The Principle and Application of Underwater Sonar Systems

Siyi Wang [1,*], Yiduo Wang [2] and Lang Yin [3]

[1] Wuhan Britain-China School, Wuhan, China

[2] Yinghua Cambridge School, Zhuhai, China

[3] Suzhou Foreign Language School, Suzhou, Jiangsu, China

* Corresponding Author Email: cici.wangsiyi@outlook.com

Abstract. As underwater detection demands continue to grow across fields such as marine scientific research, resource exploration, and underwater engineering, the performance and application scope of sonar systems have become a focal point of research. Against the backdrop of rapid technological advancement and an increasing emphasis on marine development, enhancing the precision, efficiency, and adaptability of sonar systems has emerged as an urgent challenge to be addressed. This article summarizes the current research status of various types of sonar systems, and it also elaborates on the operation principle of the sonar system in terms of the classification of single-beam and multi-beam. This article then further analyzes the advantages and disadvantages of different sonar systems and concludes the applicable scenarios for them. In terms of principle, this article explains the differences and advantages/disadvantages between single-beam and multi-beam technologies. For instance, single-beam has a low cost but is not very precise and has limited applicable scenarios; multi-beam is more advanced and can accurately survey complex seabed topographies, but it has a higher cost. This paper generalizes the existing underwater sonar systems, which can help identify the deficiencies of the current sonar systems and facilitate further research and development.

Keywords: Underwater Sonar Systems; Underwater engineering; Principle and Application.

1. Introduction

The ocean is rich in resources and serves as the country's most important defense line. Among them, the sonar system has played a significant role in exploring marine resources and safeguarding national security. However, as this technology is put into use, many problems gradually emerge. The most significant drawback is that factors such as water temperature and salinity cause the refraction of sound waves, thereby affecting the path of the sound waves.

The full name of Sonar is “Sound Navigation and Ranging”, which is a technology that uses the propagation characteristics of sound waves in water for underwater detection and positioning. Sonar detects and locates underwater objects by emitting sound waves and then receiving the echoes that bounce back. Therefore, it is called the "underwater eye" for its ability to see things from a distance. Sonar technology has a history of over 100 years. It was invented by Lewis Nixon of the British Navy in 1906. In 1914, the United States successfully used an echo detector to detect an iceberg at a distance of two miles, marking the significant military application of sonar technology. It was first applied to the battlefield during World War I, and was used to detect submarines that were lurking beneath the water surface. Improvements and adjustments by French physicist Paul Langevin and Russian electrical engineer Constantin Chilowski, the first active sonar device for detecting submarines was born. In recent years, with the development of technology, sonar systems have been continuously updated and improved, with a wide variety of types and extensive applications.

The low-frequency sound wave pulses emitted by sonar can travel through water and air via the transmitter. When encountering obstacles, the sound wave pulses will be reflected back to the receiving device. By measuring the speed of the sound pulses and the time of the echoes, the distance between the obstacles can be determined. It was based on the echolocation of bats and dolphins that humans invented sonar. The signals emitted by bats during foraging, orientation, and flight are composed of ultrasonic phonemes similar to language phonemes. Bats must receive the echoes and analyze the sound characteristics, such as amplitude, frequency, and signal intervals of these echoes, before they can decide what action to take next. Dolphins generate high-frequency sound waves through the air sac structure on their heads. The sound waves emitted by dolphins propagate in water, and the reflected sound waves carry information about obstacles. Based on this, dolphins determine the direction of their next movement.

Nowadays, there have been significant breakthroughs in this field of research, such as the proposal of the INS/USBL/DVL tightly coupled model; the design of the distributed collaborative positioning system; the experimental implementation of Doppler-assisted beamforming; the development of innovative algorithms; breakthroughs in signal processing; and the application of new hardware and system architectures, among others. The sonar system is widely used in various fields such as military, science and technology, business trade, and environmental monitoring. The sonar system utilizes the characteristics of sound waves propagating and reflecting through a medium to achieve navigation and distance measurement functions. It is one of the most widely used devices in underwater acoustics applications. With technological advancements, current sonar systems can now provide two-dimensional or three-dimensional imaging, playing a significant role in numerous important tasks such as marine military operations, underwater search and rescue, earthquake prediction, and seabed topography exploration. This article will discuss the application of sonar systems in different fields of the marine environment, as well as the performance improvement resulting from further improvements of the sonar system.

2. The Current Research Status of Sonar Systems

2.1. Research on Imaging Sonar Systems

Imaging sonar systems are a technology that uses sonar to survey and image. It conducts an underwater survey by emitting sound waves and receiving the reflected sound waves. According to the features like time, strength and frequency, and using signal processing technology and imaging algorithms to provide high-resolution images of the underwater environment [1]. This technology is being widely used in regions like marine resource exploration, underwater navigation safety, seabed topography survey, safety inspection of water conservancy projects, and the search for sunken ships.

The volumes of underwater small targets are small. The detection of it is easily affected by the noise. As a result, the detection of small underwater targets needs highly specialized sonar systems. The underwater small target detection sonar is used to recognize and locate those tiny objects, such as frogmen, unmanned underwater vehicles, etc. [1]. This technology plays an important role in improving areas such as the safety of the country, scientific research, and the detection of sources in the ocean. For the reason that high-frequency acoustic waves can provide higher resolution. This kind of sonar system [1].

In 2006, a British firm, Sonardyne, invented Sentinel IDS. This is a "Sentry" intruder detection sonar system. Its outstanding performance makes it one of the most widely deployed detection systems. Moreover, it makes the underwater small target detection sonar get to the next level [1]. The weight of Sentinel ID is only 30kg and its volume is small. These features make this kind of sonar system easy to take and install. It can work independently, and it is also possible to form multiple sets to operate in a network in a coordinated manner. It can be installed at the port or on a ship. It can work under 50 m depth [1]. There are many reasons that make it sell well all over the world. Furthermore, the working frequency of this sonar system is 70kHz, the bandwidth is approximately 20kHz, the exploration range is within 1km, and the azimuth accuracy is between 0.1° and 0.5° [1]. This sonar system can efficiently detect the small underwater targets, frogmen, underwater vehicles, etc. After it finds out the targets, it will alarm.

The sonar system used by the United States Navy in the 1990s, AN/WQX-2, can detect frogmen within a 750-meter circle. It can distinguish frogmen and other underwater creatures accurately [1].

Many countries launched the DDS system. “The Underworld Gate-hound 360” is a high-performance active DDS invented by the British company called QinetiQ. It can detect, recognize and trace automatically. Its detection zone can be extended to 1000m [2]. Diver reconnaissance system (DRS) was invented by QinetiQ, which is a handheld DDS. The weight of this sonar system is 10kg, and the weight underwater is 0.5kg. It can work at 100m depth. Batteries are used to provide energy for it, which makes it keep working for 6.5 hours [2]. An Israeli firm, DSIT, invented “Water-Shield” and “Spike-Shield”, 2 portable DDS. “Water-Shield” DDS can provide permanent protection for naval bases and submarine pipelines, etc [2]. Modular design makes it very flexible, with three types of fan-shaped coverage: 120°, 240° and 360°, and covers the entire relevant cylindrical surface. Its detection distance is 1000m for an Open-circuit frogman and 700m for a closed-circuit [2]. In June 2014, the “Water-Shied” DDS extension system was launched and had made a giant leap forward. Its detection distance for the frogman carrier is 3500m, 1800m for open-circuit frogman and 1200m for the closed-circuit frogman [2]. “Spike-Shield” portable DDS also supports fully automatic operation. It is portable, durable, and suitable for permanent installation. It has high accuracy and a low error rate and all-around coverage [2]. The detection distance for an open-circuit frogman is 700m and 500m for a closed-circuit frogman [2].

At present, SAS can produce high-resolution images. Compared with traditional imaging sonar systems, SAS can provide high-resolution imaging along the track dimension that is independent of frequency and detection range.

Although imaging sonar systems are already widely used in fields such as marine geological exploration and national defense security, there are some challenges still waiting to be overcome, such as blurry images and insufficient depth.

2.2. Multi-static Sonar Systems

2.2.1 Principle of Multi-static Sonar Systems

Multi-static sonar is an active detection system, primarily consisting of two components: a transmitter and a receiver [1]. The former is responsible for generating and radiating signals into the water, while the latter is responsible for receiving and processing target-scattered signals, as well as the direct blast. The direct blast refers to the wave that propagates directly from the transmitter to the receiver, which is used to calibrate the transmitter-receiver distance and propagation time. If a target is present along the signal propagation path, the signal will be scattered by the target, and a portion of the scattered signal will reach the receiver (as shown in Figure 1)

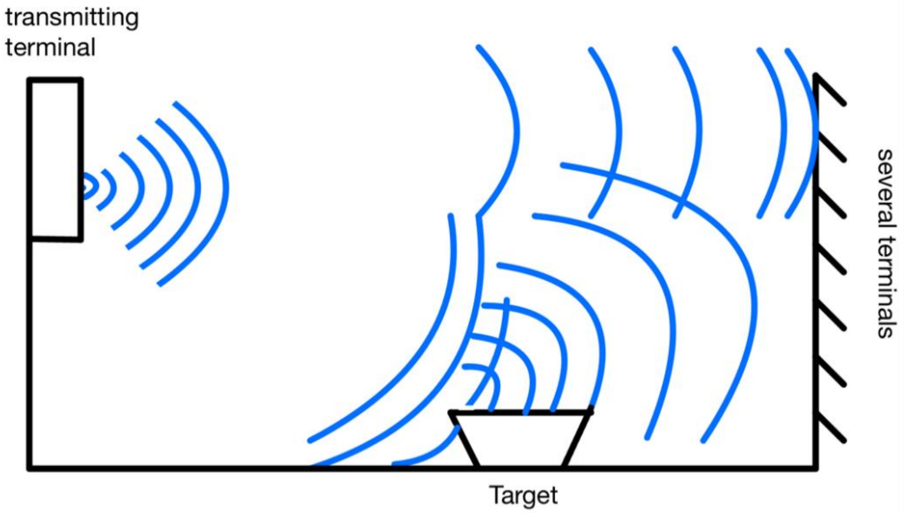

Figure .1 Schematic diagram of target scattering signal reception

By taking the difference between the time the scattered signal arrives at the receiver and the arrival time of the direct blast, a time difference is obtained. Multiplying this time difference by the speed of sound yields the difference in propagation length between the path from the transmitter to the target to the receiver and the propagation length of the direct blast. The set of points satisfying this distance difference forms a rotating hyperboloid, representing the possible locations of the target, with the two foci being the transmitter and the receiver, respectively [2]. A single receiver can only determine one such hyperboloid, meaning the target can only be localized to this surface, but its exact position cannot be pinpointed. In contrast, multiple receivers can detect several such hyperboloids, and their intersection provides an estimated three-dimensional position of the target [3-6].

2.2.2 Advantages and Disadvantages of Multi-static Sonar Systems

Compared to mono-static sonar, multi-static sonar offers several significant advantages, primarily including the following: Covert Receiver Operation: In multi-static sonar, the transmitter and receiver are separated, with the receiver operating passively. This significantly reduces the risk of detection by submarines. While a submarine can easily locate the transmission source, it is difficult to detect the covertly deployed receiver buoys [7]. Reduced Susceptibility to Target Aspect: Submarines find it difficult to evade detection by adjusting their attitude to counter multidirectional echoes. Mono-static sonar relies on the strength of the target's backscatter, whereas multi-static systems can utilize forward- and side-scattered energy, enabling effective detection of low-reflectivity targets such as quiet submarines [8]. Expanded Search Area: The deployment of multiple receivers forms a wide-area detection network, resulting in a search area significantly larger than that of mono-static systems [9]. Cost-Effectiveness: Chen Ligang's simulations demonstrated that a bistatic sonobuoy array can increase the search area by over 40% compared to a mono-static array with the same spacing, while also being more cost-effective [7]. Rich Target Feature Information: Multidirectional echoes carry abundant target characteristic information. For instance, multi-static specular echoes can be used for continuous tracking of a target's course, and when combined with sparse representation algorithms, they enable high-precision identification of the target's attitude angle [8].

However, this system also faces numerous challenges. Synchronization and Localization: The bistatic configuration requires precise time synchronization and high spatial positioning accuracy.Environmental Impact on Accuracy: The marine environment (e.g., water density, temperature, salinity) causes instability in acoustic propagation delays, adversely affecting positioning accuracy. Direct Blast Interference: The receiver must suppress the direct blast signal; otherwise, it can overwhelm the weaker target-scattered echoes. Channel-Dependent Performance: The oceanic channel (temperature, salinity, seabed topography) significantly influences the detection range of bistatic systems. Typical hydrological simulations show that multi-path effects in shallow water can cause fluctuations in the detection range of up to 50% [10].

2.3. Seabed Topography Sonar Detection Systems

2.3.1 Principle of Seabed Topography Sonar Detection Systems

The core principle of seabed topography detection sonar is based on the propagation characteristics of sound waves in water and the analysis of reflected signals. It acquires three-dimensional spatial information through the interaction of high-frequency sound waves with the seabed topography. This type of sonar system emits high-frequency acoustic pulses via a transducer. When these sound waves encounter the seabed or target objects, they generate reflected echoes. The receiver array captures the time difference, intensity, and phase difference of the echoes, which are used to calculate depth and interpret topographic variations and seabed characteristics.

Further improvements include phase interferometry, specifically phase-difference bathymetric sonar, which utilizes a multi-receiver array to analyze phase differences and reconstruct three-dimensional models. However, such models are influenced by several factors. For instance, reflection intensity depends on the acoustic impedance ratio between the target and the seabed sediment. A significant difference in acoustic impedance results in strong reflection contrast, while similar impedances require reliance on shadow interpretation. Hard seabed rock produces strong reflections but is prone to acoustic shadow artifacts, whereas soft sediment absorbs sound waves, leading to reduced signal-to-noise ratio.

2.3.2 Advantages and Disadvantages of Seabed Topography Detection Sonar

Traditional side-scan sonar offers high-resolution imaging but has limitations in positioning. Its dual-frequency design provides high-resolution images, enabling clear identification of seabed features (with swath width error < 0.5 m): [11] Towed operations, improved by researchers such as Zhang Haitao et al., now support detection depths of up to 2000 meters; [12] Additionally, traditional side-scan sonar has up to eight times more sampling points compared to coherent sonar, providing a significant advantage in data density [12]. However, the inherent drawbacks of traditional side-scan sonar cannot be overlooked. It is susceptible to disturbances from ocean currents, resulting in significant positional errors of 8 to 9 meters in the target plane [12], and it cannot directly obtain specific topographic information [13].

Coherent sonar excels in positioning and data fusion. It can improve positioning accuracy through fixed hull-side installation combined with RTK-GNSS (e.g., GPS and other positioning satellites) [14]. It simultaneously outputs sonar images and water depth point clouds [15]. By manually setting terrain-trend water depth values, the inversion error of pipeline suspension height can be reduced by 90% [14].

3D scanning sonar demonstrates significant technological innovation advantages. The CAATI algorithm enables real-time resolution of full water column point clouds, covering a width of 14 times the water depth [15]. The HYBRID beam mode can detect both flat seabeds and vertical targets [11]. However, beam-width settings affect accuracy (with a deviation of ±0.2 m at a 45° depression angle), and there is a detection blind spot directly below the transducer due to angular limitations [16].

2.4. Synthetic Aperture Sonar

2.4.1 Principle of Synthetic Aperture Sonar

Synthetic Aperture Sonar (SAS) overcomes the challenge of constructing large physical arrays by instead utilizing a small array mounted on a moving platform. This system employs a compact transmitter and receiver unit installed on the vehicle, with its physical size along the direction of motion kept relatively small to enhance resolution [17]. As the platform moves in a straight line at constant velocity, the sonar system emits acoustic signals at fixed time intervals. The base station then receives information such as amplitude, phase, and time of arrival, which is stored for subsequent synthetic aperture processing.

For each target point in the water, the corresponding echo data is selected. Phase and timing errors caused by factors such as platform motion (e.g., pitch, yaw, and heave) are calculated and compensated. After correcting these values, the echo signals are coherently combined. This process enhances the target signal while suppressing or even canceling out noise.

2.4.2 Advantages and Disadvantages of Synthetic Aperture Sonar

The advantages of SAS include extremely high azimuth resolution and the use of a small array to achieve a large effective aperture. SAS achieves azimuth resolution at the sub-wavelength level by moving a small-aperture array along the track, which is far superior to traditional sonar. For instance, Circular Synthetic Aperture Sonar (CSAS) can achieve sub-wavelength resolution in two-dimensional planes under broadband conditions [18]. The azimuth resolution of SAS depends solely on the synthetic aperture angle and is independent of detection range and frequency [19]. Thereby solving the problem of resolution degradation in long-range detection faced by traditional sonar.

Furthermore, traditional sonar requires high frequencies to achieve high resolution, but this is limited by acoustic attenuation in water, which reduces detection range. SAS, through synthetic aperture processing, enables low-frequency sonar to obtain high resolution even in shallow water areas [20].

2.5. Research on the Towed Array Sonar System

2.5.1 The principle of the towed array sonar system

The towed array sonar system is a kind of technique used to detect sound waves underwater and measure the distance. It is always used to detect targets like submarines, fish schools, and terrain. The main components of the towed array sonar system are the emitter and acceptor. The emitter is used to produce wave signals with a fixed wavelength and spread them. When sound waves encounter obstacles, a reflection phenomenon will occur. The receiver is used for receiving and recording. The reflected wavelength is received by the receiver and converted into an electrical signal. After a series of processing, useful information is extracted from the electrical signal.

The towed array sonar system is used to in marine surveying and geological research. The towed sonar can generate detailed seabed topographic maps through post-processing of the received echoes. This technology can generate high-resolution seabed topography, which helps scientists obtain information about the seabed topography. It is convenient for conducting oil exploration, mineral resource assessment and seismic research. The towed sonar system plays a significant role in underwater target detection and tracking. By repeatedly emitting sound waves and receiving echoes, the towed sonar system can determine the movement state, trajectory, direction, etc. of underwater targets. It is mainly used for tracking fish schools and estimating their numbers in the fishing industry. The underwater target detection and tracking capabilities of the towed sonar system are still utilized in the military field for anti-submarine warfare. The towed sonar system is also used in marine navigation and the deployment of underwater pipelines. The towed sonar system can provide a clear topographic map of the seabed, ensuring the safety of ship navigation and preventing ships from traveling in dangerous areas. During the process of laying the submarine pipelines, a towed sonar system can also be used to select the optimal laying path.

2.5.2 The advantages and disadvantages of the towed array sonar system

The towed sonar system is generally used to be equipped on surface ships, submarines, anti-submarine helicopters, and surveillance vessels for exploration purposes. Its advantage is that the array is submerged relatively deep. The working depth of the array can be adjusted by controlling the length of the towing cable and the speed of the carrier platform. Moreover, the array is far from the platform, thus being less affected by the platform's noise and having a longer effective range. The array can also be retracted at any time, making maintenance more convenient.

However, this system also has some limitations that cannot be ignored. For instance, the large array, the long-dedicated towing cables, and the complex deployment and retrieval devices will occupy valuable space on the transport platform, including the cargo hold and the deck area. This poses challenges to the design of the platform structure and the layout of the space; when used tactically, the towing cable will increase the rotational inertia of the platform, restricting its maneuverability and tactical flexibility. Moreover, during steering and speed changes, there is a risk of the towing cable getting tangled, breaking, or being detected by the enemy. Meanwhile, the array is located far behind the platform, which may result in a blind zone for the detection of the area near the platform. There is also a time lag between the detection of the target and the platform's response. In a high-threat environment, this may lead to a tactical disadvantage.

3. Conclusions

In conclusion, different types of sonar systems play a crucial role in various fields. The use of sonar systems is particularly significant in marine exploration, providing technical and resource support for the development of marine science. With the continuous improvement of the sonar system, the topographical maps that can be obtained will become increasingly clear, facilitating human preparations before exploring unfamiliar areas. The extremely high resolution enables the sonar system to accurately detect extremely small targets and precisely locate any potential threats to the security of coastal areas, making a significant contribution to making the coastal areas safer. As technology continues to develop, the sonar system will be applied to more aspects in the future to benefit humanity.

4. Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Zhang Haoran. Research on Resonant MEMS Hydrophone Arrays for Underwater Imaging Sonar Systems [D]. Harbin Engineering University, 2024. DOI: 10.27060/d.cnki.ghbcu.2024.003279.

[2] Huang Yingsong, Ge Huiliang, Wang Fuyin, et al. Review of Frogman Detection Sonar System Development [J]. Journal of Underwater Unmanned Systems, 2020, 28(1): 1-9.

[3] Dong Dexing. Research on Background Noise Suppression Technology of Drifting Sonar in Marine Environment [J]. Science and Innovation, 2024, 27(10): DOI: 10.15913/j.cnki.kjycx.2024.10.027

[4] Yang Shiwuo, Yang Desen. Principles of Underwater Acoustics [M]. Harbin: Harbin Engineering University Press, 2015: 212-220.

[5] Li Z, Yan B, Zhang R. Bistatic Sonar Target Localization with Ocean Environmental Mismatch Compensation [J]. IEEE Journal of Oceanic Engineering, 2018, 43(3): 723-732.

[6] He You, Jian Keyan, Peng Yingning. Introduction to Sonar Signal Processing [M]. Beijing: Defense Industry Press, 2016: 185-190.

[7] Chen L G. Effectiveness Analysis of Multistatic Sonobuoy Systems for Anti-submarine Operations [J]. 2022(2): 7-9, 32. [8] Scott R. Leonardo's ULISSES multistatic acoustic processor [J].Janes International Defense Review, 2021, 54(4): 42-45.

[8] Xu W C, et al. Optimization of sonobuoy deployment for multistatic antisubmarine operations [J]. Fire Control & Command Control,2025, 50(1): 112-118.

[9] Preisig J C, et al. Experimental study of bistatic sonar performance in shallow water [J]. ,The Journal of the Acoustical Society of America, 2019, 146(2): 1103-1113.

[10] Wang R, Chen L X, Liu Y, et al. Fuzzy terrain side-scan sonar positioning error correction model [J]. Ocean Engineering, 2020, 38(6): 124-130.

[11] Zhang HT, Li Z W, Wu XF. Imaging performance research of deep-sea towed side-scan sonar [J]. Ship Mechanics, 2021, 25(3): 45-52.

[12] Zhou M Z, Zhao Y H, Zheng Y. Verification of positioning accuracy of coherent sonar in shallow water engineering detection [J]. Surveying and Mapping Bulletin, 2022 (Supplement 1): 89-94.

[13] Sun J H, Liang B, Ma X. Application of GeoSwath Plus in the detection of suspended pipelines on the seabed [J]. Petroleum Engineering Construction, 2021, 47(5): 112-117.

[14] Xu T Y, Wang Z H, Dong H. Optimization experiment of 3DSS-iDX-450 3D reconstruction algorithm [J]. Journal of Harbin University of Engineering, 2023, 44(2): 210-218.

[15] Yang F, Liu J, Zhou X. Research on blind area compensation method of 3D side-scan sonar detection [J]. Journal of Instrumentation and Measurement, 2022, 43(8): 101-109.

[16] Xu W, Sun F, Pan X, et al. AUV dual-base synthetic aperture sonar imaging experiment [J]. Applied Acoustics, 2019, 38(4): 660-665.

[17] Du X M, Zeng S. Review of circular synthetic aperture sonar technology [J]. Acoustic Technology, 2022, 41(3): 320-326.

[18] Chen Q. Low-frequency shallow-water synthetic aperture sonar: Signal processing and system implementation [D]. Hangzhou: Zhejiang University, 2010.

[19] HAYES M P, GOUGH P T. Challenges in seafloor imaging and mapping with synthetic aperture sonar[J]. IEEE Transactions on Geoscience and Remote Sensing, 2011, 49(10): 3677-3687.

[20] Peixuan Y. An imaging algorithm for high-resolution imaging sonar system [J]. Multimedia Tools and Applications, 2023, 83(11): 31957-31973.