

Underwater Sensing Technologies and Applications

Subjects: Engineering, Marine

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Currently, a variety of sensing methods based on optics, acoustics, and electromagnetics are widely applied for ocean observation and exploration. Acoustic sensing contains various sonar devices for seafloor mapping, submersible navigation, and underwater object. Optical sensing technologies applied to ocean exploration include underwater imaging for objects inspection, spectrophotometry, and fluorophotometry for environmental parameters monitoring. Technologies of electromagnetics are used for underwater metal detection such as mines and mineral resources, and for underwater inspections of cables and pipelines.

Keywords: submersible ; sensors

1. Geological Survey

Although ocean observation has been made for hundreds of years, only a limited percentage of the entire seabed has been measured for depth ^[1]. The lack of seafloor maps has significantly limited the progress of human investigation and understanding of the oceans. With the advancement of sensing technologies and the increase in human activities in the oceans, low-cost and high-resolution ocean observation devices have been developed and equipped on various platforms, such as single-beam sonar, multibeam sonar, sub-bottom profiler, and side-scan sonar. The Nippon Foundation and the General Bathymetric Chart of the Oceans (GEBCO) plan to cooperate globally to map the whole seafloor topography by the end of 2030 ^[1]. The detailed charted topography of the whole ocean will have a great help on understanding of marine geology, utilizing the marine mineral and renewable energy resources, monitoring the marine geohazards and providing route surveys for underwater cables and pipelines ^{[2][3]}. Because of the efficiency and convenience, remote sensing devices have also become a popular research topic in recent years, such as satellite altimetry, bathymetric LiDAR, and satellite-derived bathymetry (SDB) ^[3]. However, their resolution and accuracy are still far from measurement at close range ^[4].

2. Navigation and Communication

Underwater navigation and communication are the key technologies to locate and control submersibles. Due to the high attenuation in seawater, the Global Navigation Satellite System (GNSS) cannot be used underwater ^[5]. For long-term tasks, submersibles must be equipped with high-precision navigation systems. Inertial/dead reckoning (DR), acoustic and geophysical navigation are introduced for underwater navigation. In addition, different technologies are developed for underwater communications. However, there is still no high bandwidth, long-distance, and low power consumption communication solution until now.

2.1. Location and Navigation

Due to the cable links and professional pilots, ROVs are not as flexible as AUVs. It is also because of this, that AUVs are more dependent on navigation and positioning. Compared to ROVs, AUVs are more flexible and with low cost of use. In addition to the battery life, navigation ranges will also limit the underwater activities of AUVs ^{[6][7]}. The inertial/dead reckoning(DR), acoustic navigation, and geophysical navigation technologies are introduced in the following sections and summarized in **Table 1**.

Table 1. Three main categories of underwater navigations ^[8].

Classifications	Principles	Methods	Characteristics
Inertial/dead reckoning	uses accelerometers and gyroscopes to estimate the current state	Magnetic compass, barometer or pressure sensor, DVL, INS	Increasing and unbounded position error

Classifications	Principles	Methods	Characteristics
Acoustic Navigation	measuring the time of flight (TOF) of signals from acoustic beacons to perform navigate	LBL, UBL, USBL	Depending on beacons
Geophysical Navigation	use external environmental information as references for navigation	Magnetic field maps, visual-based seabed images, identify feature acoustically	Depending on sensors to identify environmental features

2.2. Underwater Communication

Due to the strong conductivity of seawater, radio frequency (RF) communications are severely attenuated in the ocean. So, it cannot be used for underwater communication. Communication systems are composed of a transmitter, a communication channel, and a receiver. The transmitter can transmit information by modulating the information signal on the carrier signal. Combined with the characteristics of the ocean, the widely used communication methods include fiber-optic communication, underwater acoustic communication, RF communication, and optical visible light communication. Moreover, some other communication methods, such as quantum communication, are also being under research.

3. Essential Ocean Variables

Human activities in coastal areas are increasing because the exploration and exploitation of the ocean are becoming more and more intensive. Most of the pollution in the ocean comes from human activities, including oil spills, garbage dumping, and domestic and industrial wastewater discharge [9][10]. The ocean has a vast area, so the source of pollution can be anywhere in any country, which makes it challenging to prevent. In addition, once the ocean is polluted, it will spread globally through ocean currents. Ocean has a considerable influence on the global climate and ecosystem. Although the ocean has a robust self-healing ecosystem, it takes a long time to recover. Therefore, it is vital to have overwhelming monitoring of the ocean environmental conditions, significantly how human activities impact the marine ecosystem. The Global Ocean Observing System (GOOS) has listed many ocean research and assessment variables, called essential ocean variables (EOVs) [11]. They are divided into four classes, physics, biochemistry, biology, and ecosystems, and cross-disciplinary. Most commercially used sensors can cover EOVs in physics and biochemistry.

3.1. CTD—Conductivity, Temperature and Depth

CTD is an instrument applied to measure conductivity, temperature, and depth in the ocean, playing an essential role in submersible navigation and environmental monitoring. Among them, the measurement of salinity, namely conductivity, is the most complex. As early as 1901, Knudsen discovered that seawater salinity could be calculated using electrical conductivity, but it was not until the 1950s that people began to put this method into practice [12]. The first multifunctional salinity sensing instrument, salinity-temperature-depth (STD), was developed [13]. Three years later, to fix the fouling problem when used in seawater, an inductive cell was added to STD [14]. In the following decades, digitalization and microprocessor were added into the development of sensing instruments gradually, which solved salinity 'spiking' issues caused by a mismatch of sensor response time between temperature and conductivity [15]. After that, the practical salinity scale was proposed, which leads to the generalization and standardization of the measurement [16][17]. In the following 30 years, the practical salinity scale of 1978 (PSS-78) [18] has made significant contributions to the research of the oceans. The most classic CTD of Seabird should be the SBE-41 series CTDs, which is designed for the Argo program to profiling 2000 m underwater. Over 15,000 SBE-41 CTDs have been equipped on Argo floats, which validated the stability of these products. In 2010, TEOS-10 was introduced and gradually replaced the practical salinity scale (EOS-80), which has also been accepted by various organizations worldwide [19]. This new standard calculates the properties of seawater by constructing a Gibbs function for seawater [20]. It considers the composition of seawater, its spatial distribution, and the influence of the central material on the density of seawater, which will significantly advance the development of marine science and related interdisciplinary disciplines. The temperature sensor used in CTD is usually a platinum thermistor because of its high accuracy and broader range. The depth measurement is still obtained by converting the pressure measurement. Their advantages and disadvantages of pressure sensors based on piezoresistive, capacitive, and resonant technologies are compared in **Table 2**.

Table 2. Advantages and disadvantages of pressure sensors used for CTDs.

Pressure Sensors	Advantages	Disadvantages
Piezoresistive	simple structure, small size, high precision	low robustness

Pressure Sensors	Advantages	Disadvantages
Capacitive	simple structure, high precision, high robustness	large non-linear error
Resonant	stable construction, high precision, high stability	complex manufacturing and high cost

3.2. Turbidity

Turbidity refers to the resistance to the passing light in solution, which includes scattering light by suspended matter and the absorption of light by solute molecules. The turbidity of water is related to the content of suspended substances in water and their size, shape, and refraction coefficient. Currently, turbidity measurement is based on transmission and scattering methods. The transmission method measures the transmitted light through solutions, but it does not apply to low turbidity measurement. Because in low-turbidity solution, it has little resistance to light, leading to measurement difficulties. The scattering method is better for the measurement of low turbidity solutions because, in a high turbidity solution, multiple scattering occurs, and accurate results cannot be obtained. The ISO-7027 standard specifies that for drinking water, the nephelometry method is used [21]. A turbidimetry can be used for the measurement of seawater turbidity.

3.3. Dissolved Oxygen

Dissolved oxygen (DO) refers to the molecular state of oxygen dissolved in water [22]. It can get continuous replenishment mainly by the dissolution of oxygen from the air and the photosynthesis of plants in the water. If seawater is polluted by organic matter, oxygen in the water will be seriously consumed. Moreover, when dissolved oxygen is not timely replenished, anaerobic bacteria in the water will get rapid reproduction, which leads to the corruption of organic matter and makes the water body more polluted and smelly. Therefore, the amount of dissolved oxygen in water is an indicator of the self-purification ability of the water. The commonly used methods for measuring DO include the Winkler method, electrochemical method, and optical method [23][24]. Winkler's method uses chemical reaction for measurement, which is highly accurate but cumbersome and cannot be measured in-situ. The electrochemical method is based on the current generated by the redox reaction at the electrode to determine the measurement, the measurement efficiency is high, but the reaction electrode is accessible to age, which needs regular maintenance and replacement [24]. The optical method overcomes these disadvantages and is more durable but also more expensive.

4. Underwater Inspections

Throughout the thousands of years in human history, many cultural heritages and a significant number of wrecks, including planes and ships, have been submerged underwater. It is not easy to search and investigate in such a vast and complex ocean. During the wreck search of flight MH370, although many ships, satellites, and AUVs equipped with advanced sensors were put into action, it has not been found since 2014 [25]. In addition to wrecks and cultural heritages, cables, pipelines, and other equipment are constructed underwater, which must be tracked and inspected regularly. Surveys in shallow waters can be carried out by diver observation and video records. However, diver's observations are time-consuming and high-risk. The inspections in marine areas are conducted by ROVs, which are equipped with 3D sonar, and LiDAR [26]. As humans increasingly explore the oceans, more targets need to be searched, detected, and maintained. Due to the successful development of computer vision and algorithms is applied in underwater and sonar images to detect objects. Moreover, in maritime security, underwater object detection technology is also used to identify intruders and ocean mines.

4.1. Underwater Detection

Usually, cultural heritages and wrecks are well preserved in low oxygen conditions underwater. However, human activities, including fishing nets, marine geohazards, and seabed geological change, can lead to damages to these monuments [27][28]. In order to help archaeologists better investigate and protect historical sites, it is necessary to do the surveys more efficiently. Currently, commonly used underwater archaeological surveys include visual methods and sonar images, which are used for object detection. In addition, in maritime security, underwater object detection technology is also used to identify moving intruders and ocean mines.

Due to the absorptive and scattering characteristic of seawater, there are many challenges for underwater imaging [29]. In addition, light can further attenuate due to the suspended particulate matter, and substances in water [30]. For the vision system, light needs to travel in three different media (water, viewports, air) as shown in **Figure 1**. Transparent viewport housing is often made from transparent glass or acrylic, made in a domed shape. As **Figure 1** shows, the refraction provokes a pin-cushion distortion, which makes that the most significant reconstruction errors appear at the edges of the

target [31][32]. Domed shape viewport housing is designed to eliminate the problem, as **Figure 1** shows. Furthermore, an image processing algorithm is another way to calibrate the system.

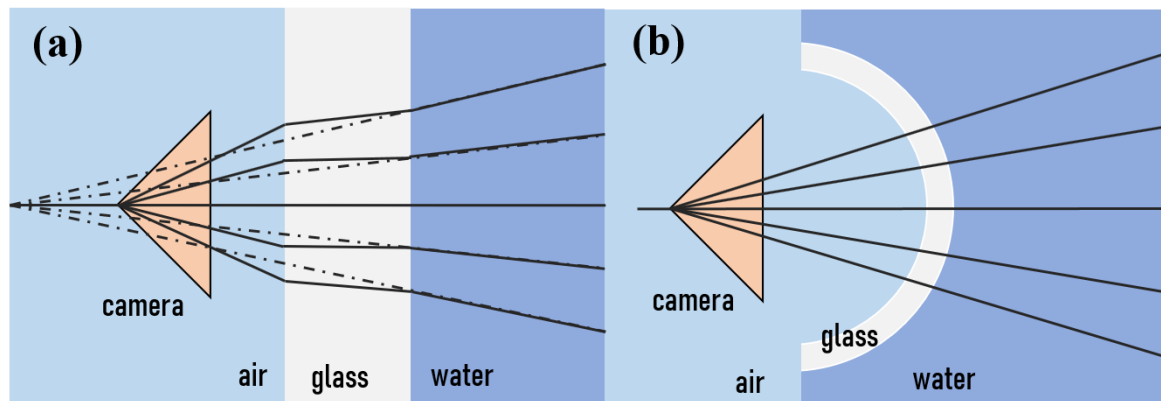


Figure 1. (a). Imaging distortion effect of non-domed shape viewport. (b). Domed shape viewport will release the imaging distortion effect [33].

4.2. Track and Inspect

By now, more than 8000 km of power cables, 1.3 million km of submarine telecommunication cables, and 3 million km of active pipelines have been laid under the oceans [34][35]. **Figure 2a,b** shows the deployed submarine communication cables which connect around the world. The percentages of causing cable damage are classified as a percentage in **Figure 2c**. Anchoring, fishing, and other human activities mainly lead to cable faults, which could have significant disturbances worldwide [36]. It is necessary to inspect cables regularly.

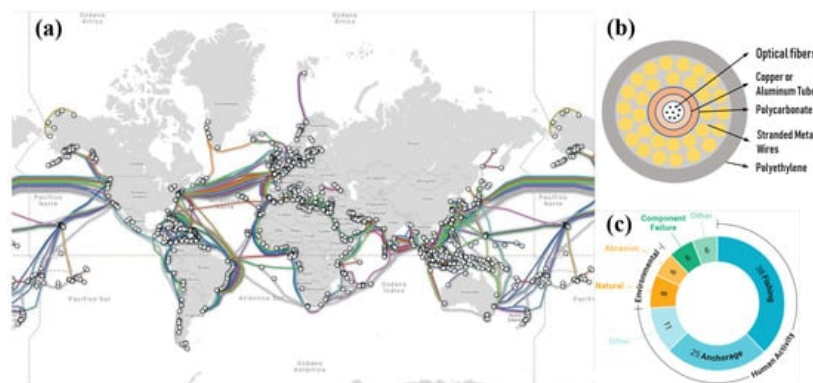


Figure 2. (a) Submarine cables around the world [37]. (b) Cross section of submarine communication cable [38]. (c) Causes of faults for cables [35].

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