwidth of the system can reach about 18MHz. Limited by the test conditions, the bit error rate of the system was not be measured. More accurate system performance results can be obtained by analyzing the actual signal received and processed by the optical receiver. In order to test the transceiver performance, the transmitter continuously sends a string of “non-

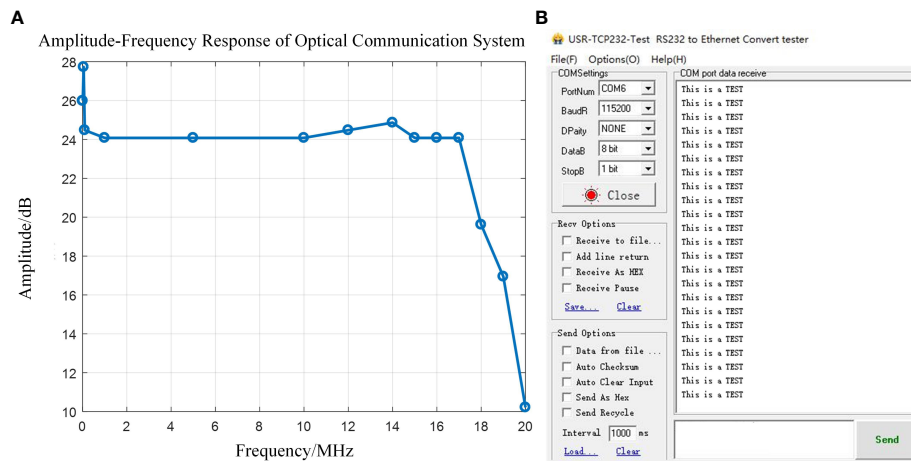


FIGURE 15
Test of optical communication system (A) Amplitude-Frequency Response of Optical Communication System (B) Serial port assistant of Optical communication system.

contact wet mateable connector for optical communication and power transmission” through the serial assistant. Then the string is read from the FIFO at a speed of 10MHz, and load to the laser through DA. After AD sampling at the receiving side, the signal is written into the FIFO, and then read out from the FIFO and sent to the host computer through the serial port assistant. The data received by the serial port assistant at the receiving side is shown in Figure 15B. It is shown that the receiving side correctly recovered the information of the transmitting side without code error. However, when the modulation rate is increased to 15MHz, garbled characters appear.

7 Conclusion and prospects

At present, the commercial watertight connectors are mainly contact-type. The socket and the plug need to be tightly inserted to realize the transmission of power and signals. Aiming at overcoming the shortcomings of traditional watertight connectors, this paper designed a non-contact wet mateable connector based on contactless power transmission and optical communication. Based on system analysis and design, a prototype of OCPT-NWMC was developed and verified by experimental tests. This system can realize the transmission of 200W power, and the efficiency can reach 94%. The correctness of the transmission and reception of the 10MHz modulation rate system was tested through the serial port. The experiments show the rationality and correctness of the system design, which provides practical reference for the design of underwater wet mateable connector.

This research has certain limitations and the work of this paper can be further deepened and improved, for example, due to the frequency splitting when adopting high-order compensation, it is necessary to use a closed-loop control system to track and optimize the operating frequency; The bandwidth of the transimpedance amplifier at the receiving end limits the system bandwidth, so a transimpedance amplifier with a high gain-bandwidth product can be selected. FPGA with higher system clock and AD and DA can be chosen to increase the bandwidth of hardware circuit. Advanced modulation algorithms such as QAM and OFDM can be used.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

ZD: Methodology, Project administration. YZ: Investigation. JH: Writing - Original Draft, Visualization, Validation. BH: Data Curation. BH: Software. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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References

- Ali, M. F., Jayakody, D. N. K., Chursin, Y. A., Affes, Soféine, and Dmitry, S. (2020). Recent advances and future directions on underwater wireless communications. *Arch. Comput. Methods Eng.* 27 (5), 1379–14125. doi: 10.1007/s11831-019-09354-8
- Baer, C. M., Alten, M., Bixler, G., Fredette, L., Owens, J., Purvinis, G., et al. (2009). "Non-contact wet mateable connector," in *OCEANS*. (Biloxi, MS, USA: IEEE) 2009, 1–6. doi: 10.23919/oceans.2009.5422298
- Best, M., Favali, P., and Beranzoli, L. (2014). EMSO: A distributed infrastructure for addressing geohazards and global ocean change. *Oceanography* 27 (2), 167–695. doi: 10.5670/oceanog.2014.52
- Chen, Y., Duan, Z., Zheng, F., Guo, Y., and Xia, Q. (2022). Underwater optical guiding and communication solution for the AUV and seafloor node. *Appl. Optics* 61 (24), 7059–7705. doi: 10.1364/ao.462678
- Christ, R. D., and Wernli, R. L. (2014). "The ROV manual (Second edition)," in *The ROV manual, 2nd ed.* Eds. R. D. Christ and R. L. Wernli (Oxford: Butterworth-Heinemann). doi: 10.1016/B978-0-08-098288-5.00028-2
- Doniec, M., and Rus, D. (2010). "BiDirectional optical communication with AquaOptical II," in *2010 IEEE International Conference on Communication Systems*. (Singapore: IEEE). 390–394. doi: 10.1109/icc.2010.5686513
- Doniec, M. W., and Rus, D. (2015) *Underwater optical communication system*. Available at: <https://patents.google.com/patent/US9031413B2/en>.
- Favali, P., Beranzoli, L., Italiano, F., Migneco, E., Musumeci, M., and Papaleo, R. (2011). NEMO-SN1 observatory developments in view of the European research infrastructures EMSO and KM3NET. *Nucl. Instruments Methods Phys. Res. Section A: Accelerators Spectrometers Detectors Associated Equip.* 626–627 (January), S53–S56. doi: 10.1016/j.nima.2010.04.139
- Gati, E., Kampitsis, G., and Manias, S. (2017). Variable frequency controller for inductive power transfer in dynamic conditions. *IEEE Trans. Power Electron.* 32 (2), 1684–1965. doi: 10.1109/TPEL.2016.2555963
- Gayathri, C.B., Deeksha, S., Durga, S. D. M., and Narendara Raj, V. (2015). "Design of high speed underwater optical communication using on-off keying algorithm," in *2015 International Conference on Communications and Signal Processing (ICCSP)*. (Melmaruvathur, India: IEEE). 1355–1360. doi: 10.1109/iccsp.2015.7322730
- Granger, R. P., Baer, C. M., Gabriel, N. H., Labosky, J. J., and Galford, T. C. (2013). "Non-contact wet mateable connectors for power and data transmission," in *2013 OCEANS*, (San Diego, CA, USA: IEEE). 1–4. doi: 10.23919/OCEANS.2013.6741173
- Kaushal, H., and Kaddoum, G. (2016). Underwater optical wireless communication. *IEEE Access* 4, 1518–1547. doi: 10.1109/access.2016.2552538
- Kawaguchi, K., Kaneda, Y., and Araki, E. (2008). "The DONET: A real-time seafloor research infrastructure for the precise earthquake and tsunami monitoring," in *OCEANS 2008 - MTS/IEEE Kobe Techno-Ocean*. (Kobe, Japan: IEEE), 1–4. doi: 10.1109/oceanskobe.2008.4530918
- Khalighi, M.-A., Hamza, T., Bourennane, S., Léon, P., and Opderbecke, J. (2017). Underwater wireless optical communications using silicon photo-multipliers. *IEEE Photonics J.* 9 (4), 1–105. doi: 10.1109/jphot.2017.2726565
- Li, S., Li, W., Deng, J., Nguyen, T. D., and Mi, C. C. (2015). A double-sided LCC compensation network and its tuning method for wireless power transfer. *IEEE Trans. Vehicular Technol.* 64 (6), 2261–2735. doi: 10.1109/tvt.2014.2347006
- Lin, Ri, Li, D., Zhang, T., and Lin, M. (2019). A non-contact docking system for charging and recovering autonomous underwater vehicle. *J. Mar. Sci. Technol.* 24 (3), 902–165. doi: 10.1007/s00773-018-0595-6
- Lin, M., and Yang, C. (2020). Ocean observation technologies: A review. *Chin. J. Mechanical Eng.* 33 (1), 325. doi: 10.1186/s10033-020-00449-z
- Li, S., Qu, W., Liu, C., Qiu, T., and Zhao, Z. (2019). Survey on high reliability wireless communication for underwater sensor networks. *J. Network Comput. Appl.* 148 (December), 102446. doi: 10.1016/j.jnca.2019.102446
- Li, Y., Wang, S., Jin, C., Zhang, Y., and Jiang, T. (2019). A survey of underwater magnetic induction communications: Fundamental issues, recent advances, and challenges. *IEEE Commun. Surveys Tutorials* 21 (3), 2466–2487. doi: 10.1109/comst.2019.2897610
- Li, D., Wang, T., and Yang, C. (2017). A novel designed load adaptive noncontact wet-mate connector for subsea devices. *Mar. Technol. Soc. J.* 51 (4), 31–405. doi: 10.4031/mtsj.51.4.8
- Mikada, H., and Chave, A. D. (2004). "Science requirements as the design drivers for ocean observatories," in *Oceans '04 MTS/IEEE Techno-Ocean '04*. (Kobe, Japan: IEEE), 4, 2164–2169. doi: 10.1109/oceans.2004.1406481
- Painter, H., and Flynn, J. (2006). "Current and future wet-mate connector technology developments for scientific seabed observatory applications," in *OCEANS 2006*. (Boston, MA, USA: IEEE) 1–6. doi: 10.1109/oceans.2006.306829
- Rémouit, F., Ruiz-Minguela, P., and Engström, J. (2018). "Review of electrical connectors for underwater applications," in *IEEE Journal of Oceanic Engineering*. IEEE, 43 (4), 1037–1475. doi: 10.1109/joe.2017.2745598
- Shi, J., Li, F., Peng, S., Cai, W., Pan, M., and Yu, H. (2020). Design and analysis of a noninsert wet mateable connector for underwater power and data transfer. *Mar. Technol. Soc. J.* 54 (1), 65–785. doi: 10.4031/mtsj.54.1.3
- Wang, C., Yu, H.-Y., and Zhu, Y.-J. (2016). A long distance underwater visible light communication system with single photon avalanche diode. *IEEE Photonics J.* 8 (5), 1–115. doi: 10.1109/jphot.2016.2602330
- Xu, J., Kong, M., Lin, A., Song, Y., Yu, X., Qu, F., et al. (2016). OFDM-based broadband underwater wireless optical communication system using a compact blue LED. *Optics Commun.* 369 (June), 100–105. doi: 10.1016/j.optcom.2016.02.044



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Gravity disturbance compensation for dual-axis rotary modulation inertial navigation system

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Gravity disturbance compensation is an important technique for improving the positioning accuracy of high-precision inertial navigation systems (INS). Aiming at the current problems of the resolution of gravity compensation background field and the robustness of gravity compensation algorithm are insufficient for gravity compensation. In this study, the error and frequency characteristics of INS caused by gravity disturbances are investigated. The gravity disturbance with a spatial resolution of $1' \times 1'$ from a high-precision satellite altimetry marine gravity field model is preliminarily introduced into the initial alignment and pure INS calculation to implement the gravity compensation of the dual-axis rotary modulation INS. Detailed calculation results show that the east gravity disturbance affects the north attitude, and the north gravity disturbance affects the east attitude in the initial alignment. In the pure INS calculation, the horizontal gravity disturbance causes a navigation error in the form of Schuler oscillation. The INS navigation error caused by horizontal gravity disturbance is mainly affected by its amplitude; however, the horizontal gravity disturbance accuracy from the satellite altimetry model for INS gravity compensation can be ignored in practice. In addition, for low-speed underwater vehicles, the influence of high-frequency gravity disturbance signals on the INS position shows an increasing trend. Finally, the effectiveness of the gravity compensation achieved by the horizontal gravity disturbance from the satellite altimeter model is confirmed by a dynamic shipborne test. The positioning accuracy of the rotary modulation INS is maximally improved by approximately 17.9% after the horizontal gravity disturbance is compensated simultaneously in the pure INS calculation and the initial alignment.

KEYWORDS

inertial navigation system, dual-axis rotary modulation, satellite altimetry, horizontal gravity disturbance, gravity disturbance compensation

1 Introduction

Inertial navigation systems (INS) are widely employed to establish autonomous navigation systems in various fields. This auto-navigation feature renders INS stable and reliable for any type of external interference. However, INS is hindered by errors caused by inertial devices, which severely restrict the underwater long-time navigation ability of the submersible. With the development and application of optical inertial devices and rotary modulation technologies, the accuracy of inertial sensors has significantly improved (Wen et al., 2009; Yuan et al., 2012; Zhou et al., 2018; Wu and Li, 2019). However, some errors have been overlooked and have become the key restricting factors to further improvements in the positioning accuracy of INS, such as horizontal gravity disturbances. In fact, systematic errors caused by gravity disturbances have gradually become one of the main errors. Accurate gravity compensation for INS is an effective means of promoting the long-endurance positioning capability of underwater vehicles (Kwon and Jekeli, 2005; Jekeli et al., 2007; Zhou et al., 2016; Tie et al., 2018; Wen et al., 2020).

Gravity compensation is an important part of gravity-aided navigation for INS. Some scholars have studied the influence of gravity disturbances on INS. Gelb and Levine (1969) modeled gravity disturbance as a Gaussian Markov process and quantitatively evaluated its impact of gravity disturbance on the INS. Jordan (1973) established a Markov model based on variance analysis and analyzed the impact of horizontal gravity disturbances on the INS. These stochastic model methods can be used to estimate gravity disturbance. However, the Earth gravity field (gravity disturbance and gravity anomaly) is inhomogeneous and complex, and a single stochastic model cannot represent the variation in the gravity field. Second, a large amount of prior information must be provided to accurately estimate the stochastic model parameters. Therefore, achieving gravity compensation for an INS based on a stochastic model is not an optimal approach. The second gravity compensation method is a real-time compensation method that uses a gravity gradiometer. The development of the gravity gradiometer made it possible to derive the gravity vector, allowing the mechanical arrangement of the INS to be improved by providing the gravity vector measured using the gravity gradiometer to the INS. Jekeli (2006) proposed an INS gravity compensation method based on a gravity gradiometer that could correct the inertial navigation error through full tensor gravity gradient measurements. However, the use of gravity compensation methods based on gravity gradiometers is hindered by their high cost (Heller and Jordan, 2015). In recent decades, a high-degree Earth gravity field model (GFM) has been developed that can be used to achieve gravity disturbance compensation for INS. Wang et al. (2016) studied gravity compensation based on the EGM2008 gravity model and focused on the impact of the truncation degree/order of the GFM for gravity compensation. Similarly, Chang et al. (2019) utilized a high-degree EIGEN_6C4 model for gravity compensation.

The mechanical arrangement of the INS can be improved by measuring the gravity disturbance determined by high-degree GFMs, such as EGM2008 and EIGEN_6C4 (Pavlis et al., 2012; Förste et al., 2014), with the maximum degree of these GFMs being only 2190 (~10 km). For high-frequency gravity field signals with a spatial resolution less than ~10 km, these high-degree gravity field models still cannot be effectively represented and have certain omission errors owing to the lack of short-wavelength information. Tscherning and Rapp's variance model showed that the gravity field models for degree 2190 have a gravity signal loss of gravity anomaly of 11.1 mGal and deflection of the vertical (DOV) of 1.7" (Tscherning and Rapp, 1974; Denker, 2013). Signal loss was more severe in the rugged terrain area. However, owing to the limited degree of high-degree GFMs, gravity compensation for INS based on GFMs cannot effectively represent high-frequency gravity field signals, which leads to accuracy loss of gravity compensation. In addition, there is a coupling effect between gravity disturbance and accelerometer drift bias (Hanson, 1988). It is still difficult to achieve gravity compensation by considering this coupling effect. From the aforementioned analysis, we can see that the gravity compensation of the INS is mainly related to two factors: (1) the accuracy and resolution of the horizontal gravity disturbance, and (2) the coupling effect between the accelerometer drift bias and gravity disturbance. Therefore, it is important to refine the gravity compensation background field and consider the coupling effect between accelerometer drift bias and gravity disturbance to achieve higher-accuracy gravity compensation.

With the continuous development of satellite altimetry missions, satellite altimetry has become the primary method for determining the global marine gravity field. The marine gravity anomaly and DOV with 1' × 1' (~2 km) resolution can be retrieved by integrating multigeneration altimetry satellites (Andersen et al., 2010; Bao et al., 2013; Sandwell and Smith, 2014; Sandwell et al., 2014; Sandwell et al., 2021). The high-resolution and high-precision marine gravity compensation background field can be determined by satellite altimetry, which provides a new way to achieve gravity compensation for INS. In addition, with the development of rotary modulation technologies, the accuracy of inertial sensors has significantly improved. Rotation modulation technology (RMT) can eliminate the accelerometer drift error by periodically rotating the inertial sensor along the rotation axis. Rotation modulation INS uses periodic dynamic motion to estimate the static error of inertial sensors. Inertial measuring unit (IMU) rotates regularly around the axis to modulate the static error into periodic signal to offset the impact of static error and improve the long-term navigation accuracy of inertial navigation. Owing to the introduction of the modulation mechanism, the accelerometer drift bias can be compensated and the coupling effect can be ignored in gravity compensation. Therefore, this study focuses on gravity compensation for dual-axis rotary modulation INS and aims to improve the positioning accuracy of the dual-axis rotary modulation INS. Herein, the error and frequency characteristics caused by gravity disturbance are

analyzed, and the effect of gravity disturbance on the initial alignment is also investigated. A high-precision and high-resolution satellite altimetry marine gravity field model is used to compensate for the error caused by gravity disturbance, which can effectively represent the high-frequency gravity field signal. The horizontal gravity disturbance determined by the satellite altimetry model is provided to the dual-axis rotary modulation INS to achieve gravity compensation in the initial alignment and pure INS calculations. Finally, the effectiveness of gravity compensation is verified using a dynamic marine shipborne test.

2 Methodology

2.1 Error equation for INS

The velocity kinematical equation of the dual-axis rotary modulation INS is given by (Simav, 2020):

$$\dot{v}^n = C_b^n C_T^b f^T - (2\omega_{ie}^n + \omega_{en}^n) \times v^n + g^n \quad (1)$$

Where v^n is the velocity in the navigation frame, C_b^n is the attitude transformation matrix from the body frame to the navigation frame, f^T is the specific force measured by the accelerometer in the rotating frame, g^n is the gravity vector in the navigation frame, ω_{ie}^n is the Earth's rate under the navigation frame, and ω_{en}^n is the angular rate of the navigation frame with respect to the Earth's frame. The ω_{en}^n and ω_{ie}^n are expressed as follows:

$$\omega_{en}^n = \left[-\frac{v_N^n}{R_M+h} \frac{v_E^n}{R_N+h} \frac{v_E^n}{R_N+h} \tan B \right]^T \quad (2)$$

$$\omega_{ie}^n = [0 \quad \omega_{ie} \cos B \quad \omega_{ie} \sin B]^T \quad (3)$$

where B and h are the geodetic latitude and geodetic height, respectively; R_M and R_N represent the radius of curvature in the meridian and prime vertical, respectively; ω_{ie} is the Earth's rotation rate; and v_N^n , v_E^n are the north and east components of the velocity, respectively.

In traditional INS, the gravity vector is usually replaced by the normal gravity by:

$$\gamma^n = g^n = [0 \quad 0 \quad -\gamma] \quad (4)$$

where γ is the normal gravity value, which can be determined by the closed-loop formula (4-60) in Hofmann-Wellenhof and Moritz (2006). However, the actual gravity differs from normal gravity, that is:

$$g^n = \gamma^n + \delta g^n \quad (5)$$

Where δg^n is the gravity disturbance vector. It can be seen that there are errors in the velocity update when a normal gravity vector is used.

Compared with the strapdown INS, the accuracy of the rotation modulation INS is improved significantly. Inertial sensor errors are eliminated by periodically rotating the inertial sensor along the rotation axis. At this time, the influence of the gravity disturbance must be considered. The error equation of INS considering gravity

disturbance can be written as follows:

$$\delta \dot{v}^n = \phi \times f^n - (2\omega_{ie}^n + \omega_{en}^n) \times \delta v^n - (2\delta\omega_{ie}^n + \delta\omega_{en}^n) \times v^n + \nabla^n + \delta g^n \quad (6)$$

$$\begin{cases} \delta \dot{B} = \frac{\delta v_N}{R_M+h} \\ \delta \dot{L} = \frac{\delta v_E}{R_N+h} \sec B + \delta B \frac{v_E}{R_N+h} \tan B \sec B \\ \delta \dot{h} = \delta v_U \end{cases} \quad (7)$$

$$\dot{\phi} = -\phi \times \omega_{in}^n + \delta\omega_{in}^n - \epsilon^n \quad (8)$$

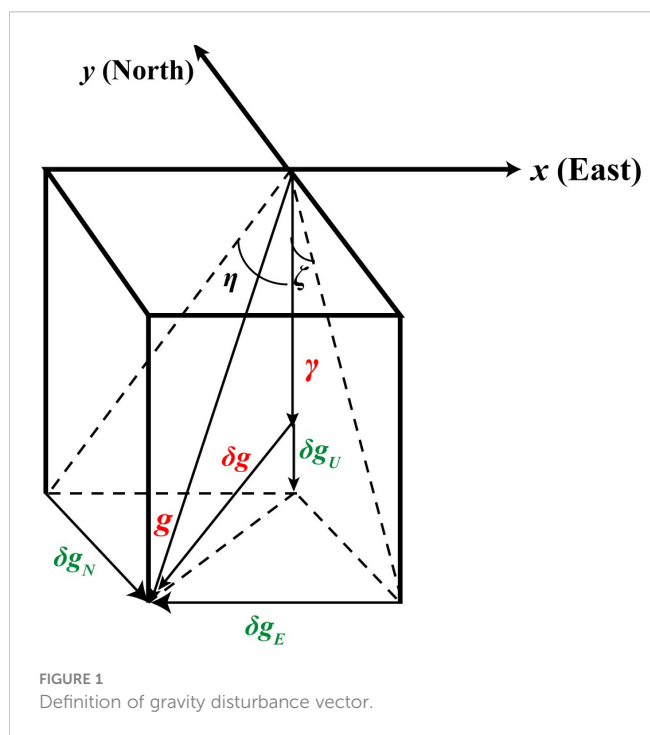
where ϕ is the attitude error, f^n is the specific force in the navigation frame, ∇^n is the accelerometer drift bias, ϵ^n is the gyro drift bias, δB , δL , and δh are the latitude, longitude, and height errors, respectively, and ω_{in}^n is the sum of ω_{ie}^n and ω_{en}^n .

Based on Eq. (6), the influence of gravity disturbance is not affected by the rotation modulation. First, the INS velocity error is caused by Eq. (6), and the position and attitude of the INS are further affected by Eq. (7) and (8). The gravity disturbance vector is given by:

$$\delta g^n = g^n - \gamma^n = [\delta g_E \quad \delta g_N \quad \delta g_U] \quad (9)$$

where δg_N and δg_E are the horizontal gravity disturbance components and δg_U is the vertical gravity disturbance component (Figure 1). However, δg_U has little influence on the gravity compensation and can be ignored in practice. Therefore, only horizontal gravity disturbance is considered in this study.

The actual gravity differs from normal gravity owing to the existence of a vertical deflection. As shown in Figure 1, ζ is the meridian component of the DOV and η is the prime vertical component of the DOV. The horizontal gravity disturbance



components on the x and y axes are negative when η and ζ are positive. Then:

$$\tan \zeta = -\frac{\delta g_N}{\gamma + \delta g_U} \quad (10)$$

$$\tan \eta = -\frac{\delta g_E}{\gamma + \delta g_U} \quad (11)$$

Because the deflection of the vertical is small, it can be approximated by $\tan \zeta = \zeta$ and $\tan \eta = \eta$, in addition, the δg_U can generally be ignored:

$$\delta g_N = -\gamma \cdot \zeta \quad (12)$$

$$\delta g_E = -\gamma \cdot \eta \quad (13)$$

The horizontal gravity disturbance components are calculated according to the DOV in the meridian and prime vertical directions. With the continuous development of satellite altimetry, the accuracy of determining the DOV from the altimetry model has been improved. In this study, the horizontal gravity disturbance determined by the altimetry model was used to achieve INS gravity compensation. The calculation process for the horizontal gravity disturbance is presented in section 3.4.

2.2 Effect of gravity disturbance on initial alignment

The initial alignment for INS is generally performed under the static base condition, which consists of two steps: coarse alignment and fine alignment. We can only obtain a coarse attitude matrix using coarse alignment. A certain misalignment angle error is observed. Gravity disturbances can be ignored in coarse alignments. However, the influence of horizontal gravity disturbance should be considered in fine alignment. System errors are estimated and corrected using Kalman filtering. According to Eq. (6)–(8), the INS error equation with static base conditions can be expressed as:

$$\begin{cases} \dot{\phi} = -\phi \times \omega_{ie}^n - \epsilon^n \\ \delta \dot{v}^n = \phi \times f^n - 2\omega_{ie}^n \times \delta v^n + \nabla^n + \delta g^n \end{cases} \quad (14)$$

The system filtering state-space of fine alignment can be defined as:

$$X = [\delta v_E \ \delta v_N \ \phi_E \ \phi_N \ \phi_U \ \nabla_E \ \nabla_N \ \epsilon_E \ \epsilon_N \ \epsilon_U]^T \quad (15)$$

According to Eq. (14), the fine alignment state-space model is constructed as follows:

$$\dot{X} = FX + U + GW \quad (16)$$

where

$$F = \begin{bmatrix} M_1 & I_{2 \times 2} & 0_{2 \times 3} \\ M_2 & 0_{3 \times 2} & -I_{3 \times 3} \\ 0_{5 \times 5} & 0_{5 \times 2} & 0_{5 \times 3} \end{bmatrix} \quad (17)$$

$$U = [\delta g_E \ \delta g_N \ 0_{1 \times 8}]^T \quad (18)$$

$$G = \begin{bmatrix} I_{2 \times 2} & 0_{2 \times 3} \\ 0_{3 \times 2} & -I_{2 \times 3} \\ 0_{5 \times 2} & 0_{5 \times 3} \end{bmatrix} \quad (19)$$

$$W = [w_{1 \times 2}^\nabla \ w_{1 \times 3}^\epsilon]^T \quad (20)$$

$$M_1 = \begin{bmatrix} 0 & 2\omega_{ie} \sin B & 0 & 2\omega_{ie} \sin B & 0 & -\gamma & 0 \\ & -2\omega_{ie} \sin B & 0 & \gamma & 0 & 0 \end{bmatrix} \quad (21)$$

$$M_2 = \begin{bmatrix} 0 & 0 & 0 & \omega_{ie} \sin B & -\omega_{ie} \cos B \\ 0 & 0 & -\omega_{ie} \sin B & 0 & 0 \\ 0 & 0 & \omega_{ie} \cos B & 0 & 0 \end{bmatrix} \quad (22)$$

where $w_{1 \times 2}^\nabla$ and $w_{1 \times 3}^\epsilon$ are the white noise errors of the accelerometer and gyro.

Taking the velocity under the static base condition as the observation, the measurement equation of the system can be given by:

$$V - \tilde{V} = [I_{2 \times 2} \ 0_{2 \times 8}]X + v \quad (23)$$

where I is unit matrix, V is the true velocity, $\tilde{V}$ the estimated velocity, and v the observation noise.

The initial alignment based on Kalman filtering takes the velocity as the measured value; therefore, the values related to velocity (v^n , $\delta \dot{v}^n$, and δv^n) can be regarded as known values. Therefore, the velocity error δv^n in Eq. (14) can be obtained. Let $y = \delta \dot{v}^n + 2\omega_{ie}^n \times \delta v^n$ be a combination of observable measurements; then, the velocity error equation can be expressed as:

$$y_E = -\gamma \phi_N + \delta g_E + \nabla_E^n \quad (24)$$

$$y_N = \gamma \phi_E + \delta g_N + \nabla_N^n \quad (25)$$

We can let $y=0$ be under a static base; therefore, the horizontal steady-state attitude error can be obtained from Eq. (24) and (25), as follows:

$$\begin{cases} \phi_N = \frac{\delta g_E + \nabla_E^n}{\gamma} = \frac{\nabla_E^n}{\gamma} - \eta \\ \phi_E = -\frac{\delta g_N + \nabla_N^n}{\gamma} = -\frac{\nabla_N^n}{\gamma} + \zeta \end{cases} \quad (26)$$

Eq. (26) shows that the fine alignment of the INS depends mainly on the ∇^n and horizontal gravity disturbance. The north gravity disturbance caused an east attitude error, and the east gravity disturbance caused a north attitude error. For a dual-axis rotary modulation INS, ∇^n can be weakened by periodically rotating the inertial sensor along the rotation axis. Horizontal gravity disturbance is the main factor affecting fine alignment. Therefore, the horizontal gravity disturbance should be compensated for during the initial alignment.

2.3 Gravity disturbance compensation for dual-axis rotation modulation INS

The gravity compensation of the INS includes compensation in the initial alignment and the pure INS calculation. The gravity compensation in the pure INS calculation means that the gravity disturbance is compensated in the velocity in Eq. (1). For gravity compensation in the initial alignment, Eq. (16) and (23) are used to construct the fine alignment state-space model, and the initial alignment errors caused by gravity disturbances are estimated and corrected. The high-resolution horizontal gravity disturbance from the satellite altimetry marine gravity field model is provided to the INS for the mechanical arrangement in this study. The specific gravity compensation process is illustrated in Figure 2.

3 Analysis of the impact of gravity disturbance on INS

3.1 Initial alignment

A corresponding static-based simulation experiment is designed to analyze the impact of gravity disturbance on the initial alignment. The simulation conditions are as follows: gyro drift bias, 0.001°/h; accelerometer drift bias, 10 μ g; INS sampling interval, 100 Hz. The static position is located at 111.8154° E and 20.7394° N, with a height of 0. The east and north gravity disturbance of static position are 34.92 mGal and -29.18 mGal (1 mGal = 10^{-5} m/s²), respectively, which is determined by satellite altimetry model (the specific calculation for horizontal gravity disturbance is given in section 4). The corresponding DOV components in the prime vertical and meridian are -7.4" and 6.2", respectively. The accelerometer and gyro data are obtained by simulation according to the static INS velocity increment, angular velocity increment law, and inertial sensor error parameter set.

The initial attitude misalignment angle is set to $[0.5^\circ, 0.5^\circ, 0.5^\circ]^T$ for fine alignment, the velocity error is set to 0.03 m/s, and the initial

alignment time is 3600 s. Figures 3A, B show the east and north attitude errors before and after the gravity compensation, respectively, and show that the attitude error is affected by the gravity disturbance. After gravity compensation, the horizontal attitude error is weakened. The improvement in the amplitude of the attitude error accuracy after gravity compensation tended to be consistent with the DOV. The DOV components in the prime vertical cause north attitude errors, while the DOV components in the meridian cause east attitude errors. In addition, the gravity disturbance and accelerometer drift bias are superimposed, which jointly affected the initial alignment attitude. The accelerometer drift bias is well estimated for the two-axis rotary modulation INS. This indicates that the attitude error in the initial alignment is mainly caused by the DOV, which has become the main factor affecting the initial alignment attitude and must be compensated.

3.2 INS calculation

In the pure INS calculation, gravity disturbance first causes a velocity error, then further affects the position and attitude of the INS. In this section, the impact of gravity disturbance on the velocity and position is analyzed by ignoring the errors of the gyro, accelerometer, and attitude. The system error Eq. (6)–(7) can be solved analytically to quantitatively analyze the influence of the gravity disturbance. Figures 4A, B show the impacts of different gravity disturbances on the north velocity and position, respectively. Table 1 lists the maximum north position and velocity influence of different gravity disturbances on the INS. As shown in the Figures, the north position and velocity errors caused by gravity disturbance show periodic oscillation, and the error period of velocity and position is 84.4 min (Schuler period). Owing to the modulation of the Schuler period, the horizontal position and velocity errors caused by gravity disturbances are limited to a fixed amplitude. In addition, the results show that the amplitude of the position and velocity errors caused by the gravity disturbance is proportional to its amplitude. Ignoring the cross-coupling effect between the

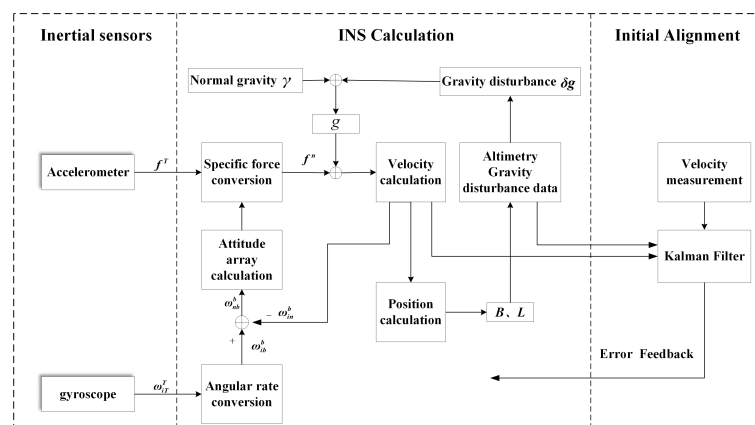


FIGURE 2
Gravity compensation procedure of dual-axis rotary modulation INS.

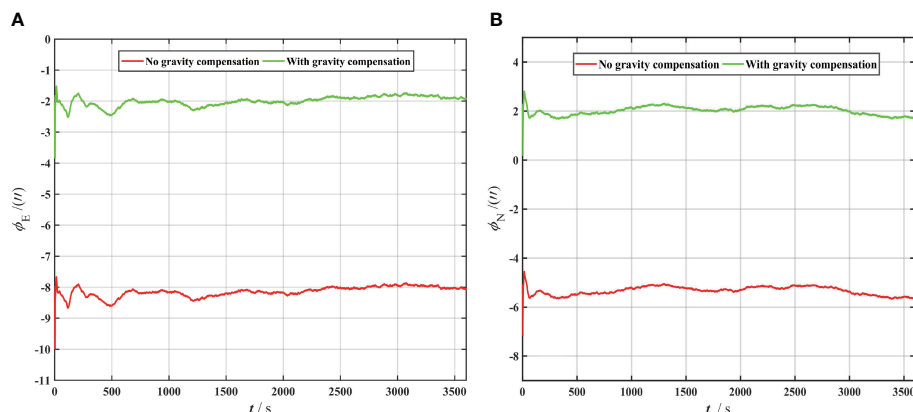


FIGURE 3
Alignment attitude error, (A) east, (B) north.

horizontal channels, the effects of gravity disturbance on the north and east positions is identical. For areas with obvious topographic variations, such as mountains or trenches, gravity disturbance has a greater impact on the INS.

The impact of gravity disturbance on the INS is analyzed above by assuming that the gravity disturbance is constant. In the actual survey line, the gravity disturbance changes from time to time. Therefore, we utilize an actual gravity survey line to study the impact of horizontal gravity disturbance on the INS. Figure 5 shows a gravity survey line with long-endurance (approximately 264 h), which starts from point A and ends at point B. The gravity sampling frequency is 1 Hz. The horizontal gravity disturbance on this gravity survey line is determined by the satellite altimetry model (see section 3.4 for the specific calculation), as shown in Figure 6. The gravity compensation for the INS is not only affected by the magnitude of the horizontal gravity disturbance but also by the horizontal gravity disturbance accuracy. Gaussian white noise with an expectation of 0 and a standard deviation of 3 mGal is added to the gravity disturbance on this trajectory to further analyze the effect of horizontal gravity disturbance accuracy. White Gaussian noise with a

standard deviation of 3 mGal is added because the accuracy of the horizontal gravity disturbance determined by the altimetry model is approximately 1–3 mGal (Sandwell and Smith, 2014; Sandwell et al., 2014; Sandwell et al., 2021).

Figure 7 shows the maximum position error caused by the horizontal gravity disturbance in each Schuler cycle with and without noise. Table 2 shows the statistics of the maximum position error caused by the horizontal gravity disturbance for all the Schuler cycles. As shown in Figure 7, the maximum position errors are consistent in both cases (with and without noise). The maximum position error caused by gravity disturbance is mainly affected by the amplitude of gravity disturbance, and the horizontal gravity disturbance accuracy have little effect on gravity compensation. It can also be seen from Table 2 that the average maximum position error caused by horizontal gravity disturbance is also consistent in both cases (with and without noise). For satellite altimetry horizontal gravity disturbance with an accuracy of 1–3 mGal, the impact of the horizontal gravity disturbance accuracy could be ignored in gravity compensation. In addition, the average values of the east and north gravity disturbances on this survey line

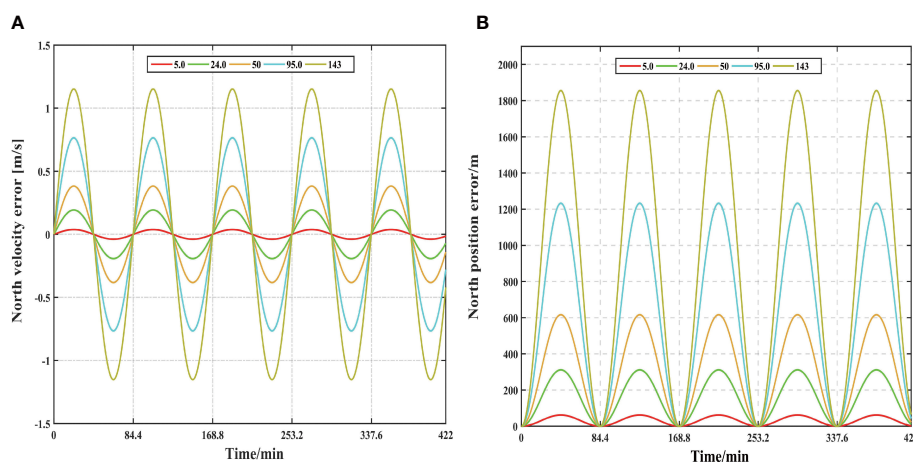


FIGURE 4
The error aroused by different gravity disturbance, (A) north velocity error, (B) north position error.

TABLE 1 The maximum influence of north gravity disturbance on north position and velocity.

Horizontal gravity disturbance (mGal)	5	24	50	95	143
North maximum position error (m)	62	311	616	1232	1856
North maximum velocity error (m/s)	0.038	0.193	0.383	0.765	1.152

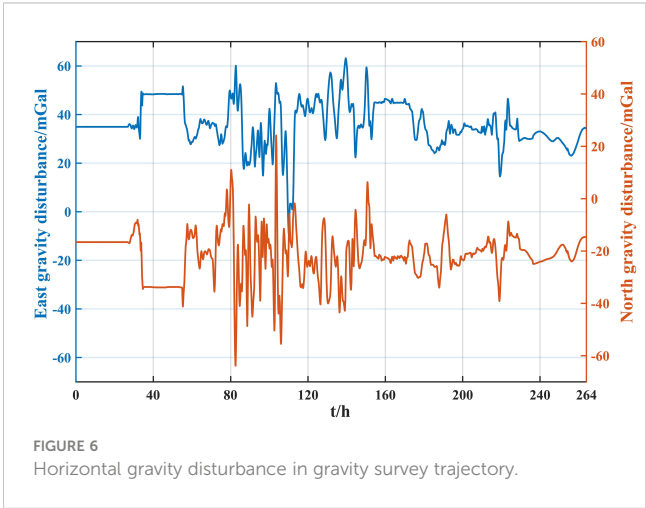
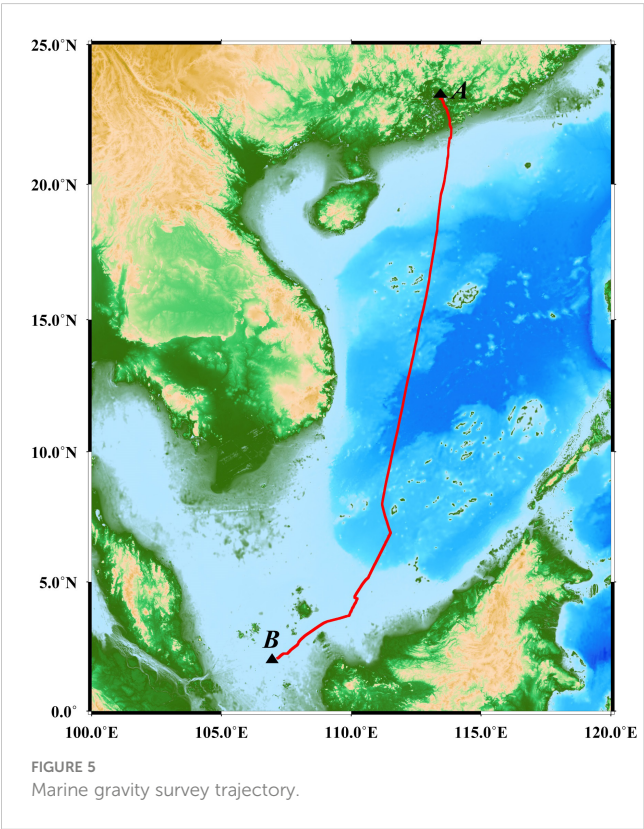
are 35.3 mGal and 21.3 mGal (after taking the absolute value), respectively. The maximum position error caused by the average gravity disturbance in a Schuler cycle is 535.9 m (theoretical analysis), and the average maximum position error caused by the horizontal gravity disturbance on this survey line in a Schuler cycle is 532.7 m (Table 2), which is consistent with both scenarios. This indicates that the average position influence of horizontal gravity disturbance is related to the average value of horizontal gravity disturbance on the trajectory.

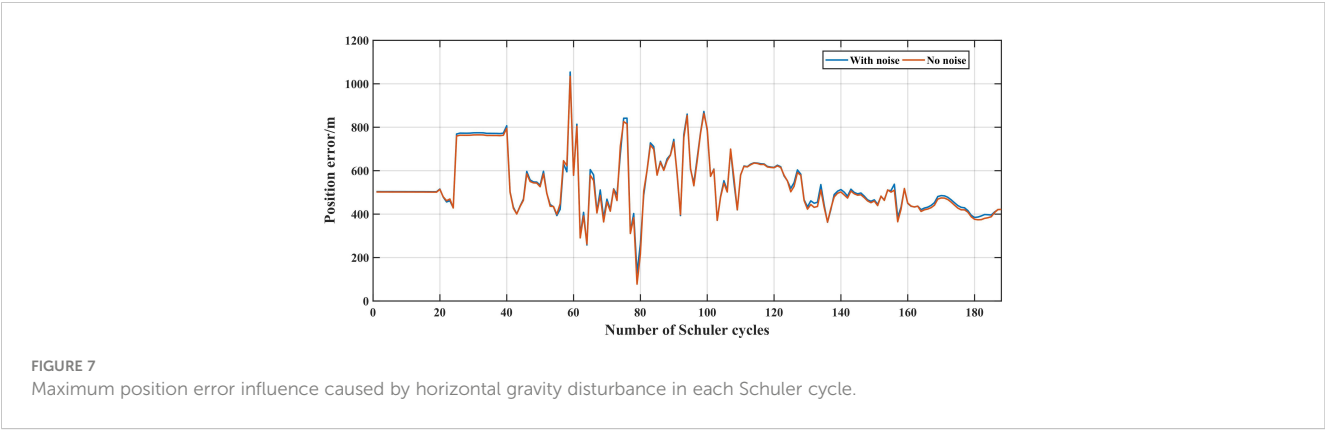
3.3 Frequency characteristics of INS affected by gravity disturbance

To analyze and obtain the frequency characteristics of the INS affected by gravity disturbance, the gravity disturbance is modeled as a Markov process (Jekeli, 2006). Therefore, the relationship between the horizontal gravity disturbance, underwater vehicle velocity V , spatial wavelength of gravity disturbance, and position error caused by horizontal gravity disturbance is established. The calculation of the root mean square value for gravity disturbance is a key factor in determining the relationship between the spatial wavelength, underwater vehicle velocity V , and position error.

The root mean square value of the horizontal gravity disturbance can be determined according to the relationship between the horizontal gravity disturbance and DOV. Therefore, the global root mean square value of the DOV is calculated using the EIGEN_6C4 model in this study (Ustun and Abbak, 2010). The global root mean square of the DOV is approximately $\pm 7.08''$ (equivalent to a horizontal gravity disturbance of ± 33.57 mGal), as shown in Figure 8. Finally, the relationship between the horizontal gravity disturbance, underwater vehicle velocity V , spatial wavelength of gravity disturbance, and position error is determined, as shown in Figure 9.

As shown in Figure 9, the position error is mainly caused by the medium-long wavelength (medium-low frequency) of the horizontal gravity disturbance when the underwater vehicle velocity is high. With a decrease in underwater vehicle velocity, the influence of the short-wavelength (high-frequency) of the horizontal gravity disturbance on the INS position become increasingly significant. The velocity of an underwater vehicle is generally 10–25 kn (1 kn = 1 n mile/h), and the spatial wavelength of the horizontal gravity disturbance, which has the greatest influence on the INS position, is approximately 5–10 km. For an underwater vehicle with a lower velocity, the gravity disturbance high-frequency signal has an increasingly marked influence on the INS. The maximum spatial wavelength of the degree 2190 gravity field model is 10 km. High-degree GFM (i.e. EGM2008 or EIGEN_6C4) can satisfy the requirements of gravity compensation for high-speed underwater vehicles ($V > 50$ km/h). However, for underwater vehicles with low-speed, determining the high-frequency signal of horizontal gravity disturbance is the key to further promoting gravity compensation accuracy, and the satellite altimetry gravity field model provides an effective means to determine high-resolution horizontal gravity disturbance.





3.4 Horizontal gravity disturbance for the China Sea and Western Pacific region

The maximum effect of the horizontal gravity disturbance on the INS position is proportional to its amplitude. For areas with obvious topographic fluctuations, such as seamount ranges or trenches, the horizontal gravity disturbance is greater. The distribution of horizontal gravity disturbance in the China Sea and Western Pacific region and its impact on INS are analyzed using a satellite altimetry model. The seafloor topography in the China Sea and Western Pacific region is complex and contains a large number of islands, reefs, submarine plains, and trenches, which can accurately reflect the distribution of horizontal gravity disturbance under different topographies.

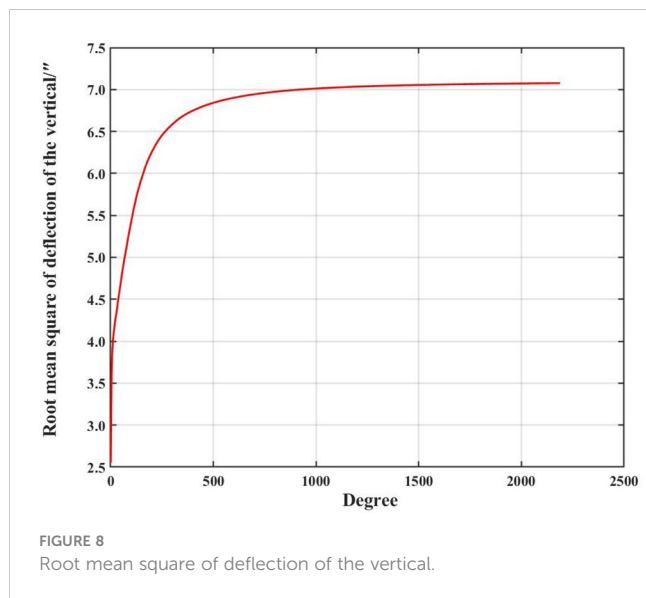
Figure 10A shows the component of the DOV in the prime vertical with a spatial resolution of $1' \times 1'$ in the China Sea and Western Pacific region obtained based on the altimetry model. Figure 10B shows the component of the DOV in the meridian with a spatial resolution of $1' \times 1'$ in the China Sea and Western Pacific region obtained based on the altimetry model. This gridded marine DOV data is one of the most advanced marine gravity databases, derived from satellite altimetry from 1997 to 2019 with a spatial resolution of $1' \times 1'$, and can better represent the marine high-frequency gravity field signal (Sandwell and Smith, 2014; Sandwell et al., 2014; Sandwell et al., 2021). The latest marine DOV data (version SIO V30.1 from the Scripps Institution of Oceanography (SIO) at the University of California, San Diego) is used in this study. As can be seen from Figures 10A, B, the DOV in the China Sea and Western Pacific region is generally between a few to tens of arcseconds. In areas where the seafloor topography changes dramatically, the maximum DOV can reach 80 arcseconds. According to Eq. (12) and (13), the horizontal gravity disturbance in the China Sea and the western Pacific region can be calculated.

Figure 10C shows the east gravity disturbance with a spatial resolution of $1' \times 1'$. Figure 10D shows the north gravity disturbance with a spatial resolution of $1' \times 1'$. The horizontal gravity disturbance in the China Sea and Western Pacific region generally ranges from a few to several hundred milligals, and the maximum horizontal gravity disturbance reaches several hundred milligals in areas where the seafloor topography changes dramatically. Four regions are divided to analyze the distribution of horizontal gravity disturbances on four important channels and their influence on the INS: region A is the South China Sea, region B is the East China Sea, region C is the Sea of Japan, and region D is a part of the western Pacific (Figures 10C, D). The size of each of the four regions was $10^\circ \times 10^\circ$. The influence of the average horizontal gravity disturbance in four regions on the maximum position influence of the INS in the Schuler period was analyzed, the results of which are presented in Table 3. It is worth noting that the range and average value of east and north gravity disturbance in Table 3 are statistical results of absolute values.

From Table 3, we can see that the horizontal gravity disturbance range in regions A, B and C is smaller than that in region D, and the maximum horizontal gravity disturbance in region D could reach several hundred milligals owing to the presence of trenches. The average gravity disturbance in regions A, B, and C had a maximum impact on the INS position of several hundred meters in the Schuler period, while the average gravity disturbance in area D had a maximum impact on the INS position of more than 1000 m in the Schuler period. In particular, in areas with rugged topography, such as trenches and seamounts, gravity disturbance has a maximum impact on the INS position error of several thousand meters in a Schuler period. For areas with a complex seafloor topography, the impact of high-frequency horizontal gravity disturbance cannot be ignored, as the gravity compensation of INS based on high-degree GFMs often leads to a loss of

TABLE 2 Maximum error of INS caused by horizontal gravity disturbance in all Schuler cycles.

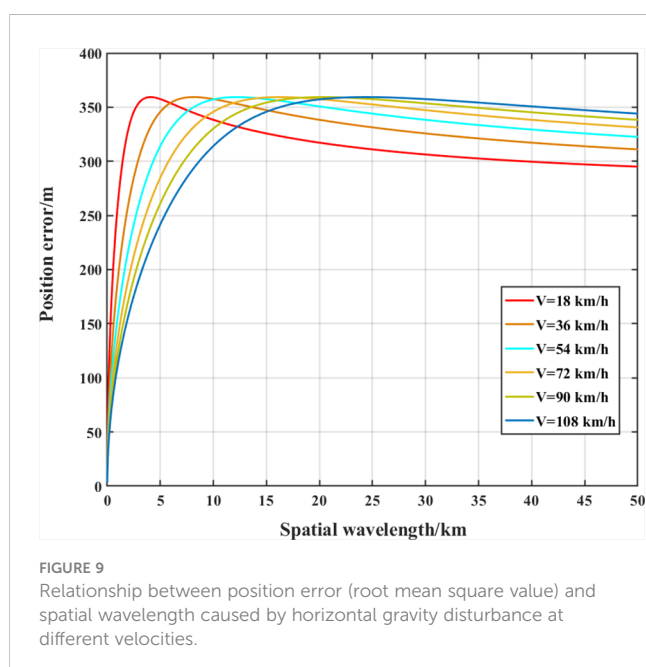
Scenarios	Max	Min	Mean
Position error (no-noise)	1034.6	88.04	532.7
Position error (with-noise)	1053.9	128.7	538.7



compensation accuracy. The gravity compensation of high-precision INS can be achieved using a high-precision marine horizontal gravity disturbance from the SIO V30.1 model.

4 Marine gravity compensation experiment

A marine dynamic shipborne test is conducted in the South China Sea to verify the effectiveness of gravity compensation. A two-axis rotary modulation laser INS, which contained three laser gyroscopes and three quartz flexible accelerometers, is used. The gyro drift bias is better than $0.001^{\circ}/\text{h}$ and the accelerometer drift bias is lower than $10 \mu\text{g}$. The INS provides 500 Hz measurements.



Differential GNSS is used to obtain the reference position information for the ship-based experiment. The horizontal positioning accuracy of the GNSS is better than 1 m, and the GNSS could provide position information at 1 Hz. The trajectory of the ship-mounted experiment is shown in Figure 11, which operates statically for approximately 4 h at the starting point, then dynamically for approximately 10.5 hours. The INS operates for approximately 14.5 hours in total.

4.1 Determination of horizontal gravity disturbance

The horizontal gravity disturbance is calculated using the SIO V30.1 model (section 3.4). For comparative analysis, the high-degree EIGEN_6C4 model is used to determine the horizontal gravity disturbance (Barthelme, 2013; Ince et al., 2019). Figure 12 shows the horizontal gravity disturbance on the ship-based experimental trajectory, $\delta g_{E-SIO V30.1}$ shows that the east gravity disturbance determined by the SIO V30.1 model, δg_{E-GGM} is the east gravity disturbance determined by the EIGEN_6C4 model, $\delta g_N - SIO 30.1$ shows that the north gravity disturbance determined by the SIO V30.1 model, and δg_{N-GGM} is the north gravity disturbance determined by the EIGEN_6C4 model. The maximum east gravity disturbance on the experimental trajectory is approximately 50 mGal and the maximum north gravity disturbance on the experimental trajectory is approximately -30 mGal.

4.2 Gravity compensation results

The horizontal gravity disturbance calculated above is used to achieve gravity compensation for the dual-axis rotation modulation INS. The specific gravity compensation process is illustrated in Figure 2 Gravity compensation includes compensation in the initial alignment and pure INS calculations. The two-axis rotary modulation INS is performed for approximately 50 min of fine alignment and accomplished gravity compensation in fine alignment. Then, the gravity compensation is completed in the pure INS calculation.

For comparison and analysis, two gravity compensation methods are adopted. The first method utilizes the gravity disturbance calculated by the EIGEN_6C4 model, while the second utilizes the gravity disturbance from the SIO V30.1 model. The longitude, latitude, and position errors with and without gravity disturbance compensation are shown in Figures 13A–C, respectively. Both compensation methods are found to weaken the INS error oscillation. The second compensation method further weakens the error oscillation of the INS owing to the higher-frequency horizontal gravity disturbance calculated by the SIO V30.1 model (satellite altimetry model). Figure 14 shows the improvement in the INS positioning accuracy after gravity compensation using two different gravity compensation methods. Table 4 shows the maximum performance improvement of the INS using the two different gravity compensation methods. After gravity

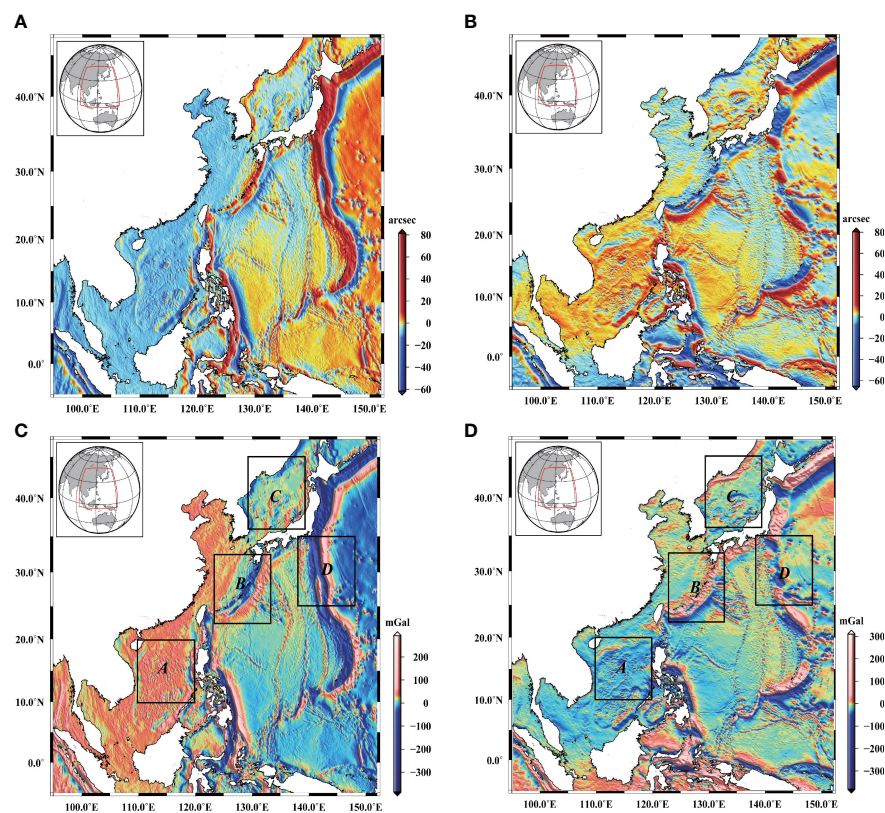


FIGURE 10 The DOV and gravity disturbances from SIO V30.1 model, (A) Component of the DOV in prime vertical, (B) component of the DOV in meridian, (C) east gravity disturbances, and (D) north gravity disturbances.

compensation by the first gravity compensation method, the longitudinal performance of the INS is improved by 152 m, the latitude performance is improved by 311 m, the position performance is improved by 309 m, and the ranges of longitude, latitude, and position are improved by 17.6%, 17.5%, and 16.6%, respectively. After using the second method for gravity compensation, the longitude performance of the INS is improved by 161 m, the latitude performance is improved by 334 m, the position performance is improved by 335 m, and the range of longitude, latitude, and position are improved by 18.5%, 18.7%, and 17.9%, respectively. These results indicate that gravity compensation can further improve the performance of high-precision INS. Compared to the high-degree gravity field model, the gravity compensation performance of the satellite altimetry

model is better because it contained a higher-frequency gravity field signal.

In the gravity compensation of a high-precision INS, the horizontal gravity disturbance determined by the satellite altimetry model could be used to achieve gravity compensation, which can improve the mechanical arrangement of the INS. In particular, for areas with large topographic changes (such as trenches or seamounts), the impact of high-frequency gravity disturbances caused by seafloor topography must be considered. As discussed in section 3.3, the influence of the higher-frequency signal of the horizontal gravity disturbance on the INS position is increasingly significant for low-speed underwater vehicles. However, the high-degree gravity field model (EGM2008 or EIGEN_6C4) could not effectively represent higher-frequency

TABLE 3 Horizontal gravity disturbance and maximum position influence caused by average gravity disturbance on INS in a Schuler period ($\delta g_{N-Scope}$ and $\delta g_{E-Scope}$ show distribution range of north and east gravity disturbance, and δP_{Max} show influence of mean gravity disturbance on INS position).

	A (South China Sea)	B (East China Sea)	C (Sea of Japan)	D (Western Pacific)
$\delta g_{E-Scope}$ (mGal)	0~237	0~123	0~100.7	0~297.336
δg_{E-Mean} (mGal)	43.05	33.04	20.60	73.27
$\delta g_{N-Scope}$ (mGal)	0~187.7	0~200.7	0~161.6	0~205.63
δg_{N-Mean} (mGal)	30.09	28.7	21.22	33.3
δP_{Max} (m)	682.8	568.9	384.5	1046.3

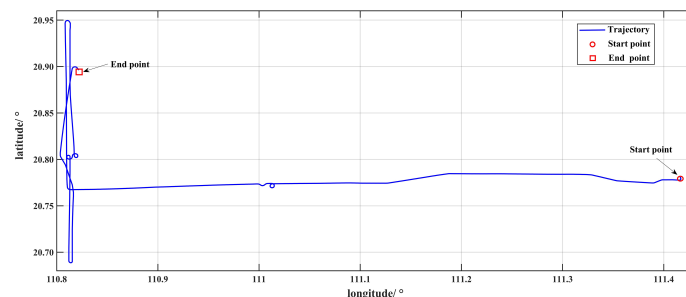


FIGURE 11
Trajectory of marine experiment.

gravity field signals because the spatial wavelength of these models is limited. The satellite altimetry model (SIO V30.1) can effectively represent the high-frequency gravity field signal, which meets the requirements of gravity compensation.

Tie et al. (2017) studied the performance of gravity compensation in initial alignment and pure INS calculations. Their results showed that only gravity compensation in the pure INS calculation improved the performance of INS, while gravity compensation in both the initial alignment and pure INS calculation worsened the performance of INS. The main reason for this is that accelerometer drift and gravity disturbances are coupled. For a dual-axis rotary modulation INS, the accelerometer drift bias can be estimated well, and the coupling effect can be ignored in gravity compensation. To further prove the effectiveness of gravity compensation simultaneously in the initial alignment and pure INS calculations, two gravity compensation strategies are adopted. The first strategy is comprised of gravity compensation only in the pure INS calculation, while the second strategy involves simultaneous gravity compensation in the initial alignment and pure INS calculation. The SIO V30.1 model is utilized for gravity compensation. The position errors from the two gravity compensation strategies are compared in Figure 15. Gravity compensation using the second strategy is found to have a

minimum position error, which indicates that gravity compensation should be carried out in the initial alignment and pure INS calculation. Chang et al. (2019) also found that the gravity compensation of high-precision INS needed to be compensated for both the initial alignment and the pure INS calculation. Therefore, for a high-precision INS, when the accelerometer drift bias is fully calibrated or modulated, the positioning accuracy of the INS could be further improved by achieving gravity compensation in the initial alignment and pure INS calculation. If the accelerometer drift bias is not fully calibrated or modulated, the horizontal gravity disturbance and accelerometer drift bias will be coupled in gravity compensation, which may not be effective.

5 Conclusion

Gravity disturbance compensation is essential for further improving the positioning accuracy of the INS. In this study, the error and frequency characteristics of INS caused by gravity disturbances are investigated. The results show that the east gravity disturbance affects the north attitude, and the north gravity disturbance affects the east attitude in the initial alignment. In the pure INS calculation, the horizontal gravity

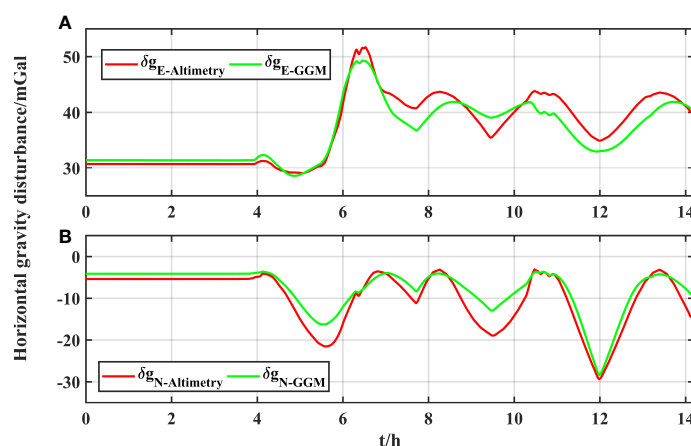


FIGURE 12
Horizontal gravity disturbance along trajectory of ship, (A) east gravity disturbance and (B) north gravity disturbance.

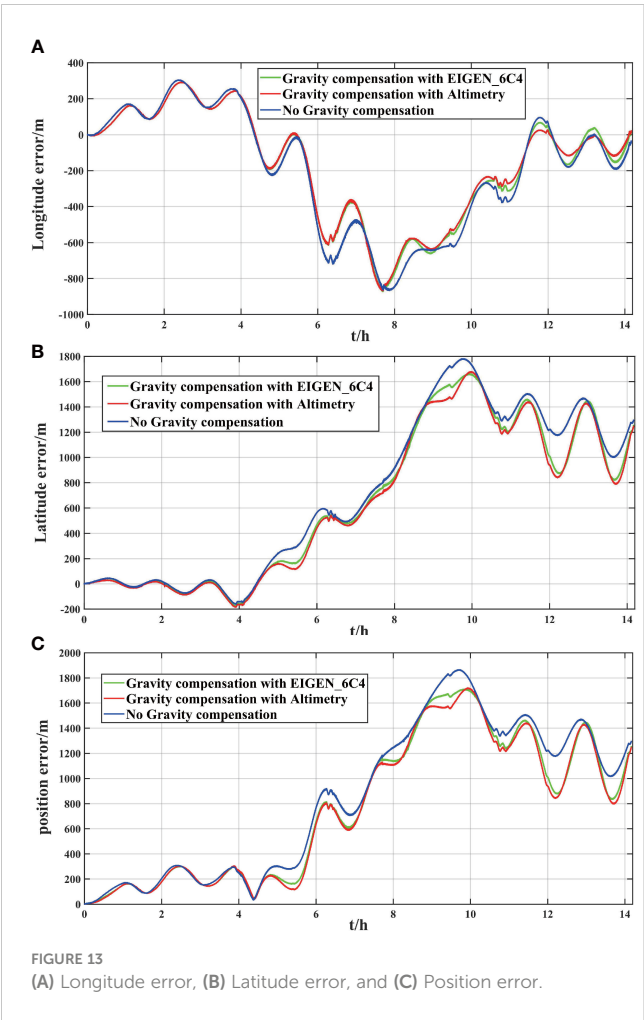


FIGURE 13 (A) Longitude error, (B) Latitude error, and (C) Position error.

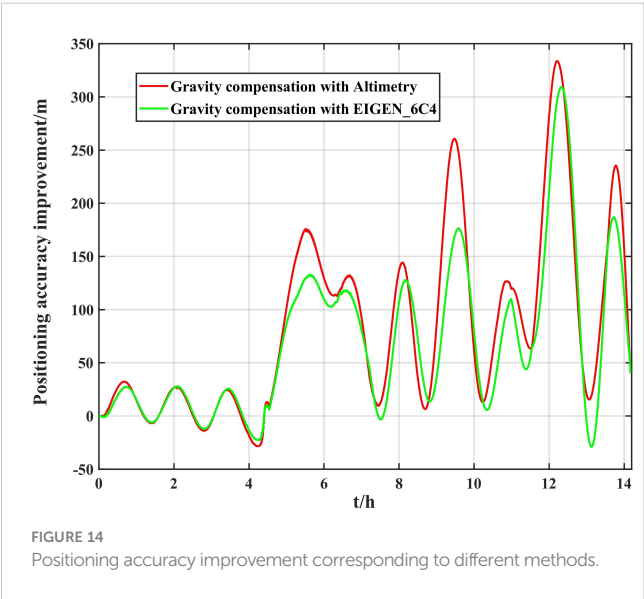


FIGURE 14 Positioning accuracy improvement corresponding to different methods.

disturbance causes a navigation error in the form of Schuler oscillation. The position error is mainly caused by the medium-long wavelength (medium-low frequency) gravity disturbance when the underwater vehicle velocity is larger. With a decrease

TABLE 4 Improvement of maximum positioning accuracy using two different gravity compensation methods.

Method	Accuracy improvement	Longitude	Latitude	Position
SIO V30.1	Error reductions (m)	161	334	335
	Improvement ranges (%)	18.5	18.7	17.9
EIGEN_6C4	Error reductions (m)	152	311	309
	Improvement ranges (%)	17.6	17.5	16.6

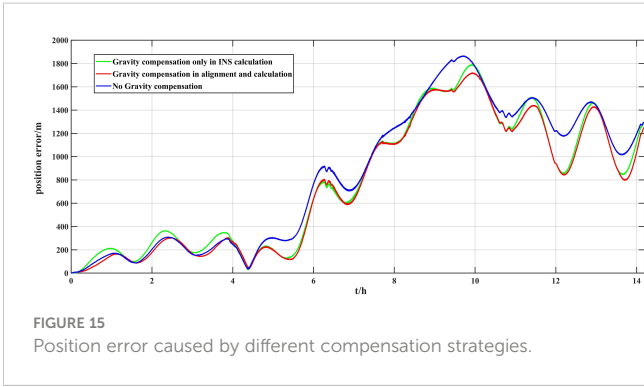


FIGURE 15 Position error caused by different compensation strategies.

in underwater vehicle velocity, the influence of the short-wavelength (high-frequency) of gravity disturbance become increasingly significant.

The distribution of horizontal gravity disturbance in the China Sea and Western Pacific region and its impact on INS are analyzed based on a satellite altimetry model (SIO V30.1). Four regions are divided to analyze the distribution of horizontal gravity disturbances on four important channels and their influence on the INS. The results show that the average gravity disturbance in the South China Sea, the East China Sea, and the Sea of Japan have a maximum impact on the INS position of several hundred meters in the Schuler period, and the average gravity disturbance in the western Pacific has a maximum impact on the INS position of more than 1000 m in the Schuler period. In particular, in areas with rugged topography, such as trenches and seamounts, gravity disturbance is found to have a maximum impact on the INS position error of several thousand meters in a Schuler period.

Finally, the dynamic ship-mounted experiment verified the effectiveness of the satellite altimetry model (SIO V30.1) in achieving gravity compensation. After gravity compensation using the altimeter model, the positioning accuracy has been improved by 18%. The satellite altimetry model is able to effectively represent the high-frequency gravity field signal, which meets gravity compensation requirements. In particular, for regions with large topographic changes (e.g. trenches or seamounts), the impact of high-frequency gravity disturbances caused by seafloor topography must be considered.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

LW, LB and YW conceived the study. The data processing and collection were conducted by QL, HL and BW. The analysis of the results was implemented by PZ, LB, and LW. And the initial draft of the manuscript was written by PZ with improvements and substantial edits from all authors. All authors contributed to the article and approved the submitted version.

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References

- Andersen, O. B., Knudsen, P., and Berry, P. A. M. (2010). The DNSC08GRA global marine gravity field from double retracked satellite altimetry. *J. Geod.* 84 (3), 191–199. doi: 10.1007/s00190-009-0355-9
- Bao, L., Xu, H., and Li, Z. (2013). Towards a 1 mGal accuracy and 1 min resolution altimetry gravity field. *J. Geod.* 87 (10–12), 961–969. doi: 10.1007/s00190-013-0660-1
- Barthelme, F. (2013). *Definition of functionals of the geopotential and their calculation from spherical harmonic models-theory and formulas used by the calculation service of the international centre for global earth models (ICGEM)* (Potsdam, Germany: GFZ German Research Centre for Geosciences Report No: STR09/02).
- Chang, L., Qin, F., and Wu, M. (2019). Gravity disturbance compensation for inertial navigation system. *IEEE Trans. Instrum. Meas.* 68 (10), 3751–3765. doi: 10.1109/TIM.2018.2879145
- Denker, H. (2013). “Regional gravity field modeling: Theory and practical results,” in *Sciences of geodesy – II. innovations and future developments*. Ed. G. Xu (Berlin: Springer), 185–182.
- Förste, C., Bruinsma, S. L., Abrikosov, O., Lemoine, J. M., Marty, J. C., Flechtner, F., et al. (2014). Data from: EIGEN-6C4-The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse. GFZ data service. doi: 10.5880/igcm.2015.1
- Gelb, A., and Levine, S. A. (1969). Effect of deflections of the vertical on the performance of a terrestrial inertial navigation system. *J. Spacecraft Rockets* 6 (9), 978–984.
- Hanson, P. O. (1988). “Correction for deflections of the vertical at the runup site,” in *Proceedings of the IEEE position location and navigation symposium 1988*. (Orlando, FL, USA: IEEE PLANS), 288–296.
- Heller, W. G., and Jordan, S. K. (2015). Error analysis of two new gradiometer-aided inertial navigation systems. *J. Spacecraft Rockets* 13 (6), 340.
- Hofmann-Wellenhof, B., and Moritz, H. (2006). *Physical geodesy* (Wien: Springer).
- Ince, E. S., Barthelmes, F., Reißland, S., Elger, K., Förste, C., Flechtner, F., et al. (2019). ICGEM-15 years of successful collection and distribution of global gravitational models, associated services, and future plans. *Earth Syst. Sci. Data* 11 (2), 647–674. doi: 10.5194/essd-11-647-2019
- Jekeli, C. (2006). Precision free-inertial navigation with gravity compensation by an onboard gradiometer. *J. Guid. Control Dynam.* 29 (3), 704–713. doi: 10.2514/1.15368
- Jekeli, C., Lee, J., and Kwon, J. (2007). Modeling errors in upward continuation for INS gravity compensation. *J. Geod.* 81 (5), 297–309. doi: 10.1007/s00190-006-0108-y
- Jordan, S. (1973). Effects of geodetic uncertainties on a damped inertial navigation system. *IEEE Trans. Aero. Elec. Sys* AES-9 (5), 741–752. doi: 10.1109/TAES.1973.309774
- Kwon, J. H., and Jekeli, C. (2005). Gravity requirements for compensation of ultra-precise inertial navigation. *J. Navigation* 58 (3), 479–492. doi: 10.1017/S0373463305003395
- Pavlis, N. K., Holmes, S. A., Kenyon, S. C., and Factor, J. F. (2012). The development and evaluation of the earth gravitational model 2008 (EGM2008). *J. Geophys. Res.* 117, B04406. doi: 10.1029/2011JB008916
- Sandwell, D. T., Harper, H., Tozer, B., and Smith, W. (2021). Gravity field recovery from geodetic altimeter missions. *Adv. Space Res.* 68 (2), 1059–1072. doi: 10.1016/j.asr.2019.09.011
- Sandwell, D. T., Müller, R. D., Smith, W. H., Garcia, E., and Francis, R. (2014). New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science* 346 (6205), 65–67.
- Sandwell, D. T., and Smith, W. H. F. (2014). Slope correction for ocean radar altimetry. *J. Geod.* 88 (8), 765–771. doi: 10.1007/s00190-014-0720-1
- Simav, M. (2020). The use of gravity reductions in the indirect strapdown airborne gravimetry processing. *Surv. Geophys.* 41 (4):1029–1048. doi: 10.1007/s10712-020-09596-3
- Tie, J., Cao, J., Wu, M., Lian, J., Cai, S., and Wang, L. (2018). Compensation of horizontal gravity disturbances for high precision inertial navigation. *Sensors* 18 (3), 906. doi: 10.3390/s18030906
- Tie, J., Wu, M., Cao, J., Lian, J., and Cai, S. (2017). “The impact of initial alignment on compensation for deflection of vertical in inertial navigation,” in *Proceedings of 8th IEEE International Conference on Cybernetics & Intelligent Systems*. (Ningbo, China: IEEE), 381–386.
- Tscherning, C., and Rapp, R. (1974). *Closed covariance expressions for gravity anomalies, geoid undulations, and deflections of the vertical implied by anomaly degree variance models* (Department of Geodetic Science and Surveying, The Ohio State University Report No: 208).
- Ustun, A., and Abbak, R. (2010). On global and regional spectral evaluation of global geopotential models. *J. Geophys. Eng.* 7 (4), 369. doi: 10.1088/1742-2132/7/4/003
- Wang, J., Yang, G., Li, X., and Zhou, X. (2016). Application of the spherical harmonic gravity model in high precision inertial navigation systems. *Meas. Sci. Technol.* 27 (9), 095103. doi: 10.1088/0957-0233/27/9/095103
- Wen, J., Liu, J., Jiao, M., and Kou, K. (2020). Analysis and on-line compensation of gravity disturbance in a high-precision inertial navigation system. *GPS Solut.* 24, 83. doi: 10.1007/s10291-020-00998-9
- Wen, H., Lu, Q., and Huang, K. (2009). Rotation scheme design for rotary optical gyro SINS. *J. Chin. Inertial Technol.* 17 (1), 8–14.

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Wu, Q., and Li, K. (2019). An inertial device biases on-line monitoring method in the applications of two rotational inertial navigation systems redundant configuration. *Mech. Syst. Signal Process* 120, 133–149. doi: 10.1016/j.ymssp.2018.10.005

Yuan, B., Liao, D., and Han, S. (2012). Error compensation of an optical gyro INS by multi-axis rotation. *Meas. Sci. Technol.* 23 (2), 91–95. doi: 10.1088/0957-0233/23/2/025102

Zhou, X., Yang, G., Wang, J., and Li, J. (2016). An improved gravity compensation method for high-precision free-INS based on MEC-BP-AdaBoost. *Meas. Sci. Technol.* 27 (12), 125007. doi: 10.1088/0957-0233/27/12/125007

Zhou, X., Yang, G., Wang, J., and Wen, Z. (2018). A combined gravity compensation method for INS using the simplified gravity model and gravity database. *Sensors* 18 (5), 1552. doi: 10.3390/s18051552



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A novel submersible-mounted sediment pressure-retaining sampler at full ocean depth

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High-efficiency pressure-retaining sampling technology for obtaining seabed sediments is required for studying marine geological history, the survival principles of marine microorganisms, and the evolution of earth life. In this paper, a novel submersible-mounted sampler capable of collecting pressure-retained samples at a full ocean depth is designed. The structure scheme is first presented, including the sampling unit, pressure-retaining unit, and pressure-compensation unit. The sampling kinematics model is then established, and the influences of pressing velocity, and the length and inner diameter of pressure pipe on the pressing force of the mechanical arm are determined, providing important guidance for the design of the sealing structure. The maximum working depth of the sampler is 11,000 m, the coring diameter of the sampler is 54 mm, the maximum coring depth is 500 mm, and obtained samples can keep close to *in-situ* pressures. The sampler can be mounted on a submersible and operated using a single mechanical arm. During cruise TS-21 from August to October 2021, the sampler was deployed 4 times at depth of 7700 m in the West Philippine Basin, and the high pressure sediment samples were successfully collected. The pressure change of the samples remained within $\pm 6\%$, which verified the rationality of the design and the feasibility of this novel submersible-mounted pressure-retaining sampler.

KEYWORDS

ocean depth, sediment, mechanical design, pressure-retaining sampler, kinematics model, sea trial

1 Introduction

Ocean depths between 6,000 to 11,000 meters are known as the hadal zone, and, due to their extreme depths, have been little explored by human beings. This is especially true for research on the sediments distributed in these depths. To date, hadal zone ecosystems are still poorly characterized due to the ultra-high pressure environment (Drazen and Yeh, 2012). In addition to the high pressures, such extreme environments lack light and have low temperatures. However, piezophiles are well adapted to such environments (Nunoura

et al., 2015; Ritchie et al., 2017). The investigation of ecosystems in such extreme environments can deepen the understanding of the adaptations of deep-sea microorganisms and the evolution of earth life (Huang et al., 2006). Currently, human beings are far from understanding the ecological system in the hadal zone due to the fact that collecting pressure-retained samples in this environment is a rather demanding task (Shillito et al., 2015). Many devices have been designed to collect pressure-retained samples from deep-sea environments, these include water samplers, microorganism samplers, and sediment samplers (Koyama et al., 2002; Kim and Kato, 2010). Previous studies have concluded that pressure is one of the most important attributes determining the *in-situ* state of samples. This is because the loss of pressure leads to dissolution of gas phase, loss of components, decomposition of organic matters, death of piezophilic microorganisms, etc. (Huang et al., 2018). Therefore, it is of significance to design a device capable of collecting pressure-retaining sediments.

Pressure-retaining samplers collect sediments in a high pressure state and retain the pressure as the samples are brought to the surface, facilitating the efficient and effective research of deep-sea sediments. Since the International Ocean Discovery Program (IODP) and the Deep Sea Drilling Program (DSDP), the world's international marine research community has carried extensive research into deep-sea sediment sampling technology and equipment, and developed various kinds of pressure-retaining sampling devices. The pressure core barrel (PCB) (Kvenvolden et al., 1982) developed and used in DSDP is able to seal samples and retain working pressures as high as 34.4 MPa by rotating a ball valve at the lower end and closing an exhaust port at the end of the sampling cylinder. The advanced piston corer (APC) (Francis and Lee, 2000) and pressure core sampler (PCS) (Dickens et al., 1997) were used in IODP. The PCS sampler was hydraulically-driven with a wire-line tool to retrieve sediments with a pressure close to *in-situ* pressure. The maximum working pressure of the PCS sampler is 69 MPa, which gives it excellent pressure-retaining performance. The hydrate autoclave coring equipment (HYACE) (Amann et al., 1997; Schultheiss et al., 2009) developed by the European Union is driven by vibration and can recover samples with working pressures as high as 25 MPa, giving the sampler good pressure-retaining performance. The hybrid PCS developed by Japan Marine Geoscience and Technology Research Center was designed by combining PTCS and PCS (Kubo et al., 2014). This hydraulic driven sampler uses cable coring in conjunction an accumulator, its maximum working pressure is 35 MPa, the core sample diameter is 51 mm, and the core length is 3.5 m. The multiple autoclave corer (MAC) designed in Germany (Abegg et al., 2008) can work at water depths of about 1000 to 2,000 m, and four pressure-retaining sampling devices can be equipped and operated during one sampling procedure, where each sampling device can collect a sample of seabed sediment with a maximum length of 550 mm and a diameter of 100 mm. The PTCS was developed by Japan Technology Research Center (Kawasaki et al., 2006) and has a maximum retained pressure of 30 MPa. The sampler has a bit diameter of 66.7 mm, so it can obtain a sample with a core diameter of 66 mm, and it can core a length of 3 m; its maximum working depth is 100 m.

With the rapid development of deep-diving technology in recent years, sampling tools mounted on human occupied vehicle (HOV) and remote operated vehicle (ROV) have become popular. The ROV "Jason" from the US and ROV "Victor 6000" from France have been equipped with sediment samplers (Eric et al., 2012) and have obtained many deep sea sediment samples, but both are unable to obtain pressure-retained sediments from depths greater than 10,000 m.

In China, the ROV "HAIMA" and HOV "HAILONG" have been equipped with sediment samplers. However, their samplers are non-pressure-retaining, which means that samples taken are unable to retain the *in-situ* pressures. The HOV "JIAOLONG" developed in China (Lu et al., 2019) was mounted with a sediment sampler capable of sampling at water depths of less than 7,000 m, sealing sediment samples, and retaining *in-situ* pressures. However, the sampling process involves the coordinated operation of two manipulators, which makes the whole working process incredibly complex. Recently, Guo et al. (2022) proposed a low-disturbance sediment sampler with a working pressure of 30 MPa. Their sampler that was also equipped with a pressure accumulator system used gas pressure energy to make up for the pressure change in the pressure-retaining cylinder during the recovery process. Pressure tests observed a pressure reduction from 30.77 MPa to 29.57 MPa, which verified the strength and sealing performance of the sampler. Subsequently, pressure-retained samples of about 700 ml were collected through a sea trial, which further validated the feasibility of the sampler. However, the working depth of their device is still limited. Case et al. (2018) designed a novel high-volume sampler, which can be mounted on an unmanned submersible to conduct pressure-retaining sampling for sediments with a working pressure of 50 MPa. The most unique function of the sampler is that it can continuously supply liquid and gas as supplements to keep the pressure in a constant state. Chen et al. (2020) developed a sampling device that can conveniently and economically sample pressurized hadal sediments. Their sampler was also equipped with a pressure accumulator system which compensates the pressure loss in the cylinder as the sampler is brought to the sea surface due to deformation caused by the great pressure difference between inside and outside the sampler. Garel et al. (2019) designed a sampler that can be adapted for use on a CTD-carousel sampler. Their sampler is capable of obtaining samples under high *in-situ* pressures (up to 60 MPa) by using one piloted pressure generator and hydraulic control that maintain constant pressure in the high pressure bottle.

The above-mentioned studies have focused on sediment samplers suitable for a water depth of less than 10,000 m. Very few have attempted to develop sediment samplers capable of working at depths greater than 10,000 m. This is because such attempts have been hindered by the fact that more sophisticated technology and equipment are needed to obtain pressure-retained sediments from ultra-deep seabed. To solve this technical problem, a submersible-mounted sampler designed for collecting pressure-retained sediments from hadal zone is proposed that will enable researchers to better understand the rich information contained in deep sea sediments. The sampler is a purely mechanical structure

that does not require a power source, therefore, it does not require an ROV or HOV to provide power or other power sources. This greatly reduces the costs of design, development, and operation. Moreover, the sampler is portable as it is light in weight, compact in structure, convenient to operate, and, has good pressure-retaining function, making it very suitable for submersible sampling operations.

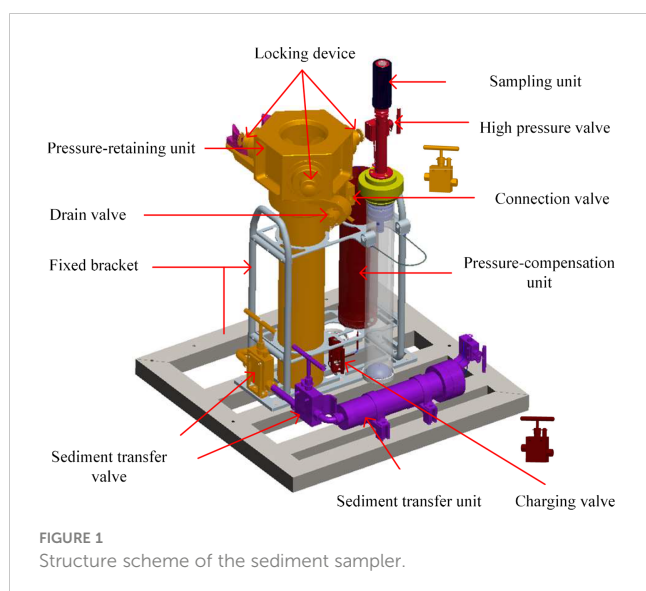
2 Design of the sampler

The novel sampler has been designed based on the program “Development of the Gas-tight Sampler for Full Sea Depth sediment” funded by the National Key Research Plan of China. The sediment sampler can be mounted on a ROV or an HOV, using a mechanical arm to operate the sampler.

The sampler does not need a submersible to provide power sources. Furthermore, it was designed to have a compact structure, it is easy to operate, and it is safe and reliable. The sampler is constructed primarily out of TC4 titanium alloy, which has a high material strength, strong corrosion resistance, low density, and good comprehensive mechanical properties. These attributes allow the sampler to tolerate the ultra-high pressures and corrosive seawater, while also keeping the sampler as light as possible. However, the fix bracket is made of alloy steel (30CrMnSiA), the O-ring is made of fluoro rubber, and the retainer is made of teflon material.

2.1 Pressure-bearing structure

The sampler's structure scheme is shown in Figure 1. It mainly consists of a pressure-retaining unit, a sampling unit, a pressure-compensation unit, a sediment transfer unit, a fixed bracket, a pressure pipe and a drain valve.



2.1.1 Sampling unit

The main function of the sampling unit is to collect deep-sea sediments. Its main components include of a sampling handle, a sealing element 1, a sampling tube assembly, sediment transfer pistons and sealing elements as shown in Figure 2. The sidewall at the end of the sampling tube is provided with a plurality of evenly distributed drain holes to facilitate the drainage. The outer side of the sampling tube is connected with sealing element 1 through threading. After the sampling is completed, the mechanical arm is used to grab the handle and put it into the pressure-retaining cylinder. The force from the lock spring enables the push-stop rod to lock the sealing element 1 of the sampling unit. At this time, the force from the support spring enables the sealing element 1 and the floating piston to be sealed.

2.1.2 Pressure-retaining unit

As can be seen from Figure 3, the pressure-retaining unit is mainly comprised of a pressure-retaining cylinder, lock springs, support springs, pull rods, push-stop rods, a sealing element 2, sealing rings, etc. A stepped hole is placed within the inner hole of the pressure-retaining cylinder, and four blind holes with a certain depth parallel to the axis of the cylinder were arranged on the stepped surface. Each blind hole is provided with a spring, and the sealing element 2 is arranged on it. A sealing ring is designed between the sealing element 2 and the pressure-retaining cylinder. The upper end of the pressure-retaining cylinder is spaced with three holes each of which is spaced with a push-stop rod respectively. The pull rod is assembled with a push-stop rod through threading. A cover is arranged on the sidewall of the pressure-retaining cylinder corresponding to the push-stop rod hole. A lock spring is spaced between the corresponding cover and the push-stop rod, and a sediment transfer interface is designed at the bottom of the pressure-retaining cylinder.

2.1.3 Drain valve

The drain valve is used to close the pressure pipe that connects the cylinder to the seawater outside. This drain valve allows the water in the cylinder to be discharged, relieving the internal pressure, which will ease the workload of the mechanical arm enabling it to press into the pressure-retaining cylinder. The valve includes a valve seat, valve trim, a valve body, a valve switch, a valve deck, and an O-ring seal. The drain valve has two main functions: first, while collecting samples through the sampling tube into the pressure-retaining cylinder, the valve switch is opened to discharge the seawater from the pressure-retaining cylinder, this ensures the initial seal between the sampling tube and the pressure-retaining cylinder. Secondly, after the sampling is completed, the valve switch is closed to guarantee the seal and retain the pressure in the pressure-retaining cylinder. The valve structure schematic is shown in Figure 4. The valve trim and the valve body are sealed using a combination of conical surface and an O-ring, and a compression spring is arranged between the valve trim and valve seat. When the valve switch positions itself in the position shown in the Figure 4, there is a gap between the valve trim and the conical surface of the valve body, and the drain valve is open. When the

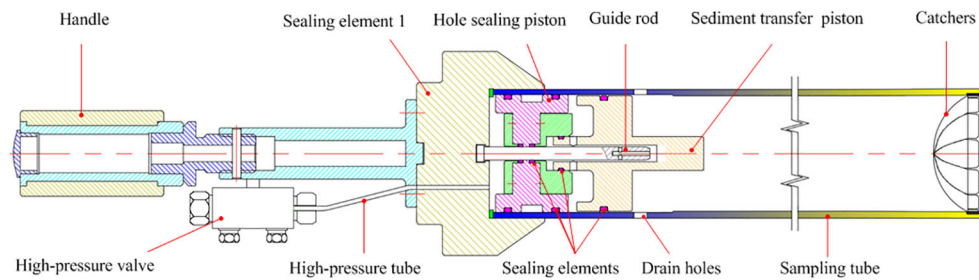


FIGURE 2
Structure scheme of the sampling unit.

valve switch is pulled up, the ejector pin of the valve trim enters the valve switch hole driven by the compression spring, and the valve trim and the valve body are sealed. Subsequently, the drain valve is closed.

2.2 Working principle

The sediment sampler is mainly used to obtain pressure-retained sediment samples. After arriving at the sampling site, a mechanical arm is operated to collect samples and place them into the cylinder to be sealed and pressure-retained until returning to the submersible workboat. As shown in Figure 5, the working process is mainly divided into four stages: preparation, diving, sampling, and recovery:

Preparation stage: As shown in Figure 5A, before the sampler is launched with the submersible, and is fastened to the submersible's

tool basket, the sampling unit is fixed on the bracket, and the pressure-compensation unit is charged with a given pressure nitrogen. At this time, the piston is at the top of the cylinder. When the pressure reaches a set value, the inflation valve is closed to achieve pre-energy storage.

Diving stage: As shown in Figure 5B, after preparation, the sampler dives with the submersible. With the increase of diving depth, the pressure in the cylinder communicating with the outside seawater increases continuously. Under the action of the pressure difference, the compensation piston is moved downward, and the pressure levels at the two ends of the piston are kept in a balanced state, thus energy is continuously stored.

Sampling stage: Once the sampling site is reached, the mechanical arm is operated to grab the handle from the basket and move it to the seabed. The sampling tube is penetrated into the sediment at a given velocity (Figure 5C) and then retracted at a given velocity. Any sediment adhered on the outer wall of the

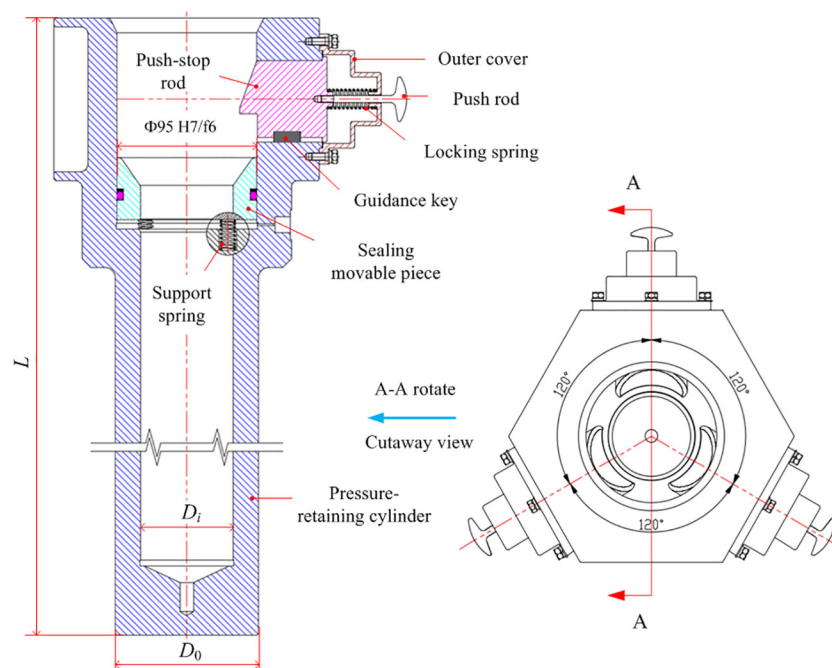


FIGURE 3
Structure scheme of the pressure-retaining unit.

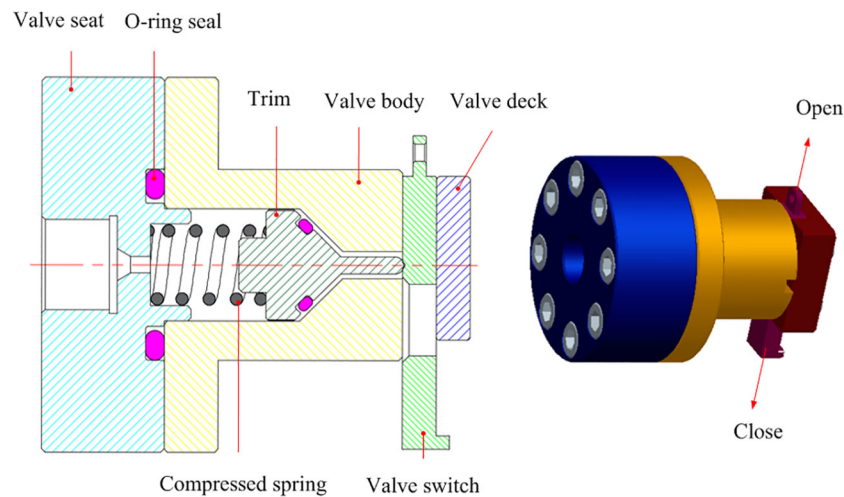


FIGURE 4
Structure scheme of the drain valve.

sampling tube is removed with a mud scraper ring and then the sampler is inserted into the pressure-retaining cylinder until the sampling unit is locked in place (Figure 5D). Finally, the mechanical arm is used to close the drain valve and the sampler is sealed (Figure 5E).

Recovery stage: As shown in Figure 5F, during ascension to the sea surface, the sampler is tightly sealed. The pressure in the cylinder changes because of the change in the environmental temperature difference as well as external pressure, and the pressure-compensation unit releases the pressure accordingly to guarantee timely compensation of the pressure loss in the obtained samples.

3 Sampling kinematics model

As shown in Figure 6, considering the high pressure and complex environment experienced by the sampler under water, the sealing surface with O-ring sealing structure is adopted to guarantee pressure retaining under the ultra-high pressure. The seal between the floating piston and the cylinder adopts a combined sealing ring structure using an O-ring and retaining ring. The seal between the sampling unit and the floating piston adopts a combined sealing structure using a conical surface and fluoro rubber O-ring. After sampling is finished, the sampling unit is moved downwards by the external force until its sealing element 2 is attached to the conical surface of the floating piston, and the floating piston spring is compressed down. During this process, the seawater in the cylinder flows out of the cylinder through the drain valve driven by the pressure difference. A stress analysis of the penetration process of the sampling unit was conducted, as shown in Figure 6. F represents the pressing force when the sampling unit is pushed downward into the pressure-retaining unit. During this downward movement of the sealing element 2 and the floating piston, the friction between the floating piston and the cylinder wall is F_f , the elastic force of the floating piston spring is F_s , and the

overall force of the internal sea water pressure acting on the whole sampling unit is P_0S .

Assuming that the whole sampling unit moves downward at a uniform velocity under the pressing force, according to the force balance, there is:

$$F_2 = \Delta P \cdot S + F_f + 4F_t - G \quad (1)$$

$$S = \frac{1}{4} \pi D^2 \quad (2)$$

$$F_t = kx \quad (3)$$

where ΔP is the pressure difference between the inside and outside of the pressure-retaining unit, $\Delta P = P_0 - P_1$; S is the cross-sectional area of the upper surface of the sealing element 2; D is the outer diameter of sealing element 2; F_f is the friction force between gas-tight piece and the cylinder wall, which can be experimentally obtained; F_s is the elastic force of the floating piston spring; k is the elastic coefficient of the spring, and G is the overall gravity.

When the sampling unit penetrates into the pressure-retaining cylinder, it is assumed that the seawater in the pressure-retaining cylinder will be discharged through the drain valve according to Bernoulli equation:

$$P_0 + \frac{1}{2} \rho v_0^2 + \rho g z_0 = P_1 + \frac{1}{2} \rho v_1^2 + \rho g z_1 + \sum \Delta h_f + \sum \Delta h_j \quad (4)$$

where P_0 is the seawater pressure in the cylinder; ρ is the seawater density; v_0 is the pressing velocity when operating the sampling unit; g is the acceleration of gravity; z_0 is the position head of the seawater surface in the cylinder; z_1 is the position head of the water outside outlet; P_1 is the seawater pressure outside the cylinder; v_1 is the seawater flow velocity the water outside the outlet; $\sum \Delta h_f$ is the total loss energy during seawater discharge; and $\sum \Delta h_j$ is total local loss energy during seawater discharge.

During the seawater discharge, Δh_f is the loss energy along the way caused by overcoming the resistance, which is calculated as

follows:

$$\Delta h_f = \lambda \frac{l}{d} \cdot \frac{v^2}{2} \rho \quad (5)$$

where l is the length of the pressure pipe; d is the inner diameter of the pressure pipe; and λ is the loss coefficient of the fluids along the pressure pipe, which is related to the Reynolds number and the roughness of the pressure pipe wall. The critical Reynolds number

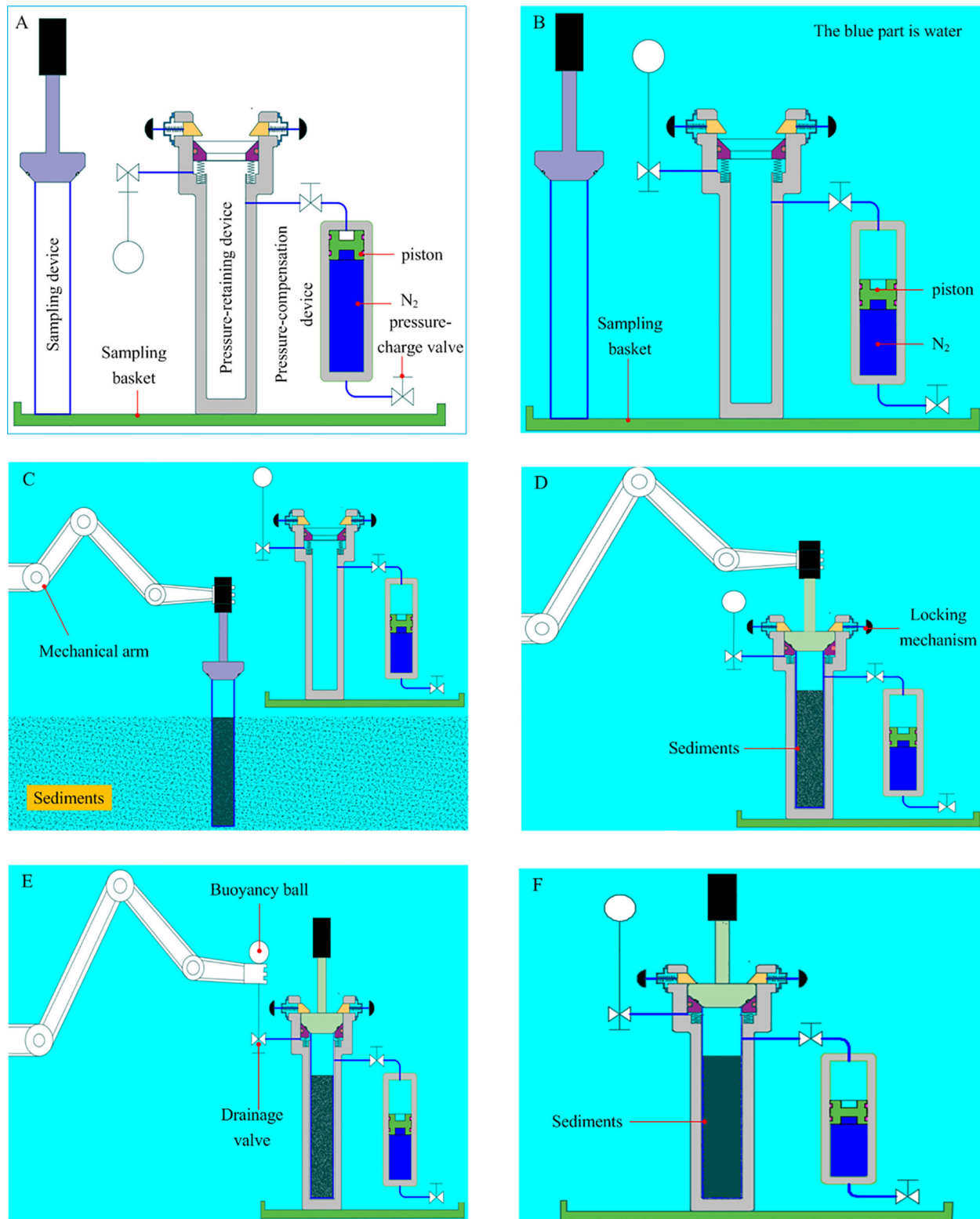


FIGURE 5

Working principle. (A) preparation stage of the sampler before diving, (B) the sampler dives with the submersible, (C) sampling at the sampling site, (D) sampling unit is locked after sampling, (E) drain valve is closed, and (F) recovery stage of the sampler.

Re_c is used as the criterion for judging laminar and turbulent flow regime, which is usually taken as $Re_c=2300$.

When $Re \leq Re_c$, the seawater fluid flow within the pressure-retaining cylinder is laminar. The value of λ is only related to Re and has nothing to do with the pipe roughness, therefore λ as the loss coefficient along the flow path is a function of Reynolds number, calculated as:

$$\lambda = \frac{64}{Re} \quad (6)$$

When $Re_c \leq Re \leq 4000$, the fluid flow in the pressure pipe is in the transition zone between laminar and turbulent flow. In actual practice, there are fewer Re number in this range, and the research within this range is limited. Hydraulic smoothness is adopted here as:

$$\lambda = 0.0025 \cdot \sqrt[3]{Re} \quad (7)$$

When $Re > Re_c$, the area where the fluid flows in the pressure pipe is a hydraulic smooth area. The value of λ in this area is only dependent on Re and has nothing to do with the relative roughness, which can be expressed by the Blasius formula as:

$$\lambda = \frac{0.3164}{\sqrt[4]{Re}} \quad (8)$$

where the value of λ is related to the flow state of the viscous fluid in the sampling tube, the inner diameter and the roughness of the inner wall of the sampling tube; and Re is the Reynolds number of the fluid, which can be expressed as:

$$Re = v \cdot \frac{d}{\eta} \quad (9)$$

where η is the kinematic viscosity of seawater and v is the flow velocity of seawater, and according to the fluid continuity equation,

there is:

$$v = \left(\frac{D}{d}\right)^2 v_0 \quad (10)$$

When seawater flows through abrupt boundaries, e.g., bends and drain valves, forces are generated that hinder its flow, thus causing local losses Δh_j :

$$\Delta h_j = \xi \frac{\rho v^2}{2} \quad (11)$$

where ξ is the local resistance coefficient, which can be obtained by consulting relevant data.

(1) For the piston movement process ($\Delta H = H_0 \sim H_1$): Δh_{f1} is the loss along the path during the seawater discharge process:

$$\Delta h_{f1} = \lambda_1 \frac{\Delta H}{D} \cdot \frac{v_0^2}{2} \rho \quad (12)$$

(2) For the drainage process of the drain valve (l): Δh_{f2} is the loss along the path during the seawater discharge process:

$$\Delta h_{f2} = \lambda_2 \frac{l}{d} \cdot \frac{D^4 v_0^2}{2 d^4} \rho \quad (13)$$

According to Formulas (12) and (13), the total loss in the seawater discharge process is obtained as:

$$\sum_{i=1}^2 \Delta h_{fi} = \Delta h_{f1} + \Delta h_{f2} = \lambda_1 \frac{\Delta H}{D} \cdot \frac{v_0^2}{2} \rho + \lambda_2 \frac{L_2}{d} \cdot \frac{D^4 v_0^2}{2 d^4} \rho \quad (14)$$

During the drainage process, local resistance mainly appears at the cross section of cylinder wall opening, the cross section between the hole and pressure pipe, and the cross section between the pressure pipe and drain valve guide holes. According to formula for calculating local loss, the local losses at each abrupt boundary during seawater discharge are obtained successively.

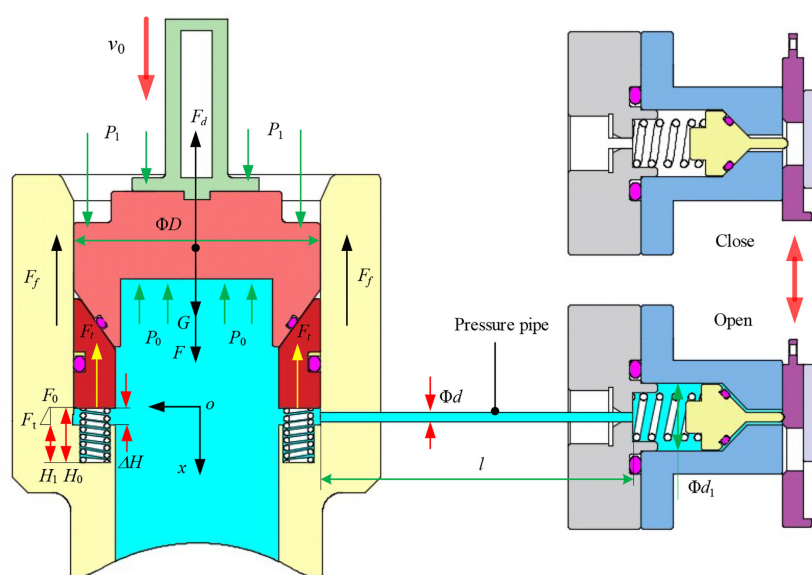


FIGURE 6
Stress analysis diagram of dynamic seal structure.

(1) When the seawater flows into the opening of the cylinder wall, the local loss coefficient is $\xi_1 = 0.5$, which can be expressed as:

$$\Delta h_{j1} = \zeta_1 \frac{\rho v_1^2}{2} = \frac{0.5}{d^4} \cdot \frac{\rho v_0^4}{2} D^4 \quad (15)$$

(2) Due to the design of the pressure pipe, seawater flows through bent sections, and the local loss coefficient of a 90° bend pipe is $\xi_2 = 0.132$. The local loss in this process can be expressed as:

$$\Delta h_{j2} = \zeta_2 \frac{\rho v_2^2}{2} = n \frac{0.132}{d^4} \cdot \frac{\rho v_0^4}{2} D^4 \quad (16)$$

where n is the number of 90° bends.

(3) The seawater flows into the drain valve, which has a one-way valve structure, at which point the loss coefficient is $\xi_3 = 2$, which can be expressed as:

$$\Delta h_{j3} = \zeta_3 \frac{\rho v_3^2}{2} = \frac{2}{d_1^4} \cdot \frac{\rho v_0^4}{2} D^4 \quad (17)$$

According to equations (15)–(17), the total local loss from these main abrupt flow sections can be obtained as:

$$\sum_{m=1}^3 \Delta h_{jm} = \Delta p_{j1} + \Delta p_{j2} + \Delta p_{j3} \quad (18)$$

With the prerequisite of satisfying the structural design of the pressure-retaining unit, during the process of pressing, the relationship between pressing force (F_2) and flow velocity (v_0) is greatly influenced by flow resistance, which is mainly determined by the design and layout of the pressure pipes.

In order to ensure a smooth pressing process, the minimum pressing force (F_m) should be $F_m \geq F$. The calculation parameters of the specific model are shown in Table 1

4 Results and discussion

Using the univariate method, the influence rules of pressure pipe length (l), pressure pipe inner diameter (d), and pressing velocity (v_0) on pressing force are calculated and obtained to provide a theoretical reference for parameter design of the sampling structure.

Figure 7 shows the relationship between pressing force and pressing displacement under the condition that pressure pipe length (l) is 100 mm and pressure pipe inner diameter (d) is 2 mm. Clearly, the pressing force and the pressing displacement change linearly as pressing velocity changes, and the greater the pressing velocity, the greater the pressing force required. When the pressing velocity is 1 mm/s, the pressing force of the pressing process is within 100 N; but when the pressing velocity reaches 6 mm/s, the pressing force of the pressing process reaches 533 N. Field experiments have shown that the maximum pressing force that the mechanical arm can provide underwater is about 500 N. If the maximum pressing force is exceeded, the sampler will be unable to lock and seal the sampling unit, so it is very important that a reasonable pressing velocity is selected.

The pressing velocity of the mechanical arm directly determines the pressing force. Figure 8 shows the relationship between the pressing force and pressing velocity (1~20 mm/s) when the pressure pipe is 100 mm in length and has an inner diameter of 2 mm. It is clear that the pressing force increases significantly with increasing pressing velocity, and the greater the pressing velocity, the larger the increase in pressing force. From the above analysis, the selection of an appropriate pressing velocity can effectively reduce the pressing force and ensure effective sealing during sampling operation. Generally, to make the operation of the mechanical arm more convenient, the pressing velocity should be as low as possible (usually 2 to 6 mm/s), while also guaranteeing that the pressing force is less than 500 N.

Figures 9 and Figure 10 show the relationships between pressing force and the length and inner diameter of the pressure pipe at different displacements. As can be seen from Figure 9, the pressing

TABLE 1 Parameters of the kinematics model.

Symbol	Name	Value	Symbol	Name	Value
m	Weight of valve trim	3.5 kg	D	Inner diameter of pressure-retaining unit	83 mm
G	Acceleration of gravity	9.8 m/s ²	d	Inner diameter of pressure pipe	1~7 mm
ρ	Density of seawater	1030 kg/m ³	d_1	Inner diameter of drain valve thimble	16.5 mm
K	Elastic coefficient	2.96 N/mm	$z_1 - z_0$	Relative head height	50 mm
E_f	Kinetic friction force	54 N	ζ_1	Coefficient of local resistance	0.5
F	Static friction force	78 N	ζ_2	Coefficient of local resistance	0.132
L	Length of pressure pipe	30~100 mm	ζ_3	Coefficient of local resistance	2
ΔH	Movement of valve trim	5 mm	n	Number of bends of pressure pipe	2
v_0	Pressing velocity	1~20 mm/s			

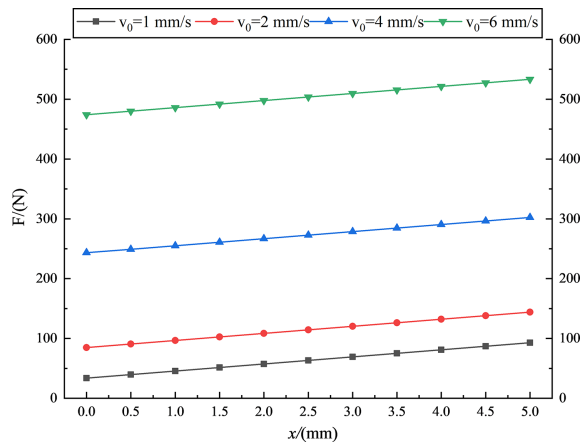


FIGURE 7
Influence of pressing displacement on pressing force.

force increases linearly with increasing length of the pressure pipe, and the degree of increase is basically the same among displacements. This further demonstrates that the length of the pressure pipe should be as short as possible when designing the drainage structure of the sampler. This is because the shorter the pressure pipe length, the smaller the loss energy along the path (Δh_f). In this way, the pressing force can be reduced to facilitate sampling and sealing.

As shown in Figure 10, when the mechanical arm presses at a constant velocity of 2 mm/s, the inner diameter of the pressure pipe has a strong influence on the pressing force when the diameter (d) of the pressure pipe is less than 2 mm. However, when the diameter (d) of the pressure pipe is greater than 2 mm, the pressing force is not greatly affected by the inner diameter of the pressure pipe. For example, at the end of the pressing displacement when $x=5$ mm, when the inner diameter increases from 1 mm to 2 mm, the pressing force decreases by 92.3%; but when the inner diameter increases from 2 mm to 3 mm, the pressing force decreases by 44.8%, which is about 0.5 that of the former. Therefore, the design of the inner diameter of the pressure pipe is of great importance because it directly determines the pressing force required from the mechanical arm.

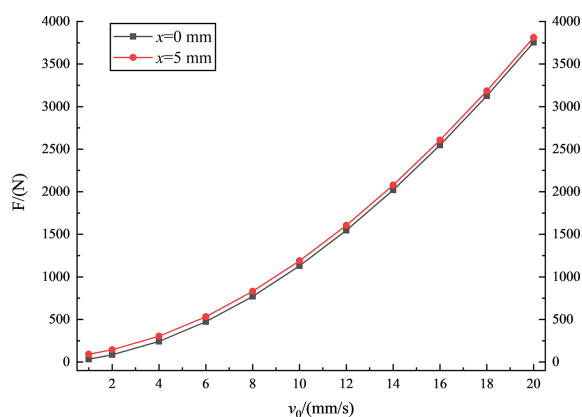


FIGURE 8
Influence of pressing velocity on pressing force.

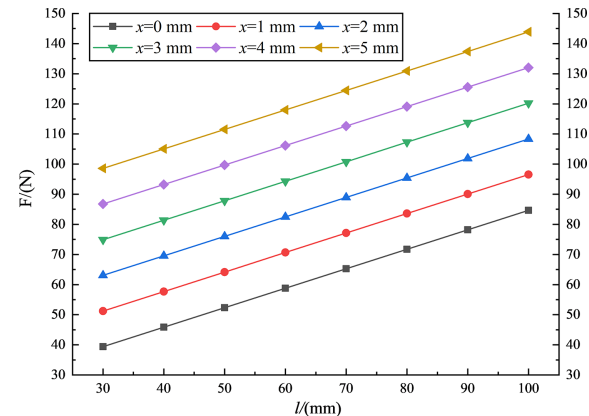


FIGURE 9
Influence of pressure pipe length on pressing force.

5 Sea trial

The sampler was mounted on the HOV *Fendouzhe* (Striver) in the West Philippine Basin during cruise TS-21 from August to October 2021, which was organized by the Institute of Deep-sea Science and Engineering of Chinese Academy of Sciences. The sampler was deployed 4 times at the water depth of 7700 m in the West Philippine Basin. Figure 11A shows that the sampler was installed and fixed in the tool basket of the submersible after all preparations and inspections were complete. Figure 11B shows the submersible robot being operated by the pilot to carry out sampling operations after the sampler reached the sampling site. Figure 12A shows the final pressure of the samples in the sampler after ascending to the surface and Figures 12B–D shows the sediment samples obtained during the sea trial.

As shown in Table 2, pressure-retained sediment samples were obtained in the third and fourth operational trials. The retained pressures were 74.5 MPa and 81 MPa, respectively, in which the respective pressure changes were -6% and +3%. The results of the fourth sampling show that the pressure of the sample was greater than the *in-situ* pressure, which was due to gas expansion caused by the temperature increase as the submersible rose to the sea surface.

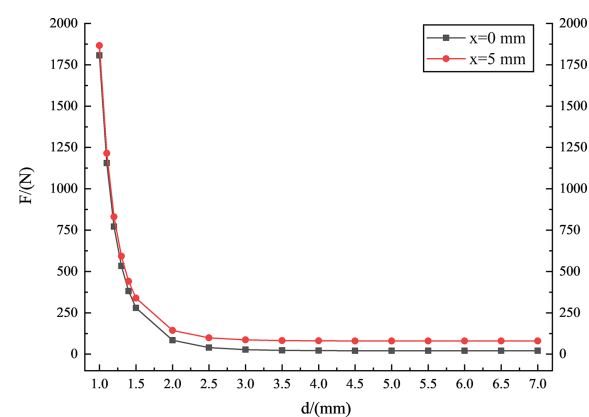


FIGURE 10
Influence of inner diameter of pressure pipe on pressing force.

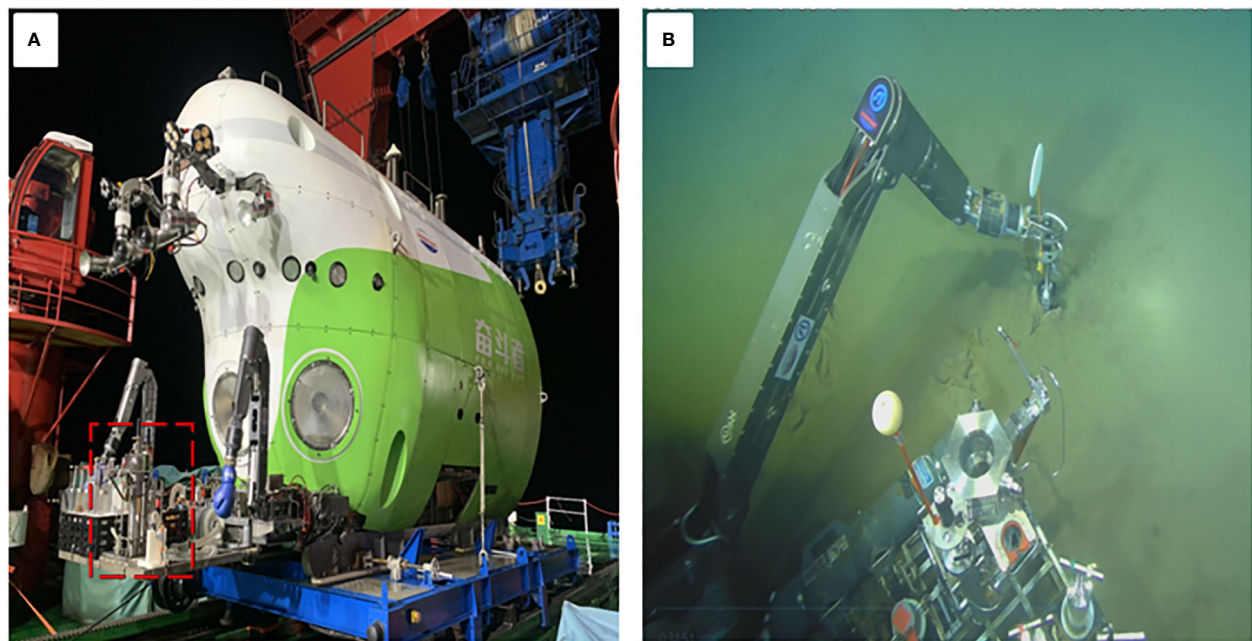


FIGURE 11

The scene of the sea trial, (A) the sampler was installed and fixed in the tool basket, and (B) the sampling operations after the sampler reached the sampling site.



FIGURE 12

Sediment sample obtained, (A) the final pressure of the samples in the sampler, (B–D) the sediment samples obtained during the sea trial.

TABLE 2 Sea trial results.

No.	Diving No.	Location	Water depth (m)	<i>In-situ</i> pressure (MPa)	Recovery pressure (MPa)	Pressure change (%)
1	FDZ031	129.697°N, 16.974°E	7723.0	79	/	/
2	FDZ032	129.697°N, 16.974°E	7721.7	79	/	/
3	FDZ036	129.736°N, 16.946°E	7728.4	79	74.5	-6%
4	FDZ038	129.700°N, 16.944°E	7715.9	79	81	3%

Upon completion, this sea trial represented the first time that China has obtained high-quality pressure-retained sediment samples from an abyssal environment at a depth of more than 7,000 m.

6 Conclusion

(1) The proposed sampler can be mounted on a submersible and used to obtain samples that are pressure-retained and sealed using a single mechanical arm. In this way, in-site sediment samples can be successfully obtained for scientific investigations interested in seabed geological resource exploration, microbial communities, chemistry, and life evolution.

(2) The sampler was tested in a field sea trial in the high seas of the Philippine Sea, and sediment samples with high pressure-retaining rates were successfully collected from the seabed at a water depth of 7700 m. The pressure change of the collected samples was within $\pm 6\%$.

(3) The novel pressure-retaining sediment sampler designed in this study is compact in structure and light in weight, making it suitable for operation by an ROV or HOV mechanical arm in the abyssal environment. This prototype provides new insight into the design of portable deep-sea samplers. Similar novel samplers will likely be widely used in the deep-sea field for the investigation of life evolution and abyssal environment.

(4) In the future, more functions will be added to the sampler. For example, an temperature-retaining function to control the temperature; a multi-functional *in-situ* test instrument to conduct *in-situ* tests on the end resistance, friction force, pore water pressure, and CT scanning technology for *in-situ* sample analysis; and chemical or physical analysis equipment for sediment.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#). Further inquiries can be directed to the corresponding author.

Author contributions

SH: software, data curation, writing original draft and visualization. SQ: data curation, writing original draft and

visualization. WT: conceptualization, methodology, writing review, editing and validation. YP: software, visualization, investigation. YJ: data curation, visualization and investigation. YP: supervision, writing review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Abegg, F., Hohnberg, H.-J., Pape, T., Bohrmann, G., and Freitag, J. (2008). Development and application of pressure-core-sampling systems for the investigation of gas-hydrate-bearing sediments. *Deep Sea Res. Part I: Oceanographic Res. Papers* 55, 1590–1599. doi: 10.1016/j.dsr.2008.06.006
- Amann, H., Hohnberg, H.-J., and Reinelt, R. (1997). HYACE—a novel autoclave coring equipment for systematic offshore gashydrate sampling. *Deutsche Wissenschaftliche Gesellschaft für Erdgas und Kohle V. (DGMK)* 9706, 37–49.
- Case, D. H., Ijiri, A., Morono, Y., Tavormina, P., Orphan, V. J., and Inagaki, F. (2018). Aerobic and anaerobic methanotrophic communities associated with methane hydrates exposed on the seafloor: A high-pressure sampling and stable isotope-incubation experiment. *Frontier Microbiol.* 8, 25–69. doi: 10.3389/fmicb.2017.02569
- Chen, J., Huang, Y., Lin, Y., Zhou, P., Fang, Y., Le, X., et al. (2020). A novel sediment pressure sampling device carried by a hadal-rated lander. *J. Mar. Sci. Eng.* 8 (11), 839. doi: 10.3390/jmse8110839
- Dickens, G. R., Paull, C. R., and Wallace, P. (1997). Direct measurement of *in situ* methane quantities in a large gas-hydrate reservoir. *Nature* 385, 426–428. doi: 10.1038/385426a0
- Drazen, J. C., and Yeh, J. (2012). Respiration of four species of deep-sea demersal fishes measured *in situ* in the eastern north pacific. *Deep Sea Res. Part I: Oceanographic Res. Papers* 60, 1–6. doi: 10.1016/j.dsr.2011.09.007
- Eric, M., Javier, E., and Nuno, G. (2012). Quantifying diffuse and discrete venting at the tour Eiffel vent site, lucky strike hydrothermal field. *Geochim. Geophys. Geosystems* 13, 4. doi: 10.1029/2011GC003990
- Francis, T. J. G., and Lee, Y. D. E. (2000). Determination of *In-situ* sediment shear strength from advanced piston corer pullout forces. *Mar. Georesources Geotech.* 18 (4), 295–314. doi: 10.1080/10641190009353797
- Garel, M., Bonin, P., Martini, S., Guasco, S., Roumagnac, M., Bhairy, N., et al. (2019). Pressure-retaining sampler and high-pressure systems to study deep-sea microbes under *in situ* conditions. *Front. Microbiol.* 10, 453. doi: 10.3389/fmicb.2019.00453
- Guo, J., Wang, Y., Wang, W., Ren, X., Zhou, P., Fang, Y., et al. (2022). Pressure-retaining sampler for sediment including overlying water based on heavy duty ROV-jellyfish. *Appl. Ocean Res.* 128, 103354. doi: 10.1016/j.apor.2022.103354
- Huang, H. C., Huang, L., Ye, W., Wu, S., Yang, C., Chen, Y., et al. (2018). Optimizing preloading pressure of pre-charged gas for isobaric gas-tight hydrothermal samplers. *J. Pressure Vessel Technol.* 140 (2), 021201. doi: 10.1115/1.4038901
- Huang, Z. H., Liu, S. J., and Jin, B. (2006). Accumulator-based deep-sea microbe gas-tight sampling technique. *China Ocean Eng.* 20 (2), 335–342.
- Kawasaki, M., Umez, S., and Yasuda, M. (2006). Pressure temperature core sampler (PTCS). *J. Jpn. Assoc. Pet. Technol.* 71, 139–147. doi: 10.3720/japt.71.139
- Kim, S. J., and Kato, C. (2010). “Sampling, isolation, cultivation, and characterization of piezophilic microbes,” in *Handbook of hydrocarbon and lipid microbiology*. Ed. K. N. Timmis (Berlin Heidelberg: Springer-Verlag), 3869–3881.
- Koyama, S., Miwa, T., Horii, M., Ishikawa, Y., Horikoshi, K., and Aizawa, M. (2002). Pressure-stat aquarium system designed for capturing and maintaining deep-sea organisms. *Deep Sea Res. Part I: Oceanographic Res. Papers* 49 (11), 2095–2102. doi: 10.1016/S0967-0637(02)00098-5
- Kubo, Y., Mizuguchi, Y., Inagaki, F., and Yamamoto, K. (2014). A new hybrid pressure-coring system for the drilling vessel chikyu. *Sci. Drilling* 17, 37–43. doi: 10.5194/sd-17-37-2014
- Kvenvolden, K. A., Barnard, L. A., and Cameron, D. H. (1982). *Pressure core barrel: Application to the study of gas hydrates, deep Sea drilling project site 533, leg 76; initial reports DSDP* (Washington, DC, USA: Texas A&M), 367–375.
- Lu, D. Q., Ding, Z., Li, D., and Liu, B. (2019). Studies and applications of cobalt-rich crust core samplers mounted on “Jiao long”. *Manned Submersibles China Mechanical Eng.* 30, 5603–5607.
- Nunoura, T., Takaki, Y., Hirai, M., Shimamura, S., Makabe, A., Koide, O., et al. (2015). Hadal biosphere: Insight into the microbial ecosystem in the deepest ocean on earth. *Proc. Natl. Acad. Sci. U.S.A.* 112, E1230–E1236. doi: 10.1073/pnas.1421816112
- Ritchie, H., Jamieson, A. J., and Piortney, S. B. (2017). Population genetic structure of two congeneric deep-sea amphipod species from geographically isolated hadal zone in the pacific ocean. *Deep-Sea Res. I* 119, 50–57. doi: 10.1016/j.dsr.2016.11.006
- Schultheiss, P. J., Holland, M., and Humphrey, G. (2009). Wire-line coring and analysis under Pressure: Recent use and future developments of the HYACINTH system. *Sci. Drilling* 2009 (7), 44–50. doi: 10.2204/iodp.sd.7.07.2009
- Shillito, B., Ravaut, J., Sarrazin, J., Zbinden, M., Sarradin, P. M., and Barthelemy, D. (2015). Long-term maintenance and public exhibition of deep-sea hydrothermal fauna: the abyss box project. *Deep Sea Res. Part II: Topical Stud. Oceanogr.* 121, 137–145. doi: 10.1016/j.dsr.2015.05.002



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Challenges, limitations, and measurement strategies to ensure data quality in deep-sea sensors

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In this paper we give an overview of factors and limitations impairing deep-sea sensor data, and we show how automatic tests can give sensors self-validation and self-diagnostic capabilities. This work is intended to lay a basis for sophisticated use of smart sensors in long-term autonomous operation in remote deep-sea locations. Deep-sea observation relies on data from sensors operating in remote, harsh environments which may affect sensor output if uncorrected. In addition to the environmental impact, sensors are subject to limitations regarding power, communication, and limitations on recalibration. To obtain long-term measurements of larger deep-sea areas, fixed platform sensors on the ocean floor may be deployed for several years. As for any observation systems, data collected by deep-sea observation equipment are of limited use if the quality or accuracy (closeness of agreement between the measurement and the true value) is not known. If data from a faulty sensor are used directly, this may result in an erroneous understanding of deep water conditions, or important changes or conditions may not be detected. Faulty sensor data may significantly weaken the overall quality of the combined data from several sensors or any derived model. This is particularly an issue for wireless sensor networks covering large areas, where the overall measurement performance of the network is highly dependent on the data quality from individual sensors. Existing quality control manuals and initiatives for best practice typically recommend a selection of (near) real-time automated checks. These are mostly limited to basic and straight forward verification of metadata and data format, and data value or transition checks against pre-defined thresholds. Delayed-mode inspection is often recommended before a final data quality stamp is assigned.

KEYWORDS

data quality, sensor, self-validation, *in-situ*, calibration

Highlights

- Define system limitations for autonomous underwater sensors operating in deep ocean. We focus on long-term deployed stationary sensors that communicate using acoustic links.
- Identify factors impacting underwater sensors, focusing on sensors deployed in deep ocean, and map out the effect of relevant factors on selected measurement technologies.
- Propose methods to extend automated real-time data quality control to cover some of the checks which are now performed in delayed mode by experienced operators.

1 Introduction

Ocean observations for both shallow and deep water are essential to understand environmental changes and ensure well founded ocean management and sustainable ocean industry operations. The collected data are among others used as input to environmental models, and for monitoring ecosystems and the environmental footprint of industrial activities. One of the challenges in ocean observations is to provide sufficient coverage, both horizontally and over depths, and provide sufficiently long time-series of measurements with an appropriate temporal resolution. The work presented here is a part of SFI Smart Ocean¹, a center of research-based innovation with an aim to create a multi-parameter observation system for underwater environments and installations. Sensors organized through Underwater Wireless Networks can cover larger seafloor areas or volumes while minimizing the energy cost related to communication (Gkikopoulou et al., 2012), but still face challenges in terms of energy limitation, low data rates and unreliable communication (Felemban et al., 2015), (Fascista, 2022). Continuous communication of raw measurement data is therefore generally not an option, and much of the data processing and analysis, including quality control and sensor self-validation must therefore be carried out at the sensor node. Although sensors operating in deep ocean conditions are less prone to biofouling, they are however exposed to several factors which may impact the measurement quality, as high pressures, corrosion and low current speed.

During the deployment period, the sensors typically operate without external calibration references, and *in situ* sensor self-validation and self-diagnostic properties are therefore relevant for improving the quality and providing some level of trust in measurement data. A long term deployed sensor in the deep sea could thus communicate its “health” status back, together with indications of any potential system malfunctioning or failures. Based on the detailed knowledge of sensor quality status, maintenance and retrieval missions can be planned in a more

cost-effective way, than if no such diagnostics information was available.

Many of the principles and techniques for fault diagnosis for industrial manufacturing systems (Gao et al., 2015) may also be relevant for quality control of deep-ocean measurement data. (Altamiranda & Colina, 2018) stress how digital applications for controlling and monitoring remote locations rely on high quality and reliable data. Commenting on the potential developments of real-time quality control of oceanographic data, (Bushnell et al., 2019) and (U.S. Integrated Ocean Observing System, 2020a) point out that sensors connected in autonomous underwater networks open up possibilities for quality control through communication and comparisons between sensors, as well as multivariate analysis. In (Whitt et al., 2020) a future vision for autonomous ocean observations is presented. Their review gives a good overview of various ocean observation systems, and how autonomous sensors may help fill some of the remaining information gaps. For the international oceanographic *in situ* Argo program, (Wong et al., 2022) divide the quality control of CTD (Conductivity, Temperature, Depth) data into a series of checks and adjustments that can be performed automatically in “real time”, and “delayed mode” controls and adjustments performed by experts.

In chapter 2.1 we present a systematic overview of factors which may affect the quality and reliability of underwater measurements. Important factors covered here are environmental cross-sensitivity including the effect of low currents, corrosion, sensor element degradation, sensor drift as well as electronic component malfunctioning. For each factor we point out possible effects on sensor signal for a selection of measurement technologies frequently used in deep-sea exploration. In chapter 2.2 we detail the system limitations in subsea measurement applications, among others related to power consumption and communication. In chapter 2.3 we describe two deep-ocean measurement data sets which we use as a basis for exploring different quality control tests described in chapter 2.4. We present results of the different automatic quality tests in chapter 3, and discuss the test performance as well as challenges in setting good thresholds in chapter 4. In chapter 5 we give a summary and point out the direction for future work.

2 Background and methodology

Knowledge of sensor failure modes, system limitations and effect of errors on sensor signal are prerequisites for establishing methods for sensor self-validation and self-diagnostics. We therefore start this chapter with a review of the predominant factors which may affect sensors in deep-ocean exploration and monitoring. These factors may directly or indirectly affect the sensor signal and measurement result. We continue with an overview of system limitations on sensors deployed long term in deep sea, both with respect to lack of external calibration references and limits in battery capacity and communication. Starting with basic tests proposed in established oceanographic manuals, we take the system limitations into account and propose additional tests tailored for automatic, *in situ* quality control.

¹ <https://sfismartoocean.no/>

Some of the central terms when discussing the quality of measurement data are *accuracy* and *measurement uncertainty*. In this paper we adhere to the definitions in (BIPM et al., 2012), with *accuracy* as a qualitative expression of the “closeness of agreement between a measured quantity value and a true quantity value(...)”, and *measurement uncertainty* as a “non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used”.

2.1 Factors affecting sensors on deep-sea observation equipment

To set up a systematic overview of factors which may affect the quality and reliability of underwater measurements, we collected and analyzed relevant literature regarding sensor challenges in oceanographic measurements. A more general review on sensor challenges in harsh conditions was also carried out, to identify any additional error sources not accounted for in the oceanographic measurement literature.

Review articles regarding underwater environmental monitoring by autonomous sensors and sensor networks refer to a selection of underwater measurement challenges. *Stability* over time, notably from *biofouling* are listed as the primary challenges for autonomous sensors by (Whitt et al., 2020). (Fascista, 2022) lists challenges as *corrosion* and adverse conditions, whereas (Xu et al., 2019) list among others hardware robustness and resistance to water ingress as prerequisites for sensors operating in harsh underwater environments. (Altamiranda & Colina, 2018) list *sensor failures*, *noise*, *drift*, *offset*, *degradation* in time and *unavailability* as data quality impairing factors. A strategy for detecting and handling data gaps as well as time-delays between signals from different sensors is mandatory when measurement data is used to make statistics or are used as input to environmental or ecosystem models.

Risks identified for other applications with comparable harsh/extreme conditions may also be relevant for deep-ocean monitoring. For sensors emerged in a glacier, (Martinez et al., 2006) list among others measurement challenges from *damage to sensors*, *water ingress*, *communication breakdown*, *transceiver damage*, *power shortage* if the sensor *fails to go into sleep mode*. For geotechnical monitoring by micro-electro-mechanical systems (MEMS), (Barzegar et al., 2022) list *water ingress*, *electromagnetic interference*, *noise*, and *degradation/damage from corrosion*, as well as *self-noise/intrinsic noise* from Brownian/thermal motion and thermal-electrical noise from the sensor electronics. Focusing on MEMS inertial sensors, (Gulmammadov, 2009) lists *drift* related to switch-on/warm-up as a source of error, together with *thermal hysteresis*, other *temperature-dependent drift* as well as *drift over time*. More general error sources as *offset*, *gain*, *non-linearity*, *hysteresis*, *cross-sensitivity*, and *long-time drift* are listed by Horn & Huijsing (1998 cited in Barzegar et al., 2022).

Underwater measurement challenges are also commented upon in oceanographic guidelines and best practice documents. The QARTOD real-time quality control manual (U.S. Integrated Ocean Observing System, 2020b) points out that in addition to

calibration accuracy, both *electronic stability*, *sensor drift*, *biofouling*, and spatial and temporal *variability* of the measurand itself contribute to the measurement uncertainty. More sensor-specific, the Argo Data Management Quality Control Manual for CTD and Trajectory Data (Wong et al., 2022) list common errors or failure modes related to conductivity cells: *Leakage* of anti-biofouling poison, *pollution* on conductivity cell, *degradation* of the cells glass surface, *geometry change*, *electrical circuit changes* and *low battery voltage*, as well as *incorrect pressure sensor coefficients* which could also be caused by air bubbles in a pressure transducer.

Based on the short review above, we will in the following sections give a brief description of different sensor-affecting factors relevant for deep sea monitoring and exploration. We also comment on how these factors are expected to affect the measurement signal of some common oceanographic sensors, focusing on conductivity sensors (both conductivity type cell and inductive type), oxygen optodes issued by Aanderaa Data Instruments AS and acoustic doppler-based current measurements. The sensor-specific findings are summarized in Table 1.

2.1.1 Degradation or contamination of sensing material

Depending on the measurement technology, sensors may have a sensing material which is exposed directly or indirectly to the harsh conditions in the deep sea.

2.1.1.1 Oxygen optodes

Over long time periods the sensing foil in an oxygen optode may degrade or bleach depending on number of excitations (Tengberg et al., 2006). (Bittig et al., 2018) separate between sensor drift during storage and during deployment. (Bittig et al., 2018) found some indication for an initially stronger, then exponentially decreasing sensitivity, and a positive drift at zero oxygen for oxygen optodes on moored equipment, but note that no sound conclusion could be drawn based on the measured data, and that more studies were recommended.

2.1.1.2 Conductivity sensors

Surface films from oil spills may result in an isolating film of the probe of an electrode type conductivity sensor, causing a sudden drop in measured conductivity.

2.1.2 Current speed

The speed of current where the sensor is deployed may affect the measurement result both directly and indirectly. High currents, especially combined with high concentration of plankton or other substances can result in abrasive scouring, for example of the conductivity cell (Freitag et al., 1999; Ando et al., 2005; Venkatesan et al., 2019). This is however not relevant for deep-ocean environments. As pointed out by (Lo Bue et al., 2011), low current and low dispersion environments are typical for the deep ocean.

2.1.3 Corrosion of the sacrificial anode

A sacrificial anode is used as a protection when there are corrosive metals at the measurement platform.

TABLE 1 Factors commonly affecting conductivity sensors, oxygen optodes and current sensors in long-term operations underwater, and the resulting effect on measurement result.

Affecting factor	Conductivity sensors	Oxygen optodes	Acoustic Doppler Current sensors
Degradation or contamination of sensing element	Isolating film or similar on conductivity probe → drop	Maturing of sensing foil → Negative drift decreasing with time	
Current speed and water movement	Abrasive scouring by high current, increased cell diameter, positive drift for conductivity cell type, change in response for inductivity cell type.	Corrosion of sacrificial Zn anode leads to Local decrease in oxygen level → negative dips in periods with low current	Low current may result in spikes and noise in measurements of current direction. Tilt, vibrations and changes in heading may affect the measurement quality.
Corrosion	Metal surface of sacrificial anode decreases → change in conductivity response		
Environmental cross-sensitivities	Offset in measured temperature and temperature at conductivity sensor → Spike in estimated salinities	Negative drift at high pressures, steepest in the beginning of the deployment period	Correction for sound speed velocity should be carried out adequately.
Biofouling	Reduced cell diameter → negative drift	Local change in oxygen level, effect on sensor depends on biofouling activity.	Low sensitivity to biofouling.

References are listed in chapter 2.1. Faulty measurements due to electronic component malfunctioning have not been investigated thoroughly in this work and are not covered in the table.

2.1.3.1 Conductivity sensors

If the sacrificial anode is too close to the sensor element, its metal surface decreases as it corrodes, and this has a direct effect on the local conductivity (Cardin et al., 2017).

2.1.3.2 Oxygen optodes

The chemical reaction consumes oxygen when metal is in contact with anode, resulting in local dips of oxygen concentration (Cardin et al., 2017). In situations with low currents (ref. previous paragraph) these local dips might not dissipate efficiently (Lo Bue et al., 2011), and the oxygen measurements are therefore less representative of the environment the sensor is intended to measure.

2.1.4 Sensor platform movement

If the sensor platform is moved, this may result in change or local spikes in the measurements (for example of oxygen concentration, conductivity, temperature, pressure). If measurement data are used for making statistics or as input to models, this may lead to erroneous results if the effects due to platform movement are not taken into account. For current sensors, one factor that could lower the quality of current measurements is how well the current sensor is able to compensate for tilt, vibrations and changes in heading for the sensor platform (Tracey et al., 2013).

2.1.5 Measurement conditions/environmental cross-sensitivity

A sensor is in most cases not only sensitive to the parameter it is aiming to measure, but will also be affected by other environmental parameters such as pressure or temperature. Additional measurements of affecting parameters are therefore often used to correct the sensor output. This environmental cross-sensitivity should be taken into account when calibrating the sensor prior to deployment, to establish a measurement function enabling continuous correction of such environmental effects. (Berntsson et al., 1997), (Tengberg et al., 2006) recommend that multivariate

calibration should be considered for sensor technologies where the measurement result is highly correlated with multiple parameters. The extreme pressure and temperature conditions encountered in the deep ocean may pose challenges related to calibration. At high pressures the temperature may fall below 0°C, and a regular temperature calibration using water is not possible due to freezing. Effects on the sensing elements due to very high pressure can also cause measurement errors.

2.1.5.1 Conductivity sensors

As salinity is estimated as a function of measured conductivity and measured temperature, the quality of the temperature measurement will influence the quality of the estimated salinity. An offset between the temperature in the conductivity cell and the measured temperature at a slightly different location may lead to spikes and thus more noise in the estimated salinities, especially in environments with rapidly changing temperatures (Jansen et al., 2021).

2.1.5.2 Oxygen optodes

(Bittig et al., 2018) give a detailed overview of how environmental factors affect oxygen concentration measurements by optodes, listing both temperature, pressure and salinity as parameters that should be corrected for. An individual (as opposite to batch) multi-point calibration, including a characterization of the temperature dependency is recommended to minimize the effects of the affecting parameters (Bittig et al., 2018). For high pressure environments (depths larger 2000 m), a negative, foil dependent drift has been observed, steepest at the beginning of the deployment period (Koelling et al., 2022).

2.1.6 Biofouling

Biofouling on sensors is mainly the focus for instruments deployed in shallower water exposed to sunlight, and less critical for stationary instruments that are permanently deployed in the deep-sea. However, macrofauna is observed also in deep-sea

ecosystems (Kamenev et al., 2022). There are observations of fouling also at instruments long-term deployed in the deep sea, as reported by (Blanco et al., 2013) and evidence that biofouling may grow on plastic pollution sinking and accumulating in the hadal zone over time, described by (Peng et al., 2020). In addition, Autonomous Underwater Vehicles may spend part of their deployed time exposed to biofouling in shallower water. We therefore find it relevant and necessary to include a discussion of potential effects of biofouling on sensor performance, also for deep sea observations. Biofouling can cover the sensing element and thus *directly affect* measurements, but it can also *change the local environment* around the sensing element.

2.1.6.1 Conductivity sensors

Biofouling can reduce the cell diameter of the electrode type conductivity cell (Venkatesan et al., 2019), resulting in an apparent increase in resistance and thus a negative drift (Bigorre & Galbraith, 2018), (Alory et al., 2015). Conductivity sensors based on the inductive principle are less sensitive to biofouling than electrode type conductivity cell sensors (Aanderaa Data Instruments AS, 2013), but a decrease in sensor bore diameter due to biofouling may still cause a negative drift (Gilbert et al., 2008), (Aanderaa Data Instruments AS, 2013), (Friedrich et al., 2014), (Tengberg et al., 2013).

2.1.6.2 Oxygen optodes

Oxygen optodes are primarily affected by biofouling indirectly, as the presence of fouling close to the sensing foil alters the oxygen content in the immediate environment. This effect is described in (Tengberg et al., 2006) and (Friedrich et al., 2014).

2.1.7 Electronic component malfunctioning

Errors in the sensor electronics may come from external factors such as vibrations before and during the deployment and ingress of seawater, or from internal factors such as drift in electronic components. One example of this is self-heating of the sensor electronics, which may affect measurements, lead to other electronic component failures and to a premature battery discharge. If water enters into the sensor housing, this may directly affect the sensor element and the sensor electronics, and usually the sensor stops operating. The effect on the measurement may range from sporadic outliers, a decreased signal to noise ratio, a sudden offset, a gradual drift or even a frozen value to complete sensor and communication failure.

2.1.8 Acoustic noise

For instruments sensitive to acoustic noise as well as for acoustic communication of measurement data, it is relevant to mention that (Dziak et al., 2017) measured and evaluated the acoustic noise levels in the Challenger trench, and listed both seismic activity (as earthquakes), biological activity (as whale communication) and anthropogenic activity (as shipping, seismic air guns for oil and gas exploration, active sonars), in addition to storm-induced wind- and wave noise propagating from the surface to the largest depths. Although somewhat sheltered both from the

trench walls and refraction in heterogenous water layers, (Dziak et al., 2017) observed that the noise levels in deep waters were still significant in the deep hadal trench.

2.2 System limitations due to subsea application

In this chapter we discuss system limitations for long-term deployed autonomous sensors operating subsea, relying on wireless communication of measurement data.

Sensors on moored observation equipment are today typically calibrated before and after deployment. *In situ* calibration campaigns can also be carried out, where the equipment is mounted, calibrated on a ship and re-deployed directly. Depending on the sensor technology and reference instrumentation available at the ship, such *in situ* calibration may consist of multi-point comparison and adjustment, or only of comparing a few measurement values against a reference. Using the vocabulary proposed by (BIPM et al., 2012), a calibration (comparison against a reference) is performed in both cases, but the term *in situ* (point wise) verification may be a more intuitive term for the latter case without adjustment. The *in situ* calibration or verification campaigns can be performed on regular time intervals which depend on the expected variability of the measured variable – which may differ significantly between seasons. Sensors on AUVs can be compared with neighbor sensors when two vehicles are sufficiently close, or sensors on (Argo) gliders can autocalibrate when the vehicle surfaces, as an in-air reading by oxygen optodes (Bittig and Körtzinger, 2015; Johnson et al., 2015; Nicholson & Feen, 2017; Bittig et al., 2018). For long-term deployed sensors in the deep sea however, periodic *in situ* calibration from ships may be practically and economically challenging, due to the remote measurement locations and large depths. This lack of access to external calibration leads to a need for on-line data quality control, self-validation and diagnostics at the sensor level and through the sensor network.

Deep-sea observation equipment relying on underwater wireless communication would need to adapt to severe limitations on data rates and battery capacity. In the case of acoustic communication, the underwater speed of sound is much lower than speed of light, resulting in long propagation delays and high doppler distortion, and only low frequencies are possible for communicating over the long ranges typically encountered in deep sea exploration (Van Walree et al., 2022). Underwater acoustic communication has high power demands, and continuous transmission of sensor raw data will be too energy-demanding, in practice infeasible for deep sea applications. As a natural consequence, more of the signal pre-processing must be handled locally on the sensor prior to transmission. This includes calculation of measurement output signal based on input measurements, averaging, but also filtering out of erroneous data. (Woo & Gao, 2020) point to data processing at sensor level to filter out information that is not relevant to avoid overloading of a network communication channel. Computationally demanding algorithms for real-time processing are however limited by the available battery power (Whitt et al., 2020). Battery lifetime can

be optimized by intelligent data transmission strategies and active use of power saving mode combined with adaptive sampling schemes, for example as described by (Law et al., 2009). Depending on the intended use of the data, different time-resolutions may be required for different parameters, and a possibility for the user to adjust sampling rates remotely would be useful.

2.3 Data description

Historical measurement data from moored pressure, conductivity, temperature, and oxygen sensors (SeaGuard, Aanderaa Data Instruments) deployed in deep-ocean environments in the Drake Passage (≈ 3950 m, data from 2009–2010, 60 minutes measurement interval) and Deep Atlantic (≈ 4000 m, data from 2010–2011, 20 minutes measurement interval) are used for illustrating the algorithms for sensor self-validation described in chapter 2.4. In the Drake Passage, data from two SeaGuards at different heights were compared, referred to as Drake 136 and Drake 137.

Table 2 give more information on the sensors. The Drake Passage and Deep Atlantic moorings were not part of a wireless network for acoustic communication of measurement data. We use this historical data for illustrating the proposed algorithms for real-time quality control at the sensor node which would be highly beneficial if the data from the moorings were a part of a wireless network. The measurement data is provided as Supplementary Material: Data Sheet 1.CSV for Drake Passage, Data Sheet 2. CSV for Deep Atlantic 136 and Data Sheet 3. CSV for Deep Atlantic 137.

2.4 Algorithms for sensor self-validation

In this chapter we describe algorithms for sensor self-validation which are tailored for real-time, *in situ* operation on sensor node level, considering the system limitations and challenges as described in chapter 2.2. We identify and compare quality control manuals currently referred to in the oceanographic measurement community (chapter 2.4.1). We proceeded to investigate methods to extend automated real-time data quality control to cover some of the checks which are now typically performed in delayed mode. Based on proposals found in some of the manuals on quality control for oceanographic measurement data, we propose tests combining measurements of different variables (chapter 2.4.2). To enable detection of sensor element or electronic drift, we also investigate strategies for automatic sensor self-validation relying on redundant measurements (chapter 2.4.3). Test results are presented in chapter 3.

2.4.1 Quality control currently applied in oceanographic measurements

Most of the guidelines and recommendations related to data quality control procedures in the oceanographic community are collected and accessible from the Ocean Best Practice System (OBPS) (Pearlman et al., 2019). In (Bushnell et al., 2019), established

quality assurance of oceanographic observations are categorized into *real-time*, *near real-time*, *delayed mode* and *reanalysis* quality control.

For CTD devices, there are several best practices/recommendations proposed by the various projects or networks operating such equipment. The U.S. Integrated Ocean Observing System (IOOS) proposes a manual for real-time quality control (U.S. Integrated Ocean Observing System, 2020b). In addition to corrections due to response time and thermal mass, the manual lists a set of required tests (gap, syntax, location, gross range, climatological), strongly recommended tests (spike, rate of change and flat line), and suggested tests (multi-variate, attenuated signal, neighbor, Temperature-Salinity (TS) curve/space, density inversion). The QARTOD (Quality Assurance/Quality Control of Real-Time Oceanographic Data) initiative (U.S. Integrated Ocean Observing System, 2020b) stresses among others that observations should have a quality descriptor (for instance quality control flags pass, suspect, fail) and be subject to automated real-time quality test. The Argo Quality Control manual for CTD devices (Wong et al., 2022) describes two levels for quality control and eventual adjustment: A real-time, automatic system and a delayed-mode system requiring expert interference. The Copernicus project for marine environment monitoring has published “Recommendations for *in-situ* data Near Real Time Quality Control” (EuroGOOS DATA-MEQ Working Group, 2010), listing automatic tests comparable to the ones recommended by the QARTOD and Argo Float programs. The Pan-European Infrastructure for Ocean & Marine Data Management (SeaDataNet) proposes a data Quality Control manual (SeaDataNet, 2010), together with a list of quality flags. In addition to valid date, time, position, global and regional ranges, the SeaDataNet manual proposes checks for instrument comparison.

The International Oceanographic Data and Information Exchange committee (IODE) and the Joint Commission on Oceanography and Marine Meteorology (JCOMM) have through the “Global Temperature and Salinity Profile Programme GTSP” issued the “GTSP Real-Time Quality Control Manual” (UNESCO-IOC, 2010). This manual proposes several tests aimed at Temperature and Salinity profiles, but also relevant for other marine data. The tests are grouped into different stages, ranging from position, time, and profile identification checks to consistency with climatologies, and finally to internal consistency checks before a visual inspection. Below is an overview of basic tests proposed by established manuals (EuroGOOS DATA-MEQ Working Group, 2010; U.S. Integrated Ocean Observing System, 2020b; Wong et al., 2022) for (near) real time quality control of oceanographic sensor data, adapted for this work as described by the pseudocode.

- **Valid range:** If value is outside the given range, then fail.
- **Flat line:** If n consecutive values differ less than ϵ , then fail.
- **Spike – absolute threshold:** If the value of a measurement i is more than a sensitivity factor S times the average of measurements $i-1$ and $i+1$, then fail.

TABLE 2 Sensor descriptions and stated accuracies.

Measured parameters	Product name, number	Stated accuracy	Drake 136	Drake 137	Deep Atlantic
Current	Doppler Current Sensor, 4520 ¹	± 1% of reading	x	x	x
Pressure incl. temperature	Pressure Sensor, 4117F ²	± 0.02% FSO standard 0.05°C	x	x	x
Oxygen concentration incl. temperature	Optode Sensor, 4330 ³	8μM < 160μM, 5% > 160μM 0.05°C	x	x	x
Conductivity incl. temperature	Conductivity sensor, 4319 ⁴ (inductive type)	± 0.018 mS/cm 0.05°C	x	x	x
Temperature	Temperature Sensor 4060 ⁵	0.03°C			x

All sensors are manufactured by Aanderaa Data Instruments. “x” indicates if the sensor is included in a particular measurement station.

¹https://www.aanderaa.com/media/pdfs/d367_aanderaa_zpulse_dcs.pdf.

²https://www.aanderaa.com/media/pdfs/d362_aanderaa_pressure_sensor_4117_4117r.pdf.

³<https://www.aanderaa.com/media/pdfs/oxygen-optode-4330-4835-and-4831.pdf>.

⁴https://www.aanderaa.com/media/pdfs/d369_aanderaa_conductivity_sensor_4319.pdf.

⁵https://www.aanderaa.com/media/pdfs/d363_aanderaa_temperature_sensor_4060_4060r.pdf.

- **Spike – dynamic threshold:** *If the value of a measurement i is more than a sensitivity factor S times the standard deviation of the n last measurements, then fail.*
- **Rate of Change – threshold based on first month of data:** *If $((\text{abs}(\text{measurement } i - \text{measurement } i-1) + \text{abs}(\text{measurement } i - \text{measurement } i+1)) > 2 \cdot 2\text{-std.dev}(\text{first month}))$, then fail.*
- **Rate of Change – dynamic threshold:** *If the difference between measurement i and $i+1$ is more than a threshold S times the standard deviation of the n last measurements, then fail.*

The results of the tests are recommended Quality Flags, to be approved by the operator. The “GTSP Real-Time Quality Control Manual” (UNESCO-IOC, 2010) expects that some of the process of visual inspection can be converted to objective tests but points out that there will always be a need for visual inspection. The manual further proposes that variables may be calculated based on others, to evaluate if the observed values are reasonable (for instance density based on temperature and salinity).

Both (SeaDataNet, 2010) and (U.S. Integrated Ocean Observing System, 2020b) propose some form of multi-variate test to make use of the correlations between related variables, but it is acknowledged that such tests are considered advanced and not usually implemented as a part of (near) real-time quality control. In addition to the (near) real-time quality control tests proposed in the manuals referred to above, extensive guidance for quality control typically performed as delayed mode are provided by (Thomson & Emery, 2014) and (Kelly, 2018).

2.4.2 Test based on correlated parameters

In delayed mode inspection of measurement data by experts, a scatter plot over the whole measurement period of related variables can be very useful for detecting measurement anomalies (Thomson & Emery, 2014). However, this is not adaptable to real-time autonomous sensor self-validation. We therefore propose two other methods for exploiting correlated measurements below.

- **Label one variable based on a breached threshold for an affecting variable**

One use especially relevant for deep-ocean conditions, is to label oxygen concentration measurements where the current velocity is below a set threshold to indicate possible sacrificial anode oxygen consumption (as discussed in 2.1.3). Another example is where the moorings are dragged down or moved. Such movement can be detected by comparing pressure measurements against a set threshold, and parameters which may be affected by this can be labelled accordingly. In more generic terms, measurements of variable 1 are marked as suspicious (or faulty), if the value or rate of change of a related variable 2 is below or above a certain threshold.

- **Running correlation between pairwise related variables**

Another possibility is to calculate the running covariance for pairwise related variables. A challenge with this method is to discern between a change in the correlation due to an erroneous measurement, and due to a change in the environmental conditions affecting the two variables differently. Designing a test based on the running correlation will therefore require detailed knowledge of both the sensor technology and the expected environmental conditions and events.

It is important that a basic time-stamp verification test is carried out before different measurements are combined or compared.

2.4.3 Reference measurements

An important limitation to the basic quality checks proposed in existing manuals for (near) real-time quality control is that they cannot be used to detect gradual changes in long-term system response such as sensor drift. To detect a systematic error, either constant or varying with time or other variables, a comparison with an independent estimate of the same variable is required. In this section we list different types of reference measurements that can be used for detecting systematic errors.

2.4.3.1 Internal reference measurements

For many sensor technologies, a point-based local reference measurement can be used to correct a model parameter. A zero-point reference reading gives the system response in absence of any measurement signal or external excitation. In practice such reference measurements are tailored to specific measurement technology. One example is the reference phase reading by use of a red LED that does not produce fluorescence in the foil, implemented in Aanderaa oxygen optodes (Aanderaa Data Instruments AS, 2017). Another example is magnetic or Hall sensors with internal reference measurements using internal chip heaters (Schütze et al., 2018).

2.4.3.2 Redundant measurements at sensor node

Depending on the sensor node configuration, more than one measurement of the same parameter may be carried out sufficiently close, enabling pairwise verification by comparison. In deep sea environments where battery power is a scarce resource, a variation of such a test could be a duty-master configuration, commonly found in metering stations for custody transfer of petroleum liquids (Americal Petroleum Institute, 2016), (Skålvik et al., 2018). A high-quality sensor, possibly with self-validation systems or biofouling protection can be activated at defined intervals, providing reference for validation of a (set of) regular sensor(s). Depending on the measurement principle, the master sensor can be partially protected from environmental wear and tear, thus prolonging the duration of its status as a high-quality reference. It is a clear advantage if different measurement technologies are used to obtain the redundant measurement, reducing the risk of common-mode errors such as uncorrected influencing environmental effects, electronic or sensor element drift, among others.

For mobile sensing units, the “neighbor test” proposed in the Argo manual for CTD Real time QC (Wong et al., 2022) is an example of a redundancy-based test, modified to apply to measurements with a certain distance in both space and time. In the Drake Passage dataset, measurement data from two nodes deployed close to each other provide redundant measurements that can be monitored both by setting absolute difference thresholds and by calculating running correlations between measurements of the same variable. Note that the definition of “acceptable close” depends on the variability of the environment, as well as the targeted data quality in terms of uncertainty.

2.4.3.3 Analytic redundancy/modelling surrogates

If the measured quantity can be estimated from combining measurements of other parameters, this estimate can be used as an analytical redundancy or indirect reference measurement. One example of this is the use of modeling surrogates presented by (Jesus et al., 2017), corresponding to “model-based” method for fault detection described in (Li et al., 2020) and (Gao et al., 2015). (Mitchell, 2007) and (Zhu et al., 2021) propose “multi-sensor fusion” to predict a sensor output and compare with the measured values.

Another example for validation of *in situ* measurements based on redundant measurements and functional relationships, is described in

both (Cullison Gray et al., 2011) and (Shangguan et al., 2022). They showed that the relationship between pH and other carbon measurements could be used for data quality control. Once again, a thorough knowledge of the sensor technologies and environmental dynamics is required for exploiting such analytical redundancies. One challenge with this approach is to consider the different time-delays between a change in the environment and change in sensor signal, as well as the distance between the involved sensors, referred to as sampling differences by (Cullison Gray et al., 2011).

3 Results – automatic tests for sensor self-validation

In this chapter we start by presenting the studied data sets from Deep Atlantic and Drake Passage, pointing out errors, outliers and other anomalies which are identified as erroneous or suspicious by manual inspection. We proceed to apply the automatic quality tests recommended by established manuals as listed in chapter 2.4.1, such as flat line/frozen values, spike/outlier, and rate of change, leaving out the most basic range tests. We then show how tests relying on correlations between different parameters as proposed in chapter 2.4.2 can be carried out to identify possible measurement errors related to low current speed and changes in mooring location from pressure measurements, before we move on to a comparison with redundant measurements on the same node and across nodes as proposed in chapter 2.4.3.

3.1 Visual test performed manually as a delayed mode quality control

Although there exist various software packages that can be used to assist in the delayed mode quality control, one important step is the visual identification of suspicious or clearly erroneous data. Figures 1, 2 give an overview of the Deep Atlantic and Drake Passage measurements. Table 3 summarizes the manual quality control observations of the time series. Each distinct observation of any suspicious or erroneous measurement is marked with a unique number (Obs₁, Obs₂, Obs₃ etc.), to enable tracing the observations across the different manual and automatic tests.

3.2 Basic automatic quality tests

Figure 3 shows that the basic flat line test successfully identifies many, but not all, of the Drake Passage conductivity measurements that would be labelled as suspicious or stuck by a visual inspection (Obs1).

Both the spike tests and rate of change tests, illustrated in Figure 4 for Drake 136 oxygen concentration, label the spikes in the oxygen concentration measurement as suspicious or erroneous.

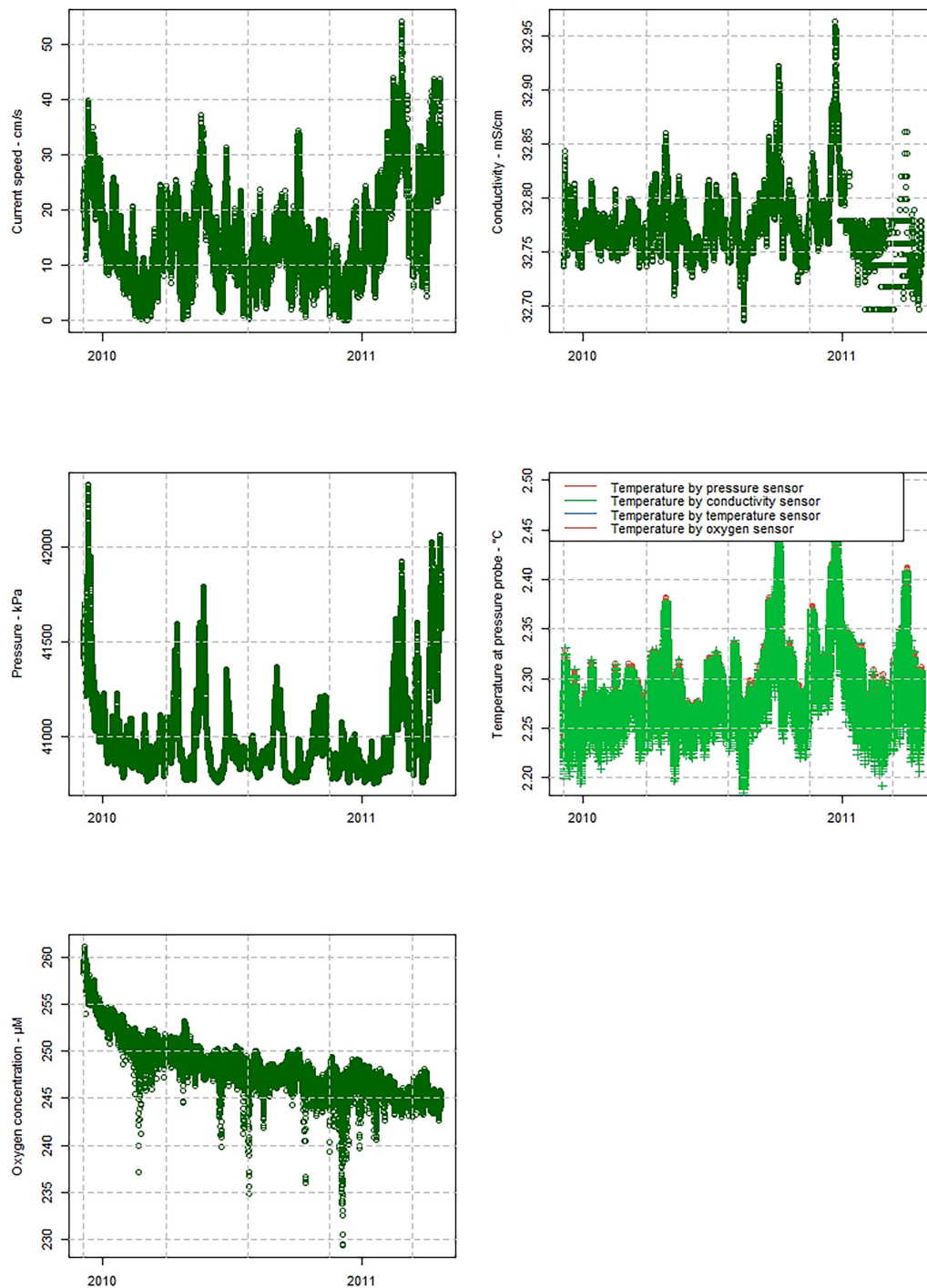


FIGURE 1
Overview of the Deep Atlantic measurements.

This corresponds to the manual/visual observation Obs4. We notice from the figures that the test performances strongly depend on the set thresholds and number of measurements used for calculating thresholds based on standard deviation (further discussed in chapter 4.2). A combination of such tests could result in a more robust performance, (further discussed in chapter 4.3). Similarly,

Figure 5 shows that the automatic tests detect a strong dip in Drake137 conductivity measurements in June 2010, corresponding to the manual/visual observation Obs6. The best performing test was a rate of change test with threshold set from the standard deviation in the first month as proposed by (EuroGOOS DATA-MEQ Working Group, 2010).

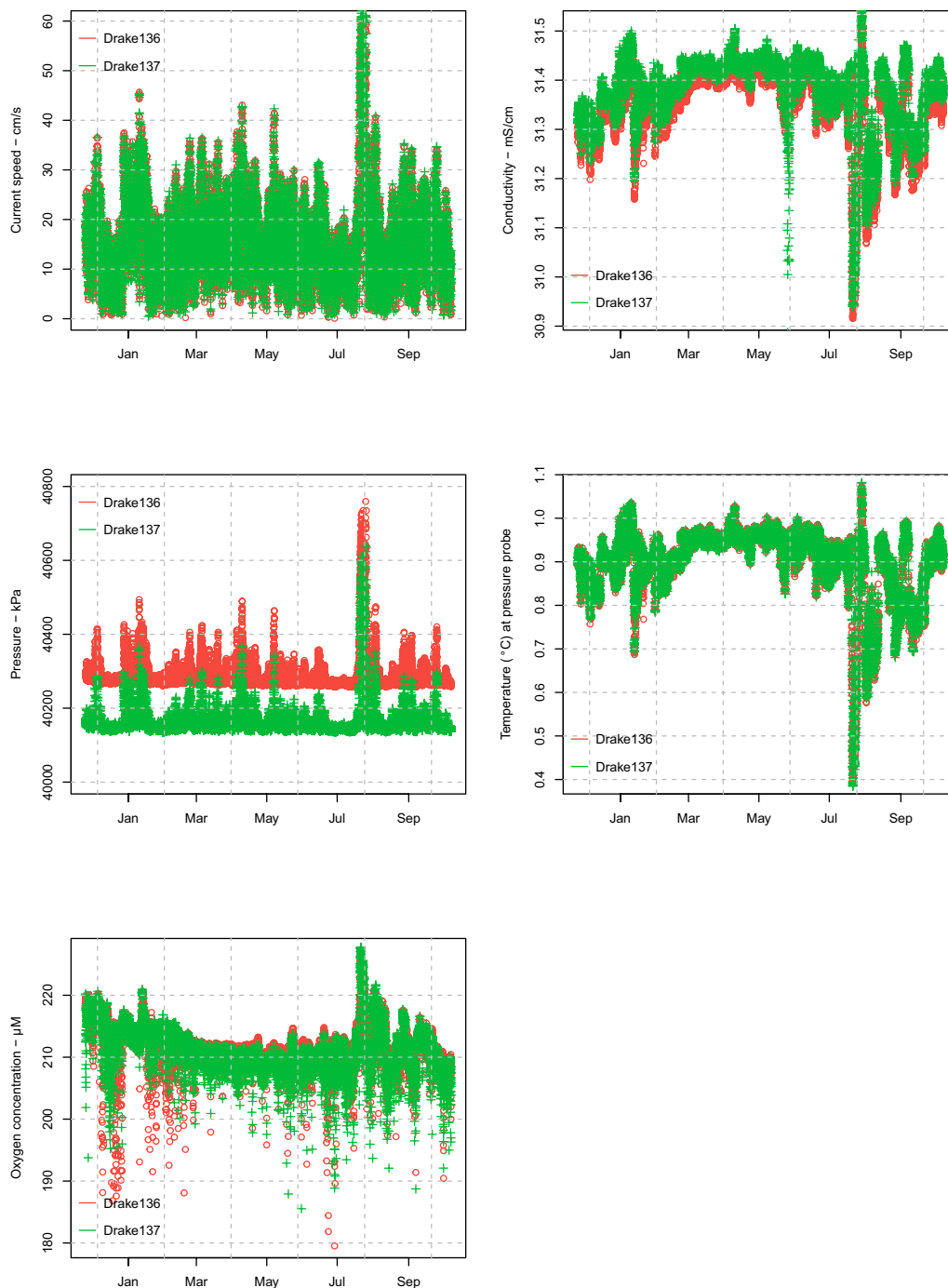


FIGURE 2
Overview of the Drake 136 and Drake 137 measurements.

3.3 Tests based on correlated parameters

Figure 6 shows Drake 136 measurements labelled for low absolute current speeds measured at the same node. The figure shows that a threshold on low currents can be used as a filter for identifying suspicious measurements of oxygen concentrations, and that most (but not all) of the manually observed “dips” in measured oxygen (Obs4) are identified by this test.

Figure 7 shows Drake 136 measurements labelled for high pressure ranges (Obs2). The test shows that several periods with changes in measured conductivity, increases in measured oxygen concentration as well as changes in temperature measurements are coinciding with increased pressure events. Such observations are not evident from a purely visual delayed mode control. Figure 7 also shows that all periods with measured absolute current speed above ≈ 35 cm/s are coinciding with increased pressure/depth. Even

TABLE 3 Summary of manual observations and automatic tests for labeling data.

Parameter	Manual/visual observation	Identifier	Automatic test labelling observation
Conductivity	Oscillations around a constant value at the end, potentially a variant of a flat line error. (Deep Atlantic)	Obs1	Flat line test
	Large dip in May 2010 (Drake 137), possibly due to animal occupying conductivity cell.	Obs6	Spike + Rate of change tests + Rolling correlation Drake 136 and 137 conductivity measurements
Pressure	Periods with important increases as the moorings are dragged down by strong currents	Obs2	Range tests with carefully chosen thresholds.
Oxygen concentration	Negative drift	Obs3	Not detected
	Periods with important “dips”	Obs4	Spike + Rate of change tests + Multivariate test (absolute speed vs oxygen concentration)
Temperature	Outlier in the conductivity (Deep Atlantic) and pressure (Drake 136) temperature measurements.	Obs5	Difference between redundant temperature measurements

though these measurements are not necessarily faulty, they are not representative for the intended environment/depth/location, and the labelling is thus useful for filtering data prior to analysis.

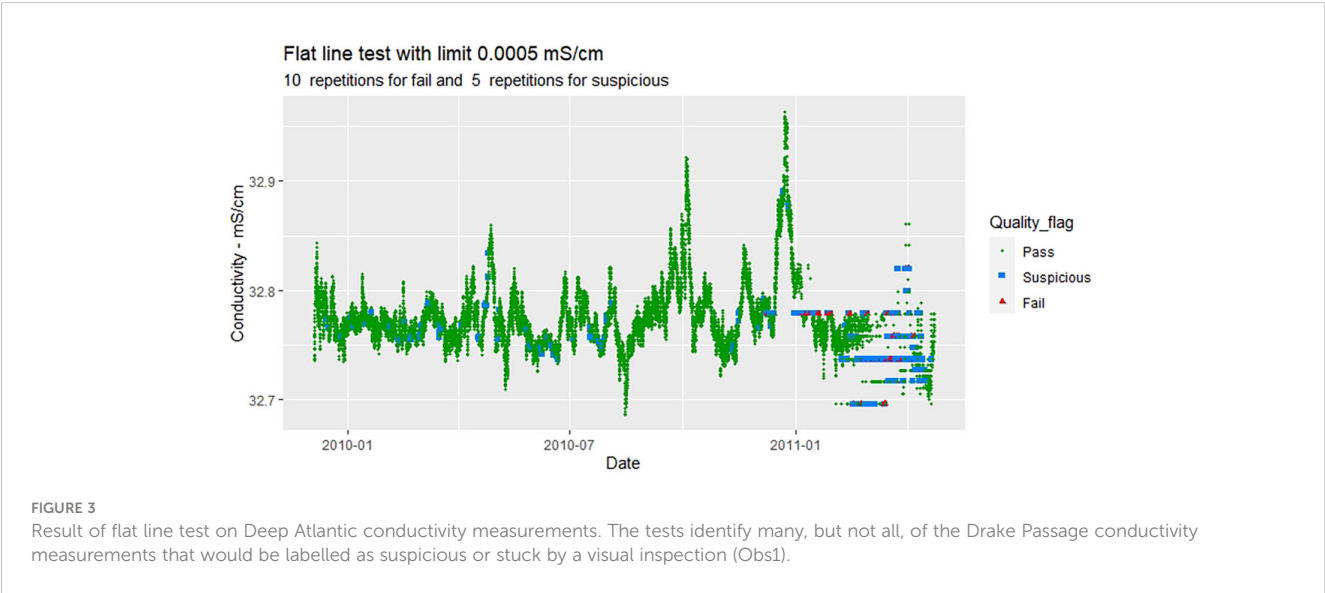
3.4 Redundant measurements of the same parameter

One example of verification by pairwise comparison on a typical CTD-node may be temperature measurements performed by both the conductivity sensor, pressure sensor, and on a dedicated temperature sensor. A change in the deviation between temperature measurements on the same node may be identified automatically on the node level, either by setting a threshold on the absolute difference or on the running correlation between the measurements.

Figure 8 shows that the difference between the Deep Atlantic conductivity temperature measurement and temperature measurements are above the set threshold for one specific data

point in April 2011, which corresponds to the manual/visual Obs5. Figure 9 shows how a test based on the difference between Drake 136 and Drake 137 conductivity measurements can identify the Drake 137 dip in conductivity (Obs6). Similarly, Figure 10 shows how a test based on the difference between Drake 136 and Drake 137 measurements of oxygen concentration identifies many of the manually observed “dips” (Obs4). Figure 11 shows a plot of the difference between Drake 136 and Drake 137 oxygen measurements, labelled for low currents measured at Drake 136, showing that the periods with large differences between the two nodes often correspond to periods with low current speeds. The comparison of two measurements based on the same sensor technology does however not detect the manually observed drift in both Drake 136 and Drake 137 oxygen measurements (Obs3).

Figure 12 shows the running correlation between pairwise conductivity measurements at the Drake 136 and 137 nodes. The running correlation test identifies a strong dip in correlation between the two datasets in the end of May 2010, corresponding to (Obs6).



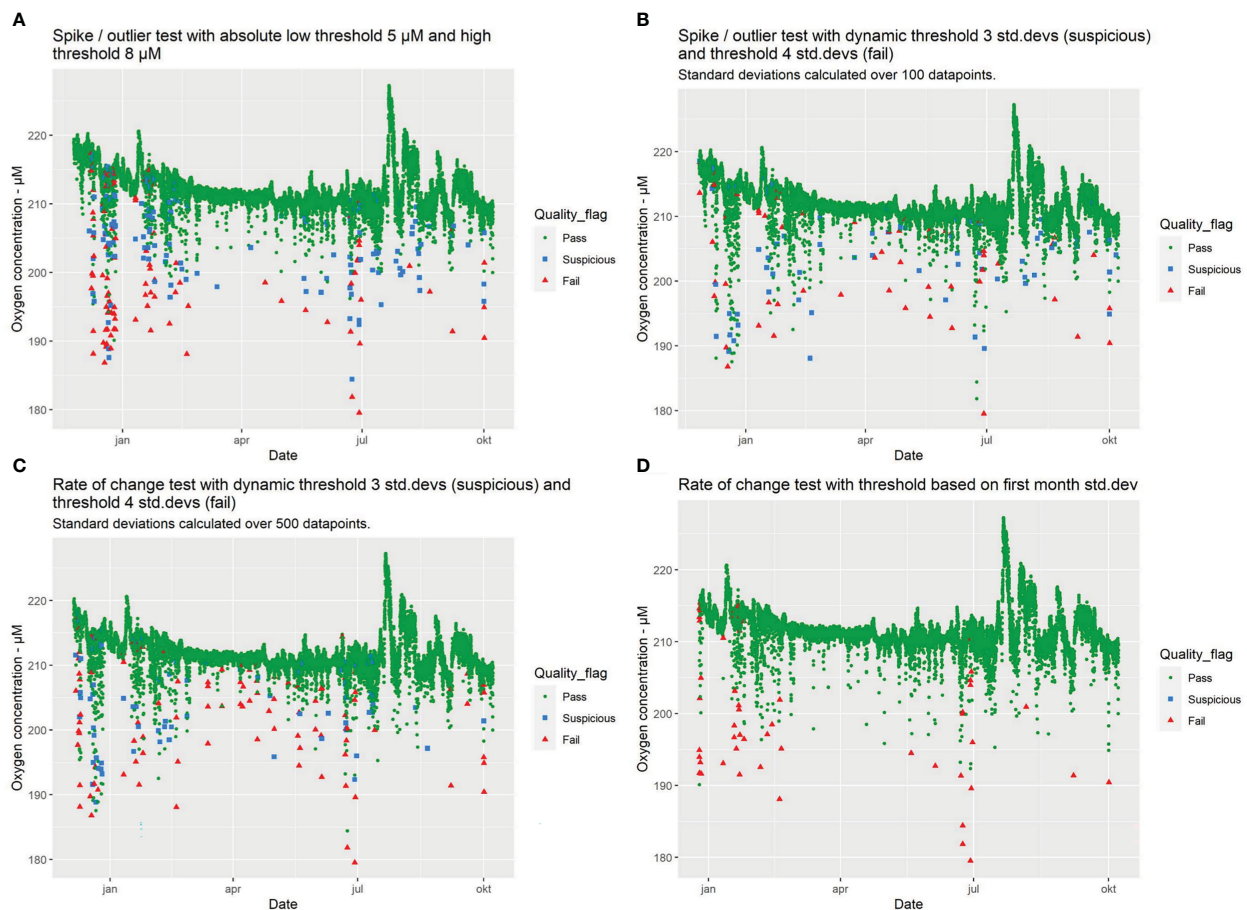


FIGURE 4

Spike/outlier and rate of change tests, for oxygen concentrations measured at the Drake 136 node. (A) shows a spike/outlier test with absolute thresholds 5 μM and 8 μM for *suspicious* and *fail* labels respectively. (B) shows a spike/outlier test with dynamic thresholds set as 3 times and 4 times the standard deviation of the last 100 measurements for *suspicious* and *fail* labels respectively. (C) shows a rate of change test with dynamic thresholds set as 3 times and 4 times the standard deviation of the last 500 measurements for *suspicious* and *fail* labels respectively. (D) shows a rate of change test with a threshold based on the standard deviation of measurements in the first month. The tests identify many, but not all, of the measurements that would be labelled as suspicious or stuck by a visual inspection (Obs4). Similar effects are observed for Drake 137.

4 Discussion

We will first evaluate how effective the automatic, real-time tests described in 2.4 are for detecting the manual delayed-mode observations. Then we discuss how knowledge of sensor technology and deep-sea environments are important prerequisites for designing tests and setting well-founded thresholds. We proceed to discuss how tests can be combined to allow for robust sensor self-validation. Furthermore, we argue that limitations imposed by deep sea measurement systems must be balanced against user requirements related to sampling frequency, data availability and quality of measurement. We round off the discussion by highlighting how the choice of sensor quality, calibration frequency, sensor redundancy and communication requirements are case specific, before pointing to other data analysis techniques that can be included in tests for sensor self-validation.

4.1 Comparison of manual and automatic observations

Except for the observed drift of the measured oxygen concentration (Obs3), the manual/visual observations of possible measurement errors in the two studied datasets are found to be detectable using automatic tests as long as thresholds and running evaluation time period are set carefully.

For the Deep Atlantic dataset, the oxygen concentration did not correlate strongly enough with any of the other measured variables at the same node to determine if the measurand changes over time or if the manually observed negative drift (Obs3) was related to the sensing element or electronics. Similarly, comparison of the oxygen concentration measurements in the Drake 136 and Drake 137 datasets did not reveal any systematic offset increasing with time. Without information from post-deployment calibration, and only based on the *in situ* measurements, it is not possible to evaluate if

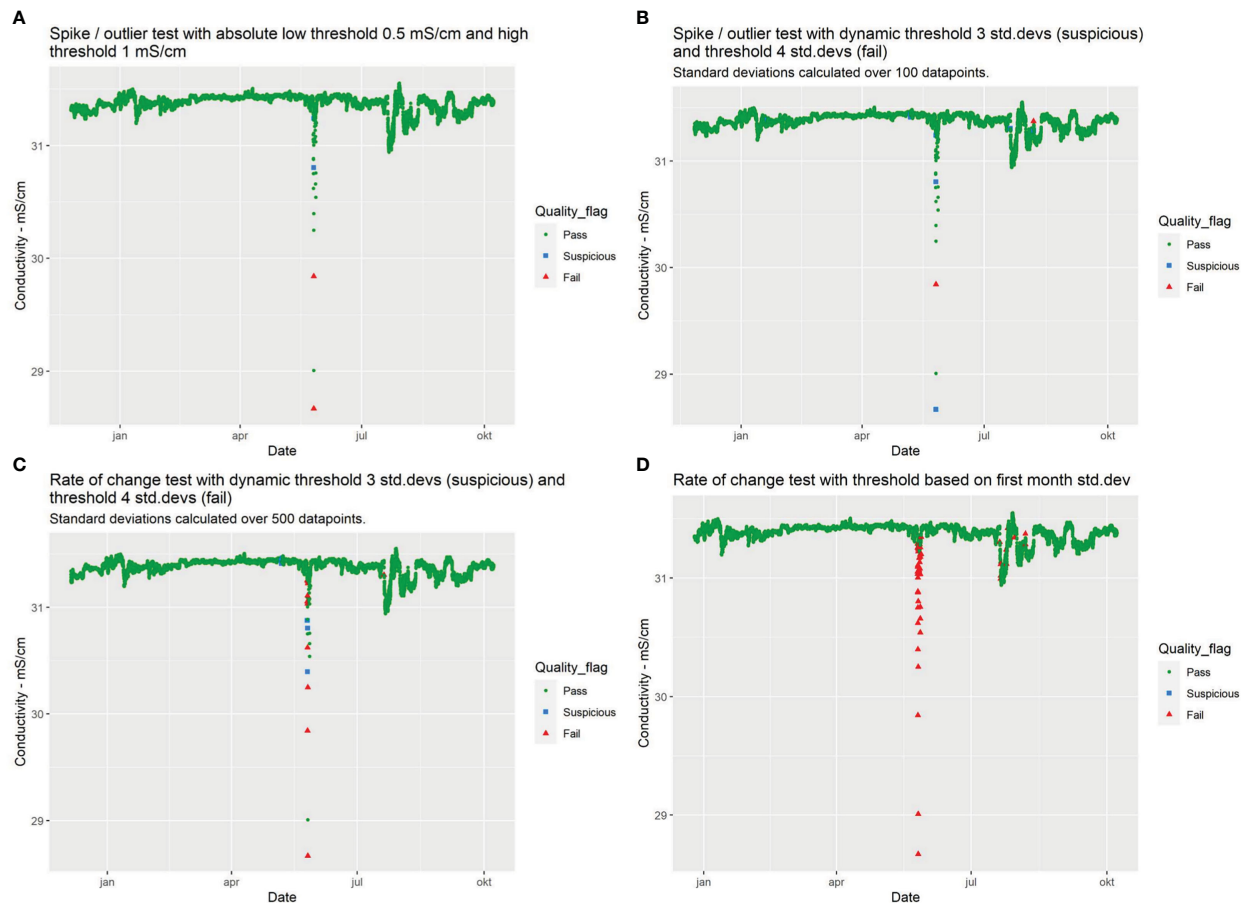


FIGURE 5

Spike/outlier and rate of change tests, for conductivity measured at the Drake 137 node. (A) shows a spike/outlier test with absolute thresholds 0.5 mS/cm and 1 mS/cm for *suspicious* and *fail* labels respectively. (B) shows a spike/outlier test with dynamic thresholds set as 3 times and 4 times the standard deviation of the last 100 measurements for *suspicious* and *fail* labels respectively. (C) shows a rate of change test with dynamic thresholds set as 3 times and 4 times the standard deviation of the last 500 measurements for *suspicious* and *fail* labels respectively. (D) shows a rate of change test with a threshold based on the standard deviation of measurements in the first month. The dip of approximately 2.5 mS/cm in June 2010 (Obs6) is partially detected by the spike/outlier (A, B) and rate of change test with dynamic threshold (C), and fully detected by the rate of change test based on the standard deviation of the first month of measurements (D).

both sensors had approximately equal drift, or if the measured, slow decrease in oxygen concentration was the true evolution of this parameter. A calibration of the sensor upon retrieval can be used for correcting the measurement drift (Koelling et al., 2022), but to detect and correct for drift automatically, real-time and in situ, a redundant measurement relying on a different technology is required.

4.2 Knowledge of sensor technology and the deep-sea environment – setting the right thresholds

The most basic tests proposed in guidance documents and manuals for (near) real-time quality control of oceanographic measurements consist of checking if the measurement is inside the expected range, based on location-specific statistics such as maximum and minimum values, or more general limits based on physical possible values. The other tests proposed by the

established oceanographic manuals such as spike, rate of change and flat line tests, rely on setting well-adapted thresholds or sensitivity limits, based on a minimum of sensor technology and environmental knowledge.

For a flat line test, the expected temporal variation of the measurand needs to be considered, as well as sensor sensitivity. For spikes/outlier-detection, and rate of change tests on the other hand, the choice of thresholds is less straight-forward and must be customized for the specific technology and application. Compared with absolute thresholds, dynamic thresholds may be an improvement, but one still must choose a sensitivity level of the detection algorithms. Too sensitive algorithms will result in alarm noise, and too lenient algorithms will detect fewer of the measurement errors.

If the standard deviation of a representative time period is chosen as a basis for the dynamic thresholds, such a period should ideally be identified automatically for sensors to be truly autonomous. The number of measurements to include when calculating such statistics must also be chosen with care.

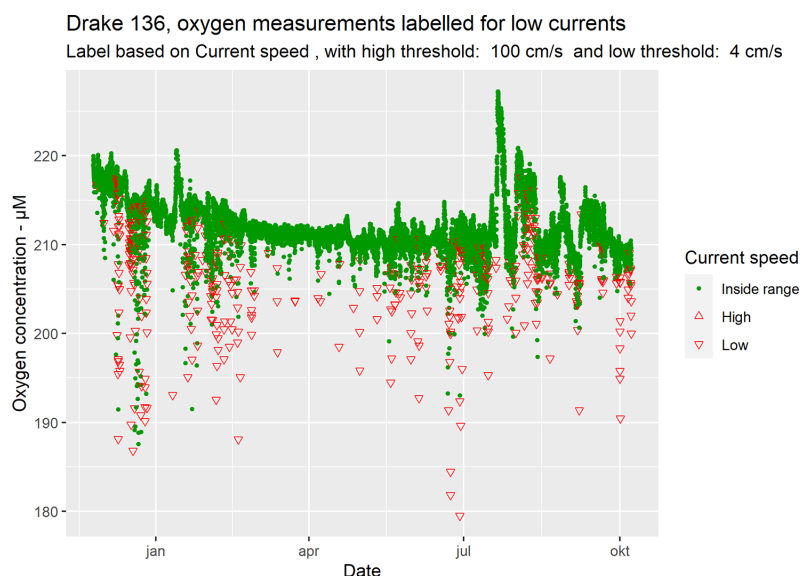


FIGURE 6

Drake Passage 136, measured oxygen concentration, labelled based on absolute current speed ranges. Most of the manually observed “dips” in measured oxygen (Obs4) coincide with periods with low current speeds. Similar effects are observed for Drake 137.

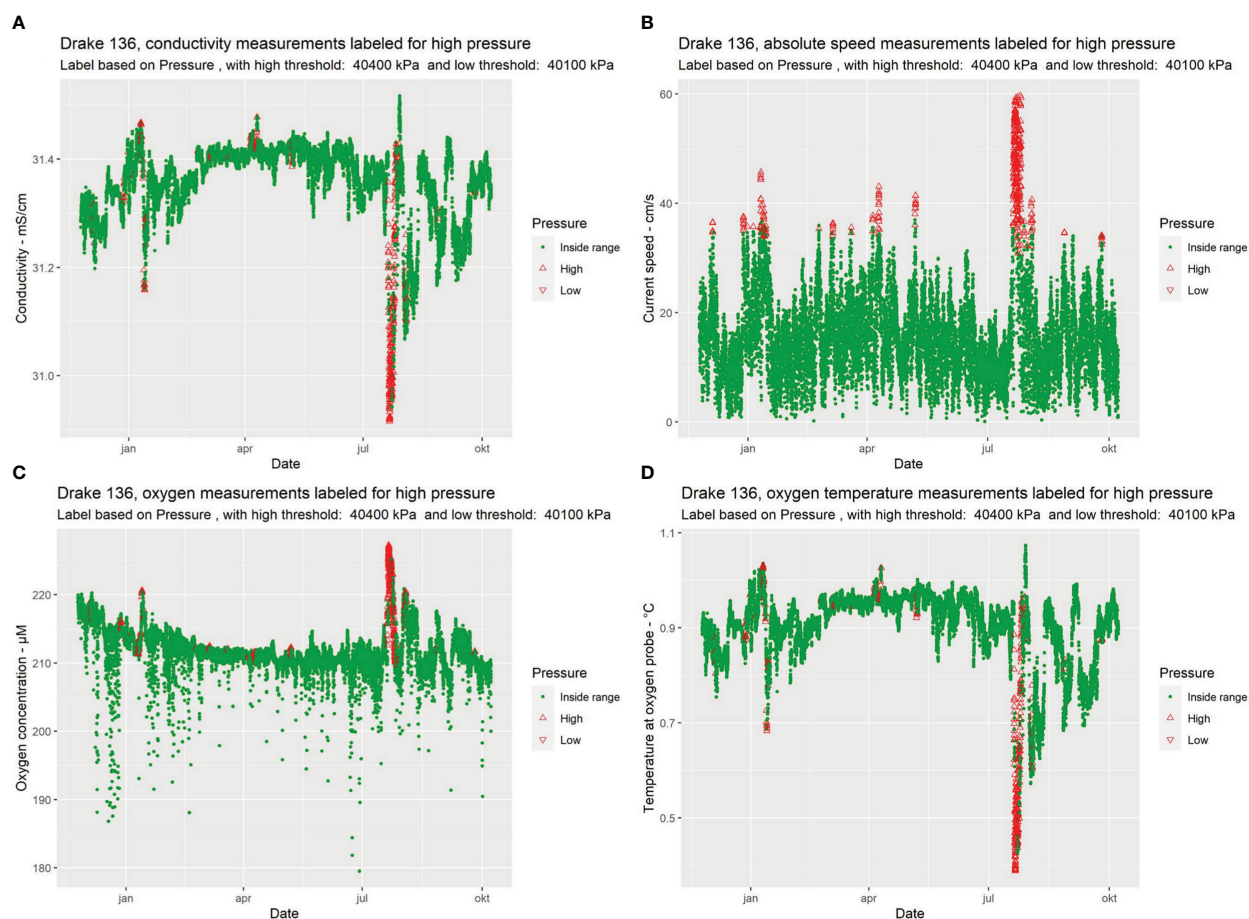


FIGURE 7

Drake Passage 136 measurements of conductivity (A), current speed (B), oxygen concentration (C) and temperature measurements at the oxygen optode (D), labelled based on pressure ranges (Obs2). A high-pressure threshold is set to 40 400 kPa and a low-pressure threshold is set to 40 100 kPa. Similar effects are observed for Drake 137.

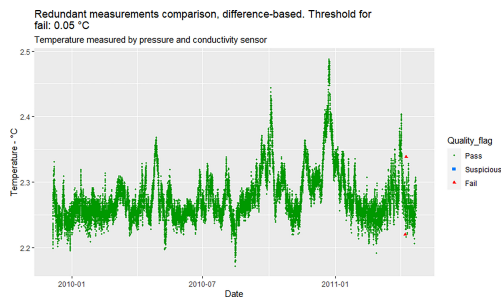


FIGURE 8

Deep Atlantic temperature measurements, labelled based on differences between temperature measurements at the pressure and conductivity sensor, with a threshold for "Fail" at 0.05°C. The outlier in the conductivity temperature measurement which can be manually observed from a scatterplot in delayed mode (Obs5) is identified by this test.

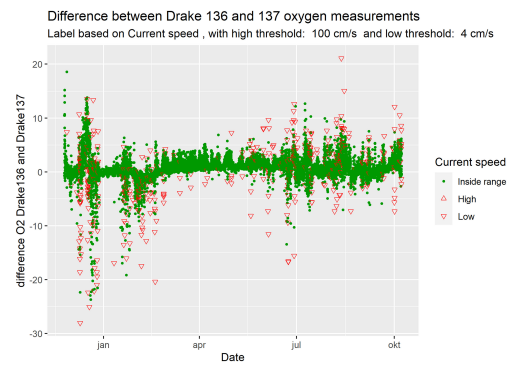


FIGURE 11

Difference between Drake 136 and Drake 137 oxygen measurements, labelled based on current speed.



FIGURE 9

Drake 137 conductivity measurements, labelled based on differences between redundant Drake 136 and Drake 137 measurements, with a threshold of 0.2 mS/cm. The dip of approximately 2.5 mS/cm in June 2010 (Obs6) is labelled as "Fail" by this test.

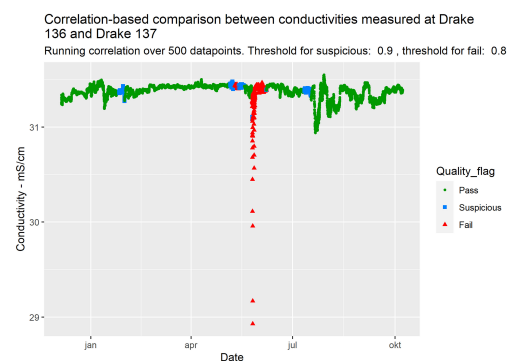


FIGURE 12

Drake 137 conductivity measurements, labelled based on running correlation (Pearson) over 500 measurements between redundant Drake 136 and Drake 137 measurements, with a threshold of 0.8. The dip of approximately 2.5 mS/cm in June 2010 (Obs6) is labelled as "Fail" by this test.

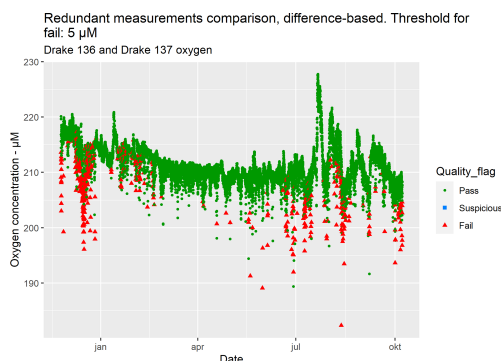


FIGURE 10

Drake 137 oxygen concentration measurements, labelled based on differences between redundant Drake 136 and Drake 137 measurements, with a threshold of 5 µM. Many of the manually observed "dips" in measured oxygen (Obs4) also result in a difference between the redundant measurements above the set threshold. Similar effects are observed for Drake 137.

4.2.1 Environmental dynamics

When setting up tests, a thorough knowledge of both the measurement technology and the expected environmental dynamics (both physical and bio/geochemical) is a pre-requisite. Both spikes/outliers and long-term drift in the measurement signal can be representative of the measurand and should not uncritically be marked as suspicious or erroneous, as illustrated by (Thomson & Emery, 2014). The time-response of the sensor must be seen in relation to the expected time-variability of the measurand/the environmental dynamics.

4.2.2 Measurement uncertainty

To avoid too many false negatives (correct measurements labelled suspicious or erroneous), the intrinsic measurement uncertainty of the sensor should be considered when designing tests. The sensor repeatability, the underlying model uncertainty, the uncertainty in the calibration process; all these uncertainty contributions can be combined to calculate the combined uncertainty of a measurement. A method for estimating the combined uncertainties in measurement

systems is detailed in (BIPM, 2008), and a very simplified application of this method to *in situ* temperature measurements is proposed by (Waldmann et al., 2022).

4.2.3 Intended use

Accurate or precise data, or high (enough) measurement quality are ambiguous terms which may have very different meanings for different applications and different users. One example is how the effect of nearby animals can be perceived as unwanted spikes or measurement noise for one user/application, masking the primary measurand that user intended to measure. For other users primarily interested in biological activity at the measurement site, such spikes can provide valuable information. When data are labelled according to well documented tests, and not deleted, it is easier for new users to re-evaluate the data with a different application in mind. The intended use of the measured data will also play a role when choosing optimal thresholds (Jansen et al., 2021).

4.3 Combining tests

Each automatic test identified some, but not all, of the measurements which visually appear suspicious for a delayed mode inspector. A more robust approach could be to run each test individually on the data set, and then follow some logical rules for combining the different data labels. A multistep solution could also be explored.

4.4 Finding the right balance

The quality control checks recommended in established best practice and guidance documents are typically carried out after data transmission but should in theory be possible to implement locally on the observation equipment. When developing or adapting algorithms for *in situ* self-validation and self-diagnostic, one must consider deep sea constraints such as communication bandwidth, data processing and power supply limitations. The optimal balance between processing power for *in situ* quality assurance, battery usage for communication of processed results or data harvesting using AUVs will be very case-specific, but in general there are strong restrictions on power usage, and methods should be chosen with care.

Some of the factors to consider when choosing an optimal self-validation strategy:

- User requirement on data quality and communication
- Measurement resolution
- Transmission frequency
- Measurement uncertainty
- Tolerance against false positives or false negatives
- Sensor coverage/density
- Expected (spatial) variation of the parameter one intends to measure
- Energy consumption of internal signal analysis/treatment of raw data
- Energy consumption of communicating with neighboring sensor
- Sensor cost
- Sensor node battery capacity, CPU performance, memory

4.5 Possible other tests and methods for automatic *in situ* quality control

4.5.1 Multivariate analysis

An extension of the tests proposed in chapter 2.4.2 is to compare the measurement of more than two parameters and thus take advantage of correlation over multiple dimensions.

4.5.2 Advanced signal analysis

The algorithms explored in this paper are examples of time-domain signal-based analysis. (Gao et al., 2015) divides signal-based fault diagnostic methods into time, frequency, and time-frequency domain. A discrete Fourier transform, among others, can be used to transform data from the time to the frequency domain. Different methods for spectral analysis can then be applied, for instance calculation of the spectral density and periodograms. (Lo Bue et al., 2011) employed a spectral analysis to find that observed drops in measured oxygen were not due to random noise, but had a periodicity related to tidal effects. For systems where the frequency spectrum varies over time, time-frequency analysis methods can be applied for fault diagnostics (Gao et al., 2015).

4.5.3 Neural networks and machine learning

Machine learning can be used for quality control of ocean data (Mieruch et al., 2021), and can be one solution to the challenge of setting efficient thresholds. Based on a separate training dataset or a running training period, the machine learning model will predict a (range of) measurement values. If the discrepancy between the predicted and measured data is higher than a dynamically adopting threshold (see for instance (Blank et al., 2011)), the data will be labeled accordingly. A self-learning method for fault-detection is described in (Li et al., 2020), where fuzzy logic and historical data can be used, provided that the modeler has knowledge of the system. A more data-driven approach also described in (Li et al., 2020) is pattern recognition. (Zhu et al., 2021) separate between self-detection of faults, proposing Least Square Support Vector Machine and back propagation neural network, self-identification of faults from historical data using wavelet packet decomposition for feature extraction, then decision tree algorithms and back propagation neural networks for pattern recognition and classification. (Han et al., 2020) proposes discrete wavelet transforms and grey models for detecting sensor drift, but do not propose any method for discerning between a trend in the measurand itself or an instrument drift. Other methods have been proposed, for example Bayesian calibration of sensor systems (Tancev & Toro, 2022).

As the built-in data processing capacities of existing smart sensors may in many cases not be sufficient to support artificial intelligence algorithms such as machine learning, a dedicated microcomputer installed locally on the sensor node could be an option.

4.5.4 Calibration through network

When several sensors or sensor nodes are operating over a defined geographic location, wirelessly connected through a (acoustic) network, it is possible to calibrate the sensors by comparison with neighboring nodes. (Delaine et al., 2019) separate between reference based and blind pairwise calibration, and (Chen et al., 2016) shows how Data Validation and Reconciliation can be used for calibration through networks.

5 Summary

Deep sea exploration and monitoring requires high-quality measurement data from sensors deployed in harsh conditions. Understanding of how sensors may be affected by the specific environment, combined with knowledge regarding both the parameter and correlations between different variables, are pre-requisites for setting up automatic tests for *in situ* data quality control. In this paper we have explored, basic range, flat line, spike/outlier, and rate of change tests as proposed in oceanographic real-time quality control manuals, in addition to more complex tests exploiting correlations between different parameters measured on the same or neighboring node. Comparisons between redundant measurements of the same parameter is particularly useful, preferably between sensors based on different measurement principles if the goal is to detect systematic drift.

Machine learning is a promising tool for automatic quality control of measurement data, but simpler, more transparent algorithms are worth investigating further. This is both due to the explainability and traceability of simpler algorithms, but also due to computing, power, and memory limitations for long time deployed sensors in remote locations. As different tests may reveal different types of errors, logic for combining the labels from a set of tests based on detailed knowledge of the measurement system and environment, may enhance the sensors self-validating and self-diagnosing properties. This is subject for future work, together with further exploration of tests in the frequency spectrum and time-series decomposition.

In the broader picture, transparent algorithms with well-documented thresholds for *in situ* quality control can contribute to increase the trustworthiness and decrease the uncertainty of EOVs (essential ocean variables).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

AS, CS and K-EF have contributed to the conception of the work. AT has provided the data. AS, CS and AT have performed data analysis and interpretation. AS has drafted the article. All authors (AS, CS, K-EF, AT, and RB) have contributed to critically reviewing and commenting on the draft. All authors contributed to the article and approved the submitted version.

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Conflict of interest

AT is employed at Aanderaa Data Instruments AS, a Xylem brand, producing the sensors used in this study.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2023.1152236/full#supplementary-material>

References

- Aanderaa Data Instruments AS (2013) *TD 263 operating manual conductivity sensor 4319*. Available at: <https://www.aanderaa.com/media/pdfs/TD263-Conductivity-sensor-4319.pdf> (Accessed 17.11.2022).
- Aanderaa Data Instruments AS (2017) *TD 269 operating manual oxygen optode 4330, 4831, 4835*. Available at: <https://www.aanderaa.com/media/pdfs/oxygen-optode-4330-4835-and-4831.pdf> (Accessed 15.11.2022).
- Alory, G., Delcroix, T., Téchiné, P., Diverrès, D., Varillon, D., Cravatte, S., et al. (2015). The French contribution to the voluntary observing ships network of sea surface salinity. *Oceanographic Res. Papers* 105, 1–18. doi: 10.1016/j.dsr.2015.08.005
- Altamiranda, E., and Colina, E. (2018). Condition monitoring of subsea sensors. A systems of systems engineering approach. *WSEAS Trans. Environ. Dev.* 495 (14), 495–500.
- Americal Petroleum Institute (2016). *Manual of petroleum measurement standards chapter 4.5 proving systems: Master-meter provers, 4th ed.* (American Petroleum Institute (API)).
- Ando, K., Matsumoto, T., Nagahama, T., Ueki, I., Takatsuki, Y., and Kuroda, Y. (2005). Drift characteristics of a moored conductivity–Temperature–Depth sensor and correction of salinity data. *J. Atmospheric Oceanic Technol.* 22 (3), 282–291. doi: 10.1175/JTECH1704.1
- Barzegar, M., Blanks, S., Sainsbury, B.-A., and Timms, W. (2022). MEMS technology and applications in geotechnical monitoring: a review. *Measurement Sci. Technol.* 33 (5). doi: 10.1088/1361-6501/ac4f00
- Berntsson, M., Tengberg, A., Hall, P. O. J., and Josefsson, M. (1997). Multivariate experimental methodology applied to the calibration of a Clark type oxygen sensor. *Anal. Chim. Acta* 355, 43–53. doi: 10.1016/S0003-2670(97)81610-8
- Bigorre, S. P., and Galbraith, N. R. (2018). “Sensor performance and data quality control,” in *Observing the oceans in real time*. Eds. R., Venkatesan, A., Tandon, E., D’Asaro, and M., Atmanand. (Cham: Springer), 243–261. doi: 10.1007/978-3-319-66493-4_12
- BIPM (2008). *ISO/IEC guide 98-3:2008 uncertainty of measurement — part 3: Guide to the expression of uncertainty in measurement (GUM:1995)* (Bureau International des Poids et Mesures). Available at: <https://www.iso.org/standard/50461.html>.
- BIPM, IEC, IFCC, ILAC, ISO and IUPAC, et al. (2012). *International vocabulary of metrology – basic and general concepts and associated terms* Vol. 200 (Bureau International des Poids et Mesures). JCGM. Available at: https://www.bipm.org/documents/20126/2071204/JCGM_200_2012.pdf/0e1ad45-d337-bbeb-53a6-15fe649d0ff1.
- Bittig, H. C., and Körtzinger, A. (2015). Tackling oxygen optode drift: Near-surface and in-air oxygen optode measurements on a float provide an accurate in situ reference. *J. Atmospheric Oceanic Technol.* 32 (8), 1536–1543. doi: 10.1175/jtech-d-14-00162.1
- Bittig, H. C., Körtzinger, A., Neill, C., van Ooijen, E., Plant, J. N., Hahn, J., et al. (2018). Oxygen optode sensors: Principle, characterization, calibration, and application in the ocean. *Front. Mar. Sci.* 4. doi: 10.3389/fmars.2017.00429
- Blanco, R., Shields, M. A., and Jamieson, A. J. (2013). Macrofouling of deep-sea instrumentation after three years at 3690m depth in the Charlie Gibbs fracture zone, mid-Atlantic ridge, with emphasis on hydroids (Cnidaria: Hydrozoa). *Deep Sea Res. Part II: Topical Stud. Oceanography* 98, 370–373. doi: 10.1016/j.dsr.2013.01.019
- Blank, S., Pfister, T., and Berns, K. (2011). “Sensor failure detection capabilities in low-level fusion: A comparison between fuzzy voting and kalman filtering,” in *IEEE International conference on robotics and automation* (Shanghai, China: IEEE), 4974–4979. doi: 10.1109/ICRA.2011.5979547
- Bushnell, M., Waldmann, C., Seitz, S., Buckley, E., Tamburri, M., Hermes, J., et al. (2019). Quality assurance of oceanographic observations: Standards and guidance adopted by an international partnership. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00706
- Cardin, V., Tengberg, A., Bensi, M., Dorgeville, E., Giani, M., Siena, G., et al. (2017). “Operational oceanography serving sustainable marine development,” in E., Buch, V., Fernández, D., Eparkhina, P., Gorringer, and G., Nolan, eds. *Proceedings of the Eight EuroGOOS International Conference*; 2017 October 3–5; Bergen, Norway. (Brussels, Belgium: EuroGOOS), 516.
- Chen, Y., Yang, J., Xu, Y., Jiang, S., Liu, X., and Wang, Q. (2016). Status self-validation of sensor arrays using Gray forecasting model and bootstrap method. *IEEE Trans. Instrumentation Measurement* 65, 1626–1640. doi: 10.1109/TIM.2016.2540942
- Cullison Gray, S. E., DeGrandpre, M. D., Moore, T. S., Martz, T. R., Friederich, G. E., and Johnson, K. S. (2011). Applications of *in situ* pH measurements for inorganic carbon calculations. *Mar. Chem.* 125 (1–4), 82–90. doi: 10.1016/j.marchem.2011.02.005
- Delaine, F., Lebental, B., and Rivano, H. (2019). *In situ* calibration algorithms for environmental sensor networks: A review. *IEEE Sensors J.* 19 (15), 5968–5978. doi: 10.1109/jsen.2019.2910317
- Dziak, R., Haxel, J., Matsumoto, H., Lau, T.-K., Heimlich, S., Nieukirk, S., et al. (2017). Ambient sound at Challenger Deep, Mariana Trench. *Oceanography* 30 (2), 186–197. doi: 10.5670/oceanog.2017.240
- EuroGOOS DATA-MEQ Working Group (2010). “Recommendations for in-situ data near real time quality control,” in *European Global ocean observing system* (Coriolis data centre).
- Fascista, A. (2022). Toward integrated Large-scale environmental monitoring using WSN/UAV/Crowdsensing: A review of applications, signal processing, and future perspectives. *Sensors* 22 (5), 1824. doi: 10.3390/s22051824
- Felemban, E., Shaikh, F. K., Qureshi, U. M., Sheikh, A. A., and Qaisar, S. B. (2015). Underwater sensor network applications: A comprehensive survey. *Int. J. Distributed Sensor Networks* 11 (11). doi: 10.1155/2015/896832
- Freitag, H. P., McCarty, M. E., Nosse, C., Lukas, R., McPhaden, M. J., and Cronin, M. F. (1999). COARE SEACAT DATA: calibrations and quality control procedures. NOAA Tech. Memo. ERL PMEL 115, 89.
- Friedrich, J., Janssen, F., Aleynik, D., Bange, H. W., Boltacheva, N., Çagatay, M. N., et al. (2014). Investigating hypoxia in aquatic environments: diverse approaches to addressing a complex phenomenon. *Biogeosciences* 11 (4), 1215–1259. doi: 10.5194/bg-11-1215-2014
- Gao, Z., Cecati, C., and Ding, S. X. (2015). A survey of fault diagnosis and fault-tolerant techniques—part I: Fault diagnosis with model-based and signal-based approaches. *IEEE Trans. Ind. Electron.* 62 (6), 3757–3767. doi: 10.1109/tie.2015.2417501
- Gilbert, S. G., Johengen, T., McKissack, T., McIntyre, M., Pinchuk, A., Purcell, H., et al. (2008). Performance verification statement for the Aanderaa data instruments 4319 b conductivity sensor. *Solomons MD Alliance Coast. Technol.* 62. doi: 10.25607/OBP-327
- Gkikopoulou, A., Nikolakopoulos, G., and Manesis, S. (2012). “A survey on underwater wireless sensor networks and applications,” in *20th Mediterranean conference on control & automation (MED)* (Barcelona, Spain: IEEE), 1147–1154.
- Gulmammadov, F. (2009). “Analysis, modeling and compensation of bias drift in MEMS inertial sensors,” in *2009 4th International conference on recent advances in space technologies* (Istanbul, Turkey), 591–596. doi: 10.1109/RAST.2009.5158260
- Han, X., Jiang, J., Xu, A., Bari, A., Pei, C., and Sun, Y. (2020). Sensor drift detection based on discrete wavelet transform and grey models. *IEEE Access* 8, 204389–204399. doi: 10.1109/ACCESS.2020.3037117
- Jansen, P., Shadwick, E. H., and Trull, T. W. (2021). *Southern ocean time series (SOTS) quality assessment and control report salinity records version 1.0* (Australia: CSIRO).
- Jesus, G., Casimiro, A., and Oliveira, A. (2017). A survey on data quality for dependable monitoring in wireless sensor networks. *Sensors (Basel)* 17 (9). doi: 10.3390/s17092010
- Johnson, K. S., Plant, J. N., Riser, S. C., and Gilbert, D. (2015). Air oxygen calibration of oxygen optodes on a profiling float array. *J. Atmospheric Oceanic Technol.* 32 (11), 2160–2172. doi: 10.1175/jtech-d-15-0101.1
- Kamenev, G. M., Mordukhovich, V. V., Alalykina, I. L., Chernyshev, A. V., and Maiorova, A. S. (2022). Macrofauna and nematode abundance in the abyssal and hadal zones of interconnected deep-sea ecosystems in the kuril basin (Sea of Okhotsk) and the kuril-kamchatka trench (Pacific ocean). *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.812464
- Kelly, D. E. (2018). *Oceanographic analysis with r* (New York: Springer).
- Koelling, J., Atamanchuk, D., Karstensen, J., Handmann, P., and Wallace, D. W. R. (2022). Oxygen export to the deep ocean following Labrador Sea water formation. *Biogeosciences* 19 (2), 437–454. doi: 10.5194/bg-19-437-2022
- Law, Y. W., Chatterjea, S., Jin, J., Hanselmann, T., and Palaniswami, M. (2009). “Energy-efficient data acquisition by adaptive sampling for wireless sensor networks,” in *Proceedings of the 2009 international conference on wireless communications and mobile computing: Connecting the world wirelessly* (Leipzig, Germany: Association for Computing Machinery).
- Li, D., Wang, Y., Wang, J., Wang, C., and Duan, Y. (2020). Recent advances in sensor fault diagnosis: A review. *Sensors Actuators A: Phys.* 309. doi: 10.1016/j.sna.2020.111990
- Lo Bue, N., Vangriesheim, A., Khripounoff, A., and Soltwedel, T. (2011). Anomalies of oxygen measurements performed with aanderaa optodes. *J. Operational Oceanography* 4, 29–39. doi: 10.1080/1755876X.2011.111
- Martinez, K., Padhy, P., Elsaify, A., Zou, G., Riddoch, A., and Hart, J. K. (2006). “Deploying a sensor network in an extreme environment,” in *IEEE International conference on sensor networks, ubiquitous, and trustworthy computing* (Taichung, Taiwan: IEEE). doi: 10.1109/SUTC.2006.1636175
- Mieruch, S., Demirel, S., Simoncelli, S., Schlitzer, R., and Seitz, S. (2021). SalaciaML: A deep learning approach for supporting ocean data quality control. *Front. Mar. Sci.* 8. doi: 10.3389/fmars.2021.611742
- Mitchell, H. B. (2007). *Multi-sensor data fusion an introduction* (Berlin, Heidelberg: Springer).
- Nicholson, D. P., and Feen, M. L. (2017). Air calibration of an oxygen optode on an underwater glider. *Limnol. Oceanography: Methods* (Berlin, Heidelberg: Springer) 15 (5), 495–502. doi: 10.1002/lom3.10177
- Pearlman, J., Bushnell, M., Coppola, L., Karstensen, J., Buttigieg, P. L., Pearlman, F., et al. (2019). Evolving and sustaining ocean best practices and standards for the next decade. *Front. Mar. Sci.* 6. doi: 10.3389/fmars.2019.00277
- Peng, G., Bellerby, R., Zhang, F., Sun, X., and Li, D. (2020). The ocean’s ultimate trashcan: Hadal trenches as major depositories for plastic pollution. *Water Res.* 168, 115121. doi: 10.1016/j.watres.2019.115121
- Schütze, A., Helwig, N., and Schneider, T. (2018). Sensors 4.0 – smart sensors and measurement technology enable industry 4.0. *J. Sensors Sensor Syst.* 7 (1), 359–371. doi: 10.5194/jsss-7-359-2018
- SeaDataNet (2010). “Data quality control procedures version 2.0,” in *Pan-European infrastructure for ocean & marine data management*. Available at: <https://www.seadatanet.org/>.

- Shangguan, Q., Prody, A., Wirth, T. S., Briggs, E. M., Martz, T. R., and DeGrandpre, M. D. (2022). An inter-comparison of autonomous *in situ* instruments for ocean CO₂ measurements under laboratory-controlled conditions. *Mar. Chem.* 240. doi: 10.1016/j.marchem.2022.104085
- Skålvik, A. M., Bjørk, R. N., Frøysa, K.-E., and Sætre, C. (2018). Risk-cost-benefit analysis of custody oil metering stations. *Flow Measurement Instrumentation* 59, 201–210. doi: 10.1016/j.flowmeasinst.2018.01.001
- Tancev, G., and Toro, F. G. (2022). Variational Bayesian calibration of low-cost gas sensor systems in air quality monitoring. *Measurement: Sensors* 19. doi: 10.1016/j.measen.2021.100365
- Tengberg, J. H., Andersson, J. H., Brocandel, O., Diaz, R., Hebert, D., Arnerich, T., et al. (2006). Evaluation of a lifetime-based optode to measure oxygen in aquatic systems. *Limnol. Oceanography: Methods* 4 (2), 7–17. doi: 10.4319/lom.2006.4.7
- Tengberg, A., Waldmann, C., Hall, P. O. J., Atamanchuk, D., and Kononets, M. (2013). “Multi-parameter observations from coastal waters to the deep sea: focus on quality control and sensor stability,” in *MTS/IEEE oceans* (Bergen, Norway: IEEE), 1–5. doi: 10.1109/OCEANS-Bergen.2013.6608046
- Thomson, R. E., and Emery, W. J. (2014). *Data analysis methods in physical oceanography* (Amsterdam: Elsevier Science & Technology).
- Tracey, K. L., Donohue, K. A., Kennelly, M. A., Watts, D. R., Chereskin, T. K., Weller, R. A., et al. (2013). Four current meter models compared in strong currents in drake passage. *J. Atmospheric Oceanic Technol.* 30 (10), 2465–2477. doi: 10.1175/jtech-d-13-00032.1
- UNESCO-IOC (2010). “GTSP real-time quality control manual, first revised edition,” in *IOC manuals and guides no. 22, revised edition*, vol. 7. (Paris 07 SP: Place de Fontenoy), 75352.
- U.S. Integrated Ocean Observing System (2020a). *QARTOD - prospects for real-time quality control manuals, how to create them, and a vision for advanced implementation* (Silver Spring, MD, U.S.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Integrated Ocean Observing System). doi: 10.25923/ysj8-5n28
- U.S. Integrated Ocean Observing System (2020b). *Manual for real-time quality control of in-situ temperature and salinity data version 2.1: A guide to quality control and quality assurance of in-situ temperature and salinity observations* (Silver Spring, MD, U.S.: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Integrated Ocean Observing System). doi: 10.25923/x02m-m555
- Van Walree, P., Kampen, A.-L., Henne, I., Otnes, R., Bjørnstad, S., and Smith, M. (2022). “Underwater communications in SFI smart ocean: Requirements, limitations and possibilities,” in *WP2-1 report* (Bergen, Norway: SFI Smart Ocean).
- Venkatesan, R., Ramesh, K., Muthiah, M. A., Thirumurugan, K., and Atmanand, M. A. (2019). Analysis of drift characteristic in conductivity and temperature sensors used in moored buoy system. *Ocean Eng.* 171, 151–156. doi: 10.1016/j.oceaneng.2018.10.033
- Waldmann, C., Fischer, P., Seitz, S., Köllner, M., Fischer, J.-G., Bergenthal, M., et al. (2022). A methodology to uncertainty quantification of essential ocean variables. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.1002153
- Whitt, C., Pearlman, J., Polagye, B., Caimi, F., Muller-Karger, F., Copping, A., et al. (2020). Future vision for autonomous ocean observations. *Front. Mar. Sci.* 7. doi: 10.3389/fmars.2020.00697
- Wong, A. K., Carval, T., the Argo Data Management Team (2022). *Argo quality control manual for CTD and trajectory data* (IFREMER). doi: 10.13155/33951
- Woo, W. L., and Gao, B. (2020). Sensor signal and information processing II. *Sensors (Basel)* 20 (13). doi: 10.3390/s20133751
- Xu, G., Shi, Y., Sun, X., and Shen, W. (2019). Internet Of things in marine environment monitoring: A review. *Sensors* 19 (7), 1711. doi: 10.3390/s19071711
- Zhu, M., Li, J., Wang, W., and Chen, D. (2021). Self-detection and self-diagnosis methods for sensors in intelligent integrated sensing system. *IEEE Sensors J.* 21 (17), 19247–19254. doi: 10.1109/jsen.2021.3090990



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An intelligent modeling framework to optimize the spatial layout of ocean moored buoy observing networks

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This research is motivated by the practical requirements in the sustainable deployment of ocean moored buoy observing networks. Ocean moored buoys play an important role in the global marine environment monitoring. Ocean buoy station layout planning is a typical multiple-objective spatial optimization problem that aims to reduce the spatial correlation of buoy stations and improve their spatial monitoring efficiency. In this paper, we develop a multi-objective mathematical model for allocating ocean buoy stations (MOLMofOBS) based on Tobler's first law of geography. A spatial neighborhood model based on a Voronoi diagram is built to represent the spatial proximity of distributed buoy stations and delimit the effective monitoring region of every station. Then, a heuristic method based on a multiple-objective particles swarm optimization (MOPSO) algorithm is developed to calculate the MOLMofOBS via a dynamic inertia weight strategy. Meanwhile, a series of experiments is conducted to verify the efficiency of the proposed model and algorithms in solving single- and multiple-buoy station location problems. Finally, an interactive portal is developed in the Cyberinfrastructure environment to provide decision-making services for online real-time planning of the ocean buoy station locations. The work reported in this paper will provide spatial decision-making support for the sustainable development of ocean buoy observing networks.

KEYWORDS

multiple-objective location modeling, particles swarm optimization, Voronoi diagram, decision-support system, ocean moored buoy

1 Introduction

Marine monitoring is an important foundation and prerequisite for understanding, developing, and utilizing the ocean. As key marine monitoring equipment, ocean moored buoys can be equipped with various sensors according to the needs of various monitoring purposes, providing a reliable observation platform to collect and transmit real-time hydrological and meteorological data with the characteristics of being systematic, long-term, continuous, and stable on a daily basis. All over the world, several ocean buoy networks have been established for monitoring and forecasting ocean conditions and ocean–atmosphere interactions. In the Aegean Sea, the POSEIDON buoy network (Nittis et al., 2002; Nittis et al., 2006) consisting of 11 ocean buoys provides the opportunity to measure wind, atmospheric pressure, conductivity, ocean current speed, dissolved oxygen water temperature, and other properties. The triangle Trans-Ocean Buoy Network (TRITON) (Kashino et al., 2007; Hase et al., 2008) buoys were deployed in the western equatorial Pacific by Japan Agency for Marine–Earth Science and Technology (JAMSTEC) to observe El Niño/La Niña Southern Oscillation (ENSO), and the Tropical Atmospheric Ocean (TAO) (McPhaden et al., 1998), with more than 70 mooring buoys, were deployed by the National Oceanic and Atmospheric Administration (NOAA) of the United States. The Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) (Bourles et al., 2008; Rouault et al., 2009) observation network consists of 18 mooring buoys and 3 island-based observation sites to observe climate and weather for prediction in the Tropical Atlantic. Argos (Tang et al., 2015) is another famous international program, which started in January 2000 and is devoted to deploying free-drifting buoys to collect and transmit temperature and salinity profile data in the upper 2000 meters of the global ocean. In the Argos buoy system, there are a total of about 16,000 buoys deployed around the world, of which about 3,900 are currently in operation. The ocean buoy network in China is strong and growing quickly, consisting of nearly 50 mooring buoys deployed by China Ministry of Natural Resources, 30 deployed by China Meteorological Bureau, and more than 30 others deployed by other institutes and departments (Wang et al., 2016).

Ocean moored buoy networks in several countries belong to different organizations in the fields of oceanography, meteorology, transportation, environment, fishery, scientific research, and industries. On one hand, different organizations make plans independently. On the other hand, there is actually a lack of effective methods to simulate and model the buoy spatial layout to achieve optimal configuration and allocation in the long term. These issues lead to insufficient integration of the existing buoy monitoring resources and limit the possibility of planning the scientific layout of future ocean monitoring activities. The rationality of the ocean buoys layout in an explicit marine space can be measured in terms of two aspects: 1) whether the density of buoy stations in the ocean monitoring network is appropriate, which significantly impacts the accuracy of the climate and weather prediction and the precision of marine science analysis such as globally meshing Argos data; and 2) whether the locations

of the buoy stations are sufficient and reasonable, which is directly related to the correctness of revealing the inherent variability of broad-scale and short-scale marine phenomena, such as water masses, ocean currents, and ocean fronts.

In view of the urgent needs for planning ocean moored buoy observing networks and addressing the key problems of buoy layout optimization, this paper carries out a spatial analysis of ocean buoy station locations to realize their location modeling for spatial optimization and to find efficient methods to calculate new potential positions for deploying additional ocean buoys. The work reported in this paper is of great significance to supporting decision-making for buoy layout planning as well as facilitating the construction of high-density and multi-parameter marine comprehensive observation networks.

This paper is organized as follows. Section 2 details spatial optimization problems and existing techniques by consulting the existing literature. This is followed by the realization of the spatial optimization modeling of ocean buoy stations, including conducting buoy station location modeling in Section 3, building the spatial neighborhood model of buoy sites, and designing an efficient multi-objective particle swarm optimization (PSO) algorithm for solving the location problem in Section 4. Then, a series of experiments is undertaken to demonstrate the efficiency and performance of the built spatial optimization model in Section 5, and an online application is established to provide planning services for ocean buoy station locations in Section 6. Finally, conclusions are provided in Section 7.

2 Related work

Optimizing the spatial layout of an ocean moored buoy observing network aims to maximize the spatial coverage of marine buoy monitoring stations by improving their scientific and rational deployment. It is a multidisciplinary problem involving spatial optimization, spatio-temporal analysis, intelligent computing, and other fields. The essence of this problem is to maximize or minimize one or more mathematical functions to solve the allocation scheme of public facilities resources, such as the locations of fire stations, hospitals, schools, and environmental monitoring stations, as well as reserve site selection (Church et al., 1996; Malcolma and Revelle, 2005; Murray, 2010; Tong and Murray, 2012). Approaches for such location modeling focus on the P-median location-allocation model (Church and Wang, 2020; Zaferanieh et al., 2022), the maximum minimization model (Wang and Zhang, 2012), the maximum coverage location problem (MCLP) (Atta et al., 2021; Taiwo, 2021), and continuous model of coverage problem (CMCP) (Yang et al., 2020; Blanco and Gázquez, 2021). Based on the vertex weights and correction costs as independent uncertain variables (both side length and vertex weights are variable), Soltanpour et al. (2020) proposed a model of an uncertain inverse P-median location problem to deal with tail values at risk targets and proved that it is a nondeterminism Polynomial(NP) problem; meanwhile, a hybrid PSO algorithm was proposed to obtain the approximate optimal

solution of the proposed model. [Nguyen et al. \(2021\)](#) solved the connected P-median problem on fully multilayered graphs and developed an algorithm for solving the P-median problem based on the branch-and-bound principle. Arana-Jimenez et al ([Arana-Jiménez et al., 2020](#)). extended the fuzzy mathematics field of the maximum coverage location model, modeled from the fuzzy perspective, and generated appropriate Pareto solutions; a solution algorithm based on the augmented weighted Tchebycheff method was proposed, which could ensure the optimal Pareto solution. Casas-Ramirez et al ([Casas-Ramírez et al., 2020](#)). studied the bi-level maximum coverage localization problem and proposed a heuristic method based on a genetic algorithm with local search to obtain the lower bound of the optimal solution. Wang et al ([Wang et al., 2016](#); [Wang et al., 2020](#)). adopted the MCPL model and took the maximum area covered by the stations as the optimization objective to solve the precipitation station location problem and plan their optimal deployment. [Song et al. \(2021\)](#) set up a nonlinear continuous maximum coverage positioning model (CMCP-Ocean) to deploy a sustainable ocean buoy observation network and built a heuristic framework based on a PSO algorithm to solve the CMCP-Ocean model.

The ocean moored buoy location problem is regarded as an NP problem because the volume of potential solutions will be so large as to cause a combined explosion so that the problem is hardly solved within the time of polynomial complexity as the number of ocean buoys for deployment increases. Promising and practical heuristic algorithms, including PSO ([Shifa et al., 2011](#)), ant colony, simulated annealing, genetic, tabu search, greedy, and neural network algorithms have all been well applied to solve spatial optimization problems in fields such as regionalization ([Liu et al., 2015](#)), resource allocation and scheduling ([Chang and Wei, 2002](#)), and urban planning ([Feng and Liu, 2013](#)). Recently, hybrid heuristic methods have been highlighted to solve large instances of districting and regionalization problems ([Duque et al., 2012](#); [Kim et al., 2016](#)). ([Li et al., 2014](#)) constructed an extendable heuristic framework by integrating a semi-greedy algorithm and improved local search to generate p regions that are as compact as possible from n atomic polygons, defined as the p -compact-regions problem, which is a representative non-linear regionalization problem in urban economic modeling. ([Kim et al., 2016](#)) proposed a hybrid heuristic algorithm by combining the Automated Zoning Procedure and a center interchange method, improving the efficiency and the quality of solutions for large-size p -functional region problems. ([Kollat and Reed, 2007](#)) built an efficient framework for long-term groundwater monitoring planning using evolutionary multi-objective optimization techniques.

Among them, the PSO and multiple-objective PSO (MOPSO) algorithms show outstanding performance due to the organic adhesion and bidirectional influences of the local search phrase and the global search phrase by adjusting particles' position and speed while referring to the individual optimal solution and the global optimal solution in each iteration. Additionally, PSO-based algorithms have a strong advantage in solving the problem of multi-station site selection because the position and flight velocity dimensions of each particle only need to be expanded

horizontally as the number of stations to be calculated increases. The addition in particle dimensions will not enlarge the complexity of the optimization problem, nor the computational complexity, which has been verified in some research ([Shifa et al., 2011](#); [Masoomi et al., 2013](#); [Xie and Xu, 2017](#)). However, both traditional PSO and MOPSO have two major disadvantages: 1) the fixed or inappropriate inertia weight factor (ω) leads to the linear attenuation of particle velocity, which makes the flight behavior of particles tend to homoplasmy, resulting in local convergence that causes the search for optimal solutions to become entrapped in local areas from which it is unable to jump out; and 2) the particle search behavior is random and lacks diversity, which leads to the uneven distribution of particles in the feasible solution space and possible failure to reach the region where the best solution is located. These shortcomings become more obvious and difficult to solve for multi-objective optimization problems.

To address these issues, two kinds of strategies are carried out in relevant research. The first strategy type is to dynamically adjust the search step in the search stage to achieve the effect of refining the search granularity and increasing the diversity of particles. In this scope, strategies based on inertia weight (IW), which is an important parameter to balance the exploitation of individuals in local search and evolution of generations in global search, are created ([Chen et al., 2006](#); [Uma et al., 2012](#); [Chauhan et al., 2013](#); [Amoshahy et al., 2016](#)). For example, [Amoshahy et al. \(2016\)](#) proposed another more superior IW called the Flexible Exponential Inertia Weight (FEIW) strategy, which is also time-varying-based and has the ability to adapt with each optimization problem by selecting suitable parameters to make IW increase and decrease. Chen et al ([Li et al., 2014](#)). created a natural exponential IW strategy to dynamically vary IW according to the number of iterations to accelerate the decrease of inertia weight, which hastens convergence. The second strategy type comprises archival non-inferior solution maintenance and the global optimal solution selection strategy to provide the correct guidance for global leaders to local search in the evolution stage. In this aspect, exclusive and fuzzy Pareto dominance concepts ([AlvarezBenitez et al., 2005](#); [Köppen and Veenhuis, 2006](#)) are commonly adopted in multi-objective problems to select global optimal solutions, and marked effects with good convergence and widespread coverage are obtained. Meanwhile, the Pareto archive evolution strategy ([Knowles and Corne, 1999](#); [Zhao et al., 2012](#); [Knowles and Corne, 2014](#)) is employed to record and update non-dominated solutions, so as to provide a repository from which calculating the distribution density of non-inferior solutions, as well as selecting the global optimal and deleting redundancy solutions, can be carried out. In addition, the crowding distance sorting strategy ([Raquel and Naval, 2005](#); [Santana et al., 2009](#); [Feng et al., 2010](#)) has been proposed as a promising method to best approximate the true Pareto front by selecting the individual with the biggest crowding distance as the global optimum to make the swarm evolve to the sparse objective space, as well as by deleting the individual with the smallest crowding distance in the external Pareto archive to reduce the redundancy of non-dominant solutions.

3 Location modeling of ocean moored buoy station

3.1 Multi-objective location selection modeling of ocean moored buoy stations

The ocean moored buoy location problem can be abstracted as follows: in a given range of marine space, under the premise of not changing the existing buoy stations' positions, find suitable positions to deploy a number of ocean buoys with the aims of increasing the density of observation and avoiding duplicate monitoring and monitoring gaps. Furthermore, two objectives are required to be achieved for computation: the first objective is that the distribution of buoy stations should be as dispersive as possible to reduce the correlation of adjacent buoy stations, and the second objective is that the area of each buoy's effective monitoring region (EMR) should be as similar as possible to achieve a uniform layout of ocean buoy stations. Based on Tobler's first law of geography (Tobler, 1970; Klippel and Li, 2011) that near things are more related to each other, we take advantage of the Euclidean distances between the selected site and each site in its neighborhood to measure the first objective. All distances are expected to be as large as possible to match the goal. To address the second objective mentioned above, standard deviation is employed as the indicator to measure the uniformity of EMR. A smaller standard deviation of EMR areas would indicate a more uniform distribution. Therefore, the multi-objective location model of ocean buoy stations (MOLMofOBS) is formulated as follows:

$$\text{Maximize}(F_1) \quad (1)$$

$$\text{Minimize}(F_2) \quad (2)$$

where,

$$F_1 = \min(\{d_{ij} | i = 1, \dots, n, P_j \in Nb(P_i)\}) \quad (3)$$

$$F_2 = \max(\{STD(\{S_{vi}, \{S_{vj}(j = 1, \dots, n) | vj \text{ is the EMR of } P_i, \forall P_j \in Nb(P_i)\}) | i = 1, \dots, n\}) \quad (4)$$

Subject to:

$$\text{Depth}(P_i) \geq 5 \quad (5)$$

$$P_i \text{ within } S_P \quad (6)$$

Where, P_i represents the i -th buoy station with longitude and latitude coordinates and P_j represents the j -th buoy station. d_{ij} is the Euclidean distance between the station P_i and the station P_j . $Nb(P_i)$ denotes the spatial neighborhood of P_i . The equation (3) indicates to get the minimum of d_{ij} . For i and j which are from 1 to n , if P_j in the spatial neighborhood of P_i , d_{ij} is calculated, otherwise, d_{ij} is not calculated. STD is the operational function of standard deviation. S_{vj} is the area of EMR of P_j which is in $Nb(P_i)$. $\text{Depth}(P_i)$ denotes the water depth in the position of P_i . S_P denotes a specific solution space in the form of polygon geometry.

In the MOLMofOBS above, two key elements need to be calculated, namely, EMR and $Nb(P_i)$. In practice, the buoy monitoring stations are distributed discretely on the sea. A set of isolated coordinate points cannot intuitively express the spatial proximity between monitoring stations, nor can it record the adjacent stations of each monitoring station in a quantitative way. Actually, in addition, the boundary of each EMR cannot be delineated effectively. To estimate EMR and $Nb(P_i)$, a spatial neighborhood model is built in the next section.

3.2 Building the spatial neighborhood model of ocean moored buoys stations

In this section, a spatial neighborhood model (SNM) is established to represent the neighborhood and delimit the EMR of each station, shown in Figure 1. Firstly, the concept of a Voronoi diagram (Dong, 2008; Okabe et al., 2008; Lee, 2010) is employed to

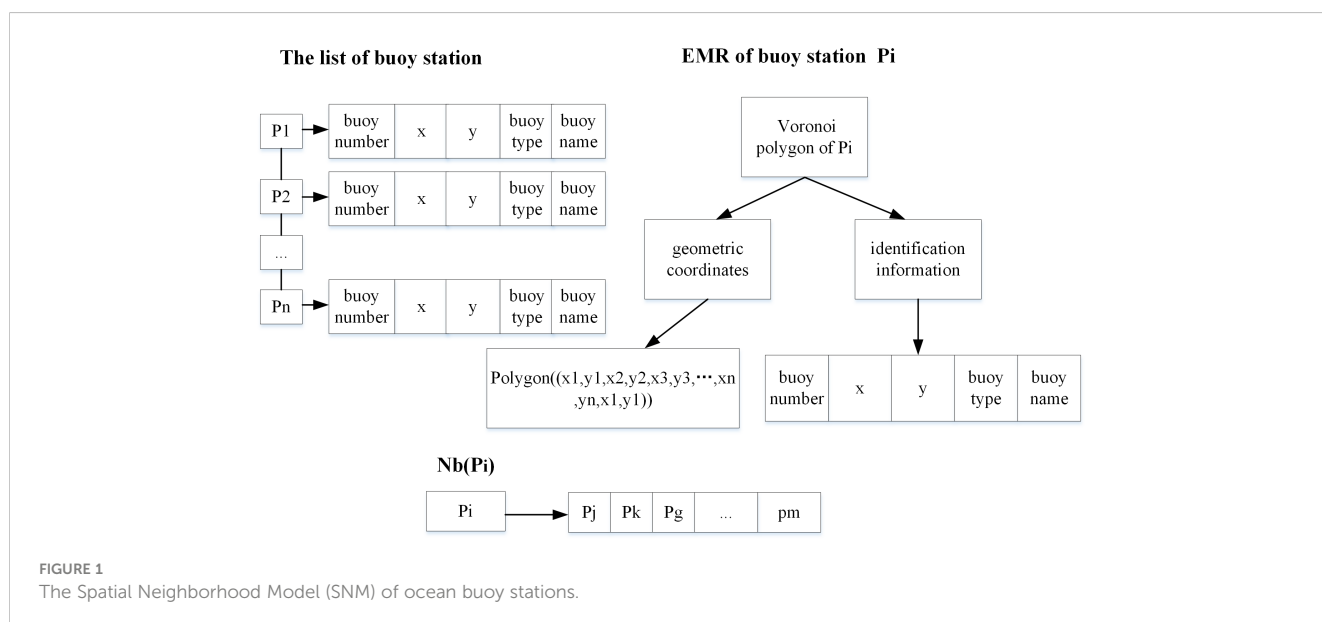


FIGURE 1
The Spatial Neighborhood Model (SNM) of ocean buoy stations.

divide the sea space; all buoy stations are treated as parent points to generate a Voronoi diagram, and each buoy station belongs to a Voronoi polygon. Inevitably, each Voronoi polygon is adjacent to other Voronoi polygons. If there is a common edge between the Voronoi polygon of station P_i and the Voronoi polygon of station P_j , P_i and P_j are adjacent. This kind of adjacent relationship is named the first-order Voronoi vicinity (1-oVv), which is adopted to measure the spatial proximity of ocean buoy stations and eliminate the effect of space barriers caused by linear obstacles, such as peninsulas or islands. $Nb(P_i)$ denotes the 1-oVv neighborhood (1-oVvN) of station P_i . A well-defined SNM is formed, as shown in Figure 1, with three components including a list of buoy stations, the EMR, and the 1-oVvN of every buoy station. The list of buoy stations includes their longitude, latitude, and identification information, such as buoy name, buoy number, and buoy type, which are the original data for location computation. Voronoi divides the entire study space and the distance between each point in the Voronoi polygon and its internal buoy station is closer than that between it and other buoy stations. Using Voronoi polygons to estimate the EMR can not only ensure that the spatial coverage of the buoy monitoring station is continuous in the whole study area, but also meet the requirement of spatial proximity. Therefore, the EMR of each buoy station is delimited by its Voronoi polygon.

4 A customized heuristic approach based on the MOPSO algorithm to solve MOLMofOBS

The MOLMofOBS in Section 3.1 is a typical multi-objective optimization problem. A heuristic method based on the MOPSO algorithm is designed to calculate near-optimization solutions of MOLMofOBS by expanding the advantages of simulating the social behavior of the population with the intelligence of the colony, sharing information among individuals, and working collaboratively. In the proposed MOPSO-based algorithm, the particle is a basic unit to calculate F1 and F2 defined in equations (3) and (4). It has two attributes of the position and the flight velocity. The position of a particle is a coordinate sequence of all buoy positions to be deployed. It is represented as $(x_1, y_1, x_2, y_2, x_3, y_3, \dots, x_n, y_n)$, where a pair of (x, y) stands for the position coordinate of a buoy station. So, a particle position contains positions of all buoys. The flight velocity of a particle is a sequence of all changes in the position of buoys and represented as $(v_1^x, v_1^y, v_2^x, v_2^y, v_3^x, v_3^y, \dots, v_n^x, v_n^y)$. Each component of the particle's velocity is added to the corresponding component of its position to obtain a new position of the particle. The new position of a particle will be divided into the coordinates of n buoy stations to calculate F1 and F2. A swarm of particles work to get new positions like above simultaneously.

The proposed MOPSO-based algorithm has a strong advantage in solving the problem of multi-station site selection because the position and flight velocity dimensions of each particle only need to be expanded horizontally, as the number of stations to be calculated

increases without enlarging the computational complexity. Compared to the traditional MOPSO algorithm, the improvement of the proposed MOPSO algorithm includes extending the formulas of adjusting particles' position and velocity to support multiple buoy stations and creating a strategy of adaptively tuning IW to diversify the particle individuals.

4.1 Adjustment formulas of particles position and velocity to support multiple buoy stations

Extending the adjustment formulas of particles position and velocity to accommodate multiple buoy stations is the crucial step for solving the MOLMofOBS in the MOPSO heuristics framework. Commonly, the population of particles move in a two-dimensional feasible solution space, and each individual particle is supposed to be a potential optimal solution. As the coordinate of each buoy station is composed of a longitude as the x -axis and a latitude as the y -axis, in the case of the n ($n \geq 1$) buoy stations location problem, the position of the i th particle containing coordinates of n buoy stations is extended to a $2 \times n$ -dimensional vector which is denoted using formulas (7):

$$(x_{i,1}(t), y_{i,1}(t), x_{i,2}(t), y_{i,2}(t), \dots, x_{i,n}(t), y_{i,n}(t)) \quad (7)$$

Similarly, the i th particle velocity vector is expressed using formulas (8):

$$(v_{i,1}^x(t), v_{i,1}^y(t), v_{i,2}^x(t), v_{i,2}^y(t), \dots, v_{i,n}^x(t), v_{i,n}^y(t)) \quad (8)$$

According to the principles of basic particle swarm optimization, the formulas (9) and (10) are designed to update the position and velocity of the particle in the x component, and the formulas (11) and (12) are used to update the position and velocity of the particle in the y component.

$$v_{ij}^x(t+1) = \omega v_{ij}^x(t) + c_1 r_1 (P_{ij}^x - x_{ij}(t)) + c_2 r_2 (P_{gj}^x(t) - x_{ij}(t)) \quad (9)$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}^x(t+1) \quad (10)$$

$$v_{ij}^y(t+1) = \omega v_{ij}^y(t) + c_1 r_1 (P_{ij}^y - y_{ij}(t)) + c_2 r_2 (P_{gj}^y(t) - y_{ij}(t)) \quad (11)$$

$$y_{ij}(t+1) = y_{ij}(t) + v_{ij}^y(t+1) \quad (12)$$

In which, ω is the inertia weight factor (IW) which is varying between 0 and 1. c_1 and c_2 are the acceleration coefficients, usually $c_1 = c_2 = 2$. r_1 and r_2 are random numbers varying between 0 and 1. t is the current iteration number. The position of buoy j is expressed in the reference frame located at particle i . The index j used for buoys extends from $j=1$ to n and the index i used for particles extends from $i=1$ to m . n is the number of buoy stations and m is the number of particles. $X_{i,j}(t)$ is the x component of the coordinate of the buoy station j reflected in the position of the particle i in the t th iteration. $v_{ij}^x(t+1)$ is the velocity of x_{ij} in the $(t+1)$ th iteration. P_{ij}^x is the x component of the individual best solution of the particle i for the buoy station j . P_{gj}^x is the x component of the global best

solution of the buoy station j . $y_{ij}(t)$ is the y component of the position coordinate of the buoy station j embodied in the position of the particle i in the t th iteration. $v_{ij}^y(t+1)$ is the velocity of y_{ij} the $(t+1)$ th iteration. P_{ij}^y is the y component of the individual best solution of the particle i for the buoy station j . P_{gj}^y is the y component of the global best solution of the buoy station j .

Formulas (7) to (12) in this part have been partially used in the paper wrote by song et al (Song et al., 2021), but without these necessary formulas, this paper would be difficult to understand. Therefore, in order to make this paper more readable and convenient for readers, these formulas are listed and illustrated here again.

4.2 Design of a dynamic inertia weight strategy

A dynamic inertia weight strategy (DIWS) is designed to adapt spatial proximity and improve the convergence and solution accuracy of optimization. The proposed DIWS focuses on adaptively adjusting the value of IW (ω) according to the variation rate of the objective values to eliminate the potential iteration stagnation brought by velocity linear attenuation and increase the diversity of particles searching behavior. The specific working mechanism of the DIWS is detailed as follows: on the one hand, when the variation rate of objective values is high, the IW is decreased to make the search step of the particles smaller so that they fly at a lower velocity. As the particles fly at a lower velocity, the number of particles in sparse regions will be increased to make the distribution of particles denser. So, a smaller IW can intensify a local search. On the other hand, when the variation rate of objective values is low, the IW is increased to make the flight step of the particles larger so that they fly at a higher velocity. As the particles fly at a higher speed, it is much more possible for them to jump out of the local search area and avoid search stagnation, so as to find new near-optimal solutions. So, a larger IW can promote a global search.

To realize the above principles, while comprehensively analyzing the characteristics of the variation rate of objective values, and comparing the variation characteristics of the classical mathematical functions (e.g., exponential, logarithmic, and power functions), we propose an empirical formula to adjust the value of IW based on the exponential function of the natural constant (e). The formula is shown as follows:

$$\omega_j^{t+1} = \begin{cases} e^{\partial-1}, & 0 < \partial < 1 \\ e^{(1/\partial)-1}, & \partial \geq 1 \end{cases} \quad (13)$$

$$\partial = \text{rate}_j^t / \text{rate}_j^{t-1} \quad (14)$$

$$\text{rate}_j^t = \quad (15)$$

$$0.367 \leq \omega^{t+1} \leq 1 \quad (14)$$

where ω_j^{t+1} is the IW factor of particle j in the $(t+1)$ th run; e is the natural constant; t is the current iteration number; k is the number of the objective functions; $f_i((x_1^j, y_1^j, \dots)^t)$ is the value of the objective function f_i of particle j in the t th iteration; rate_j^t is the difference of all objective function values between two adjacent iterations; w_i is the preference weight, which is used to adjust different objective values to make their magnitude the same; and ∂ is the variation rate of the objective values. The variation curve of the IW value with the change rate of the objective values is shown in Figure 2.

4.3 The workflow to solve the multi-objective location problem of ocean buoy station using the MOPSO algorithm with DIWS

A workflow using the MOPSO algorithm with DIWS, named DIWS-MOPSO, is designed in a heuristic framework to ensure the MOLMofOBS can be solved more efficiently and reliably. The workflow is illustrated in Figure 3 and the detailed steps are described as follows.

Step 1. Prepare spatial data.

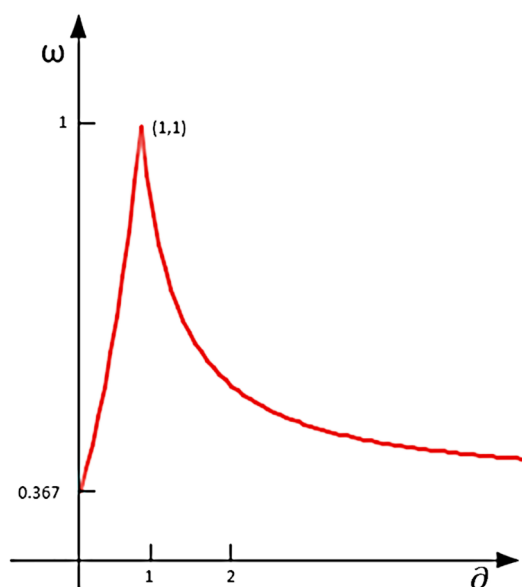
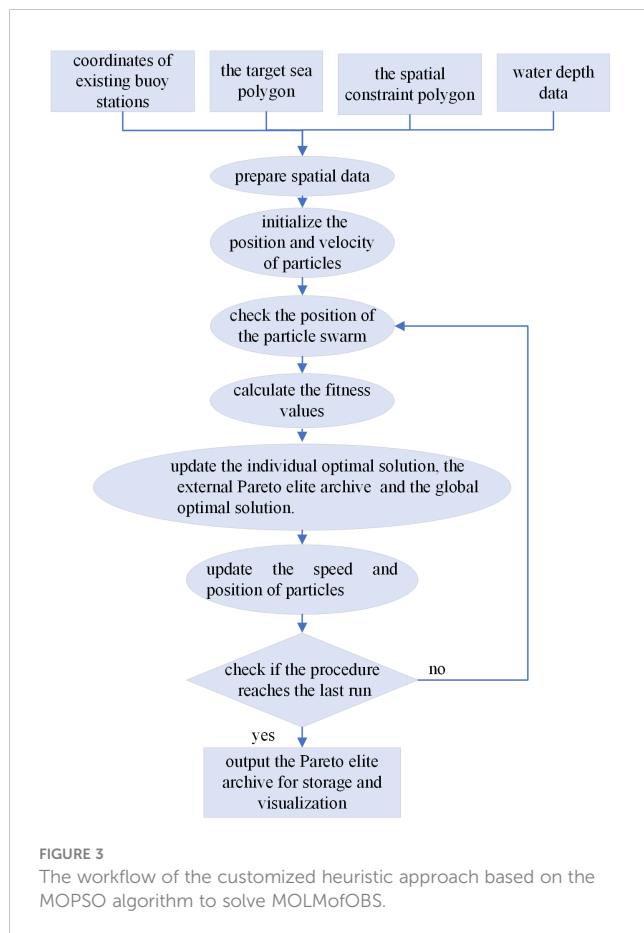


FIGURE 2

Variation curve of the inertia weight factor (ω) according to the change rate of the objective values (∂). It can be observed from Figure 2 that ω_j^{t+1} increases with the increase of ∂ . Then $0 \leq \partial < 1$. The large ∂ indicates that the objective values calculated by two adjacent iterations are close, and the diversity of particles is decreased. Increasing ω expands the local search to a much broader space. When ∂ approaches 0, ω is near 0.367. When $\partial \geq 1$, ω decreases with the increase of ∂ . A bigger ∂ indicates a bigger difference between the objective values calculated by two adjacent iterations. Decreasing ω increases the search intensity of particles. When ∂ approaches either 0 and infinity, ω is near 0.367. Therefore, in theory, such a DIWS has the potential to increase the diversity of particles and avoid local convergence.



The spatial data required for the multi-objective location calculation of ocean buoy stations described in this paper includes the following:

- A list of existing buoy stations, in the format of point geometry.

- A target sea polygon, denoted as $S_Polygon_1$, providing basic marine geographic information such as coastline, peninsula, islands, and isobar of 100 meters depth.

- A spatial constraint polygon, denoted as $S_Polygon_2$, taken as the feasible solution space to limit the position of particles to prevent them from crossing the boundary.

- ETOPO1 water depth data (Amante and Eakins, 2009) with a spatial resolution of 1 arc minute, used to provide the water depth of any point in the feasible solution space.

Step 2. Initialize the position and velocity of particles.

Firstly, the minimum velocity and the maximum velocity are set as -0.05 and 0.05. For each particle, the absolute value of the difference between the maximum velocity and the minimum velocity is multiplied by a random number between 0 and 1, and added to the minimum speed to produce a final computational result, which is set as the initial velocity of a particle. Then, the positions of all individuals are initialized in the particle swarm by utilizing the center point of $S_Polygon_2$ as the reference point to radiate around at random distances that are not out of $S_Polygon_2$. Finally, the initial value of IW is set as 1.

Step 3. Check the position of the particle swarm.

For each particle, we check whether the position of each point is outside of $S_Polygon_2$. If it is, it is moved to a position with specific offsets of the center point on both the x - and y -axes, where the x or y offset is set to $2/5$ of the x or y distance between the point that is on the boundary of $S_Polygon_2$ and closest to the out-of-boundary point in the particle's position, and the center point of $S_Polygon_2$. If the water depth at the station point is less than 5 meters, a point with a water depth of more than 5 meters and 1 nautical mile away will be searched as a substitute.

Step 4. Calculate the fitness values.

For each particle, the coordinates of n buoy sites are parsed from the position vector of each particle and combined with the existing buoy sites to form a complete set of buoy sites. A Voronoi diagram of all buoy stations is generated by the algorithms described in Section 3.2, and the 1-oVvN of each station is calculated. For all station sites with a 1-oVv neighborhood relationship, the fitness values are calculated using equations (3) and (4). The calculated fitness value is a two-tuple group, denoted as $(f1, f2)$.

Step 5. Update the individual optimal solution.

For each particle, according to the Pareto dominance concepts, we update its individual optimal solution as follows. If $f1$ and $f2$ in the new solution are both superior to those in the old solution, that is, the new solution dominates the old solution, the new solution is set as the individual optimal solution. If the new solution is dominated by the old one, the new solution is discarded. If there is no dominant relationship between the new solution and the old one, then any solution is randomly selected as the individual optimal solution.

Step 6. Update the external Pareto elite archive.

An external elite archive is established to store Pareto non-inferior solutions. The external Pareto elite archive is updated as follows: first, the Pareto boundary of the current particle swarm is calculated, and the Pareto boundary and its corresponding particles are added to the elite archives. Second, an additional filter in the elite archive is applied according to the dominant relationship to remove all the dominated particles. Third, we determine whether the elite archive set exceeds the specified size. If it does, we use the crowding measurement method (Moubayed et al., 2014) to remove those particles with low crowding distance.

Step 7. Update the global optimal solution.

According to the crowding distance method, the particle and its fitness with the lowest crowding density is selected as the global best solution.

Step 8. Update the speed and position of particles.

For each particle, if the current run number is more than 4, the dynamic IW is calculated according to the formulas in Section 4.2. Otherwise, the IW value is fixed. The formulas in Section 4.1 are used to update the position and velocity before running to the next iteration.

Step 9. Check if the procedure reaches the last run.

If the last run has been reached, the algorithm outputs the Pareto elite archive for storage and visualization, and the iteration is quit. Otherwise, the algorithm goes to the step 3.

The differences between the calculation process in the DIWS-MOPSO heuristic framework and the traditional MOPSO include

the following: a) In step 2, the particle swarm initialization assignment method with the spatial center point as the reference point is used. b) Polygon geometric elements consisting of coastlines, isobaths, and islands are used as feasible solution spaces to constrain particles to prevent them crossing the spatial boundary in step 3. c) The IW is dynamically calculated in Step 10. All these measures effectively ensure that the proposed heuristic framework has good convergence, and that the obtained non-inferior solutions have good accuracy.

5 Experiments

A series of experiments is conducted to verify the effectiveness of the MOLMOFBS and the performance of the DIWS-MOPSO. Meanwhile, the convergence of the algorithm and the diversity of the non-inferior solutions are compared. Bohai Bay of China is selected as the study area, and the region delineated by the red polygon in Figure 4 is set as the feasible solution space. Although the two objectives F1 and F2 belong to different dimensions, they are compared separately without cross comparison, so no normalization processing is needed in the following experiments.

5.1 Performance analysis of DIWS-MOPSO for single buoy station location problem

In this section, a set of experiments is conducted by computing the single buoy station location problem using both the MOPSO algorithm with the fixed IW (IW-MOPSO) and the DIWS-MOPSO algorithm to prove the correctness and efficiency of these two heuristic algorithms and compare their performance. The performance evaluation indexes adopted in this paper include the following:

(1) Convergence evaluation index

Generation Distance (GD) (Menchaca-Mendez and Coello, 2015), representing the distance between the obtained Pareto

non-inferior solutions and the real Pareto frontier, is used to measure convergence, where a smaller GD value indicates that the calculation result is closer to the real Pareto frontier. The formula used to calculate GD value is as follows:

$$GD = \frac{1}{n} \left(\sum_{i=1}^n d_i^p \right)^{1/p}, \quad (16)$$

where n is the number of Pareto non-inferior solutions, p is the number of objectives, and d_i is the Euclidean distance between the i th Pareto non-inferior solution and the nearest solution of the real Pareto frontier in the objective space.

(2) Distribution uniformity evaluation index

The distribution uniformity of Pareto non-inferior solutions on the real Pareto frontier is measured by space metric (SD), where a smaller SD indicates a more uniform distribution of Pareto non-inferior solutions. The formula used to calculate SD is as follows:

$$SD = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\bar{d} - d_i)^2} \quad (17)$$

where $d_i = \min_j (|f_1^i(x) - f_1^j(x)| + |f_2^i(x) - f_2^j(x)|)$ ($i, j=1, 2, \dots, n, i \neq j$). n is the number of Pareto non-inferior solutions; and $\bar{d}$ is the mean of d_i .

In these experiments, the particle size is set to 100, the archive set size is set to 200, the initial search step is 0.05, and the number of iterations varies in terms of 100, 200, 400, 600, 800, and 1000. Experiment results are shown in Figures 5–7. Figure 5 shows a comparison of the real Pareto frontier obtained and Pareto non-inferior solutions calculated by IW-MOPSO and DIWS-MOPSO with 1000 iterations. It can be observed from Figure 5 that most of the Pareto non-inferior solutions (green triangles in Figure 5) obtained by both IW-MOPSO and DIWS-MOPSO are within the objective space formed by the real Pareto frontier (red diamonds in Figure 5), which indicates that the Pareto non-inferior solutions are all efficient solutions. In another aspect, the principal space of solutions obtained by IW-MOPSO is [16694, 52525] in the F1 term and [8.39E+09, 9.02E+09] in the F2 term, as shown in the lower-left area of Figure 5A, and the principal space of solutions obtained by DIWS-MOPSO is [13863, 54909] for F1 and [8.37E+09, 9.12E+09] for F2, as shown in the lower-left area of Figure 5B. These results indicate that the solutions space of DIWS-MOPSO is much wider than that of IW-MOPSO, which means the evolution of particle swarm in the DIWS-MOPSO algorithm is more diverse than that in the IW-MOPSO algorithm.

Figure 6 shows a convergence comparison between IW-MOPSO and DIWS-MOPSO using GD values, where the GD value of the DIWS-MOPSO algorithm is smaller than that of IW-MOPSO for each group of data with the same number of iterations. Furthermore, as the number of iterations increases, the GD value of IW-MOPSO fluctuates greatly. However, with the increase of the number of iterations, the GD value of DIWS-MOPSO gradually decreases, showing a stable trend on the 200th iteration, and finally becomes stable between 2.6E+06 and 3.2E+06. These results indicate that the stability of the DIWS-MOPSO algorithm is better, and the corresponding solutions are more concentrated. On the other hand, it can be observed from Figure 7 that the SD value of DIWS-MOPSO is smaller than that of IW-MOPSO as the

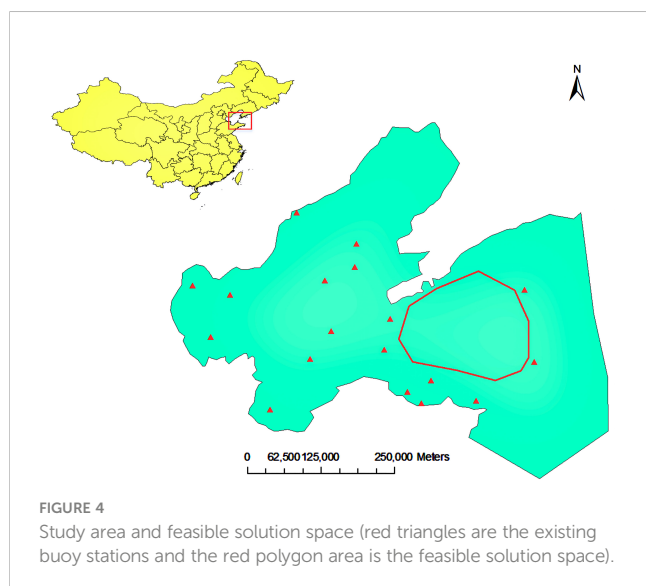


FIGURE 4

Study area and feasible solution space (red triangles are the existing buoy stations and the red polygon area is the feasible solution space).

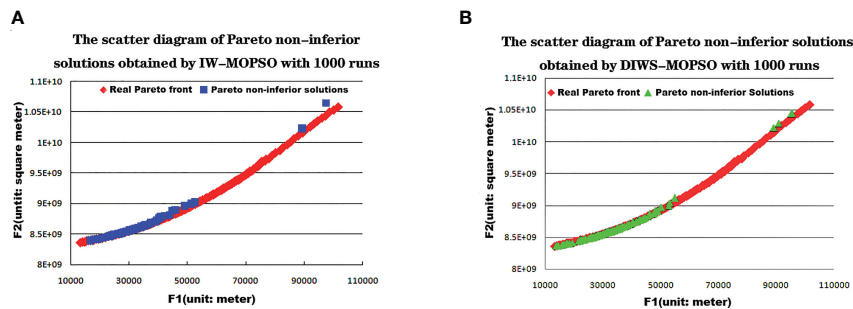


FIGURE 5

The scatter diagrams of Pareto non-inferior solutions obtained by IW-MOPSO and DIWS-MOPSO with 1000 runs for single buoy station location selection. (A) Pareto non-inferior solutions of IW-MOPSO (B) Pareto non-inferior solutions of DIWS-MOPSO.

number of iterations varies. Therefore, the distribution of Pareto non-inferior solutions obtained by DIWS-MOPSO is more uniform in the objectives space than that obtained by IW-MOPSO.

Based on the above results, MOPSO-based heuristic algorithms are effective in solving the single buoy station location problem, and the obtained Pareto non-inferior solutions can approximate the real Pareto frontier. Furthermore, the proposed DIWS-MOPSO algorithm has better stability and convergence than the IW-MOPSO algorithm, and the non-inferior solutions obtained by DIWS-MOPSO are more diverse and more evenly distributed than that obtained by IW-MOPSO in objective spaces.

5.2 Experiments solving multiple buoy stations location problem

Experiments are conducted on the location problem for 2, 3, 4, 5, and 6 buoy stations. To more closely observe the convergence effect of the algorithms, the particle size is set to 10, the number of iterations is set to 10, 20, 40, 60, 80, 100, 200, 400, or 600, the initial search step (i.e., particle velocity) is set to 0.05 arc-degrees, and the speed range is $[-0.05, 0.05]$. In fact, it is impossible to calculate the real Pareto frontier of the multiple buoy station location problem in a limited time as it is an NP problem, and, as such, it can rarely determine the optimal GD values. Instead, the layout pattern, which

is referred to as a description of the spatial features distribution in terms of being random, clustered, and dispersed, is adopted to measure the convergence of the algorithms in the performance comparison. In our application, the pattern that is more dispersed, more uniform in spatial distribution, and more balanced in distance between buoy stations is considered to be an acceptable and good pattern, which is used as a standard to evaluate the advantages and disadvantages of the algorithm calculation results. Here, we visually judge the patterns qualitatively.

The results of the experiments are given in Table 1, including good patterns obtained by the IW-MOPSO algorithm and the DIWS-MOPSO algorithm as the number of buoy station changes and the number of iterations required to obtain an acceptable and good pattern. An acceptable and good pattern is a spatial layout in which the value of F1 is biggest and the value of F2 is as smallest in a specific scenarios of buoy deployments. It can be observed that as the number of buoy stations (denoted by n) increase, the number of iterations required to obtain a good pattern increases continuously. When $n=2$, only 10 iterations are needed to generate a good pattern. However, when $n=6$, several hundred iterations are needed for a good pattern. When $n \geq 4$, as the number of buoys increases, the number of iterations required for DIWS-MOPSO to converge to a good pattern becomes much less than that of IW-MOPSO. Moreover, the gap between these two algorithm also increases as n increases. For example, when $n=5$, the number of iterations differs by only 20 between the two methods, whereas when $n=6$, the IW-MOPSO method converges to a fine pattern after 600 iterations, but the DIWS-MOPSO method requires only 200 iterations (a difference of 400 iterations). The number of iterations represents the convergence of the algorithm, where the fewer the number of iterations, the faster the convergence. Therefore, it is proved by the above experiments that the convergence of the DIWS-MOPSO algorithm is better than that of the IW-MOPSO algorithm, and this advantage becomes more obvious as n increases in the situation of multiple buoy stations location selection. In addition, with the same number of iterations, the non-inferior solution set obtained by DIWS-MOPSO is more diverse than that of IW-MOPSO. Therefore, after involving the DIWS in the MOPSO algorithm, it becomes much easier to obtain the new Pareto non-inferior solutions, and the diversity of the particle swarm is greatly improved as well.

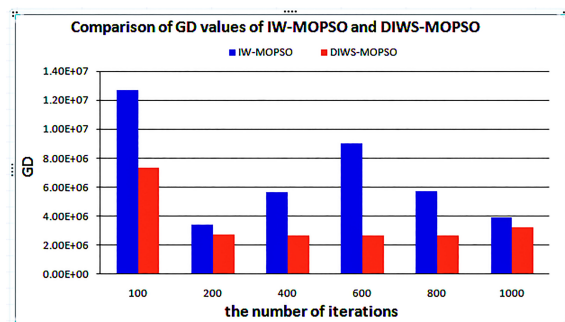
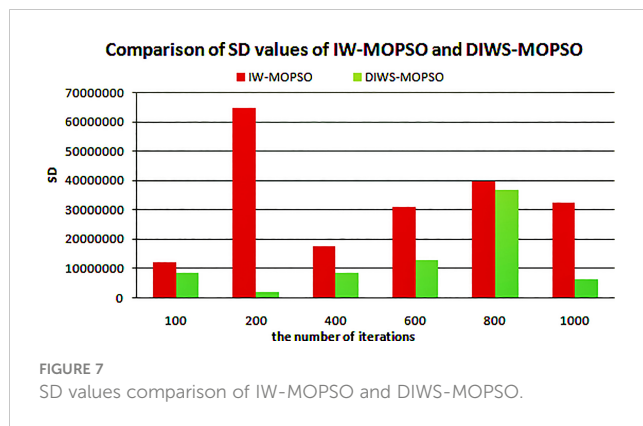


FIGURE 6

Convergence comparison of IW-MOPSO and DIWS-MOPSO algorithms by GD values.



From the experiments of the multi-buoy station location problem, we deduce that the optimal solution selection method based on the spatial pattern has important practical value. An MOPSO algorithm based on the swarm intelligence mechanism has the trait of searching for the extremum of the objective functions. However, if the extreme value of the objective function is pursued blindly, it is easy for the search to fall into the extreme region. For example, in the minimum value area of F2, the value of F1 is too large, and in the minimum value area of F1, the value of F2 is too large—both of which show solutions with a poor spatial pattern, which is reflected in the fact that some stations are far away from each other, and some stations are especially close and not scattered enough. In practice, neither of these results is what the decision-makers want. Therefore, the pattern-preferred approach provides an effective method for decision-makers to filter non-inferior solutions.

6 An ocean buoy location real-time planning portal

By integrating the ocean buoy location model, the SNM, and two kinds of MOPSO algorithms (i.e., IW-MOPSO and DIWS-MOPSO), an interactive portal is developed in the Cyberinfrastructure (CI) framework, which is a promise solution to enable spatial computing modules in web (Li et al., 2015; Miaomiao et al., 2016; Li et al., 2016a; Li et al., 2016b), to provide decision-making services for online ocean buoy station location real-time planning. The Architecture of the CI portal includes the data layer, the computing layer, and the presentation layer from bottom to top. The coordinates of buoy stations, electronic navigation charts and water depth data are stored using the PostgreSQL database in the data layer. The ocean buoy location model, the SNM, and the MOPSO-based algorithms including IW-MOPSO and DIWS-MOPSO are integrated in the computing layer using Python programming platform. Finally, the target sea area, Voronoi polygons and position points of buoy stations are visualized in the presentation layer using web programming technologies. This portal presents a unique Web-based spatial

analysis platform for buoy location selection, which is different from other existing portals.

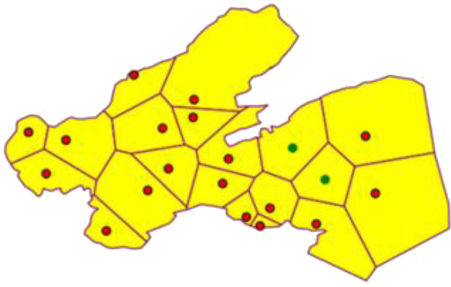
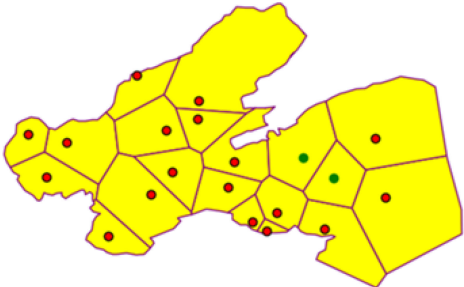
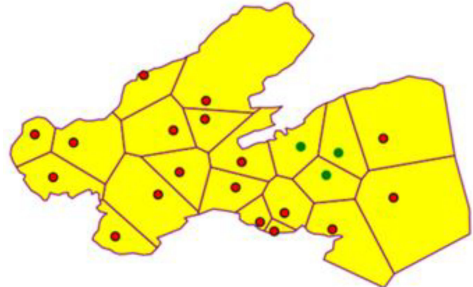
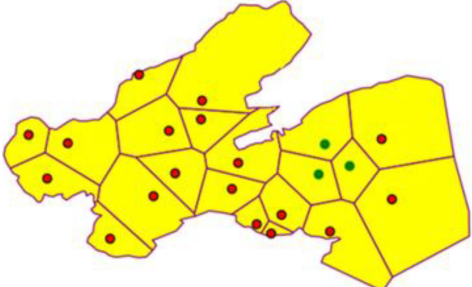
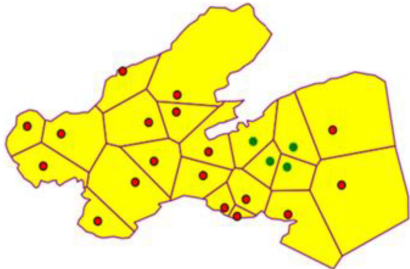
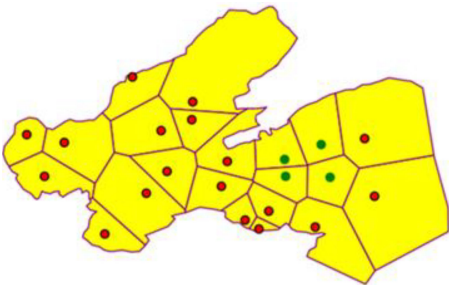
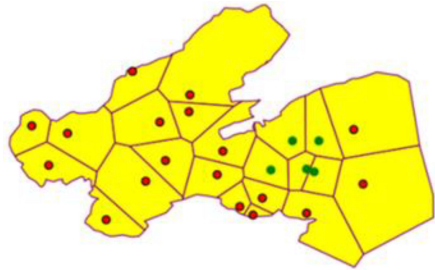
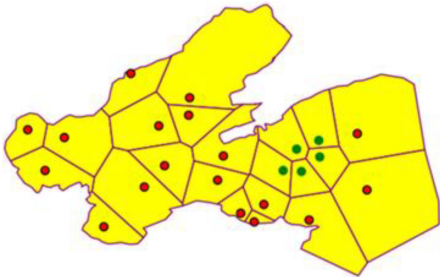
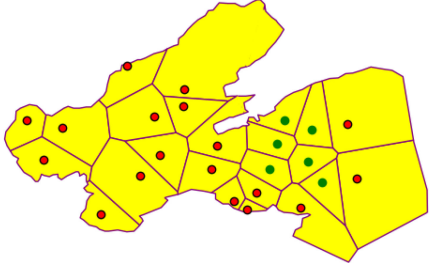
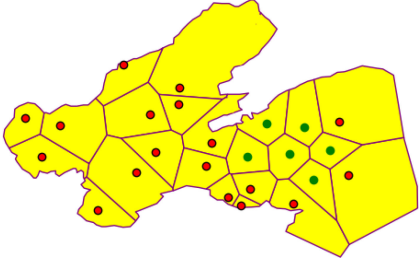
In the CI portal, the target sea area is selected by drawing a polygon on the online map, and the operation parameters (e.g., the particle size, buoy station count, the number of iterations, and the initial search step) can be tuned on demand and adjusted in real time. The arbitrary shape of the sea area is supported as the calculation area, and the calculation results are displayed in real time and are able to be operated interactively. Furthermore, both of the algorithms (IW-MOPSO and DIWS-MOPSO) are provided for online calculation, and the computational results can be compared visually for the selection of the optimal planning references. In addition, the portal also provides auxiliary tools for measuring distance and calculating area. Figure 7 shows the interface of the CI portal and demonstrates the calculation results of the three buoy stations. The red polygon is the target area drawn interactively, the small blue icons are the existing buoy stations, the green dots stand for the calculated buoy placement positions, and the blue lines are the boundaries of the Voronoi polygons. In Figure 8, four sets of calculation results were obtained and listed in the tree control on the left side of the interface. Ten particles were used to iterate 10 times and 100 times by the IW-MOPSO and DIWS-MOPSO algorithms, respectively. Each result set also contains several solutions, which can be visualized on the map to show a spatial pattern. Through this interactive and visualized portal, decision-makers can grasp the buoy distribution from a global perspective and select a layout scheme with a fine pattern according to actual needs.

7 Conclusion

This research reports the procedures and techniques for spatial optimization modeling of multi-objective locations of ocean buoy stations. Structuring the issue of ocean buoy station location selection as an explicit spatial optimization problem, as well as building an efficient heuristic algorithm to solve the problem and present computational results, effectively supports decision-making in ocean buoy observation network layout planning. In this paper, the MOLMoFOS is established by clear mathematical formulas based on Tobler's first law of geography. A Voronoi diagram is adopted to realize the spatial division of the target sea area for buoy observing, and an SNM is established to implement the spatial proximity estimation by measuring the 1-oVvN, ensuring the computability of the buoy station location model in practical applications. On the basis of sufficient investigation, comparative analysis, and testing, the traditional multi-objective PSO algorithm is improved by introducing a dynamic IW factor, and a new heuristic algorithm named DIWS-MOPSO is established.

In the DIWS-MOPSO algorithm, the dynamic formula of IW factor is designed, and the IW factor of each particle is calculated in real time according to the change rate of objective values in each run. The experimental results have proved that the DIWS-MOPSO algorithm has a great improvement in performance over IW-

TABLE 1 Comparison of selection results of multi-buoy stations location.

Number of buoy stations	IW-MOPSO		DIWS-MOPSO	
	a fine pattern	T ¹	a fine pattern	T ¹
2		10		10
3		20		20
4		60		20
5		80		60
6		600		200

1. T is the number of iterations required for a fine pattern.

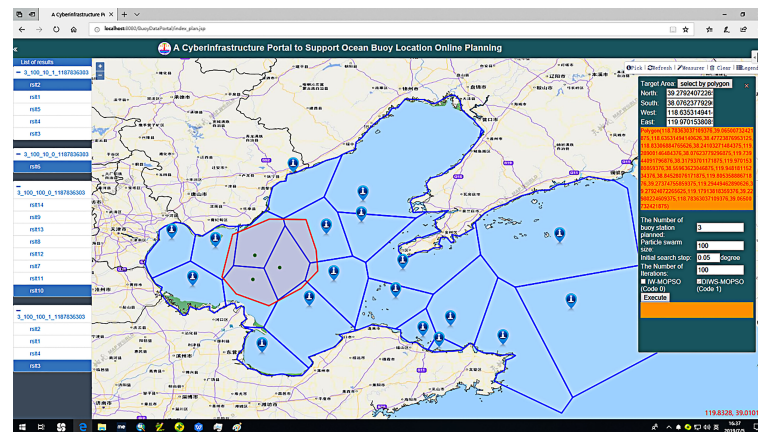


FIGURE 8

Screenshot of a cyberinfrastructure portal aggregating the SNM, the ocean buoy location model and the algorithms of IW-MOPSO and DIWS-MOPSO to support ocean buoy layout planning.

MOPSO. When calculating the buoy placement position, the DIWS-MOPSO algorithm not only effectively avoids local search stagnation, but also improves the diversity of non-inferior solutions. A spatial pattern is introduced to filter non-inferior solutions, and qualitatively judging the dispersion and aggregation of the ocean buoy layout pattern provides supplementary reference for decision-makers. Finally, we successfully integrated the proposed models and algorithms into an online analysis portal in the CI environment for real-time ocean buoy location planning. This portal provides a gateway and testbed where the general public, decision-makers, and researchers can select a target sea area by drawing a polygon directly on the map, change parameters on demand, and view computational buoy station locations immediately. To the best of our knowledge, this is the first time such spatial optimization modeling techniques have been developed and integrated into an interactive portal for ocean buoy location planning. This work has important significance for the sustainable development of marine buoy monitoring networks.

In the future, we will extend and deepen our research in the following aspects: first, we will further refine the site selection model. The influence of the spatial distribution of large-, medium-, and small-scale ocean phenomena such as water mass, cold/warm current, and ocean peak on the position of ocean buoy placement will be taken into account to restrict the spatial influence sphere of the buoy station in its corresponding Voronoi polygon, and a finer buoy spatial sphere model will be designed. Second, we will investigate the method of generating distance attenuation coefficients to calculate the effective monitoring coverage area of ocean buoy stations, aiming to accurately evaluate the ocean buoy monitoring density. Third, we will explore the potential of other heuristic algorithms (e.g., genetic algorithm, simulated annealing algorithm, and tabu algorithm) in solving the location problem of ocean buoy stations, as well as study the hybrid heuristic algorithm framework to improve the accuracy and spatial-temporal efficiency of calculation. Lastly, we will plan to promote the use of the multi-objective location modeling techniques of ocean buoy stations

planning in government departments and further improve it according to feedback provided. Spatial optimization modeling of multi-objective location of ocean buoy stations is a complex model, and will take much efforts for others to develop it to design buoy monitoring strategies. It's also our plan to open source the modeling code to benefit to the broad research communities and GeoAI (Hsu et al., 2021) technologies will be explored to speedup the computation of location selection of buoy deployments.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

SL and MS was responsible for the overall organization of the paper and wrote Section 1, Section 3, and Section 7. The contributions of SL and MS are equal and both the first author. MS and SC wrote Section 2. MS, XF, SZ, WH, SG, and KC wrote Section 4, Section 5, and Section 6. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2023.1134418/full#supplementary-material>

References

- AlvarezBenitez, J. E., Everson, R. M., and Fieldsend, J. E. (2005). A MOPSO Algorithm Based Exclusively on Pareto Dominance Concepts[C]// *Evolutionary Multi-Criterion Optimization, Third International Conference, EMO 2005* (Guanajuato, Mexico).
- Amante, C., and Eakins, B. W. (2009). *ETOPO1 1 arc-minute global relief model: Procedures, data sources and analysis* (Boulder, Colorado, USA: NOAA Technical Memorandum NESDIS NGDC-24).
- Amoshahy, M. J., Shamsi, M., and Sedaaghi, M. H. (2016). A novel flexible inertia weight particle swarm optimization algorithm. *PloS One* 11 (8), e0161558. doi: 10.1371/journal.pone.0161558
- Arana-Jiménez, M., Blanco, V., and Fernández, E. (2020). On the fuzzy maximal covering location problem. *Eur. J. Operational Res.* 283 (2), 692–705. doi: 10.1016/j.ejor.2019.11.036
- Atta, S., Mahapatra, P. R. S., and Mukhopadhyay, A. (2021). A multi-objective formulation of maximal covering location problem with customers' preferences: Exploring pareto optimality-based solutions. *Expert Syst. Appl.* 186, 115830. doi: 10.1016/j.eswa.2021.115830
- Blanco, V., and Gázquez, R. (2021). Continuous maximal covering location problems with interconnected facilities. *Comput. Operations Res.* 132, 105310. doi: 10.1016/j.cor.2021.105310
- Bourles, B., Lumpkin, R., Mchaden, M. J., Hernandez, F., Nobre, P., Campos, E., et al. (2008). The PIRATA program: History, accomplishments, and future directions. *Bull. Am. Meteorological Soc.* 89 (8), 435–447. doi: 10.1175/2008BAMS2462.1
- Casas-Ramírez, M.-S., Camacho-Vallejo, J., Díaz, J. A., and Luna, D. E. (2020). A bi-level maximal covering location problem. *Operational Res.* 20 (2), 827–855. doi: 10.1007/s12351-017-0357-y
- Chang, N. B., and Wei, Y. L. (2002). Comparative study between the heuristic algorithm and the optimization technique for vehicle routing and scheduling in a solid waste collection system. *Civil Eng. Syst.* 19 (1), 41–65. doi: 10.1080/10286600212162
- Chauhan, P., Deep, K., and Pant, M. (2013). Novel inertia weight strategies for particle swarm optimization. *Memetic Computing* 5 (3), 229–251. doi: 10.1007/s12293-013-0111-9
- Chen, G., Huang, X., Jia, J., and Min, Z. (2006). Natural exponential inertia weight strategy in particle swarm optimization. in *2006 6th World Congress on Intelligent Control and Automation, Dalian*. (Dalian, China: IEEE) pp. 3672–3675. doi: 10.1109/WCICA.2006.1713055
- Church, R. L., Stoms, D. M., and Davis, F. W. (1996). Reserve selection as a maximal covering location problem. *Biol. Conserv.* 76 (2), 105–112. doi: 10.1016/0006-3207(95)00102-6
- Church, R. L., and Wang, S. (2020). Solving the p-median problem on regular and lattice networks. *Comput. Operations Res.* 123, 105057. doi: 10.1016/j.cor.2020.105057
- Dong, P. (2008). Generating and updating multiplicatively weighted voronoi diagrams for point, line and polygon features in GIS. *Comput. Geosciences* 34 (4), 411–421. doi: 10.1016/j.cageo.2007.04.005
- Duque, J., Anselin, L., and Rey, S. J. (2012). The max-P-Regions problem. *J. Regional Sci.* 52 (3), 397–419. doi: 10.1111/j.1467-9787.2011.00743.x
- Feng, Y., and Liu, Y. (2013). A heuristic cellular automata approach for modelling urban land-use change based on simulated annealing. *Int. J. Geographical Inf. Sci.* 27 (3), 449–466. doi: 10.1080/13658816.2012.695377
- Feng, Y., Zheng, B., and Li, Z. (2010). Exploratory study of sorting particle swarm optimizer for multiobjective design optimization. *Math. Comput. Model.* 52 (11–12), 1966–1975. doi: 10.1016/j.mcm.2010.04.020
- Hase, H., Masumoto, Y., Kuroda, Y., and Mizuno, K. (2008). Semiannual variability in temperature and salinity observed by triangle trans-ocean buoy network (TRITON) buoys in the eastern tropical Indian ocean. *J. Geophysical Res. Oceans* 113 (C1), 1–10. doi: 10.1029/2006JC004026
- Hsu, C.-Y., Li, W., and Wang, S. (2021). Knowledge-driven GeoAI: Integrating spatial knowledge into multi-scale deep learning for Mars crater detection. *Remote Sens.* 13, 2116. doi: 10.3390/rs13112116
- Kashino, Y., Ueki, I., Kuroda, Y., and Purwandani, A. (2007). Ocean variability north of new Guinea derived from TRITON buoy data. *J. Oceanography* 63 (4), 545–559. doi: 10.1007/s10872-007-0049-y
- Kim, K., Dean, D. J., Kim, H., and Chun, Y. (2016). Spatial optimization for regionalization problems with spatial interaction: a heuristic approach. *Int. J. Geographical Inf. Sci.* 30 (3), 451–473. doi: 10.1080/13658816.2015.1031671
- Klippel, A., and Li, R. (2011). Interpreting spatial patterns: An inquiry into formal and cognitive aspects of Tobler's first law of geography. *Ann. Assoc. Am. Geographers* 101 (5), 1011–1031. doi: 10.1080/00045608.2011.577364
- Knowles, J., and Corne, D. (1999). The pareto archived evolution strategy: A new baseline algorithm for pareto multiobjective optimisation. *Proc. Congress Evolutionary Computation*. doi: 10.1109/CEC.1999.781913
- Knowles, J. D., and Corne, D. W. (2014). Approximating the nondominated front using the pareto archived evolution strategy. *Evolutionary Comput.* 8 (2), 149–172. doi: 10.1162/106365600568167
- Kollat, J. B., and Reed, P. (2007). A framework for visually interactive decision-making and design using evolutionary multi-objective optimization (VIDEO). *Environ. Model. Software* 22 (12), 1691–1704. doi: 10.1016/j.envsoft.2007.02.001
- Köppen, M., and Veenhuis, C. (2006). Multi-objective particle swarm optimization by fuzzy-pareto-dominance meta-heuristic. *Int. J. Hybrid Intelligent Syst.* 3 (4), 179–186. doi: 10.3233/HIS-2006-3401
- Lee, I. (2010). Interactive analysis using voronoi diagrams: Algorithms to support dynamic update from a generic triangle-based data structure. *Trans. GIS* 6 (2), 89–114. doi: 10.1111/1467-9671.00099
- Li, W., Cao, K., and Church, R. L. (2016a). Cyberinfrastructure, GIS, and spatial optimization: opportunities and challenges. *Int. J. Geographical Inf. Sci.* 30 (3), 427–431. doi: 10.1080/13658816.2015.1112906
- Li, W., Church, R. L., and Goodchild, M. F. (2014). An extendable heuristic framework to solve the p-compact-regions problem for urban economic modeling. *Comput. Environ. Urban Syst.* 43 (1), 1–13. doi: 10.1016/j.compenvurbsys.2013.10.002
- Li, W., Song, M., Zhou, B., Cao, K., and Gao, S. (2015). Performance improvement techniques for geospatial web services in a cyberinfrastructure environment - a case study with a disaster management portal. *Computers Environ. Urban Syst.* 54, 314–325. doi: 10.1016/j.compenvurbsys.2015.04.003
- Li, W., Wu, S., Song, M., and Zhou, X. (2016b). A scalable cyberinfrastructure solution to support big data management and multivariate visualization of time-series sensor observation data. *Earth Sci. Inf.* 9 (4), 449–464. doi: 10.1007/s12145-016-0267-1
- Liu, Y., Yuan, M., He, J., and Liu, Y. (2015). Regional land-use allocation with a spatially explicit genetic algorithm. *Landscape Ecol. Eng.* 11 (1), 209–219. doi: 10.1007/s13555-014-0267-6
- Malcolm, S. A., and Revelle, C. (2005). Representational success: A new paradigm for achieving species protection by reserve site selection. *Environ. Modeling Assess.* 10 (4), 341–348. doi: 10.1007/s10666-005-9015-5
- Masoomi, Z., Mesgari, M. S., and Hamrah, M. (2013). Allocation of urban land uses by multi-objective particle swarm optimization algorithm. *Int. J. Geographical Inf. Sci.* 27 (3), 542–566. doi: 10.1080/13658816.2012.698016
- McPhaden, M. J., Busalacchi, A. J., Cheney, R., Donguy, J.-R., Gage, K. S., Halpern, D., et al. (1998). The tropical ocean-atmosphere observing system: A decade of progress. *J. Geophysical Res. Oceans* 103 (C7), 14169–14240. doi: 10.1029/97JC02906

- Menchaca-Mendez, A., and Coello, C. A. C. (2015). GDE-MOEA: a new MOEA based on the generational distance indicator and ϵ -dominance. *2015 IEEE Congress on Evolutionary Computation (CEC)*, 25–28 May 2015, Sendai, Japan. doi: 10.1109/CEC.2015.7256992
- Miaomiao, S., Song, M., Li, W., Zhou, B., and Lei, T. (2016). Spatiotemporal data representation and its effect on the performance of spatial analysis in a cyberinfrastructure environment - a case study with raster zonal analysis. *Comput. Geosciences* 87, 11–21. doi: 10.1016/j.cageo.2015.11.005
- Moubayed, N. A., Petrovski, A., and McCall, J. (2014). D2MOPSO: MOPSO based on decomposition and dominance with archiving using crowding distance in objective and solution spaces. *Evol. Comput.* 22 (1), 47–77. doi: 10.1162/EVCO_a_00104
- Murray, A. T. (2010). Advances in location modeling: GIS linkages and contributions. *J. Geographical Syst.* 12 (3), 335–354. doi: 10.1007/s10109-009-0105-9
- Nguyen, K. T., Nhan, T. H. N., Teh, W. C., and Hung, N. T. (2021). The connected p-median problem on complete multi-layered graphs. *Discrete Mathematics Algorithms Appl.* 14 (03), 2150118. doi: 10.1142/S1793830921501184
- Nittis, K., Zervakis, V., Papageorgiou, E., and Perivoliotis, L. (2002). Atmospheric and oceanic observations from the POSEIDON buoy network: Initial results. *J. Atmospheric Ocean Sci.* 8 (2–3), 137–149. doi: 10.1080/10236730290004076
- Nittis, K., Perivoliotis, L., Korres, G., Tziavos, C., and Thanos, I. (2006). Operational monitoring and forecasting for marine environmental applications in the Aegean Sea. *Environ. Model. Software* 21 (2), 243–257. doi: 10.1016/j.envsoft.2004.04.023
- Okabe, A., Satoh, T., Furuta, T., Suzuki, A., and Okano, K. (2008). Generalized network voronoi diagrams: Concepts, computational methods, and applications. *Int. J. Geographical Inf. Sci.* 22 (9), 965–994. doi: 10.1080/13658810701587891
- Raquel, C. R., and Naval, P. C. (2005). An effective use of crowding distance in multiobjective particle swarm optimization. *Genet. Evolutionary Comput. Conference*. doi: 10.1145/1068009.1068047
- Rouault, M., Servain, J., Reason, C. J. C., Bourlès, B., Rouault, M. J., Fauchereau, N., et al. (2009). Extension of PIRATA in the tropical south-East Atlantic: an initial one-year experiment. *South Afr. J. Mar. Sci.* 31 (1), 63–71. doi: 10.2989/AJMS.2009.31.1.5.776
- Santana, R. A., Pontes, M. R., and Bastosfilho, C. J. A. (2009). A Multiple Objective Particle Swarm Optimization Approach Using Crowding Distance and Roulette Wheel. In *2009 Ninth International Conference on Intelligent Systems Design & Applications*. 30 November 2009 - 02 December 2009, Pisa, Italy. doi: 10.1109/ISDA.2009.73
- Shifa, M. A., Ma, S., He, J., Liu, F., and Yu, Y. (2011). Land-use spatial optimization based on PSO algorithm. *Geo-spatial Inf. Sci.* 14 (1), 54–61. doi: 10.1007/s11806-011-0437-8
- Soltanpour, A., Baroughi, F., and Alizadeh, B. (2020). A hybrid algorithm for the uncertain inverse p-median location problem. *Facta Universitatis Ser. Mathematics Inf.* 35 (5), 1399–1416. doi: 10.22190/FUMI2005399S
- Song, M., Liu, S., Li, W., Chen, S., Li, W., Zhang, K., et al. (2021). A continuous space location model and a particle swarm optimization-based heuristic algorithm for maximizing the allocation of ocean-moored buoys. *IEEE Access* PP (99), 1–1. doi: 10.1109/ACCESS.2021.3060464
- Taiwo, O. J. (2021). Maximal covering location problem (MCLP) for the identification of potential optimal COVID-19 testing facility sites in Nigeria. *Afr. Geographical Rev.* 40 (4), 16. doi: 10.1080/19376812.2020.1838306
- Tang, W., Yueh, S. H., Fore, A. G., and Hayashi, A. (2015). Validation of aquarius sea surface salinity with in situ measurements from argo floats and moored buoys. *J. Geophysical Res. Oceans* 119 (9), 6171–6189. doi: 10.1002/2014JC010101
- Tobler, W. R. (1970). A computer movie simulating urban growth in the Detroit region. *Economic Geogr.* 46 (Supp 1), 234–240. doi: 10.2307/143141
- Tong, D., and Murray, A. T. (2012). Spatial optimization in geography. *Ann. Assoc. Am. Geographers* 102 (6), 1290–1309. doi: 10.1080/00045608.2012.685044
- Uma, S. M., Rajiv Gandhi, K., and Kirubakaran, E. (2012). A hybrid PSO with dynamic inertia weight and GA approach for discovering classification rule in data mining. *Int. J. Comput. Appl.* 40 (17), 32–37. doi: 10.5120/5074-7471
- Wang, J., Wang, Z., Wang, Y., Liu, S., and Li, Y. (2016). Current situation and trend of marine data buoy and monitoring network technology of China. *Acta Oceanologica Sin.* 35 (2), 1–10. doi: 10.1007/s13131-016-0815-z
- Wang, K., Chen, N., Tong, D., Wang, K., Wang, W., and Gong, J. (2016). Optimizing precipitation station location: a case study of the jinsha river basin. *Int. J. Geographical Inf. Sci.* 30 (6), 1207–1227. doi: 10.1080/13658816.2015.1119280
- Wang, K., Gong, Y., Peng, Y., Hu, C., and Cheng, N. (2020). An improved fusion crossover genetic algorithm for a time-weighted maximal covering location problem for sensor siting under satellite-borne monitoring. *Comput. Geosciences* 136 (Mar.), 104406.1–104406.13. doi: 10.1016/j.cageo.2020.104406
- Wang, C., and Zhang, Z. (2012). A maximum loss minimization model for portfolio selection based on the CVaR measurement. *Advanced Materials Res.* 524–527, 3828–3833. doi: 10.4028/www.scientific.net/AMR.524-527.3828
- Xie, X., and Xu, Y. W. (2017). *Multi-sensor image fusion algorithm based on multi-objective particle swarm optimization algorithm* (Society of Photo-optical Instrumentation Engineers). doi: 10.1117/12.2295802
- Yang, P., Xiao, Y., Zhang, Y., Zhou, S., Yang, Y., and Xu, Y. (2020). The continuous maximal covering location problem in large-scale natural disaster rescue scenes. *Comput. Ind. Eng.* 146, 106608. doi: 10.1016/j.cie.2020.106608
- Zaferanieh, M., Abareshi, M., and Fathali, J. (2022). The minimum information approach to the uncapacitated p-median facility location problem. *Transportation Lett.* 14 (3), 307–316. doi: 10.1080/19427867.2020.1864595
- Zhao, F., Zhang, Z., and Zou, J. (2012). A new algorithm using pareto archive evolution strategy to multi-objective optimization problem. *Advanced Sci. Lett.* 6 (1), 406–410. doi: 10.1166/asl.2012.2237



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Vision-based underwater target real-time detection for autonomous underwater vehicle subsea exploration

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Autonomous underwater vehicles (AUVs) equipped with online visual inspection systems can detect underwater targets during underwater operations, which is of great significance to subsea exploration. However, the undersea scene has some instinctive challenging problems, such as poor lighting conditions, sediment burial, and marine biofouling mimicry, which makes it difficult for traditional target detection algorithms to achieve online, reliable, and accurate detection of underwater targets. To solve the above issues, this paper proposes a real-time object detection algorithm for underwater targets based on a lightweight convolutional neural network model. To improve the imaging quality of underwater images, contrast limited adaptive histogram equalization with the fused multicolor space (FCLAHE) model is designed to enhance the image quality of underwater targets. Afterwards, a spindle-shaped backbone network is designed. The inverted residual block and group convolutions are used to extract depth features to ensure the target detection accuracy on one hand and to reduce the model parameter volume on the other hand under complex scenarios. Through extensive experiments, the precision, recall, and mAP of the proposed algorithm reached 91.2%, 90.1%, and 88.3%, respectively. It is also noticeable that the proposed method has been integrated into the embedded GPU platform and deployed in the AUV system in the practical scenarios. The average computational time is 0.053s, which satisfies the requirements of real-time object detection.

KEYWORDS

autonomous underwater vehicle, subsea exploration, real-time target detection, lightweight convolutional neural network, underwater image enhancement

1 Introduction

The ocean occupies the most extensive space on Earth and is an important place for the spread, exchange, and development of human civilization. During their long history, influenced by navigation technology and unpredictable marine weather conditions, a large number of ships, unfortunately sank at sea, and the ships themselves, together with the cargo they carried, were scattered on the seabed and remained dormant for thousands of years. These cultural relics are scattered on the seabed and contain rich information on history, culture, and the level of technological development and are of great significance to the study of human civilization and economic and social development. At the same time, the ocean features in a large amount of minerals and a place for military and economic activities. In addition to shipwrecks and historical cultural relics, researchers are also concerned about subsea targets such as rare biological resources, mineral resources such as manganese nodules, special geological formations such as hydrothermal and cold springs, underwater lost objects and military targets on the seafloor. The abovementioned targets, together with underwater artifacts, are the focus of attention for seabed exploration.

Autonomous underwater vehicles (AUVs) are commonly used equipment in subsea exploration and have advantages in operational range, detection efficiency, and operational flexibility compared with human-occupied vehicles (HOVs), remotely operated vehicles (ROVs) and other underwater exploration equipment (Manley, 2016). During subsea exploration missions, AUVs usually carry acoustic and optical loads, such as forward-looking sonar (FLS), 3D multibeam echosounder, side-scan sonar, camera, and so on. For the AUV studied in this paper, a forward-looking sonar, a side-scan sonar, and a camera were installed, taking into account the price, size, and weight of the load, as well as the operational objectives of the AUV. Among them, the forward-looking sonar is used to detect obstacles ahead, and the side-scan sonar and the camera are used to detect targets on the seafloor. For subsea target detection applications, the side scan sonar has a large detection range, but its resolution is low, and the target information that can be obtained is limited. For the AUV mentioned above, the side scan sonar is mainly used for rapid searches over a large range. The camera has a small detection range, but it can obtain rich information such as target shape, color, and texture, which is convenient for underwater target recognition. For the AUV mentioned above, the camera is mainly used for close range fine detection on the deep seafloor where the water quality is relatively good.

In the process of traditional underwater exploration based on AUVs, AUVs usually perform comb searches (lawn mower mode) on the seafloor according to the preplanned navigation path and take video image information of the seafloor. After the AUV is recovered to the research vessel, it is then manually judged whether the target to be searched exists in the captured video. If the target is found in the video, the location of the found target is inferred from the navigation information recorded by the AUV. When operating in this mode, the AUV cannot determine whether it has photographed the target, so even if the target is encountered in the underwater search process, it can only follow a preplanned path

and cannot conduct further detailed exploration of the target and its surroundings. During subsea explorations, if the AUV can autonomously identify the targets in the captured video images, it can replan the navigation path based on the location of the discovered targets and take more shots around the targets of interest for subsequent analysis and judgment (Lin and Zhao, 2020). Therefore, it is necessary to carry out research on vision-based underwater target recognition methods so that AUVs can autonomously analyze the videos captured during operations online to improve the operational efficiency and intelligence of AUVs.

There are still many challenges for underwater target recognition, especially online underwater target recognition based on AUV platforms.

- (1) The poor image quality of underwater target images. Underwater images typically suffer from color deviations and low visibility due to wavelength-dependent light absorption and scattering (Zhang et al., 2022). At the same time, insufficient lighting and low-end underwater imaging devices on board AUVs further degrade the quality of underwater images (Qiang et al., 2020; Lei et al., 2022).
- (2) Underwater target samples are difficult to obtain. Due to their long history, underwater targets usually have problems such as sediment cover, marine organism attachment, damage, and incomplete shape. However, it is difficult to obtain enough samples with relevant characteristics in the early research on target recognition algorithms.
- (3) Low arithmetic resources for embedded computers. Due to the limitations of equipment size and power supply capacity, high-performance computing equipment such as mainframe computer workstations commonly used in the laboratory cannot be used on AUV, and only embedded computers, for example, the NVIDIA series, can be selected for online target detection (Lin and Zhao, 2020).

In response to the above problems, this paper proposes a vision-based algorithm for real-time underwater target detection, with the following main contributions:

- (1) Design of the underwater image enhancement network component. The contrast limited adaptive histogram equalization with the fused multicolor space (FCLAHE) algorithm is designed to improve the quality of underwater target images. It achieves this by performing histogram equalization in multiple color spaces.
- (2) An underwater target detection algorithm based on a convolutional neural network is designed. Through group convolution and inverted residual blocks, the lightweight and efficient feature extraction network design is completed, which can further reduce the model calculation while ensuring the accuracy of the algorithm.
- (3) An underwater visual inspection system that can meet the needs of the AUV online application has been built. By collecting a large number of underwater target images, the

establishment of the UCR dataset is completed, and the system proves the robustness of the algorithm through a large number of tests.

Section 2 of this paper presents related research work in the area of underwater target detection algorithms. Section 3 details the algorithmic framework and specific design elements. Section 4 describes the acquisition and production of the datasets used for the experiments. Section 5 is the experimental results section, where the advancement of this algorithm is analyzed through test comparisons. Section 6 summarizes the whole paper, illustrating the advantages of our approach in high-precision and real-time underwater target detection scenarios, as well as future research directions.

2 Related work

There are two important branches of underwater target detection algorithm research as follows. One is based on the traditional image processing method, which enhances the target detail features and then accomplishes the target detection task. The other is a deep learning-based approach, which analyzes image features and designs a feature extraction network to accomplish target detection (Yeh et al., 2021).

Traditional underwater target detection algorithms first digitize the images and then analyze them by modeling them with statistical learning theory to finally complete the detection task. One of the representatives of traditional underwater target detection is the surface feature ripple extraction underwater target detection algorithm proposed by Xu et al. (2019), which models the photoelectric polarization image and then performs underwater target detection. However, this algorithm presents different shapes when imaging at different angles, resulting in a complex mathematical model that cannot be applied in real underwater scenarios. The traditional underwater target detection algorithm has problems such as a low detection rate and poor real-time performance when detecting multicategory targets in low-light underwater environments.

The rapid expansion of underwater image data has spurred research into deep learning-based detection algorithms for various underwater marine targets. Compared with traditional algorithms, underwater target detection algorithms using deep learning have significantly improved accuracy and robustness (Moniruzzaman et al., 2017). Valdenegro-Toro (2016) introduced a CNN-based approach to build an end-to-end system, designing shared convolutional layers for object detection and recognition in sonar images. Zacchini et al. (2020) designed a deep learning-based underwater automatic target recognition (ATR) system for identifying and locating potential targets in FLS images. Song et al. (2023) proposed a two-stage underwater target detection algorithm with boosting R-CNN, which improves the detection of buried and obscured targets by modeling the uncertainty of underwater targets and difficult sample mining. Zeng et al. (2021) proposed the Faster R-CNN-AON network for the case of limited underwater samples, which effectively improved the overall

detection performance by introducing an AON adversarial network to prevent the detection network from overfitting. Although the above studies have significantly improved the performance, the algorithms are poor in real-time and cannot be applied to online detection systems. To address these problems, Lei et al. (2022) introduced the Swin Transformer into the backbone network of YOLOv5 to enhance feature extraction from underwater blurred images, making the network suitable for underwater detection tasks with blurred targets. Yan et al. (2022) added the CBAM attention mechanism to the one-stage target detection model to make the network more focused on target feature information, improving detection accuracy and reducing the model. Guo et al. (2021) combined target keyframe extraction with network channel pruning to reduce the model complexity. Deep learning-based underwater target detection algorithms show better performance in complex underwater environments, but the above algorithms still cannot adapt to low computing power resources and thus cannot achieve online target detection.

3 Algorithm framework

The vision-based lightweight underwater target detection algorithm proposed in this paper and the overall framework of the algorithm are shown in Figure 1. This algorithm framework contains the following main components: (1) This paper designs an underwater image enhancement model of FCLAHE with fused multicolor space to enhance the quality of underwater target images. (2) A spindle-shaped backbone network is designed by introducing inverted residual blocks to improve the extraction of target feature information. (3) Use group convolution instead of the original standard convolution to reduce model parameters and improve inference speed.

3.1 Image enhancement algorithm of FCLAHE

Contrast limited adaptive histogram equalization (CLAHE) is a classical image enhancement algorithm that sets a threshold for each region of the histogram and spreads the number of pixels above that threshold evenly to other regions of the histogram, avoiding over-enhancement (Aggarwal and Ryoo, 2011). The specific steps of the CLAHE algorithm are as follows:

- (1) Image subregion division: the original image is divided into several subregions of equal size, each subregion is nonoverlapping and contiguous, and the number of pixels in each subregion is C ;
- (2) A histogram of a subregion denoted by $H_{ij}(k)$;
- (3) Calculate the threshold value: calculate the truncation limit value according to equation (1)

$$\beta = \frac{c}{L} \left(1 + \frac{\alpha}{100} (S_{\max} - 1) \right) \quad (1)$$

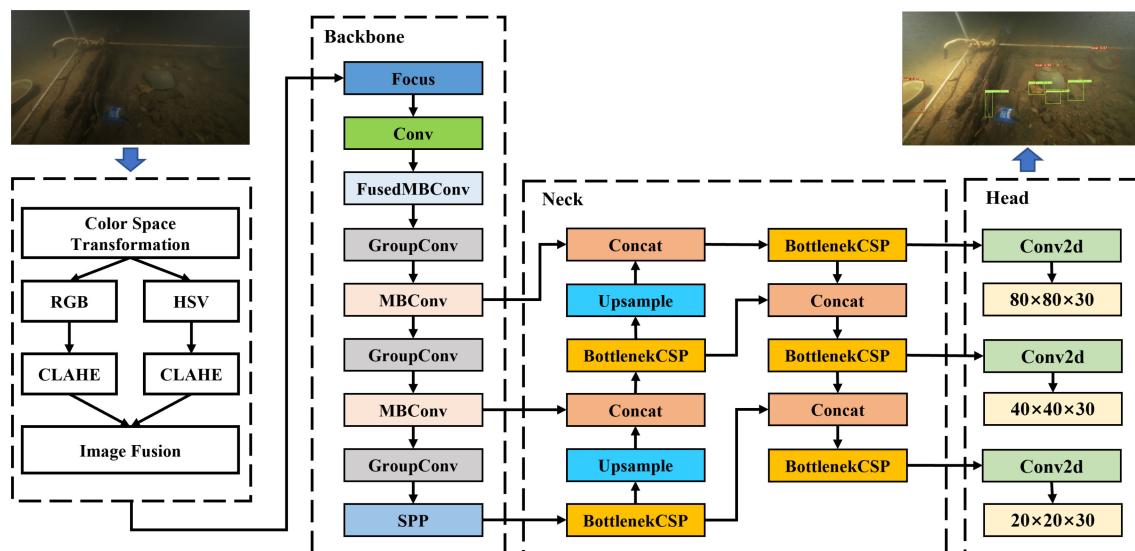


FIGURE 1
Algorithm framework.

where β is the calculated limit value; α is the truncation factor, whose value ranges from $[0, 100]$; and S_{max} is the maximum slope.

- (4) Reallocation of pixel points: each subregion, $H_{ij}(k)$ is cropped using the corresponding β value. The cropped pixels are reassigned to each gray level of the histogram in a loop until all the cropped pixels are assigned;
- (5) Histogram equalization is performed separately for the cropped grayscale histogram of each subregion;
- (6) Reconstructing pixel point grayscale values: the center point of each subregion is used as a reference point to obtain its gray value, and the gray value of each pixel in the output image is calculated by linear interpolation using a bilinear interpolation method.

Although the CLAHE algorithm achieves better results in image enhancement, its application in underwater environments results in color deviation and contrast reduction in underwater images due to light scattering, and the single use of the CLAHE algorithm leads to poor contrast enhancement (Ancuti et al., 2012). Therefore, this paper proposes the FCLAHE algorithm with fused multicolor space to enhance the image by pulling the gray dynamic range of the image, thus enhancing the image contrast.

To solve the problems in the CLAHE algorithm, this paper designs the algorithm of FCLAHE with fused multicolor space, which is shown in Figure 2, where the specific steps are as follows:

- (1) the input images are converted into RGB and HSV color spaces and input into the CLAHE algorithm module to obtain the enhanced images I_{rgb_c} and I_{hsv_c} ;

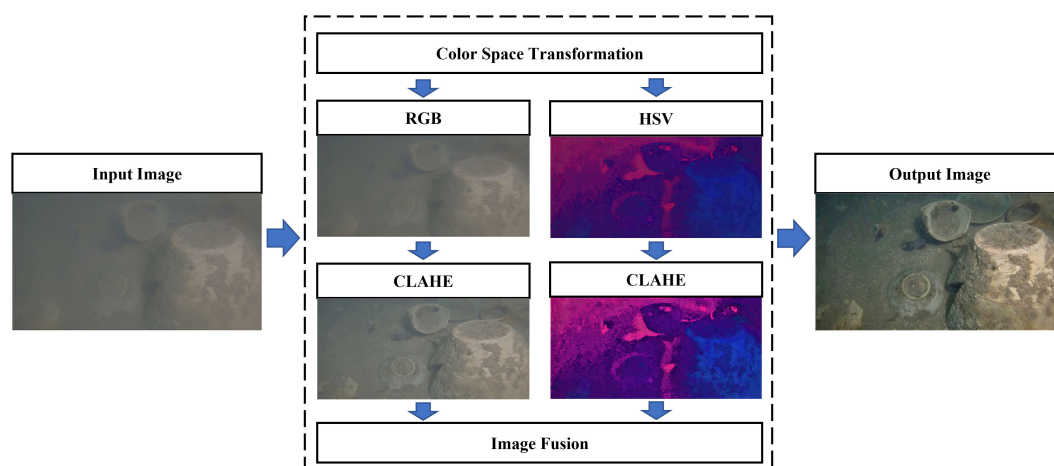


FIGURE 2
The flow of the FCLAHE algorithm.

- (2) Euclidean parametric calculation of the enhanced image I_{rgb_c} , I_{hsv_c} , according to equation (2), completes the image fusion.

$$I_{merge}(i, j) = \sqrt{I_{rgb_c}^2(i, j) + I_{hsv_c}^2(i, j)} \quad (2)$$

$$(i = 0, 1, \dots, M - 1; j = 0, 1, \dots, N - 1)$$

In this paper, the algorithm is applied to underwater artifact images, and a partial comparison of the enhancement effect is shown in Figure 3.

3.2 Inverted residual block

The inverted residual block enhances the gradient propagation of the feature extraction network and significantly reduces the memory footprint required for inference. Under the same amount of computation, the network consisting of an inverted residual block contains more model parameters and is more efficient in feature extraction. The method uses the crush-and-excite attention (Hu et al., 2018) mechanism in the channel dimension to make the feature extraction network focus more on the information-rich channel features and remove the unimportant channel features, which makes it easier to distinguish between the sensing target and background information and further improves the model accuracy. The inverted residual block is mainly divided into two structures, the MBConv block (Howard et al., 2019) and Fused-MBConv (Xiong et al., 2021), as shown in Figures 4A, B.

Since most existing GPU gas pedals are optimized for standard 3×3 convolution, the MBConv block, while having fewer parameters and smaller computation, cannot take advantage of existing gas pedals, resulting in computational inefficiencies. However, the Fused-MBConv block can take advantage of GPU gas pedals to achieve a more ideal state of computational efficiency.

Therefore, the accuracy of the underwater target detection algorithm is ensured while further reducing the computational effort of the model. In this paper, we design the strategy of using

the Fused-MBConv block and MBConv block together, placing the Fused-MBConv block in the shallow layer of the network and the MBConv block in the deep layer of the network. This strategy greatly improves the training and prediction speed of the model by making full use of CPU and GPU. The description of the backbone feature extraction network is shown in Table 1. The input of the backbone network is the image with a size of 640×640×3, and the feature is extracted through the Focus and Conv layers. The output is the feature map (map size: 320×320×64) which is extracted through the Fused-MBConv to obtain the shallow features of the target. The output 160×160×64 feature map goes through two MBConv layers of different scales to extract deeper feature information about the target. With the Fused-MBConv block and MBConv block, the backbone network can fully extract the features of the input image.

3.3 Group convolution

With the strategy of using the Fused-MBConv block and MBConv block together, the detection accuracy is guaranteed, and part of the computation of the model is reduced. To further satisfy the low arithmetic resource scenario of AUVs, this paper adopts group convolution instead of the original standard convolution. By grouping the input feature maps by channel, each group of feature maps is convolved with the corresponding convolution kernel in the group. Each convolution kernel is not involved in the convolution operation of the rest of the group, reducing the dimensionality of the convolution kernels and thus the computational effort.

The calculation of standard convolution and group convolution is shown in (Figures 5A, B), where C is the number of channels of the input feature map, H and W represent the height and width of the feature map, respectively, and N is the number of channels of the output feature map. When the number of convolution kernels is and the size is, the operations of the two convolutions are analyzed as follows: the size of the convolution kernel of standard

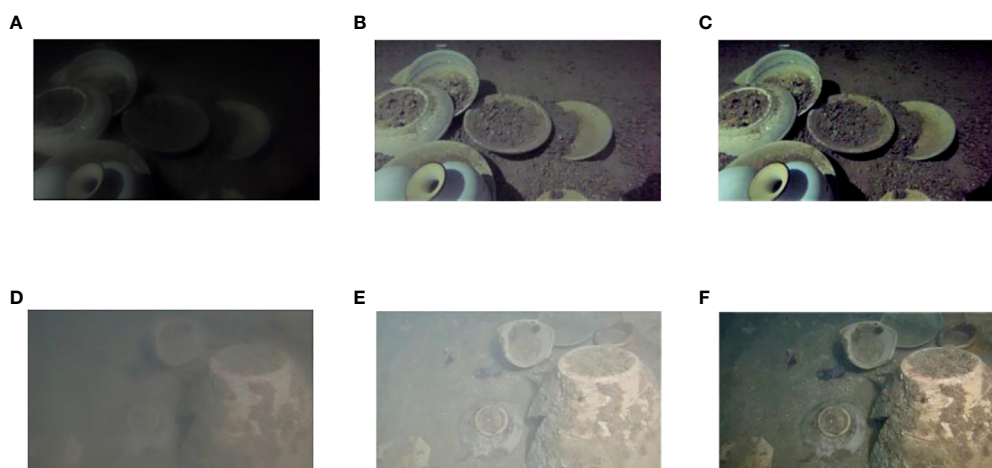


FIGURE 3
Comparison of enhancement algorithms: (A, D) original image, (B, E) CLAHE, (C, F) FCLAHE.

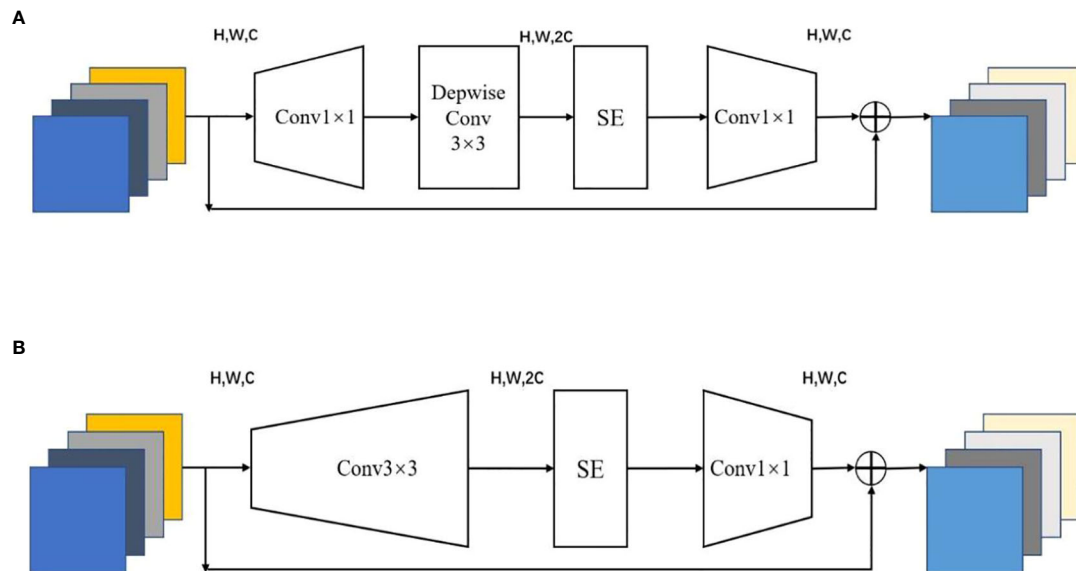


FIGURE 4
Inverted residual block: (A) MBConv, (B) Fused-MBConv.

convolution is $C \times K \times K$, and the total operation of the network is shown in equation (3).

$$Q_1 = N \times C \times K \times K \quad (3)$$

Let the number of convolutional groups be G , the number of channels per group of feature maps is $\frac{C}{G}$, the number of channels per group of output feature maps is $\frac{C}{G}$, the size of each convolutional kernel be $\frac{C}{G} \times K \times K$, the number of convolutional kernels per group is $\frac{N}{G}$, and the total number of network operations be as shown in equation (4).

$$Q_2 = N \times \frac{C}{G} \times K \times K \quad (4)$$

From equations (3)(4), it can be seen that the group convolution is $1/G$ of the total number of operations of the standard convolution under the same input conditions, and the use of group convolution significantly reduces the number of model operations.

4 Dataset

4.1 Image acquisition

The underwater target dataset constructed in this paper is obtained from two sources, one from real seafloor photography and the other from experimental simulations. The real underwater target data are images of various types of porcelain taken at an underwater archaeological site, totaling 10,000 images (resolution 1920×1080). In the experimental simulation scenario, porcelain plates, bowls, jars, and other types of porcelain targets are dropped into the water, showing different scattered states, and then filmed from different angles using underwater cameras. A total of 10,000 (resolution 1920×1080) simulated underwater target data were collected to simulate the scenes when the AUV was

conducting subsea exploration, including four cases of blurring, burial, stacking, and low light. Some of the acquired images are shown in Figures 6A–D.

4.2 Production of dataset

Using Labeling, the locations of underwater targets were manually labeled with rectangular boxes in each image, and real box labeling files in text format were obtained. The images in the dataset were enhanced using the FCLAHE image enhancement algorithm based on fused multicolor space to improve the generalization of the model to underwater blurred images. The final UCR underwater dataset was created. The dataset comprises five categories of objects, including porcelain plates, bowls, jars, censers, and porcelain fragments. These five types of porcelain are commonly found as underwater cultural relics. The completed

TABLE 1 Specification of the designed network.

Input	Operator	Channels	Activation Function	Output
$640 \times 640 \times 3$	Focus			$320 \times 320 \times 12$
$320 \times 320 \times 12$	Conv, $k3 \times 3$	64	SiLu	$320 \times 320 \times 64$
$320 \times 320 \times 64$	Fused-MBConv, $k3 \times 3$	64	ReLu6	$160 \times 160 \times 64$
$160 \times 160 \times 64$	MBConv, $k5 \times 5$	128	H-swish	$80 \times 80 \times 128$
$80 \times 80 \times 128$	MBConv, $k3 \times 3$	256	ReLu6	$40 \times 40 \times 256$
$40 \times 40 \times 256$	SPP, $k5 \times 5$, 9×9 , 13×13	512		$20 \times 20 \times 512$

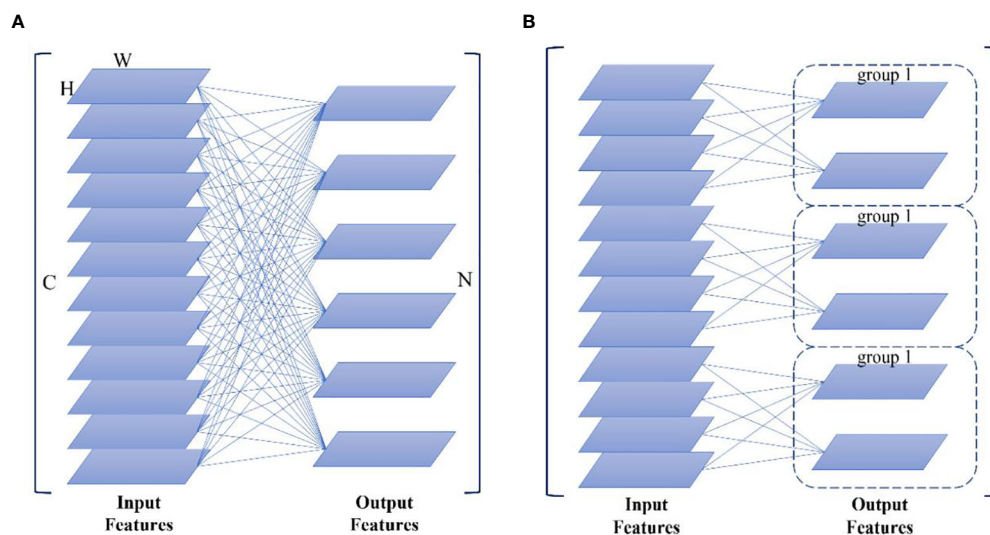


FIGURE 5
Convolution blocks: (A) standard convolution, (B) group convolution.

annotated dataset was randomly divided into a training set, a validation set and a test set at a ratio of 8:1:1. The training set was used to train the model, the validation set was used for iterative optimization during model training, and the test set was used to test the accuracy of the optimal model.

5 Algorithm comparison and experimental analysis

The hardware environment of the experimental platform in this paper is a high-performance server, which is configured as follows: Intel Core i7 processor, CPU main frequency is 3.6 GHZ, 16 GB RAM, and equipped with four Nvidia Geforce GTX 1080Ti

graphics cards with 11 GB of video memory. The software environment is the Ubuntu 18.04 operating system, Python 3.7, and CUDA 11.0.

The relevant training parameters in the experiments are shown below. The gradient descent optimizer used to update the convolution kernel parameters is Adam, the optimizer momentum is 0.937, the maximum learning rate is 0.001, the batch size of training is 16, the weight attenuation coefficient is 0.0004, and the epoch (training iteration cycle) is 200.

To verify the superiority of the proposed algorithm, the following experiments are conducted: (1) comparative performance analysis of underwater vision detection algorithms. (2) The AUV deploys a visual inspection system and tests the relevant performance in an underwater environment.

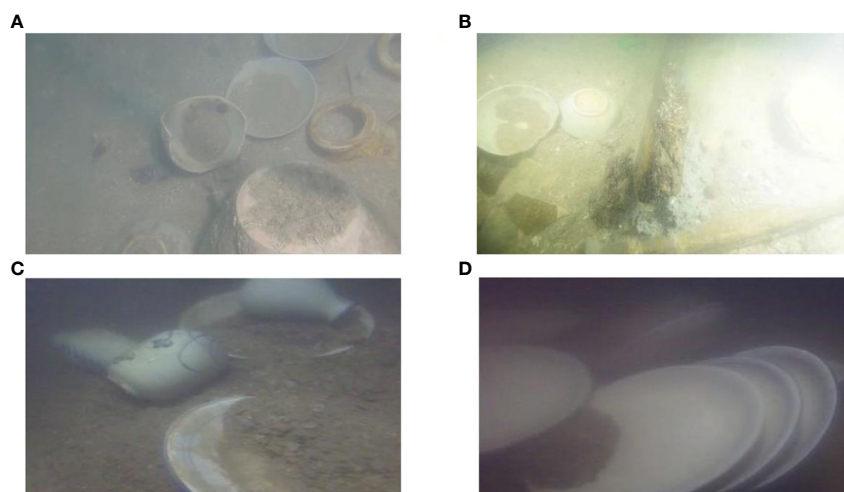


FIGURE 6
Example datasets: (A, B) real underwater target data, (C, D) simulated underwater target data.

5.1 Underwater vision inspection algorithm performance comparison analysis

To better validate the detection performance of the proposed underwater vision detection algorithms in this paper, three typical strategies are selected: DPM+SVM (Felzenszwalb et al., 2009), YOLO algorithm (Bochkovskiy et al., 2020) (Jocher, 2020), and Mask R-CNN (He et al., 2017) are compared with the algorithm in this paper.

The detection results of each strategy are shown in Figures 7A–D. Our method benefits from the optimization of the backbone feature extraction network, which can detect all targets even when they appear to be buried and overlapped. And the algorithm is robust. The DPM+SVM algorithm is the least effective, and the model generalization becomes poor when the target presents multiple angles or occlusion, and cannot be effectively detected, and the algorithm has a high rate of missed detection. The YOLO algorithm appears to miss detection when the target buried part is too large, and the robustness of the algorithm is poor. Mask R-CNN detection is obviously better than DPM+the SVM algorithm and YOLO algorithm, and can detect all targets even when they are buried and overlapped, but the confidence of the algorithm is lower than this method. The algorithm in this paper has better recognition than DPM+SVM, YOLO, and Mask R-CNN.

To better observe the superiority of each module of the algorithm proposed in this paper, the YOLO and Mask R-CNN algorithms with better detection effects were selected and three sets of comparison experiments were conducted using the UCR dataset as follows: the first group shows the performance comparison of the detection network; the second group shows the performance comparison of the algorithm with the addition of the CLAHE image enhancement module; the third group shows the performance comparison of the algorithm with the addition of the FCLAHE image enhancement module. To evaluate the algorithm performance, five general performance metrics are introduced: Precision, Recall, F1, mean Average Precision (mAP), and Parameters for evaluating the algorithm performance. The performance metrics of the three groups of algorithms are shown in Table 2.

This method outperformed other algorithms in all indicators, with 91.2%, 90.1%, 87.9%, and 88.3% for precision, recall, F1, and mAP, respectively, for the following analytical reasons. (1) The backbone network of the underwater target detection algorithm proposed in this paper uses a combination of inverse residual blocks and SE attention mechanism with feature correction capability in the channel direction, which enables the network to enhance the effective feature channels and achieve adaptive calibration of the feature channels. The algorithm helps to distinguish the foreground and background of the image more clearly, and the detection results of the model are more accurate. In the UCR dataset test, the single underwater target detection network detects better than the original YOLO algorithm and Mask R-CNN algorithm. In the second and third groups of comparison experiments, the detection network in this paper has higher detection performance improvement and better compatibility with image enhancement modules compared to the two comparison algorithm networks. (2) The FCLAHE image enhancement model designed in this paper reduces the probability of color bias in the CLAHE algorithm by fusing multiple color spaces and improves the underwater image enhancement performance. Compared with the CLAHE model, the image enhancement model designed in this paper improves the network detection performance, with 4.8%, 4.7%, 2.6%, and 2.9% improvement in precision, recall, F1, and mAP, respectively. The experimental data show that the FCLAHE image enhancement model has a more positive effect on underwater target recognition.

5.2 AUV vision inspection system performance testing

To better test the performance of the visual detection system in this paper, the system was deployed to the actual embedded computer on board the AUV, and the algorithm performance was tested using real underwater images taken at the underwater archaeological site.

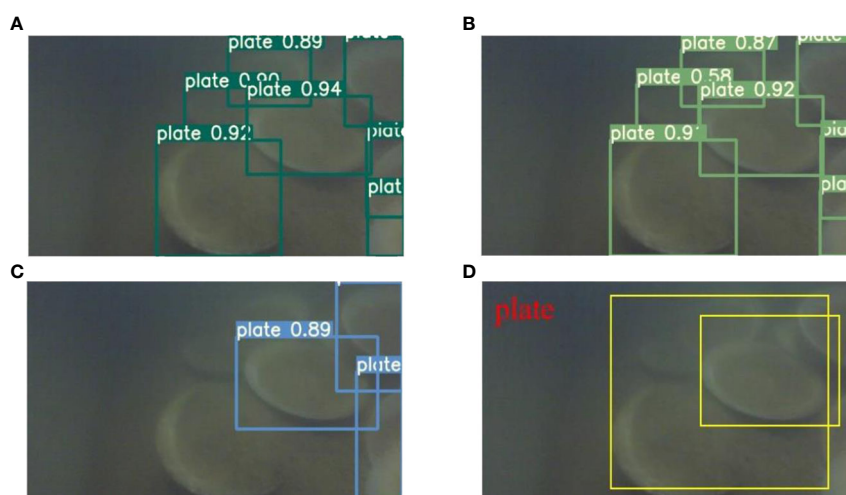


FIGURE 7
Detection results: (A) Ours, (B) DPM+SVM, (C) YOLO, (D) Mask R-CNN.

TABLE 2 Algorithm performance metrics.

Algorithm	Precision(%)	Recall(%)	F1(%)	mAP(%)	Parameters(M)
YOLO (Jocher, 2020)	81.8	80.4	81.5	81.4	45.5
Mask R-CNN(He et al., 2017)	86.4	85.3	85.5	85.3	65.1
SS-net	86.1	85.3	84.7	84.9	10.8
CLAHE+YOLO(Jocher, 2020)	84.5	82.8	83.2	82.6	47.0
CLAHE+Mask R-CNN(He et al., 2017)	89.2	88.2	87.2	87.4	66.2
CLAHE+SS-net	89.2	88.3	87.1	87.5	12.3
FCLAHE+YOLO(Jocher, 2020)	86.4	83.9	85.1	84.2	48.2
FCLAHE+Mask R-CNN(He et al., 2017)	90.3	89.7	87.8	88.0	67.5
FCLAHE+SS-net	91.2	90.1	87.9	88.3	13.3

The detection network of this paper in the experiment is called SS-net.
The bold value is the best value in the comparison.

5.2.1 Introduction of the AUV experimental platform

AUVs are commonly used equipment in seafloor exploration and have an important role in underwater-related research (Xu et al., 2016). An AUV with an online target detection function was developed for the search of underwater artifacts, shipwrecks, and other undersea targets, the main parameters of the AUV are shown in Table 3. The conceptual design of this AUV is shown in Figure 8.

The camera is arranged on the bottom of the AUV to facilitate the filming of subsea targets. To improve the underwater lighting effect, one lighting lamp is arranged at the bow and one at the stern of the AUV. The bow light was designed to be tilted backward to better illuminate the camera, as shown in Figure 9.

5.2.2 Performance test

High-power, high-load computing platforms are difficult to apply in AUVs due to space and power constraints. The Nvidia Jetson TX2 image edge computing device was selected as the AUV embedded platform based on actual requirements. The reasons are as follows: (1) The embedded platform is 50×87 mm in size and consumes only 7.5 W under regular load, meeting the power consumption and size requirements of AUVs; (2) The CPU adopts ARM Cortex-A57, and the GPU adopts Nvidia Pascal GPU with 256 CUDA cores to meet the requirements of algorithm operation.

The vision inspection system in this paper was deployed to the actual Nvidia Jetson TX2 on board the AUV, and performance tests were conducted using images obtained from the underwater archaeological site. The experiment was conducted at the shipwreck site of the Yuan Dynasty, situated on the southeast coast, at a depth of 30 meters underwater. The wreck measures 13.07 meters in length and 3.7 meters in width. The employed AUV camera examined an area spanning 48 square meters. The site contains an array of cultural artifacts, including porcelain plates, bowls, and incense burners, which constituted the primary targets of this test. The empirical results of this study are illustrated in Figure 10. This method has achieved effective detection results. The implementation of the channel attention mechanism within the inverse residual block has enabled the proposed algorithm to exhibit a high degree of robustness, particularly in circumstances where the cultural relics are obscured or partially buried.

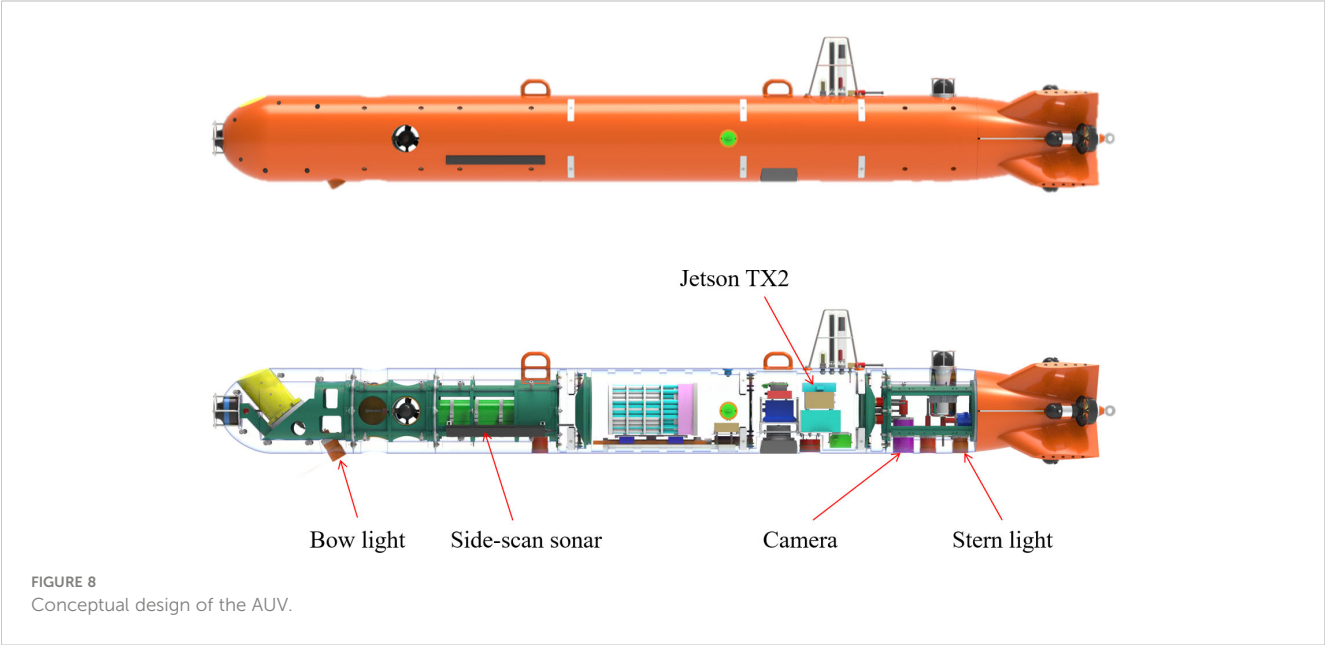
To assess the real-time performance of the proposed algorithm in target detection, two superior strategies from Section 5.1, namely FCLAHE+YOLO and FCLAHE +Mask R-CNN, were selected for comparative analysis. Concurrently, two performance metrics—Frame Per Second (FPS) and Parameters—were introduced to facilitate a quantitative evaluation of the algorithm. The system performance metrics are presented in Table 4. This algorithm detects the frame rate FPS higher than the FCLAHE+YOLO algorithm and FCLAHE +Mask R-CNN algorithm in the actual test. The reasons for the analysis are as follows: (1) This algorithm uses group convolution instead of the original standard convolution, making the number of model parameters significantly reduced; (2) By introducing the inverse residual block and use strategy, the memory space occupation is reduced during inference, and the GPU inference acceleration is improved. This algorithm achieves a detection speed of 20 frames per second in images with a resolution of 1280×720 and 16 frames per second in images with a resolution of 1920×1080, which basically meets the requirements of real-time detection.

6 Conclusions and discussions

To achieve real-time online detection of underwater targets that meet the requirements of AUV applications with limited image quality and processor computing performance, in this paper, a vision-based lightweight underwater target detection algorithm is designed. To improve underwater imaging, an image enhancement

TABLE 3 Main parameters of the AUV.

Parameters	Value
Maximum operating depth	1000 m
Cruising speed	2 knots
Maximum speed	5 knots
Diameter	φ350 mm
Length	3.6 m
Weight in air	250Kg



module is added in front of the detection network, and an FCLAHE enhancement algorithm with fused multicolor space is designed for underwater image enhancement. In the detection algorithm backbone network, a new lightweight and efficient feature extraction network is designed using group convolution and inverse residual blocks to ensure the feature extraction depth while reducing the number of model parameters. This algorithm is lightweight and suitable for deployment on image edge computing devices. To verify the effectiveness of this algorithm, the UCR dataset is built to train and test the algorithm. The experimental results show that the algorithm achieves scores of 91.2%, 90.1%, 87.9%, and 88.3% for precision, recall, F1, and mAP, respectively. It is also noticeable that this method has been integrated into the embedded GPU platform and deployed to the AUV system in the real test scenario. The average computational time is 0.053 s, which satisfies the requirements of real-time object detection.

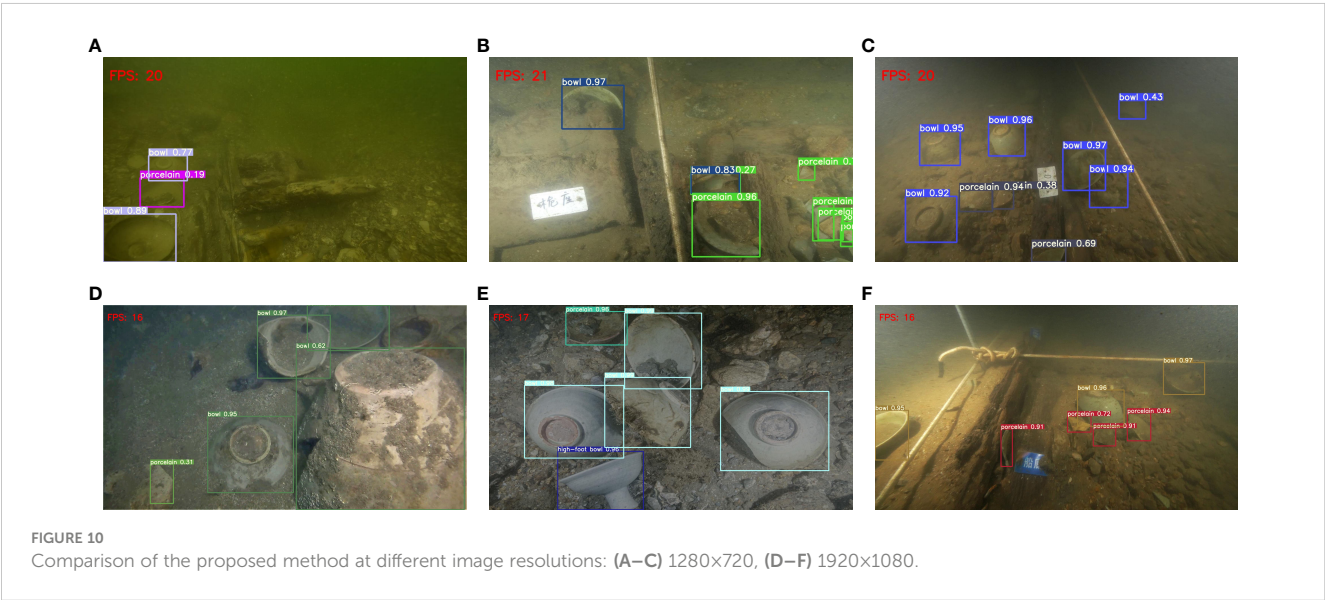
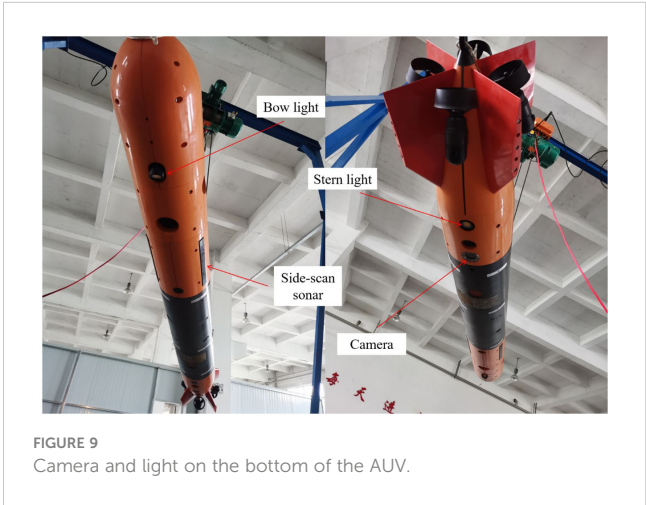


TABLE 4 Algorithm performance metrics.

Algorithm	mAP (%)	Parameters (M)	Input shape	FPS
FCLAHE+YOLO(Jocher, 2020)	84.2	48.2	1280×720	12
			1920×1080	9
FCLAHE+Mask R-CNN(He et al., 2017)	88.0	67.5	1280×720	7
			1920×1080	5
FCLAHE+SS-net	88.3	13.3	1280×720	20
			1920×1080	16

The bold value is the best value in the comparison.

The algorithm proposed in this paper has high detection accuracy and computational efficiency, which can satisfy the requirements of detecting artifact targets in underwater environments. The lightweight idea of this algorithm can also be applied to other underwater target detection tasks. However, there are still some problems, such as detection failures when marine organisms are attached to the target. In future research, we will expand richer datasets to further improve the generalization ability of the algorithm model. It should also be noted that instead of choosing the NAS-like architecture search strategy to obtain the optimized models in the designed hardware platform, we design a new strategy to seamlessly integrate the MBConv and Fused-MBConv together based on their structural characteristics, which can take full advantage of the hardware performance in the prediction process. Concretely, the authors put the Fused-MBConv block in the shallow layer of the network and the MBConv block in the deep layer of the network.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

References

- Aggarwal, J. K., and Ryoo, M. S. (2011). Human activity analysis: a review. *ACM Computing Surveys (Csur)* 43 (3), 1–43. doi: 10.1145/1922649.1922653
- Ancuti, C., Ancuti, C. O., Haber, T., and Bekaert, P. (2012). “Enhancing underwater images and videos by fusion,” in *Proceedings of the IEEE conference on computer vision and pattern recognition*. (Providence, RI, USA: IEEE), 81–88.
- Bochkovskiy, A., Wang, C. Y., and Liao, H. Y. M. (2020). YOLOv4: optimal speed and accuracy of object detection. *arXiv preprint arXiv 2004.10934*. doi: 10.48550/arXiv.2004.10934
- Felzenszwalb, P. F., Girshick, R. B., McAllester, D., and Ramanan, D. (2009). “Object detection with discriminatively trained part-based models,” in *IEEE Transactions on Pattern Analysis and Machine Intelligence (IEEE)*, Vol. 32, 1627–1645.
- Guo, W., Zhang, Y., Zhou, Y., Xu, G., and Li, G. (2021). Underwater real-time target detection based on key frame and model compression. *J. Physics: Conf. Ser.* 1800 (1), 012001. doi: 10.1088/1742-6596/1800/1/012001
- He, K., Gkioxari, G., Dollár, P., and Girshick, R. (2017). Mask r-cnn. *Proc. IEEE Int. Conf. Comput. Vision*, 2961–2969. doi: 10.1109/ICCV.2017.322
- Howard, A., Sandler, M., Chu, G., Chen, L. C., Chen, B., Tan, M., et al. (2019). Searching for mobilenetv3. *Proc. IEEE/CVF Int. Conf. Comput. Vision*, 1314–1324. doi: 10.1109/ICCV.2019.00140
- Hu, J., Shen, L., and Sun, G. (2018). “Squeeze-and-excitation networks,” in *Proceedings of the IEEE conference on computer vision and pattern recognition*. (Salt Lake City, UT, USA: IEEE), 7132–7141.
- Jocher, G. (2020). YOLOv5. Available at: <https://github.com/ultralytics/yolov5>.
- Lei, F., Tang, F., and Li, S. (2022). Underwater target detection algorithm based on improved YOLOv5. *J. Mar. Sci. Eng.* 10 (3), 310. doi: 10.3390/jmse10030310
- Lin, S., and Zhao, Y. (2020). Review on key technologies of target exploration in underwater optical images. *Laser Optoelectronics Prog.* 57 (6), 060002. doi: 10.3788/LOP57.060002
- Manley, J. E. (2016). Unmanned maritime vehicles, 20 years of commercial and technical evolution. *OCEANS 2016 MTS/IEEE Monterey*, 1–6. doi: 10.1109/OCEANS.2016.7761377
- Moniruzzaman, M., Islam, S. M. S., Bennamoun, M., and Lavery, P. (2017). “Deep learning on underwater marine object detection: a survey,” in *Proceedings of the 18th International Conference on Advanced Concepts for Intelligent Vision Systems*. (Springer Cham), 150–160.
- Qiang, W., He, Y., Guo, Y., Li, B., and He, L. (2020). Exploring underwater target detection algorithm based on improved SSD. *Xibei Gongye Daxue Xuebao/Journal Northwestern Polytechnical Univ.* 38 (4), 747–754. doi: 10.1051/jnwpu/20203840747

Author contributions

GX designed the study, analyzed the data and wrote the initial draft of the paper. DZ and LY performed the research, analyzed the data and wrote the initial draft of the paper. WG designed the study and revised the initial draft of the paper. ZH collected the data and revised the initial draft of the paper. YZ conceived of the research, contributed the central idea and revised the initial draft of the paper. All authors contributed to the article and approved the submitted version.

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- Song, P., Li, P., Dai, L., Wang, T., and Chen, Z. (2023). Boosting r-CNN: reweighting r-CNN samples by RPN's error for underwater object detection. *Neurocomputing* 530, 150–164. doi: 10.1016/j.neucom.2023.01.088
- Valdenegro-Toro, M. (2016). "End-to-end object detection and recognition in forward-looking sonar images with convolutional neural networks," in *2016 IEEE/OES Autonomous Underwater Vehicles (AUV)*. (Tokyo, Japan: IEEE), 144–150.
- Xiong, Y., Liu, H., Gupta, S., Akin, B., Bender, G., Wang, Y., et al. (2021). "Mobiledeets: searching for object detection architectures for mobile accelerators," in *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*. (Nashville, TN, USA: IEEE), 3825–3834.
- Xu, G., Liu, K., Zhao, Y., Li, S., and Wang, X. (2016). Research on the modeling and simulation technology of underwater vehicle. *OCEANS 2016-Shanghai*, 1–6. doi: 10.1109/OCEANSAP.2016.7485607
- Xu, M., Qiu, S., Jin, W., Yang, J., and Guo, H. (2019). Radon transform detection method for underwater moving target based on water surface characteristic wave. *Acta Optica Sin.* 39 (10), 25–37. doi: 10.3788/AOS201939.1001003
- Yan, J., Zhou, Z., Su, B., and Xuanyuan, Z. (2022). Underwater object detection algorithm based on attention mechanism and cross-stage partial fast spatial pyramidal pooling. *Front. Mar. Sci.* 2299. doi: 10.3389/fmars.2022.1056300
- Yeh, C. H., Lin, C. H., Kang, L. W., Huang, C. H., Lin, M. H., Chang, C. Y., et al. (2021). "Lightweight deep neural network for joint learning of underwater object detection and color conversion," in *IEEE Transactions on Neural Networks and Learning Systems* (IEEE), Vol. 33, 6129–6143.
- Zacchini, L., Franchi, M., Manzari, V., Pagliai, M., Secciani, N., Topini, A., et al. (2020). "Forward-looking sonar CNN-based automatic target recognition: an experimental campaign with FeelHippo AUV," in *2020 IEEE/OES Autonomous Underwater Vehicles Symposium (AUV)*. (St. Johns, NL, Canada: IEEE), 1–6.
- Zeng, L., Sun, B., and Zhu, D. (2021). Underwater target detection based on faster r-CNN and adversarial occlusion network. *Eng. Appl. Artif. Intell.* 100, 104190. doi: 10.1016/j.engappai.2021.104190
- Zhang, W., Zhuang, P., Sun, H. H., Li, G., Kwong, S., and Li, C. (2022). Underwater image enhancement via minimal color loss and locally adaptive contrast enhancement. *IEEE Trans. Image Process.* 31, 3997–4010. doi: 10.1109/TIP.2022.3177129

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