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Underwater Drones: Advances in AUVs, ROVs, and Soft Robotics for Ocean Exploration

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ABSTRACT: The research paper examines the transformative role of the underwater drone. Including Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), in advancing ocean exploration. It examines the technological components driving these innovations, including propulsion systems, power sources, navigation tools, and underwater communication. A special focus is placed on the rise of soft robotics, highlighting their bio-inspired flexibility, low acoustic signature, and minimal ecological impact. The paper discusses how material selection, ranging from titanium to silicone elastomers, enables drones to withstand extreme underwater environments. Applications span marine biology, environmental monitoring, archaeology, and resource exploration, with examples from leading institutions like WHOI and Ocean Infinity. Challenges such as battery limitations, communication barriers, and pressure resistance are addressed alongside emerging trends like AI integration and swarm robotics. The study concludes by identifying the field's potential to inspire young interdisciplinary researchers, while emphasizing the vital role underwater drones play in protecting fragile ecosystems and expanding our understanding of the deep ocean.

KEYWORDS: Robotics and Intelligent Machines, Biomechanics, Autonomous Underwater Vehicles, Ocean Exploration, Soft Robotics.

Introduction

To understand the ocean, we need to study it and what it provides, as it serves as a life and regulatory resource for ocean resource management. There are multiple facets to the ocean we are exploring and experiencing, and experiences that would drive people to be motivated, sustainable stewards.[1] By exploring the ocean, we discover new resources, such as medicines, vaccines, food, and energy, that create sustainable thinking and creative ideas.[2] Participating in ocean discovery adds to our understanding of how environmental change (i.e., climate and weather) not only impacts the Earth, but also helps in understanding adaptation for natural disasters (i.e., earthquakes and tsunamis).[3] Science and technology have undergone radical shifts in the exploration and discovery of the ocean, enabling us to access and study the deep sea in a deeper, safer, and more precise manner than ever before.[4]

The devices being used today for ocean exploration are Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs). AUVs, or autonomous underwater vehicles, are unmanned underwater vehicles that perform underwater surveys such as detecting and mapping underwater wrecks and obstacles. AUVs are classified as autonomous and do not require an operator, which does not surface prior to calculating the specific location of that vehicle for its data collection. Remotely operated vehicles, or ROVs, are unmanned underwater vehicles whose movements are completely tied to and connected to a host ship. ROVs can be directly controlled remotely and contain object recognition as one of their generic applications that acts as a substitute for diver assessments in situations where divers are not available or are not being performed due to safety concerns.[5]

Table 1: Differentiation between AUVs and ROVs applications.

Aspect	AUV (Autonomous Underwater Vehicle)	ROV (Remotely Operated Vehicle)
Control	Autonomous, pre-programmed	Remote-controlled via tether
Power	Battery-operated	Powered through cable from host ship
Communication	Limited, non-real-time	Real-time via tether
Mobility	Free-ranging	Range limited by cable
Main Applications	Mapping, surveying, data collection	Inspection, maintenance, object retrieval

There have been tremendous advancements in underwater exploration technology over the years. In earlier decades, researchers built submersibles with reinforced hulls and ballast systems to achieve new ocean depths, such as the Bathyscaphe Trieste. When underwater science became more commonplace in the mid-1960s, sonar systems and underwater photography provided researchers with an unprecedented level of detail about the features and landforms of the ocean floor. In the late 1980s, remotely operated vehicles (ROVs) began to be widely used as well. ROVs were able to be outfitted with manipulator arms for property and sampling, video transmission, and a tethering system that enabled researchers to be miles away. Beginning in the early 2000s, autonomous underwater vehicles (AUVs) also began to be utilized. The value of the AUV was its pre-programmed autonomy on mission-based tasks dictated by GPS, inertial navigation, and onboard sensors. Today, the latest generation of underwater drones is as sophisticated and advanced as the terrestrial unmanned drones for land and aerial flights, as they are equipped with artificial intelligence, real-time data communication, and high-resolution, scaled 3D mapping. This technology represents a big evolution in deep-water research that makes for safer, more accurate, data-rich investigations.[6]

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Drones are valuable tools in the marine environment because they can reach inaccessible places and depths without risking safety. There are many advantages to using drones, including: safety, data collection, cost effectiveness, use of space, environmental monitoring, and operations for search and rescue. In the marine environment, drones are a cost-effective and efficient means of exploration as opposed to fulfilling their goal of marine research, mapping of infrastructure, or environmental monitoring. Drones can capture high-definition images, sonar readings, and collect water samples, allowing for usable information to be located in the assessment of the ocean ecosystem and marine diversity.[7] Drones can support search and rescue operations and help increase situational awareness for emergency response teams during environmental emergencies by providing up-to-date information.[8] An example of a company is Ocean Infinity: a marine robotics company employing fleets of AUVs for deep sea mapping, subsea infrastructure inspection, and environmental monitoring. Ocean Infinity's "Armada" fleet has the ability to operate with a few crew members, and with controlled drone operations, safety is improved. Another company is WHOI (Woods Hole Oceanographic Institute): A global leader in research based on developing and deploying AUVs such as Sentry. WHOI has been involved in oceanographic exploration, climate research, and deep-sea missions, making a significant contribution to marine science.[9]

Result and Discussion

Technology Behind Underwater Drones:

ROVs and AUVs are built to operate through different mechanisms for their intended functions. ROVs remain connected to a surface vessel, which supplies the ROV with continuous power and the ability to complete tasks, such as deep ocean sampling and inspection, in real-time.[10] AUVs operate independently of any support vessel and utilize pre-programmed instructions, together with onboard navigation systems, such as inertial navigation systems (INS) and Doppler velocity logs (DVL), to carry out their tasks autonomously. AUVs can operate in a manner to explore large areas, conduct mapping, and perform environmental monitoring projects. Although AUVs can travel and conduct successful projects in areas that may be cost-prohibitive for ROVs, their distinct advantages are the real-time control and human precision they can offer for a task.11

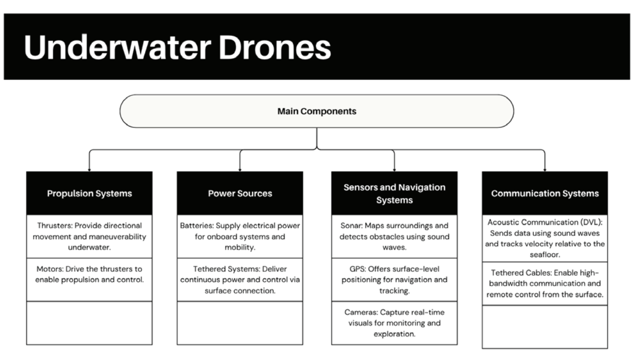

Figure 1: The main systems of an underwater drone and the components they consist of.

Components:

To understand how an underwater drone works and its functioning, it is important to consider all of the components that make underwater navigation, data collection, and real-time control possible. Figure 1 briefly showcases the components in an underwater vehicle.[12]

Propulsion System: The propulsion system allows for the movement and control of underwater vehicles. Underwater vehicles contain thrusters that use electric motors that provide thrust to move in the water. Thrusters can be mounted in different configurations to achieve six degrees of motion (pitch, yaw, roll, transition in vertical, lateral, or longitudinal motion). Most thrusters use a brushless DC motor because of its advantages of being highly efficient, reliable, and long-lasting without brushes, thereby reducing friction and mechanical wear. They provide speed and torque control with great accuracy, while also being capable of operating smoothly and quietly at very low speeds. Motors are small and lightweight, providing lower heat, which enhances performance with limited space/thermal capacity, such as in electric vehicles, underwater robotics, and drones. More advanced drones have incorporated principles and systems for dynamic positioning, allowing the vehicle to almost hover and provide the accurate control needed for inspections or delicate tasks such as sampling. Dynamic positioning in underwater drones employs sensors (DVL, INS, acoustic systems) that observe position, movement, past position, etc. A control system processes the data collected from the sensors and controls the thrusters accordingly in a timely fashion to hold in a precise location and orientation, even with currents or turbulence present.[12]

Power Source: The power systems of underwater drones directly determine their operational range and operational time. Autonomous Underwater Vehicles (AUVs) are based on lithium-ion batteries. They typically use batteries as their power source due to lithium-ion batteries as their power source due to their high energy density, rechargeability, and light weight. Although battery management is critical for safety and sustainability, it is especially crucial for deep-sea operations, in these cases, due to high-pressure environments. Whereas Remotely Operated Vehicles (ROV) are, by definition, tethered power systems, this allows for a continuous power supply and continuous energy from a surface support vessel while tethered. The continuous power source allows for longer mission durations that have fewer limitations for the supplies onboard for the autopilots.[12]

Sensors and Navigation Systems: The accuracy of sensors and navigation approaches results in the efficacy of underwater drone missions. AUVs typically use an Inertial Navigation System (INS) for dead reckoning, which estimates position based on motion data. Due to accumulating errors (drift), it is common for INS to be aided by an independent sensor, such as Doppler Velocity Logs (DVL). The DVL measures velocity relative to the seafloor. AUV position fix is intermittent due to the inability of GPS signals to penetrate water. AUVs surface on a scheduled basis to acquire a GPS fix, permitting them to correct positional errors that occurred during submerged operation. For environmental mapping and situational awareness,

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AUVs utilize sonar, including side-scan sonar to detect submerged objects and multi-beam sonar to map the seafloor in a high-resolution 3D format. AUVs are also equipped with integrated optical cameras and environmental sensors to monitor temperature, salinity, and depth. With images and environmental data collected in real-time, AUVs can be utilized in a range of applications, including scientific investigations and infrastructure inspections.[12]

Communication Systems: Underwater communication has unique difficulties. Acoustic communication systems (the most common type of system to use for data transmission), and in particular, a style of communication based on acoustic transmissions, or more specifically, underwater, is most common for data exchange, especially for AUVs, because the movement of radio/optical transmissions in water is limited. Acoustic communication systems support low-bandwidth, long-range communication. In contrast, ROVs work with tethered cables, encouraging high-speed, real-time transmission of video, sensor information, and control commands to and from surface operators.[12]

Role of Soft Robotics in Underwater Drones:

Soft robotics refers to the field of robotics that uses compliant materials to create machines that show locomotion that mimics a variety of real-life forms in nature. Soft robots can bend, twist, and deform because they can operate with gentler motions than stiff robots.[13]

With soft robotic underwater drones, soft robotics offers various benefits over traditional robotic designs, primarily in underwater manipulation, where the environment is hostile to grasping. Imagine a soft robotic arm or gripper that achieves effective, safe travel to fragile organisms, such as corals, jellyfish, or even starfish. Soft robotic arms can transform into variable shapes and can maintain a firm grip that does not harm other organisms under flowing water conditions.[14]

Considering the ocean's fluid and changing environment, soft robots with flexible parts have some advantages over traditional rigid robots with stiff parts. Soft robots can be less vulnerable to mechanical damage from impacting rocks and other debris. Their flexibility allows them to explore uncertain or dubious water. In addition, because the mechanical approaches used in soft robotics carry little noise, soft robots normally have low acoustic signatures, making them suitable for secret missions to collect biological information or military information. Incorporating soft robotics into underwater drones also highlights additional possibilities, giving drones more flexibility to adapt with an overall less negative impact on delicate ecosystems, while still enabling them to conduct difficult missions with little disturbance.[15]

Recent advancements in biomimetic soft robotics provide a snapshot of amazing technological evolution to mimic a natural organism in soft, flexible materials. It includes multiple features, flexible multi-degree-of-freedom actuators, and design inspiration from biological systems. The industry has transitioned from traditional synthetic rubber-making processes into new fabrication systems such as 3D printing of elastomers, mould casting, and thin-film layering. These methods enable complex soft structures that resemble biological tissues in terms of compliance and flexibility. The range of actuation methods available has moved from hydraulic to electromechanical systems, and now to smart materials (electroactive polymers, shape memory alloys, and magnetic composites). The combination of high levels of design freedom with this selection of actuation methods means soft robots could provide smooth, fine, fluid three-dimensional motion similar to jellyfish, worms, and octopi. The vast array of possible applications for these soft robots has appeared on the market, including medical soft robots that can provide minimally invasive procedures; soft robots with sensors for marine life interactions; and adaptable systems for engineering capabilities in various industrial and operational approaches of the defense sector.[16,17]

Materials Used in Underwater Drones:

Material Requirements:

When designing underwater drones, material selection is important, especially given the environment they operate in while underwater. The challenges of underwater operation require these submersibles to meet quite tough performance requirements to function properly and remain safe. The primary requirements are:

Pressure Resistance: The deeper you go, the more the water pressure will increase exponentially. The materials used must be strong enough to withstand such great forces without bending, as you conduct exploration in the deep sea.[18]

Corrosion Resistance: Saltwater is extremely corrosive, and when a material is left for a while, it will erode. Costs need to be kept low and operational, so materials that can resist corrosion are important for carrying out any exploration or mission.[18]

Durability in Extreme Temperatures: Underwater drones often experience a wide range of temperature variation, particularly in the deep sea. The drones must be able to perform efficiently regardless of temperature fluctuation.[18]

Commonly Used Materials:

Metals:

Aluminum Alloys: Aluminum alloys tend to be one of the more popular materials used on a drone frame because of the unique strength-to-weight ratio and the corrosion-resistant qualities of aluminum. No, aluminum isn't the best material for the deepest dives, but an anodized aluminum structure will do well in the mid-depth situations.[19]

Titanium: Renowned for its incredible strength, plus its natural corrosion-resistant properties, titanium is the gold standard for deep-water operations. It is more expensive and difficult to fabricate and handle than aluminum, but it is unmatched for high-pressure, saltwater applications.[19]

Plastics and Composites:

ABS Plastic: Acrylonitrile Butadiene Styrene is lightweight, well-mouldable, and provides acceptable strength. It is found in the housings for typical underwater drones, allowing for variable operation at shallow to mid-depths. *Carbon Fiber Composites:* These are characterized by high tensile strength,

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high rigidity, and very low weight. They are also very chemically stable, allowing for exposure over long periods of time, both in the long term and underwater. However, they are required to be combined into waterproof resins and sealed to prevent water intrusion.[15]

Flexible and Soft Materials:

Silicone Rubber: This is a commonly used material for soft robotic components because of its flexibility, resistance to chemicals, buoyancy, and its inert state, making it non-toxic to any animal species in the sea.[18]

Elastomers: They can elongate and return to their original form. It is this extension, along with the strength of the elastic material, that lends itself to the design of actuators, soft-bodied designs, grippers, etc.[18]

Benefits of Soft Materials in Soft Robotics: while flexible materials allow drones to mimic shapes of complex underwater environments, reducing damage upon interaction, flexible materials such as silicone and elastomers used in soft robotics allow designs to be inspired by nature, including a propulsor shaped like a tentacle or bell. These elements would not only be soft but would also enhance hydrodynamic efficiency, allowing for quieter and more efficient locomotion.[15]

Additionally, using soft materials decreases the failure rates of the drone in extreme environments. Soft robots can absorb and accommodate forces instead of resisting them, reducing structural stress. Buoyant materials reduce the total energy to remain afloat, a feature prominent in battery-powered systems. In conclusion, choosing materials, whether hard or soft, is the single most critical choice for the function and longevity of underwater drones. As the industry grows, we will start to see increasingly hybridized designs that focus on blending hard metals and soft polymers, finding an appropriate balance between durability, agility, and environmental considerations.[20]

Table 2: The suitable materials for each depth range with their examples.

Depth Category	Suitable Materials	Example Uses
Shallow (<100m)	ABS Plastic, Silicone Rubber	Consumer drones, educational submersibles
Mid-depth (100–500 m)	Anodized Aluminum, Carbon Fiber Composites, Elastomers	Survey drones, inspection robots
Deep-sea (>1000m)	Titanium, Carbon Fiber (sealed), Specialized Elastomers	Scientific exploration, oil & gas inspection, military drones

Applications of Underwater Drones in Ocean Exploration:

Underwater drones, or Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs), have renewed ocean exploration. AUVs and ROVs have also enabled access to previously inaccessible, fragile ecosystems and remote underwater areas for scientists. The flexibility of these devices has been based on several critically important sectors, ranging from biology to archaeology to sustainable resource management.[21]

Drones afford marine biologists a non-invasive opportunity to survey marine organisms. AUVs can come equipped with cameras and motion sensors that allow them to track the behavior of animals in the wild, as they allow researchers to track and observe migration, feeding, and social behavior, for endangered species such as deep-water jellyfish or sea turtles. Soft robotic equivalents have been implemented for these species. Because these researchers employ a soft robotic gripper mode that imitates the soft-bodied animals, such as octopuses and squids, they can take samples while ecologically studying biodiversity.[22]

In environmental monitoring, drones are used to detect and monitor pollution in the world's oceans. For instance, machine vision and infrared sensors can see floating plastics, and detection sensors can characterize oil spills, etc. In monitoring coral reefs, the most fragile kinds of ecosystems in the ocean, drones fitted with a mixture of environmental sensors and soft robot arms permit researchers to inspect reefs very closely and sample organisms from the reef without an impact on the organisms. Close inspection of offshore reefs is critical when applying conservation and rehabilitation techniques.[23]

ROVs can help explore shipwrecks, sunken cities, and underwater caves that are either too dangerous to dive/or impossible to dive for most humans. ROVs had a significant role in documenting information about the RMS Titanic, while recently demonstrating their capabilities in uncovering antiquities from the Roman period off the coast of Croatia through similar geomorphology. Underwater drones can help scientists and researchers document fragile environments while taking and collecting samples with high-definition sonar, mapping, and robotic arms.[24]

Further, in the field of resource exploration, primarily in the mapping of the ocean floor, vessels that research minerals from the seabed can map for hydrothermal vent sources, etc. AUVs, with multi-beam sonar, will show a reference to resources that companies can use to correctly map future ocean mineral depletion, which have sustainability as needed; e.g., companies exploring manganese nodules, companies exploring rare earth elements, etc., can survey before they are exploitable. These demonstrable cases can be related to the NOAA which will use AUVs to monitor coral bleaching of corals, for example, in the Pacific, or the Schmidt Ocean Institute's SuBastian ROV - which has also helped discover new species and map explorable seafloor, while mapping unknown floors, all exemplify, how both underwater drones and ecosystems have pioneered ocean research taking into considerations of variations to soft robots, ocean opportunities, AI, etc.[25]

Challenges and Future Prospects of Underwater Drones:

Despite their growing role in marine exploration, underwater drones face several key challenges that limit their full potential. One of the primary limitations is battery life; most AUVs and ROVs operate for limited durations due to the high energy demands of propulsion, lighting, and onboard systems. Depth restrictions are another concern, as increased pressure at deeper levels requires advanced, pressure-resistant housings and materials that can withstand extreme environments without failing. Furthermore, underwater communication is severely constrained; radio waves do not travel well through water, so drones must rely on slower acoustic signals or surface periodically for data transmission, affecting real-time control and coordination.

In terms of materials, maintaining durability under extreme pressure and corrosion remains an engineering challenge. Traditional rigid components often cannot cope with deep-sea dynamics, leading to increased interest in soft robotics. These systems, made from flexible, biocompatible materials, show great promise for the future, especially for delicate marine tasks such as coral monitoring or deep-sea sampling.

Emerging trends are helping address these issues. Artificial Intelligence (AI) is being integrated into AUVs to allow for autonomous decision-making, adaptive navigation, and environmental learning. Another innovation is swarm robotics, where multiple small drones cooperate, like schools of fish, to explore wide areas collaboratively and efficiently.

The future of soft robotics in underwater applications looks particularly exciting. Bio-inspired designs, such as those mimicking jellyfish or octopuses, offer enhanced maneuverability, silent movement, and better adaptability in complex terrains. These developments promise safer, more efficient exploration of previously unreachable ocean zones.

For young researchers and scientists, like myself, this is a field rich with opportunity—from robotics and marine biology to AI and materials science. As oceans remain largely unexplored, the next wave of breakthroughs will come from interdisciplinary minds pushing the boundaries of underwater innovation. [26]

Conclusion

In conclusion, by fusing robotics, material science, and artificial intelligence, underwater drones are transforming ocean exploration. These developments are opening up new avenues for marine research, from autonomous vehicles mapping the ocean floor to soft robotic grippers protecting fragile ecosystems. The quick development of soft robotics and AI-driven autonomy presents encouraging answers to problems like short battery life, communication limitations, and material durability. Looking ahead, future research is projected to increase the operational depth of underwater drones from the current average of 1,000 meters to over 6,000 meters within the next decade, while improving energy efficiency by up to 40% through advances in hydrodynamic design and adaptive AI navigation. The integration of next-generation composite materials could reduce overall drone weight by 25–30%, extending mission duration and reducing manufacturing costs. These quantified improvements will help underwater drones remain at the forefront of our exploration of the vast, unexplored ocean depths—empowering scientists, protecting biodiversity, and inspiring a new generation of researchers to better understand and preserve the last frontier of our planet.

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Aryaman Jain is an aspiring mechanical engineer with a deep fascination for the ocean and an even deeper curiosity about how machines can navigate its complexities. He envisions a future where soft robotic AUVs redefine underwater exploration. Aryaman is passionate about bio-inspired design, fluid dynamics, and autonomous systems, and is currently exploring how compliant materials and undulatory propulsion can revolutionize the stealth, efficiency, and scalability of subsea robotics. His long-term goal is to create a new class of Unconventional AUVs (UAUVs) that operate not against the ocean but with it.