Dynamic obstacle avoidance algorithm of ships in Bridge Area based on potential energy field: A Case study of Shanghai-Suzhou-Nantong Yangtze River Railway Bridge

Liu Yihua*, **Wang** Ting* and **Liu** Nian*
*Shanghai Maritime University, Shanghai, 201306 China

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ABSTRACT

With the large-scale, high-speed and professional development of ships, the risk of ship collision is increasingly serious, navigation safety of bridge area is a research focus. This paper proposes an intelligent collision avoidance method for ships in navigable waters of bridge area based on potential field theory, which dynamically plans the optimal collision avoidance routes of ships considering the restrictions of channels, piers and ships. The potential energy field in the water area of the ship-bridge-channel integrated bridge area is established according to the real-time navigation situation. A* algorithm is used to search the minimum potential energy path, and the main nodes of the minimum potential energy path are extracted as collision avoidance route nodes. Taking Shanghai-Suzhou-Nantong Yangtze River Railway Bridge as a case study, the results show that the method can realize the digital description of navigable waters in the bridge area, and the dynamically planned collision avoidance route can ensure the navigation safety of ships in the bridge area. This method can provide technical reference for intelligent collision avoidance of ships, and can be used for safety management of bridge area by maritime authorities.

1. Introduction

Bridge area navigable water environment is complex [1]-[2], there are ship-bridge, ship-ship collision and other situations, is a collision accident high-risk area. Collision accidents not only damage ships and Bridges, but also affect navigation of bridge areas, resulting in economic losses in many aspects. How to avoid bridge collision accident is the key problem of water traffic. Some scholars put forward a ship collision early-warning system [3]-[5] from the perspective of Bridges to reduce the harm of ship collision. Based on the ship field, ship collision risk identification [6]-[9] is proposed, and a dangerous collision identification model is established between the target ship and its own ship to reduce the collision risk between ships. In this paper, from the perspective of ship navigation, the environment model of ship-bridge-channel integrated bridge area is established to plan the optimal collision avoidance route [10]-[21], so as to reduce the collision probability of ships in navigable waters of bridge area.

2. Description of collision avoidance problems of ships in bridge area

Navigation analysis of the bridge area is shown in Figure 1. Two piers and three ships constitute the situation of ships meeting in the bridge area. Taking the midpoint of the bridge navigation hole as the coordinate origin O, the following rectangular coordinate system is established. Set the width of pier as D_{pier}, navigable hole width as L_{bridge}, captain as L_{ship}, ship width as W_{ship}, (x_0, y_0) as ship position, and v as ship speed.

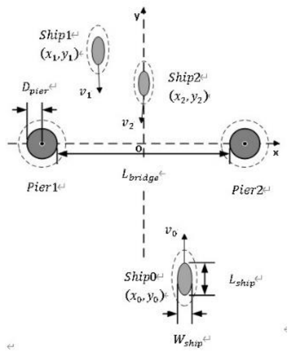


Figure 1 Collision avoidance analysis diagram of ships in bridge area

As can be seen from Figure 1, ships need to avoid bridge piers and meeting ships to pass the bridge area safely. Bridge area navigable water environment is complex, the bridge pier is fixed and the ship is in a dynamic position. and there are collision risks between ships, piers and meeting ships. Collision will not only damages the ship and the bridge itself, but also affects the navigability of the bridge area. Therefore, based on the potential field theory [22]-[25], A* algorithm [26] is used to search the minimum potential energy path in the potential field of the bridge area and plan the optimal collision avoidance route to reduce the ship-ship and ship-bridge collision risks.

3. Intelligent collision avoidance model of ships in bridge area

3.1 Intelligent collision avoidance model framework for ships in bridge area

Intelligent collision avoidance of ships in bridge area can be divided into three steps: construct potential environment, search potential energy environment and generate collision avoidance route. Intelligent collision avoidance frame of ships in bridge area is shown in Figure 2:

1) Construct potential environment: ship size data, channel water depth data and bridge pier size data are processed to construct the potential energy field of ship-bridge-channel integration;
2) Search potential energy environment: using A* algorithm to search the minimum potential energy path in the potential energy field of the bridge area;
3) Generate collision avoidance route: extracting the main path node of the minimum potential energy path as the path node of the optimal collision avoidance route.

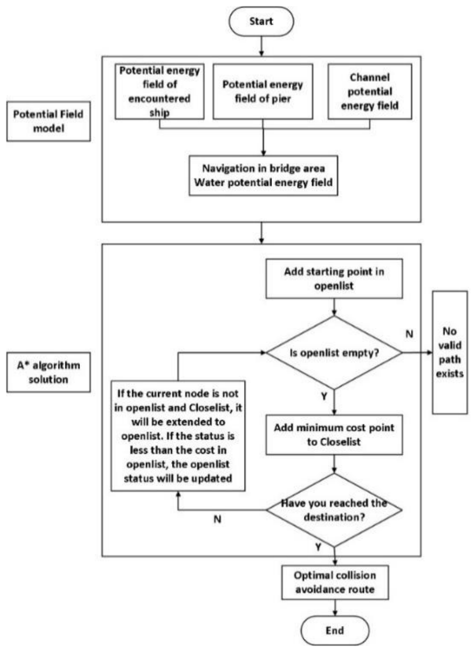


Figure 2 intelligent collision avoidance framework for ships in navigable waters of bridge area

3.2 Mathematical description of collision avoidance route

Ships need more navigation operations in collision avoidance, so the collision avoidance routes of ships are divided into sub-sections, as shown in Figure 3. The model is as follows:

$$P_i = (x_i, y_i) \tag{1}$$

$$P_{set} = \{P_1 、 P_2 、 \cdots P_i \cdots P_{n+1}\},\ i \in [1, n+1] \tag{2}$$

$$L: \underset{l_1}{\rightarrow} + \underset{l_2}{\rightarrow} + \cdots + \underset{l_i}{\rightarrow} + \cdots + \underset{l_n}{\rightarrow} \tag{3}$$

$$L_{set} = \left\{ \underset{l_1}{\rightarrow} 、 \underset{l_2}{\rightarrow} 、 \cdots \underset{l_i}{\rightarrow} \cdots \underset{l_n}{\rightarrow} \right\} \tag{4}$$

P_{set} Ship collision avoidance route point set, P_i is the ith main waypoint, where P_1 is the starting point and P_n is the ending point. L represents the total route from the starting point to the end, L_{set} represents the sub-segment set, and $\underset{l_i}{\rightarrow}$ represents the sub-segment i.

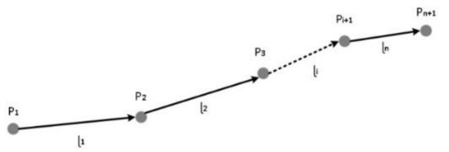


Figure 3 route diagram

3.3 Potential energy field

3.3.1 Channel potential field

With the development of large ships, the increasing draft of ships has more stringent requirements on channel depth. It is a prerequisite for navigation that the water depth of channel meets the ship's draft. Based on water surface as zero potential energy surface and channel depth as the value of channel potential energy field, the channel potential energy field is established. As show in Figure 4(a) and the function model is as follows:

$$E_c(x, y) = (a * x + b * y) ** 2 - D_{max} \tag{5}$$

Where $E_c(x, y)$ represents the channel potential energy of point (x, y) and D_{max} is the maximum water depth of bridge area. a and b are potential energy influence coefficients so that the function value is equal to the actual channel size. The channel potential energy value is higher in the position with high water depth, and lower in the position with low water depth.

3.3.2 Potential energy field of bridge pier

Collision between ship and pier will cause great economic loss, so pier must be avoided when sailing. The position of the pier will not change with time. The potential energy field of the pier takes the central point of the pier as the zero potential energy point, and the relative distance of the central point of the pier is the basis for the value of the potential energy of the pier. As show in Figure 4(b) and the function model is:

$$E_b(x, y) = \frac{b}{2\pi\sigma_x\sigma_y} e^{-\frac{(x-x_b)^2}{2\sigma_x^2} - \frac{(y-y_b)^2}{2\sigma_y^2}} \tag{6}$$

Where $E_b(x, y)$ represents the pier potential energy at point (x, y), and the position of the center point of (x_b, y_b) pier; b is the influence coefficient of potential energy, so that the function value is equal to the actual size of the bridge pier. σ_x and σ_y represent the influence radius of the X-axis and Y-axis of the bridge pier in the horizontal region. Near the center point of the pier, the greater the potential energy value of the pier, the higher the collision risk; Conversely, the smaller the pier potential energy value, the lower the collision risk.

3.3.3 Ship potential field

The navigation of a ship is affected by the ships it encounters. The ship's space position changes with time, leading to the dynamic change of the ship's potential energy field. The ship potential energy field takes the center point of the ship as the zero potential energy point and the relative distance from the center point of the ship as the basis for the potential energy value. As show in Figure 4(c) and the function model is:

$$E_{es}(x,y,t) = \frac{b}{2\pi\sigma_{xt}\sigma_{yt}} e^{-\frac{(x-x_t)^2}{2\sigma_{xt}^2}-\frac{(y-y_t)^2}{2\sigma_{yt}^2}} \tag{7}$$

Where $E_{es}(x,y,t)$ represents the potential energy of the point (x,y) at time t, (x_t,y_t) the position of the center point of the obstacle at time t, and the center point movement function is $x_t = x(t), y_t = y(t)$ indicates the navigation route of the vessel to be encountered. B is the potential energy influence coefficient, so that the function value is equal to the value of the size of the encountered ship, σ_{xt}、σ_{yt} refers to the x-axis and y-axis influence radius of the ship in the horizontal plane. Near the center of the ship, the higher the ship potential energy value, the higher the collision risk; On the contrary, the smaller the ship potential energy value, the lower the collision risk.

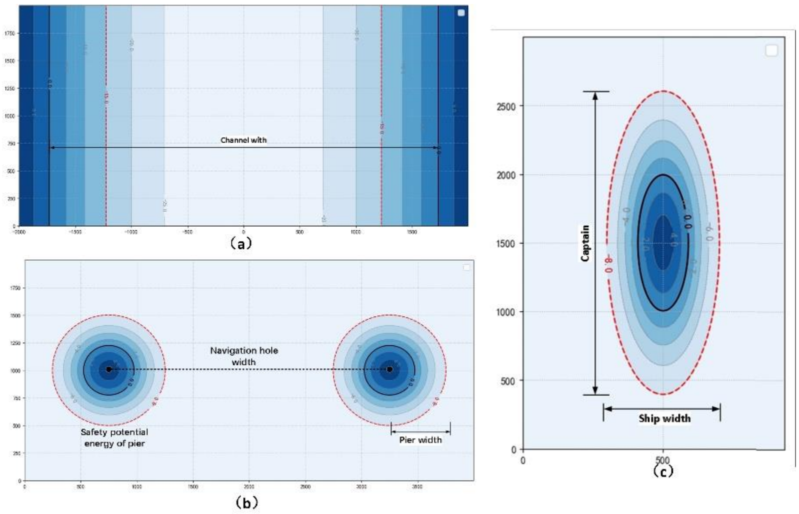


Figure 4 Schematic diagram of potential energy field

3.4 Objective function

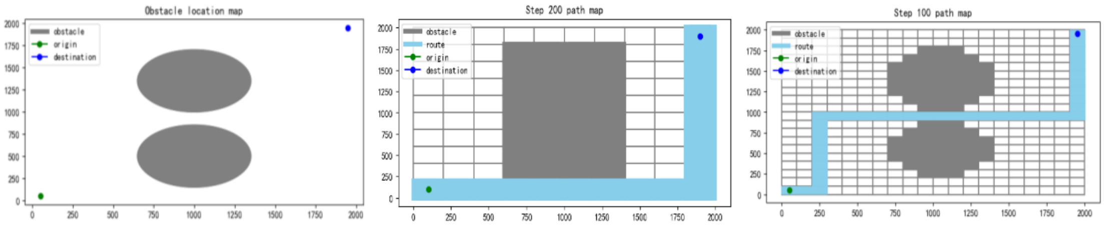
Potential energy fields of channel potential energy field, pier potential energy field and ship potential energy field are based on channel water depth, pier size and ship size. The values of the three potential energy fields are all based on space distance. Therefore, the three potential energy fields are superimposed to construct the potential energy field of water area of ship-bridge-channel integrated bridge area, Ship collision risk is higher at the position with high potential energy value, and lower on the contrary. To find the minimum potential energy path as the optimal collision avoidance route for navigable waters in the bridge area. The functional model is:

$$minE_{\text{sum}} = \{E_c(x,y) + E_b(x,y) + E_{es}(x,y)\} \tag{8}$$

$$\begin{cases} E_c(x,y) > E_c(safe) \\ E_b(x,y) > E_b(safe) \\ E_{es}(x,y) > E_{es}(safe) \end{cases} \tag{9}$$

3.5 Solution algorithm

A* algorithm is a heuristic search algorithm with high speed in path search and raster map is often used in its environment composition. However, raster method has poor capability in describing micro-environment, and the value of grid step is always difficult. In Figure 5(a), the shadow area is obstacle. In Figure 5(b) and (c), the environment is rasterized with step size of 200 and 100 respectively, and path search is carried out. The path found is the path connected by blue blocks. It can be seen from the figure that the selection of grid step has different influence on the description of obstacles, which directly leads to different planned paths. To sum up, an accurate description of the environment is the basis of the search path.



(a) (b) (c)

Figure 5 Diagram of rasterized environment

Bridge area belongs to micro environment for ship navigation and has high requirements for environment description. Rasterized map mainly stores map information through two-dimensional data, which is suitable for low-precision environment description. The potential energy field is described by three-dimensional space data, which is suitable for the environment description of high precision requirement. Therefore, potential energy field is suitable for the description of complex environment of bridge area.

4.Experimental analysis

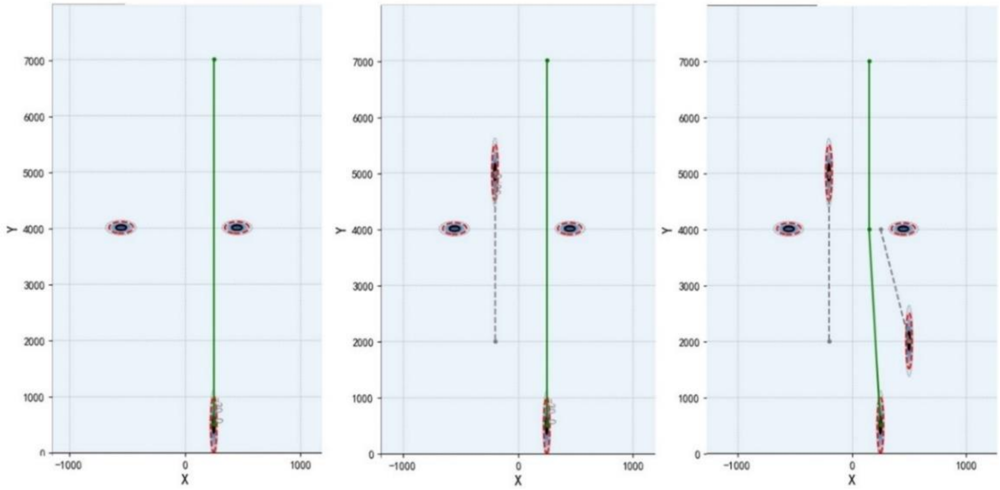
The purpose of the experiment is to verify the effectiveness of the collision avoidance method proposed in this paper. By verifying the safety and practical feasibility of collision avoidance path to verify the effectiveness of the method. Safety verification experiment: By comparing the safety of collision avoidance path with or without potential energy field modeling, the safety evaluation is based on the space distance between the planned route, bridge pier and other ships. Practical feasibility verification experiment: Taking the water area of the main navigable bridge area of shanghai-Suzhou-Nantong Yangtze River Highway and Railway Bridge [27]-[29] as the case study, the optimal collision avoidance route of navigable water area of the bridge area is planned to verify the practical feasibility of the intelligent collision avoidance method of ships.

4.1 Safety verification experiment

In the safety verification experiment, the control variable method is adopted. In the case of potential energy field and no potential energy field, A* algorithm is used to search ship collision avoidance paths for navigable waters of bridge areas with no other ship, single other ship and multiple other ships, and the safety of planned routes is compared. As shown in Table 1, ships and piers in the simulation experiment are simulated. Figure 6 is the collision avoidance route under potential energy field in bridge area, Figure 7 is the collision avoidance route without potential energy field in bridge area, (a) no other ships, (b) a single other ship, (c) multiple other ships. In the figure, the red dotted line represents the safety area of pier and ship, the black line represents the zero potential energy surface, the gray dotted line represents the shipping route, and the green line represents the shipping route planning.

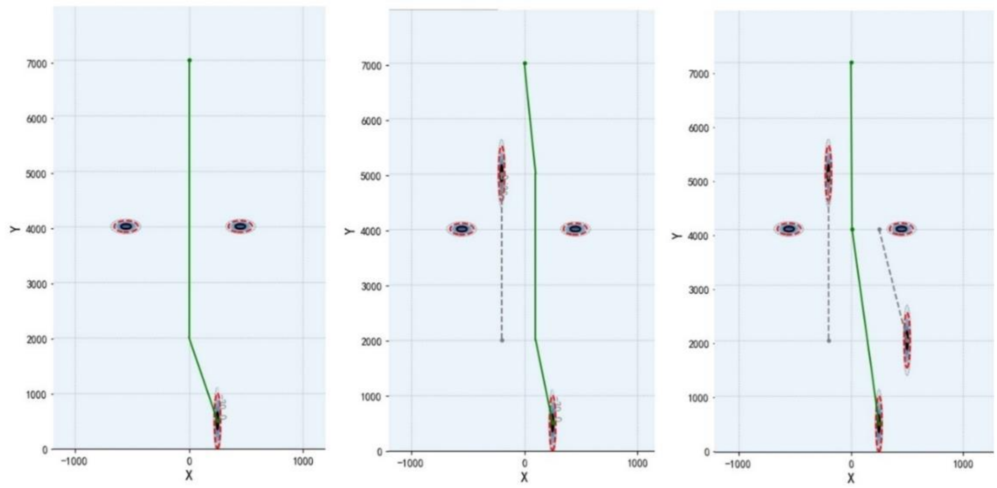
Table 1 Bridge area water area and representative ship type information table

Width of main navigation hole Unit: m	The width of the piers Unit:m	Represents ship type captain Unit:m	Represents the type and width of the ship Unit:m	Represents the maximum height of a ship above waterline Unit:m	Represents the full draft of the ship type Unit:m
900	60	250	30	22	13



(a) (b) (c)

Figure 6 Intelligent collision avoidance of ships without bridge potential field



(a) (b) (c)

Figure 7 Intelligent collision avoidance of ships under potential energy field in bridge area

The direct cause of ship collision is that the ship is too close to the obstacles in the environment, so the evaluation basis of collision avoidance path safety is as follows: the minimum distance between the collision avoidance path and the surrounding obstacles. When the minimum distance is larger, it means that the ship is far away from the obstacles on the route, and the route safety is higher. On the contrary, the lower the airline safety.

Table 2 Minimum distance table

Minimum distance (Unit:： m)	without bridge potential field			bridge potential field		
	no other ships	a single other ship	multiple other ships	no other ships	a single other ship	multiple other ships
	48	48	38	384	198	136

According to the data in Table 2, the minimum distance of potential energy field under three different conditions is better than that without potential energy field. Therefore, the collision avoidance path planned under the potential energy field in bridge area has better safety.

4.2 Practical feasibility experiment

4.2.1 Analysis on navigable situation

The Shanghai-Suzhou-Nantong Yangtze River Rail-highway Bridge has a total length of 11,072 meters. The bridge is located in the busiest section of the Golden Waterway of the Yangtze River. The channel width is limited, and the ship traffic flow is dense and complex, with an average daily flow of more than 2,000 ships. The navigable environment of the bridge area is complex, with many navigation channels and high traffic density, and there is a certain risk of ship collision. Therefore, this paper chooses the water area of 2 km upstream and downstream of the main navigable hole of Shanghai-Suzhou-Nantong Yangtze River Rail-highway Bridge to conduct the experiment.

4.2.2 Bridge section data

In this paper, the upstream and downstream 2 km range of the main navigable hole of Shanghai-Suzhou-Nantong Yangtze River Bridge is selected as the navigation warning area for ships. The bridge pier 28# and 29# of the main navigable hole are 58.7 meters wide, representing the type of 50,000t container ship. The detailed information is shown in Table 3.

Table 3 Bridge area water area and representative ship type information table

Size of main navigation hole area Unit：m^2	The width of the piers Unit：m	Represents ship type captain Unit：m	Represents the type and width of the ship Unit：m	Represents the maximum height of a ship above waterline Unit：m	Represents the full draft of the ship type Unit：m
900x62	58.7	293	32.3	21.8	13.0

4.2.3 Generates collision avoidance course

Firstly, the potential energy field of channel, pier and ship is established, and the potential energy field of bridge area is obtained by superposition of the three. Then, the path of minimum potential energy in bridge area is searched. Finally, the main path node of the minimum potential energy path is extracted as the path node of the planned route. As shown in Figure 8, the potential energy value of the darker position is higher; On the contrary, the potential energy value is low, and the solid black line is the collision avoidance path, which can effectively avoid encountering ships.

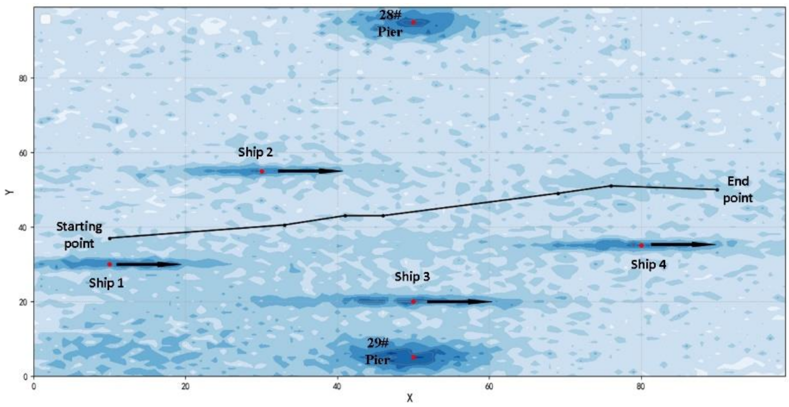


Figure 8 Potential energy diagram of collision avoidance path

As shown in Figure 9, the planned route is put into the electronic chart. The bridge position line is red dotted line, pier 28# and pier 29# are green dots, the meeting ship’s position and sailing direction are shown in the red arrow, collision avoidance path is black solid line, collision avoidance path node is shown in Table 4.

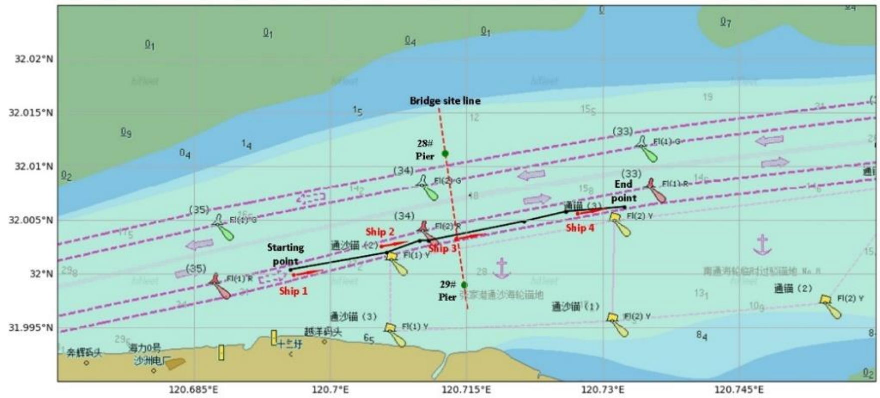


Figure 9 Electronic chart of collision avoidance path

Table 4 nodes of collision avoidance path

Collision avoidance path node	[[120.6956, 32.0004], [120.70618, 32.001975], [120.70986, 32.0031], [120.71078, 32.0031], [120.72136, 32.0049], [120.72596, 32.0058], [120.7324, 32.00625]]

5. conclusion

Based on the potential field theory, this paper proposes an intelligent collision avoidance method for ships in bridge area. According to the water depth, pier and ship data in bridge area, the potential energy field of ship-bridge-channel integrated bridge area is established. A* algorithm is used to search the minimum potential energy path and extract the main route points to obtain the optimal collision avoidance route.The effectiveness of the ship collision avoidance method is verified by comparative experiments and the shanghai-Suzhou-Nantong Yangtze River railway bridge.

1) The navigable water environment of bridge area is complex, and the risk of collision is greater. The bridge is static while the ship is dynamic, so the ship has relatively better spatial flexibility. From the perspective of ship navigation, this paper realizes intelligent collision avoidance of ships in navigable waters of bridge area, improves the safety of space relative position between ships, piers and ships in encounter, and reduces the collision risk of ships in bridge area.
2) Grid method in the mathematical description of microscopic environment, the selection of grid size has always been an unsolved problem. In this paper, the three-dimensional potential energy model is used to accurately describe the micro-environment of ship-bridge integration, which effectively avoids the problem of grid size selection.
3) The collision avoidance method proposed in this paper dynamically plans collision avoidance paths according to the real-time bridge area environment. The initial potential energy field is constructed according to the relevant information of navigable waters in the bridge area. When a new meeting vessel is detected, the potential energy field of the vessel will cover the corresponding position of the initial potential energy field, effectively realizing the dynamic description of the navigable environment in the bridge area and the dynamic collision avoidance of vessels.

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Author's Biography

Liu Yihua, born in 1980 in Hunan province, received his bachelor's degree in ocean Navigation from Shanghai Maritime University in 2002, master's degree in Vehicle Operation Engineering from Shanghai Maritime University in 2004, and doctor's degree in vehicle operation Engineering from Shanghai Maritime University in 2020. He is currently associate professor, doctoral supervisor and master supervisor of Shanghai Maritime University. His research interests include maritime traffic engineering, traffic flow theory, big data and machine learning, port and navigation simulation and its application, global meteorological navigation, intelligent transportation (navigation), etc.

Wang Ting, born in 1997 in Anhui province, is now studying for her master's degree in Vehicle Operation Engineering at Merchant Marine College of Shanghai Maritime University. Her research interests include maritime traffic engineering, global meteorological navigation, intelligent ship path planning, etc.