Engineering Solutions to Mechanics, Marine Structures and Infrastructures

Eng. Solut. Mech. Mar. Struct. Infrastruct.
2024.1(3).4
ISSN：3006-2837
https://doi.org/10.58531/esmmsi/1/3/4

Review

Machine Learning Based on Underwater Communication Technology

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Academic Editor: Weiwei Wang <zhwangww@ytu.edu.cn>

Received: 16 July 2024; Revised: 10 August 2024; Accepted: 17 August 2024; Published: 19 August 2024

Abstract: Underwater communication is a complex and critical technology with significant value in the fields of marine resource development, marine scientific research, and military applications. The research on Underwater communication mainly focuses on improving the communication rate, enhancing the stability of signal transmission and anti-jamming ability, and combining it with artificial intelligence to meet the growing demand for Underwater communication. Machine learning is an important development direction for Underwater communication. Therefore, this paper firstly reviews the development of China and the rest of the world based on the time-tracing method to analyze Underwater communication technology in both regions, and then this paper analyzes the different machine learning algorithms based on the topic classification, and introduces the challenges of machine learning in the field of Underwater communication, and discusses the limitations of the traditional methods, including the signal fading, multipath propagation, and noise interference. noise interference. Next, the paper describes the potential role of machine learning in Underwater communications, including channel modelling, signal modulation, demodulation, and adaptive aspects. Finally, it summarizes the current research progress and looks forward to the future development trend of machine learning in Underwater communications.

Keywords: Underwater communication; Machine learning; Analysis of Chinese and foreign underwater communication Technology

Citation: Yang. K., Xie Y., Si K, Zeng S., Yang K, Zhang D. Machine Learning Based on Underwater Communication Technology. Eng. Solut. Mech. Mar. Struct. Infrastruct., 2024, 1(3), doi: 10.58531/esmmsi/1/3/4

1. Introduction

Underwater communication is a rapidly evolving technology within the research field. In recent years, it has gained significant attention as a popular research direction in the domains of ocean engineering and marine science. Both in China and foreign countries, researchers have devoted their efforts towards the advancement of Underwater communication. Their studies encompass various areas such as climate change, natural disaster prediction, marine environment, aquatic organism monitoring, ocean propagation, and data collection [1-5]. As illustrated in Figure 1. Underwater communication, in general, pertains to the exchange of information between an aquatic entity and an underwater target, such as a submarine, unmanned submarine vehicle (UAV), or underwater observation system, and so on, Additionally, it encompasses communication between multiple underwater targets. These interactions primarily occur within seawater or freshwater environments.

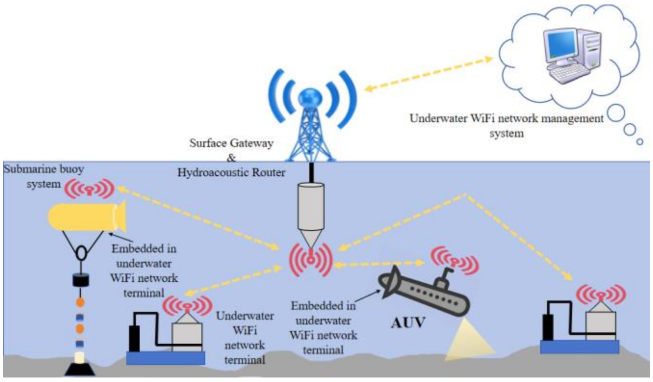

Figure. 1. Working principle of underwater communication.

As a pivotal marine technology, underwater communication holds immense significance in the realms of marine resources exploration, underwater observation, and seabed engineering. As humanity delves deeper into oceanic research and development, the importance of underwater communication technology becomes increasingly indispensable. Numerous research institutions and enterprises, both in China and foreign countries, have made substantial investments in the research and innovation of underwater communication technology. These endeavors have spurred continuous progress and advancement within the field. Figure 2 illustrates the classification of underwater communication into two main categories: underwater wired communication and underwater wireless communication. underwater wireless communication can be further subdivided into underwater wireless electromagnetic wave communication [6-9] and underwater non-electromagnetic wave communication. The latter encompasses hydroacoustic communication [10-13], underwater optical communication [14-17], underwater quantum communication [18-20], underwater neutrino communication [21-22], gravitational wave communication [23-25], among other.

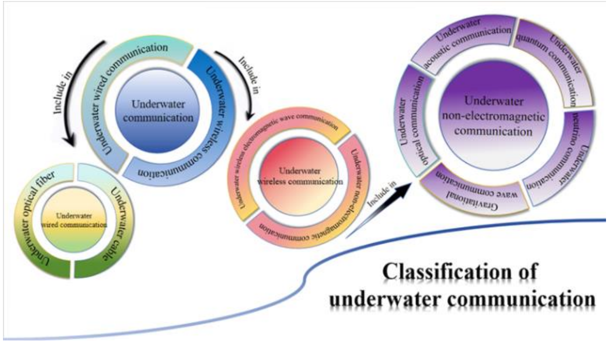

Figure. 2. Classification of underwater communications.

Underwater communication technology based on machine learning encompasses several research aspects, including signal modeling and prediction [26], signal demodulation and detection [27], communication link optimization [28], and adaptive modulation [29]. In signal modeling and prediction, machine learning algorithms are utilized to model and predict the propagation characteristics of underwater signals, facilitating real-time monitoring and adjustment of the signal transmission process. In signal demodulation and detection, machine learning algorithms efficiently demodulate and detect underwater signals by learning known signal patterns and features, thus improving the performance and reliability of the communication system. Regarding communication link optimization and adaptive modulation, researchers use machine learning algorithms to dynamically optimize and adjust the underwater communication link, selecting the optimal modulation method and parameters according to real-time environment and demand changes. This enhances the adaptability and flexibility of the communication system. Underwater communication technology based on machine learning has made significant progress in theoretical research and achieved successful practical application cases. For instance, deep learning algorithms [30] have been employed to intelligently identify and classify underwater signals, enabling real-time monitoring and analysis of underwater targets and environments. This provides powerful support for marine scientific research and resource exploration. Moreover, underwater communication systems based on machine learning have been extensively employed in ocean monitoring, seabed geological exploration, and underwater robot control, providing innovative ideas and approaches for deep-sea technology and marine resource development.

The objective of this paper is to provide a comprehensive analysis and discussion of the current research status of Machine learning in underwater communication. Through analyzing the theoretical significance and practical application value of machine learning in underwater communication technology, as well as the significance of improving the performance and reliability of the underwater communication system, this study aims to deepen the understanding of machine learning technology in the field of underwater communication. This promotes cooperation and exchange in related fields, and enables underwater communication technology to achieve a broader prospect of development. With the continuous development of machine learning algorithms and underwater communication technology, it is believed that machine learning-based underwater communication technology will play an increasingly important role in the future, bringing new opportunities and challenges for deep-sea exploration and marine resource development.

2. Analysis of Chinese and foreign underwater communication technologies

2.1 Research background

With the foreign economy's development and escalating energy demands, human exploitation of marine resources is on the rise. Consequently, the issue of the marine environment has grown increasingly prominent, rendering the monitoring and protection of the marine environment a crucial concern [31]. The development of marine resources necessitates a dependable underwater communication system for monitoring, control, and data transmission to ensure the seamless progression of development activities. Moreover, underwater communication technology facilitates real-time monitoring and transmission of marine environmental data, aiding in the timely detection and response to marine pollution, climate change, and other issues [32-34]. In order to gain a comprehensive understanding of the marine environment for enhanced comprehension of the Earth, scientists conduct various oceanic research endeavors through underwater communication technology, including marine geology, marine biology, and marine meteorology, thereby advancing marine science [35]. Simultaneously, navies and military organizations of various countries rely on underwater communication for sea vessel command and control, as well as intelligence transfer. Hence, the study of underwater communication technology holds significant importance in upholding national maritime security [36-38].

However, underwater communication technology confronts numerous challenges and issues. Seawater-related factors such as absorption, scattering, and multipath effects can significantly impact signal transmission and reception, limiting the stability and reliability of underwater communication. Moreover, the complexity and variability of the marine environment present considerable challenges to underwater communication research and application. Hence, future underwater communication studies must continue to bolster basic theoretical research to enhance technical proficiency and response capability. Continuous exploration and innovation are also necessary to address new marine development and security challenges and requirements.

2.2 Research history of underwater communication technology

Underwater communication technology holds paramount significance in the domains of marine science, military navigation, and marine resource development. Its origins can be traced back to the late 19th century, and its evolution has witnessed several distinctive phases and significant milestones (as shown in Figure 3).

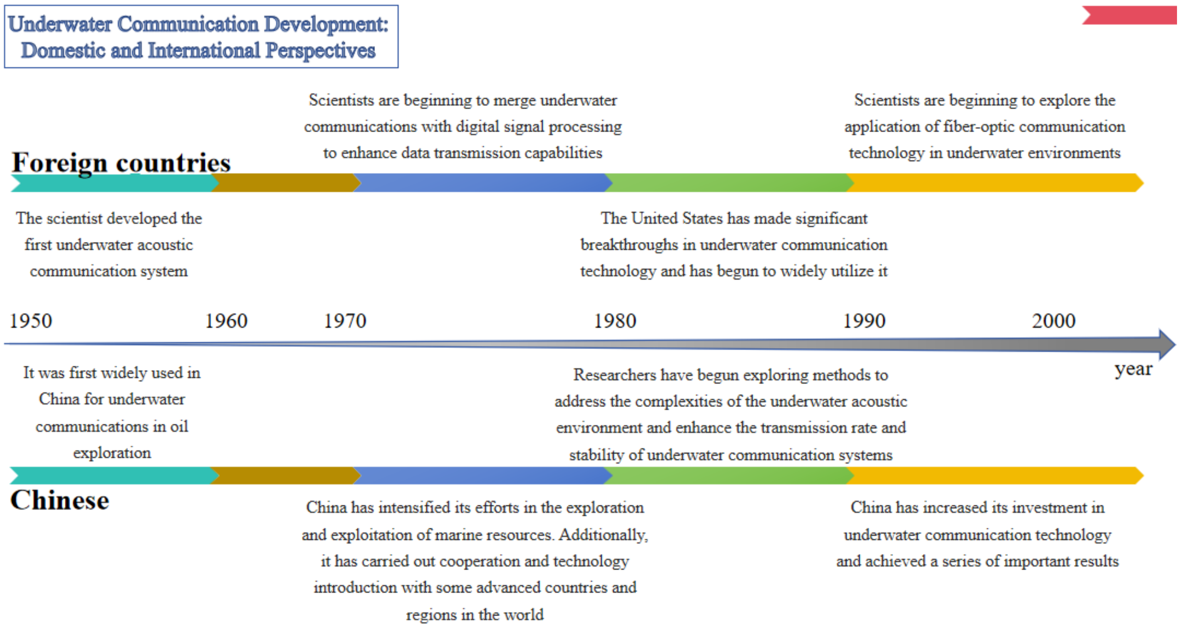

Figure. 3. Development stages of underwater communication in China and foreign countries.

Underwater communications technology experienced rapid development during the 1950s and early 1960s. Extensive research was conducted by scientists in the U.S. Navy during this period, leading to the development of the earliest underwater acoustic communication systems for communication between underwater ships. Among these researchers, Harold Edgerton, a U.S. Navy engineer, played a pivotal role in the field of underwater acoustic communication. Renowned as the pioneer of high-speed flashlight photography, Edgerton's research on ultrashort pulsed light greatly contributed to the application of underwater acoustic communication, providing crucial technical support for the field's advancement. From the 1970s to the 1980s, underwater communication technology began incorporating digital signal processing technology due to advancements in computer technology. This integration significantly enhanced the stability and reliability of the communication systems. Notably, David W. McCurdy and other U.S. scientists specializing in digital signal processing made important breakthroughs in the digitalization of underwater communication technology, laying the foundation for its intelligence capabilities. During the 1980s to the early 1990s, the United States achieved a series of significant milestones in underwater communication. These included the research and development of new underwater communication equipment, the establishment of underwater communication protocols and standardization, and the construction of underwater communication networks. Furthermore, the widespread application of underwater communication technology in fields such as ocean exploration, seabed resource development, and military communication provided crucial support and guarantees for various marine projects. By the 1990s to 2000s, with the rapid progress of fiber optic communication technology, underwater optical communication emerged. U.S. marine scientists and engineers began exploring the application of fiber-optic communication technology in underwater environments, resulting in significant research outcomes. During this period, the U.S. Naval Research Laboratory (US NRL) and other organizations conducted extensive exploration and experiments in underwater optical communication technology. Notably, in 1999, the U.S. National Science Foundation (NSF) funded the NEPTUNE project, aimed at establishing an underwater observation and data transmission network system. The implementation of this project promoted the application of underwater communication technology in scientific research and ocean observation, contributing to further advancements in the field.

China also has significant time points and contributors in the development history of underwater communication technology. In the 1960s, Chinese underwater communication was first widely utilized for oil exploration. From the late 1970s to the early 1980s, China intensified its exploration and exploitation of marine resources, with underwater communication technology becoming a crucial support for marine engineering. During this period, China actively cooperated with some advanced countries and regions worldwide, accelerating the pace of the development of underwater communication technology through technology introduction. In the 1980s and early 1990s, China began to focus on research and development of underwater communication technology. The Institute of Oceanography of the Chinese Academy of Sciences, Harbin Engineering University, and other units-initiated research on underwater acoustic communication technology, exploring how to deal with complex underwater acoustic environments, improve transmission rates, and enhance the stability of underwater communication systems. In the late 1990s and early 2000s, China increased its investment in underwater communication technology and achieved notable outcomes. For instance, the Institute of Oceanography of the Chinese Academy of Sciences conducted in-depth research on underwater acoustic communication technology, developing an underwater acoustic communication system with independent intellectual property rights that laid the foundation for the development of Chinese underwater communication technology. From the 2000s to the 2010s, China's research on underwater communication technology diversified, exploring the application of new technologies such as optical communication and laser communication in the underwater environment. The Institute of Oceanography of the Chinese Academy of Sciences and other organizations conducted innovative research in the field of underwater optical communication technology, making important breakthroughs and promoting the continuous progress of underwater communication technology. In recent years, with the deepening of marine resource development and scientific research, the application of underwater communication technology has become increasingly widespread in China. Certain Chinese enterprises have played essential roles in the research and development and production of underwater communication equipment, making positive contributions to the development of underwater communication technology in China.

2.3 Current status of research on underwater communication technology

Underwater communication technology is rapidly developing both in China and foreign countries. With the increasing demand for the development and utilization of marine resources, marine scientific research, and continuous innovation of communication technology, the application scope and technical level of underwater communication technology continue to improve. Figure 4 shows that in CNKI, the number of literature about underwater communication technology has reached a plateau, indicating that the technology has encountered a bottleneck in recent years. In contrast, Web of Science indicates that the number of literature on underwater communication technology has been increasing from 2019 to 2022, reflecting the growing interest in this field during this period. However, after 2022, the curve of the literature number becomes a plateau again, which implies that underwater communication technology is experiencing another bottleneck.

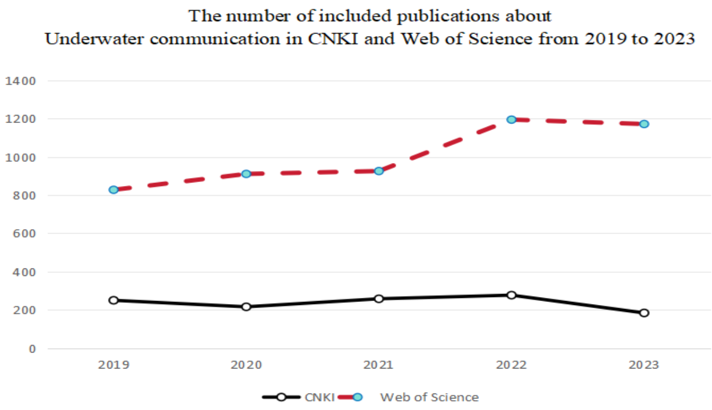

Figure. 4. Number of papers related to underwater communication included in CNKI and Web of Science, 2019 – 2023.

2.3.1 Major research on underwater communication technology

2.3.1.1 Underwater acoustic communication technology

Underwater Acoustic Communication (UAC) [39] is a technology that uses sound waves to transmit information in underwater environments. In this context, acoustic waves serve as the most important information transmission medium because of their faster propagation speed in water and less susceptibility to the underwater environment. The working principle of UAC is similar to acoustic communication on land, with the added advantage of underwater acoustic signals propagating at approximately 1,500 meters per second, about four times faster than signals traveling through air. This high-speed propagation makes underwater communication vital in fields such as detection, monitoring, and marine scientific research. Typically, an underwater communication system comprises a transmitter that converts electrical signals into acoustic signals propagated into the water and a receiver that receives and decodes signals from the transmitter, converting them into electrical signals for processing and analysis. However, the complexity of the underwater environment, including changes in water density, temperature, salinity, and other factors, coupled with the multi-channel and multi-path effects of underwater acoustic propagation, makes underwater communication challenging.

2.3.1.2 Underwater optical communication technology

In the contemporary era, there is rapid advancement in underwater communication technologies, with one particularly noteworthy innovation being underwater Optical Communication (UOC), leveraging optical signals for underwater data transmission[40]. In contrast to conventional hydroacoustic communication, UOC offers superior data transmission rates, reduced latency, and expanded bandwidth, thus revolutionizing the domain of underwater communication. UOC leverages the light propagation characteristics in water by emitting light signals through light sources like lasers or LEDs and subsequently receiving and decoding these signals using optical receivers. Unlike optical communication in air, underwater optical communication is influenced by factors such as water absorption, scattering, and dispersion, necessitating specialized optical transmission techniques. UOC technology boasts a broad spectrum of applications across diverse domains. In the realm of marine scientific research, UOC can facilitate real-time monitoring of marine environmental parameters, data collection, and seabed topography detection. Within the domain of marine resource exploration, UOC can be harnessed for controlling underwater drones or remote devices to enable the detection and exploitation of subsea oil, gas, and mineral resources. Furthermore, UOC has found application in underwater robot communication, underwater monitoring, and underwater remote sensing, providing a dependable communication avenue for underwater operations. Nonetheless, despite the remarkable strides made in UOC technology, it continues to confront numerous challenges.

2.3.1.3 Underwater electromagnetic communication technology

Underwater communication is inseparable from electromagnetic induction communication[41], which utilizes electromagnetic principles to transmit information underwater. The transmission of information can be realized through the change of the magnetic field generated by the conductor carrying the electric current. Although the underwater environment will be affected by the absorption and scattering of water and other factors, resulting in a more limited transmission distance, which can only be applied to short-distance communication in offshore and shallow water areas, electromagnetic induction communication is still an important mode of underwater communication, and it is widely used in the fields of underwater robot control, seabed resource exploration and other fields, which provides a reliable means of communication for underwater scientific research and engineering applications.

2.3.1.4 Underwater robot

Amidst the current wave of scientific and technological advancements, underwater robots have emerged as crucial tools extensively employed in marine scientific research, seabed resource exploration, and marine environment monitoring, and so on[42]. The progress in underwater communication technology plays a pivotal role in facilitating the operation and control of these underwater robots. As depicted in Figure 5, this paper aims to elucidate the significant role of underwater communication technology for underwater robots through an exploration of four key aspects: underwater acoustic communication technology, underwater electromagnetic wave communication technology, underwater optical communication technology, and extended underwater acoustic communication.

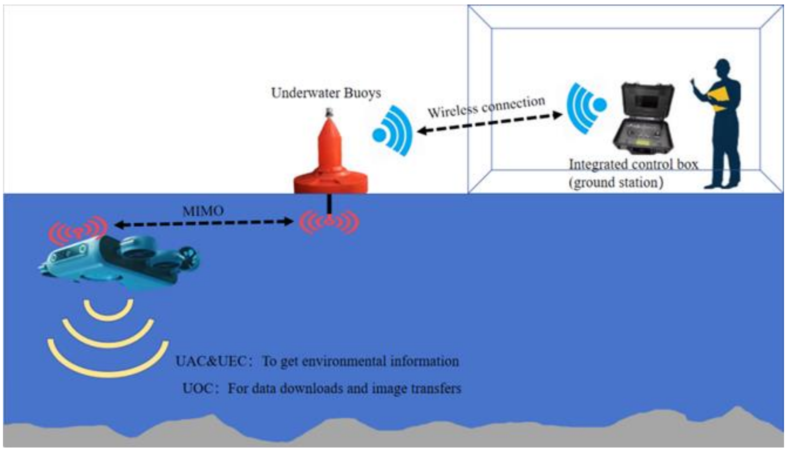

Figure. 5. Working principle of underwater robot.

Underwater acoustic communication technology, being one of the primary forms of underwater communication technology, possesses the advantages of versatility in various underwater environments, long-range transmission capabilities, and high reliability. Consequently, it plays an irreplaceable role in facilitating communication for underwater robots. By employing sound waves for transmission and reception, underwater acoustic communication technology enables underwater robots to engage in remote communication with control stations, exchange data, and acquire environmental information. Additionally, underwater electromagnetic wave communication technology also holds significant importance in data transmission within shallow water areas and offshore environments. Despite certain constraints on radio wave propagation underwater, the current underwater electromagnetic wave communication technology remains an effective choice for short-range communication among underwater robots or long-range communication with surface control stations. As an emerging underwater communication technology, underwater communication technology exhibits notable advantages such as high-speed transmission and low latency. Optical communication can be utilized for close-range communication, data downloading, and image transmission, thereby offering a more efficient mode of communication. Lastly, the expanded underwater acoustic communication technology provides an effective solution to overcome the limitations of acoustic wave transmission in the underwater environment. Utilizing sonar arrays, MIMO (Multiple-Input Multiple-Output), and other technologies, the communication reliability, bandwidth, and distance range of underwater robots have been significantly enhanced, subsequently improving the overall performance of the underwater communication system.

2.3.2 Current status of Chinese research on underwater communication technology

The evolution of underwater communication technology in China can be traced back to the 1960s, when it was primarily utilized for submarine oil exploration and marine scientific research [43]. As science and technology have advanced, underwater communication technology has also undergone significant development. From the initial acoustic communication technology to later optical communication and artificial intelligence technology, Chinese underwater communication technology has progressed towards high-speed [44], large bandwidth [45], intelligence [466], and autonomy [47].

Currently, in China, the development of underwater communication technology is experiencing rapid growth. This can be attributed to the country's continuous emphasis on the development of marine resources, marine scientific research, and marine environment monitoring, which has led to an increasing demand for underwater communication technology. The application scope of this technology encompasses a broad range of fields, ranging from marine energy exploration to deep-sea scientific research, thereby necessitating higher technical requirements. China has achieved significant progress in underwater communication technology, with notable research and development efforts focused on underwater acoustic communication, underwater optical communication, and underwater artificial intelligence technology. These technological advancements have established a robust foundation for China's exploration and utilization of the marine domain [48].

China has made significant strides in underwater acoustic communication technology, with key contributions from Sun Zhi [49], Yang Peng [50], and Li Juan [51]. Underwater acoustic communication uses sound waves to transmit information through water. Chinese researchers have focused on enhancing transmission rates and distances. [52-56] Recently, China has developed various underwater communication systems with independent intellectual property rights, supporting ocean exploration, marine research, and environmental monitoring [57-60].

Secondly, underwater optical communication technology represents a significant area of focus in Chinese underwater communication technology development. Underwater optical communication exploits the propagation characteristics of light waves underwater to achieve high-speed data transmission and large bandwidth. China has embarked on systematic research and conducted experiments in the field of underwater optical communication technology, leading to noteworthy advancements [61-64]. Researchers are dedicated to addressing various technical challenges in underwater optical communication, including optical signal attenuation [65], scattering [66], and multipath propagation [67], with the ultimate goal of enhancing the stability and reliability of underwater optical communication systems [68].

Besides, underwater artificial intelligence (AI) technology has emerged as a prominent field within the development of underwater communication technology in China. With the rapid advancement and widespread application of AI technology, underwater AI technology is increasingly being utilized in the marine domain. Chinese researchers are actively exploring the integration of AI technology into underwater robots, unmanned submersibles, and underwater data analysis, aiming to enhance the efficiency and accuracy of underwater detection, monitoring, and data processing. The works of Guangming Xie [69] and Lijuan Liu [70] highlight China's development of underwater AI technology, wherein advanced AI algorithms such as Deep Learning and machine learning are employed to facilitate seamless collaboration between AI systems and researchers in underwater environments. At present, China is actively developing intelligent and autonomous underwater equipment and systems, which are expected to provide robust technical support for marine scientific research, marine resource exploration, and marine environment monitoring.

Underwater communication technology will continue to assume a pivotal role in the development of China's marine economy and the implementation of its maritime strategy [71].

2.3.3 Research status of foreign underwater communication technology

The development of underwater communication technology foreign countries can be traced back to the early 20th century, originating from research and application of sonar technology. Although China entered the field a bit later, over time, underwater communication technology has gradually advanced and achieved a leading position. The growing demand for underwater communication technology in various countries, including marine resource development, national defense and security, and scientific research, has stimulated continuous innovation and development in this field. Moreover, the international community has also taken a leading role in the development of international standards, industry chain construction, and international cooperation, thereby making significant contributions to the foreign advancement of underwater communication technology.

Regarding underwater communication, international scholars continue to propose innovative theoretical models and technical solutions to adapt to diverse underwater environments, as compared to China. For instance, Ali and Elmustafa Sayed have published literature that enhances underwater communication in various environments, including deep and shallow seas, by proposing a range of effective channel models and developing corresponding signal processing algorithms to achieve high rates and reliability in complex underwater environments [72]. Additionally, foreign scholars have conducted extensive research on the topology design [73], routing protocols [74], and energy management [75] of underwater communication networks, which provide critical support for the realization of intelligent underwater systems.

Foreign scholars have also made remarkable achievements in optical communications, with fiber optic communication being widely used as one of the core technologies in underwater optical communication. Alberto iBononi [766], a foreign scholar, and Chinese scholar Yang Shaojian [77] have equally shared their ideas and conducted in-depth research on the design of fiber optic communication systems and fiber optic sensing technology, which provide crucial technical support for high-rate and long-distance underwater communication. Furthermore, laser communication, a new type of underwater communication technology with high-speed rates and low latency, has garnered significant attention worldwide [78]. Scholars foreign countries have conducted extensive research on the design of laser communication systems, beam modulation technology, and more, which presents new possibilities for the development of underwater communication technology.

In terms of underwater AI technology, the world has a more mature technology and rich experience in this field. For instance, in June 2023, Shankar Achyut published "Efficient Data Interpretation and Artificial Intelligence Enabled IoT-Based Smart Sensing System" [79], which addresses the crucial question of AI - reducing consumption. On the other hand, in "Underwater Internet of Things-Based Solutions for Intelligent Marine Target Recognition" [80], published by Chinese scholars Hu et al. on August 23rd, 2022, they suggest that AI should initially tackle the problems of poor data processing ability of underwater hardware devices and low accuracy of classification algorithms. This demonstrates the differing views of China and the rest of the world regarding AI.

In summary, as depicted in Fig. 6, the current research status of Chinese and foreign underwater communication technology presents distinctive characteristics. Foreign underwater communication technology has achieved significant advances in hydroacoustic communication, optical communication, underwater network, and other areas [81-83], providing vital support for the development of underwater resource exploration and ocean monitoring. In contrast, there is still a considerable gap in China's underwater communication technology. Nevertheless, the government and scientific research institutions have acknowledged this issue and are increasing their investment and support in related fields [84]. In the future, China can learn from the foreign advanced experience, strengthen domestic research and development in underwater communication technology, and achieve independent innovation and a leading position in marine resource development and marine environment monitoring.

	First point	Second point	Third point
Foreign scholars (Unlike Chinese scholars)	Foreign scholars may pay more attention to technological innovation and bsic theoretical research.	They may be more inclined to explore new principles, algorithms, and methods of underwater communicationtechnology to improve system performance and overcome technical bottlenecks.	Due to the support of foreign governments is different, the focus of foreign scholars may differ.
similarities (between Foreign scholars and Chinese scholars)	Both domestic and foreign scholars are dedicated to enhancing the performance and reliability of underwater communication systems.	They encounter similar technical challenges, such as unstable underwater channel characteristics and significant signal attenuation. Consequently, they are focused on identifying solutions to overcome these hurdles.	In terms of collaboration and exchange, scholars from both domestic and foreign spheres actively share research findings and engage in discussions on technical issues, thereby fostering the advancement of underwater communication technology.
Chinese scholars (Unlike Foreign scholars)	Domestic scholars may be influenced by government policies and national strategies, guiding their research directions toward national development needs and policy objectives.	They often focus on domestic underwater communication application scenarios and requirements, such as marine resource development and environmental monitoring.	Facing the vast domestic market and diversified needs, some domestic scholars in the field of Underwater communication may give priority to the practical implementation and commercialization of technology applications.

Figure.6. Trends that differentiate the current status of underwater communication research in China from that of the world.

3. Machine learning

3.1 Basic concepts of machine learning

3.1.1 Definition and classification of machine learning

Machine learning is a crucial branch of the artificial intelligence (AI) field [85-87]. Its primary aim is to enable computer systems to perform specific tasks without explicit programming by allowing them to learn from data. Machine learning diverges from traditional rule-based programming as it focuses on enhancing system performance through data and experience.

Machine learning can be categorized based on how it learns and the target task. Here are a few common classifications of machine learning :

(1) Supervised Learning [88]: In supervised learning, the algorithm is provided with labeled training data, where each data sample consists of an input feature and an output label. The objective of the algorithm is to learn the mapping relationship between inputs and outputs, enabling accurate predictions for new inputs. Common tasks in supervised learning include classification and regression.

(2) Unsupervised Learning [89]: In unsupervised learning, the algorithm operates on training data without any labeling information. The objective of the system is to autonomously discover patterns and structures within the data. This type of algorithm is commonly used for tasks such as clustering, dimensionality reduction, and association rule mining.

(3) Semi-supervised Learning [90]: Semi-supervised learning is a hybrid approach that combines supervised and unsupervised learning techniques. It leverages both labeled data for supervised learning and unlabeled data for unsupervised learning. This approach is commonly employed when data labeling is expensive or when there is a limited availability of labeled data.

(4) Reinforcement Learning [91]: Reinforcement learning is a method of learning optimal behavioral strategies through an interactive process with the environment. In reinforcement learning, an algorithm (also known as an intelligent agent) adapts its behavior based on the rewards or penalties associated with the actions performed, thus gradually learning how to maximize the cumulative rewards.

3.1.2 Commonly used machine learning algorithms

Throughout the evolution of machine learning, several crucial concepts, techniques, and algorithms have surfaced to drive the incessant progress and innovation within the field. Presented below are some prevalent machine learning techniques and algorithms:

(1) Decision Trees [92]: As illustrated in Figure 7, Decision Trees serve as a straightforward yet influential algorithm for classification and regression tasks. They partition data by constructing a tree structure where each node represents a feature, and each branch signifies a potential output. Decision trees offer ease of comprehension and interpretation, while possessing a certain capability to handle nonlinear relationships. These algorithms have garnered extensive research attention and practical application in the realm of underwater communication. Notably, some researchers have employed decision trees for the classification and identification of underwater signals, enabling differentiation between various types of hydroacoustic signals like sonar signals and biological sounds. Furthermore, decision trees have been utilized for fault diagnosis and optimization of underwater communication systems, facilitating swift problem localization and resolution by system engineers. While the application of decision trees in underwater communication offers several advantages, it also presents certain limitations. On the positive side, decision trees

possess a simple and intuitive structure that facilitates tasks such as classifying and recognizing underwater signals. However, when confronted with high-dimensional and complex data, decision trees may encounter overfitting issues, resulting in diminished model generalization ability.

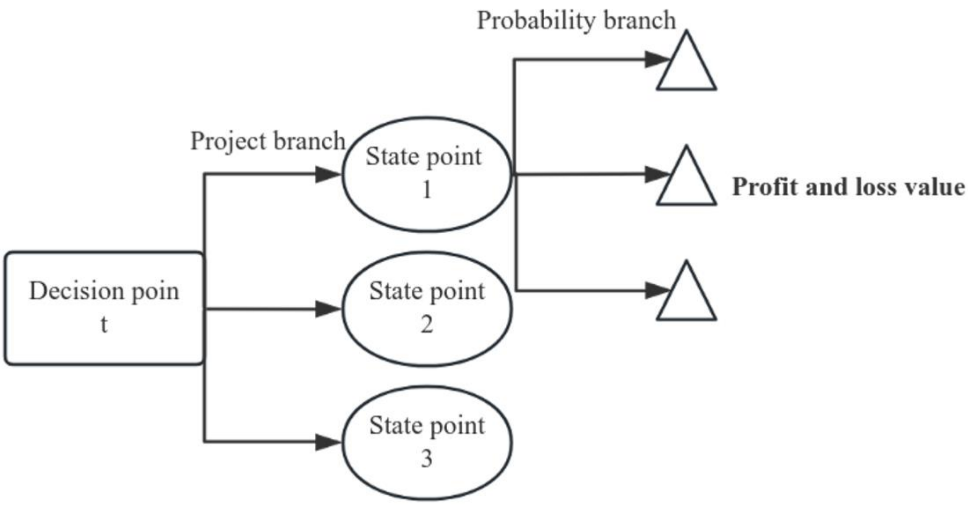

Figure.7. Schematic diagram of decision tree algorithm.

(2)Support Vector Machines (SVMs) [93]: As depicted in Figure 8, Support Vector machines emerge as potent supervised learning algorithms extensively utilized for classification and regression tasks. The fundamental concept behind SVMs is to identify the optimal hyperplane that maximizes the margin between classes, thereby achieving optimal segregation by maximizing inter-class distance. SVMs can be employed alongside kernel functions, enabling data mapping into high-dimensional spaces to address intricate nonlinear relationships. This attribute empowers SVMs to excel in handling high-dimensional and nonlinear data, exhibiting robust generalization capabilities. In the sphere of underwater communication, SVMs have found applications in various tasks, including signal classification, target identification, and fault diagnosis. For instance, SVMs can effectively classify hydroacoustic signals, facilitating the identification of diverse underwater entities such as organisms, ships, and sonar signals. Given the prevalent interference and noise in underwater communication environments, SVMs' immunity to noise and generalization properties render them an ideal choice.

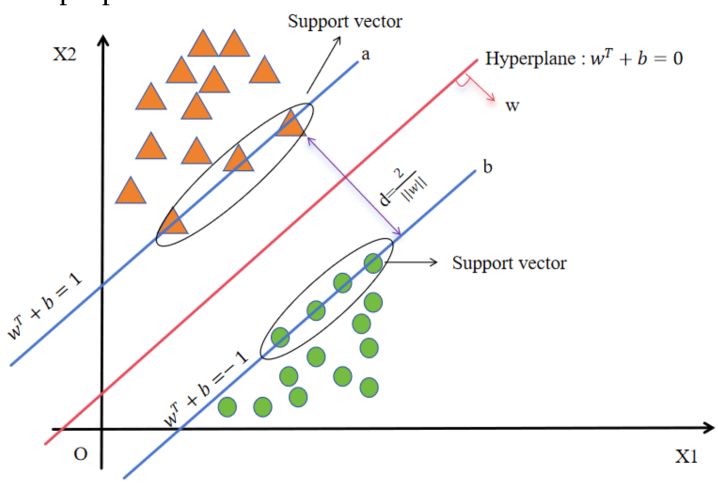

Figure.8. Schematic diagram of support vector machine algorithm.

（4）Deep Learning [94]: Deep learning is a machine learning method based on artificial neural networks, as illustrated in Figure 9, characterized by a multi-level neural network structure. Through multilevel nonlinear transformations, deep learning models can autonomously learn the feature representation of data, leading to remarkable achievements in tasks such as image recognition, speech recognition, and natural language processing. In the field of underwater communication research, deep learning has been leveraged to enhance the performance of underwater communication systems. Researchers have employed deep learning techniques to optimize underwater acoustic signal processing, enhancing the signal's anti-jamming capability and data transmission rate. Additionally, deep learning has been utilized for underwater communication channel modeling and prediction, facilitating a more accurate understanding of underwater channel characteristics and dynamics. Concerning underwater communication applications, deep learning technology enables the realization of intelligent underwater sensor networks and underwater robotic systems. However, deep learning models encounter challenges such as high computational complexity, substantial data requirements, and limited model interpretability. The practical applications of deep learning models necessitate comprehensive consideration of their performance and feasibility.

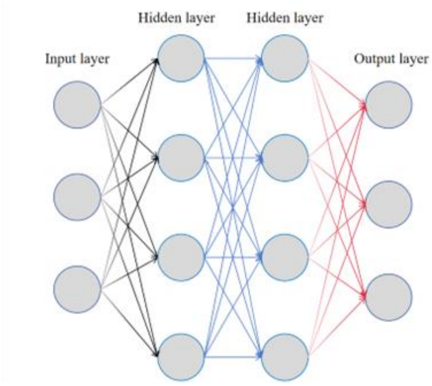

Figure.9. Schematic diagram of deep learning, neural network algorithm.

(6)Ensemble Learning [95]: Integrated learning improves the overall prediction performance by combining the prediction results of multiple underlying models. Common integration methods include, for example, Boosting in Figure 10, and Stacking in Figure 11. And in the field of underwater communication, experts such as Yan, J and Cao, WQ (2022) [96] have conducted in-depth research on the application of ensemble learning in underwater communication systems. Their work aims to utilize integrated learning techniques to improve the data transmission rate, reliability, and coverage of underwater communication systems to meet the demand for efficient communication in the fields of ocean exploration, seabed resource exploitation, and underwater robotics. The advantage of the integrated learning approach is the ability to integrate the strengths of multiple models, which improves the prediction accuracy and robustness of underwater communication systems to effectively cope with the complexity of the underwater environment. However, it should be noted that integrated learning also has disadvantages such as increasing the cost of computational resources and time, and increasing the complexity of the system, which need to be fully considered in the design and implementation process.

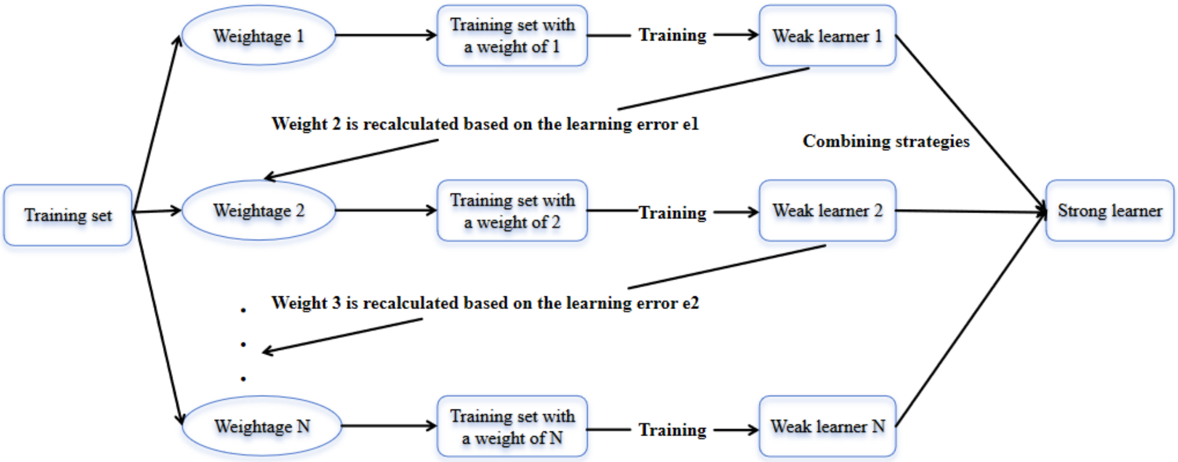

Figure.10. Schematic diagram of the algorithm for Boosting.

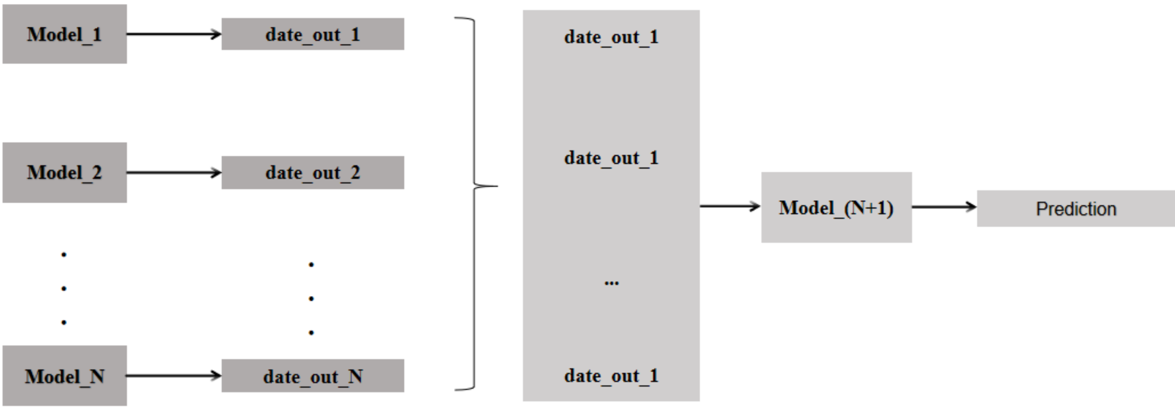

Figure.11. Schematic diagram of the algorithm for Stacking.

(7)Dimensionality Reduction Algorithms (DRA) [97]: Dimensionality reduction algorithms are utilized to reduce data dimensionality while preserving essential features, with the aim of decreasing computational complexity, eliminating noise and redundant information, and enhancing the model's generalization ability. In the field of underwater communication, researchers have also applied dimensionality reduction algorithms to optimize underwater signal processing and data transmission. For instance, Huang, LH et al. (2020) [98] employed a PCA algorithm, such as the one shown in Fig. 12, to reduce the dimensionality of signal features in underwater communication, thus improving accuracy and stability of signal recognition. Dimensionality reduction algorithms can help optimize underwater signal processing and data transmission processes, improving the reliability and efficiency of data transmission. By reducing data dimensionality, these algorithms alleviate computational complexity, leading to improved response speed and real-time performance of the system. Additionally, dimensionality reduction algorithms eliminate noise and redundant information in data, thereby enhancing the accuracy and stability of data transmission, meeting the requirements for high-quality data transmission in underwater communication systems.

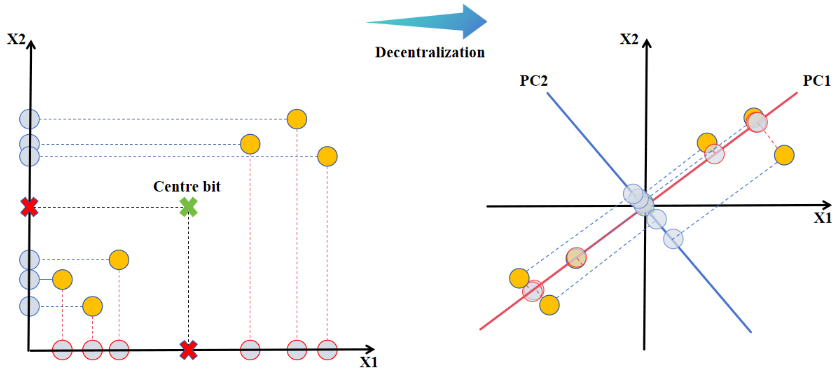

Figure.12. Algorithmic schematic of PCA in dimensionality reduction algorithm

3.2 Machine learning based application of underwater communication technology

3.2.1 Underwater channel modeling and prediction

Underwater channel modeling and prediction encompass the utilization of machine learning techniques to model and predict the signal transmission environment in underwater communication. This process entails capturing the properties of the underwater environment, including water temperature, salinity, and suspended matter, as well as the physical characteristics associated with sound wave propagation through water. Accurate modeling and prediction of the underwater channel facilitate the design of efficient underwater communication systems while enhancing communication performance and reliability. Noteworthy methodologies encompass theoretical modeling, computational simulation, and field testing. The prediction and modeling of underwater channels necessitates a comprehensive approach that combines theoretical analysis, computational simulation, and field testing to obtain precise channel characteristics and propagation parameters that support the design and optimization of underwater communication systems.

3.2.2 Channel processing and mediation techniques

Signal processing and demodulation techniques play a pivotal role in the realm of underwater communication. Signal processing encompasses fundamental operations such as sampling, filtering, and signal transformation to extract or modify their inherent characteristics. Conversely, demodulation entails the conversion of modulated signals back to their original form. In underwater communication, the signal undergoes modulation and transmission, necessitating demodulation at the receiving end to restore it to its original state. Common modulation techniques encompass frequency modulation (FM), amplitude modulation (AM), phase modulation (PM), among others. The demodulation process varies based on the modulation method, typically involving steps such as signal extraction, filtering, and demodulation. Furthermore, the integration of machine learning with signal processing and demodulation techniques gives rise to numerous cutting-edge applications and domains. Notably, the fusion of machine learning and signal processing facilitates noise suppression and signal enhancement. Confronted with intricate signal environments and noise interference, conventional signal processing approaches may appear inadequate. Leveraging the robust learning capabilities of machine learning, models can be trained to effectively extract signals from noise or enhance signal quality, thereby improving system performance and data accuracy.

3.2.3 Error correction and channel coding

Amidst the ongoing advancement of communication technology, error correction and channel coding have emerged as crucial technical mechanisms for ensuring the reliability and performance of communication systems [99]. Significantly, machine learning, renowned for its formidable data analysis capabilities and pattern recognition prowess, is progressively finding application in the realm of error correction and channel coding. Consequently, this integration has ushered in novel breakthroughs and advancements within underwater communication systems.

The integration of machine learning in error correction has yielded superior error correction performance within communication systems. Conventional error correction codes, including convolutional codes and LDPC codes, demand prior design of coding methodology and error correction capabilities. In contrast, machine learning techniques can optimize error correction coding design by learning from vast datasets and channel characteristics. This fosters enhanced adaptability of encoders and decoders to differing channel environments and noise models, resulting in improved error correction performance within communication systems.

The incorporation of machine learning in channel coding further elevates the coding efficiency and system throughput within underwater communication systems. Traditional channel coding algorithms necessitate substantial computational and storage resources within the communication system. Conversely, machine learning technology can optimize channel coding methods and parameter configurations by assimilating data and channel characteristics. This optimization reduces computational complexity and resource consumption during the coding process, thereby enhancing the coding efficiency and system throughput.

4. Challenges and perspectives

4.1Challenges of both technologies

Underwater communication technology, being a pivotal technology connecting marine resource development, scientific research, and safety monitoring. Primarily, the complexity of the underwater environment stands as a key restricting factor in the development of underwater communication technology. The underwater environment harbors diverse noise sources, including water currents, biological sounds, ship engine sounds, and the like, which interfere with underwater communication signals. These noise sources not only occur frequently and irregularly but also overlap with the frequency of communication signals, rendering signal identification and extraction more arduous. Consequently, effectively suppressing underwater noise interference and enhancing the signal-to-noise ratio of communication signals have emerged as crucial challenges in the advancement of underwater communication technology. Furthermore, factors such as depth, temperature, pressure, and seawater properties affect signal transmission, reception, and light propagation, ultimately leading to limited underwater communication spectrum resources and bandwidth constraints. These limitations hinder high-speed data transmission and long-distance communication, consequently limiting the data transmission rate and communication capacity, thereby increasing the time cost associated with underwater communication.As traditional modulation techniques and signal coding schemes often fail to fully utilize the limited spectrum resources, there is a pressing need for scientists to develop more efficient modulation algorithms and spectrum utilization techniques aimed at enhancing the data transmission rate and communication efficiency of underwater communication systems [100-104]. Secondly, the energy supply problem faced by underwater communication systems poses a challenge that requires resolution. Underwater communication devices are required to function for extended periods in deep-water environments, yet sourcing energy presents a formidable challenge. The traditional battery power supply method suffers from issues such as low energy density, short life, and charging difficulties, which limit the utility and efficiency of underwater devices [105-108]. Therefore, realizing effective energy management and leveraging novel energy technologies have become crucial development directions for underwater communication technology.

Therefore, the utilization of machine learning techniques for optimizing underwater communication systems introduces a series of challenges due to the aforementioned limitations:

The primary challenge in underwater communication pertains to the scarcity and quality of data. The closed and intricate nature of underwater environments makes it exceedingly challenging to procure extensive, high-quality data, thereby posing a significant obstacle to the training and efficacy of machine learning algorithms. Nodes within underwater communication networks are typically dispersed across the seafloor, water surface, and underwater mobile platforms, locations that are often arduous to access directly, resulting in limited data acquisition. Data obtained by underwater sensors are subject to influences from environmental factors such as water quality and current, rendering them susceptible to noise, distortion, and other interferences, thus further diminishing the quality and accessibility of the data.Additionally, the intricacy of underwater signal transmission represents a crucial concern. Underwater signals are influenced by water absorption, scattering, and multipath effects, culminating in a wide array of complexities during signal transmission and reception and intensifying the challenges associated with algorithm design. Underwater channels exhibit characteristics such as high latency, low bandwidth, and multipath fading, rendering the direct application of conventional communication technologies in underwater communication arduous. Consequently, novel machine learning algorithms and communication protocols must be devised to accommodate these distinctive characteristics.

4.2 Perspective

The synergy between machine learning and underwater communication technologies presents numerous development trends and solutions for existing challenges. Future developments will likely encompass multi-modal fusion communication, such as acousto-optic communication and acousto-electric communication, aimed at enhancing communication rates and reliability.Simultaneously, adaptive signal processing algorithms and intelligent perception technology are integrated to accomplish automatic adaptation and optimization of the intricate underwater environment, augmenting the communication system's adaptability. With mounting demands for marine resource development, marine scientific research, and marine safety monitoring, the future of underwater communication technology will likely witness the establishment of a foreign underwater communication network, enabling worldwide data and communication connectivity. Furthermore, novel materials and technologies such as nanotechnology and quantum communication are harnessed to enhance the performance and functionality of underwater communication devices, consequently propelling the innovative progression of underwater communication technology. In underwater communication, machine learning technology can serve multiple roles, encompassing but not confined to the following aspects:

1) Communication link optimization: machine learning can analyze the characteristics and variations of underwater communication links, enabling real-time adjustment of communication parameters to optimize link performance. This includes enhancing transmission rates and reducing latency.
2) Adaptive modulation and coding: machine learning-based algorithms can dynamically adjust the modulation and coding scheme based on the characteristics of the current underwater environment and noise conditions, thereby maximizing the efficiency and reliability of data transmission.

The development of machine learning technology in the field of underwater communication holds significant strategic importance and plays a crucial role in advancing marine resource utilization, enhancing maritime safety, and fostering the progress of marine scientific research, among other areas. As future technology continues to evolve and application domains expand, the development of underwater communication technology and machine learning technology will encounter new opportunities and challenges. To fully leverage these opportunities and promote the development of machine learning technology in underwater communication, this paper posits that particular emphasis should be placed on the following aspects:

1. Technological innovation and investment in research and development (R&D): Continuous technological innovation serves as the pivotal driving force in propelling the progress of underwater communication and machine learning technologies. This entails exploring novel communication methods (e.g., optical communication, electromagnetic communication, etc.) and enhancing existing technologies (e.g., acoustic communication technology). Simultaneously, augmenting investment in machine learning R&D, encompassing not only financial support but also personnel training and research infrastructure establishment, can indirectly foster the advancement of underwater communication.
2. Energy technology updates: Addressing the energy supply issue for underwater communication equipment is crucial to ensure the stable and long-term operation of

machine learning technology. The development of novel and efficient energy technologies, including harnessing ocean energy (e.g., wave energy, tidal energy, etc.) to power underwater communication equipment or the creation of advanced high-energy-density batteries, represents important avenues for future progress .

3. International cooperation and standardization: The ocean represents a foreign public resource, necessitating international collaboration and communication for the development of machine learning technology and underwater communication technology. Facilitating the harmonization of technical standards through international cooperation will not only bolster technology adoption but also foster the equitable sharing of foreign countries
4. marine resources and the joint preservation of the marine environment.
5. Physical impact and ecological protection: The development and utilization of underwater communication technology may exert various effects on marine life and ecosystems, including noise interference, electromagnetic radiation, and other factors. Consequently, future research must remain vigilant regarding the implications of underwater communication technology on marine organisms. Moreover, machine learning technology should be employed to mitigate the adverse impact of underwater communication devices on the ecosystem, thus ensuring that the utilization of such

Through the efforts of the above aspects, I believe that future underwater communication technology will continue to move to new heights, bringing more innovation and progress to human society in the fields of marine development, scientific research and environmental protection, and realizing the sustainable use and protection of marine resources.

5.Summary

With the continuous advancement of modern science and technology, underwater communication has emerged as a pivotal and increasingly pertinent field. Therefore underwater communication technology based on machine learning has significant implications for marine development. For example, machine learning can be applied to underwater channel modeling and prediction. Through the collection of vast amounts of underwater channel data and the application of machine learning algorithms, accurate channel models can be constructed, and channel variations can be predicted to optimize the design and parameter configuration of underwater communication systems. Machine learning algorithms enable adaptive modulation and demodulation, dynamically adjusting the modulation scheme according to real-time channel conditions to enhance the anti-interference ability and signal transmission efficiency of the communication system. These networks typically consist of numerous nodes, with complex and variable interconnectivity. By employing machine learning algorithms, intelligent node collaboration and optimized routing can be achieved, enhancing network stability and transmission efficiency.In recent years, with the development of artificial intelligence, Internet of Things and other emerging technologies, a series of new technologies and research directions have emerged in the field of underwater communication. For example, the design of underwater

Internet of Things system, etc. These new technologies provide new ideas and methods for solving the difficult problems in underwater communication. In the international arena, countries have carried out extensive cooperation and exchanges in the field of underwater communication, and strengthened the common exploration and promotion of underwater communication technology through international conferences, academic papers, joint R&D projects and other ways. Such cooperation helps countries to jointly address the challenges in the field of underwater communication, thus promoting the development and application of foreign underwater communication technology.

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Regarding the current state of underwater communication research in China and foreign countries, several aspects can be discussed. Firstly, in terms of domestic underwater communication technology development, Chinese scholars have demonstrated continuous innovation in various technical domains, including hydroacoustic communication and fiber optic communication. Their efforts aim to enhance the transmission rate and stability of communication. Moreover, recognizing the unique characteristics of the marine environment, domestic research institutions actively promote the establishment of underwater sensing networks to facilitate real-time monitoring and data collection of marine environments. Additionally, with the advancement of underwater robotics technology, China has also begun to focus on communication technology between underwater robots to enable collaboration and control of underwater operational tasks. In terms of security and privacy protection, domestic researchers have proposed a range of solutions to ensure the safety and reliability of underwater communication. On a foreign scale, underwater communication technology has made significant advancements. In the field of marine scientific research, it has been extensively employed to support data transmission and communication requirements for projects such as ocean exploration and seabed geological investigations. Within military applications, underwater communication technology has emerged as a crucial research area, driven by the growing demands of the foreign military sector. Furthermore, progress in fields like underwater energy development and underwater unmanned aerial vehicles has also contributed to the advancement of underwater communication technology. These developments provide robust support for marine resource development and scientific research.

Looking towards the future, the development of underwater communication technology necessitates ongoing efforts in several key areas. Firstly, technological innovation and increased research and development investment serve as the core driving forces for advancing underwater communication technology. Exploring new communication methods, improving existing technologies, and increasing R&D investments are essential steps towards achieving better outcomes. Secondly, the advancement of energy technologies is crucial to ensuring the long-term and stable operation of underwater communication equipment. This includes the development of efficient energy technologies and high energy density batteries. Furthermore, the construction of improved systems and networks, along with international cooperation and standardization, are vital directions for enhancing the efficiency of marine resource utilization and the effectiveness of marine environment monitoring. Attention must also be given to security and privacy protection, addressing issues related to environmental adaptability, durability, ecological preservation, and disaster prevention. Finally, emphasis should be placed on commercialization and the development of industry chains to promote widespread application of underwater communication technology in commercial fields. By combining these efforts, the future of underwater communication technology will continue to progress, fostering innovation in marine development, scientific research, and environmental protection. It is important to address challenges and risks while adhering to the principles of sustainable development.

This paper explores the application of machine learning in underwater communications and finds that it significantly improves the reliability and efficiency of communications. By applying deep and reinforcement learning algorithms, complex underwater signals can be processed more accurately and data transmission can be optimized, which significantly reduces the BER and signal loss. Despite the challenges of underwater communication such as data scarcity and environmental interference, experimental results show that the machine learning model maintains stable communication quality under various underwater conditions. Future developments may include combining multiple communication modes, adaptive signal processing algorithms, and emerging technologies such as nanotechnology and quantum communication to address existing challenges and drive innovation in underwater communication technology.

In general, remarkable achievements have been made in technological innovation and application expansion in both China and foreign research on underwater communication. However, when compared to the rest of the world, there is still a gap between China and other countries, specifically in key technology breakthroughs, system integration, and application scenarios. Despite this, underwater communication technology has encountered several challenges, including transmission distance, transmission rate, signal interference, and other issues. As the demand for underwater communication technology increases due to the development of marine resources and increased needs for marine environment monitoring, basic research and technological innovation should be strengthened to improve the performance and reliability of underwater communication systems, promote its development in deep-sea, long-distance, and complex environmental applications. Additionally, international cooperation should be strengthened to jointly overcome key technical problems, promoting continuous innovation and application of underwater communication technology, contributing to the development of the marine industry. However, Machine learning technologies have sparked new directions in underwater communication, such as designing underwater IoT systems. Countries are actively collaborating through international conferences, academic exchanges, and joint projects to address underwater communication challenges and enhance technology development. Future progress relies on technological innovation, increased R&D investment, improved energy solutions, and international cooperation. Additionally, the application of machine learning, has shown promise in improving communication reliability and efficiency. Addressing data scarcity, environmental interference, and integrating new technologies will be crucial for advancing underwater communication.Driven by international cooperation and innovation, it is believed that underwater communication technology will continue to break through bottlenecks and provide more reliable and efficient communication support for marine scientific research, marine resource development, military defense, and other fields.

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