Underwater Robots

From Remotely Operated Vehicles to Intervention-Autonomous Underwater Vehicles

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Remotely operated vehicles (ROVs) revolutionized the subsea industry when they were introduced in the 1960s. They were more powerful and inherently safer, and they could go deeper than divers. However, they require a tether and a support ship, which makes their use complex and expensive. Autonomous marine vehicles (AMVs) have long been seen as a game changer in the exploration and exploitation of the marine environment. Repeated access to remote and hazardous places for data gathering and intervention, enabled by their autonomy, is the key to their adoption. While historically the focus has been on autonomous underwater vehicles (AUVs), unmanned surface vehicles (USVs) have recently been developed and adopted at an increasing rate. Interestingly, whereas AMVs (AUVs and USVs) have now been adopted in niche areas (bathymetric surveys and mine countermeasures), they have not yet hit the mainstream. In this article, we review the state of the art in unmanned underwater vehicles (UUVs), which include ROVs and AUVs; current obstacles to their adoption, both technical and commercial; and recent advances in technology. We also present an outlook on the future of these systems.

Brief History of UUVs

Robotics has played a major role in subsea marine science, engineering, and operations since the introduction of ROVs. Initially designed for marine science and rescue operations, they became mainstream in the 1980s as oil and gas exploitation reached depths exceeding the reach of human divers. ROVs, which are teleoperated robotic systems (see Figure 1), are now the mainstream tool of subsea operations, enabling the performance of many tasks, from construction to

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inspection, repair, and maintenance. They range from small, portable vehicles to large work-class systems. Most of today's oil and gas operations and marine science would be impossible without them.

The 1990s saw the development of torpedo-shaped AUVs to provide fast, large-scale, high-resolution surveys of the seabed [1] (see Figure 2). This new technology removed the need for a tether (required by ROVs) and their associated support ship. It also provided higher-resolution data than traditional approaches as well as access to restricted areas, for instance, under ice or in shallow waters. These vehicles found widespread applications in defense [2], oil and gas, and cable surveying [3]. However, they were not able to interact with structures for close-up inspection or manipulation. Moreover, while AUVs have commercially been used routinely for surveying [4], surveillance [5], and, recently, inspection [6], their economic benefit is greatly reduced if another system (typically an ROV) and an expensive ship are required to perform the intervention resulting from the inspection. Therefore, the next efforts in UUV technology focused on the development of intervention AUVs (I-AUVs) and hybrid ROV-AUVs (H-ROVs) endowed with manipulation capabilities. This is still an area of ongoing research and probably the key technology development required to move AUVs into the mainstream of subsea operations.

The United States led the way early on in the mid-1990s with one-degree-of-freedom (1-DoF) I-AUVs [7]. In the late 1990s, the Advanced Manipulation for Deep Underwater Sampling European Union (EU) project developed the first robust 7-DoF electrical robot arm [8]. During the 2000s, the first autonomous intervention [9] and first free-floating intervention within the milestone Semi-Autonomous Underwater Vehicle for Intervention Mission project [10] took place. In the last decade, lighter I-AUVs have been developed, such as the Girona 500 used in several EU projects (TRIDENT [49], PANDORA [50]). Meanwhile, free-floating manipulation flourished. For instance, in TRIDENT, for the first time, a vehicle and manipulator of similar weight performed autonomous grasping, coordinating the base and arm movements [11]. Dual-arm manipulation was achieved initially in the early 2000s [12], but, currently, there are research projects dealing with dual-arm, free-floating underwater manipulation using H-ROVs [13], [14].

Current Capabilities and Challenges

Over the years, the capabilities of UUVs have steadily increased, from ROVs to AUVs and now I-AUVs and H-ROVs. Transitioning from ROVs to AUVs pushed new developments in localization, autonomy, and communications. H-ROVs and I-AUVs helped drive new manipulation capabilities. Software development has been made easier by middleware frameworks such as Mission Oriented Operating Suite-Interval Programming or, more recently, the Robot Operating System. Simulators, such as Gazebo or the UnderWater Simulator, obviate the need for the complexity and cost of at-sea testing. However, while progress has been steady, some important challenges remain.

In the following sections, we first explain the current state of the art by grouping the most successful and relevant approaches for each capability and then present the remaining challenges. We conclude with a short summary exemplifying the evolution of robots and capabilities through the years.

Sensing

The range of sensors that AMVs and UUVs can carry as payload is very wide and depends on the application. We focus here exclusively on sensors used by the robot to extract the information needed to perform its mission safely and efficiently. The most common sensors used in UUVs are optical and acoustic sensors. Optical cameras can be used for many applications, such as object detection and classification, 3D reconstruction, mosaicking, and simultaneous localization and mapping (SLAM). They can also be used for obstacle avoidance or keeping a constant distance from the bottom for safety reasons. Similarly, for inspection tasks, optical cameras can help UUVs survey the area without coming into

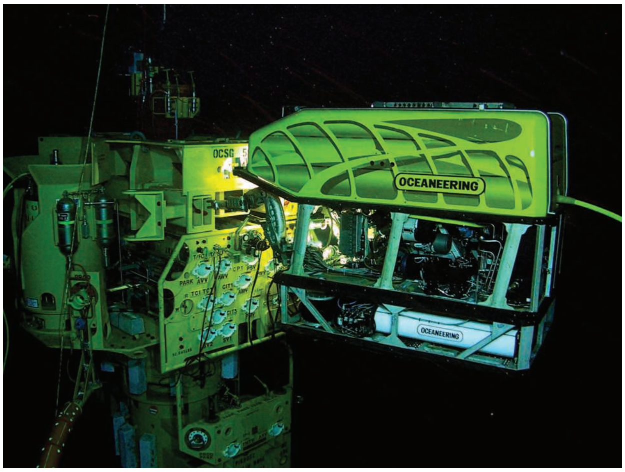

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Figure 1. A typical work-class ROV used in industry today.

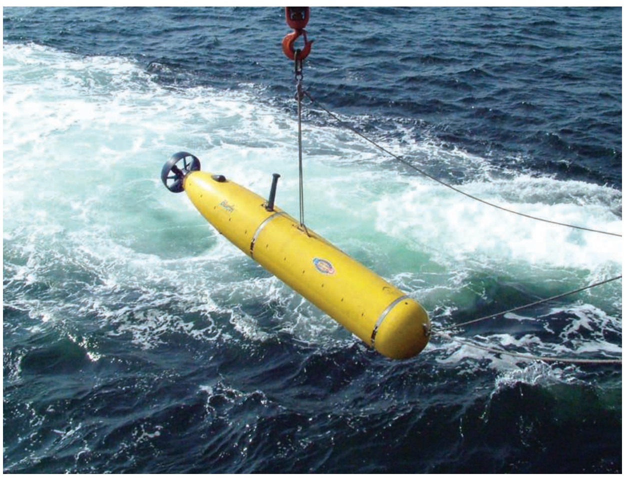

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Figure 2. A typical survey AUV.

contact with the inspected structure. For more complete inspection or object recognition, 3D sensing can be achieved using stereo camera systems and active structured light [15] at short ranges.

Acoustic sensors are the other main class of payload sensors that can increase mission safety. For instance, echo sounders can measure altitude from the bottom (using the time-of-flight principle) and so help make sure UUVs keep at a safe depth. Imaging sonars can be used for many applications and vary greatly in range and resolution. The synthetic aperture sonar can reach centimeter resolution, an order of magnitude greater than conventional sonars. It can be used for seabed mapping, mine detection [16], or shipwreck surveying, as instrumental to the UUV mission. Side-scan sonar, also a down-looking sonar, is used for similar applications but provides a lower resolution. The multibeam forward-looking sonars (FLSs) can be used for obstacle avoidance, object detection and recognition, and navigation, increasing mission safety. FLSs can reach ranges of hundreds of meters and thus can help AUVs avoid obstacles at a greater range than optical cameras. In recent years, FLSs at higher frequencies (up to 3 MHz) have produced images with millimeter resolution for very small ranges (fewer than 10 m). These sonars can be used to safely inspect ship hulls and chains or to detect divers or structural damages at a close distance. The market now includes multibeam 3D high-resolution sonars. The most advanced 3D sonar can provide real-time 3D images at 20 Hz [51]. These sensors introduce very-high-resolution inspection possibilities at a safer distance, although their cost is still too high to popularize them.

Navigation capabilities can also be improved with exteroceptive sensors (optical or sonar) that identify specific landmarks in the environment and use them to localize the UUV.

The challenges in sensing are mostly correlated to the physical medium and, thus, hard to solve. Optical cameras suffer from light attenuation and water turbidity, preventing their use (without artificial lighting) below 30–40-m depth. Artificial lighting systems can be used to improve their usability at the cost of extra disturbances due to nonhomogeneous lighting. One way of solving these challenges is to combine optical cameras with other sensors. For instance, pairing them with lidar is becoming popular for high-resolution mapping and 3D reconstruction. Combining optical cameras with sonars is another way of solving the optical cameras' intrinsic challenges. Sonars, however, present their own challenges. In particular, they need to be correctly calibrated, as sound propagation in water depends on temperature and salinity. Moreover, their resolution is typically lower than that of optical cameras (except for short ranges), although their ranges are typically greater. Acoustic shadows and multipath artifacts are two other common issues, but they can be mitigated and even explored for object detection. Nonetheless, the fusion of optical and acoustic cameras (high-resolution imaging sonars) is a way to solve the inherent challenges of each sensory modality. It can be used for improving navigation (thus allowing safer operation), 3D object reconstruction, inspection, and augmented reality [17]. Nonetheless, it is a complex challenge still to be fully solved, and a good calibration of the heterogeneous stereo systems is required.

Another way of alleviating optical cameras' challenges is the recent trend of using hyperspectral imaging sensors. While these sensors have been used for many years in airplanes and satellites, only recently have they entered the marine domain. These cameras can sense both within and beyond the visible spectrum. Although they suffer absorption and scattering issues similar to those of optical cameras, they provide better spectral resolution (with hundreds of bands instead of a three-channel red-green-blue). This leads to improved object identification and more efficient mapping [18].

Navigation, Guidance, and Control

A classical control architecture for UUVs is presented in Figure 3. Navigation uses the sensor data (and possibly external input) to estimate position and velocity and feed the guidance and control modules. Currently, UUVs largely rely on proprioceptive sensors, such as an inertial navigation system (INS) integrated with Doppler velocity logs (DVLs). This is because electromagnetic waves do not propagate well underwater, and, thus, global navigation satellite systems are not an option. However, INS and DVL are subject to drift and biases, leading to growing position uncertainty. Moreover, DVL usage is limited by its range. The state of the art includes a combination of internal sensors with acoustic positioning systems from long baseline (LBL) to short baseline (SBL) and ultrashort baseline (USBL). Acoustic positioning systems, though, require careful calibration of the sound velocity, as they suffer from multipath Doppler effects and susceptibility to

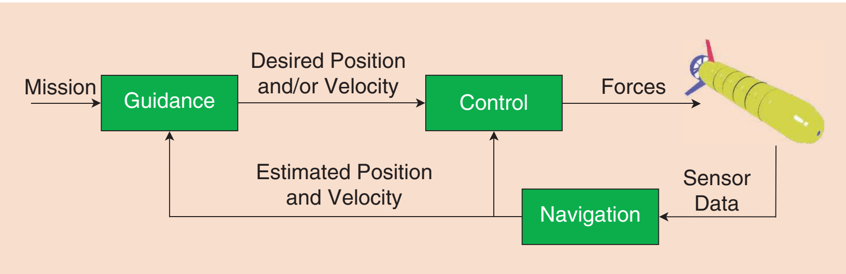

Figure 3. The scheme of a navigation, guidance, and control architecture for a UUV.

thermoclines. They also have a limited range and can be used only in confined areas (LBL) or require a support vessel following the UUV (SBL or USBL) [19].

As mentioned previously, navigation capabilities can also be improved with exteroceptive sensors (optical or sonar) that identify specific landmarks in the environment and use them to localize the UUV. If a map is available, this approach is known as *map-based localization* [20]. When no map is available, AUVs can perform SLAM, in which the vehicle concurrently builds a map of relevant features and uses it to navigate. The latter approach is most effective when the vehicle revisits the same area multiple times, enabling loop-closing and a global reduction of the uncertainty in vehicle position [21]. While SLAM is very effective in land and aerial robotics, it is still a challenge to use it in the subsea domain [22] because of the relative paucity of unique features underwater, the short range of high-resolution optical sensors, and the low resolution of long-range acoustic sensors. The biggest challenge that remains is to navigate in an unknown environment without a priori information or external position updates and without using a very precise (and costly) INS or DVL.

Guidance [23] focuses on high-level trajectory planning, while control is devoted to the low-level kinematics and dynamics control of actuators to achieve guidance objectives [24]. High-performance and achievable control systems are the current state of the art [25]. Indeed, while guidance and control for a single vehicle are mature domains, cooperative navigation and control of networked UUVs remain challenges. To the best of our knowledge, no commercial system based on multiple AMVs exists. In [26], adaptive ocean sampling was first tested with a fleet of gliders. In a recent EU-funded project, MORPH [27], significant advancements in coordinated control have been achieved, while in another European project, Widely Scalable Mobile Underwater Sonar Technology (WiMUST) [28], cooperative control was designed and implemented in a survey operation involving two autonomous surface catamarans and six AUVs. The WiMUST application, i.e., acoustic-based geophysical and geotechnical surveys, required the vehicles to carry streamers of hydrophones whose positions needed to be synchronized and known.

Challenges in guidance and control of multiple vehicles mainly reside in the bottleneck presented by using the same limited-bandwidth physical medium for both navigation and communication, i.e., acoustic. Thus, algorithms need to be robust in handling frequent packet loss and multipath arrival of data. Beyond the theoretical aspects, from a purely practical perspective, a significant barrier is the difficulty of launching and recovering a large number of vehicles in any kind of weather.

Communications

Underwater communications are a challenge. Currently, acoustic communications can be used for navigational updates from the surface (SBL or USBL) or the bottom (LBL) and to communicate a UUV's status to operators. UUVs can also receive messages from other vessels for control and coordination. Acoustic communications allow for longer ranges than optical communications; recently, however, optical communications solutions have been developed thanks to the availability of powerful LEDs and lasers combined with high-sensitivity avalanche photodiodes [29]. The advantage is that the bandwidth is typically much higher than acoustic communications (up to 500 Mb/s for a range of tens of meters compared to Kb/s over a few kilometers).

As mentioned, acoustic sensors underwater require good calibration, which is sometimes a practical challenge. The low bandwidth of acoustic communications and the short range of optical communications drastically limit the level of coordination and supervision possible. This is a challenge for the development of underwater acoustic networks [30]. Moreover, these networks are normally associated with permanent deployments because making them portable is challenging. At the same time, the underwater communications challenges have promoted the development of more autonomy inside the vehicles. Unlike other domains, underwater roboticists have no choice but to embed autonomy to enable useful and safe operations.

The biggest challenge that remains is to navigate in an unknown environment without a priori information or external position updates and without using a very precise (and costly) INS or DVL.

Autonomy and Planning

The first UUVs had only basic levels of autonomy and executed strictly prescribed missions. They were equipped with a number of safety behaviors that would become activated in the case of problems and would generally lead to the termination of the mission [31]. More complex autonomy levels were slowly introduced for autonomous inspection [4]. Complex mission-planning algorithms were able to adapt the initial plan based on new data gathered or changes in environmental conditions [32]. These were applied to ocean sampling [33] and autonomous intervention [34]. Extensions to multivehicle coordination and planning were explored and demonstrated in actual large-scale experiments using a collection of UUVs and USVs for marine science [35] and defense. We are, therefore, on the cusp of a new era in which large numbers of autonomous systems can be deployed and collaborated to perform complex, long-term missions.

However, a number of challenges remain. First, as the complexity of the embedded planning abilities grows and increasingly involves some form of machine learning, so does the need to keep the operator situated and maintain operator trust in the embedded intelligence. Moreover, currently deployed embedded autonomy solutions are still brittle and often require support from the operator. Specifically, operators have to deal with complexity in controlling multiobjective, multivehicle missions. They simultaneously face uncertainty over the current status and safety of several remote high-value assets. This is due to the limited bandwidth and poor reliability of the communication channel. True autonomy solutions will thus not be adopted by operators unless shared-autonomy solutions are developed in which vehicles can explain their decisions to operators and ask for help when needed, and operators can query vehicles about their intentions and support them [36]. This is especially critical for remote operations, where long delays in communications force the embedded autonomy to be in control of all real-time operations. In such cases, the remote supervisor can only trigger behaviors to support the mission. If these problems can be solved, long-term, persistent autonomy will become possible—and, we believe, routine—for a wide range of applications.

Manipulation

Underwater manipulation is a challenging problem addressed in the literature from a control perspective [37]. Typical tasks include valve-turning, pick-and-place, and plug-connector operations. The state of the art at the industrial level is still confined to master-slave robotic systems with the operator constantly in the loop. Due to the specific difficulties in working in the marine environment, such as high pressure and currents, this task remains tedious and expensive.

As mentioned previously, progress has been made since the early 1990s in manipulation capabilities, advancing from 1 DoF to current dual-arm free-floating manipulation. Operations such as valve turning or plugging in a connector have been demonstrated in laboratory experiments [38]. Haptic-based control of a dual-arm system has been implemented in the Ocean One project [13]; here, two hands helped the operator in recovering an object from the sea floor. From a research perspective, in underwater manipulation, the trend is to provide the robotic system with a sufficient level of autonomy while keeping the human in the loop for high-abstraction-level decisions. This has been achieved by the European project Dexterous ROV [14], which used a satellite-based control architecture able to handle intermittent or low-frequency communication. Its proof of concept used an architecture composed of an on-shore learning system, able to recognize the user's input instructed by an exoskeleton, and an off-shore twin cognitive node in charge of reconstructing the desired end-effector movement [39].

Having fully autonomous manipulation in demanding environments is one of the challenges that remain. To solve it, the future of intervention robots needs to merge control with issues coming from the communication and perception systems. This could provide the underwater system with sufficient autonomy to safely execute the operator's high-level commands even in nonideal conditions.

Short Summary

As shown, the capabilities of UUVs have increased over the years at the same time that their autonomy has grown. To briefly summarize the differences among the various types of vehicles and their evolution, we compare three popular systems in Table 1. Early ROV systems were mostly teleoperated, with a low degree of autonomy and using black-and-white cameras, but they included manipulation capabilities that made them popular. Remote Environmental Monitoring UnitS (REMUS) AUV, originally built by the Woods Hole Institute (like the Jason ROV), has been used as a low-cost vehicle designed for environmental monitoring since 1997, later becoming a commercial vehicle. In this AUV, manipulation is not present, and the standard sensor suite is related to the specific application. The AUV mission could be changed in real time using acoustic communications. More recently, I-AUVs such as the Girona 500 introduced autonomous, free-floating manipulation while using simpler deployment localization systems (USBL instead of LBL) and a reconfigurable payload suite.

Table 1. The evolution of UUVs and their capabilities.

Vehicle	Year	Sensing	Navigation	Communications	Autonomy and Planning	Manipulation
Jason ROV	1988	Side-scan sonar, altimeter, black-and-white camera	LBL, INS, dynamic positioning	Optical-fiber tether	Remotely controlled and preplanned track following	Teleoperated
REMUS AUV	1997	Acoustic Doppler Current Profiler, side-scan sonar, conductivity temperature profiler, light scattering sensor	DVL, INS, LBL	Acoustic modem	Preplanned missions and acoustic commands	No manipulation capabilities
Girona 500 I-AUV	2011	Profiler sonar, side-scan sonar, video camera	DVL, attitude and heading reference system, USBL	Acoustic modem and optional tether	Preplanned missions and autonomous inspection	Autonomous free-floating manipulation

Safety, Standards, and Benchmarking

The safety of any unmanned vehicle is of utmost concern. Work-class ROVs operating in harsh environments are no exception. These vehicles require a considerable number of logistics and trained personnel. Given that they have been on the market for decades, several standards and rules can be found. For instance, the Norsk Sokkels Konkurranseposisjon standard established by the Norwegian oil and gas industry [40] classifies ROVs by type and defines technical, operational, safety, and personnel requirements, among others. Another standard [41] published by DNV-GL, the world's largest classification society, defines precise principles for the construction of ROVs and requirements for their equipment and the launcher. The International Organization for Standardization (ISO) 13628-8:2002 standard defines ROV interfaces on subsea production systems for the petroleum and natural gas industries [52].

AUVs have a lower degree of standardization. Rules concerning AUVs are inspired by ROV rules [41], and there is no ISO standard. However, standardization and evaluation of AUV performance through benchmarks have been performed by the U.S. National Institute of Standards and Technology [42] and by the euRathlon [43], [44] and European Robotics League [53] competitions.

Legal rules also need to be established for the operation of AUVs, as international regulations were not designed with unmanned systems in mind, and, thus, the legal status of AUVs has still to be better defined [45].

Future of UUVs

According to the latest market report by Douglas-Westwood, AUV demand is expected to grow 37% in the 2018–2022 period, with the commercial sector experiencing a 74% increase. Another report estimates the global market for AUVs to reach US$835.0 million by 2022, of which US$537.2 million represents the commercial market [54]. The use of UUVs has extended over the years in terms of scope, capabilities, and types of vehicles (from ROVs to I-AUVs). Inspection tasks that were previously mostly performed by ROVs can now be performed by AUVs. The so-called I-AUVs will become omnipresent as the inspection and maintenance market expands. This market has mostly been represented by the oil and gas industry, but, currently and in the future, offshore wind farms and wave-energy generators will enlarge it.

As the operational cost of ROVs can be substantially higher than that of AUVs, this market requires I-AUVs to replace ROVs. For this to happen, persistent autonomy needs to be fully developed. Currently, AUV operations are limited by their endurance (up to some hours in most AUVs). While a few vehicles can last up to months and have a range of up to hundreds of kilometers [46], making them fit for under-ice missions, most vehicles need to be recovered for recharging or battery swapping. Alternatively, AUVs can dock to a recharging station. Docking is then another enabler for persistent autonomy. Docking stations mounted in oil rigs or wind farms could create self-sustainable AUV operational environments.

The market opportunities are not limited to inspection and maintenance. Underwater mining is also growing, and deep-sea-mining prospecting is underway. The Viable Alternative Mine Operating System [55] project aims to demonstrate the economic feasibility and environmental friendliness of underwater mining, while the Autonomous Underwater Explorer for Flooded Mines [56] project assesses the potential reopening of flooded mines. The International Seabed Authority issued 29 contracts for the exploration of deep-sea mineral deposits in May 2018. Commercial mining is expected to start by 2020 in national waters off Papua New Guinea and in international waters in 2025. This new market can have a potential societal impact by diminishing open-pit mining on land but also presents several environmental concerns [57]. Autonomous deep-sea landers and crawlers are being developed [47] for mapping and monitoring. Deep-sea exploration is also addressed by the US$7 million Shell Ocean Discovery XPRIZE [58], while NASA testing of underwater vehicles to explore Europa, Jupiter's moon [59], can stimulate extreme-environment exploration.

Legal rules also need to be established for the operation of AUVs, as international regulations were not designed with unmanned systems in mind.

Related to the deep sea but flexible enough to be used as a payload transporter, the Large Modifiable Underwater Mothership (MUM) [48] AUV can carry several tons and work at a 5,000-m depth for several weeks. This can represent a revolution in cargo transportation with a considerable impact on society because, at the moment, there is no underwater vehicle with cargo capabilities comparable to the MUM.

Finally, bio-inspired and humanoid robots, which have been popular over the past several decades, are starting to hit the oceans too. For instance, the humanoid-shape Ocean One H-ROV mentioned previously [13] and the popular bio-inspired FESTO AquaJellies, AquaPenguins, Aqua_ray, and Airacuda AUVs [60] are just a few examples of this trend.

Conclusions

UUVs have a long history, starting from the 1960s with the use of ROVs for marine science and then in industries such as oil and gas. AUVs have a more recent introduction to the market; being untethered, however, they can access areas that ROVs cannot easily. Cutting the cable required developments in power efficiency, sensing, control, and autonomy. However, ROVs kept being used extensively, as their manipulation capabilities were extremely useful. The next and current development is I-AUVs and H-ROVs. The goal for them is to achieve the best of both worlds, combining compact and light AUVs with manipulation capabilities usually found in ROVs. As shown, this is essential to keep up with the growing market for inspection and maintenance and the emerging markets of deep-sea mining and cargo transportation while at the same time reducing operational costs. The wide range of R&D directions shows the vitality, potential, and societal impact of AUVs. Although safety procedures for ROVs have been taken very seriously by industry, standardization, safety, and legal issues still hinder the seamless operation of AUVs and will need to be solved to increase AUV usage.

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