Deep ocean exploration and marine data acquisition: uses of autonomous underwater vehicles (AUVs)

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Abstract

Recent advancements in Artificial Intelligence (AI) and technological communication are transforming manned vehicles utilized on land, in the air, and at sea into Unmanned (UM) Vehicles (UVs) that function autonomously without supervision. UM Marine Vehicles (UMVs), comprising UM Underwater Vehicles (UUVs) and UM Surface Vehicles (USVs), possess the capability to execute marine operations unattainable by manned vessels, mitigate personnel risk, enhance the efficacy of military missions, and generate substantial economic advantages. This review aims to uncover historical and contemporary patterns in UMV growth and provide viewpoints into potential advancements in UMV technology. The assessment examines the prospective advantages of UMVs, such as executing marine operations unattainable by crewed vessels, mitigating the danger associated with human involvement, and enhancing capabilities for army operations and financial gains. The advancement of UMVs is comparatively sluggish compared to UVs employed on land and in the air, attributable to the challenging circumstances for UMV operations. This study emphasizes the difficulties in creating UMVs, especially in hostile environments. It underscores the necessity for ongoing developments in transmission and connecting methods, navigational and acoustic finding methods, and multi-vehicle mission planning methods to enhance UMV collaboration. The research underscores the need to integrate AI and Machine Learning (ML) technology in UVs to augment their independence and capability to execute intricate operations. The article offers perspectives on the present status and prospective trajectories for UMV growth.

Keywords: Deep ocean, Marine, Autonomous underwater vehicles, Data acquisition

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Introduction

During World War II, numerous advanced weaponry was developed, and Unmanned (UM) Marine Vehicle (UMV) technologies (Humphries *et al.*, 2023) emerged during smoke-screen missions to facilitate mine clearance. UMVs were employed to evaluate combat damages, gather water specimens, and retrieve lost gadgets. Every country endeavored to secure victory in the conflict by concealing the specifics of its armaments. Specifically, underwater surveillance equipment remained classified until the conclusion of the Cold War, following which the development of UM Vehicles (UVs) (Soy and Balkrishna, 2024) commenced in earnest.

UVs function in various habitats, like aerial, terrestrial, aquatic, and subaqueous settings. They can monitor combat conditions by collecting, processing, and verifying data through sensors. Generally, UVs facilitate the safe exploration of perilous or uncharted regions that are not readily accessible to humans, as they function without human presence (Khedr, Pravija Raj and Al Ali, 2020). Independent of the constraints of diurnal cycles, these can function for prolonged durations; hence, operational expenditures and mission input expenses are reduced compared to those associated with crewed spacecraft (Nordin *et al.*, 2022; Wang *et al.*, 2024).

Initial UVs were operated by personnel. They are developing into sophisticated UM Grounded Vehicles (UGVs), UM Aerial Vehicles (UAVs) (Iyer and Deshpande, 2024), and UM Marine Vehicles (UMVs) that operate by perceiving and assessing their ecosystems or executing preprogrammed instructions (Yu *et al.*, 2024; Nazarova and Bobomuratov, 2023). UVs are utilized in diverse models alongside combat systems.

UGV was initially designed for Explosive Ordnance Disposal (EOD), authorization, intelligence, monitoring, and inspection. UGV has transitioned from its original army growth aims, broadening its applications to farming (Shetty and Kapoor, 2024; Jaiswal and Pradhan, 2023). UAVs provide the capability to remotely manage the navigation of UM aircraft remotely, facilitating reconnaissance and information gathering in hazardous locations that are challenging for humans to reach (Highfill and MacDonald, 2022). UAVs are ideal for tracking operations as they can traverse patrol areas at considerable speeds, utilizing cameras and offering superior communication features. UAVs have been employed for military and civilian applications across diverse sectors, including logistics, drone photography, farming, and meteorological observation (Menon and Patil, 2023).

UMVs have been emphasized as crucial in future naval missions, specifically mine control, maritime safety, and blockade tasks. UMVs encompass UM Surface Vehicles (USVs) and UM Underwater Vehicles (UUVs). UUVs are categorized as Remotely Operating Vehicles (ROVs), which are tethered to vessels, and Automated Underwater Vehicles (AUVs), that operate wirelessly (Prasath *et al.*, 2024). UUVs are deployed to profound depths beyond human reach, utilizing onboard monitors and sonar sensors for underwater exploration, equipped with a robotic arm for sample collection (Das and Rajini, 2024). UUVs are extensively employed for military and civilian applications, including marine studies, mine detection and clearance, and long-range surveillance (Yeo and Jiang, 2023).

A novel, diverse swarm surveillance structure has been rigorously examined, transcending a singular platform. This framework collaboratively monitors the entire region utilizing UAVs, UGVs, USVs, and UUVs. The domains of land, sea, air, space, electromagnetism, and systems are progressively interlinking within the battlespace, evolving into a multipurpose combat paradigm across various settings (Yu *et al.*, 2024).

Background

There have been substantial advances in robotic investigation and visual perception in the past three decades. This section succinctly examines the contributions of significant authors (Rathore and Shaikh, 2023). VP methods were utilized for ship hull examination; a preliminary rough map was necessary to strategize exploring the rotors and rudders. A comparable methodology for structure inspection with UAVs is suggested. The same researchers have recently introduced a method utilizing a Rapidly-exploring Random Tree (RRT) (Mohsan *et al.,* 2022) for discovery without a prior map. A study introduced a VP target reinspection technique for AUVs outfitted with Synthetic Aperture Sonar (SAS). The research introduced a 2.5-dimensional (2.5D) methodology for examining intricate underwater structures. This method involves pre-planning a nominal path with an existing map of the environment (Biswas and Tiwari, 2024). Throughout the mission execution, the trajectory is dynamically adjusted to address navigation drift and discrepancies from the original map (Wibisono *et al.*, 2023).

A study introduced a VP methodology for three-dimensional (3D) site mapping with UGVs. A limited set of covered views is initially devised in 2D, utilizing a pre-existing scene map. This is followed by an enhancement of the final model in a subsequent phase when additional 3D views are formulated. A study introduced the Next-Best-View (NBV) technique (Lee and Woo, 2022) for autonomously planning viewpoints for reassembling a three-dimensional object. A study implemented NB V techniques for robotic exploration. A study introduced an NBV approach for modeling arbitrary things in three dimensions, while another study enhanced this method by incorporating uncertainties. Their methodology does not utilize previous understanding of the object's design; it requires information concerning its position and dimensions. A study has created an NBV technique using uncertainty for active cubic 3-dimensional reconstruction. A study investigated feedback mechanisms and expanded their use to many robots (Khan, Gupta and Gupta, 2022).

Proposed Marine Data Acquisition

Currently, fully AUVs are not accessible. Technology is essential to reduce the pilot's loading duration and the USV's reaction time, ensuring reliable operation for semi-automatic management and data transmission to the operation for direct oversight, even in an autonomous mechanism within the USV. In the context of UUVs, as opposed to terrestrial or aerial settings, navigational data or detectors employing position understanding are utilized in challenging ecosystems; engineers invest significant effort to incorporate intelligence for executing submerged UM automated navigation without reliance on interaction.

The UUV must effectively navigate diverse aquatic ecosystems while traveling from the origin to the sink following a specified path, particularly when remote management is not functional beyond visual range. To execute a designated task, the vessel or obstruction analyzed throughout navigation must be autonomously circumvented without manual intervention from the controlling component on board; the material ought to be identified, evaluated, and responded to independently; and it should possess the capability to self-recover in the event of a failure or system error. For autonomous functionality, UVs must include essential methods like planning routes, path control, location calculation, and learning.

It is essential to retrieve the UUV and the USV. These exhibit sensitivity to minor fluctuations in maritime circumstances during automated launches. It is necessary to analyze sea state data via sensors, ascertain the path, and secure a safe docking. Many innovations must be amalgamated to facilitate precise docking contact tactics, including sensing, communication, hydrodynamics, driving, robotics, oversight, combining information, and advanced fault-tolerant control systems. In recent years, swarm robotics utilizing swarm intelligence has been the subject of ongoing research. This will be elaborated upon in the subsequent section. This part focuses exclusively on control, identification, categorization, discrimination, characterisation, and ISR, wherein AI autonomously navigates the USV and UUV.

Regulation of USVs

Figure 1 illustrates an example of an autopilot navigation system for a USV, incorporating various detectors and models. Progress in Deep Learning (DL) and amassed expertise created detectors and platforms for USV navigation, analysis, oversight, telemetry, movement, and trajectory prediction. Multiple organizations consistently engage in USV development endeavors outlined in the following initiatives.

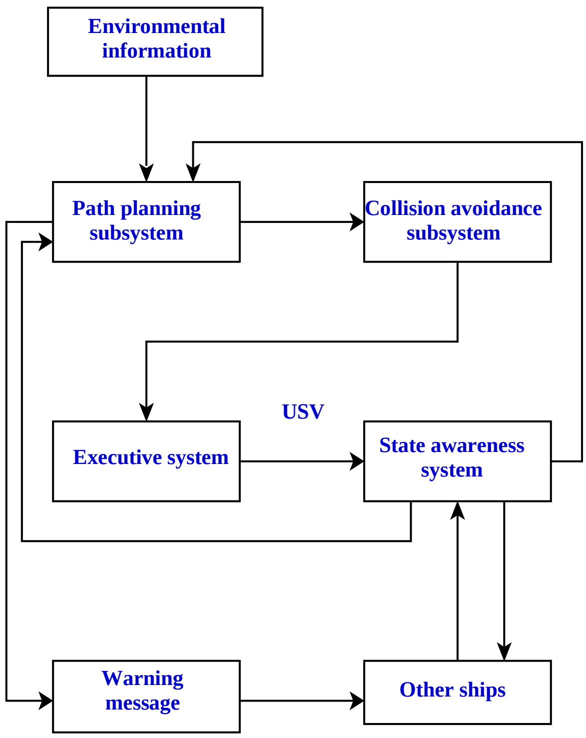

Figure 1: USV navigation system.

Alongside extensive projects, sonar, photography, and various sensors are employed in several locations to ascertain the boundaries of specified water bodies, facilitating identification, adaptation, and demining efforts. A circuit algorithm can search for a covering in target seas characterized by regular forms and known surroundings. At the same time, frontier-based approaches and enhanced methods are primarily utilized for complicated, unknown settings with dynamic impediments. Techniques for assessing water depth relative to the natural sea have been established, utilizing automated UM irradiance lines based on Global Navigation Satellite Systems (GNSS) readings or satellite imagery.

Regulation of UUVs

Artificial Intelligence (AI) is necessary to regulate the UUVs by modulating the velocity for rush, sway, and heave and the velocity for pitch and yaw during UUV operation. The controlling of UUVs is a topic of significant focus. Modifying the UUV structure is necessary because transmission is challenging, and the UUV must be effectively retrieved within a constrained transmission channel. Figure 2 depicts the method for driving an AUV.

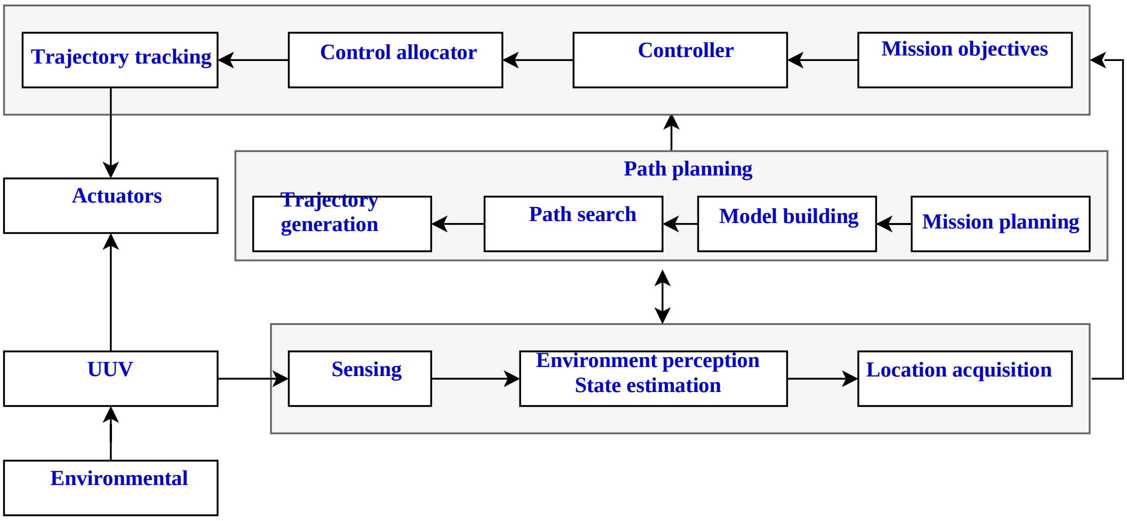

Figure 2: UUV automated navigation model.

A technique has been devised to actively attain self-rescue control by modulating the movement control of autonomous AUV fins through Deep Deterministic Policy Gradients (DDPG), enhancing the self-navigating navigation capabilities of UUVs. Programs are being devised to circumvent underwater barriers and improve the autonomy of AUVs.

Research has been undertaken to develop systems for the efficient movement and navigation of underwater vehicles along a designated route. Multiple methods are being formulated to monitor underwater perimeters with UUVs. Monitoring underwater borders is problematic due to the UUV's reliance on scalar detectors and acoustical and asynchronous transmission methods. The Monterey Bay Aquarium Studies Center has created a snake program and oceanic unmanned vehicle gas technologies to track oceanic boundaries.

Intelligence, Surveillance, and Reconnaissance (ISR)

Unmanned vehicles primarily conduct border patrols, monitoring, and strikes in critical regions during investigations. A border region is monitored along the boundary and frequently assessed using one or many unmanned vehicles during patrols. The objective is to monitor and engage the mobile target while evading torpedoes during a show or emergency. This assignment presents a challenge that necessitates decreasing distance while effectively identifying or circumventing barriers; hence, an algorithm designed with awareness is required. The techniques for determining the shortest path through integrating neural networks and swarm maintenance in deploying numerous unmanned marine vehicles (UMVs) have garnered significant interest. A study introduced an adaptive navigator utilizing deep learning to enable the Autonomous Underwater Vehicle (AUV) to conduct precise searches, accounting for measurement deviations of Microelectromechanical Systems (MEMS) sensors. It employs deep learning to produce low-frequency localization data for rectifying search inaccuracies. It uses the x2 rule to mitigate influence from Doppler Velocity Log (DVL) anomalies during DVL measurement failures. A study introduced a Current Bio-inspired Neural Network Path Planning (CBNNP) method. It is an algorithm based on neural networks that integrates distance and direction minimization with neural network theories to deduce the shortest path while circumventing potential collisions. An algorithm is employed, and modifications to elements based on the parallelogram rule, which compensates for deviations induced by current effect, have been suggested. A collision avoidance method was presented based on the velocities of many USVs.

Identification, Categorization, Differentiation, and Analysis

Automated sensors are essential for UUVs and USVs, enabling them to independently gather data and identify targets using sonar. The intelligence being created to automate target detection and tracking has yet to replicate the expertise of professional experts. A study introduced an Order-Truncate-Average (OTA) - Continuous False Alarm Rates (CFAR) method that integrates the OTA method for normalizing noise levels and discarding collected averages. They created a signal processing framework that establishes limits for detection techniques in an auto-sensing device and mitigates the effects of environmental noise and disturbance on the likelihood of incorrect alerts in the overall system. Identification methodologies were presented utilizing the extraction of features, Matched Field Processor (MFP), and cognition. Intelligent target detection approaches encompass methods that enhance the signal-to-noise ratio and detection area through the integration of machine learning and traditional signal analysis, as well as independent cognitive approaches to detection that emphasize adaptive identification and computing grounded in intelligent neural mechanisms.

Additional Categories

A Towed Underwater Panel (TUP) linked to a USV is being engineered to rectify navigation inaccuracies in the undersea milieu and address communication constraints arising from battery issues and prolonged operational periods. Alongside incorporating a sensor, both physical and material methodologies can be employed. Utilizing an anechoic tiling or diminishing radiated noise can preserve the stealth capabilities of the UUV. Particularly with bionic AUVs, it is challenging to ascertain their status as adversaries when they attempt to minimize vibrational noise or employ sound-absorbing substances, as they produce solely physical and hydraulic noise.

Conclusion

This research examines the development of UUVs and USVs, and their utilization in recent conflicts, with a specific emphasis on UMVs employed in maritime environments, alongside various other UVs. Besides military uses, UUVs and USVs possess other civilian uses. UUVs are utilized to examine and repair underwater infrastructure, including oil rigs and pipes, in addition to marine biological research and surveillance of the environment.

From a hardware standpoint, research is underway to improve battery efficiency and communication underwater in UMV; additional technological advancements are still necessary in these domains. In the realm of mine countermeasures, it is anticipated that the duration of mine removal will be reduced and enhanced by the utilization of SAS technologies and numerous UVs.

Additional improvement of the control knowledge for UMV is necessary regarding the software. This is because UVs have not yet been built; hence, they cannot entirely supplant people now. Developing autonomy in a singular vehicle is crucial, and recent advancements in collaborative systems have addressed the constraints of distance and operating ease; both platforms now cooperate to resolve diverse challenges.

The previous functioning of marine systems reliant on massive vessels is swiftly transitioning to small, UM cooperative platforms. To autonomously run an intelligent UMV, it is essential to enhance its intelligence level and to develop a collaborative strategy for utilizing multi-robot and swarm technologies. Regardless of the quality of the sensors and AI designs, their efficacy is compromised if inter-device communication is unreliable. Numerous advancements are necessary for formative regulation and collaboration in contexts of inadequate interaction.

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