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Autonomous Underwater Vehicle Navigation and Control: A Brief Review

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Abstract

This paper presents a brief review of the latest advancements in navigation and control technologies for Autonomous Underwater Vehicles (AUVs). It discusses the challenges and solutions in AUV navigation, including the integration of various sensors and algorithms to ensure accurate and reliable operations in complex underwater environments. The paper also explores the advancements in control systems, highlighting adaptive, intelligent, and fault-tolerant strategies that have significantly enhanced AUV capabilities. This review underscores the technological evolution in AUV systems, emphasizing the importance of these developments for future underwater exploration and tasks.

Overview

Autonomous Underwater Vehicles (AUVs) represent a remarkable technological achievement, playing significant role in enhancing our understanding of oceanographic sciences and the management of underwater. resources. They have advanced our approach to exploring and engaging with one of the most challenging frontier on Earth. The transformative impact of AUVs is rooted in their sophisticated navigation and control technologies, which equip them with the ability to execute complex operations with exceptional accuracy and dependability. The remarkable autonomy of AUVs is one of their most defining features, enabling them to undertake extensive underwater explorations and gather crucial data, all while operating free from the constraints of continuous human oversight or the physical limitations of being tethered to surface vessels. This level of independence is made possible by state-of-the-art navigation systems that integrate various technologies. When near the surface, AUVs utilize GPS for positioning; once submerged, they rely on a combination of inertial navigation systems and acoustic positioning methods to navigate the ever-shifting and intricate underwater landscapes with remarkable precision [1]. This advanced navigation capability is a cornerstone of AUV technology, empowering these vehicles to venture into uncharted marine territories, monitor environmental conditions with unprecedented detail, and conduct extensive surveys for scientific research, commercial ventures, and security related missions. The ongoing evolution and refinement of AUVs continue to push the boundaries of what is possible in underwater exploration and operations, showcasing a remarkable symbiosis of technology and marine science [2]. Moreover, the control technology in AUVs is equally of significance. It encompasses sophisticated algorithms and sensor systems that enable the vehicle to make real-time decisions, adjust to changing underwater currents, avoid obstacles, and maintain stability in various oceanic conditions. This technology is essential for tasks like seabed mapping and inspection of underwater infrastructure, where precision and adaptability are paramount [3]. The ongoing advancements in AUV technology, including improved energy efficiency, enhanced sensor capabilities, and more intelligent decision-making algorithms, continue to expand the potential applications of these vehicles. As a result, AUVs are not only invaluable tools for scientific research and environmental monitoring but also play critical roles in national security and the burgeoning field of deep-sea mining. Their ability to operate in environments that are inaccessible or dangerous for humans underscores their significance as a cornerstone of modern underwater exploration and exploitation technologies [4,5].

Missions involving autonomous underwater vehicles (AUVs) docking with underwater nodes for battery recharging and data transfer significantly expand the range of their potential applications. A critical aspect of these missions is the development of robust and accurate vehicle guidance systems that can effectively dock with small, simple, and reliable structures [6]. One innovative guidance scheme involves using an optical quadrant tracker. This tracker operates by locking onto a visible light source located at the docking station, functioning similarly to how certain air-to-air missiles track their targets. Further advancements in this field include the development of a six degreeof- freedom adaptive controller for autonomous underwater vehicles (AUVs) [7]. This controller uses quaternions for representing attitude errors, offering an advantage over traditional Euler angle descriptions which are prone to singularities. Such technological advancements have transformed the way researchers and industries gather underwater data, enabling cost-effective seabed surveying and exploration. Another notable development is the application of a new Simultaneous Localization and Mapping (SLAM) algorithm, specifically tailored for synthetic aperture sonar data acquired by AUVs [8]. This algorithm, which employs innovative target detection strategies, has been proven to deliver consistent and accurate results, even when compared to established full covariance SLAM algorithms [9]. The field of underwater data muling has also seen significant progress, with the creation of systems that integrate autonomous underwater vehicles and static underwater sensor nodes [10]. These systems utilize both optical and acoustic networking to facilitate data collection and transmission.

One of the pioneering achievements in this domain is the development of an underwater vehicle capable of autonomous manipulation. This vehicle represents a major step forward in addressing the challenges inherent in autonomous underwater manipulation, opening new possibilities for intervention missions. The area of formation control for multiple underactuated AUVs has also been explored, with techniques such as position tracking control being developed using Lyapunov and backstepping synthesis. These methods enhance the coordination and efficiency of AUV fleets, facilitating complex underwater missions [11,12]. Path planning methods for maximizing mutual information have also been introduced, along with field results from ocean trials demonstrating the effectiveness of these methods for specific types of AUVs, such as underwater gliders. This research contributes to the optimization of AUV navigation and data collection. In addition to these advancements, several other influential works have contributed to the field, furthering our understanding and capabilities in underwater autonomous vehicle technology and its applications [13].

In recent advancements, researchers have proposed a novel underwater system that enables simultaneous wireless power transfer and data transfer for autonomous underwater vehicles (AUVs). The introduction of a double-sided LLCC compensation topology effectively minimizes interference to the data channel during switching moments, marking a significant step forward in underwater communication technology [14]. A key development in the field of maritime transportation systems, particularly in the realm of the underwater Internet of Things, is the use of multi-AUV-based Underwater Wireless Networks (UWNs). These networks are gaining attention for their robustness and distributed nature, with AUVs serving as network nodes and their interactions forming potential network links [15]. This concept represents a new paradigm in underwater communication and coordination. In the area of underwater exploration, significant progress has been made in integrating submersible fluxgate magnetometers with AUVs [16]. This integration facilitates the detection of underwater unexploded ordnances (UXOs), demonstrating the potential of AUVs in conducting magnetic measurements in challenging underwater environments. Another focus in underwater technology is dynamic target tracking, crucial for applications like marine resource exploration, underwater engineering, naval surveillance, and precision guidance. Researchers have developed a novel control method for AUVs that enables efficient tracking of dynamic underwater targets by predicting their trajectories [17,18]. Addressing the challenges posed by ocean currents, external disturbances, and other uncertainties, a new model-free trajectory tracking control architecture for AUVs has been introduced. This architecture ensures stable and precise navigation in complex underwater environments, even in the presence of factors like measurement noise, thruster malfunction, and initial tracking errors. In the realm of underwater communication, green light-emitting diode (LED)-based visible light communication (VLC) is emerging as a promising solution for mobile AUVs and remotely operated vehicles, especially in coastal and harbor areas. A neural network-based auto equalization model (NNAEM) using end-to-end learning has been proposed to enhance the speed and bandwidth efficiency of underwater VLC links using green LEDs [19]. Furthermore, obstacle detection and avoidance in complex ocean environments pose a significant challenge for AUVs. Leveraging images captured by forward-looking sonar, a novel algorithm for obstacle detection and avoidance has been developed, enhancing the operational safety and efficiency of AUVs [20]. In addition to these breakthroughs, other influential works in the field continue to contribute to the evolving landscape of autonomous underwater vehicle technology and its diverse applications [17].

AUV Navigation

Navigating accurately underwater is a complex yet essential task for autonomous underwater vehicles (AUVs). To achieve this task, two different paradigms have been proposed and implemented: a centralized iterative UKFbased navigation approach and a sensor fusion framework with parallel local UKFs [21]. These frameworks are crucial given that AUVs are typically equipped with multiple sensors like an inertial navigation system (INS), ultra-short baseline system (USBL), and Doppler velocity log (DVL) to facilitate autonomous navigation. One study focuses on a robust integrated navigation algorithm that combines INS, USBL, and DVL using graph optimization [22]. This algorithm addresses the challenges of multi-sensor fusion and non-Gaussian noise, which are pivotal in underwater navigation. Autonomous

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navigation is critical for AUVs to complete underwater tasks effectively, and attitude estimation is a key aspect of this. Drawing inspiration from biomimicry, three attitude estimation models based on a pressure sensor array have been constructed: a direct method, a multi-layer perception model, and an attitude estimation model based on physical knowledge [23].

For underwater missions, particularly in the absence of additional underwater absolute positioning measurements, the unknown errors introduced by navigation system modeling and state estimation processes can impact navigation accuracy, leading to the proposal of an integrated navigation method tailored for small-sized AUVs in shallow-sea applications [24]. Addressing the challenges of underwater target detection, a real-time detection method using side-scan sonar mounted on AUVs has been proposed. This method is particularly valuable for missions requiring underwater target detection in real-time [6]. In the context of marine surveys, which are costly and challenging, especially under adverse sea conditions, a profile AUV system has been developed to facilitate multipoint short-term synchronous offshore surveys [25].

Moreover, a statistical model and corresponding sequential Bayesian estimation method for terrain-based navigation using side-scan sonar data have been introduced [26]. This method is especially suitable for small autonomous platforms and can be extended to AUVs, combining sidescan sonar sensor data with a compass for effective navigation [26]. Furthermore, to address varied navigation scenarios, sensors such as Doppler velocity log, magnetic compass pilot, pressure sensor, and global navigation satellite system can be tightly coupled with advanced navigation systems [27]. A novel model has been proposed for this purpose, featuring a floating LBL slant range difference factor model tightly coupled with IMU preintegration factor to unify global position above and below water [28]. Finally, considering the complex ocean environment where AUVs are often disturbed by obstacles, an obstacle detection and avoidance algorithm based on images collected by forward looking sonar on AUVs has been proposed [29]. This contributes significantly to enhancing the operational safety and efficiency of AUVs in challenging underwater tasks.

In the field of autonomous underwater vehicle (AUV) navigation, ensuring precise and reliable navigation remains a challenging yet vital objective. Recent studies have explored and compared two distinct frameworks: a centralized iterative UKF (Unscented Kalman Filter)-based approach, and a sensor fusion framework employing parallel local UKFs [30]. These methods reflect ongoing efforts to refine AUV navigation through advanced filtering techniques. AUVs are typically outfitted with multiple sensors, such as inertial navigation systems (INS), ultra-short baseline systems (USBL), and Doppler velocity logs (DVL), to facilitate autonomous navigation [31]. A robust integrated navigation algorithm that combines INS, USBL, and DVL data through graph optimization has been studied. This algorithm addresses the challenges of multi-sensor fusion and handling non-Gaussian noise, showcasing the potential of complex data integration in enhancing navigation accuracy [32]. The significance of autonomous navigation and accurate attitude estimation for AUVs is underscored in another study, which draws inspiration from biomimicry. Researchers have constructed three attitude estimation models based on a pressure sensor array, exploring direct methods, multi-layer perception models, and models based on physical knowledge. This approach indicates the growing influence of biomimicry in technological developments [33]. In underwater missions, particularly in shallow-sea contexts, the absence of additional underwater absolute positioning measurements introduces unknown errors in navigation system modeling and state estimation processes [34]. An integrated navigation method tailored for small-sized AUVs has been proposed to address these challenges, highlighting the unique demands of shallow-sea navigation [35].

Another research focuses on real-time detection of underwater targets using side-scan sonar mounted on AUVs [35]. This method describes the system operation for effective real-time underwater target detection, demonstrating the integration of sonar technology in operational AUV systems [36]. Addressing the high cost and limitations of marine survey ships, especially in multipoint synchronous marine surveys and offshore surveys under adverse sea conditions, a profile AUV system has been developed. This system aims to facilitate short-term synchronous offshore surveys, offering a cost-effective and reliable alternative to traditional marine survey methods [37]. A novel statistical model and corresponding sequential Bayesian estimation method for terrain-based navigation using side-scan sonar (SSS) data have been introduced. This method, suitable for small autonomous platforms, leverages the combination of SSS sensors and compasses, illustrating the potential of integrating terrain data in navigation systems [38]. The integration of various sensors, such as DVL, magnetic compass pilot (MCP), pressure sensor (PS), and global navigation satellite system (GNSS), into a tightly coupled system has also been explored [39]. A floating LBL (Long Baseline) slant range difference factor model, tightly integrated with IMU preintegration factors, has been proposed to achieve unified global positioning above and below water [40]. Additionally, the complexity of ocean environments often leads to AUVs encountering obstacles during missions. An obstacle detection and avoidance algorithm based on images from a forward-looking sonar has been proposed to enhance operational safety and effectiveness of AUVs in such environments [41], [42]. These developments, along with other influential work in the field, continue to push the boundaries of AUV technology, offering innovative solutions to the complex challenges of underwater navigation and operation.

AUV Control

Control systems for vehicles, especially those operating in challenging environments like underwater, have traditionally been based on simplified vehicle models. While this approach was practical, it often resulted in less-thanoptimal performance due to the complex, nonlinear, and time-varying dynamics of vehicles, as well as uncertainties in their parameters [43]. A groundbreaking approach emerged with the use of neural networks for learning control systems in underwater robotic vehicles. This marked a significant shift towards adaptive and intelligent control systems, better suited for the intricate dynamics of underwater vehicles. Following this, a new feedback control law was introduced for nonholonomic underwater vehicles, promising exponential convergence to a desired state [44]. This law leveraged a kinematic model represented in SE (3) using homogeneous transformation matrices, with attitude deviations captured through Euler parameters. This method provided a more accurate and responsive control mechanism for underwater vehicles [45]. Further advancements were made in addressing the limitations of traditional vehicle control systems. A novel system capable of learning and adapting to changes in vehicle dynamics and parameters was developed [46]. This adaptive approach significantly enhanced the performance and reliability of vehicle control systems, especially under varying conditions [47]. The development of a semi-autonomous underwater vehicle for intervention missions also marked a notable advancement. This vehicle was equipped with multiple on-board CPUs, redundant sensors and actuators, an independent power source, and a robotic manipulator [48]. The review of AUV control architectures during this period led to the introduction of a sensor data bus based control architecture (SDBCA), underlining the evolution towards more complex and capable underwater robotic systems [49]. The field of underwater robotics further advanced with the introduction of dynamic control aspects, including fault-tolerant control and coordinated control [50]. These new features, highlighted in updated works, underscored the importance of reliability and coordination in complex underwater operations, marking a significant progression in underwater robotics technology.

The underwater environment presents formidable challenges in the fault-tolerant control of unmanned underwater vehicles (UUVs). The high dependence on the accuracy of the dynamic model, coupled with the difficulty in handling system uncertainty and external disturbances, makes this a complex area of research. However, recent advancements have marked significant progress [18]. A novel adaptive fault-tolerant control algorithm based on residual drive has been proposed to adapt to the changing dynamics of underwater vehicles, significantly improving reliability in the presence of system uncertainties. Additionally, an intelligent fault-tolerant control (FTC) strategy has been developed, specifically targeting the trajectory tracking issues of underwater vehicles with thruster damage, including power loss. This strategy ingeniously combines a refined backstepping algorithm with sliding mode control and employs the Grasshopper Optimization Algorithm for effective thruster force compensation [51]. Furthermore, the study of a robust state feedback optimal control strategy for Autonomous Underwater Robotic Vehicles (AURVs) focuses on 3D path following using a backstepping approach, addressing both horizontal and vertical dynamics to enhance control precision. In the realm of underwater dynamic target tracking, research based on trajectory prediction for autonomous underwater vehicles has shown remarkable effectiveness in dynamic underwater environments, validated through simulations and experiments [52]. The proposal of a novel model-free control architecture for autonomous underwater vehicles is particularly notable. This architecture, designed to withstand various disturbances and uncertainties, ensures stable and precise trajectory tracking in complex underwater conditions. In addition, a new method for dynamic positioning of UUVs using an autonomous tracking buoy has emerged, employing ultra-short baseline measurements for indirect positioning and demonstrating promising results in simulations and sea trials [53].

Another significant contribution is the development of a collision-free planning and control framework for biomimetic underwater vehicles, incorporating a fuzzy inference module to manage the nonlinear relationship between control parameters and force/torque. The sphere region tracking control scheme using barrier Lyapunov functions, which estimates the effects of external disturbances and modeling uncertainty, shows clear advantages over other region-tracking control schemes [53]. The introduction of compound fault diagnosis technology for underwater vehicle actuators focuses on enhancing operational safety and diagnostic accuracy under positioning error constraints. Lastly, the robust optimal control approach for underwater vehicle manipulator systems (UVMS), optimized using the grey wolf optimizer, addresses the nonlinear control problem in UVMS, taking into account modeling uncertainties and water disturbances [54]. These developments collectively represent a significant leap forward in the control systems of underwater vehicles, greatly enhancing performance and reliability in the complex and unpredictable environments of the underwater world. Optimum linear filter and control theory has been applied to the practical problem of supplementing an inertial navigation system with discrete reference information. This involves formulating a model representative of the system's dynamics, appropriate for the application of optimum filter and control theory [55]. An Event Calculus program for controlling the navigation of real robots has been developed using Theory Completion techniques. This method encompasses extraction-case abduction, the simultaneous completion of two mutually related predicates, and learning based solely on positive observations [56]. The use of an ultrasonic distance measurement system based on time-of-flight

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theory for estimating AGV triangulation position has also been explored. This approach focuses on an adaptive navigation and control system that can position the AGV at any arbitrary location and with any arbitrary two dimensional attitude [57]. Research has delved into the system design and control technology of vision-based vehicles, discussing the vehicle structure, performance parameters, and dynamic model. The development of computer image processing technology and control theory has made vision navigation and advanced control theory key areas in the field of vehicle automatic navigation [58]. The relationship between navigation and selection in bimanual interaction, based on certain theoretical models, has been investigated. This includes designing experiments to verify and establish this relationship [59]. The concept of human driver participation in robotic control processes, especially when the navigation module is active, has brought up the issue of shared control. A new approach for collaborative planning between two agents, utilizing optimal control theory and a threelayer architecture, has been presented. Speed optimization control for wheeled robot navigation with obstacle avoidance, based on viability theory, has been studied. Viability theory deals with the dynamic adaptation of evolutionary systems to the environment. This method involves integrating the robot's dynamic model, environmental constraints, and navigation control [60]. The development of a novel robot motion planning model based on visual navigation and fuzzy control has been proposed. Fuzzy control technology, an interdisciplinary field combining fuzzy science, artificial intelligence, and knowledge engineering, employs the theory of fuzzy control to achieve this integration [61,62]. These developments, along with other influential works, continue to advance the field of navigation and control systems, integrating various technologies and theories to enhance the effectiveness and efficiency of navigation systems in various applications.

Conclusion

The paper concludes that recent developments in navigation and control technologies have significantly advanced the capabilities of Autonomous Underwater Vehicles. These advancements not only improve the accuracy and reliability of AUVs in challenging underwater environments but also expand their potential applications. The integration of sophisticated sensors, adaptive algorithms, and innovative control strategies marks a pivotal step in underwater robotics, promising to enhance oceanographic research, environmental monitoring, and various maritime operations. The continued evolution of AUV technology is set to play a crucial role in exploring and understanding the depths of our oceans.

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