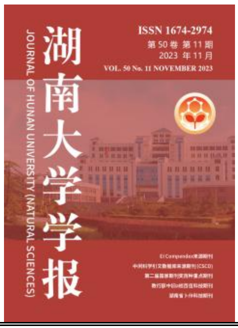

湖南大学学报（自然科学版）
Journal of Hunan University (Natural Sciences)

第 50 卷 第 11 期
2 0 2 3 年 11 月

Available online at http://jonuns.com/index.php/journal/index

Vol. 50 No. 11
November 2023

Open Access Article

https://doi.org/10.55463/issn.1674-2974.50.11.8

Unmanned Underwater Vehicles: Applications and Challenges

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Received: August 16, 2023 / Revised: September 6, 2023 / Accepted: October 9, 2023 / Published: November 30, 2023

Abstract: Unmanned underwater vehicles (UUVs) are widely used for scientific, commercial, and military underwater applications, some of which require accurate positioning and path control. Modeling, system identification, and control of these vehicles are still primary areas of research and development. They pose severe challenges due to their complex design, inherently nonlinear, and time-varying dynamics. This study aims to present a comprehensive survey of the literature discussing the classification and importance of underwater vehicle systems related to cost-effectiveness and versatility. Using UUVs in military, commercial, and civilian areas has led to tolerable results. These include but are not limited to, oil and gas industries, ocean seafloor mapping, hydrothermal vent studies, air crash investigations, mine countermeasures, and information operations. Because of the vehicles' complex, inherently nonlinear and time-varying dynamics, UUV modeling, system identification, and control remain essential areas of study and development. A presented comprehensive literature review relates to primary applications, electrical power technology, underwater communication challenges, system modeling identification, and control techniques. This study provides an advantageous and thorough overview of the underwater system domain, serving as a valuable resource for upcoming researchers. It encompasses the key facets of UUVs, including their design, control mechanisms, and use. In addition, it delves into recent scholarly works concerning this technology and explores potential forthcoming advancements.

Keywords: underwater vehicles, autonomous underwater vehicle, unmanned underwater vehicle, unmanned vehicle system identification, unmanned vehicle modeling.

無人水下航行器：應用與挑戰

摘要：無人水下航行器廣泛用於科學、商業和軍事水下應用，其中一些需要精確定位和路徑控制。這些車輛的建模、系統識別和控制仍然是研究和開發的主要領域。由於其複雜的設計、固有的非線性和時變動力學，它們帶來了嚴峻的挑戰。本文旨在對討論水下航行器系統與成本效益和多功能性相關的分類和重要性的文獻進行全面調查。在軍事、商業和民用領域使用無人潛航器已經取得了令人滿意的結果。這些包括但不限於石油和天然氣工業、海洋海底測繪、熱液噴口研究、空難調查、水雷對策和資訊操作。由於車輛的複雜性、固有的非線性和時變動力學，無人水下航行器建模、系統識別和控制仍然是研究和開發的重要領域。所提出的綜合文獻綜述涉及主要應用、電力技術、水下通訊挑戰、系統建模識別和控制技術。這項研究提供了水下系統領域的有利而全面的概述，為即將到來的研究人員提供了寶貴

的資源。它涵蓋了無人水下航行器的關鍵方面，包括其設計、控制機制和使用。此外，它還深入研究了有關該技術的最新學術著作，並探討了未來潛在的進步。

关键词：水下航行器、自主水下航行器、无人水下航行器、无人航行器系统识别、无人航行器建模。

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1. Introduction

A few underwater vehicle design attempts were introduced for limited applications and data collection starting in the 1960s [1]. Research institutes and universities began to develop unmanned vehicle (UV) platforms during the 1970s [2-6]. Remarkable efforts and achievements were noticed in the 1980s due to advances in software and technology during that period [5]. In 1980, the University of New Hampshire hosted the first worldwide Symposium on Unmanned Untethered Submersible Technology, where many research groups presented their UV progress and platforms [7-9]. From 1990 to 2000, operational functional prototypes were developed for specific missions and tasks [10-12]. UVs were used for commercial purposes in different industrial purposes in the 2000s [13, 14].

The shape design of the UV prototype went through different development and optimization techniques to fulfill the required parameters in terms of mission time, drag resistance, pressure distribution, hydrodynamics, and thrust force required [15-17]. Axisymmetric bodies, including elliptical parabolic and hyperbolic geometries and polynomials of various degrees are presented in [16].

Fig. 1 shows that underwater vehicle systems can be manned and unmanned [1]. UV systems can include four different sub-classes: submersibles towed behind ships, remotely operated vehicles (ROVs) [18], unmanned untethered vehicles [19], and untethered, fully automated submersible platforms [20]. The submersibles towed behind ships are the simplest platforms where different sensors can be used. A vessel using a tether directly controls the remotely operated vehicle (ROV). The third category is the unmanned untethered vehicle, which is controlled remotely by wireless communication and has an onboard computer. Due to the mission's constraints, a fully automated platform was developed that includes onboard control, navigation and guidance sensors, and a payload system.

In recent years, unmanned underwater vehicles (UUVs) have gained importance in underwater operations. They can be very hostile to humans and have proved to be an ideal platform for aquatic search, rescue operations, and deep-sea explorations. UUVs have gained significant prominence over the years as specialized tools for programming various underwater missions, leading to a considerable increase in research studies. The main challenge for deep-sea explorations has been the complex issues associated with hazardous and unstructured seabed environments. As a consequence, developing underwater robotics technology has grown steadily over the last few decades, with a particular focus on UUVs, which have enabled us to reach the depth of the ocean to conduct seafloor mapping and other scientific and military missions.

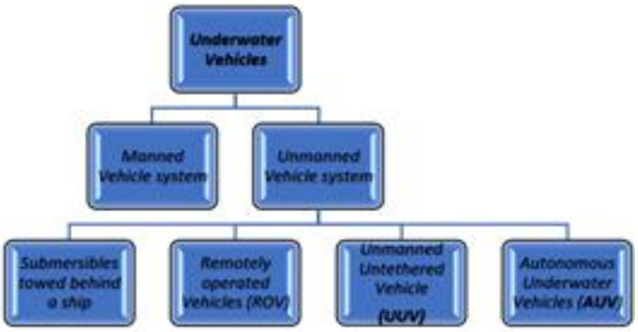

Fig. 1 Underwater vehicle systems categories [1]

This article describes the numerous UUV types and their design principles, modeling, and control techniques for various applications. There are different applications for underwater vehicles, including discovering historical shipwrecks such as the Titanic and tracking the environmental consequences in regions where petroleum resources are being extracted.

This article provides a comprehensive review of the existing literature on underwater systems, which is not easily accessible elsewhere. It also evaluates some recent research papers on this technology. It compares different control systems and designs of underwater vehicles. Depending on the needs, applications, and cost of various missions, there have been significant advances in marine technology. Many remotely operated vehicles have been designed for different educational and industrial purposes.

The article contains the following parts. Section 2 presents the major UV applications, including ocean seafloor mapping, mine countermeasures, hydrothermal vent studies, and air crash investigations. Section 3 provides a broad overview of the existing electrical engineering technology currently used for UUV systems, including energy sources and charging systems. Section 4 discusses underwater communication technology, sensors, and instrumentation systems. Section 5 discusses the classical and intelligent control techniques for these vehicles. Section 5 covers UV's dynamic model identification and presents traditional modeling and intelligent identification techniques. Section 7 discusses the challenges and future of UV.

2. UV's Primary Application Areas

In the literature, UV applications are mainly centered on the following areas: ocean seafloor mapping, mine countermeasures, hydrothermal vent operations, and air crash investigations. In the following subsections, a detailed review was carried out for each application area.

2.1. Ocean Seafloor Mapping

Wynn et al. [21] explained the past, present, and future contributions of autonomous underwater vehicles (AUVs) to the advancements of marine geoscience. The ability of AUVs to maneuver at relatively low depths over the seabed allows them to capture spatial data at significantly higher resolution than surface vehicles, particularly in deep water. They concluded that when used in conjunction with other platforms as part of a nested survey, a complete package of regional vessel-based mapping, high-resolution targeted AUV survey, and ROV video ground-truthing and sampling can be deployed. Sahoo et al. [22] clearly explained the advancements in the field of AUV. This paper presents research trends in the field of AUVs and highlights future research directions. Furthermore, the localization and navigation techniques employed in modern AUVs, such as inertial navigation to simultaneous localization and mapping, are thoroughly examined. Docking method for hovering-type AUVs to seafloor stations described by [23]. The authors proposed a technique that plays an essential role in long-term seafloor monitoring, and the performance of the proposed method was verified through a series of tank and sea experiments. AUVs dock to the seafloor station autonomously according to both acoustic and visual landmarks attached to the seafloor station for charging the batteries, and AUVs observe the LED markers by a forward-looking camera and calculate their position relative to the seafloor station.

Lin and Yang [24] proposed an AUV docking method in a confined reservoir with good visibility. This study proposes a novel navigation system that fuses downward-looking visual odometry and model-based velocity for homing, recognizes and tracks the light marker for final docking, and overcomes the defects of the conventional navigation method. The reservoir experimental results validate the proposed method's performance and indicate a high potential for further implementation in normal underwater cruises. Chen and Guo [25] discuss real-time map synthesis using side-scan sonar scanlines for autonomous underwater vehicles. The seabed was mapped using occupancy grid mapping methods.

Costa et al. [26] described a cost-efficient light AUV specially tailored for coastal archaeology applications exploring a large part of the heritage sites. To discover and identify ancient items in the ocean, the proposed vehicle contains sonars, an optical camera, and a magnetometer. Bloomer et al. [27] conducted extensive research to increase the efficiency of multi-sensor mapping of massive seafloor ulphide (SMS) deposits using an AUV. The relevance of SMS deposits as copper and gold forebodies is highlighted in this article. The authors present the findings of two technical tests that enabled the simultaneous gathering of conventional payload AUV data and electromagnetic data for quick target identification. The resultant system proved to be a cost-effective and efficient method for concurrent high-resolution multisensory and electromagnetic mapping in an SMS context. Bore and Folkesson [27] used a conditional generative adversarial network to model and simulate sidescan. The proposed data-driven models are a way of removing tradeoffs because of the quality of the produced images, the fidelity of the environment simulation, and the complexity of the sidescan model. Hong et al. [28] addressed the problem of visual simultaneous localization and mapping (SLAM) in an unstructured seabed environment using an unmanned underwater vehicle equipped with a single monocular camera as the primary measurement sensor. This study presents a robust loop-closure approach for improving operational efficiency in navigation and mapping by effectively recovering image matching constraints.

Hong et al. [29] conducted a research project on the dynamic modeling and motion simulation of an unmanned ocean platform to overcome the constraints of existing unmanned ocean platforms for ocean exploration. Newton's second law and the lumped-mass method were used to derive the equations of an unmanned surface vehicle, an unmanned underwater vehicle, and an underwater cable. The design considerations for unmanned remotely operated underwater vehicles (ROSUB 6000, PROVe-500) and the outcome of scientific expeditions conducted for deep sea mineral exploration, ocean biodiversity, and polar science have been discussed in detail by [30]. Zhang et al. [31] explained the instability state of the UUV and established a mathematical model of the instability state. The authors considered the coupling of the UUV between the flow field and seabed, and the numerical simulation calculation was completed using Ansys CFX for four different flow velocities, four different distances, and four different attack angles. Zhou et al. [32] integrated a low-power mechanical scanning sonar into a Slocum underwater glider to improve its environmental mapping capability. The mechanical scanning sonar is installed in the extended and free-flooded area of the nose of the glider. Following the successful integration, preliminary field testing was carried out to assess performance in both seabed surveying and iceberg mapping modes. Yamagata et al. [33] presented MONACA (Mobility Oriented Nadir Antarctic Adventurer), a changeable and small AUV that may deliver the essential and adequate compositions for diverse survey demands through modular design. The authors also mentioned that the MONACA' range is less than that of conventional AUVs. However, a simple and small AUV can minimize operational risk, and MONACA is expected to lessen the barrier to executing difficult under-ice operations. Marouchos et al. [34] provided an overview of the Starbug X AUV system and its operational characteristics, including vision-based navigation and oceanographic sensor integration. The authors further explained the unique capability and flexibility of Starbug X AUV in the collection of both shallow-water coastal benthic habitat and water column information.

Zhang et al. [35] discussed the diving and parking characteristics of an UUV. A numerical simulation model suitable for the large angle of attack movement and analysis of the changing rules of the angle of attack, sideslip angle, velocity, and pitch angle of UUV is proposed. Maeda et al. [36] performed mapping observations using an AUV equipped with sensors to monitor physical and chemical conditions in the vicinity of CO_2 and numerically simulated the behavior of the low-pH plume caused by CO_2 leakage within the calculated tidal current in the bay. They examined the AUV mapping findings and discovered that the physical and chemical properties of the water mass in Ardmucknish Bay are susceptible to tidal changes (low or high tide). The tidal phase in the bay predominantly controls the ascent speed of the leaked CO_2 bubble and the pH decrease in the vicinity of the CO_2 leakage area.

Okamoto et al. [37] proposed a method to avoid obstacles suitable for the steep terrain of the deep seafloor. The authors discussed ways to enhance the robustness of the observation by AUVs by reducing the false detection of obstacles and planning proper distance when avoiding obstacles. Hovering-type AUV HOBALIN equipped with cameras and line lasers, obstacles detected by simple image processing techniques, and three-dimensional positions measured by a light-sectioning method are employed. Huang et al. [38] presented an online seabed obstacle identification approach based on sonar scanlines for submarine cable installation applications. Sonar scanlines, rather than sonar pictures, were established in that work to provide an effective method for detecting seabed obstacles. The authors highlighted that the map of obstructions on the planned corridors is beneficial for future route design, clearing, and pre-lay grapnel run activities, and the online detection not only analyzes the efficiency of route survey but also saves funds for undersea construction.

Sangekar et al. [39] discussed in detail the autonomous landing of underwater vehicles using high-resolution bathymetry. This article focused on the safe and reliable landing of AUVs in actual seafloor environments. The algorithm uses millimeter-resolution (mm-resolution) bathymetry to detect regions where an AUV of known geometry can safely and stably land on the seafloor. Salhaoui et al. [40] recommended an AUV model system designed to overcome latency challenges in the supervision and tracking process using edge computing in an IoT gateway. The proposed model successfully carried out a long-term monitoring mission to follow the undersea Pinna Nobilis (fan mussel) species in a designated area of shallow water in the Mar Menor (Spain). The obtained results justify the proposed system's design and highlight the cloud and edge architecture performances. The authors also indicated the need for hybrid cloud/edge architecture to ensure a real-time control loop for better latency and accuracy to meet the system's requirements. Danckaers and Seto [41] implemented a vector quantization method to compress and send snippets of side-scan sonar images from autonomous underwater vehicles in motion to an operator. The work was confirmed using controlled indoor tank tests and many at-sea trials. The fidelity of the received images is such that trained operators can recognize targets in the acquired images as well as in the original images. Zhang et al. [42] researched the factors influencing the balance weight parameters on UV motion performance in the vertical plane based on dynamic equations. This research set the references for the overall design, internal layout planning, and trimming of the vehicle. The offshore trial data of the seafloor mapping AUV developed by Tianjin University verified the calculation principle of these parameters. Armstrong [43] shared the limitations of using satellite remote sensing and the importance and benefits of AUV and ROV in achieving high-resolution optical imaging of coral reefs and other benthic communities in Puerto Rico and the US Virgin Islands. AUV and ROV benthic assessments could provide the required information for selecting unique areas of high coral cover, biodiversity, and structural complexity for habitat protection and ecosystem-based management. Kilgour et al. [44] used REMUS 6000 AUVs to collect presence data for vulnerable species, communities, habitats, and ecosystems (VSCHEs) in a rapid assessment of the Physalia Seamount. AUVs were programmed to obtain digital images, side-scan sonar (120/410 kHz), and environmental parameters and could navigate a 40° slope. The authors presented the preliminary results of this approach, predicated on the assumption that coarse taxonomic resolution adequate for management needs to protect VSCHEs, and finally indicated that AUVs can be a useful tool for extensive area surveys in short periods. Zwolak et al. [45] described the process of complex data acquisition and bathymetric product generation using the AUV operated in partnership with an unmanned surface vessel (USV). Both vehicles acquired data using hydroacoustic mapping devices. Additionally, the USV provided the AUV with positioning data and served as a communication link between the AUV and the operators’ station onshore. Chochrane et al. [46] assessed the deposition of drill cuttings on the bottom over a transect at eight drilling locations in the southern Barents Sea and the Norwegian Sea and compared standard visual surveying methods with underwater hyperspectral imaging (UHI). The locations varied from recently drilled to approximately 30 years post-drilling, and the UHI-based identification of drill cuttings therefore confirmed the results of visual evaluations in general and might be extended further as a tool for automated surveying of drilling sites. Campbell et al. [47] shared that AUV technology has revolutionized the deep-water near surface, geohazards, and site-survey industry. Anonsen et al. [48] explained that terrain navigation can be used to facilitate submerged MCM operations without the need for surfacing for Global Navigation Satellite System fixes or pre-deployed infrastructure on the sea floor. They demonstrated the concept using test data from one of the real Norwegian Navy’s newly acquired Kongsberg HUGIN AUVs.

The number of AUV surveys will continue to increase, and new applications will be developed in the future. The authors further added that AUV technology continues to evolve to provide improved and additional types of data for various survey applications that are important for safe and efficient petroleum exploration, development, production, and decommissioning activities.

2.2. Mine Countermeasures

Crawford and Connors [49] described an evaluation of a 3-D sidescan sonar system, the Ping DSP 3DSS, for mine countermeasures (MCM) applications. The authors performed testing trials over the seabed and moored mid-water targets, and the mid-water targets showed better performance than the conventional sidescan sonars typically used in mine hunting surveys. Luo et al. [50] addressed an offline and online path planning algorithm for UUVs in a marine area with obstacles based on rectangular grid division and spanning tree circumnavigation for mine detection measures. In this algorithm, the area to be detected is equally divided into (2×M) × (2×N) rectangular cells, and the UUV circumnavigates the spanning tree of the graph induced from the 2×2 mega cell division while visiting every 1×1 grid with minor backtracking. Simulation results showed that the path generated by the algorithm is complete and efficient. For mine countermeasures, considered ocean currents, intricate bathymetry, and vehicle dynamics (MCM). They proposed a Physical Traveling Salesman Problem (PTSP) technique to create movements for the reacquisition and part of the MCM mission while considering the temporally and geographically complicated maritime environment as well as the AUV’s nonlinear dynamics. Fransman et al. [52] examined mine countermeasures (MCM) operations with multiple cooperative AUVs within the distributed constraint optimization problem (DCOP) framework. The objective of an MCM operation is to search for mines and mine-like objects within a predetermined area so that ships can pass through the area through a safe transit corridor. Song and Chu [53] investigated current MCM systems and their operations in minefields for possible technological improvements in future my neutralization. They shared the key technologies required such as system efficiency, the capability of fast data processing, communication efficiency, and cost-effectiveness for future MCM systems. Yordanova et al. [54] discussed adaptive track orientation strategies for mine countermeasures using an autonomous underwater vehicle and proposed two adaptive methods: one aimed at resource efficiency, and another at data quality. Ferreira et al. [55] explained that the current Automatic Target Recognition (ATR) techniques applied to raw data lead to many false positives and require human supervision. The authors shared the advantages of mosaicking forward-looking sonar (FLS) data, which increases the target contrast and reduces the false positive rate. They added that mosaicking FLS data also results in considerable data size reduction and plays a vital role in the real-time exchange of data with limited bandwidth in an acoustic channel. Dugelay et al. [56] presented an overview of the Centre for Maritime Research and Experimentation (CMRE) approach to autonomous mine countermeasures and highlighted the development of specific enabling technologies regarding sensors, automatic target recognition, autonomy, and in situ planning and evaluation.

2.3. Hydrothermal Vent Operation

Kim et al. [57] conducted a hydrothermal field survey mission by deploying multiple vehicles. Since September 2016, they have completed 21 multiple AUV dives in 7 bottom survey missions conducted in hydrothermal vent sites near Japan and accomplished this with enhanced efficiency. Neettiyath et al. [58] described a method for estimating the volumetric distribution of cobalt-rich manganese crusts (Mn-crusts) by combining multimodal sensor data collected using an autonomous underwater vehicle (AUV). The thickness of Mn crusts was calculated using sub-bottom sonar and a 3D colour reconstruction of the seafloor was generated using a light sectioning mapping system. Sasano et al. [59] used a hovering-type AUV "Hobalin" to examine hydrothermal fields and collect data from deep seabed photos and water sensors. They established the validity of both optical observations and water sensor readings for detecting tiny hydrothermal vents. Zain et al. [60] conceived and developed the X4-ROV, a micro-observation class that is primarily used for visual observation of underwater structures or environments using a high-resolution web camera. The designed vehicle structure focused on portability and maneuverability in attitude motions of roll, pitch, and yaw, and translational motion forward/reverse/lateral. Okamoto et al. [61] described an improved obstacle avoidance system to cope with steep and complex structures in active hydrothermal vent fields and its implementation in the hovering-type HOBALIN AUV. The avoidance system enabled HOBALIN to avoid alleged obstacles on the seafloor and managed to retain the frame body of the AUV unscathed. The authors confirmed the use of HOBALIN in active hydrothermal fields and its improved avoidance system. Wu et al. [62] successfully explored hydrothermal areas on the Southwest Indian Ridge using the Qianlong-II, a completely autonomous underwater vehicle developed for the research of submerged resources, notably polymetallic sulfides. They described the investigation of hydrothermal systems using Qianlong-II, providing extensive details of its installation and the data management and quick mapping tools employed. Finally, they introduced a method to remove magnetic platform interference using magnetic data while Qianlong-II was in spinning mode. Bloomer et al. [63] demonstrated that a physical calibration routine and a mathematical treatment of AUV collected magnetic data and produced magnetic maps useful for the interpretation of regional and subsurface geological structures in commercial surveys. The authors in this paper highlighted the future scope of applying these techniques in other marine geological environments, such as gas hydrate deposits. Ali et al. [64] developed and demonstrated an efficient underwater path planning control system with an android application and surveillance function for an underwater mobile robot based on the Arduino Mega 2560 R3. Okamoto et al. [65] deployed a hovering-type AUV (HOBALIN) in an active hydrothermal vent field located in the western offshore of Kumejima Island at a depth of approximately 1,400 m, and visual observations were performed using still cameras. Hobalin facilitated a useful survey of hydrothermal vents, and the acquired data can be used for subsequent sampling by HOVs and ROVs. Matsuda et al. [66] presented a navigation method for a group of AUVs consisting of a single high-performance parent AUV and simple child AUVs. They realized accurate and efficient seafloor observations and sea experiments with AUVs in a hydrothermal vent field. The proposed method achieved long-distance navigation, maintaining an accuracy more than five times better than that of navigation performed independently by a child AUV. Garg et al. [67] explained the chemotaxis-inspired adaptive biased random walk (ABRW) guidance-control law for an AUV. They evaluated the performance of a heuristics-based ABRW guidance-control law against a realistic plant model. The authors further added that the ABRW strategy uses common plume-tracking and heuristic schemes for real-time path planning of the AUV.

2.4. Air Crash and Shipwreck Investigations

Rahadian et al. [68] discussed the importance of seafloor mapping. Furthermore, they explained that these technologies were used to search and rescue (SAR) when AirAsia QZ8501 was missing in the southern Karimata Strait using three vessels, RV. Baruna Jaya I, MV. Java Imperia and KN. Trisula. Sung et al. [69] explained the disadvantages of crosstalk noise during underwater object detection and proposed the detection and removal of crosstalk noise using a convolutional neural network in images of forward scan sonar. They applied the proposed method to three-dimensional point cloud generation, generated a more accurate point cloud, and finally verified the performance by conducting multiple indoor and field experiments. Hong and Kim [70] proposed a visual mapping method for 3D reconstruction of a moderately curved underwater ship hull surface using piecewise-planar panel measurements estimated by a set of monocular images. The practical validity of the proposed method is demonstrated using an experimental dataset obtained from a field experiment conducted with a full-scale ship in a real sea environment. Nornes et al. [71] presented the results of an ROV-based photogrammetric survey of an intact standing steel wreck with a complex structure and high vertical profiles. The resulting 3D model was reconstructed using available freeware and commercial software. The results highlighted potential improvements such as reducing the reliance on a pilot, both in terms of data quality and in reducing the required resources for a survey even further. LeHardy and Moore [72] presented a detailed investigation of undersea search services in response to the disappearance of Malaysia Airlines Flight 370 (MH370). In support of this tasking, Phoenix deployed nine personnel, the Navy’s Towed Pinger Locator (TPL), and Phoenix’s Bluefin 21 AUV – a system called Artemis – to Perth, Australia. The authors further explained that over the next month and a half, Artemis collected side-scan sonar imagery of the seafloor in search of MH370 wreckage. Despite not finding the aircraft, the successful collection of high-quality data at extreme depths in a remote and unfamiliar part of the world is a noteworthy accomplishment and indicative of the future uses of AUV technology. Damour et al. [73] presented a comparative analysis of multiple datasets collected at shipwreck sites within differentially spill-impacted areas, which indicated that wood degradation and metal corrosion increased at sites affected by the 2010 oil spill. They further added that analysis of 3D optical and acoustic data along with a time series of high-resolution photos indicated that the rate of metal corrosion appeared to have increased at German U-boat 166 after the spill between 2010 and 2014.

3. Electrical Engineering Technology Usage in the UUV

Powering the UUV with electrical energy is crucial in determining their traveling range, speed, and payload and should be charged in a convenient method as it has a big impact in improving these factors. Additionally, the power source must be able to hold the hydrostatic pressure and be small in size and mass.

3.1. Electrical Engineering Technology Usage in the UUV

In the initial stages, UUVs used primary batteries such as alkaline subsea batteries and lithium primary cells. They have relatively high energy density (specific energy 200 W·h/kg ~ 400 W·h/kg and 1.5-kW·h). Although they are safe and easy to use, their cost and limited life are major disadvantages [74, 75].

Usually, modern secondary batteries power UUVs because they can be recharged for a few thousand cycles. They include lead-acid, nickel-cadmium (Ni-Cad), nickel metal hydride (Ni-MH), lithium-ion (Li-ion), and lithium-polymer (Li-Po) battery types. The disadvantage of this type of battery is that it has a relatively low energy density, which limits their range and the endurance of UUVs [74, 75]. However, the results show that pressure does not affect the resistance and capacity of the battery. However, the low ambient temperature significantly increases the battery resistance and thus decreases its capacity [76]. Fuel cells that generate electrical energy by the chemical reaction of fuel and oxygen are also used in UUVs. This technology is suitable for longer ranges with higher speeds and payloads [77]. A semi-fuel cell generates electricity by oxidizing a metal with oxygen. In semi-fuel cells, seawater is used as an electrolyte with a metal anode and an air cathode, achieving specific energy up to 500 Wh/kg, far more than any of the secondary batteries [78]. Zuo et al. [79] proposed a strategy to improve the conductivity of nickel foam by introducing multi-walled carbon nanotubes to effectively improve its discharge performance. Furthermore, the durability of the nickel electrode was improved by adopting a sandwich structure to prevent the carbon from falling off the nickel electrode. As a result, the present Mg–Ni seawater battery with 3.5 wt% sodium chloride solution as the electrolyte can offer an excellent open-circuit voltage of 1.6 V, obtaining an incredible specific energy of 1950 Wh/kg and a capacity of 1500 mAh/g at a current density of 1 mA/cm^2. This Mg–Ni seawater battery, with distinct advantages of high specific energy, cost-effectiveness, and safety, will be a promising underwater power source for many applications.

The open water power (OWP) system consists of an alloyed aluminum anode, a cathode alloyed with a combination of elements (primarily nickel), and an alkaline electrolyte positioned between the electrodes. When a UUV is placed in the ocean, seawater is pulled into the battery and split at the cathode into hydroxide anions and hydrogen gas. Hydroxide anions interact with the aluminum anode, creating aluminum hydroxide and releasing electrons. These electrons travel back toward the cathode, donating energy to a circuit along the way to begin the new cycle. Both aluminum hydroxide and hydrogen gas are considered harmless waste [80].

3.2. Charging Systems in the UUV

Battery swapping can be performed during operation or downtime in ports or on motherships [81]. In water, wired or wireless chargers can charge the UUVs, offering increased charging power rate and enhanced autonomy. The challenge in wired charging is to construct a stable docking station that can establish and maintain the connection during charging. Researchers at MTU, USA developed ROUGHIE which is an underwater glider capable of charging underwater from another UUV which serves as an energy carrier. The glider is a working robot. The wings serve as guides to force the two vehicles together. Upon successful capture, the glider will enable the switchable magnet to make the coupling rigid before power transfer begins [82]. The early generation of solar charging requires the UUV to surface during the daytime to harvest solar energy and store it in onboard batteries [83]. Rohr et al. [84] reproduced solar irradiance spectra at varying depths using an LED solar simulator and used them to examine Si, CdTe, and GaInP solar cells. They found that GaInP solar cells outperform both Si and CdTe solar cells for underwater applications, with efficiencies reaching 54%. Subsequently, they discussed ways to improve existing technologies to boost underwater performance.

Röhr et al. [85] stated that compressed hydrogen storage and metal hydride-based hydrogen storage are preferably used in UUVs. Any UUV with a power capacity of up to 3-10 kW encapsulated with metal hydride-based hydrogen storage tanks because larger power capacities require more significant amounts of hydrogen to store. By applying metal hydride storage, more substantial amounts of hydrogen are held in minimal volumes than in a compressed hydrogen tank. Therefore, the use of compressed hydrogen storage technology is justified for AUVs with lower power capacities up to 2–3 kW because the required hydrogen amount to be stored is quite a few. Wireless power transfer (WPT) can be classified as radiative, which uses microwaves or laser beams. Its application underwater resulted in low system efficiency [86]. Moreover, none-radiative, which includes capacitive and inductive power transfer methods through electric or magnetic fields. The capacitive (CWPT) system consists of submerged insulated electrodes separated by water as a lossy dielectric medium with a dielectric constant of about 80 and uses a few hundred kHz fields to transfer power, as demonstrated in [87]. Inductive wireless power transfer (IWPT) uses coils and near-field magnetic coupling for power transfer. IWPT is more commonly accepted for underwater charging because it is safe and more efficient and uses lower frequencies than CWPT. Chakridhar Reddy et al. [88] reviewed state-of-the-art IWPT solutions for underwater applications and discussed the engineering challenges of IWPT system design.

4. Underwater Communication Technology

For the past four decades, the technologies available for underwater wireless communications, which rely on radio frequency (RF), optical, and acoustic transmissions, have played a significant role [89].

Palmerio et al. [90] presented the advantages and disadvantages of using electromagnetic, optical, and acoustic data telemetry in the maritime environment.

In the literature, the main limitations of sound waves and optical signals on water are their low data rates, attenuation, and backscattering caused by suspended particles [91]. Because marine water has a limited capacity for the propagation of electromagnetic radiation, acoustics is often the ideal medium for permitting subaquatic communication. In addition, high-speed communication is challenging due to the underwater acoustic channel’s confined bandwidth, broad multi-path, medium’s refractive properties, severe fading, high ambient noise, higher bit error rate, rapid time fluctuations, considerable Doppler shifts, and delay in propagation [92]. Substantial attenuation in seawater limits underwater radio communication. Even at low frequencies, only a very small range can be reached.

Zeng et al. [93] studied underwater optical wireless communication (UOWC) because it can provide a much higher data rate and transmission bandwidth than RF and acoustic transmissions. Another promising and interesting approach is to deploy the internet of underwater things (IoUT) and next-generation (5G) networks [94], which result in improved data rates, connectivity, energy efficiency, extremely low latency rate, and improved quality of service.

4.1. Sensor and Instrumentation Systems

Frames, as with a GPS, and some are taken in the vehicle’s reference frame, such as the Inertial Management Unit (IMU) [95]. Therefore,two reference frames should always be considered when describing a vehicle’s status [96]. One must be able to transform measurement vectors from one reference frame to another to utilize all sensor data for navigational operations.

A pressure sensor, which senses the vehicle’s external pressure, is the most typical sensor used in vehicle depth measurement [97]. Strain gauges and quartz crystals are the two pressure sensor mechanisms most frequently used in deep-ocean applications [98].

Superior 3-D navigation features may be obtained using a GPS. It can only be used when a vehicle occasionally surfaces to adjust its measurements because water blocks its radio transmissions in underwater situations [99]. This indicates that additional sensors, such as the Long Baseline (LBL), Doppler Velocity Log (DVL), magnetometer, or compass, are essential for underwater vehicle tracking and navigation between GPS fixes [98]. For instance, the Bluefin-21 AUV occasionally surfaces for GPS fixes. The echo sounder [100], which was employed in the MAKO AUV project, is another method for measuring vertical depth, but only if the depth of the water’ is known.

LBL, USBL, and SBL systems are three basic categories of underwater acoustic location systems to determine depth [98]. When a vehicle triangulates its position using acoustic ranges within a network of surveyed transponders (beacons) planted to the seabed, the positions of which it is aware, it uses the LBL system, which is essentially a type of triangulation [101]. In contrast, when a sonar array is used to calculate the range and bearing of a vehicle, USBL and SBL acoustic navigational systems are used. The duration between the initial acoustic pulse transmission and the detection of the reply is calculated and transformed into a range for the entire system, which comprises a transceiver positioned under a ship and a transponder on the vehicle [101].

A DVL is a sensor that measures Doppler changes in sonar waves reflected by the ground to determine a vehicle’s bottom velocity [97]. It does this by using a high-frequency, multi-beam Doppler sonar. This navigating method is only effective if the ship is close to the ocean’s bottom (18–100 m), as it is more precise at moderate speeds and when the sea’s currents do not affect the vehicle speed [99].

The two types of sensors most frequently seen in maritime equipment are magnetic sensors and electronic compass modules. The vector values of the Earth’s magnetic field are obtained using a magnetometer to measure the Earth’s magnetic field in the X, Y, and Z directions and returning these three data independently [102].

Various single-axis (heading only) and three-axis flux-gate magnetometers are commercially available, many of which use the flux-gate magnetic sensing technique, whereas others use magneto-resistive and magneto-inductive magnetic sensing techniques. A navigation system’s total performance mostly depends on the magnetic sensor’s accuracy, which is said to be the main cause of mistakes. Errors can come from three different sources: 1) a magnetic disturbance caused by the vehicle or its surroundings [103], 2) the orientation of the compass mounting within the car, and 3) acceleration of the vehicle, which affects gravity-based roll and pitch adjustment.

The acceleration of the vehicle is detected by the inertial navigation system (INS) or inertial management unit (IMU) using accelerometers and gyroscopic sensors, one of each kind fitted on each of the three axes [104]. Although more expensive than velocity sensors, gyroscopes and accelerometers monitor rotation rates and linear accelerations,, respectively. Because these measurements are unaffected by sea currents, they are more precise than the velocity sensor' readings. The double integral of the accelerometer readings is required to determine a vehicle's location. Although IMU sensors are not vulnerable to magnetic disturbances, they drift with time, which introduces a significant amount of inaccuracy into integral computations because all mistakes add up and become more significant as a function of location. The most recent INS employ moving-part-free laser or fiber-optic gyroscopes [97].

Some of the top AUV navigational systems to date have been created by fusing two or more of the aforementioned technologies. Multi-sensor integration is the efficient use of data from several sensory instruments that can reduce navigational faults and assist a system in completing the required mission [95].

The primary goal of navigational sensors is to gather online and real-time information and circumstances from AUV's surroundings. The AUV's control system uses the information it receives from the processing unit to successfully navigate and control the vehicle underwater to complete a predetermined mission. Because of the characteristics of underwater dynamics and the uncertainty associated with hydrodynamic parameters, the dynamics and control of AUVs present significant challenges for designers. An overview of previous research on the philosophy of an AUV control system and its approaches is provided in the following sections.

5. UUV Control Philosophy

UVs perform various underwater tasks, some of which require very strict positioning and path planning. The AUV's dynamics are inherently nonlinear and time varying, i.e., its mass and buoyancy change according to the working conditions and surrounding environments. It is also subjected to uncertain and unexpected external disturbances because the UAV's hydrodynamic forces and coefficients depend on the surrounding environment and its velocity, shape, weight, and size [96].

Criteria for sensing, computation, and control are growing as the complexity of AUV missions increases. The AUV's control architecture should be capable of consistently integrating a broad range of sensors, tracking the vehicle's status, and executing the required mission. According to [105], it can be classified into three categories: deliberative, behavioral, and hybrid.

Deliberative architectures are based on planning using a model that allows predicting the environment [106]. They are ideal for standardized and highly predictable environments; however, when dealing with a highly dynamic environment, delays in response times are their key disadvantages.

Behavioral architectures, also known as reactive architectures [105, 107], deal with non-structured and complex environments. While behaviors respond continuously to a situation sensed by the perception system, because each pursues its own target, the response actions taken by one cause another to deviate from its respective target. Consequently, the action of a vehicle is often unpredictable.

Hybrid architectures take advantage of the two previous architectures while mitigating their drawbacks and typically consist of three layers: deliberative, behavioral, and control execution. Various comparative studies on control architectures in the field of underwater robotics have been conducted to improve their autonomy [108-111].

5.1. UUV Control Philosophy

In line with the mission objective and the application requirements, the wide variety and range of controllers that have been designed and implemented for underwater vehicles to achieve partially or fully autonomous missions can be classified as non-adaptive and adaptive control systems, as shown in Fig. 2. The adaptive control system can be generally defined as a direct or indirect control system.

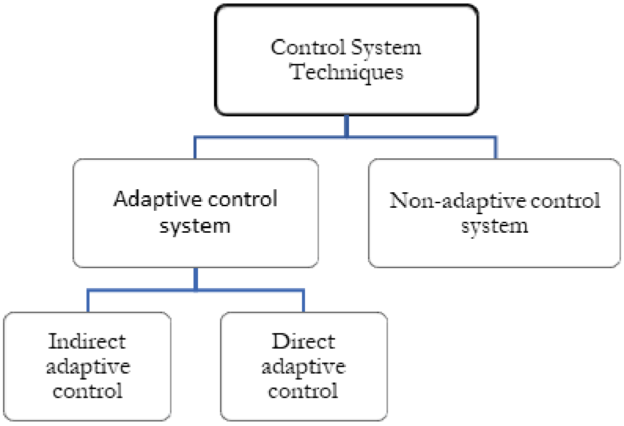

Fig. 2 Underwater vehicle systems categories (Developed by the authors)

For the AUV control system, a variety of algorithms have been examined, ranging from basic techniques such as the proportional integral derivative (PID) controller [113, 114] to more complex ones such as the sliding mode controller (SMC) and $H\infty$ [115-120].

5.2. Classic Control

Because of its simplicity and ease of use, the PID controller is a traditional feedback control approach. It has the advantages of fast response, high precision, and stabilization [121, 122]. If a precise system model with predefined operating conditions and moderate interruptions is provided, [123] is capable of attaining control goals. PID gains are altered either using analytical or trial-and-error methods [124, 125] in addition to being aware of the impacts of different gains before achieving adequate output [126].

Traditionally, the AUV was controlled by a PID control system, with PID controllers employed at all control levels in a distributed, decoupled control scheme [127]. The distributed architecture for mobile navigation (DAMN)-based control system for the Oberon submersible was investigated. Control objectives for the vehicle's direction included line tracking, moving to a specific location, avoiding obstacles, maintaining a minimum depth, and maintaining a minimum attitude. Votes from various behaviors within the system are combined by a central arbiter in this behavior control architecture [128]. Two low-level PID controllers are proposed for the motion control system to direct the AUV to follow the desired paths in the longitudinal and lateral planes. A defined and predictable sea-current disturbance has also been proposed as part of an intelligent high-level navigation strategy for AUVs.

The NDRE AUV uses the PID for its yaw control system [129] and moves at a constant speed, even though its dynamics are typically non-linear in terms of speed [130]. Fjellstad and Fossen [115] described a virtual velocity reference signal that combines the target speed, path-tracking error, tracking error integration, and controller in a linear fashion. The controller comprises a PID controller and a feed-forward component that is the multiplication of AUV dynamics and virtual velocity.

Chellabi and Nahon [131] linearized AUV dynamics and decoupled into 6 SISO second-order subsystems proportional-derivative (PD) controllers, which also include an error correction term. A linear PD controller combined with an optimal LQR controller is used to control each subsystem. A PD controller was proposed for a platform with linear I/O [132]. The system dynamics are linearized using the Lie derivative in the linearization approach, and asymptotically regulation or error tracking is then achieved using state feedback control. Another approach, computed torque control, has been developed [123]. It is based on the PID controller used to linearize the thruster outputs so that their torque is regulated as opposed to the input voltages to produce a more effective control system. This study demonstrated that the PID controller may deliver acceptable outcomes when a vehicle runs in constrained areas.

For each controlled DOF, PD or PID controllers are commonly used for dynamically positioned underwater vehicles, and PID control algorithms are developed under the straightforward assumption that the vehicle model is a second-order linear time-invariant dynamic system, meaning that its disruption and uncertainty conditions are constant. However, as [133] observed, the PID controller is unable to offer precise trajectory tracking for a linear second-order plan (both theoretically and practically). Additionally, PID control's robustness is declining, and to obtain the desired performance, its gains must be changed. This is because PID control cannot dynamically adapt to unmodeled vehicle hydrodynamic forces and unknown disturbance variations [134].

The SMC approach is another control system that is robust against parameter variance disturbances, making it one of the most used control systems for underwater vehicles [135]. The NPS ARIES AUV experiments in [136] employ a very simple SMC to track each of the decoupled modes. The sliding surface developed by pole placement was recognized as the optimum LQR in [119] to guarantee global asymptotic convergence. SMC was used individually for speed control, steering, and diving. To guarantee the global stability of state variable errors and reduce chattering, the switching surface employed in SMC is expressed by the Lyapunov function [136, 137]. A high-order sliding mode controller (HOSMC), based on third-order sliding modes, was utilized by [138] to regulate the depth of the AUV. By eliminating the control vector discontinuity, high-order approaches enable the removal of chattering. The authors demonstrated that these controllers retain the characteristics of traditional SM control laws. The performance and efficacy of the proposed strategy have been demonstrated in that article using various simulations.

The SMC controller has two shortcomings [139]. It chatters because the system's phase trace cross the switching surface at a very high frequency, which necessitates full-state feedback. Numerous AUV control SMC strategies have been analyzed in [140-142] to combat the problem of chattering.

The backstepping controller was used by [143] in the underactuated AUV, and the outcome demonstrated the efficacy and robustness of the developed scheme. The authors validated the efficiency of the proposed control approach using simulations. A non-linear model of the autonomous underwater vehicle "CWolf" was provided by [144], who emphasized the significance of precise modeling of the system for reliable autopilot. In this study, the drag and added inertia variables that impact the vehicle were calculated using the finite element analysis ANSYS.

Mukherjee et al. [145] developed a novel area tracking controller that requires only position measurement. The proposed controller is designed to enable the underwater vehicle's beginning location to converge to the targeted region and to keep tracking inside the restricted area. The authors used a Lyapunov function to verify the closed-loop system's stability, and simulation results demonstrated the effectiveness of the developed controller in conserving energy during region tracking. To account for system uncertainties and adequately smooth limited external uncertainties, [146] emphasized the creation of a nonlinear control architecture for a fully actuated AUV that has been developed at the University of Florida. The designed controller was experimentally tested in both controlled and open-water environments.

The AUV MARIUS is under control of [147]. Although the simulation results were only briefly presented, both position and depth were well tracked. Three H∞ controllers were employed, but they were not compared, for each gain schedule for a separate vehicle speed. When the control case from [148] was investigated using [149], it was observed that its efficiency matched that of the traditionally designed controller.

A linearized model of simple, constant-speed, and straightforward motion was used as the foundation for the control strategy in [150] AUV control system. The direct relationship between altitude and pitch angle was considered by the H∞ framework employed in the proposed hierarchical control structure in [151] for vertical actions of AUVs. The linear parameter varying polytopic controller [152] has been developed for altitude control with an altitude planned set according to the sampling interval for asynchronous data, and the linear time invariant controller has been computed for pitch angle.

A precise model of the system under control is often necessary for traditional control procedures. However, a computationally efficient controller is needed because the performance of these systems is not very satisfactory because of the presence of undesired aspects, such as nonlinearities, disturbances, and time-varying parameters. The AUV, for which a reliable control process model is only complex and ambiguous and the system parameters vary over timeto thus the most effective technique for intelligent control systems. Since they have great approximation capabilities and do not need to completely understand the dynamics of controlled vehicles, intelligent techniques such as fuzzy control and neural networks (NNs) have been widely employed in UUV control systems in recent years.

5.3. Intelligent Control

A feedback system that has the ability to modify its properties in a dynamic environment in line with a predetermined criterion is referred to as an adaptive control system [153]. Observations of the controlled process enable adaptive controllers to enhance their performance. Direct and indirect adaptive control are two efficient adaptive control systems [154]. The implicit former determines the controller settings by comparing the reference and actual output values. Indirect adaptive control uses online identification of the plant and its parameters to modify the controller's parameters [155].

Explicit adaptive control, which uses the specified model as the basis for determining the controller parameters, is the method used in this system [156].

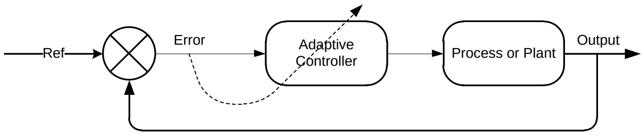

Fig. 3 Direct adaptive control block diagram [157]

Model reference adaptive control (MRAC) is the most effective approach for mitigating the nonlinearities and uncertainties of underwater vehicles, as illustrated in Fig. 3. It uses a reference model to alter the controller, and the control parameters are adjusted to match the output of the reference model. When input disturbances affect the plant, the effectiveness of the MRAC technique might be compromised because of modeling misjudgments [158]. Because of the lack of a direct mechanism for verifying the modified controller before it is used on the plant, this technique may provide results with inadequate responses for complicated nonlinear systems.

An identification model of the plant is employed in an indirect adaptive control approach to assist the controller's process of parameter adaptation [155]. Indirect adaptive control is a method that produces a controller using an SI methodology to generate a model of the process from input– output investigations. As illustrated in Fig. 3, the controller gains are tuned using both the plant output and the identification model output. It uses a process model in which the difference between the model and process outputs is used to adapt the identification model parameters. Before being given to the plant, the controller outputs are compared and verified against the plant model. Indirect adaptive control is exemplified by a self-tuning regulator, in which the controller design is altered in response to outputs from the identifier model, and the error difference between the reference input and plant output is used to compute the subsequent set of plant inputs. For both linear and nonlinear systems, a self-tuning regulator is a common option for indirect adaptive control [153, 159-161].

Bessa [162] describes the implementation of a dynamic positioning system for ROVs. The SMC technique was used as the basis for the modified approach, which was strengthened by an adaptive fuzzy algorithm for uncertainty and disturbance correction. The Lyapunov stability theory and Barbalat's lemma were used to analyze the stability of the final AUV closed-loop control system. Additionally, the modification of a reduced-order mathematical model for the vehicle to develop a decentralized control system without considering cross-coupling factors is addressed.

The proposed adaptive fuzzy SMC (AFSMC) based on the decomposition technique employs a fuzzy basis function expansion (FBFE), a PI-augmented sliding signal, and expert knowledge for underwater flight vehicle (UFV) depth control [163]. It offers four key benefits: a simple method for breaking down the UFV depth control system into a MIMO system; improved online robustness; a continuous control input with reduced power consumption and acoustic noise; and an adaptive method that can address the speed dependency of the controller parameters. Hyun [164] also used expert knowledge and fuzzy based on function expansion to design an expanded adaptive fuzzy SMC (EAFSMC). The simulation results showed that the average absolute values of the depth and pitch control errors verified that the EAFSMC was the most effective in terms of both performance and control attempt with respect to the overall maneuvering of the UFV. The proposed EAFSMC, PID, and AFSMC controllers were then compared.

Kodogiannis [165] introduced the adaptive NN control approach as a controller for UUV at 6-DOF. The performance of the adaptive controller was evaluated using computer simulation, and there was no requirement for any prior off-line training phase or explicit knowledge of the vehicle’s structure. In this design, the network acquired the vehicle’s inverse dynamics to generate the appropriate control input. Additionally, the controller was developed with the assumption that, as is typical in adaptive control, vehicles with six degrees of freedom (DOF) have linear dynamics with linear parameters that can be parameterized linearly. Radial basis function (RBF) networks and multi-layer perceptron (MLP) networks are two separate types of NNs that have been used to mimic the nonlinear dynamics of underwater vehicles.

The development and implementation of an NN-based adaptive control technique for the depth control system of an AUV is described in [166]. An online adaptive adjustment of the feed-forward NN parameters was used to estimate the unknown nonlinearity and drive the AUV to cruise at a predetermined depth. The adaptive control system was designed using the Lyapunov synthesis methodology, and the control law was divided into two sections: certainty equivalent control and compensation for the NN approximation error. However, it should be noted that a larger updated gain may have resulted in oscillatory behavior. Therefore, further adjusting the update gain and increasing the number of neurons in the hidden layer may attain better performance.

Based on a decoupled control system, an adaptable NN is used to control an AUV with three NNs that have been modified by adaptive interaction (ANNAI) [167, 168] and to govern the heading, depth, and speed of the vehicle [169]. The simulation demonstrated that the control system could handle nonlinearities, uncertainties, and external disruptions without being aware of the controlled plant beforehand. Because the ANNAI performed well with the nonlinear and time-varying properties of the AUV, it was not essential to employ the AUV model parameters when designing its controller, in contrast to earlier NN controllers developed in [169]. Additionally, the model’s inaccuracy could be avoided, it had the potential to be trained online to adapt to new situations and conditions, and it was not very sensitive to measurement noise in the input signals.

The Naval Postgraduate School (NPS) AUV is used as a case study in [170, 171] under the direction of Kuljaa [170] proposed an adaptive multi-layer NN controller for high-precision UV maneuvering, in which the NN control system worked with the standard controllers LQG and PID. The adaptive NN did not need to be trained and its weights were adjusted online because it included two adjustable layers, which eliminated the issue of choosing a suitable basis. To correct the tracking faults of AUVs, an online multi-layer perceptron NN (OMLPNN) that computes forces and moments in the fixed frame of the Earth has been created [171]. Another OMLPNN was created to create an inverse model of an AUV, using back-propagation to train the network and determine the right propeller speed and control surface angles to receive forces and moments in the body’s fixed frame.

AUV low-level control techniques employing a NN approach have been developed for the University of Idaho Miniature Submarine’s navigational control and track control of the underwater crawler [172]. For the latter, PID controllers were used to direct the velocity of the tracks to the required setting after the heading and intended speed were fed to a neutrally adapted controller. With the assumption that there was no correlation between the axes, the submarine system consisted of two low-level hierarchical controllers, a PD for heading control and a PID for depth control. The NN was trained using batched error back propagation and has a hidden layer of seven neuron input to a single output neuron (EBP).

Cavalletti et al. [173] studied the tracking control problem when an AUV was subjected to various load configurations, which occasionally generated significant fluctuations in their masses and inertial characteristics. Because of the lengthy adaption phase, classic adaptive control approaches were unable to govern this type of mode-switch process effectively. A switching control technique was devised to address this issue, and the stability of this multi-controller system was examined using Lyapunov theory. To store the diverse dynamics of the system and balance the impacts of nonlinearities and plant uncertainties, several radial basis function networks (RBFNs) have been proposed. The goal of this study was to develop NN-based nonlinear stabilizing controllers for each job using several RBF nets to predict the nonlinear functions of various plant operating circumstances. A supervisor chose which potential NN-based controller to include in the processfeedback loop at each time instant, and numerical simulations assessed the performance of the switched controller.

The primary challenge in using an NN is training the control system it has created, although a popular weight-adjustment technique, the BP algorithm based on the teaching signal, has been shown to work well in practice [174, 175]. It has been claimed repeatedly, nevertheless, that BP learns an NN too slowly to be effective for real-time control. This is accurate in the sense that its overall error convergence is sluggish, the local minimum frequently occurs, and it is challenging to identify a linear or nonlinear equation that may serve as the teaching signal for NN learning because of the complexity of AUV dynamics [175]. When using NNs for control, there are two primary types of controllers: learning using a forward model and direct learning. The forward model in the former is often trained using the output error or state error and then used for gain derivation, whereas in the latter, the state error is used directly to map the desired control input [139].

In general, NN systems attempt to replicate the hardware of the human brain, whereas adaptive fuzzy system attempt to emulate its software. Combining them creates a system that attempts to mimic how the human brain functions [176].

An adaptive controller for an AUV was developed using an FNN based on an extended RBFNN [177], and the stability of the resulting closed-loop control system was examined using the Lyaponov stability theory. The efficiency with which the impacts on AUV's motion control were reduced showed its capacity to learn a disruption to an AUV in a complicated underwater environment. A network was used to test an online generalized dynamic (GD)-FNN learning algorithm that conducted structure identification and parameter estimation tasks automatically and concurrently. The number of membership functions and gains' fuzzy rules were established by structure identification, and the parameters in the IF and THEN sections of the fuzzy rules were changed by parameter estimations.

An adaptive neuro-fuzzy inference system (ANFIS) with a chemotaxing tuning methodology and a fixed fuzzy rule-based approach was used in [178] to design an AUV autopilot. The 5-DOF and linearized state-space model used in the simulation and the fuzzy sets of the premises in the ANFIS structure were optimized using the BP method. ANFIS has also been used in an AUV height control system [179]. Based on the data returned by the sensors, this method was able to acquire the necessary fuzzy membership functions and fuzzy rules through self-study, demonstrating that the control system could outperform a single-NN or single-fuzzy system.

For tracking control of a ROV with four degrees of freedom, an adaptive neuro-fuzzy sliding mode-based genetic algorithm (ANFSGA) control system has been proposed [180]. It is examined using a direction-based GA comparable to the SMC and adaptive neuro-fuzzy (ANFS)-based evolutionary methods. By modifying the ANFS inference parameters, parametric uncertainties and disturbances were dealt with using an online learning capability. The proposed controller is based on a GA control system, and stability could be indirectly guaranteed by the SMC without rigid restrictions and in-depth system knowledge. The presented controllers could be used online and did not require any prior training in the sense of a Lyapunov stability analysis.

An adaptive neural fuzzy network (ANFN) controller is designed and applied to guide and control the AUV in [181] as the path controller of the AUV is a challenging problem because of the nonlinearities and uncertainties of the AUV dynamics. Thus, the controller should be adaptive to handle variations in the dynamics of the AUV under different maneuvering regimes and disturbances arising from both internal and external sources. Initially, the controller parameters are generated randomly and tuned using the differential evolution algorithm (DE). The back propagation algorithm based on the error between the actual outputs of the plant and the desired values is then used to adopt the controller parameters online. As a result of the fuzzy rules, the proposed ANFN controller employs a functional link neural network (FLNN). As a result, the controller's consequence is a nonlinear combination of input variables. The results show that the performance of the AUV with the ANFN controller is better than that of the conventional PID, even in the presence of noise and parameter variations.

Liang et al. [182] described an FNN control based on intended state programming. Its structure matched the motion of the moving characters, and simulation tests using an ROV with general detection were performed. As indicated in that research, it is exceedingly challenging to guide a NN's learning using a linear or nonlinear equation as a teaching signal because of the complexity of underwater vehicles. To guide the NN's learning by online programming the desired velocity, a new module dubbed "desired state programming" was introduced.

For the AUV motion control, a real-time control technique based on an FNN that did not need comprehensive knowledge of the dynamics of the controlled system was developed [175]. To help the FNN maintain a low track error and act as a teaching signal for direct network training, a real-time desired state planning (DSP) technique based on a sigmoid reference model was proposed. The results of simulation experiments conducted on the AUV-XX simulation, which used a modified BP as the learning algorithm, demonstrated the capability of the built multi-layered NN architecture.

The next section reviews system identification methods that have been used for nonlinear system dynamics and AUV applications, as system identification is the initial step in indirect adaptive control design. Hong et al. [183] studied the impact of buoyancy on an AUV's pitch and heave dynamics, including a proposal for a controller system that explicitly accounts for the impact. The authors suggested a condensed model for pitch dynamics that accounts for buoyancy of the AUV. They used field data from a closed-loop depth maneuver to determine the model parameters. With an inner pitch control loop and an outside depth control loop, they used a dual-loop control system.

In the field of formation control of various autonomous underwater vehicles (AUVs), [184] proposed the concept of formation learning control, which specifies a joint objective of distributed formation tracking control and learning/identification of nonlinear uncertain AUV dynamics. Extensive simulations were performed in this study to illustrate how successfully the proposed outcomes were performed.

To assure stable operation of deep-sea autonomous vehicles and minimize the energy consumption of system regulation, Wang et al. [185] proposed a real-time residual buoyancy identification approach and utilized it for the deep-sea driverless vehicle. Cui et al. [186] investigated the trajectory tracking challenge for a fully actuated AUV that moves in the horizontal plane. In this design, a discrete-time adaptive trajectory tracking control law for a fully actuated AUV was constructed using the NN approximation.

The challenge of obtaining exact location estimations was explored in [187] in discussion of the fact that AUVs mapping the distribution of multiple tagged fish have not yet been able to adjust their search trajectories. The authors proposed a solution for this issue in the form of payload control software (Synthetic Aperture Override, SAOVR), which enables the AUV to move with trajectories effective for determining the position of the tag from a synthetic aperture.

A three-dimensional (3D) path-following control issue for an underactuated AUV exposed to both internal and external uncertainty was addressed in [188]. The authors provide a two-layered system that combines heuristic fuzzy control with a 3D guiding rule to accomplish robust adaptive following along a predetermined path. The outcomes of the numerical simulation confirm the efficacy of the suggested control system.

The velocity synthesis technique was integrated by [189] into a self-organizing map (SOM)-based technique for commanding a group of AUVs to visit dynamic targets in a dynamic 3-D ocean current environment. A multi-AUV system uses the SOM-based technique to handle task assignment. The velocity synthesis method was applied to determine AUV's travel shortest routes. Chu and Zhu [190] proposed an adaptive sliding mode heading control solution for AUVs that consider the dynamics of the rudder.

Designing a self-adaptive fuzzy PID controller based on a nonlinear MIMO structure for an AUV was the main goal of [191]. This study verifies the full nonlinear model of the AUV that was developed using kinematics and dynamic equations and then treated in an open-loop system. Mamdani fuzzy rules are used in this designed controller to update the PID parameters, and SIMULINK is used to analyze the controller performance.

Intelligent collaborative navigation and control (CNaC) was employed by [192] to estimate the location and control of the AUV to complete tracking tasks. Yin and Wang [193] explored the use of a fuzzy-predictor-based AUV trajectory tracking predictive control system. The results show the viability and efficacy of the proposed control technique in terms of precision and stability. The authors performed a comparative simulation of the AUV trajectory tracking control in the scenario of an offshore platform's underwater operation. Herlambang et al. [194] successfully used the square root ensemble Kalman filter technique to predict the UNUSAITS AUV's nonlinear system trajectory with a high degree of precision.

For the AUV, [195] discussed a cutting-edge navigation control system supported by an intelligent velocity model. The proposed intelligent vehicle model is more adaptable than a conventional vehicle dynamic model and may provide speed when Doppler velocity log (DVL) data are inaccurate or erroneous.

6. UV System Identification Techniques

A system model is a crucial part of its design, analysis, and control. The system model is generally classified into two types: a physical or an input– output data model [196]. In the physical model, the physical properties, mathematical equations, and physical and mechanical laws are used to describe the system behavior in different manners, while the input– output model is developed based on the input– output data acquired from the system. In the physical modeling method, either the model perfectly describes the system and it is possible to develop it entirely from prior knowledge and physical insight or when some physical insight is known but some other model parameters need to be determined from observed data. Based on the prior knowledge of a system, models are classified as white boxes, gray boxes, and black boxes [188]. White-box modeling requires the complete dynamics of a system to be known prior to its use , and when this is achieved, the system identification problem becomes a parameter identification problem [199]. As the second method has no physical insight into the system, it uses the input–output data to develop the relationship between these data and, thus, system behavior, which is the superior method for system identification [200].

6.1. Classical Identification Techniques

Parameter estimation techniques, such as maximum likelihood estimators [201], the least squares method [202], Kalman filters [203], state space methods [204], and other robust estimation methods [203-205], are considered as white-box modeling.

Using the recorded data from on-board sensors, [206] developed an accurate approach to detect the unknown parameters of the roll dynamics of an AUV (offline). In this study, a PID controller was created using an initial approximation of the hydrodynamic coefficients, and the robustness of the controller was assessed using -analysis. The identification technique is developed on the basis of the reduction of one-step prediction error, and a nonlinear optimization problem is handled using PSO to improve accuracy and prevent distinguishing the output of the gyro. A 6-DOF simulation was run to assess the suggested approach. Abtahi et al. [207] developed fusion and identification methods to precisely compute the hydrodynamic coefficients of a UUV and design a high-performance controller. To assess the effectiveness of the proposed approach in this work, a 6-DOF simulation was run to ensure the precision of the proposed fusion and identification procedures. Hamid et al. [208] investigated the issue of AUV identification-based robust motion control. The unknown system parameters in this study are approximated using an adaptive parameter identifier, the gains of which are optimized using the particle swarm optimization (PSO) technique.

The effects of hydrodynamic forces and moments on the mobility and controllability of an underwater vehicle have been addressed by [200] using velocity and displacement observations together with an extended Kalman filter (EKF) estimator to determine its hydrodynamic coefficients.

Sabet et al. [210] described AUV 6-DoF dynamic model parameter identification, including viscous damping, body lift, and control input coefficients. These parameters have the greatest influence on the modeling error. In this study, the estimation filters were transformed unscented Kalman filter (TUKF), cubature Kalman filter (CKF), and extended Kalman filter (EKF). Due to its ability to resolve both the CKF nonlocal sampling problem and the EKF linearization problem, TUKF was determined to be the most accurate hydrodynamic model.

Min et al. [211] described a model identification technique for AUVs based on CFD calculations and the maximum likelihood algorithm. The proposed approach is adaptable and exhibits good convergence. In particular, the identification results of the turning force and torque parameters were remarkably consistent across various identification experiments, indicating that the proposed method can effectively extract the maneuvering characteristics of AUVs and thus contribute to the controller design of AUVs. Wadi et al. [212] derived the kinematic and dynamic models governing the motion of an AUV and identified its hydrodynamic parameters. The identification technique for AUV hydrodynamic properties is described in [213], and virtual hydrodynamics software and trajectory measurements of the state vector in various motion modes are employed.

Shen et al. [214] explored the path-following (PF) problem of an AUV, considering the vehicle’s speed profile as a supporting factor. This study attempts to accommodate path-priority following tasks by developing a multi-objective model predictive control (MOMPC) framework.

To explore the impact of free surface on the drag and lift coefficients of an AUV, [215] conducted a series of two-phase flow numerical simulations and compared the outcomes to those from a single-phase flow simulation in which there was no surface effect. Using a 1:1 scale model, the authors contrasted the numerical findings with the experimental findings obtained in a towing tank. The authors propose an adaptive identification technique for modeling uncertainties based on radial basis function (RBF) neural networks and the convergence of the control system attained by Lyapunov stability theory.

For crucial and expensive applications such as AUV, [216] emphasized the importance of using fault detection and isolation (FDI) approaches to achieve high levels of safety and productivity. The authors compared several methodologies used on over-actuated AUVs under a single fault condition (SFC) and only considered abrupt faults.

6.2. Intelligent Identification Techniques

White-box modeling might not be acceptable when it is difficult to establish the entire dynamics of a nonlinear AUV system because of the uncertainties and nonlinearities. A black-box model, which comprises two phases—model structure determination and model parameter calculations—relies entirely on the input–output data gathered from experiments and does not require any physical understanding of the dynamics of a plant.

A black-box modeling tool in the field of general control system engineering is the system identification (SI) approach [217]. Ljung [218] provided a thorough analysis of it, arguing that it was a huge topic with a variety of techniques that varied depending on the properties of the models to be estimated, such as linear, nonlinear, hybrid, and nonparametric, and that a few main aspects were sufficient to characterize the extensive area. It is advised that one should make sound decisions about model complexity, information in the data, and effective validation with the goal of generating a sustainable description.

Nonlinear system identification has gained popularity as a method for improving control design and performance. This is certainly relevant for systems with nonlinearity and unmodeled disturbances. Hassanein et al. [219] proposed an autogenerating fuzzy system modeling mechanism (AGFSM) with online adjustment capacity without considering any prior knowledge of the physical relationships within the system or the behavior of the system, the proposed mechanism offers a universal black-box modeling tool for any physical system, whether linear or nonlinear. The proposed process consists of two phases: one for producing structures and another for learning parameters. The phase that generates the structure depends on the entropy measure used to regulate the correctness of the model. The back propagation technique is used in the parameter learning phase of the supervised learning algorithms. Using input–output data, the proposed AGFSM method is used to create models for both linear and nonlinear systems. This method has been used to manage and identify the AUV in [220], which developed indirect adaptive controllers and system identification based on the hybrid neuro-fuzzy network (HNFN) approach for AUV. The HNFN technique is used for online identification and customization of the model and controller. The approach employs input–output data to generate a structure for the controller and optimal parameter adaption to achieve the required precision. Before conducting the trials, hardware-in-loop (HIL) simulations were used to validate the controller. The experimental outcomes reveal that the developed controller can control the AUV in a real situation and demonstrate its robustness.

In underwater vehicles, some clustering techniques (Mamdani, basic fuzzy, and TSK models) have been used to learn the internal organization of a given neuro-fuzzy (NF) architecture and create an effective NF system (NFS) [221]. The basic fuzzy rule has been translated into a three-layered structure in NEFCLASS, the Mamdani fuzzy rule into a five-layered structure in FALCON, and the TSK fuzzy rule into a six-layered structure in ANFIS. Computer simulations of the IRIS AUV classification challenge were used to validate the NFS performances.

On the basis of fuzzy system models with initially known model structures and parameters described in [222], two nonlinear system IDs were created. The findings of their simulation of the chaotic glycolytic oscillator demonstrated that they were greatly enhanced by the addition of linguistic descriptions. To address the issue of creating a fuzzy system for recognizing dynamic systems, the chaotic ant swarm (CAS) approach of chaotic optimization was developed. The CAS method was iterated at each learning time step to provide the best fuzzy system parameters based on fitness theory [223].

For AUV heading control, the system discussed in [224] used model predictive control (MPC) with a GA-optimized controller. The controller then computed a series of controlled modifications to optimize the future behavior of the AUV using a class of algorithms. Naeem [225] provides a thorough analysis of earlier work on MPC-based underwater vehicle control systems, the background of this method, and a new method for applying MPC that was used on the Hammerhrad AUV.

The total least squares (TLS) and ordinary least squares (OLS) techniques have been used to estimate a 3-DOF decoupled finite-dimensional plant model of an underwater vehicle [226]. The TLS estimate that best matched the dynamics of the system would perform as well as or better than the best OLS estimate for translational DOFs, according to laboratory tests on the JHUROV.

Hegrenses et al. [227] used OLS to identify the surge, heave, and heading of the Hugin 4500 AUV coupled dynamic plant model and discovered a partial set of hydrodynamic mass parameters, hydrodynamic drag terms, and a few quadratic drag terms related to the coupling between the lateral and heading directions. The authors evaluated the coupled and decoupled models and observed that the coupled model had a smaller error between the velocity data from the numerical simulation and the velocity data from the experiments.

Tiano et al. [228] used the observer Kalman filter identification (OKID) approach to develop linear discrete-time multi-variable models of an uninhabited surface vehicle (USV). In addition, various system identification passes have been carried out [207] to mimic the dynamic response of a USV and stimulate system modes. The linear time-invariant plant model and the related pseudo-Kalman filter were identified using the OKID approach. A human pilot operated the catamaran on nearly straight-line runs to obtain the system identification input, and the fourth-order discrete time model created from the data produced good prediction outcomes.

AUV dynamics disturbances were predicted using the auto regression (AR) model [229]. Numerous methods have typically been employed to estimate and modify underwater vehicle model parameters offline [230-233].

Moreover, applying current techniques to numerous complicated systems with nonlinear time-varying characteristics still involves several challenges. Using a fuzzy model to represent the static and/or dynamic behavior of these systems is a potential solution to these problems. To analyze the motion control of the GARBI AUV, [234] produced a system identification model based on two methodologies. The first involved using the step/frequency response method to determine the transfer function of the vehicle’s open-loop (local) models, and the second involved fuzzy modeling of a group of open-loop linear models that each locally approximated the original nonlinear system around various operating points while a supervisory scheduling system determined which specific local open-loop linear model was pertinent. However, it has frequently been possible to combine mathematical tractability with the physical relevance of the model structure and parameters using linear models (for linear or very linear systems) [235].

Several NN structure types for detecting AUV systems have been investigated in [236-239]. Single degree of freedom neural network identification (SDFNNI) for each degree of freedom in Twin Burger 2. is developed. Twin Burger 2 was first built in 1994 as the twin of Twin Burger 1, which was built in 1992. Coupled Model NN Identification, which [240] devised for a MIMO system, is an extension of Ishii's model for the coupled mode (CMNNI). In addition to the simulation findings from the proposed SDFNNI and CMNNI, several tests and collection of the essential training data sets were performed. The NNI was then trained in both the single degree of freedom and linked modes.

Van De Ven et al. [241] explained how to use a NN to find models for underwater vehicles. The damping of an underwater vehiclewas identified using NNs, and the performance of the NN-based model was demonstrated in simulations using the feed-forward controller. Rather than applying a NN in parallel with the known model to account for unmodeled phenomena in a model-wide manner, knowledge regarding the various parts of the model was used to apply the NN for those parts that were most uncertain. In addition, the types of NNs, their use in various industrial applications, and further information on using NNs to find nonlinear models are discussed. Using training data acquired from actual trials, [242] presented a dynamic model that used artificial neural networks (ANNs) for the construction of a 5-thruster underwater vehicle. The thrusters' input voltages, UUV variables, and the resulting velocity vector were used to describe the dynamic model, and the results were accurate and reliable.

Hassanein et al. [243] presented the online system identification of AUV dynamics to derive the coupled nonlinear dynamic model of AUV as a black box. Instead of using a mathematical model with hydrodynamic parameter estimation, this black box has an input–output relationship based on online adaptive fuzzy model and adaptive neural fuzzy network (ANFN) model techniques to overcome the uncertain external disturbance and difficulties of modeling the hydrodynamic forces of the AUVs. The parameters of the models were changed using the back propagation technique depending on the difference between the identified model and the actual output of the plant. Because of the fuzzy rules, the proposed ANFN model employs a functional link neural network (FLNN). As a result, the ANFN model's output is a nonlinear mixture of input variables. The AUV is guided and controlled using a fuzzy control system that employs both adaptive and mathematical models. The simulation results demonstrate the superiority of the proposed adaptive neural fuzzy network (ANFN) model in properly tracking the behavior of the AUV in the presence of noise and disturbance.

The advantages of both NNs and fuzzy systems can be demonstrated in hybrid NN fuzzy systems. While fuzzy logic offers a structural framework that exploits these low-level capabilities, NNs offer fundamentally low-level learning and computational ability to handle massive volumes of data. As a result, integrated systems are more effective at simulating nonlinear dynamic systems than pure fuzzy systems or NNs [244-246]. As a result, an FNN that combines the benefits of a fuzzy system with NN has great potential for use in controlling the motion of AUVs [247].

Neuro-fuzzy modeling approaches in identifying the Ocean Voyager AUV proved their effectiveness [248]. In addition, the nonlinear SI based on Neuro-Fuzzy enhanced the controller performance and produced a strong fault-tolerant behavior [249].

Cervantes et al. [250] presented a neuro-fuzzy system that employs differential neural networks (DNNs) because of Takagi–Sugeno fuzzy inference rules. The proposed technique helps identification, and the proposed system overcomes several shortcomings, such as the black-box character of the neural network and the challenge of locating appropriate membership functions for fuzzy systems.

A system model based on an adaptive strategy for determining the ideal values of model parameters was developed using alternative techniques. In [251], fuzzy modeling of dynamic systems employing OBF-fuzzy for the representation of the model's input signals is provided. Alci [252] proposed a Laguerre network-based fuzzy (LNBF) system model that combines orthonormal Laguerre bases with a static nonlinear fuzzy system. ANFIS modeling, Oliveira's OBF-fuzzy technique, and the traditional Sugeno-type fuzzy modeling were used to compare the performance of the suggested modeling approach. Three benchmark issues were simulated, and the results showed that the presented LNBF model produced more accurate models.

Hassanein et al. [253] introduced a novel identifier scheme, which is a semi-serial-parallel model, to improve the online identification process in the presence of noisy data for the identification of nonlinear systems with disturbances. To improve the accuracy and generalize the model to handle different datasets, the differential evolution technique is employed, whereby the parameters of the model are suitably tuned using the evolutionary technique. The proposed mechanism is used and compared with the classical Sugeno, adaptive network-based fuzzy inference system (ANFIS) modeling, and Laguerre network-based fuzzy system for the identification of a nonlinear benchmark problem. In addition, the proposed technique is used to model a rotary wing unmanned aerial vehicle (UAV) from real test input–output data. The modeling performance and generalization capability are superior to those of our method.

Van De Ven et al. [254] presented a method for creating TSK models using fuzzy genetic modeling. There were two stages to the model-building process: structure learning and parameter learning. Genetic-based structure learning (GBSL) was used to learn the structure, and the GBPL method was used to refine the parameters of the initial model. Shen and Chouchoulas [255] proposed a method that combined a crude set-assisted feature reduction technique with a fuzzy rule induction procedure. Salehfar et al. [256] presented learning techniques for the automated development of fuzzy rules. These learning algorithms learn/optimize the system's I/O behavior and provide fuzzy rules based on learning vectors.

An alternate method for synthesizing the Takagi–Sugeno fuzzy logic controller with a smaller rule base was presented in [257] using the Multi-objective Genetic Algorithms-based Genetic Approach to Fuzzy Supervised Learning algorithm, or GAFSL. Neuro-fuzzy state estimation has been combined with fuzzy local linearization (FLL), a practical "split and conquer" strategy for handling challenging issues such as data-based nonlinear process modeling [258].

Support vector machine technology, which is developed from machine learning technology, was used in [259] to identify the dynamic parameters of an AUV, and simulations were used to confirm the method's viability. To determine the surge-related hydrodynamic characteristics of a prototype AUV constructed by the Institute of Undersea Technology (IUT) at National Sun Yat-sen University, [260] used laser line scanning for hydrodynamic parameter identification (LSHPI). This work presents the experimental findings and the specifics of using the LSHPI to derive surge-related hydrodynamic parameters.

7. Conclusion

This article provides a comprehensive literature review of underwater vehicles and their main application areas. It also covers the main challenges of electrical, communication, and system control and modeling for such applications. This article emphasizes the importance of modeling and system identification and the controllers used in UUVs to understand the need for control systems for AUVs due to the non-linearity and uncertainty of the modeling. This assumes that a model-based adaptive controller using intelligent techniques is the best choice for controlling a UUV. This article also compares the design challenges of UUVs with those of unmanned aerial vehicles (UAVs) and proposes validating the controller against these types of vehicles. Future work includes introducing new control and guidance algorithms for various maneuvers of the AUV based on computer vision, machine learning, and artificial intelligence systems. It also includes designing the AUV system based on multi-agent techniques that enable the AUV system to cooperate with UAV systems to expand its applications.

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