WHITE PAPER

Sensors and IoT define future designs for autonomous underwater drones

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1 Foreword

The use of sensors in aquatic environments is growing rapidly. Factors driving this growth include new use cases in ocean, lake, and river systems made possible by the development of new sensors for such tasks as inspecting the properties of water and performing complex underwater manoeuvres. The composition of water makes it difficult to translate existing measurement and sensing methods from land-based operations directly to operations in the water, such as the use of electromagnetic waves in certain frequency bands. Consequently, a variety of acoustic and optical sensor units are used in underwater applications. Sensors on an underwater vehicle can detect widths and depths at high precision. Sensor technology is continuously being developed, modified, and optimised for use in aquatic environments. This white paper summarises the ocean, lake, and river technologies used in a variety of critical underwater applications, including geological studies, navigation and communication, marine environment parameters, and underwater inspections. Trends in the development of underwater sensor technology are influenced largely by future requirements for research and monitoring in aquatic environments.

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2 Introduction

Developments in sensor technology have made it possible to use a variety of optical, acoustic, and electromagnetic sensing methods for applications including ocean observation and exploration. Acoustic sensors can be used to map the ocean floor, navigate underwater, and study underwater objects. Optical sensor technology is used for object inspection, spectrophotometry, and fluorophotometry for environmental parameter monitoring. Electromagnetic technologies are used for underwater metal detection, such as to locate mines and mineral resources, as well as for underwater cable and pipeline inspections.

This white paper has two purposes:

- to establish a reference architecture in order to highlight some of the challenges to be addressed in making autonomous underwater drones more broadly accessible
- to present an overview of how underwater drone work, which types of sensors are used today, what their current capabilities are, and what capabilities they will need in the future.

There is a demand among Danish businesses for information on how they can use modern sensor systems to make underwater drones/ robots more autonomous. Underwater drones used today are typically connected to a drone pilot via a cable. From the water's surface, the drone pilot operates the drone manually using a video signal received from the drone, showing what the drone "sees" in front of itself. This makes for a relatively inexpensive drone solution and allows the drone to send high-quality images to its pilot. However, it also imposes limitations, such as a limited operating radius and limited autonomy.

Underwater drones are divided primarily into ROVs (Remotely Operated Vehicles) and AUVs (Autonomous Underwater Vehicles):

- An ROV is remotely controlled. It has a connecting cable for a drone pilot to control it with a joystick. ROVs typically feature one or more video cameras, and possibly a high-frequency imaging sonar to provide the pilot with visual feedback. The disadvantages of wired drone operation are that the operating radius is limited by the length of the cable, and that the cable may become caught on an object when operating in tight spaces, such as when inspecting fish cages, tanks, and underwater installations.
- An AUV is an autonomous unit that lacks a connecting cable. It is equipped with a battery. The unit is controlled by the AUV's computer. AUVs are equipped for use in monitoring large, possibly difficult-to-access areas and performing autonomous missions.

The primary categories of underwater drones are shown in the figure on the next page.

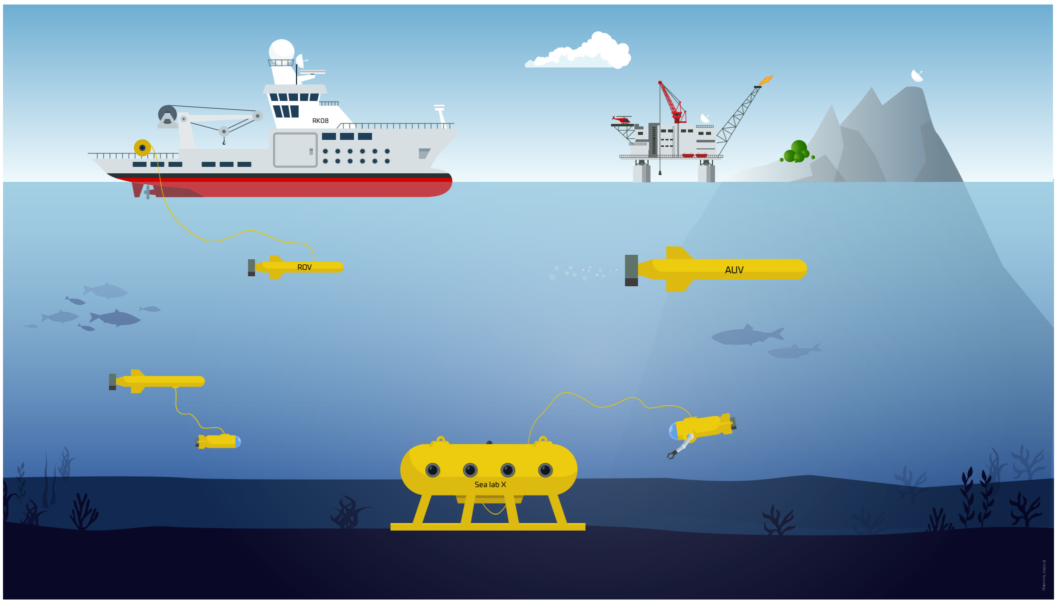

Figure 1. ROVs, or remotely operated underwater vehicles. These drones depend on humans to operate them, whether nearby or at a distance. They are expected to dominate the underwater drone market in the immediate future. AUVs, or autonomous underwater vehicles. These are also known as UUVs, or unmanned underwater vehicles. These drones operate without real-time human input. Hybrid underwater vehicles combine features of ROVs and AUVs and may or may not use cables. Future technologies: Underwater technologies, stationary deep-sea facilities, industrial facilities, underwater laboratories (Sealab X) with long-term occupants assisted by underwater drone technology, or unmanned facilities like data centres.

Apart from ROVs and AUVs, there are also hybrid underwater drone solutions that combine the use of a connecting cable and an autonomous drone. One example of this is a two-drone solution in which one drone serves as a relay station and a platform for launching the other drone. This drone is typically connected to the surface with a cable. The other drone is an AUV that can freely manoeuvre about, such as to inspect ballast tanks in ships. The distance between the two drones is limited by the range of the wireless communication technology used, since the two drones must be able to communicate. Another example is stationary systems comprising a communication and charging station on the ocean floor with a cable to the surface and one or more associated AUVs that can be programmed to inspect a given area at regular intervals (see Figure 1).

Major developments in autonomy are under way, including the use of ASVs (Autonomous Surface Vessels) combined with an ROV, or a WROV (Working ROV) connected to a TMS (Tether Management System), and other combinations–see Figure 3. The possible applications for underwater drones are continuously expanding as the underlying technologies are developed. According to MarketWatch, the global market for underwater drones is expected to grow from 235 million USD in 2021 to 2.104 billion USD in 2028.[1]

Underwater drones are widely used for inspections, particularly visual inspections. However, as sensor technologies develop, they are being increasingly used for other tasks, such as inspecting oil/gas/wind facilities, ships, transmission and communication connections, aquaculture, and ports. Figure 2 presents an overview of potential areas where the use of underwater drones is possible

1 "Global Underwater Drone Market Size 2023-2028 | Industrial Analysis by Key Companies Profiled, Sales, Recent Developments," MarketWatch, [Online]. Available: https://www.marketwatch.com/press-release/global-underwater-drone-market-size-2023-2028-industrial-analysis-by-key-companies-profiled-sales-recent-developments-2022-12-17. Inspiration for figure: *(insert lakes/holes on golf courses)*

now or will become possible in the future. Inspection includes reporting on the physical condition of underwater structures and determining whether repairs should be begun.

Underwater drones are also used to track and collect objects. Collecting objects may be convenient when attempting to identify impurities and unwanted objects, as well as for disposal or recycling.

3 Underwater drones today

Today, underwater drones are used in high-value industries, ordinary consumer applications, and everything in between:

- Inspections of offshore energy facilities, ships, infrastructure (e.g., transmission and communication connections on the ocean floor), safety inspections, repairs, defence, and research.
- Removal of hard and soft marine fouling from offshore installations and ships.
- Removal of plastics and other unwanted materials.
- Filming. Drones may be controlled using a cable connected to a smartphone or by following a person at a distance of, say, two metres.
- Drones for long-distance applications, such as automated oxygenation monitoring along paths longer than 1000 km.
- For 360-degree inspections of ships' ballast tanks and similar objects, including measuring tank wall thicknesses.
- Exploring oceans, lakes, and rivers; oceanography.

Figure 2 shows an overview of current and future aquatic environments where underwater drone technology may be useful.

Figure 2:

An overview of possible aquatic environments where underwater drone technology may be useful. 1: glaciers; 2: reservoir lakes; 3: rivers and streams; 4: man-made canals; 5: man-made reservoirs; 6: lakes; 7: man-made lakes; 8: port facilities; 9: large water and discharge pipes; 10: urban facilities; 11: offshore wind turbine facilities; 12: underwater gas infrastructure, pipelines, and cabling; 13: drilling platforms; 14: future undersea facilities (data centres, laboratories, etc.); 15: geology, environmental studies, shipwrecks, etc.

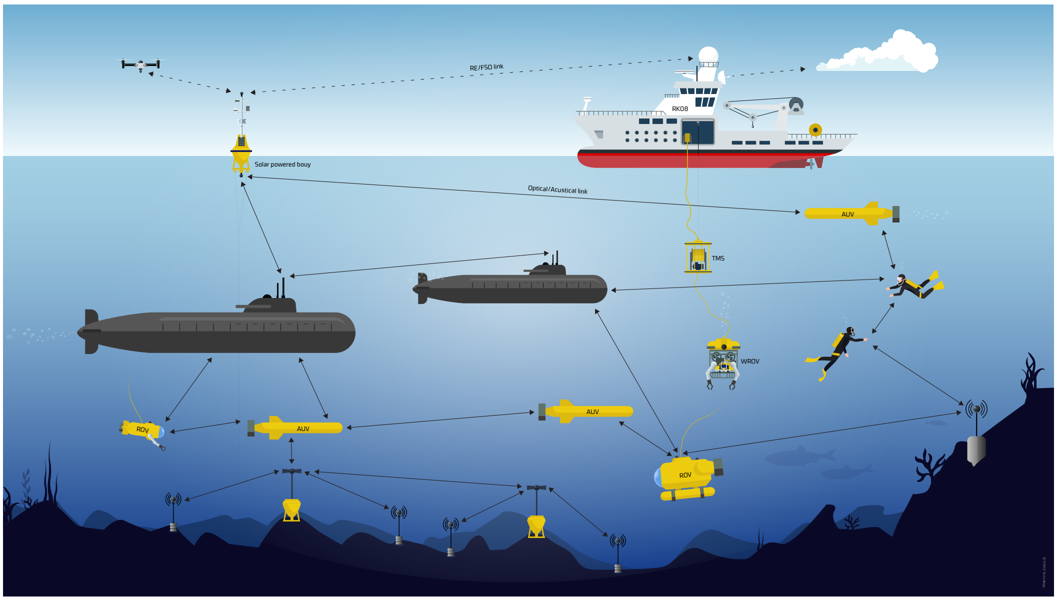

Figure 3: An overview of possible underwater drone technologies and the means of communication between them. For instance, from the cloud to sensors anchored in the ocean floor, in the case of nodes and sensor technologies with many communication lines.

4 Sensors as a central element in the AUV reference architecture

The various means of communication presented in Figure 3 form a broad network that makes it possible to retrieve data from a variety of sensors on the ocean floor–including fixed and anchored sensors–from the surface, then store that data in the cloud. Apart from its sensors (nos. 10 and 11 in the figure), an AUV consists of a battery pack (1), a power management unit (2), a built-in control computer (3), propulsion motors (4), buoyancy adjustment systems (5), INS/IMU (6), underwater communication systems (7) radio communication systems (8), and a GNSS receiver (9), all explained below.

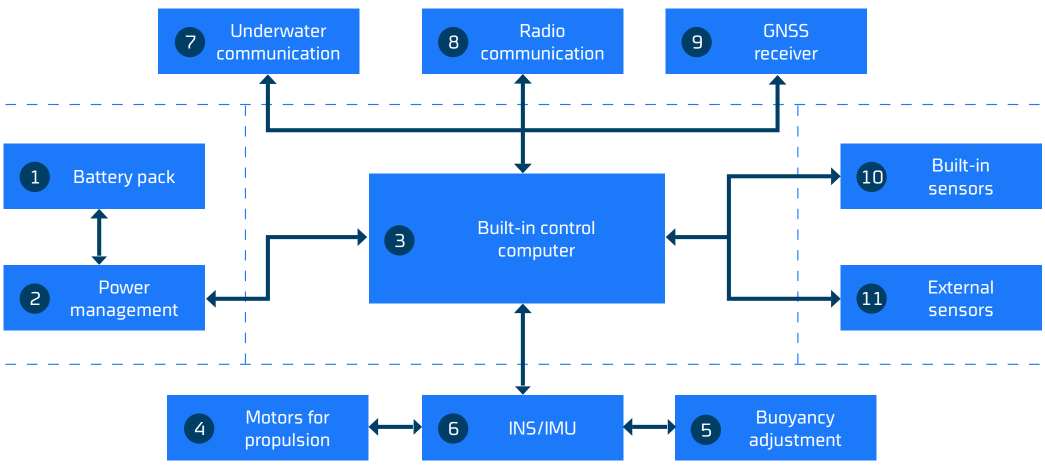

Figure 4: Reference architecture for an underwater drone. The drone consists of components numbered from 1 to 11.

1 **The battery pack** is necessary for the drone to operate independently of electricity supplied from the surface. Batteries must be designed to provide enough energy to operate the electric propellers, sensors, cameras, and control computers for the duration of a mission in order to avoid the need for service visits from the surface.

2 **The power management unit** is a small unit that distributes power supplied by the battery pack to the individual components of the drone. The power management unit also monitors the remaining operating time to ensure that there is enough power for the drone to return to the surface in case it detects an irregularity in its power supply. For the sake of clarity, only one connection to the control computer is shown in the figure, but the power management unit is connected to all of the AUV's components.

3 **The control computer** is a central computer that handles on-board data processing for the AUV. It calculates locations, collects data from all sensors, ensures that the drone follows its predefined route, and sends commands to the power management unit to start and stop propulsion along all axes when the drone moves.

4 **Buoyancy adjustment** can be accomplished by emptying and filling tanks with water, or using a glider that moves backwards and forwards to cause the AUV to either rise or sink deeper.

5 **Propulsion motors** are an important element of the reference architecture; they are included for the sake of completeness.

6 **INS/IMU:** An IMU (Inertial Measurement Unit) consists of a three-axis accelerometer, a three-axis gyroscope, and a three-axis magnetometer. Data from the IMU is processed using filters and sensor fusion to precisely determine the drone's speed and relative position, as well as its orientation in terms of roll, pitch, and yaw (heading). The processing itself takes place in the INS (Inertial Navigation System).

7 **Underwater communication** is typically accomplished via cable, acoustic underwater communication, or visible light. Each approach has advantages and disadvantages, making it important to fully understand how the AUV will be used before deciding which form of underwater communication to employ.

8 **Radio:** Radio-based communication is only possible when the AUV is near the surface. Even at 10 MHz, water dampens the signal by more than 100 dB per metre. This makes it impossible to receive GNSS (Global Navigation Satellite System) signals, which are sent over frequencies from 1 GHz to 1.6 GHz, or to use mobile telephony technology, which starts at 450 MHz.

9 **GNSS receiver and position determination:** Precisely determined positioning/geolocation is fundamental for an autonomous underwater drone to be able to operate independently and correct for any drift induced by currents in the water. The drone must be able to understand the world around it in three dimensions, know where it needs to go in order to do its job, and identify when it has reached its destination.

An underwater drone is not guaranteed continuous availability of position data, so it must be able to use its sensors to log its movements in order to minimise drift when position data is unavailable. Three navigation methods exist for AUVs.

Dead reckoning (most common)	**Ultra-short baseline (USBL) and long baseline (LBL)** (most precise, with centimetre accuracy[2])	**Geophysical navigation** (not very common)
The INS processes the raw data obtained from the IMU. Apart from the data it receives from the IMU, the INS module also receives navigation information from a Doppler Velocity Log (DVL), also known as an acoustic modem. A DVL sends out focused acoustic signals, which are then reflected by the bottom of an ocean or lake. The DVL's transducer receives the echo. This echo allows the drone to calculate its own speed and distance from the bottom of the body of water. The precision of the position calculation becomes worse over time.	Acoustic navigation solutions use time-of-flight (TOF) measurements from acoustic beacons, which serve as reference points for calculating positions via tri-angulation. The acoustic method is used to determine the position of an underwater drone relative to the locations of the acoustic beacons. In USBL, beacons are sent from a ship or other floating unit. In an LBL system, the beacons are placed on the bottom of the body of water.	The underwater drone navigates using sensors that recognise structures in its surroundings. This is possible using artificial intelligence. The sensors may be underwater cameras, which can enable a drone to follow changes in the height of the ocean floor or to navigate a port. Alternatively, the drone can measure magnetic fields if it needs to follow a pipeline or underwater cable.

2 K. Sun, W. Cui and C. Chen, "Review of Underwater Sensing Technologies and Applications," MDPI Sensors, 2021.

Each navigation method has advantages and disadvantages. Consequently, combining them can help to improve stability and precision. Note, however, that many fully automated future use cases will require precise, continuous geolocation, which can be accomplished by relaying GNSS data acoustically from surface equipment.

5 Built-in and external sensors

A typical underwater drone is equipped with various types of sensors. It uses the sensors not only to navigate underwater, but also to perform a task, such as an underwater inspection.

Sensor data may also be helpful for maintaining the drone itself. Collecting and processing data from the drone's sensors can offer critical insights into the drone's condition. These insights can then be used to predict and prevent potential future failures, as well as to optimise the ordering of reserve parts, the scheduling of vehicle operations, and other maintenance-related activities.

Many kinds of sensors can help an underwater drone to do its job, such as environmental monitoring and research (aside from the navigation and positioning sensors already mentioned, such as the IMU). Which sensors a drone is equipped with depends on its intended applications, including civil, military, and research applications.

Some of the kinds of sensors that can be installed on drones are presented below.

Optical camera
A high-resolution camera is one of the most important types of sensors that can be installed on an underwater drone. Potentially in concert with built-in, AI-assisted classification and analysis, a camera can be used for such tasks as object location, optical infrastructure inspection, surveillance, environmental surveying and monitoring, and more. Cameras can also be used for machine vision, which provides an underwater drone with an advanced means of navigation. One of the challenges associated with underwater cameras is the distortion of the image caused by the water's absorbing and scattering properties, as well as particles present in the water. This challenge is exacerbated by the fact that light must pass through various materials: first water, then glass, and then air. Software calibration and special camera designs can help to mitigate this issue. However, as a result of this challenge, cameras are primarily used for short-distance sensing applications.

Laser (LiDAR)
Lasers are used in a variety of applications for measurement and precision photogrammetry, including underwater structural measurements in situations when existing drawings are not up to date or otherwise satisfactory, as well as when wear and corrosion must be documented as part of a fitness-for-purpose evaluation. Additionally, LiDAR can be used for ocean floor and port measurements, even in areas with low visibility. LiDAR measurements can be used to generate a digital twin for an underwater structure or component as part of future expansion and maintenance plants.

Acoustic sensor / echo sounder
Echo sounding technology and echo sounding units are primarily used on underwater drones for inspections, ocean floor mapping, and object detection (aside from navigational applications). The transducers in a sonar unit emit and receive acoustic impulses, enabling the instrument to estimate the positions of objects using the travel times and phase differences in the impulses. This makes it possible to generate a 3D reconstruction of the surface beneath the drone. While sonar has a low resolution, it also has a long range and is not impacted by turbidity, or the presence of particles in the water. There are various types of echo sounders, including side-scan echo sounders, multi-beam echo sounders, and single-beam echo sounders. Each one has different applications given its

technical characteristics (number of beams emitted, price, etc.). For example, a single-beam echo sounder is relatively affordable and suited for taking low-precision measurements of the depth of a sunken object, although it has low coverage. A multi-beam echo sounder, on the other hand, is capable of high-precision measurements and offers greater coverage. Advancements in artificial intelligence are bringing object detection and classification with underwater acoustic object detection into a new era with many opportunities.

CTD (conductivity, temperature, and depth) sensor

CTD is an instrument comprising a set of sensors used to measure three essential variables in the ocean that play important roles in environmental monitoring. Salinity, which influences conductivity, is calculated by measuring the water's conductivity. Temperature is typically measured using a thermistor, given the high precision and large measurement range of thermistors. Lastly, depth is usually measured using a pressure sensor (available in several varieties, each using a different measurement principle, such as piezo-resistive or capacitive measurement), taking advantage of the fact that the further down a drone descends, the more water there is above it, increasing the measured pressure.

Magnetometer

A magnetometer is a sensor that measures magnetic fields. These can be useful to install on underwater drones for scientific, military, and commercial applications. For example, a magnetometer can be used to detect magnetic anomalies caused by metallic objects, such as underwater piping and cables. One of the challenges associated with the use of magnetometers in underwater drones is electromagnetic interference from the drone itself, which can impact the precision of the measurements. Special sensors (self-compensating magnetometers) can help to mitigate this problem by compensating for the interference in software.

Field gradient measurement

Anodes on underwater structures are essential for providing protection from corrosion. Over time, the protection afforded by an anode can decrease, posing a risk to the protected structure. Field gradient measurement can be used to measure the effectiveness of the cathodic protection. Advanced software can then generate a 2D or 3D image of the anodic protection of an underwater structure and calculate the remaining useful life of each anode. This knowledge is essential in extending the lifetimes of underwater structures.

Eddy current measurement

Eddy currents are used to detect surface-breaking cracks in steel underwater structures. Measurement using this technique requires cleaning and surface contact. The eddy current sensor is placed on the surface using an ROV manipulator or attached to a remotely controlled scanner (connected by a cable to the ROV) which the ROV can place on the surface. Then, the size and extent of a crack can be investigated, and this information can be used to plan remedial action.

Ultrasonic measurement

Ultrasound is used to measure thicknesses and the corrosion of steel structures. Close access (but not direct contact) to the surface to measured is required, and the surface must be clean. The ultrasonic frequencies used for measuring thicknesses propagate well in water. The ultrasonic sensor is placed on or close to the surface using an ROV manipulator or attached to a remotely controlled scanner (connected by a cable to the ROV) which the ROV can place on the surface. When measuring corrosion over a larger area, a remotely controlled scanner capable of X-Y movement while recording measurement data is needed.

Ultrasound can also be used to measure deeper faults in underwater structures, although this requires the use of a remotely controlled scanner that operates on the structure's surface.

Additionally, ultrasound can be used to measure the tension of bolted joints. This typically involves using an ROV to place a measurement instrument on the bolt, at which point readings can be taken from the ROV control room.

Water clarity (turbidity) sensor

The clarity of water can be measured with light, taking advantage of the fact that a beam of light passing through a solution will be absorbed and scattered by suspended matter and dissolved molecules. The quantity, size, and form of the suspended matter and its molecules in the water impact the water's turbidity.

Dissolved oxygen sensor

Dissolved Oxygen (DO) is a good indicator of water quality. DO levels are influenced by oxygen diffused into the water from the air, as well as the level of photosynthesis of algae and plants present in the water. There are a few ways to measure dissolved oxygen in water, the most common of which are Winkler titration, the electrochemical method, and the optical method.

Nitrate sensor

Nitrate, an ion comprising nitrogen and oxygen atoms, dissolves readily in water and is measured in many applications, including surface water and drinking water (groundwater) applications. This is because harmful algae can develop in the presence of high concentrations of nitrate, and they can produce dangerous toxins. Nitrate sensors typically use either electrochemical methods or spectrophotometry using UV light.

Ammonium/ammonia sensor

Ammonium, or its uncharged form, ammonia, is a nitrogen species that aquatic plants absorb and transform into proteins. Unusually high concentrations of ammonium in seawater, most commonly caused by human activity, can lead to uncontrolled growth of algae and other aquatic plants, posing hazards to life in the ocean. Ammonium sensors most commonly use the electrochemical method of measurement.

Phosphate sensor

Phosphorus is one of the most important chemical elements in organic life, and it occurs naturally in the water in the form of ions (phosphates). As is the case with nitrates and ammonium, very high concentrations of phosphates in water can lead to uncontrolled algae growth (algal blooms), which can break down oxygen and produce harmful toxins. Consequently, measuring concentrations with phosphate sensors is important.

Fluorometer

A fluorometer is a device that measures the intensity and wavelength of the fluorescence emitted by various fluorescing objects. In the context of underwater drones, fluorometers can be useful for detecting and measuring the concentration or even presence of oil (typically hydrocarbons), chlorophyll-a, rhodamine, and other substances in the water. A typical use case for a drone with such a sensor installed would be locating, monitoring, and spatially mapping oil spills.

pH sensor

pH values indicate the acidity of ocean water, which is important for almost all water quality applications. High and low pH values can be signs of contamination. pH measures the activity of hydrogen ions and can be determined using either the electrode method (with an ion-selective electrode) or the spectrophotometric method.

Dissolved methane sensor

A dissolved methane sensor typically uses the non-dispersive infrared (NDIR) principle to measure the concentration of methane dissolved in the water. This measurement can be useful in such applications as undersea pipeline leak detection and optimisation of the placement of oil and gas wells.

Dissolved carbon dioxide sensor

Monitoring the concentration of dissolved CO_2 in oceans and lakes is important for studying and better understanding the global carbon cycle. Water is understood to absorb large quantities of CO_2 from the air. The classical method of measuring dissolved CO_2 concentrations is to take a sample and analyse it in a laboratory. However, some dissolved CO_2 sensors allow for in situ measurement using the NDIR (non-dispersive infrared absorption) method.

6 Conclusion

The field of underwater drones and their applications has been developing rapidly in recent years. These developments are driven by the need to study what is taking place beneath the water's surface, which is increasing due to geopolitical and social challenges, as well as by the fact that many of the core technologies needed are already familiar. There is additionally a need for the capability to perform underwater operations autonomously, which demands the use of various sensors, artificial intelligence (AI), and machine learning (ML). The idea is for sensor systems to take on a more active role, using sensor data to actively control a drone's actions underwater and allowing drones to operate more autonomously. Autonomy will be important for minimising operating costs and ensuring that tasks can be performed responsibly, with minimal risk to those involved.

There are major developments under way in remotely controlled inspection, with ROVs and AUVs launched in the water from ships or platforms while data collection takes place in real time in a land-based control room. This requires reliable data connections, which are not yet available in all locations globally. The advantages of this are opportunities for managing several operations simultaneously and a reduced need for offshore crews.

The jobs underwater drones will be able to perform in the future depend largely on the specific needs that arise, but to name a few examples for the sake of inspiration, we have OceanOne, which involves a humanoid robot with touch sensors that can provide feedback to its operator; as well as Nereus, the world's deepest-diving underwater vehicle, used to inspect and map the ocean floor with sonar and cameras. We can also imagine underwater laboratories and large data centres located on the ocean floor regularly being serviced by underwater drones for inspections, repairs, and deliveries.

Read more about Sensors and IoT define future designs for autonomous underwater drones

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