Research on the safe and efficient collision avoidance methods for large autonomous merchant ships in open and busy waters

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ABSTRACT

According to the actual needs of autonomous navigation and safety control of ships in open and busy waters, this study puts forward a complete technical chain of "autonomous navigation environment construction - collision avoidance and track control algorithm research - verification and incremental update of real ship data", and gives the specific technical scheme and process route. That is to construct the virtual reality integrated simulation environment of ship autonomous navigation. Considering the multiple responses of large merchant ships, the ship handling model is coupled with the environment, and the ship autonomous collision avoidance algorithm model is established. By comparing the VDR data and simulation results, the algorithm and model are constantly updated, so as to finally realize the safe and efficient autonomous collision avoidance decision-making ability of ship intelligent navigation. The research results have important theoretical and technical support for expanding and improving the technical methods of ship navigation autonomous decision-making, and finally realizing the commercial application of ship intelligent navigation.

Keywords: Open busy waters, intelligent navigation of ships, collision avoidance, environment building, method validation

1. INTRODUCTION

Intelligent navigation of ships can not only solve the challenge of further leapfrog improvement of shipping efficiency, safety and economy, but also be the necessary way and trend to actively integrate into the future intelligent world and realize the transformation and upgrading of the shipping industry. Vessels in busy waters are dense, navigable environment is complex, and the risk degree is high. The navigation of ships in complex waters is affected by channel conditions, traffic flow, hydrometeorological conditions, obstructing objects and other factors, and there is a great water traffic safety risk[1]. The autonomous navigation of ships in busy waters is the focus and difficulty of research at home and abroad. this paper proposes a research method of safe and efficient collision avoidance methods for large autonomous navigation merchant ships, which is used to solve the core scientific problem of autonomous collision avoidance for ships in open and busy waters.

2. SET UP THE INDEPENDENT NAVIGATION ENVIRONMENT OF LARGE MERCHANT SHIPS INTEGRATING VIRTUAL AND REALITY

2.1 Mathematical abstraction and modeling of ship autonomous navigation environment

The autonomous navigation environment of a ship includes static environment and dynamic environment. The static environment refers to the natural navigation environment composed of infrastructure, wind, waves and current, and obstacles to navigation, etc. The modeling can be completed by three-dimensional model construction method[2]. Dynamic environment refers to the dynamic environment modeling with real-time real perceptual information data based on the static environment modeling by using multi-source sensing devices such as vision, AIS and radar to integrate the external traffic environment perception data[3, 4]. Figure 1 shows the overall architecture of modeling the autonomous navigation environment of ships:

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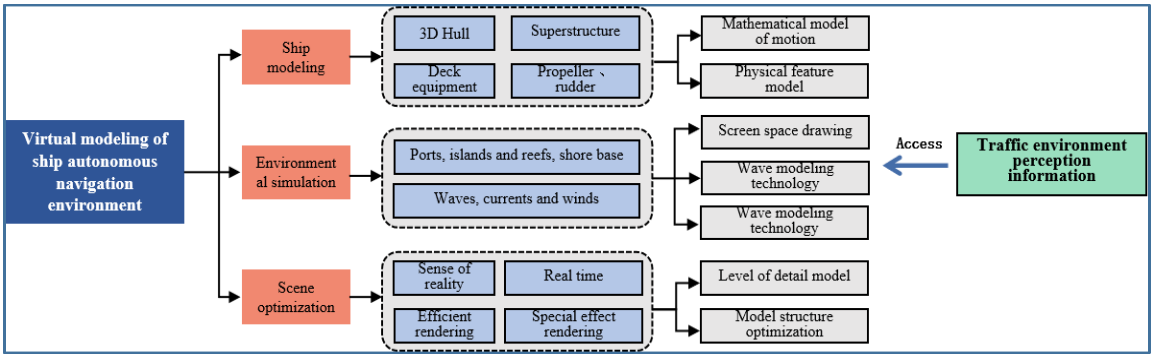

Figure 1. Overall architecture of virtual simulation modeling of ship autonomous navigation environment.

2.2 Research on ship operation motion model and environmental coupling

Based on the interaction of the hull, propeller and steering gear, a multi-degree of freedom motion response model of the ship was established. Considering the shallow water effect and the hysteresis of the drive response, the multi-degree of freedom motion response characteristics of the ship under different state parameters were studied, and the ship steering model suitable for the dynamic collision avoidance process was constructed. Considering the environmental disturbance such as wind, wave and current, the mathematical model of disturbance force is established and introduced into the ship maneuvering response equation, the change law of ship motion response under the disturbance is analyzed, and the parameters of the model are modified[5]. The overall structure of the ship maneuvering response model is as follows in Figure 2:

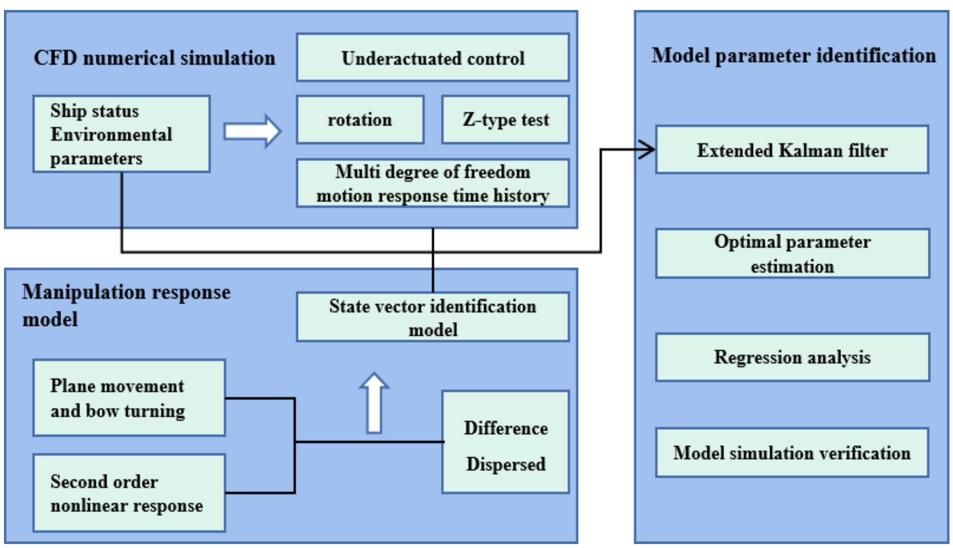

Figure 2. Overall architecture of ship manipulation response model construction.

The second-order nonlinear response model of ship maneuvering motion is shown as follows:

$$T_1T_2\ddot{r}+(T_1+T_2)\dot{r}+r+\alpha r^3=K(\delta+\delta_r+T_3\dot{\delta}) \tag{1}$$

where $T1$, $T2$ and $T3$ are time constants, K is the rudder angle gain coefficient, γ is the yaw angular velocity, α is the coefficient of nonlinear term, δ is the steering angle, and δ_γ is the rudder angle required for initial direct navigation. Establish the observation equation as follows:

$$Y_{t+1} = C_{k+1} X_{k+1} \tag{2}$$

Thus, the identification model is transformed into a Second-Order Vector response model. Based on the response structure of numerical simulation and the measured ship data, the extended Kalman filter method is used to optimally estimate the system state X_k, and then identify the elements in λ to solve the response model parameters *T1*, *T2*, *T3*, *K*, α and δ_γ. The correlation and regression between the ship state and environmental parameters and the above response model parameters are analyzed, and the correction method of maneuvering response model under the coupling influence of ship itself and environmental factors is established; Finally, the corresponding working conditions are selected, and the ship motion simulation is carried out based on the identified response model, which is compared with the numerical simulation and measured data to verify the generalization ability of the identification model[6].

3. INDEPENDENT COLLISION AVOIDANCE AND NAVIGATION TRACK CONTROL ALGORITHM MODEL AND SIMULATION VERIFICATION

3.1 Research on autonomous collision avoidance algorithm based on reinforcement learning and deep supervised learning

Based on the investigation of captain's experience, the key information needed by large merchant ships sailing in complex waters is preliminarily determined. On this basis, the selection of key information is characterized as the problem of information preprocessing and multi-modal fusion in busy waters[7]. It is planned to use principal component analysis and Transformer structure combined with attention mechanism to study the multi-modal fusion method of image, sound wave and text, so as to provide a basis for the subsequent research on collision avoidance algorithm[8]. The main structure is shown in Figure 3.

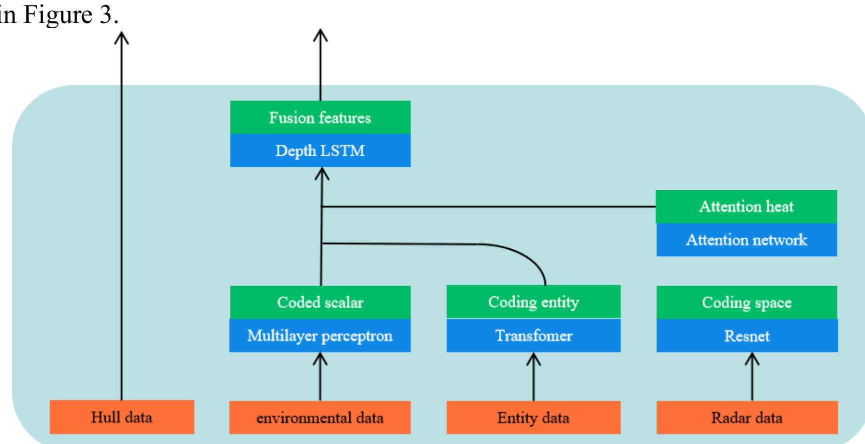

Figure 3. Navigation data preprocessing module structure.

Then, reinforcement learning combined with artificial potential field method is used to study the autonomous collision avoidance algorithm[9].

The reward function group $\mathbb{R}$ is designed. For the autonomous collision avoidance of large merchant ships, sub-tasks are divided. Each sub-reward function reflects the details of obstacle avoidance tasks, including the following aspects:

$\mathrm{R_t}$ is defined as a time reward and punishment function, as follows:

$$R_t = \begin{cases} r_f \cdot (t_{exp} - t_o) - [max(t_{exp}, t_o) - t_{exp}], & t_o \le t_{thres} \\ -t_{exp}, & t_o > t_{thres} \end{cases} \tag{3}$$

where, r_f is the arrival sign of the ship at the end of navigation. If the ship does not arrive at present, it will be set as 0, and if it arrives, it will be set as 1; $t_{\exp}$ is the expected time required for obstacle avoidance navigation, which is analyzed by human experts in many real ship tests; t_0 is the current sailing time; t_{thres} is the end threshold of the algorithm to avoid falling into the local optimal solution. This value is set artificially.

R_c: For the function of ship collision hazard, the space collision hazard is defined as follows:

$$R_c = \begin{cases} -1, |DCPA| < d_1 \\ \frac{1}{2}\sin\left[\frac{\pi}{d_2 - d_1} * \frac{|DCPA|(d_1 + d_2)}{2}\right] - \frac{1}{2}, d_1 \le |DCPA| \le d_2 \\ 0, \end{cases} \tag{4}$$

where d_1 represents the shortest safety distance for collision avoidance, and d_2 represents the allowable influence range, which depends on the task.

R_r: For the route deviation reward and punishment function. After consulting the captain and expert experience, set the allowable deviation range of the course under sail. The definition is as follows:

$$R_r = \begin{cases} +1, & S_{bumper} \ge S_{thres} \text{ and deviate from the route} \\ +0.8, & S_{bumper} < S_{thres} \text{ and did not deviate from the route} \\ 0, & S_{bumper} \ge S_{thres} \text{ and did not deviate from the route} \\ -0.2 & other \end{cases} \tag{5}$$

S_{bumpur} is the area of the overlapping part of the ship area, and S_{thres} is the artificially set collision risk threshold. There are two types of ship domain models, as shown in Figure 4 below. The left side of Figure 4 below is the simplified collision domain model without considering the international maritime collision avoidance rules, and the right side is the simplified collision domain model considering the international maritime collision avoidance rules. In the research process, two different simplified models will be tested to observe the effect of algorithm decision-making[10].

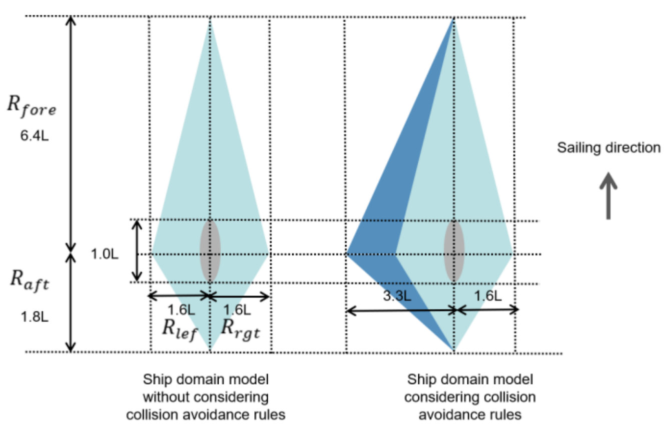

Figure 4. Two different simplified models of the ship domain.

The ship domain model can be characterized in the following form:

$$S_k + (x, y)\left| f_K(x, y, Q) \le \{R_{fore}, R_{aft}, R_{lef}, R_{rgt},\}\right.$$

$$f_K(x, y, Q) = \left(\frac{2x}{[1+\text{sgn}(x)]\cdot R_{fore} - (1 - sng(x)\cdot R_{aft}}\right)^k + \left(\frac{2y}{[1+\text{sgn}(y)]\cdot R_{rgt} - (1 - sng(y)\cdot R_{lef}}\right)^k \tag{6}$$

Ship domains of different shapes can be controlled with different values of k and different Q parameters. The above l sub reward functions together form a one-dimensional reward function matrix $\mathbb{R}$, and the calculation formula of the final reward value R is also given:

$$R = \mathbb{R} \cdot \Theta^T \tag{7}$$

where Θ is the weight parameter matrix of reward function, and the shape and size are the same as $\mathbb{R}$.

3.2 Study on trace control of proportional calculus based on neural network

Track control is the executive part of the collision avoidance algorithm, and its effect will be fed back to the algorithm[11]. Therefore, it is necessary to pay attention to the fast response and accuracy of the track control algorithm to implement the collision avoidance decision accurately and reduce the noise error[12]. By changing environmental factors such as wind, waves and flow in the simulation environment, the neural network can realize dynamic control of the three parameters controlled by calculus, as shown in Figure 5.

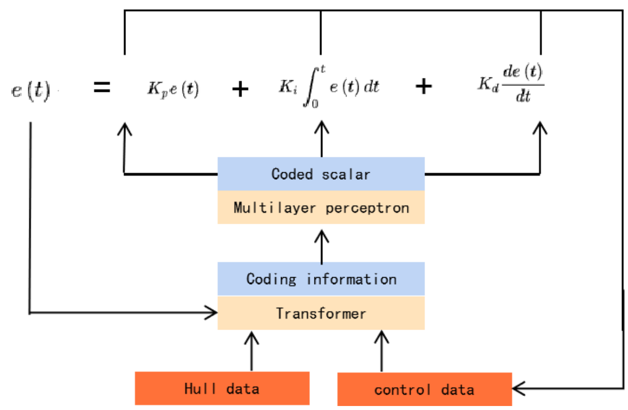

Figure 5. Dynamic PID parameter control method based on Transformer and MLP.

4. SOLID SHIP VERIFICATION AND INCREMENTAL UPDATE

The real ship verification uses VDR data for comparative verification, compares the reliability and effectiveness of the training algorithm, and establishes the foundation for the subsequent work; studies the algorithm optimization and effect improvement of the network of collision avoidance algorithm and track control[13]. For collision avoidance algorithm, all VDR data and optimization algorithms are used to reduce the calculation load of real ship, and conduct a new round of algorithm training. For the track control part, all VDR data are used and LSTM module is added to supplement the timing features[14], and comparative test is made to verify the effectiveness and reliability of the algorithm.

5. CONCLUSION

Closely following the major national needs and the main economic battlefield and taking the development trend of intelligent water transportation and the practical needs of autonomous navigation and safety control of large ships in complex waters as the topic background, this study aims to solve the key problem of autonomous collision avoidance of ships in open and busy waters, and puts forward a complete technical chain of “autonomous navigation environment construction—collision avoidance and track control algorithm research—real ship data verification and incremental update”. The specific technical scheme and path are given. The research results have important theoretical, technical and practical significance for expanding the research technical methods of independent decision-making of ship intelligent navigation, verifying and continuously improving the practicability of the algorithm model combined with real ship data, forming a new way to construct and grow the intelligent consciousness of ship machine driving from knowledge to data, and finally realizing the commercial application of ship intelligent navigation.

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