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Review

A Review of the Various Control Algorithms for Trajectory Control of Unmanned Underwater Vehicles

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Abstract: Unmanned underwater vehicles (UUVs) have become increasingly popular in recent years due to their use in various applications. The motivations for using UUVs include the exploration of difficult and dangerous underwater environments, military tasks in mine detection, intelligence gathering and surveillance, the inspection of offshore oil and gas infrastructure in the oil and gas industry, scientific research for studying marine life, and the search and rescue of missing persons or submerged airplanes or boats in underwater environments. UUVs offer many advantages in achieving the desired applications with increased safety, efficiency, and cost-effectiveness. However, there are also several challenges associated with their communication, navigation, power requirements, maintenance, and payload limitations. These types of vehicles are also prone to various disturbances caused by currents of the ocean, propulsion systems, and unmolded uncertainties. Practically, it is a challenging task to design a controller that will ensure optimal performance under these conditions. Therefore, the control system design is of prime importance in the overall development of UUVs. Also, the UUV controller receives input from different sensors, and the data from these sensors are used by the controller to perform different tasks. The control systems of UUVs should take into account all uncertainties and make them stable so that all sensors can perform optimally. This paper presents a complete review of different control system design algorithms for UUVs. The basic logic designs of several control system algorithms are also presented. A comparison is made based on reliability, robustness, precession, and the ability of the controller to handle the nonlinearity that is faced by UUVs during their missions. Simulation and experimental results are thoroughly studied to gain insight into each algorithm. The advantages and disadvantages of each algorithm are also presented, which will facilitate the selection of a suitable algorithm for the control system design of UUVs.

Keywords: UUV control system; model predictive control; adaptive control; $H\infty$ control; fuzzy control; PID control; backstepping control

Citation: Bashir, A.; Khan, S.; Iqbal, N.; Bashmal, S.; Ullah, S.; Fayyaz; Usman, M. A Review of the Various Control Algorithms for Trajectory Control of Unmanned Underwater Vehicles. *Sustainability* **2023**, *15*, 14691. https://doi.org/10.3390/su152014691

Academic Editor: Claudia Casapulla

Received: 1 August 2023
Revised: 9 September 2023
Accepted: 18 September 2023
Published: 10 October 2023

1. Introduction

Underwater vehicles are becoming popular in the research community due to their wide variety of uses. Studies related to these types of vehicles started in the 1960s and are continuously being improved by the addition of the latest technology. During the decade of the 1970s, universities started making prototypes of these vehicles [1–3]. Nowadays, UUVs are considered a force enhancer on the defense side of the nation. UUVs are considered primary military equipment for the anti-submarine battlefield [4]. The main reason behind their popularity is that UUVs do not risk the precious lives of human beings during dangerous operations [5–9]. Scientists can also use them in order to model and understand natural phenomena occurring underwater and to identify the effects of human actions on marine life [10,11]. A considerable amount of research has been carried out on UUVs [12–17]. UUVs can also be used for the inspection of a ship's hull [18]. Some commercial companies use them to explore natural resources like oil and gas and build underwater structures [19]. They are also used to clean the ocean by collecting marine debris [20]. Advancements in navigation, control, communication, sensors, and other fields have played a vital role in the human understanding of seas and oceans. The field of oceanography is also being revolutionized by using UUVs. Compared to a single UUV, a fleet of UUVs can perform a task more efficiently and effectively [21]. Another type of UUV is the glider, which is self-propelling and can be used for ocean surveys [22]. The main applications for UUVs are in areas such as surveillance and intelligence, mine detection, underwater battlefields, ocean surveys, delivery agents for payloads, and wireless network nodes for communication. Underwater wireless communication has numerous advantages, and UUVs play an important role in this area. UUVs will act as mobile nodes in the ocean observation network, as they are flexible and reconfigurable. The wireless communication of UUVs will also be helpful for the remote control of the offshore industry. UUVs can also act as nodes or repeaters for the wireless communication of submarines with the base station. The cybersecurity industry's efficiency should be analyzed when adding security features to wireless communication systems. Multi-agent systems can be used to solve complex problems by dividing the problem into smaller tasks. Multiple inputs, such as the history of an agent's actions and interactions with its neighboring agents, are used by multi-agent systems [23]. Wang et al. [24] used a combination of DEA window analysis along with the Malmquist index approach to assess the efficiency of the cybersecurity industry. The launch and recovery system of the UUV is also considered critical. Different schemes are used for the launch and recovery of UUVs. Some schemes utilize the onboard crane of the mothership for this purpose. In some cases, UUVs are deployed through submarines. In the case of submarines, the deployment is somewhat easier, but the recovery of the UUV is very challenging [25].

The major problems faced during the launch and recovery of UUVs are the risk of the cable being screwed into the propeller, space constraints in marine vessels, which require that the system be small in order to occupy less space on the mother platform, and the weight limitation of the onboard crane of the mother ship. UUV designers should also consider the weight limitation of the vehicle's launch and recovery system. Unmanned underwater vehicle design is a very challenging task. The designers must take into account different scenarios that will be faced by the UUV during its operation. The UUV's design mainly consists of three steps, i.e., hull design, propulsion system design, and control system design. The hull of the UUV is designed to keep the operational depth and stability requirements in view. The hull's thermal signature is also of key importance because it helps the UUV to be in a stealth state during operation [26]. The hull can be costly if manufactured from costly materials. In order to reduce the cost, PVC pipes can be used. A major issue in designing the hull of the vehicle is its waterproofing because there will be hull openings for cables and, in some cases, for pipes. A hull opening can cause water ingress under the high pressure of water at depth. One remedy to this issue is to use glands with the proper ingress protection rating. These glands are used as cable passages from the pressure hull to the free-flooded area. Another way to mitigate this issue is to use bulkhead connectors. These connectors are found to be more effective than glands because the cable can be removed from the external side as needed. These connectors are available in the international market with various pressure ratings. During the design of a UUV, a User Requirement Document (URD) dictates the operational depth of the vehicle, which, in turn, allows the designer to choose connectors with appropriate ratings [27].

The UUV's power system is also of critical importance, especially with the latest research on renewable energies, which will be the primary power source in the next generation of UUVs. As mentioned above, the UUV's weight is the prime concern of designers because it will affect the propulsion power and the launch and recovery system. Designers are always looking for weight reductions. Typical lead–acid batteries are very bulky and require more space; hence, they are not ideal for use in UUVs. Moreover, the energy density and depth-of-discharge limitations are also major drawbacks of lead–acid batteries. Li-ion batteries are lighter than lead–acid batteries, and their energy density and depth of discharge are comparatively higher than those of lead–acid batteries. Another great advantage of Li-ion batteries is that they have a high charging rate. Some manufacturers allow charging rates of up to 1 C (normally 0.1 C for lead–acid batteries). These features of Li-ion batteries make them an ideal candidate for UUV power systems, but Li-ion batteries are costly as compared to lead–acid batteries and require a sophisticated battery management system. As Li-ion batteries have small dimensions and high charge densities, special care should be taken to avoid the short circuiting of the batteries. One way to resolve this issue is to use a watertight container for the batteries so that in an incident of water ingress, the water should not reach the batteries [28].

Based on the necessity of efficient control algorithms for the control of UUVs, this paper presents a complete review of different control system design algorithms for UUVs. A comparative study is performed based on reliability, robustness, precession, and the ability of the controller to handle the nonlinearity that is faced by UUVs during their missions. Simulation and experimental results are thoroughly studied to gain insight into each algorithm. The advantages and disadvantages of each algorithm are also presented in tabular form, which will facilitate the selection of a suitable algorithm for the control system design of a UUV.

2. Methodology

The control system of an unmanned underwater vehicle acts as the brain of the system. Various applications require efficient control system design for their operation [29–33]. The vehicle's security and reliability depend on the control system. It is very important that this system be given utmost attention while designing the vehicle. As shown in the flowchart in Figure 1, the current study starts with a discussion of the problem statement that necessitates the need for an effective control system design for UUVs. A literature review of modern and old techniques was carried out, and only the most suitable, reliable, and cost-effective techniques are explained in detail. A comparative analysis is presented in Section 4 that compares the various control strategies, and the pros and cons of all of the discussed algorithms are given in this section. Finally, the literature review and the comparative analysis are concluded in the Section 5.

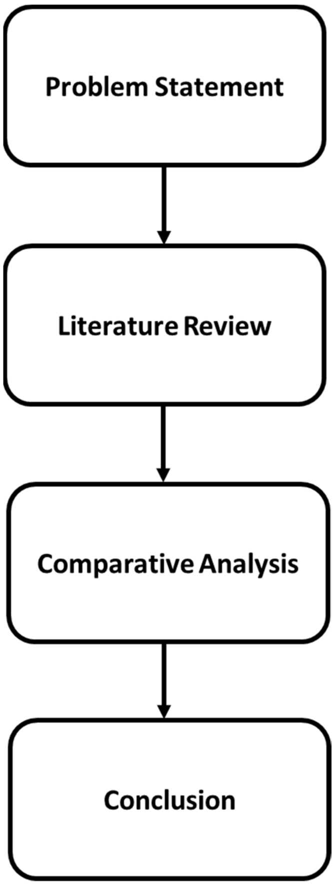

Figure 1. Flowchart of the study process.

3. UUV Control System and Control Algorithms

3.1. UUV Control System Design

The control system of a UUV is considered the backbone of the vehicle. Control system design for multiple agents has also become popular in recent times [34]. Path planning with safety and low energy consumption is key in UUV applications [35]. The mathematical modeling of a UUV is a tedious task because a UUV is highly coupled, and it is also highly nonlinear. Moreover, a UUV is subjected to complex interferences and disturbances [36]. The modeling of the various uncertainties associated with the operation of the UUV and the coupling of various equations make the system highly nonlinear. Therefore, control system design is the most challenging task in the overall design of the vehicle because it has six degrees of freedom, which is extremely nonlinear. Forces and torques applied to the UUV are also designed using a nonlinear dynamic controller. The main reason for using a nonlinear model is that one model will cover the whole UUV's flight envelope, instead of linearizing the model about many working points [37]. One of the major problems of UUVs is that their payload varies during their operation. Due to this change in the payload, the total mass of the vehicle, as well as the center of gravity (COG) and buoyancy of the vehicle, changes. This variation is the main cause of the poor performance of linear controllers like PID controllers, which have a fixed gain based on the basic dynamics of the vehicle. Linear controllers are not able to tackle disturbances and may have unwanted oscillations. If the oscillations are sufficiently high, they can interact with the outputs of the vehicle sensors, especially with visual sensors, resulting in poor visual images. The basis block diagram of the UUV control system is shown in Figure 2.

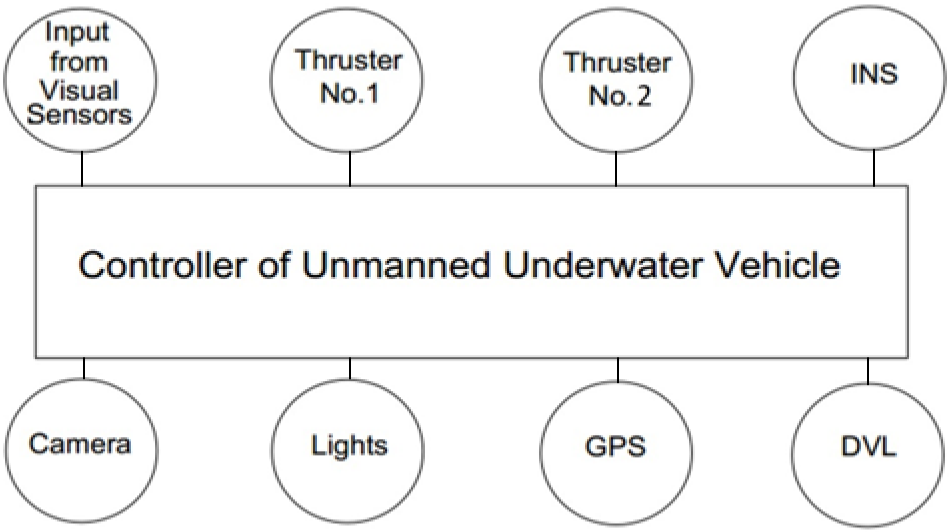

Figure 2. Layout of UUV control system elements.

The control system of the UUV should take into account all uncertainties and make them stable so that all sensors can perform optimally. The requirement of the controller is that it has the capability of educating itself and can handle the changes that occur in the UUV during the mission. In Figure 2, it is shown that the UUV controller receives input from different sensors, and the data from these sensors are used by the controller to perform different tasks. These types of vehicles have not been given considerable attention like aerial or land-based autonomous vehicles and, therefore, need further research [38].

Vardhan et al. [39] studied the design optimization of the UUV hull. Bayesian optimization (BO) was selected for optimization purposes. Two different cases of the UUV design were used to validate the execution of their tool. Vardhan et al. [40] studied the technique for the optimal universal hull design of autonomous underwater vehicles having the least resistance. Computational Fluid Dynamics (CFD) simulations with an AI-based optimization algorithm were utilized in their study. It was concluded that the design that gave optimal results under high-velocity and high-turbulence conditions would give near-optimal results across a wide range of velocity and turbulence conditions. Lei et al. [41] proposed a multisource information fusion-based environment perception and dynamics model for underwater vehicles in irregular ocean environments. A real-time dynamic model of the underwater vehicle was developed by combining multisource information, environmental perception, and sensor observations. A novel underwater glider was also analyzed through experiments during their study. An et al. [42] presented a review of intelligent path-planning technologies for UUVs. The characteristics of the used algorithms in the present underwater vehicle path planning were discussed in detail. Path-planning technologies for UUVs were summarized in their study, and the final development direction was also prospected.

Szlęg et al. [43] presented the importance of using a simulated environment for testing an autonomous vehicle's performance. A customized framework was developed using Unity3D to simulate different aspects of underwater operation, such as buoyancy and caustics. Bingul et al. [44] investigated the model-free trajectory-tracking control problem for an autonomous underwater vehicle (AUV) under different conditions, including ocean currents, external disturbances, measurement noise, etc. Their comparative study results showed that PID with a PD feedforward controller results in an effective trajectory-tracking control performance and good disturbance rejections for the entire trajectory of the AUV. Cai et al. [45] studied the semi-supervised visual tracking of marine animals with the help of autonomous underwater vehicles. The real-world performance was evaluated by using a semi-supervised algorithm on an autonomous underwater vehicle to track marine animals in the wild. Ahmed et al. [46] performed a survey of traditional and artificial-intelligence-based estimation methods for hydrodynamic coefficients of autonomous underwater vehicles. The pros and cons of the different methods, with their literature results and their effectiveness for autonomous underwater vehicles, were discussed in their study.

Yao et al. [47] studied the vision-based environmental perception of unmanned underwater vehicles. Two schemes were proposed in their study, i.e., the UNDERWATER-CUT model for underwater image enhancement and the YOLOv5s model for object detection. Experiments were conducted on visual perception and obstacle avoidance, which showed that the proposed methods could be applied to a UUV in a complex underwater environment. Liu et al. [48] presented a review of the fault diagnosis of UUVs. The findings in the literature from the past three decades were classified and analyzed in their study. The task, capability, and component layers of fault diagnosis for the specific control structure of the UUV were defined, and finally, a summary of some worthwhile issues to be solved was presented. Tijjani et al. [49] presented a review of the conceptual designs and theoretical frameworks of the main control schemes from the literature on UVVs. Detailed experimental-based comparative studies of the available control schemes were presented in their study. They also performed experimental scenario tests on the Leonard UUV under different operating conditions. Finally, they pointed out potential investigation gaps and future research trends. Hua et al. [50] focused their study on the trajectory-tracking control problem of UUVs with position–velocity constraints (PVCs) and on modeling the uncertainties. They designed a novel adaptive position–velocity-constrained tracking controller for UUVs. Finally, they presented both simulation and experimental results to validate the effectiveness and practicability of the proposed control scheme.

Li et al. [51] addressed the problem of interval velocity estimation for UVVs that are subjected to multiple model uncertainties. They used the $H\infty$ approach in the design of the interval observer to attenuate the effects of uncertainties. Their simulation results demonstrated the effectiveness of the proposed algorithm. Kilavuz et al. [52] carried out numerical and experimental investigations of the flow characteristics of UUVs with a commonly used Myring profile. They used CFD and the particle image velocimetry (PIV) technique under the influence of a free surface. They found that the CFD approach was in excellent agreement with PIV measurements when simulating the essential unmeasured flow features required in the research and development process of UUVs. Konoplin et al. [53] presented the development of a control system for multilink manipulators on UVVs. Their system was based on an improved method that utilized point clouds received from machine vision systems (MVSs). They developed the system in the C++ programming language. Their results showed the high efficiency of the system, both in processing sensor information and in providing the dynamic control of the movements of UUVs. Bibuli et al. [54] analyzed the UUV propulsion model for motion control. They designed a procedure for small-size, low-speed vehicles. They finally described a control system design based on the acquired dynamic characterization.

Sands et al. [55] studied the control of DC motors to guide UUVs. They used deterministic artificial intelligence (DAI) to control DC motors used by UUVs directly by comparing the performance of three state-of-the-art nonlinear adaptive control algorithms. They found that DAI closely follows a challenging square wave at each switch of the square wave in comparison to all other state-of-the-art methods. Manzanilla et al. [56] focused their study on the design of a robust control algorithm for the three-dimensional trajectory tracking of a 4-degree-of-freedom UUV. They used Lyapunov theory in order to verify the stability of the closed-loop system. Their results showed that the proposed controller converges to the desired references and causes a high reduction in the chattering effect on the input control. Yar et al. [57] designed a low-cost UUV. They proposed a basic software, electrical, and mechanical hardware design for the designed UUV. They used a PVC structure for the UUV, a Raspberry Pi as a processor, and bilge pumps as propellers. Their designed UUV carries out different tasks, i.e., goal post-detection, color detection, and obstacle detection based on template matching. They also used a special waterproof container to protect the whole circuitry. Kutzke et al. [58] presented a case study on UUVs based on digital twin development. They established a general procedure for finding a set of priority-based system components needed for digital twin development. They mentioned that their technique is not limited to use in UUVs, but rather, it can be applied to any system targeting cost and reliability.

The control systems of UUVs require knowledge of a number of disciplines, which include control system theory, inertial navigation systems (INSs), vectorial kinematics and dynamics, and hydrodynamics. As mentioned above, the main trouble in UUV control is its parametric uncertainties, i.e., added mass, hydrodynamic coefficients, and nonlinear and coupled dynamics [59].

3.2. Governing Equations

In order to design an efficient controller for UUVs, it is necessary to study and understand the motion and forces, specific position, and coordinate systems of UUVs. Mostly, the two coordinate systems shown in Figure 3 are required for the modeling of UUVs [60]:

a. Ground Coordinate System (E-ξηζ);
b. Vehicle Coordinate System (O-xyz).

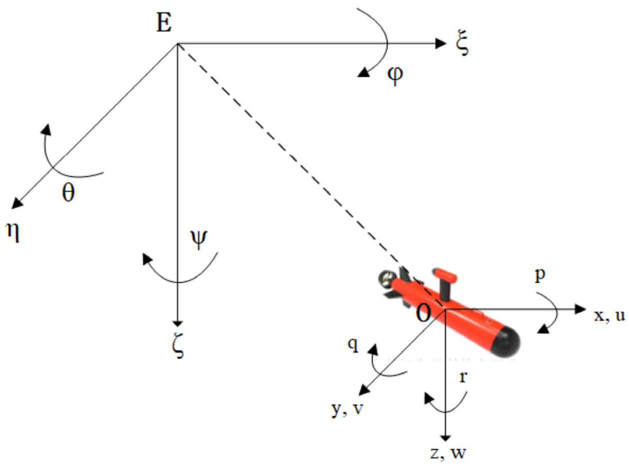

Figure 3. Coordinate systems of UUVs [60]. Reprinted from Li et al. (2023).

The motion of the UUV in the water is six-degree-of-freedom spatial motion, namely, heave, roll, pitch, surge, yaw, and sway [61]. The position of the vehicle can be expressed by Equation (1):

$$\eta = [x\ y\ z\ \varphi\ \theta\ \psi]^T \tag{1}$$

Similarly, the vector for the velocity is given by Equation (2):

$$v = [\ u\ v\ w\ p\ q\ r]^T \tag{2}$$

UUV motion will follow Equation (3):

$$\dot{\eta} = J(\eta)V \tag{3}$$

The six-DOF equations of the UUV are given in Equation (4):

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \mathrm{v}\cos\theta\sin\psi + \mathrm{v}(\cos\theta\sin\psi + \sin\varphi\sin\theta\cos\psi + v(\sin\varphi\sin\psi - \cos\varphi\sin\theta\cos\psi) \\ v\sin\theta - v\sin\varphi\cos\theta + v\cos\varphi\cos\theta \\ -v\cos\theta\sin\psi + v(\cos\varphi\cos\psi - \sin\varphi\sin\theta\sin\psi + v(\sin\varphi\cos\psi + \cos\varphi\sin\theta\sin\psi) \\ \omega - \omega\cos\varphi\tan\theta + \omega\sin\varphi\tan\theta \\ \omega\cos\varphi + \omega\sin\varphi \\ (-\omega\sin\varphi + \omega\cos\ \varphi)/\cos\theta \end{bmatrix} \tag{4}$$

where $\dot{x}$ is the translational velocity in the x-axis direction, $\dot{y}$ is the translational velocity in the y-axis direction, $\dot{z}$ is the translational velocity in the z-axis direction, $\dot{\varphi}$ is the angular velocity about the x-axis, $\dot{\theta}$ is the angular velocity about the y-axis, and $\dot{\psi}$ is the angular velocity about the z-axis.

In order to simplify the above-mentioned equation, two dimensions are considered at a time [62], which reduces the equation to Equation (5):

$$\dot{\eta} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} \tag{5}$$

Using the above-mentioned equations as a mathematical model for the UUV, different control algorithms can be applied for control system design [63]. The control algorithms discussed in this study are model predictive control (MPC), adaptive control, $H\infty$ control, fuzzy control, PID control, and backstepping control.

3.3. UUV Control Algorithms

3.3.1. Model Predictive Control (MPC) Algorithm

Various control algorithms are described in the literature for UUVs. Ding et al. [64] used a model predictive control (MPC) algorithm for the motion control problem of UUVs. MPC is an innovative control technique in which the system is controlled by satisfying a set of constraints. The biggest advantage of MPC is that, in this technique, the current time slot is optimized while taking future time slots into account. The motion control performance of UUVs can be improved in real time by using MPC. Figure 4 shows the schematic diagram of an MPC algorithm [65]. The basic idea of this type of controller is to forecast the entire system's output based on data from past and future inputs. This controller guarantees that the UUV will follow the chosen trajectory swiftly and efficiently. MPC is based on three principles, i.e., rolling optimization, feedback correction, and predictive modeling [66].

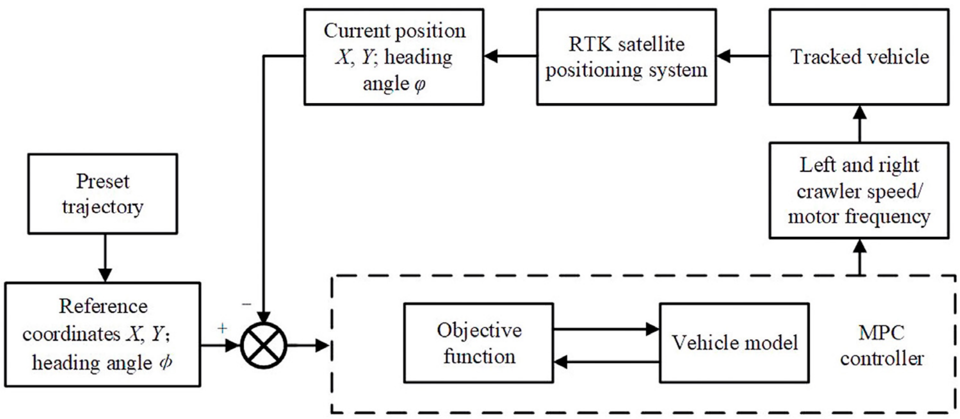

Figure 4. Schematic diagram of MPC algorithm [65]. Reprinted from Wang et al. (2023).

For the motion of UUVs, as defined by Equation (5), the control input is defined by Equation (6):

$$\mathrm{v} = [\,u\ v\ r]^T \tag{6}$$

whereas the state quantity is defined by Equation (7):

$$\eta = [x\ y\ \ \psi]^T \tag{7}$$

The above two equations are used in Equation (3) to obtain the linear error model with the given reference trajectory. Ding et al. [64] solved the equation and transformed it into a quadratic relation, given below in Equation (8):

$$J(k) = \sum_{i=1}^{Np} \left\| \eta(k+i|t) - \eta_{ref}(k+i|t) \right\|_Q^2 + \sum_{i=0}^{Nc-1} \|\Delta v(k+i|t\|_R^2 \quad (8)$$

Np represents the time-domain prediction, Nc specifies the control domain, and the weights of the matrices are given by Q and R. Similarly, the difference between speeds at previous times is given by $\Delta v(k+i|t)$.

Wei et al. [67] applied Event-triggered Nonlinear Model Predictive Control (ENMPC) to an unmanned underwater vehicle. The controller designed by them was able to handle disturbances of the sea and was able to keep the vessel tracking its trajectory with high accuracy. They used a five-degree-of-freedom model for their system and applied NMPC to it. Ullah et al. [68] presented a robust global fast terminal attractor based on a full-flight trajectory-tracking control law for the available regular form, which is operated under matched uncertainties. The proposed design improved the performance of the controller in full flight and also reduced the noise in the system's velocities. Chen et al. [69] proposed a method to identify and attack multi-UUV groups. The proposed method reconstructed the network structure of the formation according to its space–time trajectory, and the importance of nodes was determined based on network structure entropy.

3.3.2. Adaptive Control Algorithm

Nie et al. [70] presented an adaptive control system for UUVs. Their research consisted of a method that restricts the UUV to known landmarks with the help of onboard sensors for inertial navigation. The control algorithm presented by them was based on adaptive control with bound estimation. This algorithm allowed them to overcome uncertainties in the system dynamics and its working conditions. The control system diagram of the adaptive control algorithm is shown in Figure 5 [71].

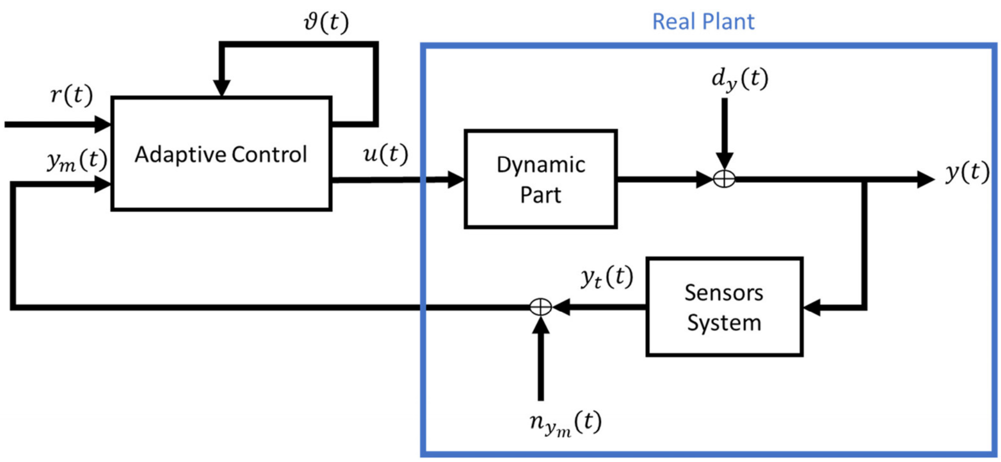

Figure 5. Block diagram of adaptive controller [71]. Reprinted from Dini et al. (2020).

The controller used basic vector equations of UUVs, and the derived equations for the above-mentioned controller are given below in Equations (9) and (10):

$$K_i = \left(\theta_i\, \hat{e}\, \underset{\sim}{\phi_i^t}\right) / (||\, \hat{e}\, ||\, ||\, \phi_i\, ||) \; ------ \text{for } ||\hat{e}\, ||\, ||\, \phi_i\, || > \delta_i \quad (9)$$

$$K_i = \left(\theta_i\, \hat{e}\, \underset{\sim}{\phi_i^t}\right) / (\delta_i) \; ------------------ \text{for } ||\hat{e}\, ||\, ||\, \phi_i\, || \leq \delta_i \quad (10)$$

where ϕ_i and θ_i show the angular position with respect to the x- and y-axes.

Nie et al. [72] presented their results by comparing them with simulation and experimental results. Figure 6 shows the trajectory followed with the adaptive controller [73].

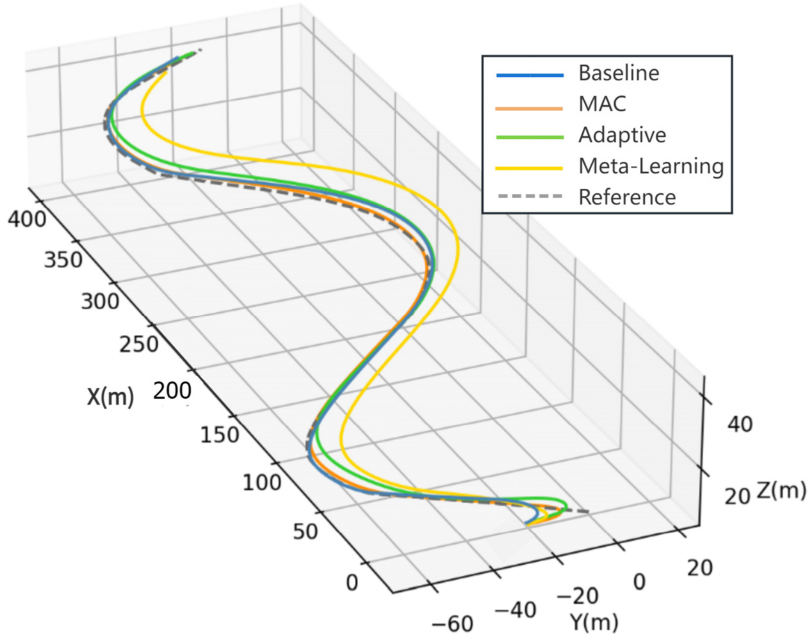

Figure 6. Trajectory followed with the adaptive controller [73]. Reprinted from Zhang et al. (2023).

The results obtained in their work do not guarantee asymptotic stability, but the advantage is that the tracking errors are bounded by small numbers depending on δ_i.

3.3.3. *H*∞ Control Algorithm

Gavrilina et al. [74] applied an $H\infty$ control algorithm to the UUV to make it stable. This control algorithm is used to make the system stable and improve its performance. In this algorithm, first, the control problem is expressed as a mathematical optimization problem, and then a controller is obtained, which solves the respective optimization problem. In the case of a UUV, the obtained stability condition is dependent on the roll inclination of the vehicle. Moreover, the roll stability is independent of other orientation angles. It was concluded that there is a low sensitivity to disturbances from the other two states, i.e., yaw and pitch. The mathematical model of the UUV used in their study is based on a body-fixed frame design and is given in Equation (11).

$$W_{UUVi} = \frac{W_i(p)}{\tau_i\ (p)} = \frac{K_{UUVi}}{\tau_{UUVi}\ p + 1} \quad (11)$$

Furthermore, the model is described by Equations (12) and (13):

$$T_{UUVi} = \frac{i_i - A\omega_i}{-Aw_i - 2\ A|_{\omega i}|_{\omega_i}\omega_i^*} \quad (12)$$

$$K_{UUVi} = \frac{1}{-Aw_i - 2\ A|_{\omega i}|_{\omega_i}\omega_i^*} \quad (13)$$

where ω_i^* is the linearization parameter, and p is the Laplace parameter.

Similarly, the propulsion transfer function is given by Equation (14):

$$W_{pi} = \frac{\tau_i(p)}{U_i\ (p)} = \frac{K_{Pi}}{T_{pi}p + 1} \qquad i = x, y, z, \quad (14)$$

where K_{Pi} and T_{pi} are the propulsion gain and the time constant, respectively. The voltage applied to the propulsion system is defined as U_i. Combining Equations (11) and (14), the mathematical model of the UUV was obtained by the researchers and is given by Equation (15):

$$W_i = \frac{\omega_i(p)}{U_i\ (p)} = W_{pi}(p)W_{UUVi}(p) \qquad i = x, y, z, \tag{15}$$

where ω_i is the angular velocity vector of the UUV about the axes O_x, O_y, and O_z, and U_i is the control signal. In Figure 7, the basic block diagram of the $H\infty$ controller is given [75].

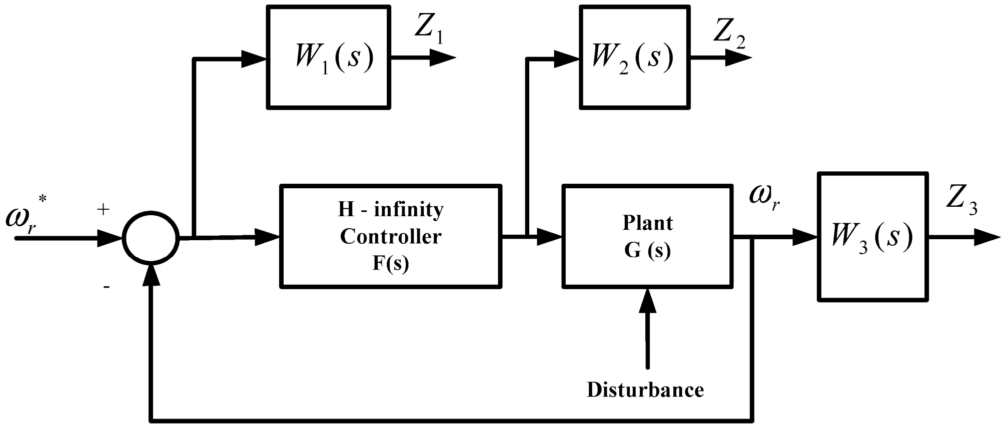

Figure 7. Block diagram of $H\infty$ control design [75]. Reprinted from Diab et al. (2019).

In the above block diagram, the external disturbances and control variables are given.

3.3.4. Fuzzy Control Algorithm

Fuzzy logic was introduced for the first time in 1965, and afterward, its use for control systems increased quickly. In this control algorithm, analog inputs of the system are analyzed as logical variables, and these logical variables have continuous values between zero and one. Fuzzy logic is not in itself a design algorithm, but it helps in designing the controller in a more efficient and cost-effective way. Fuzzy logic appears to be a good choice for autopilot. A similar algorithm was applied by Iswanto et al. [76] for the efficient control of UUVs. Du et al. [77] also presented a similar control algorithm for the control system design of UUV. The block diagram of the fuzzy controller is shown in Figure 8 [78].

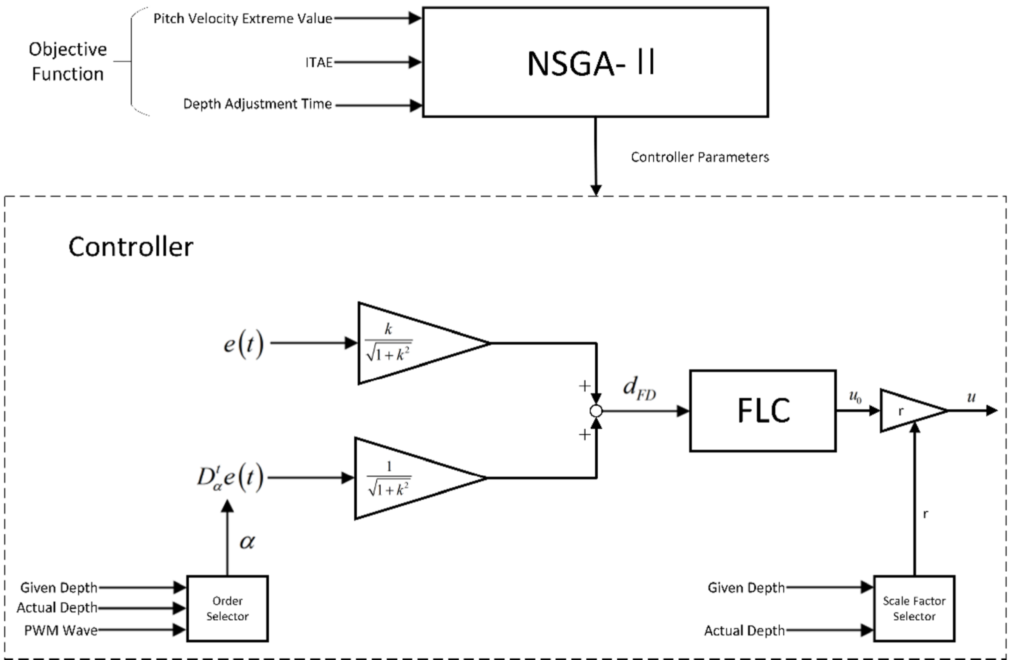

Figure 8. Block diagram of fuzzy controller for UUV [78]. Reprinted from Zhu et al. (2022).

Membership functions were used by Boyu et al. [78] to define the inputs. The membership functions for the input and output are shown in Figures 9 and 10, respectively.

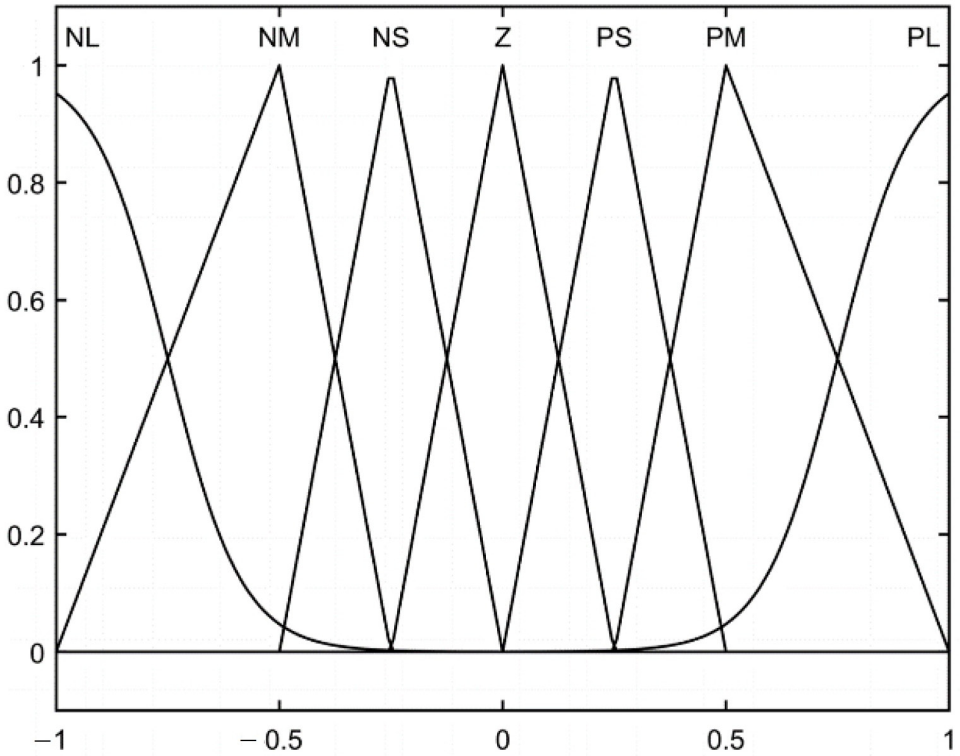

Figure 9. Input membership function [78]. Reprinted from Zhu et al. (2022).

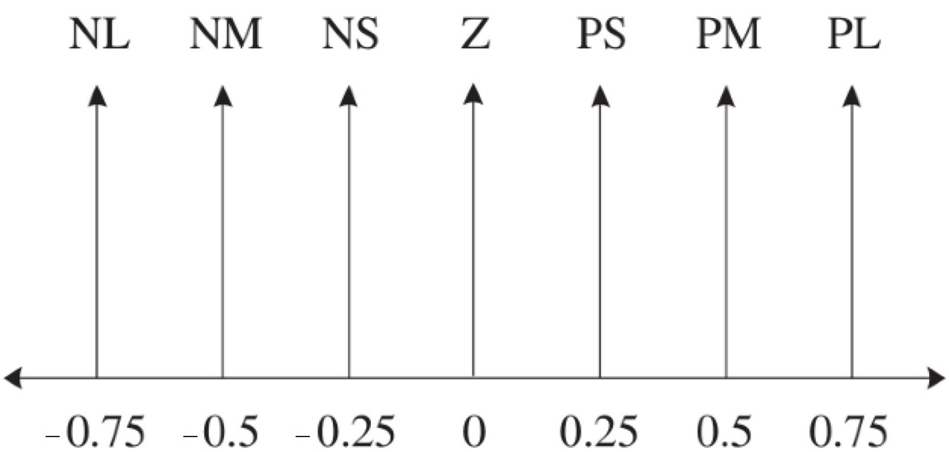

Figure 10. Output membership function [78]. Reprinted from Zhu et al. (2022).

3.3.5. PID Control Algorithm

PID is one of the most widely used control algorithms in UUVs because of its ease of implementation. In this algorithm, an error value is calculated, which is basically the difference between the set value and the measured value of the process variable. The most important feature of this algorithm is that it uses three control terms, i.e., proportional, integrative, and derivative, on the output of the controller. These types of controllers are mostly applied to control the depth, heading, and surge of UUVs [79,80]. Zhang et al. [72] used the Particle Swarm Optimization (PSO) technique for the optimization of the parameters of PID. Both the PID and fuzzy controllers are used for the control of autonomous underwater vehicles. Although the control capability of the PSO-PID controller is better as compared to the traditional PID controller, the PSO-PID controller still has a weaker performance than the fuzzy controller in terms of the control of UUVs.

Li et al. [81] presented a robust PD control approach, which was adaptive in nature, for the control of UUVs. This controller has two parts: proportional derivative (PD) nonlinear control and adaptive feedback control. Uncertainties were reduced with the help of a regression matrix. The major benefit of this control system design method is that when the primary error is sufficiently high, PD feedback plays a crucial part in clearing the unnecessary primary torque output; similarly, if the primary error is low, the control system plays a key part in sustaining the superior active performance of the system of the vehicle. The robust PD controller was used for the heading system of the UUV to avoid high initial output torque. Figure 11 shows the block diagram of a PID controller [82]. The gains *kp*, *ki*, and *kd*; affect the speed of convergence, the static error, and the magnitude of oscillations, respectively.

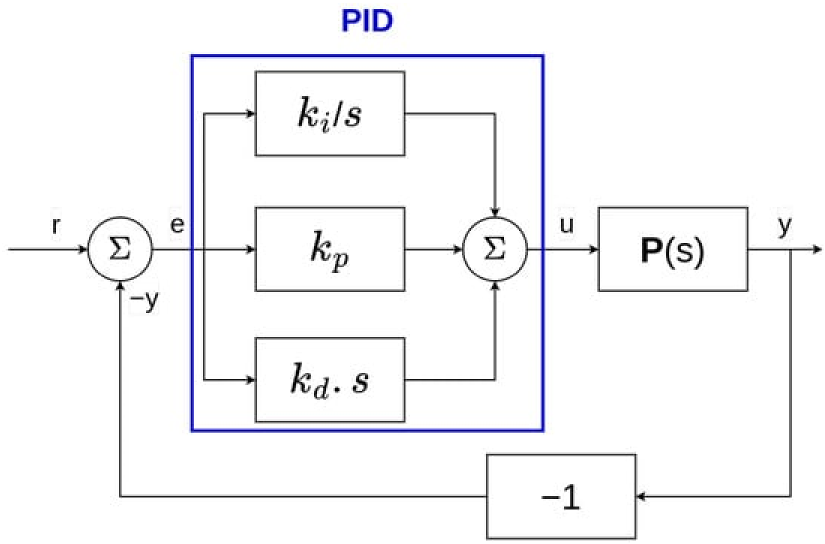

Figure 11. Block diagram of a PID controller [82]. Reprinted from Sola et al. (2022).

3.3.6. Backstepping Control Algorithm

Backstepping control algorithms have also been used in the literature to control UUVs [83–85]. Backstepping control algorithms are generally used for the control of highly nonlinear systems. These are the types of systems that are constructed from subsystems, and they will be stabilized by using different algorithms. In this control algorithm, the designer starts from a known-stable system and then backs out new controllers that will stabilize each of the outer systems. Planar backstepping control has been used for the control of underactuated UUVs. The backstepping control method has also been used for three-dimensional space [86].

Zheping et al. [87] applied a backstepping controller design algorithm for the trajectory tracking of a UUV. A 5-DOF dynamic model of an underactuated UUV was used. A mathematical approach was used to prove that tracking errors in the closed-loop system of the UUV control design converge to the neighborhood of the origin. It can also be stated that the system is uniformly ultimately bounded (UUB). All of the simulations in their study were carried out using MATLAB/Simulink. The parameters of the kinematics and dynamics of the vehicle were first defined. The reference trajectory was generated using the guidance system in the next step. Finally, the backstepping control algorithm was used for the control of the vehicle in order to track the desired trajectory smoothly and efficiently. Figure 12 shows the tracking results of the UUV using the backstepping control algorithm. There are also certain shortcomings of this algorithm. Firstly, the larger the values of the gains, the better the tracking accuracy will be, but large gains will cause signal chattering and may render the system unstable. Secondly, environmental and model uncertainties were not considered during the simulation. These will be present in the real-time scenario, and the controller will not be able to compensate for these uncertainties.

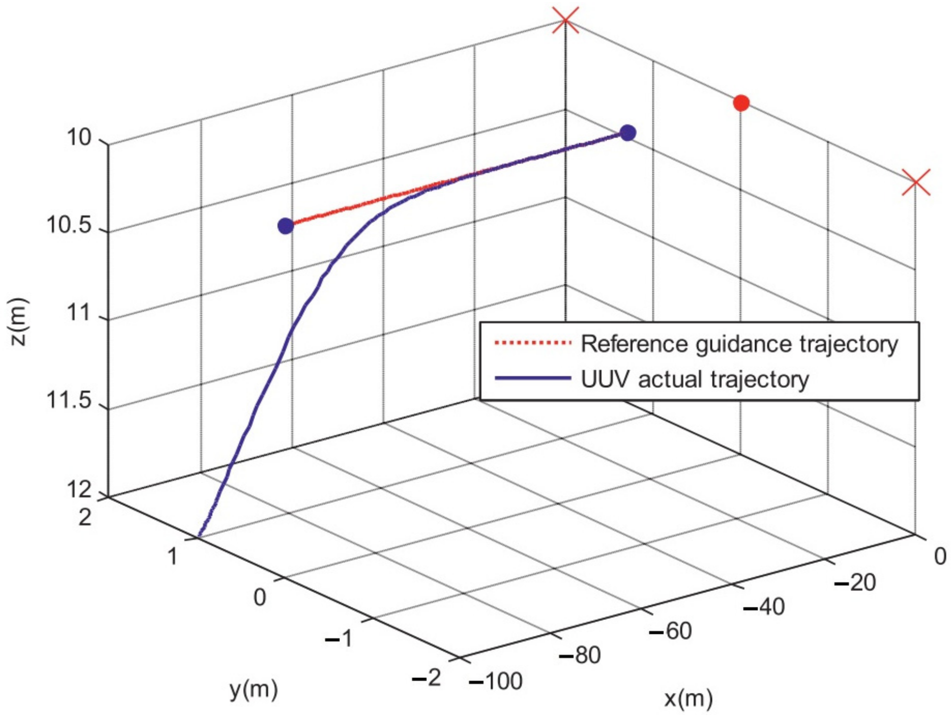

Figure 12. Trajectory tracking of UUV using backstepping control algorithm [87]. Reprinted with permission from Yan et al. (2019).

4. Discussion

Control systems for UUVs can be designed using different control algorithms. Most of the classical control algorithms are not very efficient in controlling UUVs due to the diversity of incalculable noise that comes from the changing speed of a UUV throughout the mission. Conventional control algorithms rely on quantitative data regarding the input and output relations. In the case of a UUV, the data to feed the system are limited due to its continuously changing environment.

Model predictive control (MPC) is one of the control algorithms that are used to control UUVs. This algorithm is intended to solve constrained control problems with optimization needs. There are certain drawbacks of this algorithm: for example, this control system design algorithm is mainly appropriate for slow dynamic processes. The MPC controller has shown good results in terms of following the desired trajectory, but it must be noted that to implement such type of control algorithm practically, very high-performance computing devices are required. This high-performance computing requirement will certainly increase the cost of the overall system, making it less cost-effective for use in small UUVs.

Another control algorithm used for UUVs is the adaptive control algorithm. The concept of adaptive control has been around for a few decades. Researchers around the globe have been applying this algorithm in different systems in order to make them stable. However, this control algorithm requires an exact and detailed model of the plant. Due to this, adaptive control is implemented in UUVs with certain modeling flaws. It is also a possibility that an unstable closed loop will be established. Therefore, this control algorithm is also not recommended for UUVs.

The $H\infty$ control algorithm has also been used in the literature for the control of UUVs. This control algorithm is used to realize the robust performance of the system. One of the biggest advantages of this control design algorithm over the classical control algorithms is that it is easily applicable to a problem that has multiple variables with cross-coupling between channels. This technique has certain drawbacks, like the requirement for a high-level mathematical understanding, and the system model must be extremely accurate for an effective controller design when using this method.

Fuzzy control algorithms are also employed to control UUVs. The advantage of a fuzzy controller is that in strident surroundings, it has a considerably improved output as compared to classic controllers. One of the major advantages of a fuzzy controller is its ability to deal with nonlinearities and uncertainties. A fuzzy control system also has combined regulation algorithmic and logical reasoning, which allows it to have an integrated control scheme. Another advantage of a fuzzy controller is that it can also work with less accurate inputs and is more robust.

The PID controller is the most applied technique among all of the control algorithms. PID controllers have been used in the past due to their fast response, good precision, and stabilization. A PID controller is very easy to implement and gives promising results. One of the limitations of the PID controller is that it needs to be tuned based on conditions. If these conditions are changed, the controller's performance will deteriorate. The traditional PID controller cannot tackle the nonlinearity of the system. However, this flaw is somewhat compensated for by making a robust PID control system.

A backstepping controller design provides promising results, but in order to design this controller, all of the states of the system should be completely known. Moreover, this algorithm requires extensive knowledge of mathematics. Similarly, another disadvantage of the backstepping control algorithm is that it produces a large-magnitude control signal, which is not easily handled by small UUVs. The system also experiences a steady-state error if the controller is designed with the backstepping method. The pros and cons of the various control algorithms discussed in this study are summarized in Table 1.

A real-world example of a model predictive control algorithm is in drones made by the UZH robotics group. A nonlinear model predictive control (NMPC) algorithm has recently shown promising results for agile quadrotor control, but it has a disadvantage, as it relies on highly accurate models for maximum performance [88]. Adaptive control is used in real-world road vehicles. Adaptive cruise control (ACC) is designed to help cars maintain a safe following distance and stay within the speed limit. This system adjusts a car's speed automatically. One of the main disadvantages of ACC is that this control system algorithm is not entirely autonomous, as it still requires the driver's intervention. Moreover, the system's sensors might be confused by poor weather conditions, like snow, rain, or fog, as well as environmental factors, such as driving through tunnels, etc. [89]. The H-Infinity control algorithm is being researched by NASA for use in large space structures in the real world. One of the properties of this control scheme is that it can handle multiple variables, which makes it suitable for space applications. A limitation of this control algorithm is that it requires a very high computational workload, and it also requires an extremely precise model [90].

Fuzzy control algorithms have been used in numerous applications in the real world, such as facial pattern recognition, air conditioners, washing machines, vacuum cleaners, antiskid braking systems, transmission systems, control of subway systems and unmanned helicopters, knowledge-based systems for the multi-objective optimization of power systems, weather-forecasting systems, etc. The key advantage of the fuzzy-based control system is that it is a robust system that works with vague inputs, but it requires a lot of testing for validation and verification [91]. PID controllers are widely used for process control applications, such as chemical processing, power generation, and manufacturing. The controller measures process variables, such as the flow rate, pressure, or level, and adjusts the input to maintain the desired process conditions. The main advantage of PID is that it provides precise and stable control. The major drawback of PID is that it has very low robustness [92]. Backstepping control system design algorithms have been applied to control the attitude and altitude of spacecraft, to design active suspension systems for cars, and to stabilize chemical reactors. The versatility of backstepping control makes it a popular choice for controlling nonlinear systems. A major disadvantage of this technique is that it has a large steady-state error [93].

Table 1. The pros and cons of the various control algorithms.

S.No.	Control Algorithms	Pros	Cons
1	Model predictive control [64,66]	• Multivariable controller that suits the UUV dynamics • Easy to tune • Can handle structural changes	• Complex algorithm that will require high-performance computing devices • Less cost-effective • High number of control parameters required
2	Adaptive control [81]	• Quick adaptations for defined inputs • Very simple to design • Self-tuning of controller parameters	• Has trouble in adapting to unknown processes or arbitrary disturbances • Stability of the adaptive control system is not treated rigorously
3	$H\infty$ control [74]	• Realizes the robust performance of the system • Easily applicable to a problem that has multiple variables	• Requirement for high-level mathematical understanding • System model also has to be extremely accurate for effective controller design
4	Fuzzy control [76,77]	• Robust system controller; no precise inputs are required • Ability to deal with nonlinearities and uncertainties • Occupies less memory space	• It is completely dependent on human knowledge and expertise • Regular updates of the rules of fuzzy logic are required • Requires a lot of testing for validation and verification
5	PID control [79–81]	• Easy to implement and gives promising results • Steady-state error is reduced • Gain can be adjusted by tracking error, and the system is treated like a "blackbox"	• It needs to be tuned based on conditions • Not suited for nonlinear systems • Low robustness
6	Backstepping control [83–87]	• Uncertainties can be handled until certain level • System convergence is asymptotic • Higher-order nonlinear system can be controlled	• All the states of the system should be completely known • Produces a large-magnitude control signal • Large steady-state error

5. Conclusions

Unmanned underwater vehicles (UUVs) have become increasingly popular in recent years due to their use in various applications. The control system design is an important aspect of UUVs due to the various disturbances caused by currents of the ocean, the propulsion system, and unmolded uncertainties. Practically, it is a challenging task to design a controller that will ensure optimal performance under these conditions. Also, the UUV controller receives input from different sensors, and the data from these sensors are used by the controller to perform different tasks. Control systems of UUVs should take into account all uncertainties and make them stable so that all sensors can perform optimally. The main algorithms adopted in the literature for the control system design of UUVs are conventional control algorithms, model predictive control algorithms, adaptive control algorithms, $H\infty$ control algorithms, fuzzy control algorithms, PID control algorithms, and backstepping control algorithms. Conventional control algorithms rely on quantitative data regarding input and output relations. Model predictive control algorithms are intended to solve constrained control problems, which have optimization needs. Adaptive control algorithms require an exact and detailed model of the plant. $H\infty$ control algorithms are used to realize the robust performance of the system. Fuzzy control algorithms have the ability to deal with nonlinearities and uncertainties. A PID controller has the limitation that it needs to be tuned based on conditions. The backstepping control technique requires extensive knowledge of mathematics.

Different control system design algorithms for unmanned underwater vehicles are studied in detail, and based on their reliability, security, and cost-effectiveness, six algorithms are discussed in detail. The pros and cons of all of the algorithms studied are presented in Table 1. Each algorithm has its own merits and demerits, and depending upon the usage of the vehicle, the control algorithm should be selected.

After going through the advantages and disadvantages of all of the control system algorithms presented in this paper, it can be concluded that $H\infty$ and fuzzy control algorithms are the best to use for UUVs, provided that the system is accurately modeled and fuzzy rules are effectively formed, keeping in mind all of the necessary conditions. It is hard to generate perfect mathematical models of UUVs that will take care of all of the uncertainties in the environments that will be faced by UUVs during their missions. However, modeling some of the uncertainties that are predicted can improve the performance of the UUV's control system.

In the future, UUVs will be equipped with AI and machine-learning technology. Advancements in nanotechnology and its applications in sensor design will also help UUVs to increase their reliability and range of operation. As sensors become more precise and decrease in weight, UUVs will become more reliable and will have a longer range due to less weight. Cutting-edge research on batteries and battery management systems will also give UUVs long submergence periods at sea and will help in their safe operation and navigation. An advanced propulsion system will give UUVs more agility, and it will help UUVs to compensate for disturbances due to ocean currents.

Author Contributions: Conceptualization, A.B., S.K., N.I., S.B., S.U. and M.U.; methodology, A.B., S.K., N.I., S.U. and M.U.; software, A.B., S.K., N.I., S.B., S.U. and M.U.; validation, A.B., S.K., N.I. and S.B.; formal analysis, A.B., S.K., N.I., S.B., S.U. and M.U.; investigation, A.B., S.K., N.I., S.B., S.U., F. and M.U.; resources, A.B., S.K., N.I., S.B., S.U. and M.U.; data curation, A.B., S.K., S.B., N.I., S.U., F. and M.U.; writing—original draft preparation, A.B., S.K., N.I., S.B., S.U. and M.U; writing—review and editing, A.B., S.K., N.I., S.B., S.U., F. and M.U.; visualization, A.B., S.K., N.I., S.B., S.U., F. and M.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors appreciate and acknowledge the support provided by King Fahd University of Petroleum and Minerals (KFUPM) by providing all the essential resources to conduct this study.

Conflicts of Interest: The authors declare no conflict of interest.

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