A Comprehensive Review of Unmanned Underwater Vehicles: Technologies, Applications, and Challenges

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***Abstract*—Unmanned Underwater Vehicles (UUVs) have emerged as vital tools in modern maritime operations, enabling safe, efficient, and precise tasks across a variety of underwater environments. This review aims to present a comprehensive examination of the current state, technological foundations, and emerging developments in UUV systems. It explores the key enabling technologies including propulsion mechanisms, energy storage and management, underwater communication protocols, sensor integration, and advanced navigation and control systems. The analysis draws attention to both Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), highlighting their respective operational capabilities and domains of use.**

Applications of UUVs are broad and impactful, spanning from naval defense, surveillance, and mine countermeasures to oceanographic research, undersea infrastructure inspection, and environmental monitoring. With increasing integration of artificial intelligence and machine learning, these vehicles are evolving into intelligent systems capable of performing complex missions autonomously.

However, several persistent challenges hinder the full operational potential of UUVs. These include limitations in power supply, difficulties in underwater communication, navigation in GPS-denied environments, and resilience against high-pressure and corrosive underwater conditions. This review further outlines the future direction of UUV research, emphasizing the importance of interdisciplinary approaches, bio-inspired design, swarm robotics, and enhanced autonomy. The findings provide valuable insights for academics, engineers, and stakeholders aiming to advance the field of underwater robotics through innovative and sustainable solutions.

***Keywords*—Unmanned Underwater Vehicle (UUV), Autonomous Underwater Vehicle (AUV), Underwater Communication, Marine Robotics, Navigation and Control Systems, Subsea Applications**

I. INTRODUCTION

The exploration of the underwater realm has long captivated human curiosity, driven by the vastness and mystery of the oceans that cover more than 70% of the Earth's surface. Historically, endeavors such as the 19th-century *Challenger* expedition laid the groundwork for modern oceanography, revealing the rich biodiversity and complex geological features of the deep sea [1]. However, the inherent challenges of high pressure, low temperatures, and limited visibility have necessitated the development of specialized technologies to probe these depths.

Unmanned Underwater Vehicles (UUVs) have emerged as pivotal tools in this context, enabling the systematic exploration and monitoring of underwater environments without direct human presence. UUVs are broadly categorized into two primary types: Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). ROVs are tethered systems controlled by operators from a surface vessel, offering real-time maneuverability and are extensively used for tasks such as underwater inspections, repairs, and data collection [2]. In contrast, AUVs operate independently, following preprogrammed missions to gather data on parameters like temperature, salinity, and ocean currents, making them invaluable for large-scale oceanographic surveys [3].

The significance of UUVs extends across various domains. In the military sector, they are deployed for mine detection, surveillance, and reconnaissance missions, enhancing maritime security [4]. Commercially, industries such as oil and gas rely on UUVs for pipeline inspections and infrastructure maintenance in challenging underwater conditions [5]. Scientifically, UUVs facilitate the study of marine ecosystems, climate change effects, and geological formations, contributing to our understanding of the Earth's processes [6].

Despite their advancements, UUVs face several challenges. Communication underwater remains limited due to the attenuation of radio waves, necessitating reliance on acoustic methods, which have bandwidth and latency constraints. Navigation is also complex, especially in GPS-denied environments, requiring sophisticated inertial and acoustic positioning systems. Energy efficiency is another critical concern, as extended missions demand robust power management solutions.

This review aims to provide a comprehensive overview of the current state of UUV technologies, their applications, and the challenges they face. The paper is structured as follows: Section II delves into the classification and design aspects of UUVs; Section III discusses the core technologies underpinning their operation; Section IV explores their diverse applications across military, commercial, and scientific fields; Section V addresses the prevailing challenges and limitations; and Section VI outlines emerging trends and future directions in UUV research and development.

II. CLASSIFICATION OF UNMANNED UNDERWATER VEHICLES

Unmanned Underwater Vehicles (UUVs) exhibit a diverse range of designs and functionalities tailored to meet specific operational requirements. The classification of UUVs is typically approached from multiple perspectives, including

TABLE I: Comparison between ROVs and AUVs

Feature	ROVs	AUVs
Control	Tethered, operator-controlled	Autonomous, pre-programmed
Power Supply	Surface-supplied via tether	Onboard batteries
Communication	Real-time via tether	Limited, post-mission data retrieval
Navigation	Operator-guided	Inertial and acoustic systems
Applications	Inspections, repairs, sampling	Surveys, mapping, monitoring

autonomy level, application domains, and size or design configurations. This section provides an overview of these classifications, supported by current literature and technological developments.

A. Classification Based on Autonomy

The autonomy level of UUVs primarily distinguishes them into two main categories: Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs). AUVs are self-directed systems capable of executing pre-programmed missions without real-time human control. These vehicles employ advanced onboard navigation, control algorithms, and sensors to adapt to dynamic underwater environments [19], [17]. In contrast, ROVs operate under direct control from human operators via tethered communication links, providing immediate responsiveness and control for intricate underwater tasks such as inspection, maintenance, and intervention [13], [15]. The choice between AUVs and ROVs depends heavily on the mission complexity, operational depth, and required precision.

B. Classification Based on Application

UUVs serve in diverse sectors, broadly categorized as commercial, military, and scientific applications. Commercial UUVs are widely utilized in offshore oil and gas exploration, pipeline inspection, and subsea infrastructure maintenance, where reliability and endurance are paramount [10], [14]. Military applications focus on mine countermeasures, surveillance, reconnaissance, and anti-submarine warfare, often requiring stealth capabilities and advanced sensor payloads [11], [18]. Scientific UUVs support oceanographic research, environmental monitoring, and marine biology studies, emphasizing data accuracy, endurance, and adaptability to harsh underwater conditions [12], [16].

C. Classification Based on Size and Design

Size and design influence the operational capability and deployment logistics of UUVs. Man-portable UUVs, typically lightweight and compact, are designed for rapid deployment and are used for shallow water inspections and mine detection [9], [14]. Mid-size UUVs offer a balance between endurance and payload capacity and are frequently deployed in scientific and commercial missions requiring moderate depth operations [8], [19]. Large-scale UUVs are engineered for deep-sea exploration, extended endurance, and heavy payloads, suitable for complex military or research tasks [7], [18].

Figure 1 illustrates a schematic overview of UUV classification based on the above criteria.

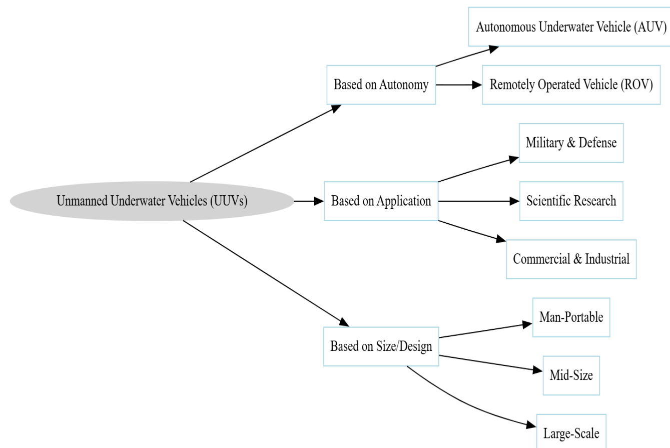

Fig. 1: Schematic classification of Unmanned Underwater Vehicles based on autonomy, application, and size/design.

Table II summarizes the key characteristics and examples of different UUV categories.

This multi-dimensional classification framework facilitates the appropriate selection and design of UUVs tailored to specific mission profiles and operational environments, advancing both their effectiveness and efficiency in underwater tasks.

III. Core Technologies in Unmanned Underwater Vehicles

Unmanned Underwater Vehicles (UUVs) rely on a suite of advanced core technologies that enable them to operate effectively in challenging underwater environments. This section provides an overview of the key technological components, including propulsion systems, power supply and energy management, communication networks, navigation and control methods, and sensor integration.

A. Propulsion Systems

Propulsion is critical for maneuverability, speed, and endurance of UUVs. Various propulsion mechanisms have been developed to meet different operational needs. Electric propulsion systems, typically using brushless DC motors coupled with propellers or thrusters, offer high efficiency and low acoustic noise, making them suitable for covert operations [20], [22]. Hydraulic propulsion systems provide high thrust and robustness, particularly in heavy-duty applications such as deep-sea exploration [23]. Bio-inspired propulsion, mimicking the locomotion of aquatic animals like fish or cephalopods, is gaining traction due to its potential for increased efficiency

TABLE II: Classification of UUVs by Autonomy, Application, and Size

Classification	Category	Characteristics	Examples
Autonomy	Autonomous Underwater Vehicle (AUV)	Self-navigated, pre-programmed missions, no tether	REMUS, Bluefin-21 [17]
	Remotely Operated Vehicle (ROV)	Tethered, human-operated, real-time control	Seaeye Falcon, Saab Double Eagle [13]
Application	Commercial	Pipeline inspection, subsea infrastructure, offshore industry	Inspectahire ROVs, OceanServer Iver3 [10]
	Military	Surveillance, mine detection, reconnaissance	Boeing Echo Voyager, Knifefish UUV [11]
	Scientific	Oceanography, environmental monitoring, research	Sentry, Nereus [12]
Size & Design	Man-portable	Lightweight, rapid deployment, shallow waters	Remus 100 [9]
	Mid-size	Moderate endurance, balanced payload	Bluefin-9 [8]
	Large-scale	Deep-sea exploration, heavy payloads	Nereus, Slocum Glider [7]

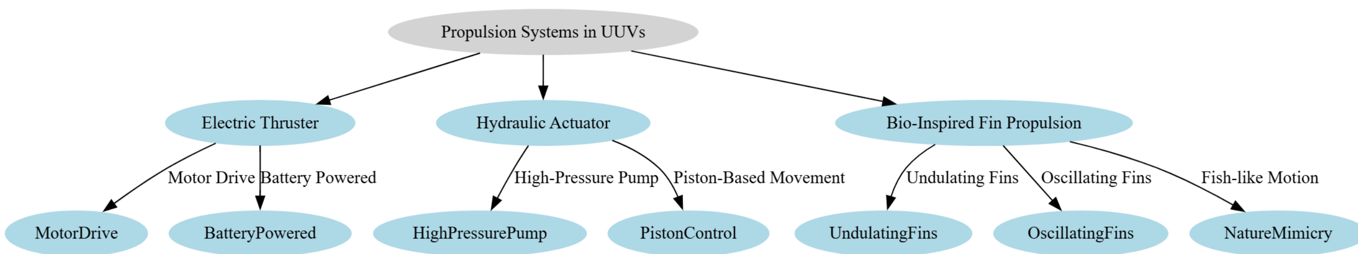

Fig. 2: Overview of propulsion systems in UUVs: (a) Electric thruster, (b) Hydraulic actuator, (c) Bio-inspired fin propulsion.

and reduced environmental disturbance [21], [24]. Figure 2 illustrates common propulsion types used in UUVs.

B. Power Supply and Energy Management

Effective power management is essential for prolonged missions and operational reliability. Lithium-ion batteries remain the most prevalent energy source, favored for their high energy density and rechargeability [25]. Fuel cells, particularly hydrogen-based types, are emerging as alternatives offering longer mission durations and faster refueling [26]. Energy harvesting technologies, such as utilizing thermal gradients or ocean currents, provide promising avenues for extending UUV endurance without increasing battery capacity [27]. Efficient power management systems balance energy consumption among propulsion, sensors, and communication subsystems, ensuring mission success.

C. Communication and Networking

Underwater communication poses unique challenges due to high attenuation of electromagnetic waves in water. Acoustic communication is the most widely used method for long-range data transmission, leveraging sound waves to transmit information over kilometers [29]. However, acoustic channels suffer from limited bandwidth and high latency. Optical communication systems offer high data rates for short distances but require clear water conditions and line-of-sight [30]. Radio frequency (RF) communication is limited to very shallow depths due to rapid signal attenuation [28]. To enhance data exchange and operational coordination, underwater sensor networks employing hybrid communication techniques are deployed, enabling multi-node collaboration and environmental monitoring [31].

D. Navigation and Control

Accurate navigation and control are paramount for UUV autonomy. Due to the inapplicability of GPS underwater, alternative methods such as Inertial Navigation Systems (INS) combined with Doppler Velocity Logs (DVL) are used to estimate position and velocity [32], [33]. Sensor fusion algorithms integrate data from multiple sources to improve accuracy and reduce drift [34]. Adaptive control algorithms adjust vehicle behavior in real time based on environmental feedback and mission objectives, enhancing robustness against disturbances and uncertainties [35].

E. Sensor Integration

UUVs are equipped with a variety of sensors to perceive the underwater environment and perform mission-specific tasks. Sonar remains the primary sensing modality for obstacle avoidance, mapping, and target detection, with both active and passive variants in use [36]. High-resolution cameras provide visual data essential for inspection and reconnaissance [37]. LIDAR systems are increasingly integrated for precise 3D mapping in shallow waters [38]. Additional sensors include pressure transducers for depth measurement and chemical sensors for detecting pollutants or biological agents [39], [40]. Table III summarizes typical sensor types and their primary functions in UUVs.

These core technologies collectively empower UUVs to perform complex underwater missions autonomously or semi-autonomously, enabling advances in exploration, monitoring, and intervention.

TABLE III: Core Sensors in UUVs and Their Applications

Sensor Type	Primary Function	Typical Applications
Sonar (Active/Passive)	Obstacle detection, navigation, target tracking	Seafloor mapping, mine detection, obstacle avoidance
Optical Cameras	Visual imaging and inspection	Structural inspection, marine biology studies, surveillance
LIDAR	High-resolution 3D mapping	Coastal surveying, underwater archaeology
Pressure Sensors	Depth measurement	Depth control, environmental monitoring
Chemical Sensors	Detection of pollutants, gas concentrations	Environmental monitoring, contamination detection

IV. Applications of Unmanned Underwater Vehicles

Unmanned Underwater Vehicles (UUVs) have revolutionized underwater operations across diverse domains, leveraging their ability to access hazardous or inaccessible underwater environments autonomously or remotely. This section elaborates on the primary applications of UUVs in military, scientific, commercial, and disaster response fields.

A. Military and Defense

UUVs play a pivotal role in modern naval operations by enhancing capabilities in mine detection, surveillance, and reconnaissance missions. Autonomous Underwater Vehicles (AUVs) equipped with sonar and imaging systems are extensively used to detect and neutralize underwater mines, thereby safeguarding naval vessels and shipping routes [41], [42]. Surveillance UUVs enable covert monitoring of strategic underwater zones and enemy vessels without risking human lives [43]. Their reconnaissance capabilities extend to gathering intelligence and mapping underwater terrain critical for mission planning [44].

B. Scientific Research

In the domain of scientific research, UUVs have significantly expanded the possibilities for oceanographic exploration and environmental monitoring. Equipped with advanced sensors, UUVs collect valuable data on temperature, salinity, and chemical composition, contributing to climate change studies and marine ecosystem analysis [45]. High-resolution seabed mapping using multibeam sonar on UUVs allows researchers to explore underwater geological formations and discover new species [46]. Additionally, UUVs facilitate long-term monitoring of fragile coral reefs and underwater habitats, supporting conservation efforts [47].

C. Commercial and Industrial

The commercial and industrial sectors benefit from UUV technology through improved inspection, maintenance, and exploration of underwater infrastructure. UUVs are widely employed in the inspection of oil and gas pipelines, ensuring structural integrity and early detection of leaks or damage, thus preventing environmental disasters and costly repairs [48]. Undersea cable inspection and maintenance are facilitated by UUVs capable of precise navigation along cable routes [49]. Moreover, UUVs contribute to marine archaeology by enabling detailed surveys and documentation of submerged archaeological sites without disturbing fragile artifacts [50].

D. Disaster Response and Rescue Operations

In disaster scenarios, UUVs provide critical support in underwater search and rescue, damage assessment, and recovery operations. Their ability to operate in hazardous or low-visibility conditions makes them ideal for locating sunken vessels, aircraft, or black boxes after accidents [51]. UUVs also assist in assessing underwater damage to infrastructure following natural disasters like tsunamis or hurricanes, providing real-time data to emergency response teams [52]. Figure 3 illustrates the broad spectrum of UUV applications across these sectors.

Table IV summarizes key UUV applications, associated technologies, and benefits.

The versatility of UUVs continues to drive innovation, expanding their applications into emerging fields such as underwater mining and autonomous cargo delivery.

V. Challenges and Limitations

Despite significant advancements in Unmanned Underwater Vehicles (UUVs), several critical challenges and limitations persist, impeding their widespread deployment and operational efficiency. This section discusses the primary issues related to power management, communication, navigation, structural durability, and data processing.

A. Power and Battery Life Constraints

One of the most significant limitations of UUVs is their power supply. Most UUVs rely on batteries that limit operational endurance, often restricting mission duration to a few hours or days [53]. Recharge or replacement of batteries underwater is challenging, necessitating energy-efficient propulsion and onboard systems [54]. Emerging technologies such as fuel cells and energy harvesting are promising but not yet fully mature for practical applications [55].

B. Communication Range and Reliability

Underwater communication is inherently difficult due to the absorption and scattering of electromagnetic waves in water. Acoustic communication remains the primary method, but it suffers from limited bandwidth, high latency, and susceptibility to noise and multi-path effects [56]. Optical communication offers higher data rates but is constrained by short ranges and water clarity [57]. These limitations affect real-time data transmission and coordination among multiple UUVs [58].

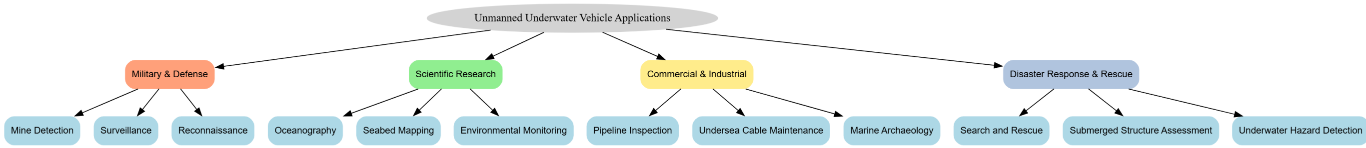

Fig. 3: Overview of Unmanned Underwater Vehicle Applications across Military, Scientific, Commercial, and Disaster Response sectors.

TABLE IV: Summary of UUV Applications

Application Area	Key Technologies	Benefits
Military and Defense	Sonar, stealth propulsion, autonomous navigation	Enhanced mine detection, covert surveillance, intelligence gathering
Scientific Research	Multibeam sonar, chemical sensors, imaging cameras	Comprehensive oceanographic data, seabed mapping, ecosystem monitoring
Commercial and Industrial	High-resolution imaging, pipeline sensors, robotic arms	Infrastructure inspection, maintenance, marine archaeology
Disaster Response and Rescue	Sonar, underwater communication, autonomous control	Rapid search and rescue, damage assessment, recovery operations

TABLE V: Summary of Challenges and Limitations in UUVs

Challenge	Description
Power and Battery Life	Limited energy storage restricts mission duration; challenges in underwater recharging and energy efficiency
Communication	Acoustic signals suffer from low bandwidth, latency, and noise; optical and RF limited by range and water properties
Navigation	GPS unavailability underwater; reliance on INS and acoustic positioning prone to drift and errors
Pressure and Corrosion	Need for pressure-resistant and corrosion-proof materials increases cost and design complexity
Data Handling	Limited onboard processing and storage capabilities affect real-time analytics and mission autonomy

C. Navigation in GPS-Denied Environments

Since GPS signals cannot penetrate underwater, UUVs rely on alternative navigation techniques such as inertial navigation systems (INS), Doppler Velocity Logs (DVL), and acoustic positioning [59]. However, these systems accumulate errors over time and require frequent calibration or surface fixes [60]. Developing robust, autonomous navigation algorithms for long-duration missions in complex underwater terrains remains a significant challenge [61].

D. Pressure and Corrosion Resistance

UUVs operate under high pressure and corrosive seawater environments, requiring durable materials and structural designs [62]. Pressure hulls must withstand depths ranging from shallow waters to several thousand meters, leading to increased size and cost [63]. Corrosion-resistant coatings and components are essential to maintain functionality and reduce maintenance [64], but balancing durability with weight and cost is difficult.

E. Data Storage and Real-Time Processing Limitations

UUVs generate vast amounts of sensor data during missions, which require efficient onboard storage and processing [65]. Limited computational resources and power constraints restrict real-time data analysis and decision-making [66]. Advances in edge computing and AI could mitigate these issues, but integration into compact UUV platforms remains an ongoing research area [67].

Addressing these challenges is crucial for advancing UUV technology and expanding their operational capabilities. Continued research in power systems, communication protocols, robust navigation algorithms, advanced materials, and onboard computing will be key drivers for future improvements.

VI. Emerging Trends and Future Directions

The field of Unmanned Underwater Vehicles (UUVs) is evolving rapidly, driven by advances in multiple disciplines such as artificial intelligence, robotics, materials science, and communications. This section highlights the most promising emerging trends and potential future directions that could significantly enhance UUV capabilities and operational efficiency.

A. Artificial Intelligence and Machine Learning in Autonomy

Recent progress in artificial intelligence (AI) and machine learning (ML) has opened new avenues for enhancing UUV autonomy. Advanced algorithms enable adaptive mission planning, real-time decision making, and improved target recognition under challenging underwater conditions [68]. Machine learning techniques are increasingly used for anomaly detection, sensor fusion, and predictive maintenance, reducing the need for human intervention and increasing mission success rates [69]. Integration of deep learning models with onboard processing units is becoming feasible due to improvements in computational hardware and energy efficiency [70].

TABLE VI: Summary of Emerging Trends and Future Directions in UUVs

Trend	Description
AI and Machine Learning	Enhanced autonomy through adaptive algorithms, improved sensor fusion, and predictive analytics
Swarm UUVs	Coordinated multi-vehicle missions for increased coverage and resilience
Hybrid UUVs	Combined autonomous and remote operation modes for flexible deployment
Bio-Inspired Designs	Energy-efficient and agile locomotion inspired by aquatic organisms
Cloud and Edge Computing	Distributed data processing frameworks for real-time and long-term mission support

B. Swarm UUVs and Cooperative Missions

The concept of swarm robotics is gaining traction in underwater environments. Swarm UUVs, operating as coordinated groups, can perform complex tasks more efficiently than individual vehicles. Cooperative behaviors such as distributed sensing, collaborative mapping, and formation control enhance spatial coverage and mission robustness [71]. Communication protocols tailored for underwater swarm operations are under active research, aiming to overcome bandwidth and latency limitations inherent in acoustic links [72].

C. Hybrid UUVs (AUV + ROV)

Hybrid Unmanned Underwater Vehicles, combining features of Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), offer flexible operational modes. These systems can autonomously execute routine tasks and switch to remote operation in complex or high-risk scenarios [73]. Hybrid designs benefit from improved endurance, fault tolerance, and versatility, making them suitable for diverse applications ranging from deep-sea exploration to infrastructure inspection [74].

D. Bio-Inspired Designs

Nature continues to inspire innovative UUV designs that mimic biological organisms such as fish, squid, and dolphins. Bio-inspired propulsion and maneuvering systems aim to improve energy efficiency, stealth, and maneuverability in cluttered underwater environments [75]. Flexible hulls, fin-based propulsion, and soft robotics concepts contribute to enhanced adaptability and reduced acoustic signatures [76]. These designs also facilitate safer interactions with marine life and sensitive ecosystems [77].

E. Cloud and Edge Computing in Marine Robotics

The integration of cloud and edge computing paradigms is transforming data processing and decision-making in marine robotics. Edge computing enables real-time data analysis and control on the UUV itself, reducing latency and bandwidth usage [78]. Meanwhile, cloud platforms facilitate long-term data storage, mission planning, and collaborative research by aggregating information from multiple vehicles [79]. Hybrid cloud-edge architectures offer scalable and resilient frameworks for complex underwater operations and fleet management [80].

In summary, the convergence of these emerging technologies promises to overcome many current limitations of UUVs, enabling more autonomous, efficient, and versatile underwater missions. Future research should focus on interdisciplinary approaches that integrate these trends, fostering innovations that expand the frontiers of underwater exploration and exploitation.

VII. Comparative Analysis

The global development of Unmanned Underwater Vehicles (UUVs) has resulted in a diverse range of platforms, each optimized for specific missions, operational depths, autonomy levels, and payload capabilities. Conducting a comparative analysis of major UUV platforms offers valuable insights into the technological landscape and strategic design decisions of different manufacturers. This section presents a concise but detailed comparative evaluation based on key technical specifications, operational use-cases, and manufacturer contributions.

Various UUVs in the market serve purposes ranging from military reconnaissance to deep-sea research and commercial inspection. Notable distinctions can be observed in autonomy levels, endurance, communication systems, and modular payloads. Some platforms prioritize stealth and maneuverability, while others emphasize endurance and multi-sensor integration. The comparison summarized in Table VII outlines these platforms across critical parameters including depth rating, endurance, propulsion type, application domain, and manufacturing origin.

As illustrated in Table VII, platforms like the *REMUS 600* and *Bluefin-21* are favored in defense and deep-ocean applications due to their modularity and endurance. In contrast, the *Iver3* is optimized for littoral missions with a compact, user-friendly interface. The *HUGIN* system, with extended endurance and superior navigation technologies, serves a dual purpose in commercial offshore activities and environmental research. WHOI's *SeaBED*, with its hovering capability, is particularly suited for high-resolution photogrammetric mapping in benthic zones.

Notably, hybrid platforms like *Proteus* mark a shift toward multipurpose UUVs that can transition between manned and unmanned operations. This reflects a growing trend in UUV development focused on mission versatility, modular payloads, and adaptive control systems.

In conclusion, the comparative analysis reveals the diversity and specialization of UUVs across manufacturers and application domains. While some platforms excel in endurance and depth, others are built for agility and sensor versatility. As technological integration progresses, future UUVs are expected to incorporate features from multiple categories to fulfill increasingly complex underwater missions.

TABLE VII: Comparison of Prominent UUV Platforms

UUV Platform	Manufacturer	Max Depth (m)	Endurance	Primary Application	Notable Features
REMUS 600	Hydroid/Kongsberg	600	24 hours	Naval mine countermeasures	Modular design, commercial and military use
Bluefin-21	General Dynamics	4500	25 hours	Deep-sea mapping	Autonomous deployment, used in MH370 search
HUGIN AUV	Kongsberg Maritime	6000	60+ hours	Pipeline inspection, research	Advanced sonar, inertial nav systems
Iver3	L3Harris Technologies	300	8–14 hours	Coastal surveillance, research	User-configurable sensors, compact size
SeaBED AUV	WHOI	2000	10 hours	Scientific exploration	High-resolution imaging, hovering capability
Proteus	Huntington Ingalls + Battelle	700	72+ hours	Special operations, payload transport	Convertible manned/unmanned mode

VIII. Conclusion

Unmanned Underwater Vehicles (UUVs) have emerged as indispensable tools in modern marine exploration, defense operations, and industrial inspection. This review systematically examined the classification, core technologies, applications, and limitations of UUVs while also highlighting recent advancements and future directions. The classification of UUVs based on autonomy, application, and size provides a structured understanding of their diverse deployment scenarios. Technological innovations in propulsion, energy systems, underwater communication, navigation, and sensor integration are driving performance enhancements and enabling more complex underwater missions.

One of the central insights of this review is the vital role of interdisciplinary innovation in advancing UUV capabilities. Progress in artificial intelligence, materials science, marine robotics, and underwater acoustics must converge to overcome enduring challenges such as energy limitations, real-time data transmission, and autonomous operation in GPS-denied environments. As UUVs evolve, their design and functionality will increasingly rely on the seamless integration of intelligent algorithms, adaptive control strategies, and energy-efficient architectures.

Looking ahead, future research should focus on scalable and resilient systems that can operate collaboratively, adapt to dynamic marine conditions, and execute long-duration missions with minimal human intervention. The development of bio-inspired designs, swarm coordination protocols, and hybrid AUV–ROV platforms reflects the direction in which the field is heading. Furthermore, advancements in cloud and edge computing will enable more responsive and data-rich underwater operations.

In conclusion, the field of UUVs is at a pivotal stage where technological maturity and emerging research trends are aligning to redefine underwater exploration. Continued investment in interdisciplinary research, standardization efforts, and international collaboration will be critical to harnessing the full potential of UUVs across scientific, commercial, and strategic domains.

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