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REVIEW OF THE GUIDANCE SYSTEM OF AUTONOMOUS UNDERWATER VEHICLES IN CONFINED SEMI-STRUCTURED ENVIRONMENTS

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Abstract: This paper provides a review and summary of previous research on the guidance system of Autonomous Underwater Vehicles (AUVs). It introduces the guidance system, analyzes its elements, and offers detailed explanations of its submodules: Guidance, Navigation, and Control. The paper also points out the current research limitations, noting that while there are numerous studies on autonomous underwater vehicles, most focus solely on hardware or navigation issues, with limited exploration of the integrated design of the guidance system. Additionally, a brief overview of the components of the guidance system for autonomous underwater vehicles in confined semi-structured environments is presented.
Keywords: Autonomous underwater vehicle; Guidance system; Navigation; Control; Autonomy

1 INTRODUCTION

An autonomous underwater vehicle (AUV) is a sophisticated robot designed to navigate and perform tasks beneath the ocean surface without real-time human intervention [1]. Unlike remotely operated vehicles (ROVs), which require continuous control from a human operator, AUVs are equipped with advanced sensors, onboard computers, and propulsion systems that enable them to operate independently. This autonomy allows AUVs to venture into remote and challenging underwater environments, making them invaluable tools for a wide range of applications.
AUVs have become indispensable in modern oceanography and underwater operations. They are utilized for mapping the seafloor, a task that is crucial for understanding the geological features of the ocean bottom and for planning underwater infrastructure projects [2]. These vehicles are also employed in locating airplane wrecks, providing critical insights into aviation accidents and aiding in the recovery of valuable data and artifacts. In addition, AUVs play a vital role in collecting oceanographic data, such as temperature, salinity, and current patterns, which are essential for climate research and environmental monitoring. They are also used for inspecting underwater pipelines, ensuring the integrity of critical infrastructure, and examining the hulls of ships for maintenance and security purposes [2].
In recent decades, the number of autonomous underwater vehicles (AUVs) has expanded dramatically, driven by advancements in technology and the increasing demand for underwater exploration and data collection [3]. Many research centers and institutions around the world have focused on this topic, recognizing the tremendous potential of AUVs for studying and comprehending the ocean environment. These vehicles are capable of operating in depths and conditions that are inaccessible to humans, providing unprecedented access to the underwater world. They can cover large areas efficiently, collect high-resolution data, and operate for extended periods without the need for constant human supervision.
Figure 1 schematically illustrates an AUV conducting seabed operations. The image highlights the key components of an AUV, including its streamlined hull, propulsion system, sensor arrays, and communication equipment. The AUV is shown navigating along the seafloor, deploying various instruments to gather data and perform tasks. Its ability to autonomously follow a pre-programmed mission or adapt to changing conditions in real-time is a testament to the advanced technologies that underpin its operation.

Figure 1 The Schematic Diagram of AUV Underwater Operations

The guidance system is critical for the successful operation of autonomous underwater vehicles [4]. This system is responsible for determining the AUV's position, velocity, and orientation, and for planning and executing its trajectory. It integrates data from multiple sensors, such as acoustic positioning systems, inertial measurement units (IMUs), and depth sensors, to provide accurate and reliable navigation. The guidance system must also account for environmental factors like currents, tides, and seafloor topography, which can affect the vehicle's movement and mission success.

Advanced algorithms and control strategies are employed in the guidance system to ensure that the AUV can adapt to unexpected situations and maintain its course. For example, if the vehicle encounters an obstacle or a sudden change in water conditions, the guidance system can autonomously adjust its path to avoid potential hazards. This level of autonomy is crucial for long-duration missions, where real-time human intervention may not be feasible.

Moreover, the guidance system plays a vital role in the communication and data transmission capabilities of the AUV. It ensures that the vehicle can relay important information back to the surface or to other AUVs, facilitating coordinated operations and real-time monitoring of mission progress. This capability is particularly important for collaborative missions involving multiple AUVs, where each vehicle may be tasked with different aspects of a larger project.

In conclusion, autonomous underwater vehicles (AUVs) represent a significant leap forward in our ability to explore and understand the ocean environment. Their versatility, autonomy, and advanced guidance systems make them ideal tools for a wide range of applications, from scientific research to industrial operations. As technology continues to advance, we can expect AUVs to play an even more prominent role in unlocking the secrets of the underwater world and contributing to our global knowledge and understanding of the oceans.

The novel mechanical design of the autonomous underwater vehicle and its distinctive onboard scientific instrumentation represent specific features [5]. The guiding system of the platform must guarantee the synchronization of such instructions with the submersible's movement, satisfying the stringent positioning criteria of the scientific sample capture for each kind of sensor. Hence, it is significant to develop an effective guidance system to enhance the performance of the autonomous underwater vehicle.

For an autonomous underwater vehicle to be able to function in the intended working circumstances, autonomy is of the utmost significance [6]. Due to the inherent constraints imposed by such an environment, the autonomous underwater vehicle's guidance system is important to achieving the intelligence and autonomy necessary for operation in the working environment [7]. Important to the development of the autonomous underwater vehicle platform is the creation of a steering system that provides the high level of autonomy required by the target application.

2 LITERATURE REVIEW

The guidance system is an integral component of a larger conceptual system, referred to as guidance, navigation, and control (GNC). This triad of concepts—guidance, navigation, and control—forms the backbone of modern vehicle autonomy and remote operation, whether it be in aerospace, maritime, automotive, or robotic applications. These concepts are intertwined yet distinct, each addressing a different layer of abstraction in the overarching challenge of autonomously or remotely controlling the movement of a vehicle [7].

Guidance can be thought of as the highest level of abstraction within the GNC framework. It is concerned with the strategic planning and decision-making processes that determine the desired trajectory or path for a vehicle to follow. This involves setting objectives, such as reaching a specific destination or performing a particular mission, and then devising a plan to achieve those objectives. Guidance algorithms often take into account factors like fuel efficiency, time constraints, and environmental conditions to optimize the vehicle's route. In essence, guidance is about determining where the vehicle should go and how it should get there in the most efficient and effective manner possible.

Navigation, on the other hand, operates at a more intermediate level of abstraction. It focuses on determining the vehicle's current position, velocity, and orientation relative to a reference frame. This is achieved through the integration of various sensors, such as Global Positioning System (GPS) receivers, inertial measurement units (IMUs), and other onboard instruments. Navigation systems process the data from these sensors to provide real-time information about the vehicle's state. This information is crucial for both guidance and control systems, as it allows them to make informed decisions based on the vehicle's actual position and movement. Navigation can be seen as the bridge between the high-level objectives set by the guidance system and the low-level actions executed by the control system.

Control is the lowest level of abstraction within the GNC framework. It deals with the actual implementation of the vehicle's movement, translating the desired trajectory and commands from the guidance and navigation systems into specific actions that the vehicle's actuators can execute. This involves managing the vehicle's propulsion, steering, and other control surfaces to ensure that it follows the planned path as closely as possible. Control systems must account for various disturbances and uncertainties, such as wind gusts, ocean currents, or uneven terrain, and adjust the vehicle's actions accordingly to maintain stability and accuracy.

These three components—guidance, navigation, and control—are not isolated but rather work in concert to achieve the overall goal of vehicle autonomy. They form a hierarchical structure where guidance sets the objectives, navigation provides the situational awareness, and control executes the actions. This integrated approach allows vehicles to operate autonomously in complex and dynamic environments, whether it be a spacecraft navigating through the vastness of space, an underwater vehicle exploring the depths of the ocean, or a robotic vehicle performing tasks in a manufacturing facility.

Figure 2 illustrates the composition of the guidance system within the broader GNC framework. It shows how the guidance system interacts with the navigation and control systems, highlighting the flow of information and the interdependencies between these components. The guidance system receives inputs from the navigation system, such as the vehicle's current position and velocity, and uses this information to generate commands that are then sent to the control system. The control system, in turn, feeds back information about the vehicle's actual movement, allowing the guidance system to adjust its plans as needed. This closed-loop interaction ensures that the vehicle can adapt to changing conditions and achieve its objectives with high precision.

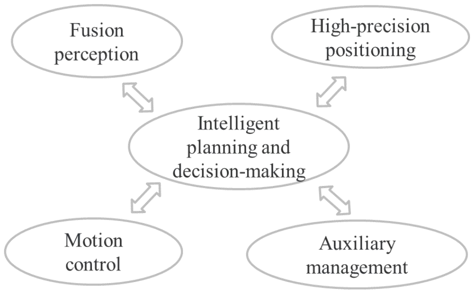

Figure 2 The Schematic Diagram of the Composition of the Guidance System

In summary, the guidance system is a critical element within the guidance, navigation, and control framework. It works in tandem with navigation and control systems to enable autonomous and remote vehicle operations. By understanding the roles and interactions of these components, researchers and engineers can develop more sophisticated and reliable systems for a wide range of applications, from space exploration to everyday transportation.

Although the actual software architectures for guiding, navigation, and control systems are highly permeable and hence defy rigorous compartmentalization, it is easiest to conceptualize them, for expository purposes, as consisting of the three distinct submodules suggested by their names. According to Fossen [8], the three submodules can be further specified in Table 1.

Table 1 Three Submodules

Submodules	Definition
Guidance	The system decodes the action that the robot needs to take to succeed in a series of tasks, and plans how those actions must be performed, which includes the continuous planning of the reference position, velocity, and acceleration required for the vehicle to be used by the motion control system. Sophisticated features such as obstacle avoidance and mission planning are thus often included in the design of guidance system.
Navigation	The system that employs available sensors to detect the status, location, velocity, and acceleration of the submersible.
Control	The system determines the necessary control forces and moments to be provided by the submersible to satisfy a particular control objective.

Path planning, that is, determining which sequence of collision-free configurations and poses the robot must follow in order to reach a predetermined target state and location while optimizing certain criteria, is, along with mission planning and the ability to sense the robot's position in relation to the environment, essential for practical autonomy in robotics. Path planning techniques established primarily for ground vehicles, robotics, and general issues are applicable to AUVs as well. In the literature, underwater route planning has frequently been treated as a 2D (two dimensions) issue comparable to and interchangeable with terrestrial path planning [9]. In this direction, Wang et al. [10] present a framework for the autonomous exploration of confined, indoor environments that shares several key characteristics with tunnel exploration, as their topology can also grow in complexity, constructing an incrementally built semantic road map that represents the topology. Several techniques connected to navigation, including current forces, have also been presented [11]. However, the latter presents additional hurdles in the form of potentially changing ambient circumstances and three-dimensional situations that require particular management. Although the reduction into a 2D (Two dimensions) issue is handy, it is insufficient for flooded mining settings, complicated ecosystems containing tunnel and shaft structures, which are intrinsically 3D (three dimensions).

The concepts of mission planning and mission execution or control are tightly interrelated: the former refers to the determination and representation of the high-level tasks that must be addressed by the robot, including their relative order, whereas the latter translates these high-level tasks into concrete, lower-level behaviors that represent how the high-level tasks must be accomplished and supervises their execution [12]. In most instances, mission execution includes an interface to a path planner for activities requiring this functionality. The lack of a prototype architecture for mission planning and mission execution for AUVs is instantly shown by the review of the relevant literature. Certain works produce architecture that adequately adheres to current standard language; for instance, Yoerger et al.'s architecture adheres closely [13]. Most works, Soylu et al., and Kairser et al., construct multilayered architecture freely influenced by Goldberg's existing multi-node standards [14-16].

However, a variety of specialized programming languages for mission planning and execution may be found, each of which corresponds to a somewhat different architectural style. Each provides a different level of integration with the lower-level commands of the robotic platform and specificity of the planned tasks, as well as a different level of deliberation in the reaction to environmental events, deterministic or stochastic behavior, and a different level of specificity of the planned tasks [17]. The mission planner module is responsible for establishing the overall mission strategy, which is specified as a list of high-level, semantic activities that include the necessary parameters to specify them, where applicable. These responsibilities will be inferred as acts. Although there are many previous studies investigating on autonomous underwater vehicle, most of them are focusing on the hardware issues or the navigation issues only, there is limited studies exploring the integrated design of the guidance system of autonomous underwater vehicle. Hence, to fill the gaps in the literature and improve the performance of AUVs, it is significant to design guidance system of autonomous underwater vehicles in confined semi-structured environments.

3 INTEGRATED DESIGN OF THE GUIDANCE SYSTEM

The previous studies on the guidance system were reviewed and summarized in the preceding text. Through the dissection of its component subsystems, the guidance system is primarily comprised of components such as the Mission Planner, Action Executor, and Trajectory Generator, as is shown in Figure 3. The details of guidance system are explained in the follows.

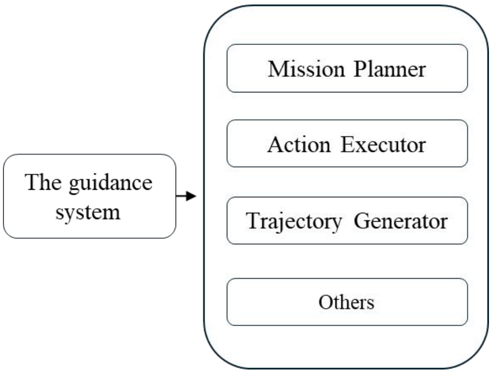

Figure 3 The Schematic Diagram of the Composition of the Guidance System

3.1 Mission Planner

The Mission Planner and the resulting action list are dynamic: actions from the existing list are sequentially read and dealt with one at a time; upon completion of the current task, the Mission Planner can modify the remaining actions of the list based on the task's result or the submersible's state. The most natural dynamic adjustment of the action list would correlate to the detection of a low battery level in the submarine, which would cancel the remaining actions and replace them with an urgent return to a safe area or the starting point.

3.2 Action Executor

The Mission Planner and the resulting action list are highly dynamic and adaptive to real-time conditions. Actions from the existing list are sequentially read and dealt with one at a time in a methodical manner. As each task is executed, the Mission Planner closely monitors the outcome and the overall state of the submersible. Upon completion of the current task, the Mission Planner has the capability to reassess the situation and modify the remaining actions of the list based on the task's result or the submersible's state. This dynamic adjustment ensures that the mission can be optimized on the fly to respond to unforeseen circumstances and maintain the safety and efficiency of the operation.

The most natural dynamic adjustment of the action list would correlate to the detection of a low battery level in the submarine. Battery management is a critical aspect of any underwater mission, as the submersible relies on its power supply to navigate, communicate, and perform its tasks. When the Mission Planner detects that the battery level is low, it triggers an immediate response. The remaining actions on the list are promptly canceled to prevent the submersible from running out of power in a potentially dangerous or inaccessible location. Instead, the Mission Planner replaces the canceled actions with an urgent return to a safe area or the starting point.

This prioritization of safety is essential, as running out of battery in the middle of a mission could lead to the loss of the submersible or compromise the integrity of the mission data. The Mission Planner's ability to dynamically adjust the action list in response to low battery levels is a testament to its advanced and adaptive nature. It ensures that the submersible can always return to a safe state, even if it means abandoning the original mission objectives temporarily.

Moreover, this dynamic adjustment process is not limited to battery level detection. The Mission Planner is designed to be responsive to a wide range of variables and conditions. For instance, if the submersible encounters unexpected underwater currents or obstacles, the Mission Planner can modify the action list to navigate around these hazards. Similarly, if the submersible's sensors detect anomalies in the environment, such as unexpected temperature changes or the presence of marine life that could interfere with the mission, the Mission Planner can adjust the action list to investigate or avoid these anomalies as needed.

3.3 Trajectory Generator

The Action Executor plays a crucial role in the navigation system of the autonomous underwater vehicle (AUV). It is responsible for transmitting the intended destination to the Trajectory Generator module. This transmission is a key step in ensuring that the AUV can navigate effectively and efficiently towards its target location.

As a consequence of the AUV's self-awareness capabilities, which include its ability to perceive its environment and understand its own state, the Trajectory Generator module is able to create a collision-free series of movements. This series of movements is carefully planned to guide the AUV toward the intended route location. The Trajectory Generator takes into account a variety of factors to ensure that the path is not only collision-free but also optimized according to specified planning criteria. These criteria might include minimizing travel time, conserving energy, or avoiding areas of high turbulence or other hazards.

Path planning, which is a fundamental aspect of this process, primarily focuses on positional references. It involves determining the most efficient route from the AUV's current position to the intended destination, while avoiding obstacles and other potential hazards. This planning is essential for ensuring that the AUV can navigate safely and efficiently through complex underwater environments.

According to the research of Coleman et al., the Movement Planning Framework serves as the foundation for the construction of the programmer. This framework provides a robust structure for developing the algorithms and systems that control the AUV's movements. Additionally, the OMPL (Open Motion Planning Library) is used as the foundation for the path planning features. OMPL is a powerful and flexible library that offers a wide range of motion planning algorithms. These algorithms are specifically designed to handle the complexities of path planning in various environments, making it an ideal choice for the AUV's navigation system [18].

3.4 Path Planner Benchmarking

When it comes to comparing multiple path planners, the complexity of the task becomes immediately apparent. Each path planner may have different self-imposed working restrictions that significantly impact its performance and applicability. For instance, some path planners operate with a fixed execution time, meaning they must generate a solution within a predetermined time frame, regardless of the complexity of the environment or the specific case at hand. This can be advantageous in scenarios where real-time decision-making is crucial, but it may also limit the planner's ability to find the optimal path if more time is needed to explore additional possibilities.

On the other hand, other path planners have a case-dependent duration. These planners adapt their execution time based on the complexity of the specific scenario they are addressing. While this flexibility allows them to potentially find better solutions by spending more time on more complex cases, it can also lead to unpredictable execution times, which may not be suitable for time-sensitive applications.

Another key distinction among path planners is the number of generated path hypotheses. Some planners are restricted to a defined number of hypotheses, meaning they can only explore a limited set of potential paths before making a decision. This approach can be efficient in terms of computational resources but may miss out on finding the best possible path if the optimal solution lies outside the predefined set of hypotheses. In contrast, other planners allow for unlimited attempts, exploring as many potential paths as necessary until they find a satisfactory solution. While this can lead to more comprehensive searches and potentially better solutions, it also demands more computational power and time.

Given these diverse working restrictions, the fair comparison of multiple path planners is not a simple task. Each planner's performance must be evaluated in the context of its specific constraints and the requirements of the application it is intended for. Therefore, a standardized approach to comparison is essential to ensure that the evaluation is meaningful and relevant.

In this context, the formulation proposed by Karaman and Frazzoli is typically followed. Their work provides a robust framework for comparing path planners by considering various performance metrics and constraints. This framework allows researchers and practitioners to systematically evaluate and compare different path planners, taking into account their execution time, the number of generated path hypotheses, and other relevant factors. By following this formulation, a more comprehensive and fair assessment of each path planner's strengths and weaknesses can be achieved, ultimately leading to better-informed decisions about which planner is most suitable for a given application [19].

3.5 Control Architecture of the Autonomous Underwater Vehicle

The autonomous underwater vehicle typically has various forms of control architecture. As a proof of concept, typical research will only investigate a subset of all devices. The eight-thruster system is commonly found in AUV equipment. Usually, four of the eight thrusters (those dedicated to forward and reverse movement) and a subsystem to control the underwater robot's motions, comprising two low-level potential controllers (one PID and one fuzzy) calibrated for various thruster configurations. The ISE&PPOOA will be typically utilized to construct the hypothetical model of the control architecture and its different configurations for the motion subsystem [20-21].

4 CONCLUSION

This paper offers a comprehensive review and summary of previous studies on the guidance system of Autonomous Underwater Vehicles (AUVs). It highlights that while there has been significant research in this field, there is a notable gap in the literature regarding the integrated design of the guidance system. The paper argues that a holistic approach to designing the guidance system is essential for enhancing the capabilities and efficiency of AUVs in various underwater missions.

By exploring the integrated design of the guidance system, several key conclusions can be drawn. Firstly, Autonomous Underwater Vehicles are poised to play an increasingly important role in the future. With advancements in technology and growing demand for underwater exploration, surveillance, and environmental monitoring, AUVs are becoming indispensable tools in both scientific research and commercial applications. Their ability to operate autonomously in challenging underwater environments makes them valuable assets for a wide range of tasks, from mapping the ocean floor to monitoring marine ecosystems.

Secondly, the guidance system is crucial for underwater robots, and autonomy is its primary evaluation criterion. The effectiveness of an AUV in accomplishing its missions largely depends on its ability to navigate and make decisions independently. An autonomous guidance system enables the vehicle to adapt to changing conditions, avoid obstacles, and optimize its path in real-time, thereby enhancing mission success rates and operational efficiency.

Thirdly, the submodules of Guidance, Navigation, and Control (GNC) are essential for the guidance system. These submodules work in tandem to ensure that the AUV can accurately determine its position, plan its route, and execute the necessary maneuvers to reach its destination. The integration of these submodules is critical for achieving seamless operation and optimal performance of the AUV.

However, a limitation of previous research is that most of the focus was on hardware or navigation issues, with limited discussion on the integrated design of the guidance system. Many studies have concentrated on improving individual components or subsystems, such as sensors, actuators, or specific navigation algorithms. While these advancements are important, they do not fully address the need for a cohesive and integrated guidance system that can optimize the overall performance of the AUV.

Through the dissection of its component subsystems, the guidance system is primarily comprised of components such as the Mission Planner, Action Executor, and Trajectory Generator. The Mission Planner is responsible for defining the overall objectives and tasks of the AUV, breaking them down into manageable actions, and prioritizing them based on mission requirements and constraints. The Action Executor then takes these planned actions and translates them into specific commands for the vehicle’s actuators, ensuring that each action is carried out accurately and efficiently. The Trajectory Generator plays a crucial role in creating collision-free paths for the AUV to follow, taking into account the vehicle’s dynamics, environmental conditions, and mission objectives.

In conclusion, this paper underscores the importance of an integrated design approach for the guidance system of AUVs. By addressing the limitations of previous research and focusing on the interplay between the Mission Planner, Action Executor, and Trajectory Generator, future studies can pave the way for more advanced and autonomous underwater vehicles. This integrated perspective will not only enhance the operational capabilities of AUVs but also enable them to tackle more complex and challenging missions in the future.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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