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Review

Positioning Systems for Unmanned Underwater Vehicles: A Comprehensive Review

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Abstract: Positioning systems are integral to Unmanned Underwater Vehicle (UUV) operation, enabling precise navigation and control in complex underwater environments. This paper comprehensively reviews the key technologies employed for UUV positioning, including acoustic systems, inertial navigation, Doppler velocity logs, and GPS when near the surface. These systems are essential for seabed mapping, marine infrastructure inspection, and search and rescue operations. The review highlights recent technological advancements and examines the integration of these systems to enhance accuracy and operational efficiency. It also addresses ongoing challenges, such as communication constraints, environmental variability, and discrepancies between theoretical models and field applications. Future trends in positioning system development are discussed, with a focus on improving reliability and performance in diverse underwater conditions to support the expanding capabilities of UUVs across scientific, commercial, and rescue missions.

Keywords: unmanned underwater vehicles; positioning systems; modeling; autonomous underwater vehicles; remotely operated underwater vehicles

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1. Introduction

Unmanned Underwater Vehicles (UUVs) have successfully entered various applications, including oceanographic research, underwater archaeology, and rescue operations. These Autonomous or Remotely Operated Vehicles are revolutionizing underwater exploration and monitoring by enabling the collection of data, inspection of submerged structures, and execution of complex missions without direct human involvement [1,2]. UUVs rely heavily on advanced positioning systems to navigate accurately and perform their tasks efficiently [3–5]. These systems utilize a combination of technologies, such as GPS (Global Position System) when near the surface, acoustic positioning, inertial navigation, and Doppler velocity logs, to determine the vehicle's precise location and trajectory [4]. Accurate positioning is essential for detailed seabed mapping, effective tracking of marine life, and reliable search and rescue missions. The development and integration of these positioning technologies are critical for optimizing resource utilization, minimizing environmental impact, and enhancing the capabilities of UUVs in scientific, commercial, and rescue applications [5,6].

However, despite the considerable potential of Unmanned Underwater Vehicles (UUVs) in various applications, numerous questions and challenges remain to be addressed. Traditionally limited by human operational capabilities, underwater exploration and operations have seen a significant transformation in the past decade, evolving into more sophisticated and technology-driven activities. This transformation has been propelled by innovations in UUVs and their advanced positioning systems. These technologies enable researchers, scientists, and operators to make well-informed decisions regarding underwater navigation, marine environment monitoring, and numerous factors affecting mission success and operational efficiency [7]. This enhancement boosts overall productivity and safety in underwater endeavors. However, these advancements also necessitate specialized knowledge and skills, along with substantial investments in hardware, software, and other infrastructural resources. Moreover, challenges such as extreme underwater conditions, restricted communication capabilities, and the requirement for long-term operational reliability further complicate UUV deployment [8]. While these obstacles add complexity to underwater missions, they simultaneously present opportunities for technological innovation and growth in marine exploration and other operations.

Our continuous research about the positioning systems in UUVs progresses with the development of a comprehensive framework for implementing advanced positioning systems in Unmanned Underwater Vehicles (UUVs), emphasizing crucial components essential for their seamless integration. Through a comparative analysis presented in detailed tables, we explore technical nuances and draw significant conclusions concerning the implementation and operational constraints of these systems. While the importance of precise positioning in UUV operations is widely acknowledged, practical applications often encounter challenges such as underwater communication limitations and environmental variables. Despite technological strides, a notable disparity exists between theoretical concepts and real-world deployment, with proposed solutions often reliant on future advancements rather than current practical implementations [9].

This study offers several novel insights and contributions to the field of Unmanned Underwater Vehicle (UUV) positioning systems that address key positioning technologies, including Inertial Navigation Systems (INSs), Doppler Velocity Logs (DVLs), and various acoustic positioning systems. Furthermore, it addresses the following:

i. Integration of Multiple Technologies: A key contribution is the emphasis on integrating multiple positioning technologies to improve navigation accuracy and reliability, particularly in GPS-denied environments;
ii. Comparison of Operational Capabilities: It offers a detailed comparison of positioning systems based on operational factors such as accuracy, cost, depth limitations, and maintenance requirements, highlighting the trade-offs for different applications;
iii. Focus on Maintenance Costs: The study addresses an often-overlooked issue—maintenance costs and recalibration needs of positioning systems—offering a practical perspective that fills a gap in the existing literature;
iv. Critical Analysis of Challenges: The paper identifies and analyzes key challenges, such as communication limitations and environmental variability, providing valuable insights for the advancement of UUV positioning technologies;
v. Future Research Directions: It highlights opportunities for future research and technological advancements, suggesting areas of improvement for enhanced UUV positioning performance.

This work offers a unique contribution by combining practical, technical, and economic perspectives, advancing the understanding of UUV positioning systems in both scientific and commercial contexts.

The structure of this research unfolds as follows: In Section 2, we initially explored the fundamental concepts of Unmanned Underwater Vehicles (UUVs), providing detailed definitions and classifications that encapsulate their full scope. We also categorize the various positioning systems employed by UUVs to enhance our understanding of the technologies used for navigation in both shallow waters and deeper ocean environments. In Section 3, we delve deeper into these positioning systems, analyzing their capabilities through tables to better illustrate their specific uses. Section 4 focuses on the practical applications of these positioning systems, organized in a table that summarizes key information such as the number of references reviewed, the type of research papers analyzed, and the specific applications and technologies associated with each system. Section 5 provides a thorough discussion of the data presented in Section 4, offering critical insights into the research papers and their broader implications. Finally, Section 6 emphasizes future research directions and technological advancements in UUV positioning systems, suggesting potential areas for further exploration based on the findings of this study.

2. Exploring the Definition and Categories of Unmanned Underwater Vehicles and Their Respective Positioning Systems

Although the development of Unmanned Underwater Vehicles (UUVs) has seen significant growth in recent years [10], the associated hardware and software technologies still appear to be in relatively early stages when compared to the theoretical models and their potential capabilities. In companies that specialize in developing underwater rescue systems, progress has been more advanced and promising compared to those focusing on commercial applications, such as underwater exploration and photography, due to the urgent need for reliable, efficient technology in life-saving operations, greater investment in safety-critical solutions, and the push for innovation driven by the potential to operate in challenging, high-risk environments where human intervention is limited. However, this disparity is not necessarily a setback, as technological advancements tend to occur in a "chain reaction". As certain companies make breakthroughs, these discoveries contribute to the overall progress of the industry, accelerating development across the board. With this in mind, it is crucial to delve deeper into the definition of UUVs, examining the positioning systems they employ, the methods by which they are utilized, and the reasons behind their use. UUVs can generally be divided into two main categories, each with distinct characteristics and applications [8,11–15]:

1. Autonomous Underwater Vehicles;
2. Remotely Operated Underwater Vehicles.

A common misconception is that Underwater Gliders and Hybrid ROV/AUVs are often mistaken for separate categories of underwater vehicles. In reality, they belong to the broader family of Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs), respectively [12,14,16].

2.1. Autonomous Underwater Vehicles

Autonomous Underwater Vehicles (AUVs) are unmanned robotic systems designed to carry out underwater tasks without requiring human control in real time. These vehicles are pre-programmed with specific instructions and can navigate independently in ocean environments. They are often equipped with various sensors, sonar systems, and cameras to collect data for scientific, environmental, rescue, and industrial purposes [15].

AUVs play a key role in oceanographic research by helping scientists map the seafloor, study marine life, and analyze water properties like temperature and salinity [8,17]. They are also used in environmental monitoring to detect pollution and study the impacts of climate change on marine ecosystems. In rescue applications, AUVs are used for tasks such as locating underwater wreckage, mapping hazardous or hard-to-reach underwater areas, and providing data to support rescue missions, while in archaeology, they help explore shipwrecks and submerged ancient structures [18,19].

In the oil and gas industry, AUVs are vital for surveying the ocean floor to locate underwater resources and inspect pipelines [20]. Unlike Remotely Operated Vehicles (ROVs), which require a direct connection and real-time control by humans, AUVs operate autonomously, relying on advanced navigation systems such as GPS, inertial navigation, and acoustic communication to complete their missions even in deep, remote parts of the ocean [5].

Autonomous Underwater Vehicles (AUVs) come in several types, each designed for specific tasks based on size, operational range, and mission requirements. One common type is man-portable AUVs (such as GAVIA [21]), which are small and lightweight, making them easy to transport and deploy by one or two individuals. These AUVs are typically used for shallow-water operations and are favored in coastal research, environmental monitoring, and search and rescue missions [22]. Their compact size and quick deployment capabilities allow for short-term, localized tasks where portability is essential, and they can operate in areas that may be difficult for larger vehicles to access [23].

Another type is the lightweight AUV, which is slightly larger and capable of deeper operations than man-portable models. These AUVs are used for moderate-depth missions, carrying more advanced sensors and payloads for tasks such as underwater mapping, pipeline inspection, and rescue tasks. Lightweight AUVs offer a balance between portability and functionality, allowing them to gather more detailed data over longer distances than their smaller counterparts while still being relatively easy to handle [24].

The largest and most capable category is heavy-weight AUVs, which are designed for deep-sea and long-duration missions. These robust vehicles are used in demanding fields like deep-sea mining, oil and gas exploration, and oceanographic research. Heavy-weight AUVs can operate at extreme depths and carry a wide range of sophisticated sensors, enabling detailed seafloor mapping, sub-surface imaging, and resource exploration. Their enhanced endurance and operational range make them suitable for missions that require extensive data collection over large areas, such as surveying remote regions of the ocean floor or monitoring deep-water ecosystems [25].

These different types of AUVs allow for a wide range of applications, each suited to specific operational needs, from shallow-water environmental studies to deep-ocean exploration and industrial tasks.

2.2. Remotely Operated Vehicles

Remotely Operated Underwater Vehicles (ROUVs) are underwater robotic systems controlled by human operators from a surface vessel or platform [11]. These vehicles are typically tethered to the surface via a cable that provides power and enables communication between the ROV and its operator. This connection allows real-time control and monitoring, making ROVs ideal for conducting complex underwater tasks in environments that are too deep or dangerous for human divers [26].

ROVs are equipped with various tools and sensors, including high-definition cameras, sonar systems, and robotic arms, which enable them to perform a wide range of operations. They are commonly used in industries such as oil and gas, marine research, and SAR (Search and Rescue) operations. In these contexts, ROVs are deployed for tasks like underwater inspection, maintenance, exploration, and environmental monitoring. Their ability to deliver live video feeds and data to operators on the surface is critical for real-time decision-making and precise manipulation in underwater environments [26].

One of the key features of ROVs is their versatility [27]. For example, in the offshore oil and gas industry, ROVs are used to inspect and repair pipelines, oil rigs, and other underwater infrastructure, helping to ensure the safety and integrity of critical systems [28,29]. In scientific research, ROVs allow for the exploration of shipwrecks, deep-sea ecosystems, and underwater geological formations. Their robotic arms can collect samples or perform fine manipulations that are impossible for divers to carry out at extreme depths [30,31].

Unlike Autonomous Underwater Vehicles (AUVs), which operate independently, ROVs require continuous human control, making them particularly useful for missions that demand real-time responsiveness or involve intricate operations. This distinction makes ROVs indispensable for tasks like underwater construction, recovery missions, and even SAR operations, such as diver assistance during rescue operations [19].

The tether that connects ROVs to the surface provides them with a consistent power supply, enabling long operational durations without the need for onboard batteries [32]. This capability allows ROVs to carry out extended missions, often lasting several hours or even days, depending on the specific task [31]. Their ability to perform a wide range of functions in challenging environments has made them a critical tool in various underwater industries and research fields.

Remotely Operated Vehicles (ROVs) can be categorized based on their size, capabilities, and the types of missions they are designed to undertake [11]. Observation-class ROVs are the smallest and simplest type, primarily used for visual inspections and light-duty tasks [33]. These ROVs are equipped with cameras and basic sensors to provide real-time video and data from underwater environments. They are ideal for applications that involve monitoring and documenting, such as inspecting underwater structures, observing marine life, or conducting environmental surveys. Their relatively straightforward design makes them easy to deploy and operate, but they are generally not equipped for heavy-duty tasks or significant manipulations [33,34].

In contrast, work-class ROVs are larger, more robust vehicles designed to handle more complex and demanding tasks [35]. These ROVs come equipped with advanced robotic arms, specialized tools, and high-resolution sensors, allowing them to perform intricate operations such as underwater construction, maintenance, and repairs. They are commonly used in the oil and gas industry for inspecting and repairing pipelines, performing underwater welding, and maintaining offshore platforms. Work-class ROVs are capable of operating at great depths and can carry a substantial payload, making them suitable for heavy-duty applications and extended missions [35–37].

A subset of work-class ROVs is the light work-class ROV, such as SEAPUP of the family of SEALION, which bridges the gap between observation-class and work-class ROVs [38]. These vehicles offer enhanced capabilities compared to observation-class ROVs but are not as large or powerful as full work-class models. Light work-class ROVs are equipped with more advanced tools and can perform moderate-depth operations, making them suitable for tasks like light maintenance, underwater inspections, and shallow-water construction projects [37]. They offer a balance between functionality and maneuverability, providing versatility for various underwater applications.

Each type of ROV is designed with specific features to meet the demands of its intended tasks, from simple visual inspections to complex underwater operations. The choice of ROV depends on the nature of the mission, the operational depth, and the required payload capabilities.

2.3. Hybrid ROV/AUV

Hybrid underwater vehicles such as EVAs are sophisticated systems designed to combine the capabilities of Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs) [39]. These vehicles are engineered to operate both autonomously and under real-time human control, providing the flexibility to adapt to various underwater missions and environments. The HROV/AUV designs can operate tethered with some autonomous functions or untethered with some range restrictions [39]. The term hybrid can also mean that the specific vehicle can be amphibious, which means it can operate both on aerial and water missions. In this paper, we are not going to focus on hybrid underwater vehicles (HUVs) because they use one of the two main categories, which we explained how they operate in Sections 2.1 and 2.2.

2.4. Positioning Systems of UUVs

Positioning systems in Unmanned Underwater Vehicles (UUVs) are crucial for accurately determining and maintaining the vehicle's location and trajectory underwater. Given the challenges of operating in the underwater environment, these systems use a combination of technologies to ensure precise navigation and positioning [4,5,13,40–43].

2.4.1. Primary Positioning Systems

1. Inertial Navigation Systems (INSs)

Inertial Navigation Systems use accelerometers and gyroscopes to measure the vehicle's movement and orientation. By tracking changes in velocity and direction, INSs can calculate the vehicle's position relative to a known starting point. INSs are valuable for underwater navigation because they do not rely on external signals, making them effective in environments where GPS signals are unavailable. However, INSs can suffer from drift over time, requiring periodic updates or corrections [44–46].

2. Long Baseline (LBL) Systems

Long Baseline systems use a network of underwater transponders placed on the seabed. The UUV communicates with these transponders to determine its position based on the time it takes for acoustic signals to travel between the UUV and the transponders. LBL systems provide high positional accuracy and are often used in environments where precise positioning is critical, such as deep-sea exploration and underwater construction [47–49].

3. Short Baseline (SBL) Systems

Short Baseline systems are like LBL systems but use a smaller array of transponders located closer to the UUV. These systems are generally used for tasks that require less precision compared to LBL systems but are advantageous in shallower waters or areas with limited space for deploying long baseline transponders [50].

4. Ultra-Short Baseline (USBL) Systems

Ultra-Short Baseline systems use a single, highly sensitive transducer mounted on the surface vessel to communicate with a transponder on the UUV. The USBL system calculates the UUV's position based on the angle and distance of the acoustic signals received. USBL systems are often used for real-time tracking and positioning of UUVs during operations and are useful for tasks requiring continuous monitoring and updates [48,51].

5. Doppler Velocity Log (DVL)

A Doppler Velocity Log measures the velocity of the UUV relative to the seafloor or water column using sonar technology. By tracking the Doppler shift in the sonar signals reflected off the seabed or particles in the water, the DVL provides information on the UUV's speed and direction. These data can be integrated with other positioning systems to improve overall navigation accuracy [52,53].

6. Dead Reckoning (DR)

Dead reckoning involves calculating the UUV's position based on its previous position, speed, and heading. This method can be used in conjunction with INSs and other systems to estimate the current position, especially when external positioning data are temporarily unavailable. It is often used to complement other systems and to provide additional navigation data [54–56].

7. Acoustic Modem Systems (AMSs)

Acoustic modems can communicate between the UUV and surface vessels or other underwater stations using sound waves [57]. While primarily used for data transmission, these modems (some low-cost) can also assist in positioning by providing additional data points and allowing for communication with an external positioning system [58,59].

2.4.2. More Positioning Systems and Navigation Aided Positioning Systems

1. Optical Methods use cameras and laser systems to capture visual data for navigation and positioning. These methods rely on the visibility of landmarks, patterns, or features in the underwater environment. Optical methods are highly effective for tasks requiring high-resolution imagery and are often used in conjunction with other systems to provide visual confirmation and detailed mapping. However, they are limited by water clarity and lighting conditions and are typically less effective in murky or deep waters [60].
2. Magnetic Positioning systems use the Earth's magnetic field or local magnetic anomalies to determine a UUV's position. By measuring variations in the magnetic field, these systems can provide positional data even in GPS-denied environments [61]. Magnetic positioning is useful for underwater navigation in areas where other positioning systems may struggle. However, it can be affected by magnetic interference from natural or man-made sources, limiting its effectiveness in certain conditions [61,62].
3. Hydrostatic Pressure Sensors (HPSs) measure the pressure exerted by the surrounding water to determine the depth of a UUV. These sensors are crucial for maintaining depth control in underwater operations. They are simple, reliable, and effective for depth measurement but provide limited information on horizontal positioning or orientation. They are typically used in conjunction with other systems for comprehensive navigation [63].

4. Satellite Navigation Aided Systems use signals from satellites to aid in the navigation of UUVs, often in conjunction with surface support vessels [64]. These systems leverage GPS or other satellite signals to provide accurate positioning data on the surface, which can be relayed to the UUV. They are highly accurate when the UUV is close to the surface but are less effective underwater, where satellite signals cannot penetrate [13].
5. Synthetic Aperture Sonar (SAS) is an advanced sonar technology that creates high-resolution images of the underwater environment by processing sonar data collected over a wide area [65]. SAS provides detailed imagery and is useful for seabed mapping, underwater inspections, and object detection. However, it requires significant data processing capabilities and can be affected by water conditions [66].
6. Beacon-based Localization uses acoustic or electromagnetic beacons deployed at known locations to provide reference points for positioning [67]. UUVs communicate with these beacons to determine their location based on the received signals. This method is effective for precise localization and tracking but requires the deployment of multiple beacons, which can be logistically challenging [68].
7. Photogrammetry involves using high-resolution images to create detailed 3D models of underwater environments [69]. By analyzing overlapping images taken from different angles, photogrammetry can provide accurate spatial information. This technique is useful for detailed surveys and inspections but is limited by visibility and lighting conditions [70].
8. SLAM (Simultaneous Localization and Mapping) is a method that allows a UUV to build a map of its environment while simultaneously determining its location within that map [71]. SLAM combines sensor data, such as sonar or cameras, with algorithms to continuously update the vehicle's position and map. It is effective for exploring unknown environments but can be computationally intensive and requires sophisticated processing [72].
9. Electromagnetic Positioning systems utilize electromagnetic fields to determine the position of a UUV. These systems can be particularly useful in environments where acoustic methods may be less effective, such as in areas with high levels of ambient noise. However, electromagnetic positioning is influenced by the conductivity of the water and the presence of other electromagnetic sources [73,74].
10. LIDAR (Light Detection and Ranging) uses laser pulses to measure distances and create detailed 3D maps of underwater environments. LIDAR systems are highly effective for capturing fine details and generating accurate models. However, they are limited by the penetration depth of laser beams in water and are typically used in conjunction with other sensors [15,75].
11. Buoy-based Positioning involves using surface buoys equipped with positioning systems to provide reference points for UUVs. These buoys can relay position data via acoustic or other communication methods, helping to track and guide UUVs. This method is useful for surface-tracked missions but may have limited effectiveness in deep or remote locations [76–78].
12. Fiber Optic Gyroscope (FOG) provides precise measurements of angular rotation by detecting changes in light polarization through fiber optics. FOGs are known for their high accuracy and stability, making them suitable for advanced navigation systems. They are, however, expensive and may require additional calibration and integration with other positioning technologies [79].
13. Towed Array Systems consist of a series of sensors or receivers deployed behind a moving vessel. These systems can detect acoustic signals or magnetic fields to determine the location and movement of UUVs. Towed arrays are useful for continuous monitoring and tracking but require the presence of a surface vessel for deployment [80].
14. Geophysical Positioning methods use geological and geophysical data to determine a UUV's position based on underwater features such as magnetic anomalies or seafloor

topography. These methods are valuable for scientific research and resource exploration but can be affected by the complexity of the underwater environment [81].

15. Seismic Navigation employs seismic waves generated by controlled sources to map the seafloor and determine the position of UUVs based on the reflections and refractions of these waves. This method provides high-resolution imaging and is useful for detailed seabed surveys but requires specialized equipment and processing [82].
16. Pinger and Hydrophone Systems use acoustic signals emitted by pingers and received by hydrophones to determine the position of UUVs. The time difference of arrival (TDOA) of the acoustic signals can be used to calculate the UUV's location. These systems are effective for tracking and localization but can be influenced by underwater noise and signal attenuation [83].
17. Synthetic Aperture Radar (SAR) is used primarily for surface-based imaging but can be adapted for underwater applications by capturing reflections from the water surface. SAR provides detailed imaging and is useful for detecting surface and near-surface objects [84]. However, its use underwater is limited and typically involves surface support [85,86].
18. Biomimetic Navigation Systems are inspired by the navigation strategies of marine animals, such as fish and dolphins. These systems use principles observed in nature to develop advanced navigation and positioning techniques. They offer innovative approaches to underwater navigation but are still emerging in practical applications [87].
19. Sonar Imaging Systems use sonar technology to create images of underwater environments by analyzing sound waves reflected from objects and the seafloor. These systems are essential for detecting and mapping underwater structures and features. They can be affected by water conditions and require substantial data processing [88].
20. Laser Scanning uses laser beams to capture detailed 3D information about underwater environments. This technology provides high-resolution scans and is effective for creating accurate models of underwater features. However, its effectiveness is limited by water clarity and the range of the laser [89,90].
21. Gravity Gradiometry measures variations in the Earth's gravitational field to determine the location and movement of UUVs. This technique is useful for detecting geological structures and anomalies. It requires sophisticated equipment and can be influenced by external factors affecting gravitational measurements [91].

Each of these positioning systems presents distinct advantages, making them particularly well suited for specific underwater applications. In many cases, Unmanned Underwater Vehicles (UUVs) will employ a combination of these technologies to enhance the accuracy, reliability, and precision of their navigation and positioning in a variety of challenging underwater environments.

Operating in difficult terrains such as murky waters, icy regions, or areas dense with algae presents significant challenges for UUVs. In such environments, the vehicles often face obstacles like reduced visibility, increased battery consumption due to colder temperatures, and the risk of thrusters becoming clogged by seaweed or debris. These factors can severely impact the vehicle's performance, making it essential for UUVs to rely on advanced sensor fusion, redundancy, and robust propulsion systems to maintain efficiency and reliability during missions. Combining different navigation technologies ensures that UUVs can effectively adapt to the diverse challenges presented by underwater exploration [92,93].

2.5. Analysis of Components and Positioning System in a UUV System

The control architecture of an Unmanned Underwater Vehicle (UUV) is illustrated in Figure 1, specifically focusing on a Remotely Operated Vehicle (ROV).

At the core of this system is the ROV Central Control Unit, which serves as the primary processing hub. This unit is responsible for receiving commands from the Surface Control Module—the interface through which the operator interacts with the vehicle. The Surface Control Module connects to a computer and controller, allowing the operator to send commands and receive real-time feedback about the ROV's status and environmental conditions.

Importantly, the power supply powers both the CCU and the Electronic Speed Controllers (ESCs), ensuring that all systems receive the necessary energy to operate effectively.

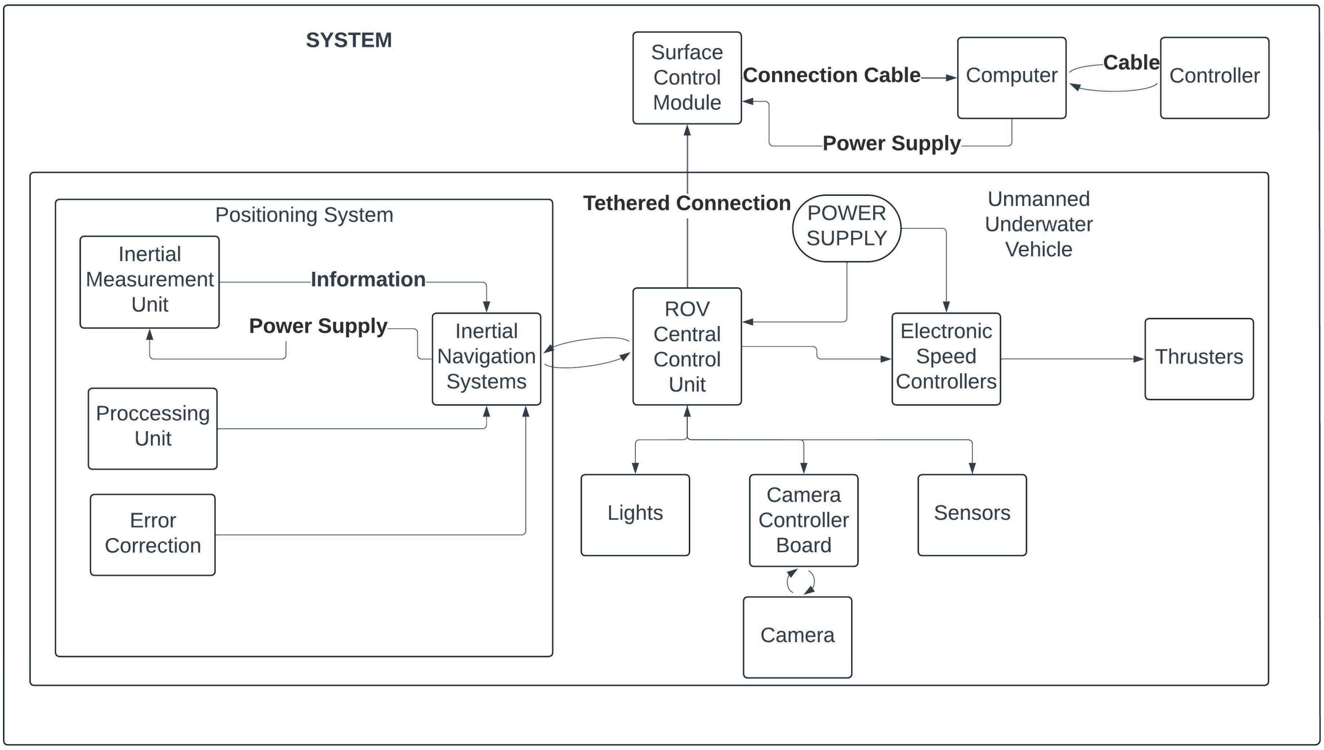

Figure 1. Block diagram of an Unmanned Underwater Vehicle (UUV) control system.

Key to the operation of the ROV is (in this case) the Inertial Measurement Unit (IMU), which provides critical information regarding the vehicle's orientation and motion. These data feed into the Inertial Navigation System [15], which utilizes the IMU's information, along with inputs from other sensors, to accurately determine the vehicle's position and trajectory in the underwater environment [44–46]. The ROV Central Control Unit processes this information and integrates it with operator commands to ensure the vehicle moves as intended.

The Electronic Speed Controllers (ESCs) play a vital role in regulating the power supplied to the thrusters and the propulsion mechanisms of the ROV. By adjusting the speed and direction of these thrusters based on commands from the control unit, the ESCs enable precise maneuvering of the vehicle [94]. Additionally, various sensors collect data on environmental factors such as depth, temperature, and pressure, which are essential for safe navigation. These sensor data are continuously fed back to the ROV Central Control Unit, allowing for real-time adjustments to the vehicle's operation.

For visual monitoring and navigation, the ROV is equipped with a camera managed by a Camera Controller Board. The camera provides essential visual feedback to the operator, especially in dark or murky underwater environments, where the accompanying lights enhance visibility. The control unit can adjust the camera's settings and manage its operation according to mission requirements.

Finally, an error correction module is integrated into the system to ensure reliable performance. This component works by correcting any discrepancies or errors detected in the data or control commands, thereby enhancing the accuracy of the ROV's navigation and control. Overall, this block diagram represents a sophisticated control system that facilitates the effective operation of an ROV, allowing it to respond dynamically to both operator inputs and the challenges of underwater environments.

3. Reviewing Positioning Systems and Their Capabilities

When reviewing positioning systems for Unmanned Underwater Vehicles (UUVs), it is essential to consider the diverse technologies that enable precise navigation and mission execution in challenging underwater environments. These systems are designed to overcome the unique limitations of underwater operations, such as signal attenuation [95], limited visibility [93], and environmental interference [96]. Positioning technologies vary in terms of their mechanisms, ranging from acoustic [96], optical [60,79], and electromagnetic methods [74] to advanced systems like Synthetic Aperture Sonar (SAS) [66] and Simultaneous Localization and Mapping (SLAM) [71]. Each of these methods offers specific advantages depending on the mission requirements, water depth, environmental conditions, and level of precision needed. Whether through direct data gathering via sonar or laser scanning or more complex techniques like gravity gradiometry [91] and photogrammetry [70], UUVs rely on a combination of systems to ensure accurate positioning. Understanding these technologies, along with their strengths, limitations, and applications, is crucial for advancing underwater exploration, resource management, and scientific research.

3.1. Main Positioning Systems

As described in Section 2.4.1, there are seven main positioning systems that we are going to emphasize. These technologies have their advantages and disadvantages, neither of which should be ignored. Factors that should be considered are their cost to build and maintain. Cost is essential when designing such complex equipment and cannot be taken out of the equation. Maintenance is a key factor in underwater vehicles and their systems, especially if we take into account the corrosion of saltwater [97]. Underwater positioning systems play a crucial role in a wide array of applications, driving advancements in fields such as marine research [8], offshore energy, environmental monitoring, and SAR. These systems are vital for accurately navigating and mapping the ocean's vast and largely unexplored depths, where GPS signals cannot penetrate. In marine biology, precise positioning is essential for tracking the movements of species, mapping coral reefs, and studying underwater ecosystems. The offshore oil and gas industry relies heavily on these systems for the installation and maintenance of underwater pipelines, rigs, and other infrastructure. Similarly, underwater positioning is critical in search and rescue missions, enabling the efficient location of wreckage, sunken vessels, or lost equipment. SAR operations, such as mapping hazardous or hard-to-reach areas and diver navigation assistance, also depend on these systems for covert and accurate navigation. The importance of these applications lies in their ability to enable safe, efficient, and cost-effective underwater operations, contributing to advancements in scientific discovery, resource management, and national security. So, another key factor that we must take into account is the application of the positioning system [19,42,98,99].

3.2. Communication Problems Due to Water Submersion

One of the major challenges faced by underwater positioning systems is the issue of depth and signal reach [95]. Unlike in the air, where signals like GPS can travel vast distances [97], underwater environments present significant obstacles to signal propagation due to the physical properties of water. As depth increases, signals like acoustic waves, electromagnetic fields, and light are absorbed or scattered, reducing their range and accuracy. Acoustic signals, commonly used in systems such as LBL (Long Baseline) and USBL (Ultra-Short Baseline), degrade in quality and precision as they encounter noise, water density changes, salinity, and temperature variations at greater depths. Electromagnetic signals, which work well in the atmosphere, suffer even more underwater, where conductivity drastically limits their range. Light-based systems like LIDAR are similarly affected, with water turbidity and particles scattering light, making these systems effective only in shallow, clear waters. The deeper an operation, the more difficult it becomes to maintain accurate positioning, leading to a reliance on technologies such as Inertial Navigation Systems (INSs) or hybrid methods to compensate for signal degradation. This problem of depth and signal reach not only limits operational effectiveness but also increases the complexity and cost of deep-sea exploration, underwater construction, and scientific research.

3.3. Categorizing Systems by Their Capabilities

In Table 1, we categorize the various technologies based on their respective advantages and disadvantages. For example, LIDAR (Light Detection and Ranging) is widely regarded as one of the most effective technologies for acquiring 3D data and mapping surface or shallow-water environments [75]. However, its primary limitation is depth, which significantly affects its performance beyond certain thresholds. Moreover, water conditions, which are influenced by a variety of factors, remain unpredictable, making it difficult to maintain accuracy. Murky waters can interfere with data collection and image processing, which are critical for the proper operation of all Unmanned Underwater Vehicles (UUVs).

Table 1. Advantages and disadvantages of different technologies.

Reference	Positioning System	Advantages	Disadvantages
[15,44,46,100–102]	Inertial Navigation System (INS)	-No need for external signals -Can operate in GPS-denied environments	-Drift over time leading to decreased accuracy -Requires periodic calibration
[47,103]	Long Baseline (LBL)	-High positional accuracy -Effective in deep water -Suitable for complex environments	-Requires installation of multiple transponders -Limited mobility during setup
[50,51,103]	Short Baseline (SBL)	-Less complex than LBL -Suitable for shallower waters -Easier and quicker to deploy	-Lower accuracy compared to LBL -Limited range and precision
[51,104–106]	Ultra-Short Baseline (USBL)	-Real-time tracking -Requires only a single transducer -Good for dynamic environments	-Less accurate at greater distances -Performance can be affected by surface conditions
[52,53]	Doppler Velocity Log (DVL)	-Provides velocity relative to the seafloor or water column -Enhances positioning accuracy when combined with other systems	-Accuracy can be affected by water conditions and seafloor characteristics -Not a standalone positioning system
[4,54–56]	Dead Reckoning	-Simple and cost-effective -Useful for estimating position in the absence of other data	-Accuracy degrades over time -Dependent on accurate initial conditions
[57–59]	Acoustic Modem Systems	-Enables communication between UUVs and surface vessels -Can assist in positioning and data transfer	-Limited bandwidth -Communication can be affected by water conditions and distance
[15,75,107–109]	LIDAR (Light Detection and Ranging)	-Provides high-resolution 3D data -Effective for shallow-water mapping	-Limited depth penetration -Requires clear water conditions

While it is essential to understand the strengths and weaknesses of each technology, a more comprehensive approach is required. In addition to categorizing their advantages and disadvantages, we should also include other key factors, such as cost, depth limitations, specific applications, range capabilities, and maintenance requirements. Creating a table with this expanded set of information will provide a clearer and more practical understanding of how each technology can be utilized effectively in different underwater environments.

3.4. Improving the Categorization

In Section 3.3, we created Table 1 to categorize positioning systems based on several key factors: horizontal range, overall cost, suitability for deep waters, maintenance costs, and the type of vehicle they are used for (AUV or ROV).

The table starts with references, which are crucial for understanding the positioning technologies discussed in each source. Identifying the positioning technology used or mentioned in each paper is essential for improving the categorization in Table 1. As mentioned in Section 1, Unmanned Underwater Vehicles fall into two categories, as shown in Table 2 [15]. During our categorization process, we noted that some papers indicated that certain positioning systems could be used for both Autonomous Underwater Vehicles and remotely operated underwater vehicles. Additionally, part of our research [39] involved hybrid underwater vehicles, and we also encountered autonomous underwater gliders [16].

Table 2. Comparison of underwater mapping and exploration technologies.

Reference	Positioning System	AUV/ROV	Horizontal Range	Cost	Suitability for Depth	Maintenance Cost
[15]	Inertial Navigation Systems	Both	High (with some restrictions)	High	All depths	High: Frequent recalibration because accuracy is needed.
[103]	Long Baseline Systems	Both	Medium	High	Ideal for deep water	High: Frequent recalibration
[91]	Gravity Gradiometry	AUV	-	-	High (1300 m)	-
[39]	Global Navigation Satellite System, Doppler Velocity Logs, Inertial Navigation System	Hybrid	-	-	-	-
[52]	Doppler Velocity Logs	AUV	Limited	Medium	All depths	-
[104]	Ultra-Short Baseline	AUV	-	-	-	-
[32]	Inertial Navigation System based on inertial measurement unit	ROV	-	Low	-	Low
[53]	Doppler Velocity Logs	ROV	Medium (200 m–700 m)	Low	Medium to high (250 m–600 m)	-
[107]	Light Detection and Ranging	AUV	Low to medium	-	Medium: Component-wise High: Image Wise	-
[29]	Inertial Navigation System	ROV	Low to medium (due to tethered connection) (60 m)	Lower than AUV	Low (depends on its sensor's maximum depth reach)	-
[110]	Doppler Velocity Logs, Long Baseline, Hydrostatic Pressure Sensor, Inertial Navigation System	Hybrid	ROV max: 2270 m AUV max: 10,843 m	High	Very high (11,000 m)	High
[93]	Inertial Navigation System, Visual Controllers	AUV	-	Low	-	-
[105]	Ultra-Short Baseline	Both	-	Low	-	-
[109]	Light Detection and Ranging	Both	-	Low	Low: 25 m	-
[38]	Not Mentioned	ROV	Cable limits its potential	Low	Medium (600 m)	Low
[73]	Electromagnetic Positioning	Both	-	-	-	-
[21]	Inertial Navigation System, Doppler Velocity Logs, Global Positioning System (on the water surface)	AUV	300m	-	Low due to risk: 25 m (can go even deeper to 100 m)	-
[69]	Photogrammetry	-	-	-	-	-
[62]	Geomagnetic	AUV	-	-	-	-
[16]	Not mentioned	AUV/GLIDERS	Low to medium	Low	Medium 300 m	-
[79]	Inertial Navigation System, Fiber Optic Gyroscope	AUV	-	Medium to high due to acoustic system	-	-
[27]	Long Baseline, Ultra-Short Baseline	ROV	-	Low	Medium: Down to 300 m	-
[86]	Synthetic Aperture Radar	-	High	Medium	Low to medium	-
[49]	Long Baseline, Short Baseline, Ultra-Short Baseline	AUV	-	-	-	-
[59]	Acoustic Modem	-	350 m	Low	Low to medium	-
[20]	Not Mentioned	AUV	High: 20 km	Low	Medium: 300 m	-
[87]	Biomimetic Positioning	AUV (with some ROV operations)	Subsea: Surface: Wi-Fi for downloading video	Affordable	Minimum 100 m	-

In underwater research, the horizontal range of a vehicle is a critical factor, as it defines the extent of the vehicle's movement freedom during its mission. Cost is another significant consideration, especially for those working within a budget. Table 2, column 5, addresses both the construction and pre-build costs of positioning systems. Depth is also crucial, particularly for deep-water operations, as pressure at great depths can be damaging if not properly managed. Maintenance costs, including those related to saltwater corrosion, are another important factor, though many papers do not provide this information. Maintaining the electronics that keep the positioning system functional is vital.

Overall, Table 2 is essential for understanding the characteristics and implications of different positioning systems. Each category in the table is interdependent. For example, in row 5, a system with limited range and medium cost is revealed, while row 11 shows that an ROV with a range of capabilities could significantly increase the cost.

4. Methodology in Reviewing Positioning Systems Applications Based on Positioning Systems

In our research methodology, we primarily relied on Scopus and Google Scholar as our principal sources of information. Initially, we conducted a comprehensive search using the query "UUVs and positioning systems", which yielded a range of insightful results and review papers. These sources significantly contributed to refining our perspective and structuring our approach to the topic.

To narrow down the vast amount of information, we employed a strategic approach utilizing specific keywords. These keywords included "positioning underwater", "AUV" (Autonomous Underwater Vehicle), "ROV" (Remotely Operated Vehicle), "INS" (Inertial Navigation System), "DVL" (Doppler Velocity Log), and "unmanned underwater vehicle positioning". By incorporating these targeted keywords, we identified over 152 relevant papers on Google Scholar and approximately 120 on Scopus.

The initial search results from both databases included a substantial number of articles, reviews, and conference papers. To manage this extensive collection of resources and maintain focus on our specific research topic, we employed a rigorous filtering process. This process was essential to ensure that our review remained concentrated on pertinent information and did not deviate from the core subject matter. Filtering was a critical step in our methodology, enabling us to systematically sift through the vast amount of data and extract only the most relevant and valuable insights for our study. In Section 4.1, we explain how we filtered out some results by using keywords and personal criteria.

4.1. Filtering

During our research, we came across a substantial number of identical papers, papers with irrelevant content, and even outdated review papers. Some papers provided insufficient information about the positioning systems that we used and conflicted with other papers. Using personal criteria and specific keywords like "INS", "LBL", "LIDAR", and more, which are the abbreviations of technologies we mentioned in Sections 2 and 3, we narrowed our selection of papers even more. In the end, we opted for 109 papers for our research. The initial screening process yielded a total of 280 research papers that required thorough examination and assessment. Our primary task was to determine which of these papers would be suitable for inclusion in our review.

To begin with, we employed a keyword-based filtering approach. This initial filter was crucial for narrowing down the extensive list of papers, enabling us to exclude those that did not align with our research objectives or were irrelevant to our study. Given the sheer volume of papers, this first filtering step was particularly challenging, as it required careful consideration to eliminate only those papers that were clearly outside the scope of our review. After the first filtering, we had to re-filter 208 papers.

Following the first round of filtering, we conducted a second, more detailed review. This stage proved to be significantly beneficial as it allowed us to further refine our selection. During this phase, we eliminated papers that were outdated or contained information that was no longer pertinent to our research. This step was essential for ensuring that the literature we included in our review was both current and relevant, thus improving the overall quality and reliability of our analysis. Before moving on to the final step of our literature research, we had 169 papers.

The third and final filtering stage was implemented to address papers that did not provide sufficient data for our review. Despite the comprehensive nature of the papers we considered, some were excluded because they focused predominantly on mathematical modeling rather than on practical positioning systems, which was the core focus of our study. This final filter was instrumental in ensuring that the papers we selected contributed meaningful and applicable insights to our research, thereby enhancing the robustness and relevance of our review findings. A total number of 110 papers can be seen in the References section.

In summary, our filtering process involved multiple stages of refinement: initially using keywords to weed out irrelevant papers, then applying a more detailed review to exclude outdated information, and finally excluding those papers that did not meet our data requirements. Each stage was critical in streamlining our selection process and ensuring that only the most pertinent and high-quality papers were included in our review.

4.2. The Categorization of the Researched Literature, According to the Main Research Objectives

After filtering out the papers that did not meet our criteria, the next crucial step was to systematically categorize the remaining literature based on the type of positioning system (PS) employed and the specific citations or projects referenced. This categorization was essential for organizing the literature and facilitating a comprehensive discussion in Section 5, where we would delve into various types of papers and their applications.

We focused on categorizing the papers according to their type, which is important for our analysis. This included distinguishing between journal articles, conference papers, and review papers. Additionally, we examined whether each paper employed Inertial Navigation Systems (INSs), Doppler Velocity Logs (DVLs), or other types of positioning systems and whether these systems were used in combination.

5. Results

As detailed in Table 3, we categorized the citations based on these criteria: the type of paper (whether it is a journal article, conference paper, or review), the presence of INSs, the presence of DVL, or the use of other positioning systems, including instances where multiple systems were utilized together. This categorization helped us to systematically organize and evaluate the literature.

Table 3. Analysis of navigation technologies and positioning systems in underwater studies.

Reference	Type of Paper	Inertial Navigation System	Doppler Velocity Log	Other Positioning System Used	Target Applications
[15]	Article	✓	x	Light Detection and Ranging	Camera Improvement, Underwater Mapping, Deep-Sea Exploration
[103]	Article	x	x	Long Baseline System	Deep-sea Operations, Subsea Mapping
[91]	Article	x	x	Gravity Gradiometry	Massive Subseafloor, Deposits Detection
[39]	Conference Paper	✓	✓	Global Navigation Satellite System	Underwater Mining, Operations Support
[52]	Journal	✓	✓	x	Seafloor Mapping, INS enhancer
[104]	Journal	x	x	Ultra-Short Baseline	Underwater Coordination
[32]	Conference Paper	✓	x	Using Inertial Measurement Units	Exploration in Hazardous Areas

Table 3. *Cont.*

Reference	Type of Paper	Inertial Navigation System	Doppler Velocity Log	Other Positioning System Used	Target Applications
[53]	Journal	✓	✓	Dead Reckoning	Observation/Monitoring/ Offshore Inspections
[107]	Conference Paper	x	x	LiDaR (Light Detection and Ranging)	Deep Underwater Life Inspection
[29]	Conference Paper	✓	x	-	Oil Spill Surveillance
[110]	Conference Paper	✓	✓	Hydrostatic Pressure Sensors, Long Baseline	Scientific Purposes and Research
[93]	Journal	✓	x	Visual Controller	Underwater Imaging and Object identification
[105]	Journal Article	x	x	Ultra-Short Baseline	Underwater Navigation with accuracy
[109]	Conference Paper	✓	-	Light Detection and Ranging	Marine Science
[38]	Conference Paper	-	-	-	Offshore Work
[73]	Conference Paper	x	x	Electromagnetic Positioning	Underwater Navigation
[21]	Conference Paper	✓	✓	Global Positioning System (on the water surface)	Underwater Ice Ridge Exploration
[69]	Book	-	-	Photogrammetry	Archaeology Research
[62]	Conference Paper	x	x	Geomagnetic Positioning	Underwater Navigation
[16]	Review	-	-	-	Oil/Gas Operations, Underwater Maintenance, Subsea Installations
[79]	Conference Paper	✓	x	Fiber Optic Gyroscope	Marine and Underwater Purposes
[27]	Conference Paper	x	x	Long Baseline and Ultra-Short Baseline	Environmental Monitoring and Mapping
[86]	Conference Paper	x	✓	Synthetic Aperture Radar	Underwater Topography
[59]	Journal	x	x	Acoustic Modem System	Various Applications
[49]	Review	✓	x	Acoustic Systems	Marine Exploration and Monitoring
[20]	Conference Paper	-	-	-	Subsea Oil and Gas Operations
[87]	Conference Paper	x	x	Biomimetic Navigation	Shipwreck Penetration

Furthermore, understanding the specific applications for which Unmanned Underwater Vehicles (UUVs) are designed was a key aspect of our review. Each UUV is built with particular objectives in mind, and identifying these applications was crucial for appreciating the relevance and significance of UUVs in various contexts. Some UUVs, as identified in our review, are designed to address multiple applications simultaneously. By uncovering these diverse applications, we gained insights into the broader impact and utility of UUVs in different scenarios.

Overall, the process of categorizing the literature based on paper type and the positioning systems used, coupled with a detailed exploration of UUV applications, was essential for understanding the scope and significance of the research. This approach allowed us to create a well-organized framework for discussing the findings and implications of our review.

A key aspect of positioning systems is their accuracy, which is influenced by various factors such as water conditions, terrain, depth, distance, noise, magnetic fields, and improper sensor calibration. These factors directly affect the positioning and navigation of Unmanned Underwater Vehicles (UUVs). Given the importance of accuracy in positioning systems, Table 4 was created to summarize the accuracy data discussed in Tables 3 and 4 from the referenced papers. The first column of Table 4 lists the references from which the data were sourced. The second column provides the numerical accuracy values, as reported by the authors, based on simulations, tests, and theoretical studies. Since accuracy depends on various factors, the third column highlights the reasons for accuracy degradation in each study. The fourth and final column presents the accuracy errors observed in the systems, as detailed in the respective papers. This structure allows for a clear understanding of how different conditions affect the performance of positioning systems, as well as the potential errors that may arise.

Table 4. Accuracy of positioning systems.

Reference	Accuracy	Reasons for Degradation of Accuracy	Error
[15]	0.1–5%	Complex Terrain	<0.1 m
[103]	-	Low Depth and Distance	0.25 m
[91]	-	-	-
[39]	-	-	-
[52]	0.2%	-	-
[104]	-	Signal-to-Noise Ratio Adjustment	-
[32]	-	-	-
[53]	0.8–3.3%	-Improper Calibration of Compass -Nearby Magnetic Field	1.2 m and 8.3 m (2 test runs)
[107]	~3 mm	Increase in Range	0.1 m at 10 m range
[29]	-	-	-
[110]	0.01°	Extreme Depth	-
[93]	-	-	-
[105]	No Specific Number is Provided	Signal-to-Noise Ratio Increase	-
[109]	0.003 m–0.0089 m	-	-
[38]	-	Compass Calibration Depth Sensor	-
[73]	No Specific Number is Provided	-	-
[21]	-	The Drift Rate of the INS	-
[69]	-	-	-
[62]	-	-	-
[16]	-	-	-
[79]	Provides Table of Accuracies	-	-
[27]	-	-	-
[86]	+/−15%	Sea State	-
[59]	-	Component Restrictions	-
[49]	No Specific Number is Provided	-	-
[20]	-	-	-
[87]	-	Air Pressure Change	-

6. Discussion

In Section 3.4, we delve for the first time into personal commentary on the significance of specific aspects of Unmanned Underwater Vehicles. Out of the 109 papers we reviewed, we selected 27 for detailed analysis and categorization in our tables. The primary reason for this selection was the depth and relevance of these papers, despite some lacking specific information. Of the 27 papers chosen, 15 were conference papers, two were review papers, nine were journal articles, and one was a book. Additional review papers, such as [98], contributed to our understanding of the positioning systems used in terrain-aided navigation.

The book [8] offers significant insights into underwater technologies and their operation, highlighting the importance of replacing human offshore tasks with Unmanned Underwater Vehicles (UUVs) to reduce risk. A key focus is on the challenges we must address, with the book providing detailed discussions and insights on these specific challenges. While there are numerous papers on underwater environments and exploration, only a few provide up-to-date information on modern positioning systems.

One of the main challenges we faced in writing our paper was the outdated information on positioning systems. For instance, the cost of electronics has decreased since 2014, the year the book was published. However, paper [110], despite being from 2008, provides valuable details about the construction and design of these systems.

The methodology of this paper was informed by the two review papers [16,49] that we utilized in Tables 2 and 3. As shown in Table 1, we categorized the papers based primarily on the key positioning systems discussed in Section 2.4.1. After categorizing them, we extracted the advantages and disadvantages presented in each paper. Some papers contributed additional insights by incorporating findings from their own research to further elaborate on the challenges, which were listed under the disadvantages column. One of the major drawbacks identified was the impact of water conditions and calibration issues.

The Inertial Navigation System (INS) was the most frequently mentioned positioning system due to its widespread use and potential for improvement. The INS is capable of functioning in GPS-denied environments, such as underwater. Using the data from Table 1, we developed Table 2, where each reference was categorized based on technology, range, overall cost, maintenance cost, and suitability for various depths. As noted in paper [15], the synthetic positioning system with LiDAR technology can improve camera performance and operation with a high degree of accuracy in deep-water environments.

From Table 1, we can extract insights from sources [15,44,46,100–102] regarding the time-consuming and high-cost maintenance required for recalibration. As highlighted in Sections 3.4 and 4, maintenance costs are a crucial factor to consider. Our research indicates that very few papers have addressed the maintenance costs necessary for the successful operation of these specific positioning systems. In Table 2, we analyzed 27 papers, of which 22 did not mention maintenance costs at all. However, papers [15,32,38,103,110] either discussed maintenance costs or emphasized that they are significant. Despite the publication dates of these papers, it is essential that both conference papers and articles explicitly address maintenance costs when developing or acquiring positioning systems or UUVs in general.

The oldest paper we reviewed was [103], published in 1979, yet it provided information that many more recent papers lacked. For instance, [16], a review paper, offered minimal details on underwater gliders. According to Table 2, the most informative paper was [105], which provided extensive information on range, with specific figures, as well as depth suitability, overall cost, and especially maintenance costs. In contrast, papers [69,73,104] offered limited details regarding range, overall cost, maintenance cost, and depth suitability.

While [109] did not provide an exact figure for the maintenance cost of LiDAR systems, it provided a comparative understanding of what those costs could be relative to other expensive methods. The authors also noted that LiDAR can be a cost-effective solution when compared to the combination of INS, LBL, and DVL. Though combined positioning methods may offer higher accuracy, they can significantly increase overall costs.

In [15], we see how INS combined with LiDaR can help in stabilization for better camera quality and a more precise mapping experience. Although [69] mathematically explains how photogrammetry works and how we can improve positioning with it, it provides little info on applications or other key factors we need, as showcased in Tables 2 and 3.

Several papers, including [21,39,49,79,93,110], propose or utilize combinations of positioning systems to enhance localization, navigation, and stabilization. Of the 27 papers reviewed, 12 use INSs either to complement other technologies or as their primary positioning system. Six of these papers [21,39,52,53,86,110] incorporate DVL, with five of them [21,39,52,53,110] combining INS and DVL.

Paper [32] focuses on IMUs, which are critical components of INSs. While [87] explores underwater navigation, it presents interesting research on using biomimetic methods to improve navigation accuracy and positioning systems. Finally, [20] acknowledges the difficulties of navigation and positioning in GPS-denied environments like underwater settings, noting that subsea navigation methods can improve mission accuracy. However, it does not specify which navigation system was employed in their project.

Table 4 presents a wide array of references that examine the accuracy of underwater navigation and positioning systems, showcasing a mixture of quantitative and qualitative data. This comparison highlights both the strengths and gaps in the current body of literature, with some studies providing clear, detailed accuracy metrics while others focus on qualitative factors without numerical precision. By analyzing these studies together, we can identify trends in the literature and pinpoint areas that require further investigation.

Several references provide detailed and precise accuracy data, making them essential for understanding system performance. Reference [15] stands out by providing an accuracy range between 0.1% and 5%, with errors of less than 0.1 m, specifically in complex terrain environments. This quantitative information allows for a solid evaluation of how underwater terrain can significantly impact system accuracy. Similarly, [53] offers an accuracy range of 0.8% to 3.3%, with corresponding errors of 1.2 m and 8.3 m across two test runs. The degradation of accuracy here is attributed to improper compass calibration and interference from nearby magnetic fields, illustrating how environmental factors can skew positioning results. The author of [107] reports impressive accuracy, with errors around 3 mm at short distances, increasing to 0.1 m at a 10 m range. This highlights a key trend in underwater positioning systems: accuracy tends to decrease as range increases. Such precise data are crucial in evaluating system limitations and identifying areas for improvement. The paper referenced as [109] similarly provides accuracy values between 0.003 m and 0.0089 m, further emphasizing the level of precision that modern systems can achieve under controlled conditions. Additionally, [110] offers a small but noteworthy accuracy measure of 0.01°, which is reported to degrade due to extreme depth conditions. Such precision is valuable for high-depth navigation applications where even small errors can have significant impacts. Reference [86] also provides a quantitative assessment, reporting an accuracy degradation of $+/-15\%$ under varying sea states, highlighting the role of environmental conditions in influencing system reliability.

Several references explore factors that degrade accuracy but fail to provide specific numerical accuracy data. Reference [103] attributes a 0.25 m error to low depth and distance, but without detailed accuracy metrics, it becomes difficult to compare the performance of this system against others. Reference [104] discusses the impact of signal-to-noise ratio adjustments on accuracy, while [105] points to an increased signal-to-noise ratio as a factor that can enhance accuracy by up to 77%. However, neither study offers specific accuracy numbers, which limits the utility of their findings. Reference [38] addresses the importance of compass calibration and depth sensor accuracy, recognizing their critical role in underwater navigation systems, but again lacks quantitative data. Reference [73] mentions a drift rate in the Inertial Navigation System (INS) as a significant factor in degradation but provides no detailed accuracy statistics, further contributing to the qualitative focus of these studies. Such information is useful for understanding the causes of degradation, but without measurable outcomes, their findings are less impactful. Reference [52] offers an interesting middle ground by providing an accuracy figure of 0.2%, although it does not delve deeply into the causes of degradation or provide error ranges. This study, while providing some numerical data, lacks the context of other influencing factors, making it less comprehensive in comparison to other references.

A notable portion of the table includes studies that neither provide detailed accuracy data nor delve into the reasons for accuracy degradation. Papers [16,27,29,32,39,59,62,69,79,91] are examples of this. These studies either focus on other technical aspects of the systems or omit accuracy and degradation discussions altogether. For instance, [79] simply provides a table of accuracies without further elaboration, while [59] discusses component restrictions without linking them to quantitative accuracy metrics. Other studies, like [20,87], only mention general factors that could affect accuracy, such as air pressure changes and environmental conditions, but they do not provide detailed information. Such omissions make it difficult to integrate these studies into a broader analysis of underwater system performance. While these references offer important insights into system design or potential limitations, their lack of focus on measurable accuracy hinders the ability to assess their contributions in a review focused on precision and reliability.

There are also a few studies that, while they do not provide specific accuracy figures, offer useful general observations. For example, [49] mentions accuracy concerns but does not provide specific numbers, instead focusing on component restrictions. Paper [21] discusses the drift rate of the INS as a key factor influencing long-term accuracy but, like many other studies, does not provide measurable data (accuracy). These observations, while valuable, fall short of providing the comprehensive information necessary for in-depth system evaluations.

Across the studies, several common factors emerge that degrade accuracy in underwater positioning systems. The most frequently cited issues include compass calibration problems (references [38,53]), signal-to-noise ratio adjustments (references [104,105]), and depth-related degradation (references [103,110]). In addition, the range is often cited as a limiting factor for accuracy, with studies like [107,109] demonstrating that accuracy worsens as distance increases. Other notable degradation factors include nearby magnetic fields and sea states, both of which can significantly skew positioning results.

This analysis of accuracy reveals both strengths and weaknesses in the current body of literature regarding underwater navigation systems. Several studies, including [15,53,107,109], stand out for their detailed reporting of accuracy, offering precise metrics that are critical for evaluating system performance. However, many other studies focus primarily on qualitative discussions of accuracy degradation factors without providing numerical data, limiting their utility for direct comparison. Additionally, some references, such as [32,39,91], fail to provide any data regarding accuracy, highlighting a significant gap in the literature.

This paper has explored various aspects of positioning systems used in Unmanned Underwater Vehicles (UUVs) and assessed their advantages and limitations based on a broad review of the literature. From the analysis of 110 papers, we selected 27 for in-depth study, focusing on the key positioning systems outlined in Section 2.4.1. Our findings underscore the significant role of Inertial Navigation Systems (INSs), which were frequently mentioned due to their ability to function effectively in GPS-denied environments, such as underwater.

Despite the comprehensive data presented, several challenges emerged. Notably, many sources lacked updated information on maintenance costs, which is a crucial factor given its impact on operational efficiency and budgeting. Only a few papers addressed maintenance costs explicitly, highlighting a gap in the current research. The high costs and time-consuming nature of recalibration were identified as major concerns, underscoring the need for further investigation into cost-effective solutions.

Our review identified that while some papers provided valuable insights into specific technologies, such as the combination of INS with LiDAR for enhanced camera quality and mapping precision, others offered limited details on practical applications or costs. Papers such as [110], although not providing much insight regarding its positioning system accuracy, stood out for their comprehensive coverage of range, depth suitability, overall cost, and maintenance, providing a useful benchmark for evaluating other sources.

The study also highlighted the growing trend of integrating multiple positioning systems to improve localization, navigation, and stabilization. Notably, combinations of INSs with Doppler Velocity Logs (DVLs) and other technologies were frequently proposed to address various operational challenges.

In summary, while significant progress has been made in understanding and improving positioning systems for UUVs, there remains a need for more up-to-date and detailed research, particularly concerning maintenance costs, practical applications, and accuracy. Future work should focus on bridging these gaps to enhance the effectiveness and cost-efficiency of positioning systems in underwater environments.

7. Future Directions

The future of positioning systems for Unmanned Underwater Vehicles (UUVs) is poised for transformative advancements, particularly through the integration of artificial intelligence (AI) and machine learning. These technologies hold the promise of significantly enhancing the accuracy and reliability of positioning systems. AI algorithms can process vast amounts of data from various sensors to make real-time adjustments, thereby improving navigation and obstacle avoidance. Moreover, machine learning models can continuously learn from environmental conditions and operational experiences, leading to adaptive systems that optimize their performance over time. As these technologies evolve, they could enable UUVs to operate more autonomously and efficiently, even in complex and unpredictable underwater environments.

The advancement of sensor fusion techniques represents another crucial direction for future research. Integrating data from diverse sensor types—such as sonar, inertial measurement units, and GPS—can lead to more precise and reliable positioning. Enhanced data fusion algorithms are expected to play a pivotal role in this development, allowing for seamless integration of multi-sensor inputs and mitigating the limitations of individual sensors. This approach will not only improve the accuracy of positioning systems but also enhance their resilience to environmental disturbances. Future systems that leverage sophisticated sensor fusion could provide UUVs with better situational awareness and operational capabilities, particularly in challenging underwater conditions.

Communication technologies also stand to benefit from significant advancements. Improved underwater wireless communication methods, such as enhanced acoustic and optical systems, could facilitate more reliable and frequent data transmission. The development of hybrid communication systems that combine multiple methods may offer increased flexibility and robustness, addressing the limitations of current technologies. By enhancing communication capabilities, UUVs can transmit positioning data more effectively and receive updates in real time, which is crucial for mission success and safety. Future research in UUV positioning systems should focus on several key areas to enhance performance and applicability. Integrating artificial intelligence and machine learning algorithms can improve navigation accuracy and adaptability in changing environments by facilitating real-time adjustments based on extensive sensor data. Advanced sensor fusion techniques will be vital for combining data from diverse sources and enhancing situational awareness in complex underwater conditions. Improving underwater communication technologies is essential for reliable data transmission, with an emphasis on developing hybrid systems that overcome existing bandwidth and range limitations. Additionally, research into cost-effective maintenance solutions and the durability of positioning systems against environmental challenges, such as murky waters and extreme pressures, will be critical for optimizing operational efficiency. Exploring emerging technologies, such as biomimetic navigation and innovative sonar modalities, alongside extensive field testing will ensure that theoretical advancements translate into practical enhancements for UUV operations in various marine applications. The review also identifies common factors contributing to accuracy degradation, such as depth, range, and compass calibration issues. To advance the field, future research should prioritize the inclusion of both qualitative discussions and quantitative data, ensuring that accuracy figures and degradation factors are consistently reported. By addressing these gaps, the underwater navigation community can work toward developing systems that are more reliable and precise across a variety of challenging environments.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AM	Acoustic Modem
APSs	Acoustic Positioning Systems
AUV	Autonomous Underwater Vehicle
CCU	Central Control Unit
DVLs	Doppler Velocity Logs
EMP	Electromagnetic Positioning
ESC	Electronic Speed Controller
FOG	Fiber Optic Gyroscope
GNSSs	Global Navigation Satellite Systems
GPS	Global Position System
HPSs	Hydrostatic Pressure Sensors
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LiDaR	Light Detection and Ranging
LBL	Long Baseline
PS	Positioning System
ROUV	Remotely Operated Underwater Vehicle
ROV	Remotely Operated Vehicle
SAR	Search and Rescue
SAS	Synthetic Aperture Sonar
SLAM	Simultaneous Localization and Mapping
SBL	Short Baseline
USBL	Ultra-Short Baseline

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