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Editorial

Intelligent Ships and Waterways: Design, Operation and Advanced Technology

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Intelligent ships have been attracting much attention with the intention of downsizing the number of staff, increasing efficiency, saving energy, etc. With the perspective of a full lifecycle for intelligent ships and waterways, this Special Issue focuses on the advanced technologies for the design and sustainable operation process. Intelligent ships need to have real-time environment perception, human-like decision making, and high-precision motion control. Intelligent waterways should provide real-time and predictive navigation services, e.g., water depth and velocity, ship traffic flow, etc. The advanced methods and technologies, including artificial intelligence, big data analysis, mixed reality, building information modeling, and digital twins, should be introduced to improve the safety, efficiency, and sustainability throughout the lifetime of intelligent ships.

The present Special Issue contains 20 research articles and 2 review articles, with 8 articles related to waterway and port monitoring, 2 articles covering ships' navigation environment perception, 4 articles handling ships' navigation decision making and motion planning, and 8 articles studying ships' motion modeling and control problems.

Navigation safety is the key issue for waterway transportation. Peng et al. [1] investigated the spatiotemporal distribution and evolution characteristics in Asia since 2000 by collecting technological water traffic accident data. The methods of gravity center and standard deviation ellipse analysis were utilized to determine the spatial and data-related characteristics of water traffic accidents. This study provides guidance for improving marine shipping safety, emergency resource management, and relevant policy formulation.

Ship collision risk identification plays a crucial role in the safe navigation and monitoring of ships in inland waterways. Wang et al. [2] proposed a new method for identifying ship navigation risks by combining the ship domain with Automatic Identification System (AIS) data to increase the prediction accuracy of collision risk identification for ship navigation in complex waterways. A ship domain model was constructed based on the ship density map drawn using AIS data. The effectiveness of this method was verified through a simulation of ships' navigation in complex waterways, with correct collision avoidance decisions being able to be made in accordance with the Regulations for Preventing Collisions in Inland Rivers of the People's Republic of China.

In high-traffic harbor waters, marine radars frequently encounter signal interference stemming from various obstructive elements, thereby presenting formidable obstacles in the precise identification of ships. Ma et al. [3] proposed a customized neural network-based ship segmentation algorithm named MrisNet to achieve precise pixel-level ship identification in complex environments. MrisNet employed a lightweight and efficient FasterYOLO network to extract features from radar images at different levels, capturing fine-grained edge information and deep semantic features of ship pixels. MrisNet accurately segments ships with different spot features and under diverse environmental conditions in

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marine radar images, exhibiting outstanding performance, particularly in extreme scenarios and challenging interference conditions, showcasing robustness and applicability.

There is insufficient research on the mechanisms underlying collision risks specifically related to merchant and fishing vessels in coastal waters. Zhu et al. [4] proposed an assessment method for collision risks between merchant and fishing vessels in coastal waters and validated it through a comparative analysis through visualization. The results indicated that this method effectively evaluated the severity of collision risks, and the identified high-risk areas resulting from the analysis were verified by the number of accidents that occurred in the most recent three years.

To improve the situational awareness ability of ships in busy inland waterways, Lei et al. [5] focused on the situational awareness of intelligent navigation in inland waterways with high vessel traffic densities and increased collision risks. A method based on trajectory characteristics was proposed to determine associations between AIS data and radar objects, facilitating the fusion of heterogeneous data. Through a series of experiments, including overtaking, encounters, and multi-target scenarios, this research substantiated the method, achieving an F1 score greater than 0.95. Consequently, this study furnished robust support for the perception of intelligent vessel navigation in inland waterways and the elevation of maritime safety.

To support ship trajectory prediction at waterway confluences using historical AIS data, Wang et al. [6] proposed a method to improve the recognition accuracy of ships' behavior trajectories, assist in the proactive avoidance of collisions, and clarify ship collision responsibility, ensuring the safety of waterway transportation systems in the event of ship encounters induced by waterway confluences or channel limitations. An improved K-Nearest Neighbor Algorithm considering the sensitivity of data characteristics (SKNN) was put forward to predict the trajectory of ships, which considers the influence weights of various parameters on ship trajectory prediction. The accuracy of the ship trajectory prediction method was above 99%, and the performance metrics of the SKNN surpassed those of both the conventional KNN and NB classifiers, which was helpful for warning ships of collision encounters early to ensure avoidance.

The global demand for oil is steadily escalating, and this increased demand has fueled marine extraction and maritime transportation of oil, resulting in a consequential and uneven surge in maritime oil spills. Xu et al. [7] introduced a methodology for the automated detection of oil spill targets. Experimental data pre-processing incorporated denoise, grayscale modification, and contrast boost. The realistic radar oil spill images were employed as extensive training samples in the YOLOv8 network model. The proposed method for offshore oil spill survey presented here can offer immediate and valid data support for regular patrols and emergency reaction efforts.

Structural damage is a prevalent issue in the long-term operations of harbor terminals. Bi et al. [8] proposed a novel digital twin system construction methodology tailored for the long-term monitoring of port terminals, which elaborated on the organization and processing of foundational geospatial data, sensor monitoring information, and oceanic hydrometeorological data essential for constructing a digital twin of the terminal. Experimental validation demonstrated that this method enabled the rapid construction of digital twin systems for port terminals and supported practical applications in business scenarios. Data analysis and a comparison confirmed the feasibility of the proposed method, providing an effective approach for the long-term monitoring of port terminal operations.

In response to the evolving landscape of maritime operations, new technologies are on the horizon, such as as mixed reality (MR), enhancing navigation safety and efficiency during remote assistance, e.g., in the remote pilotage use case. Ujkani et al. [9] initially tested and assessed novel approaches to pilotage in a congested maritime environment, which integrated augmented reality (AR) for ship captains and virtual reality (VR) and desktop applications for pilots. The efficiency and usability of these technologies were evaluated through in situ tests conducted with experienced pilots on a real ship using the System Usability Scale, the Situational Awareness Rating Technique, and Simulator Sickness Questionnaires during the assessment.

In scenarios such as nearshore and inland waterways, the ship spots in a marine radar are easily confused with reefs and shorelines, leading to difficulties in ship identification. To accurately identify radar targets in such scenarios, Kang et al. [10] proposed a novel algorithm, namely YOSMR, based on a deep convolutional network. The YOSMR uses the MobileNetV3 (Large) network to extract ship imaging data of diverse depths and acquire feature data of various ships. Meanwhile, taking into account the issue of feature suppression for small-scale targets in algorithms composed of deep convolutional networks, the feature fusion module known as PANet was subject to a lightweight reconstruction, leveraging depthwise separable convolutions to enhance the extraction of salient features for small-scale ships while reducing model parameters and the computational complexity to mitigate overfitting problems. As a result, the YOSMR displays a substantial advantage in terms of convolutional computation.

The trajectory planning of multiple autonomous surface vehicles (ASVs) is particularly crucial to provide a safe trajectory. In [11], a swarm trajectory-planning method was proposed for ASVs in an unknown and obstacle-rich environment. Specifically, a kinodynamic path-searching method was used to generate a series of waypoints in the discretized control space at first. Then, after fitting B-spline curves to the obtained waypoints, a nonlinear optimization problem was formulated to optimize the B-spline curves based on gradient-based local planning. Finally, a numerical optimization method was used to solve the optimization problems in real time to obtain collision-free, smooth, and dynamically feasible trajectories relying on a shared network.

To effectively deal with collisions in various encounter situations in open water environments, Zheng et al. [12] established a ship collision avoidance model and introduced multiple constraints into the Velocity Obstacle (VO) method, which was proposed to determine a ship domain by calculating a safe approach distance. Meanwhile, the ship collision avoidance model based on the ship domain was analyzed, and the relative velocity set of the collision cone was obtained by solving the common tangent line within the ellipse. The timing of starting collision avoidance was determined by calculating the ship collision risk.

Electronic Navigational Charts (ENCs) are geospatial databases compiled in strict accordance with the technical specifications of the International Hydrographic Organization (IHO). Facing the urgent demand for high-precision and real-time nautical chart products for polar navigation under the new situation, Jiao et al. [13] systematically analyzed the projection of ENCs for polar navigation. Based on the theory of complex functions, the direct transformations of Mercator projection, polar Gauss–Krüger projection, and polar stereographic projection were derived. A rational set of dynamic projection options oriented towards polar navigation was proposed with reference to existing specifications for the compilation of the ENCs. Taking the CGCS2000 reference ellipsoid as an example, the numerical analysis shows that the length distortion of the Mercator projection is less than 10% in the region up to 74°, but it is more than 80% at very high latitudes.

Sorting out the requirements for intelligent functions is the prerequisite and foundation of the top-level design for the development of intelligent ships. Taking the technical realization of each functional module as the goal, Hao et al. [14] analyzed the status quo and development trend of related intelligent technologies and their feasibility and applicability when applied to each functional module. This clarified the composition of specific functional elements of each functional module, put forward the stage goals of China’s inland intelligent ship development and the specific functional requirements of different modules under each stage, and provided a reference for the Chinese government to subsequently formulate the top-level design development planning and implementation path of inland waterway intelligent ships.

Predicting the maneuverability of a dual full-rotary propulsion ship quickly and accurately is the key to manipulate a ship with machines. Yu et al. [15] performed integrated computational fluid dynamics (CFD) and used the mathematical model approach to simulate ship turning and zigzag tests, which were then compared and validated against a full-scale trial carried out under actual sea conditions. The results indicate that the proposed method has a high accuracy in predicting the maneuverability of dual full-rotary propulsion ships, with an average error of less than 10% from the full-scale trial data (and within 5% for the tactical diameters in particular), in spite of the influence of environmental factors, such as wind and waves. It provides reliability in predicting the maneuverability of a full-scale ship during the ship design stage.

Automatic berthing is at the top level of ship autonomy. Zhang et al. [16] introduced the berthing maneuver model, which is able to predict a ship's responses to steerage and external disturbances and provide a foundation for the control algorithm. The similarities and differences between the conventional MMG maneuvering model and automatic berthing maneuvering model were elaborated. Bibliometric analysis on automatic berthing was also carried out to discover common issues and emphasize the significance of maneuver modeling. Furthermore, the berthing maneuver's specifications and modeling procedures were explained in terms of the hydrodynamic forces on the hull, four-quadrant propulsion and steerage performances, external disturbances, and auxiliary devices.

The challenge of accurately modeling and predicting dynamic environments and motion statuses of ships has emerged as a prominent area of research. In response to the diverse time scales required for the prediction of a ship's motion, Zhang et al. [17] explored and analyzed various methods for modeling ship navigation environments, ship motion, and ship traffic flow. Additionally, these motion prediction methods were applied for motion control, collision avoidance planning, and route optimization. Key issues were summarized regarding ship motion prediction, including the online modeling of motion models, real ship validation, and consistency in modeling, optimization, and control. Future technology trends were predicted in mechanism-data fusion modeling, large-scale modeling, multi-objective motion prediction, etc.

The complex navigational conditions, unknown time-varying environmental disturbances, and complex dynamic characteristics of ships pose great difficulties for ship course keeping. Lin et al. [18] proposed a Particle Swarm Optimization (PSO)-based predictive PID-Backstepping (P-PB) controller to realize the efficient and rapid course keeping of ships. The proposed controller took a ship's target course, current course, yawing speed, and predictive motion parameters into consideration. The parameters in the proposed course-keeping controller were optimized by utilizing PSO, which can adaptively adjust the value of parameters in various scenarios, and thus further increase its efficiency.

Cargo Transfer Vessels (CTVs) were designed to transfer cargo from a Floating Production Storage and Offloading (FPSO) unit into conventional tankers. Liu et al. [19] presented a synchronization control strategy based on the virtual leader–follower configuration and an adaptive backstepping control method. The position and heading of the following vessel were proven to be able to globally exponentially converge to the virtual ship via the contraction theorem. Then, the optimization problem of the desired thrust command from the controller was solved through an improved firefly algorithm, which fully considered the physical characteristics of the azimuth thruster and the thrust forbidden zone caused by hydrodynamic interference. The SAF algorithm outperformed the SQP and PSO algorithms in longitudinal and lateral forces, with the R-squared (R2) values of 0.9996 (yaw moment), 0.9878 (sway force), and 0.9596 (surge force) for the actual thrusts and control commands in the wave heading 180°. The experimental results can provide technical support to improve the safe operation of CTVs.

It is challenging to understand and collect correct data about USV dynamics. Zhang et al. [20] proposed a modified Backpropagation Neural Network (BPNN) to address this issue. The experiment was conducted in the Qinghuai River, and the receiver collected the data. The modified BPNN outperformed the conventional BPNN in terms of ship trajectory forecasting and the rate of convergence. The updated BPNN can accurately predict the rotational velocity during a propeller's acceleration and stability stages at various rpms.

To satisfy the needs of autonomous navigation and high-precision control of ship trajectories, Han et al. [21] proposed a fuzzy control improvement method with an Integral Line-Of-Sight (ILOS) guidance principle. A three-degree-of-freedom ship motion model was established with the battery-powered container ship ZYHY LVSHUI 01 built by the COSCO Shipping Group. Then, a ship path-following controller based on the ILOS algorithm was designed. A controller was applied that uses a five-state extended Kalman filter (EKF) to estimate the heading, speed, and heading rate based on the ship's motion model with the assistance of Global Navigation Satellite System (GNSS) position measurements. The research results provided a reference for the path-following control of ships.

The USV is an emerging marine tool due to its advantages of automation and intelligence in recent years. Li et al. [22] proposed a novel prescribed performance fixed-time fault-tolerant control scheme for a USV with model parameter uncertainties, unknown external disturbances, and actuator faults, based on an improved fixed-time disturbance observer. Firstly, the proposed observer not only accurately and quickly estimated and compensated for the lumped nonlinearity, including actuator faults, but also reduced the chattering phenomenon by introducing the hyperbolic tangent function. Then, under the framework of prescribed performance control, a prescribed performance fault-tolerant controller was designed based on a nonsingular fixed-time sliding mode surface, which guarantees the transient and steady-state performance of a USV under actuator faults and meets the prescribed tracking performance requirements.

In conclusion, the articles presented in this Special Issue cover broad research topics related to advancements in the design, operation, and advanced technology of intelligent ships and waterways, guiding readers through the best methods for carrying out analysis.

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