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Editorial

New Techniques in Motion Control and Path Planning of Marine Vehicles

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Currently, with the continuous improvements and advancements in artificial intelligence, wireless data transmission, and sensing technologies, increasing amounts of marine vehicles are being designed and applied to promote the marine economy and protect the environment. To ensure the realization of these goals, motion control and path planning strategies must also be of a high standard [1,2].

Research on intelligent and autonomous motion control systems for ships is a current hotspot, including navigation and localization technology, path planning technology, and trajectory tracking technology. For the motion control of marine vehicles, the traditional control method uses a robust control strategy with a constant response, which leads to low control efficiency [3]. Compared with traditional control methods, intelligent control methods do not rely on a precise model of the controlled object. Therefore, in view of the high complexity, nonlinearity, and uncertainty of real scenarios, intelligent control methods can perceive environmental changes in real time and make smart decisions based on real-time data [4].

Path planning is one of the most significant technologies for the automation and intelligence of marine vehicles and carrying out complex tasks [5]. Based on the specific mission requirements, an efficient path is planned that connects the starting and target points and avoids obstacles. An algorithm needs to consider the dynamic and kinematic model of the ship, as well as the water map model. Meanwhile, for different scenarios, path planning algorithms also consider multi-objective optimization problems, such as achieving the shortest duration, minimum fuel consumption, and maximum safety distance, to generate the optimal path [6].

Nowadays, ocean-going vehicles have developed intelligence, networking, and clustering. Realizing the clustering operation through intelligent collaboration is one of the future main methods of ocean operation. In the future, marine vehicles will also be able to carry out cluster cooperative operations in the field of deep-sea mining. Deep-sea mining has been an area of intense competition among countries in recent years, owing to the abundance of metal nodule minerals, metal sulfide deposits, and other metal components at the bottom of the deep sea [7]. The method of adopting a cluster of deep-sea mining robots can improve the efficiency of mining through cooperative operations with multi-objective allocation. Due to the small size and convenient transportation of individual vehicles, the damage to seafloor microorganisms can be reduced [8]. The method has significant theoretical research significance and value.

With global warming, research on ship path planning decision making for icebreaker escorts in polar ice regions will be a hot spot of future research [9]. The study of ship performance modeling or ice navigation risk analysis aims to solve the problem of pathfinding in ice under uncertainty and to realize ship collision avoidance decision making for icebreaker escorts [10]. This is of great practical significance to ensure the safety of ship navigation for icebreaker escorts of in polar ice regions.

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This Special Issue presents optimization strategies for path planning for autonomous underwater vehicles (AUVs), surface unmanned vehicles (USVs), remotely operated vehicles (ROVs) and deep-sea landing vehicles (DSLVs), as well as new approaches to motion control technology. All of them enable navigation, environment sensing, autonomous operation, and the performance of multiple complex tasks by carrying different mission payloads. This paper aims to summarize the research papers on motion control and path planning for marine vehicles.

In contribution 1, Wang et al. proposed a novel smooth sliding mode control (SSMC) based on a finite-time extended state observer (FTESO) to solve the curved path problem of a USV with unknown sideslip angles and model uncertainty. First, they modeled a USV with rudderless propellers. Second, FPLOS was introduced to compute the desired heading angle with sideslip angle compensation in the kinematic task. Third, they introduced a finite time observer to estimate the unrecognized sideslip angle and proposed a new smooth second-order control law. Simulation results demonstrate that the designed strategy is more effective than PID and conventional SMC, and the USV performs satisfactorily in path tracking under unknown disturbances.

In contribution 2, Zhang et al. proposed a novel finite-time extended state observer (FTESO)-based distributed closed-loop model predictive control scheme to study collision-free formation tracking of autonomous underwater vehicles (AUVs) with complex disturbances in complex marine environments. First, a fast FTESO was designed to accurately estimate both model uncertainties and external disturbances for each subsystem. Subsequently, they developed outer and inner loop formation controllers by combining disturbance compensation with distributed model predictive control (DMPC). In addition, to mitigate the increase in computation due to the control structure, the Laguerre orthogonal function was applied to reduce the computational burden during the time interval. Finally, the simulation results show that the computation time of the proposed formation control system utilizing the Laguerre function is reduced. The scheme can respond quickly, minimize the control cost, and improve the real-time execution and dynamic performance of the system.

In contribution 3, Pan and colleagues presented the Safe Energy–Dynamic Window Approach (SE-DWA) algorithm to ensure the safety and energy efficiency of autonomous sampling operations for deep-sea landing vehicles (DSLVs). They introduced an improved additional evaluation subfunction to address the safety concerns of forward-looking sonar due to the degradation in accuracy caused by underwater noise and other factors and to reduce the energy consumption of autonomous sampling operations. When encountering U-shaped obstacles, the trajectory comparison evaluation subfunction was utilized to decrease the path length and energy consumption by making predicted trajectories. Finally, they conducted a simulation experiment using a map of the deep-sea environment. Simulation results show that compared with the DWA algorithm, the path planned by the SE-DWA algorithm not only ensures greater safety, but also reduces energy consumption. The SE-DWA algorithm aligns better with the requirements of DSLVs for autonomous sampling in deep-sea environments.

In contribution 4, Fu et al. discussed a model predictive control (MPC) method based on an improved nonlinear disturbance observer (NDO). The aim was to tackle the degradation of the kinematic performance of USVs due to sea wind, wave, and current disturbances during navigation. First, they approximated and discretized the USV model and designed an MPC system with multiple constraint variables. To compensate for the effect of disturbances, they presented an improved NDO to reduce the computation time of the MPC. The simulation results show that NDO-based MPC can effectively compensate for external disturbances and exhibit good tracking and disturbance-rejection performances. Compared with a USV using MPC based on an unimproved NDO, the proposed method has a similar tracking performance.

In contribution 5, Xu et al. presented an acoustic guidance method for underwater docking to address the problem of continuous underwater operation of autonomous underwater vehicles (AUVs). Firstly, the underwater docking guidance method was divided into three phases and an associated guidance strategy was provided for each phase. Then, the authors proposed a correction method based on the ultra-short baseline (USBL) system for ARV estimation of the docking station depth, relative position, and azimuth. Finally, they verified the method via testing in a lake and a shallow sea area. The experiments show that the tests meet the docking accuracy requirements and prove the reliability of the acoustic navigation algorithm on the lake. However, the docking success rate was reduced in the ocean environment due to its complexity.

In contribution 6, Liang and colleagues proposed an IWSO-DWA algorithm—the improved White Shark Optimization Algorithm (WSO) combined with the Dynamic Window Approach (DWA)—for global path planning for USVs. Firstly, they initialized the white shark population using cyclic chaotic mapping, which improved the initial solution quality of the algorithm. Secondly, the adaptive weight factor was introduced to obtain the best position of the population. Thirdly, IWSO was combined with the DWA to improve the USV navigation performance and avoid falling into local optima. The experimental simulation results show that the proposed method reduces the path length and steering angle and improves the path smoothing cost compared with WSO. The proposed IWSO-DWA can not only plan the optimal global navigation path but also help USVs avoid other vessels in real time.

In contribution 7, Cho et al. developed a trajectory tracking controller for underpowered torpedo-type autonomous underwater vehicles (AUVs). The proposed controller combined the required error dynamics and time-delay estimation (TDE) with an appropriate design. To alleviate the effect of noise on the controller, they used an average moving window filtering technique. In addition, in order to consider the driving constraints, they designed an anti-reversal structure and uses time delay estimation to control the vehicle inputs and outputs. The experimental results show that the proposed controller has an accurate tracking performance and is suitable for surveying tasks that require a tracking error of less than one meter.

In contribution 8, Xu and colleagues developed a high-precision long-term trajectory prediction algorithm for oil tankers to improve the efficiency of maritime transportation. The historical training trajectory key points were extracted via DBSCAN clustering of historical AIS data. Furthermore, they developed a novel pathfinding algorithm for sequentially identifying a subset of waypoints. The experimental results show that the proposed method can achieve high-precision long-term trajectory prediction and higher trajectory smoothing than existing trajectory prediction algorithms.

In contribution 9, Li et al. discussed an improved APF-ACO algorithm for collision avoidance and path planning. Initially, they constructed a ship collision avoidance constraint model based on COLREGs to enhance the safety and applicability of the algorithm. Then, a dynamic APF gradient was formed by introducing factors such as speed, position, and shape parameters to avoid collisions with moving obstacles. The results show that the algorithm can effectively realize dynamic collision avoidance and generate safe and feasible paths.

In contribution 10, He et al. analyzed a VK-RRT* algorithm for the automatic design of planned routes. First, they utilized an electronic navigation chart (ENC) vector data search to reduce the data errors when converting from vectors to grid charts. In addition, Delaunay triangulation was used to organize the vector data and to consider the depth value factor. In addition, they proposed a new implementation strategy of the path planning algorithm to predict the turning trajectories in the form of arcs and to consider the ship's kinematic performance. Finally, experimental validation shows that the proposed algorithm can generally reduce the path length and save planning time.

In contribution 11, Chen et al. designed a novel robust IMM filter utilizing a variational Bayesian (VB) inference framework. They utilized random Bernoulli variables (RBVs) to describe the one-step random measurement delay (OSRMD) in a pairwise jump Markov system (JMS). Moreover, they constructed a hierarchical Gaussian state-space model and utilized the VB technique to estimate the state vectors, model probabilities, and unknown parameters. The simulation results show that the proposed IMM filter has a higher estimation accuracy than existing IMM filters for target tracking.

In contribution 12, Zhang et al. presented a non-vectorized terminal sliding mode and active disturbance suppression decoupled control (NTSM-ADRDC) scheme for three-dimensional (3D) trajectory tracking of autonomous underwater vehicles (AUVs). First, they introduced the ADRC technique and a new virtual control vector to decouple the five-DOF AUV model. Then, they estimated the internal unmodeled perturbations and external perturbations of the system using LESO. Subsequently, they designed NTSM nonlinear state error feedback control to compensate for the total system perturbations. Finally, the simulation results demonstrate the effectiveness and robustness of the NTSM-ADRDC trajectory tracking method.

In contribution 13, Li et al. analyzed a multi-AUV formation control method combining CNN-LSTM prediction and inverse-stepping sliding mode control to handle hydroacoustic communication constraints in multi-AUV leader–follower formations. First, they utilized a feedback linearization method to transform an AUV nonlinear model into a second-order integral model. In addition, they combined the advantages of CNN feature extraction, noise filtering, and LSTM spatio-temporal memory to build a prediction model. The effectiveness of the CNN-LSTM prediction model and the designed controller is verified by simulations.

In contribution 14, Zhang et al. presented a novel control strategy against model uncertainty, unknown environmental disturbances, and input constraints for dynamically localized ships. An improved manual potential function (MAPF) algorithm was proposed, utilising the inverse stepping technique and active dynamic positioning control to avoid collisions. An auxiliary dynamic system (ADS) was constructed to solve the input constraint problem. Simulation experiments prove that the ship can avoid obstacles and verify the feasibility and effectiveness of the control strategy.

In contribution 15, Ma and colleagues presented a horizontal trajectory tracking control method for solving the problem of underdriven AUVs in the presence of model uncertainty, time-varying external perturbations, and input saturation. Initially, they introduced a coordinate transformation to solve the underdriven problem, and a disturbance observer (DO) was designed to estimate the total unknown disturbances. Then, a saturation controller was designed and quantitatively analyzed to determine estimation and tracking errors. Finally, the simulation results show that the designed controller enables the AUV to track the expected trajectory well and avoids the input saturation problem.

In contribution 16, Xing et al. proposed a deep Q-network algorithm (DQN) for full-coverage path planning for USVs. First, the USV full-coverage workspace was modeled and preprocessed with raster maps. Next, the neural network was trained using area coverage information, and the learning history information from reinforcement learning was utilized to select the action capability. Finally, simulation experiments show that the algorithm improves the shortcomings of traditional full-coverage path planning algorithms, ensures coverage with a higher efficiency, and greatly reduces the duplication rate of the coverage path.

In contribution 17, Tian et al. discussed a fuzzy controller based on an established kinematic and dynamic model of an AUV system to solve the AUV path tracking problem. To optimize the target function, the path length, smoothness, and cross-trajectory position are considered. They used the particle swarm optimization (PSO) algorithm for optimization. The test results show that the designed controller ensures the path tracking system perform well, with a higher tracking accuracy, better smoothness, and shorter path length than the traditional algorithm.

In contribution 18, Xu and colleagues presented a combined nonlinear extended state observer (NESO) and non-stellar fast terminal sliding mode surface (NFTSM) approach for the trajectory control of underdriven USVs in the presence of wind, wave, and current disturbances in the external environment. Based on the error model, they constructed the NFTSM model to realize finite-time control. They designed two types of disturbances with different amplitudes and periods to verify the effectiveness of NESO in all observed sea states. Finally, the MATLAB numerical simulation results show that the NFTSM control method can realize fast trajectory tracking control within an environment with disturbances, uncertain model parameters, and unpredictable states.

In contribution 19, Zhang et al. explored a distributed robust fast finite-time formation control algorithm that incorporates directed graph and neural network methods to solve the coordinated formation problem of autonomous surface vehicles (ASVs) under information disruption constraints. They designed two adaptive parameters to compensate for model uncertainties and perturbations in the external environment. In addition, they developed an improved dynamic surface control (DSC) technique to model the exponential term of the Lyapunov function. The feasibility and effectiveness of the algorithm are verified through numerical simulations.

In contribution 20, Xing et al. reviewed existing algorithms and the latest achievements in USV path planning regarding global path planning, local path planning, approximate response avoidance, and path planning with clustering. Then, they summarized the advantages and disadvantages of different research methods and the potential for improving various algorithms by classifying USV path planning. Therefore, the main contribution of this work is that it broadens the horizon of USV path planning and proposes future directions and research priorities for USV path planning based on existing technologies and trends.

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

List of Contributions

The research contents and prominent findings in this Special Issue are as follows:

1. Wang, Y.; Qu, Y.; Zhao, S.; Cajo, R.; Fu, H. Smooth Sliding Mode Control for Path Following of Underactuated Surface Vehicles Based on LOS Guidance. *J. Mar. Sci. Eng.* **2023**, *11*, 2214. https://doi.org/10.3390/jmse11122214.
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