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Current Status and Prospects of Metrological Calibration Technologies for Underwater Robot Environmental Perception Systems

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Current Status and Prospects of Metrological Calibration Technologies for Underwater Robot Environmental Perception Systems

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Abstract: The metrological calibration of environmental perception systems for underwater robots serves as the technical foundation for ensuring the accuracy, reliability, and international comparability of marine observation data. As for now, major problems of this field are the interference brought about by complicated underwater environment to acoustic and optical sensing measurement, and the disruption of traceability chain due to it. Even though there's relative maturity in the laboratory-based reference calibration for acoustic and optical sensors, field calibration relies mainly on some operational procedures and lacks universal standard specifications and high-precision dynamic transfer techniques. In the future, technology will concentrate more on creating an intelligent underwater metrology system. Using Digital Twin to achieve virtual simulation and optimization of calibration process, utilizing Artificial Intelligence algorithm for autonomous prediction and compensation of sensor error, using new infrastructure such as Mobile Calibration Platform for in-situ value transfer. And these achievements will help the development of underwater metrology to progress from single-sensor calibrations to systematic, online, as well as intelligent calibrations, and ultimately give strong technological backing to the accurate recognition ability of marine equipment.

1. Introduction

The ocean takes up the vast majority of the earth's surface. It not only plays an important role in regulating the earth's climate but is also a reservoir for many kinds of living species and minerals. It's also very important for national security and economic development strategy. In such a vast and complex world, Unmanned Undersea Vessels (UUVs) [1] are the main intelligent tools for people to explore, develop, and make use of the sea. They are commonly used in seabed resource investigation, maintenance of underwater buildings, marine scientific research, national defense and other areas. According to the propulsion mode, control mode, operating features, they can be systematically classified as.(Table 1).

Table 1. Classification of Unmanned Underwater Vehicles (UUVs)

Classification	Control/Propulsion Method	Typical Examples
ROV	Powered and remotely operated in real-time via an umbilical cable from the mother ship	Hyper Dolphin（Figure 1）Jason2/Medea（Figure 2）
AUV	Untethered, relying on built-in power source, operates autonomously based on pre-set missions Untethered	REMUS 6000（Figure 3）China's "Qianlong" Series AUVs（Figure 4）
HOV	Manned and piloted	"Fendouzhe"Manned

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Hybrid UUV	Hybrid (tethered/autonomous)operation using a micro-umbilical	Submersible（Figure 5） Nereus（Figure 6）

Figure 1. Hyper Dolphin

Figure 2. Jason2/Medea

Figure 3. REMUS 6000

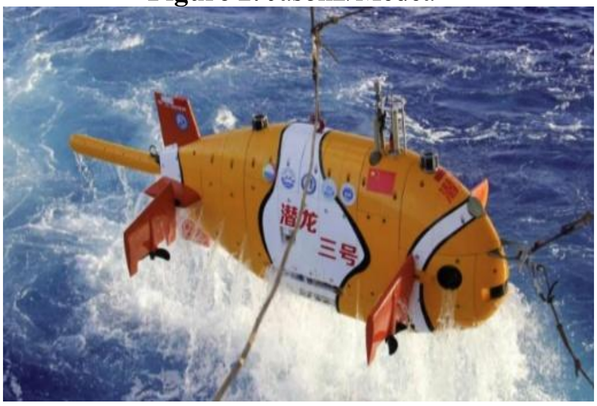

Figure 4. China's "Qianlong" Series AUVs

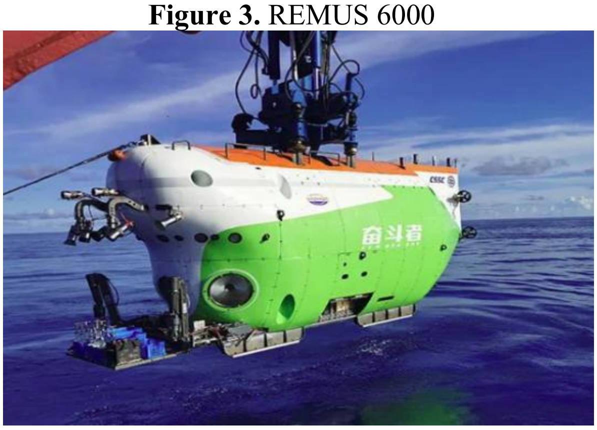

Figure 5. "Fendouzhe"Manned Submersible

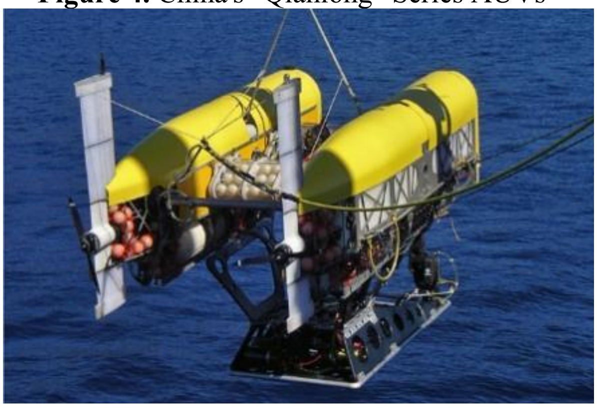

Figure 6. Nereus

These effective, correct task completions are mostly reliant upon the accuracy and correctness of the environment's perception and comprehension by the underwater robotic vehicle.

Underwater robot environmental perception system is mostly constituted by many sorts of sensors. Primarily acoustic systems, such as multibeam echosounders, side-scan, forward-looking sonars, Acoustic Doppler Current Profilers (ADCP), and imaging sonar systems. Optical systems, such as underwater cameras [2], lidar, and spectrometers. Auxiliary sensors, such as magnetometers, depth, CTD profilers. Acoustic systems use acoustic wave propagation characteristics in water for medium to long distance detection and identification purpose,whereas,it is also used where higher resolution and clear visuals are needed close up, optical systems provides.

But the real marine environment has many high pressure, low temperature, corrosion and complex hydrodynamic disturbance[3]. The above conditions are very inconvenient to the lasting operating stabilities and measurements accuracy of sensor. More unique is that the propagation laws for underwater sound and light are controlled by the combined effects of temperature, salinity, pressure, and many other fields. Their physical properties vary a great deal from what we find in air, and so it would seem almost certain that the sensor data will be contaminated with deviations and uncertainties. Like in water, light is severely cut back and scattered easily; sound has a speed that varies according to whether you're in the different temperatures, salinities or depths. These factors make it difficult to take the results of the calibration carried out under the perfect conditions of a laboratory and apply them to real ocean situations.

At present, ensuring the correctness of underwater robot perception systems is still an engineering science problem that has not been solved yet. Traditional methods based on laboratory calibration and static parameter compensation find it hard to follow the dynamic change of the actual marine environment. There is no standard technical framework and norms for the spatiotemporal coordination and system-level calibration of multiple sensors [4].

This article, taking account of the actual application requirements and complex environment of underwater robot perception systems, comprehensively sorts out the latest research status and development trends of the key metrology calibration technologies. and explores them from several dimensions such as sensing technologies, calibration methods, systems integration, and future paradigms so as to supply theoretical references and technical pathways for the improvement of the perception performance of China’s underwater equipment and the quality of marine observation data.

2. Development Status at Home and Abroad

Metrological calibration technologies for underwater robots' environmental perception systems represent a key link involved in the overall quality of marine observation data. Research institutes across the world have begun to pay attention to this field of study as early as several years ago. Under the influence of various types of underwater environment and varying needs on applied products, every country’s focus is different as well when developing this area.

2.1. International Development Status

The US and European countries, which are the world’s top marine high-tech powerhouses, continuously establish more and more comprehensive laboratory calibration systems within the field of acoustic sensors. , like the National Institute of Standards and Technologies (NIST), which mostly does research on underwater acoustic metrologic referencing, has set up underwater absolute calibration techniques, including the free-field reciprocity method and also included coupling reciprocity methods which then create an accurate measuring reference foundation for underwater sound sensors. At the same time， the US Woods Holt Oceanographic Insititute (WHOI) had also been developing pressure chambers which can create the 6000m deep oceanic pressured environment[6], providing acritical platform to reveal the acoustic equipment’s performance under extremenvironmental conditions. As for the Norwegian Defence Research Establishment (FFI) field calibration technology for hydroacoustic sensors arrays, it proposes performance evaluation methods using standard spherical targets[7] as a support for equipment calibration in the real marine environment.

Optical sensor calibration: MBARI in the US has developed a laser scanning imaging system that can perform high-definition imaging and 3D terrain reconstruction of objects in low-visibility underwater environments[8]. This greatly enhances the visual perception capabilities of underwater robots. the Norwegian University of Science and Technology(NTU) has developed a hyperspectral imagery[9] mounted on autonomous underwater vehicles (AUV), it can be used for in-situ recognition and mapping of seabed Sediment and Mineral Chemical Composition and provide an important technical means for deep sea scientific research work.

Field calibration is an important supplement to laboratory calibration and has made many advances in recent years. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) has carried out study on dynamic sensor calibration through underwater vehicles and put emphasis on tackling calibration problems during movement.

Table 2. International Development Status

Institution	Research Outcomes
National Institute of Standards and Technology (NIST)	Established absolute calibration methods including the free-field reciprocity method and coupler reciprocity method
Woods Hole Oceanographic Institution (WHOI)	Developed pressure chamber test devices capable of simulating deep-sea high-pressure environments at 6000 meters
Norwegian Defence Research Establishment (FFI)	Proposed system performance evaluation methods based on standard spherical targets
Monterey Bay Aquarium Research Institute (MBARI)	Developed laser scanning imaging systems capable of high-definition imaging and 3D terrain reconstruction in low-visibility underwater environments
Norwegian University of Science and Technology (NTNU)	Developed hyperspectral imaging systems integrated with Autonomous Underwater Vehicles (AUVs)
Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Conducted research on dynamic sensor calibration based on underwater vehicles

2.2. Domestic Development Status

Although China's underwater sensor metrological calibration technology began relatively later compared to its international counterparts, it is catching up fast. Significant progress has also been made in many special areas. In the field of acoustic measurements, the Institute of Acoustics from the Chinese Academy of Sciences set up a large scale anechoic tank laboratory, focusing on low frequency calibrations for hydro acoustical sensors, which provided valuable laboratory infrastructure for underwater acoustic measurements in China. High Pressure Environmental Calibration Device from Harbin Engineering University With a maximum of 50MPa Working Pressure is an important tool for deep sea transducer's High Pressure Calibration moreover, China ship Science and Research center have also made a breakthrough in acoustic reference standard study， and successfull developed the series of standard hydrophones and acoustic sources, which is greatly contribute to the establishment of china`s own domestic underwater acoustic measurement traceability system.

In the calibration of optical sensors, several domestic colleges and universities have put forward new kinds of calibration techniques. Using underwater camera calibration method based on multi-medium refraction model of Zhejiang University [10] which effectively improves the accuracy of underwater visual measurement. Tianjin University created an underwater spectral radiation calibration system, it can correctly examine the radiation traits of underwater optical sensors. Harbin Engineering University created an underwater camera calibration algorithm [11] relying on a refraction compensation model, it can alleviate calibration mistakes brought about by the water-glass-air multi-interface refraction effect: Ocean University of China undertook research into the modeling and exploration of the Modulation Transfer Function (MTF)[12] for underwater imaging, and utilized the Monte Carlo method to form a theoretical MTF model for underwater optical images, which can be used as the basis for evaluating and improving the image quality of an underwater camera.

Regarding field calibration technologies, Ocean University of China has been involved in studies about mobile calibration tech about hydroacoustic sensor using unmanned surface vessel, which results in fast calibration of underwater acoustical equipment in shallow sea waters. Northwestern Polytechnical University presented an online calibration method of the underwater sensor networks, the sensor parameters could be self-corrected through mutual comparison with adjacent node [13] Harbin Engineering University came up with a calibration system that can be placed on unmanned underwater robots, which enables sensors to get real-time adjustment while being used, thus making the practical usability and adaptability of calibration technology better.

Table 3. Domestic Development Status

Institution	Research Outcomes
Institute of Acoustics, Chinese Academy of Sciences	Established a large anechoic tank laboratory for low-frequency calibration of hydroacoustic sensors
Harbin Engineering University	Developed a high-pressure environmental calibration device with maximum working pressure of 50 MPa
China Ship Scientific Research Center	Developed series of standard hydrophones and acoustic sources
Zhejiang University	Proposed an underwater camera calibration method based on multi-medium refraction model
Tianjin University	Developed an underwater spectral radiation calibration system
Harbin Engineering University	Developed an underwater camera calibration algorithm based on refraction compensation model
Ocean University of China	Established theoretical MTF model for underwater optical imaging using Monte Carlo method
Ocean University of China	Conducted research on mobile calibration technology for hydroacoustic sensors based on unmanned surface vessels
Northwestern Polytechnical University	Proposed online calibration method for underwater sensor networks
Harbin Engineering University	Developed underwater robot-mounted calibration system

3. Underwater Acoustic Perception System Calibration Technology

Underwater acoustic perceptual systems are the main methods of marine environmental detection and target perception, which determines the reliability and accuracy of the observational data based on the metrological calibration quality. Acoustic signals underwater spread in the complex water area environment, with multiple physical fields like water temperature, salt concentration, pressure, etc., coupling affects the transmission of acoustic signals, making it hard for acoustic sensor calibration to proceed. As for now, underwater acoustic calibration tech has developed into a technical system made up of laboratory reference calibration and maritime field calibration, including measurement and traceability of major parameters such as source level, receiving sensitivity and directivity char.

Laboratory calibration refers to the traceability of the entire system. Here, anechoic tanks, made by putting down very good at soaking up noise materials, try to copy the noise field where sounds don't bounce off much, so they can cut out those bounces from what they're measuring. This gives them the perfect place to check how sensitive their special underwater microphones, called hydrophones, are at picking up sounds[14]. In such an environment, the reciprocity calibration can be used for the absolute calibration of hydrophone receiving sensitivity [15]. The IEC has a set of standards and experimental procedures that specify how to implement hydrophone calibration. take an example standard like IEC 60565-2, they lay out the actual steps and requirements of calibrating hydrophones by the use of the reciprocity method in an anechoic tank. The unique advantage of the reciprocity calibration method is that it only requires the measurement of electrical quantities, without any pre-calibration of a reference hydrophone to obtain the absolute sensitivity of a hydrophone[15]. Under controlled laboratory conditions, influencing factors such as the effective radius of the auxiliary transducer, sound field symmetry, immersion time and oxygen content, and attenuation corrections [15] are accurately accounted for through the reciprocity calibration method, which allows for quite accurate measurements.

Simulation of deepsea environment requires pressure chamber calibration device as well. For example, the high pressurization test chamber of China ship scientific research center can achieve the pressure of 100MPa, which can achieve the ultra high pressure under sea water depth of 10,000 meters.

research also shows that underwater acoustic transducer has large change in underwater acoustic transducer performance is mainly manifested in change in resonant frequency, and change in receiving sensitivity. are all a product of the high pressure effect on the transducer material modulus, structural deformations and sealing performances. So it can be seen that the pressure characteristic calibration of the transducer in a high-pressure environment is a key factor for normal use in the deep sea. This calibration work can illustrate the responding condition of transducers of different pressures, so as to give data support to deep-sea exploration and measurement.

While laboratory calibrations are the basis of how we can trace the values from our measurements, there is often a great difference in how the laboratories perform compared to what a sensor would actually see out in the marine environment. this has to be verified and compensated with field calibration. At present, the standard-sphere-target method is the most widely applied technique for calibrating the field.[16] This method uses a standard sphere with a known target strength as a reference target. For example, it can be a tungsten carbide steel sphere with a diameter of 38.1 mm, and its target strength is about -35.4 dB at 200 kHz. To evaluate the performance of both transmits and receives in the acoustic perception system, measuring and analyzing the echo signals of the standard spheres are performed [17]: But it is sensitive to sea state conditions and its measurement is much worse in rough seas [18]:

To help out the field calibration, they came up with a lot of cool ways. Take the transducer reciprocity method for example: It extends the laboratory principle of reciprocity to the field. Using 3 transducers and adding an on-line measurement of environmentals as part of the calibration to correct for sound speed can yield fairly accurate calibrations in complex ocean conditions[19]. Additionally, seabed fixed calibration reference ranges will be created for a new kind of long-term, stable calibrations. Institutions such as the Monterey Bay Aquarium Research Institute (MBARI) in the U.S. also carry out relevant experimental studies. These institutions established stable and controllable acoustic benchmarks on the seabed so that acoustic sensors could be calibrated periodically and continuously to obtain precise calibration results.

But there are still many problems that have not been successfully solved and have become the difficulties of underwater acoustics at this time. firstly, there are a lot of errors caused by different speeds of sound on different locations and times and multipath propagation. Environmental noise is another major source of error due to spatiotemporal inhomogeneity, causes sound-ray curvature and convoluted sound travel path that causes higher chance of measurement errors;[18] Multipath Propagation effect happens when the sound signals reach the receiving area from many paths. This results in signal distortion and aliasing. Environmental noise consists of biological noise, vessel noise and the ocean's ambient background noise. It interferes with the reception and processing of valid signals[20]: It is difficult to be so precise in this complex marine environment[21]: Secondly, the impact of deep-sea high pressure on sensor performance is multifaceted, including changes in the material's elastic modulus, risk of electronic component failure, and reliability of seals. Therefore, it is crucial to fully consider factors like pressure sensitivity, sealing performance, and material deformation during the calibration process [22]. and finally, it's difficult to establish a traceability chain of traceable measurements from field calibration back to the laboratory benchmark to verify that the accuracy of the field measurement can be traced back to national or international measurement standards, a recognized tough technical problem internationally.

Then to deal with them in a study direction that we should do further as the followings. we must push first to integrate fully environmental parameters into measurements. Utilizing real-time temperature, salinity, and depth data received from a CTD or similar integrated sensor, a dynamic sound speed profile model is constructed for feedforward compensation to sonar ranging/positioning. so that time-variant hydrographic environment-induced errors can be suppressed well, which means to give the acoustic system an "effective environmental sensing module" so that it can actively adapt to the marine environment. The second point is regarding how deep sea high pressure affects sensor performance, there needs to develop new kinds of pressure-proof material when it comes to the physical part, but in the calibration methods they also need to introduce a systematic set of "pressure"-related performance response. Perform systematic characterization with varying hydrostatic pressures in the lab and form a so called "pressuresensitivity"-Correction databank. This turns out difficult to predict pressure's impacts into the system error that's online fixable, so it makes measure deeper under-ocean more reliable. And there are also hybrid calibarion networks composed of both "mobile platforms" and "fixed benchmarks". Dedicated calibration AUV's could function as "mobile calibration stations" taking laboratory standards to operational sites. Acoustic reference beacons placed on the seabed in key sea areas would behave like stable" value anchors" offering long-term, easy comparison services to the vehicles in their area(Figure 7).

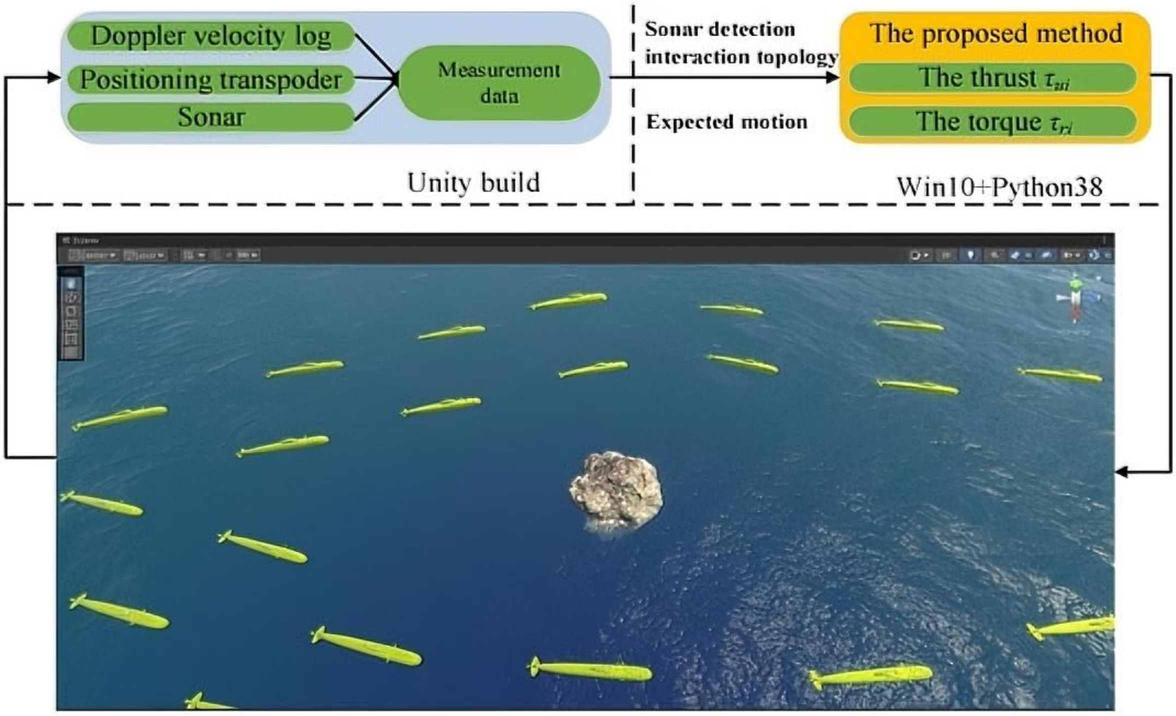

Figure 7. Unity Simulation[23]

4. Underwater Optical Perception System Calibration Technology

Underwater optical perception system is an important way of observation and target identification for detailed marine environment, which can obtain underwater visual information by means of optical perception instruments such as visible light, lasers [24] But there are many complicated reasons for affecting its result. Light absorbed or scattered in water, refraction undersea and variation of light in surroundings all cause large deviations on optical measurement and will be seriously harmful to perception system [25]. Well then, making a scientific and useful calibration tech system that works well for underwater robot's optical sensing instruments would be key if we want underwater robots to sense the environment better [26].

Calibration of underwater optical systems should pay attention to many aspects: geometric calibration; Radiometric Calibration; Color Calibration Geometric parameters include the parameters related to the intrinsic parameters of the focal length, the center point of the main image point, and the distortion coefficient. Extrinsic parameters, which define the position of the sensor relative to the carrier [27]. Radiometric Parameters are response linearity, dynamic linearity and noise linearity. color parameters include white balance, color reproduction accuracy and as well as that, there is a quantitative measurement of performance metrics like the MTF (modulation transfer function), signal to noise ratio etc [25].

Controlled calibration, as performed in any controlled laboratory environment, uses controlled water tanks as a set up for basic calibration. Geometric calibration mostly adopts high-precision 2D or 3D calibration targets. Using the camera to take pictures of the target in different poses and calculating the camera's intrinsic parameters and distortion coefficients. [27] However, the refraction at the water-glass-air interface causes refraction phenomenon and does not apply to traditional pinhole model, therefore it is necessary to introduce accurate modeling methods based on the principle of optical refraction[28].

Radiometric Calibration uses things like Integrating Spheres and standard light source panels. We look at the response of a camera to a target of a known radiance, so we make a relationship of a pixel and a value of radiance. color calibration needs to adopt standard color chart,calculate color correction matrix to guarantee correct color recreation.

Field calibration compared to field work's controlled environment in the conditions of a lab have even greater complications. Underwater environment cannot be controlled, so it is necessary to develop applicable calibration method for the in-situ work. The current practices are to place dedicated calibration instruments in the operational site, and then the underwater robot will shoot through photos to do on-site geometric calibration. Alternatively, self-calibration based on natural features, utilizing techniques like feature matching and Structure-from-Motion (SfM), can be employed to estimate camera parameters online. Moreover, multi-sensor approaches combining the output of an IMU and Depth sensors can improve the accuracy and robustness of the calibration process.

Among the above field calibration process, radiometric calibration is the most difficult[29] The light gets less intense within the water the farther away you go which then affects the radiometric properties based off the observer's position at distance[29]. To solve the problem, we could use physical optical model in combination with data driven method: It is about setting up a kind of radiative transport model that includes water's attenuation coefficient and imaging distance as a fundamental optical correction on the images. Deep learning methods can be used, and models can autonomously learn the patterns of illumination diminishment and color alteration across many underwater pictures under various water qualities, distances, etc., from a large number of field pictures, thus achieving automatic compensation for radiometric distortion in complicated environments(Figure 8). Another front: it is urgently needed for us to come up with in-situ calibration equipment which could be placed in the water by underwater robots easily. An example is to illuminate active standard sources panels or calibrators with known and consistent reflectance using robotic arms. These panels or calibrators could be used periodically while the camera is not in use to present real on-sensor (in-situ) reference data for radiometric correction.

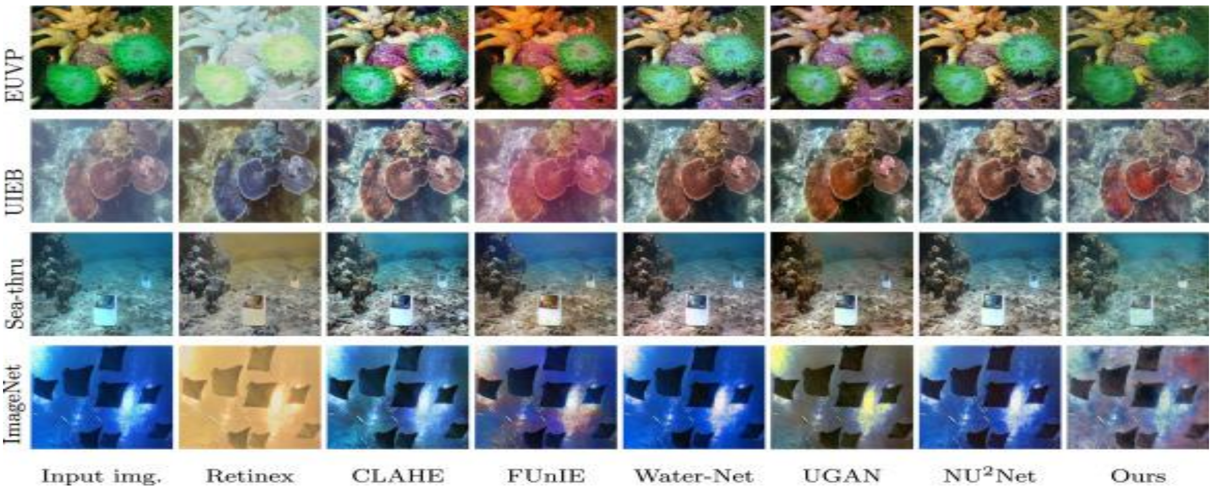

Figure 8. GAN-Based Compensation for Complex Scattering Environments[30]

5. Multi-sensor System-level Calibration and Uncertainty Assessment

Underwater robot applications increase, but with increasing demand for perception in complex marine environments, single-seed perception is inadequate. Multi-sensor fusion systems are becoming the mainstream configuration now[31](Figure 9). However, due to factors such as different working performance among sensors, space-time differences, and environmental interference, it creates new problems for system-level testing and uncertainty assessment [32]. As the multi-sensor system level in addition to considering the characteristics of each sensor, one also has to consider the sensors joint effect and their data coherence so as to guarantee the accuracy and reliability of the fused result[33].

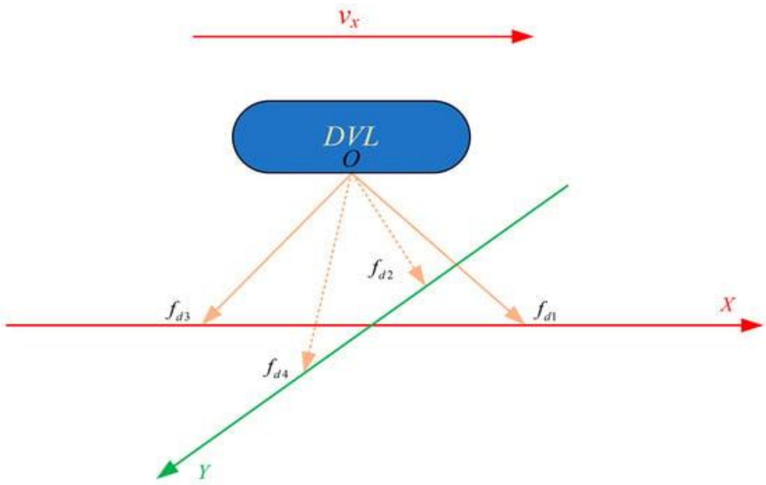

Figure 9. DVL Operating Principle Diagram[34]

The key task of multi-sensor system level is to form a uniframeset spatiotemporal refrence. Time Synchronization, Clock synchronization protocols must be the same so that all sensor data has the same time stamp [35]. hardware-triggered or high-accuracy time synchronization algorithms is usually applied to limit the time offset between nanosecond and microsecond or even sub-millisecond. [36] Spatial calibration refers to the accurate determination of relative positions and directional relationships among sensors, which is also called hand-eye calibration[37]. As for underwater robot systems, it is necessary to calibrate the transformation relationship between acoustic sensors, optical sensors, inertial navigation system, etc. A unified coordinate system was established. The most common calibration method is to use a certain calibration object to make an offline calibration, the other method is to calibrate online according to the existence of nature feature[38].

As for the multi-sensor data fusion problem, the propagation and accumulation of errors of each sensor are unavoidable problems[39]; Sources of Uncertainty mainly come from the errors in the measurement of the sensor itself, calibration errors, interference from the environment, and errors from the model approximation [40]. If we want to get an accurate estimate for the system as a whole, then we need a complete uncertainty propagation model. Probability based methods, Kalman filter & particle filter: these use sensor readings for merging info, estimates uncertainty as well[41](Figure 10),For example, the extended kalman filter estimates an object position using IMU state equation and UWB measurement equation, it takes into account uncertainties in IMU and UWB data at the same time [42]. For nonlinear system, the higher order term can't be ignored.

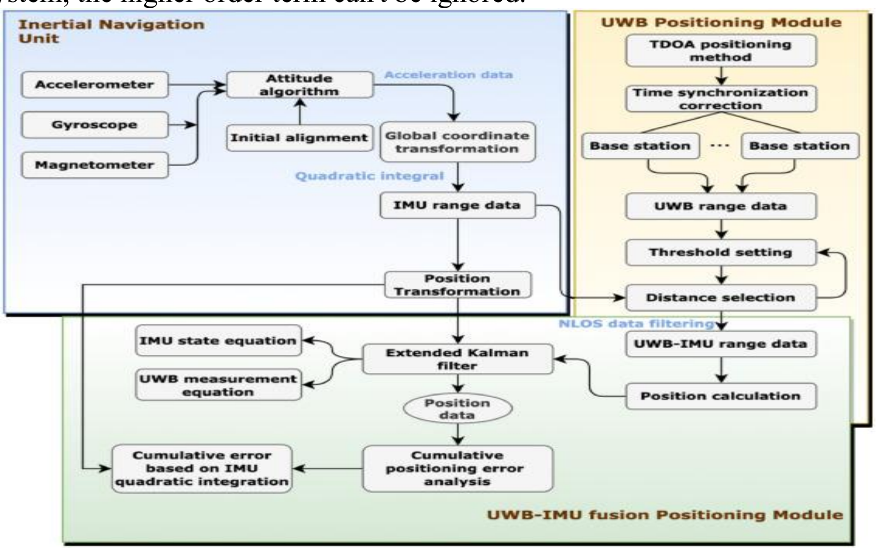

Figure 10. Extended Kalman Filter Framework[34]

Another big part of system - level calibration is multi - sensor cooperative calibration Use the correlation between data from different sensors observing the same target or scene to estimate the parameters of all the sensors at once by means of an optimization algorithm [43]. For example, there is an underwater robot, which has been fitted with three NDT systems, one monocular RGB camera, an ECT system, and an UT system. Complementary data can be mixed up so as to improve detection reliability and lower uncertainty. Joint calibration can also be performed using the distance information measured by the acoustic sensor and the image feature obtained by the optical sensor [44] or by using the motion information provided by the inertial navigation system to help calibrate the acoustic sensor [45]. This kind of cooperative calibration method has the advantages of improving calibration efficiency as well as having better consistency.

An assessment of uncertainty is done with a full set of metrics. [46] Accuracy and repeatability apart, we should also bear in mind stuff like environmental adaptability and long term stability. Assessment method is Monte Carlo simulation, experimental verification, theoretical analysis. Through the large amounts of experimental data to do statistical analysis, can create uncertainties models as the base of system performance prediction and improving [47]. at the same time, we have to probe into the dissemination patterns of uncertainty along the data processing chain so as to direct the system design.

In practice, we also need to take the impact of the environment on the calibration of the system. Temperature, pressure and water qualities change affect on the sensors so the calibration results. Therefore, it is necessary to conduct research on environmentally adaptive calibration methods, which requires environmental parameter monitoring at any time and calibration parameter modifications to ensure the stability of the system's performance. And what about the issue of gradual loss of effectiveness when used for a long time, some kind of regular re-sampling and care should also be established.

6. Conclusion and Prospects

Although great achievements have been made on metrological calibration technology of environmental perception system under the underwater robot, many technical challenges and development bottlenecks still exist, mainly as follows:

1)The measurement traceability chain is broken because of the complex underwater environment. There are great differences between laboratory and field calibration methods.

2)Field calibration technology is under-developed for extreme environments, just like high pressure environment. It does not have automatic and dynamic calibration method.

3)It is still difficult to the multi-sensor collaborative calibration. There are many problems such as low spatiotemporal registration accuracy, interference between sensors, data synchronization and so on, which limit the accuracy and stability of multi-sensors fusion system[48].

To address the aforementioned issues, further research can be conducted in the following five directions:

1)Developing micro-reference acoustic sources based on MEMS technology and miniaturized optical reference targets to achieve rapid in-situ calibration of the main acoustic array and optical cameras on underwater robots.

2)Establishing error compensation models leveraging artificial intelligence technologies such as deep learning to correct sonar ranging deviations and enable adaptive scattering correction for underwater images[49-50].

3)Constructing a virtual marine environment with multi-physics coupling to simulate the impact of hydrological parameters such as temperature and turbidity on sensor performance, forming a novel calibration paradigm that integrates virtual calibration with physical verification.

4)Integrate lightweight, modular, and embeddable calibration equipment, such as micro-MEMS acoustic sources and foldable optical calibration panels, into AUVs to enable periodic self-calibration of sensors.

5)Developing error propagation model based on the Extended Kalman Filter to transition from single-sensor calibration to system-level calibration[51], and from laboratory-based calibration to field in-situ calibration. It will establish end-to-end calibration capabilities covering shallow to deep-sea environments, providing highly reliable perception assurance for underwater robots.

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