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ABSTRACT

With the continual development of modern transportation technology and artificial intelligence technology, how to recognize the complex phenomenon of ship behavior existing in maritime traffic has become a hot topic. Maritime traffic is a complex system, the emergence of ship behavior is a leading cause of traffic complexity, and make up the core ideas of this research. This research studies ship behavior from three aspects: ship individual behavior, ship-ship interaction and multi-ship behavior. According to the movement state attribute, the improved Social Force Model has been developed by considering of the interactive effects between ships. On that foundation, the complex network model has been built to analyze the emergence of multi-ship behavior in a macroscopic view. Through experimental analysis of ship behavior in different scenarios, the results show that the repulsive force between ships changes in the ship behavior dynamic model can express the dynamic characteristics of the ship. And structural entropy in marine traffic situation complex network has been proved to describe the maritime traffic system. As such, the framework proposed in this paper can provide a new perspective for further understanding and research of ship behavior.

1. Introduction

1.1. Background

Traffic system is a typical self-driven, non-equilibrium and multi-particle system, which is a complex system with nonlinear interaction (Damon, 2010; Cao and Chugh, 2018). Ship behavior is influenced by the natural environment, infrastructure, traffic rules, and the marine traffic situation constituted by the surrounding ships, which have the characteristics of dynamics and uncertainty (Murray and Perera, 2021). Based on the intuitive judgment of Officer on Watch (OOW) and Vessel Traffic Services Operators (VTSOs), it is difficult to understand and analyze the ship's behavior from the complex environment in a short period and to have a deep knowledge of it (Yoo and Lee, 2021). With the continuous development of technology, various navigational aids such as radar, Automatic Identification System (AIS), electronic charts and other equipment are widely used on ships, which can collect, send and feedback the ship-related dynamic information in real-time, helping OOW and VTSOs to track and supervise ships effectively (Cervera et al., 2011). Whereas, it is still difficult to discover some hidden behaviors of ships in the massive data and complicated situations, which may lead to the formation of urgent situations between ships or even collision accidents (Wen et al., 2015; Chen et al., 2018). The current study about ship behavior focused on collision avoidance and ship behavior pattern mining (Gao and Shi, 2020; Liang et al., 2021). But the key issues of how to perceive ship behavior and how to analyze the evolutionary characteristics of ship behavior still need further breakthroughs.

1.2. Motivation

The above-mentioned problems and challenges will be faced during the development of intelligent traffic supervision, and new solutions

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need to be found to enable VTSOs to obtain comprehensible ship behavior quickly and accurately (Zhong et al., 2018). Maritime traffic system is a complex dynamic evolutionary system with a large number of stochastic and non-linear factors, such as changes in the environment and interactions between ships. To this end, it is critical to construct a dynamic model to analyze the mechanism of ship behavior. Therefore, an improved Social Force Model (ISFM) has been proposed to model the dynamics of ship behavior in this research. The ISFM takes the individual ship as the research object and simulates the ship interaction under real conditions by mathematical and physical methods. As an important class of microscopic models, ISMF plays a very important role in the study of ship behavior. This research introduced improved social force to modeling ship behavior dynamics, which the method proposed in this paper can provide a promising angle of view to explore the laws of ship behavior. And then the marine traffic situation complex network (MTSCN) has been built to research the phenomenon of mulita-ship behavior, the emergence of ship behavior in macroscopic view. This research analyses the maritime traffic system from a system behavior perspective and proposes a more scientific and comprehensive methodology.

1.3. Research objectives and contributions

This paper aims at dynamic modeling ship behavior for marine traffic situation analysis. The ship-ship interaction model will be developed to explain how individual excitation will be executed at the micro-level. And the multi-ship behavior dynamic model will be done to obtain an as realistic as possible description of the maritime traffic system. Considering the current demand for ship behavior modeling, the traffic scene can be modularized in future applications based on the method proposed in this research, and a multiscale ship behavior dynamics simulation system would be developed to meet the needs of maritime traffic supervision and planning. The contributions of the work have two folders:

(i) Firstly, this research introduced social force model and complex network theory into describing multiscale ship behavior, based on which the ship behavior dynamic model was built.
(ii) Secondly, a research framework for marine traffic situation analysis is proposed and realized the integration of ship behavior microscopic model and macroscopic model.

The remainder of this paper is organized as follows. Section 2 reviews research related to the ship behavior model in traffic. Section 3 is the research methodology, followed by case study in Section 4. Finally, the discussion and conclusions are summarized in Section 5.

2. Literature review

2.1. Related works on the ship behavior model

Modeling of ship behavior is an important topic in maritime traffic research. Recently the study of the ship behavior model can be divided into rule-based models and mathematical models (Zhou et al., 2019). For the internal features (position, course, speed, heading) of the ship, some special models based on rules such as Cellular automata (CA) consider the position of the ship as cell (Liu et al., 2010, 2021; Suo et al., 2021; Qi et al., 2021), other general rule-based model modeled the position as a specific distribution (Gucma et al., 2017), or distribution generated from historical data (Xu et al., 2015; Özlem et al., 2021). The ship speed is regarded as constant or depends on ship type, or is determined by historical data and extreme value section or distribution are used to represent (Goerlandt and Kujala, 2011; Rayo, 2013; Huang et al., 2016). In respect of course of ships, most models designed the course to follow the trend of the waterway, however, the course will change instantly when the direction of the routes changes, therefore, the course has been defined as proportional feedback of rate-of-turn (Aarsather, 2011). Considering the external impacts on ship behaviors, random variables have been generated to simulate the effects of sea conditions on ship behaviors (Qu et al., 2012; Li et al., 2021a), and the effects of the tidal window was proposed for ship behaviors (Piccoli, 2014; Orseau et al., 2021). The behaviors of collision avoidance is widely studied in rule-based models. Some rules have been defined for decelerating based on distance in one-dimension space (Qi et al., 2017; Gucma et al., 2017). And fuzzy approach have been used to resolve multi-ship collision avoidance problem based on experimental validation in virtual and real environment (Fiskin et al., 2021; Brcko et al., 2021). Besides, ship domain and adapted model related are also proposed to determine the behavior when two ships encounter (Colley et al., 1984; Davis et al., 1980; Fiskin et al., 2020; Rawson and Brito, 2021; Du et al., 2021). More models focus on the situation defined in International Regulations for Preventing Collisions at Sea (COLREGS), closest point of approach (CPA) and distance to closest point of approach (DCPA) was calculated in most models to determine the evasive actions, some research determined the evasive actions for increasing CPA and TCPA, separating axis theorem and CPA was united to recognize the collision candidates (X. Chen et al., 2018; Yuan et al., 2021; Vestre et al., 2021; Chun et al., 2021). Furthermore, the behaviors in the starboard-to-starboard situation and multi-vessel situation are also modeled (Miyake et al., 2015; Huang et al., 2016; Yoo and Lee, 2019).

In recent years, mathematical methods have been widely used in the modeling of ship behavior. Artificial Potential Field (APF) is an emerging method for ship defined as an agent to determine the actions especially for turning in the context (Lyu et al., 2019). Thus, more attention was paid to the modeling of attractive and repulsive forces. Fixed objects including banks, boundaries of channel and obstacles are defined as potential fields in most models, wind and current are also included (Xiao, 2014; Rong et al., 2014; Cheng et al., 2017). Besides, the encounter situations are taken into consideration at the same time. However, the speed in the APF is ignored to a certain extent, most models assume the speed is constant or changes when the encounter with other vessels or obstacles and the effects in the context like wind and current on the speed are seldom mentioned. The optimal control model presents the behavior of the ship in detail which is a function of position, speed, heading and rate-of-turn (He et al., 2022). The goal of the behavior adopted is to minimize the cost function under the condition of constraints, more specific, to minimize the CPA and TCPA in an encounter situation, other factors in the context are not considered, except for bank and bending of the waterway (Shu et al., 2015a, 2015b). The system dynamics model presents the ship behaviors in a state-space to demonstrate the evolution in a system over time. The motion features, wind, current and bank effects are the input of the differential equation or PID control, and the actions are taken to avoid the collision or danger output (Sarioz and Narli, 2003; Lisowski, 2016; Liu et al., 2020). However, present dynamic models rely more on the simulation or vessel with specific parameters, lack the data about multi vessels in a large scale region.

2.2. Related works on behavior dynamic in traffic

Behavior dynamics have always been a hot topic in different areas of traffic. In the field of pedestrian traffic, the force-based approach is a very common method of dynamic modeling, which is based on Newtonian mechanics, where pedestrian motion is quantitatively described as a result of the sum of various forces, i.e., self-driven, non-contact, and contact forces (Helbing and Molnar, 1995; Johora and Müller, 2021). The magnetic force model (Okazaki and Matsushita, 1993) and centrifugal force model (Chraibi et al., 2010) are the simulation models widely used in the framework of force-based approaches. The concept of a hypothetical social force has been proposed to represent the interaction of untouched pedestrians to construct a social force model (Helbing and Molnar, 1995; Helbing et al., 2000; P. Chen et al., 2018). Based on this, many suggestions were made to improve the model (Kretz et al., 2018; Li et al., 2021b). Additional rules are also proposed for some specific scenarios such as sidewalks, stairs and subway stations (Wang et al., 2014; Zeng et al., 2014; Qu et al., 2015; Cantillo et al., 2015; Seriani and Fernandez, 2015; Yang et al., 2021). The force-based approach can reproduce many typical self-organization phenomena, which is very consistent with empirical studies.

The air transportation system is also a typical large-scale complex system. In recent years, flight delay is an important aspect of dynamic modeling in air transportation. Some researchers built a delay propagation tree based on the Bayesian network model, which well simulated the delayed propagation in airline networks (Wu et al., 2018 and 2019). Du et al. (2018) constructed a delay causal network (DCN) based on granger causality test and investigated the topological and temporal characteristics of the delay causal network, thus revealing the characteristics of specific airports. Zhang et al. (2020) established an Airport Susceptible Infection Recovery (ASIR) model has been established based on the transmission mechanism of infectious diseases, and abstracted different network configurations under complex network theory to simulate the ASIR model. Qin et al. (2019) defined metrics to quantify the overall delay level and proposes an agent-based data-driven model including four factors: aircraft rotation, combat connectivity, scheduling process and interference, constructs a simulator to simulate the propagation of aircraft delays in the aviation network, and analyzes the degree of influence of different factors on the propagation of delays.

With the increase of water activities, dynamic modeling is also the main focus of attention in maritime traffic. Marine traffic flow complexity model have been constructed using traffic characteristics such as relative distance, relative speed and intersecting trajectories (Wen et al., 2015). Inspired by the theory of network dynamics, the maritime traffic has been modeled as a virtual network, called Marine Traffic Situation Complex Network (MTSCN), then the evolution of the maritime traffic system was be analyzed through the topological characteristics of the MTSCN such as degree, vertex strength, clustering coefficient and network structure entropy (Sui et al., 2020). On this basis, the marine traffic profile and ship importance evaluation model have been developed (Sui et al., 2021, 2022).

3. Methodology

The framework for the dynamic model of ship behavior is depicted in Fig. 1. It consists of the three components: description of ship individual behavior, modeling of ship-ship interaction and analysis of multi-ship behavior based on complex network.

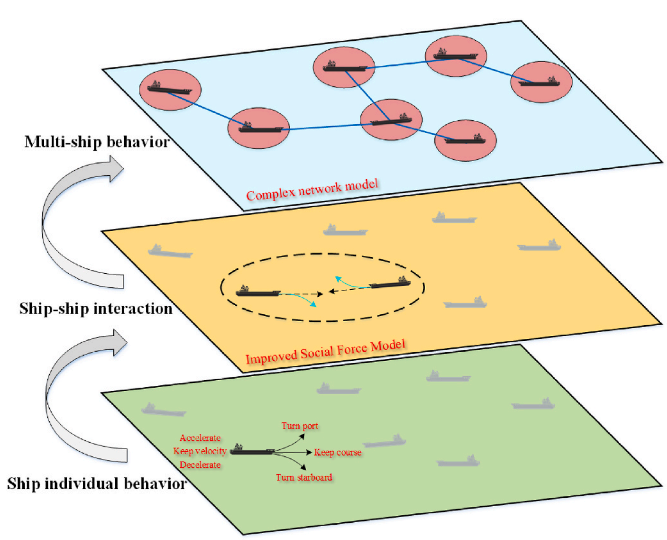

Fig. 1. Logic framework in this research.

3.1. Description of ship individual behavior

In order to describe ship individual behavior, Wen et al. (2021) have developed the concept of ship atomic behavior to describe the micro behavior of ships. The navigation status of a ship at each time mainly includes state sets composed of position information (longitude and latitude), ship speed, course, and other dynamic attributes. And atomic behavior is the behavior that the ship navigation status does not change in a period of time. The navigation status of a ship can be expressed as follows.

$$p_l = \{s_l, v_l, c_l, t_l\}, \quad (1)$$

where $s_l = (lat_l, lon_l), l \in [1, n]$, n is the number of trajectory points. lat_l and lon_l is latitude and longitude respectively. v_l is the ship speed, the unit of ship speed is the "knot". c_l is the ship course. t_l is the time. Therefore, the atomic behavior of ships is given by:

$$atom = \{p_1, p_2, \cdots p_m\}, \quad (2)$$

where m is the number of trajectory points in a atomic behavior. According to the movement state attribute of the ship, the ship individual behavior is divided into 10 types based on ship atomic behavior (Wen et al., 2021). It can be seen in Table 1.

3.2. Modeling of ship-ship interaction

In the process of ship navigation, it will form a temporary group with the surrounding ships, and the ships in the group form different spatial relationships. This relationship may be stable, or it may change due to the action of one or several ships. In this group, the behavior of ships will directly or indirectly affect other ships, resulting in the change of other ships' behavior, or the change of the relationship between ships, or even the traffic situation. We define this influence as the ship-ship interaction.

3.2.1. Process of ship-ship interaction

If a certain parameter of the ship at a certain time, such as changing the course and speed, the navigation status of the ship will produce a variation Δp_l. At this time, there will be an overall variation $\Delta S = \sum \Delta p_l$ in the maritime traffic system. When the variation of system status is large enough, it is easy to cause ship safety accidents if the ship does not adjust the speed or course. Therefore, when the navigation state of a ship changes, other ships in the waters need to decide whether they need to make corresponding changes to their behavior according to the perceived state variables to ensure navigation safety. The process of ship-ship interaction is summarized as follows:

(i) Perceive the surrounding traffic environment and determine the intention and behavior characteristics of other ships.
(ii) Determine the movement trend of other ships.
(iii) Determine whether a change of navigation is required.
(iv) Movement execution.

Table 1
Ship individual behavior type.

Number	Ship individual behavior
1	Keep velocity and keep course
2	Keep velocity and turn port
3	Keep velocity and turn starboard
4	Accelerate and keep course
5	Accelerate and turn port
6	Accelerate and turn starboard
7	Decelerate and keep course
8	Decelerate and turn port
9	Decelerate and turn starboard
10	Halt

The ship-ship interaction can be divided into three stages: situation awareness, decision making and action execution. When the ship constantly perceives the traffic situation, receives the navigation information of other ships around, and judges the security threat of other ships to own ship. According to the navigation rules, the ship behavior is constantly adjusted, such as steering, deceleration, etc., until the safety threat between the two ships is removed. When the ship behavior changes, it will have an impact on the current traffic situation, and the changes in the traffic status will be feedback to the traffic supervision system to provide reference information for the supervisors' perception and decision on the traffic situation. As shown in Fig. 2, the hierarchical diagram of the ship-ship interaction structure is shown.

3.2.2. Improved social force model

According to the characteristics of the ship individual behavior, description of the information interaction when the ship behavior changes are the key problem to building the ship-ship interaction model. In this research, the improved social force model is introduced to analyze the mutual forces that exist during the movement of ships to construct a mathematical model describing the interaction of ship behavior. The behavioral interaction process among ships is reflected by analyzing the changes of the forces acting on the ship during its movement.

The idea of the social forces model originates from Lewin's theory of the personal domain (Lewin, 1951), which suggests that people are under the influence of 'social fields' or 'social forces', and that changes in their movement are the result of interactions between people and environment. In 1995, Helbing quantified this idea in the form of a mechanical equation, which led to the construction of the Social Force Model (SFM), a new field of simulation modeling (Helbing et al., 2000 and 2000). Helbing argued that the movement of an individual is mainly due to the self-driven force of its consciousness being influenced by the surrounding individuals and the environment and that the state of movement is constantly changing. So it is necessary to research ship behavior from a microscopic perspective.

According to the social force model (Helbing et al., 2000 and 2000), the interactions between ships, between ships and surrounding obstacles, etc. are quantified as forces, and the acceleration of the ship at each moment is calculated using Newton's second law, and the ship position is continuously updated. The ship behavior dynamics model can be expressed as follows:

$$\frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^{\,0}(t) + \sum_{j(i\neq j)} \vec{f}_{ij}(t) + \sum_{o} \vec{f}_{oi}(t) + \vec{\varepsilon}_i(t), \tag{3}$$

where $\vec{f}_i^{\,0}(t)$ is the individual self-driving force, $\vec{f}_{ij}(t)$ is the repulsive force between ship$i$ and ship$j$, $\vec{f}_{oi}(t)$ is the repulsive force between ship$i$ and obstacle, $\vec{\varepsilon}_i(t)$ is the random fluctuation force, t is the time. This study focuses on the analysis of the behavioral disturbance effects between ships, so the repulsive force between ship and obstacle and the random fluctuation force is not considered. equation (3) can be simplified as:

$$\frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^{\,0}(t) + \sum_{j(i\neq j)} \vec{f}_{ij}(t), \tag{4}$$

In the social force model, a circle is used to model the individual safety domain. The various homogeneities exhibited by the circular domain lead to the fact that the occupied space of the ship is the same for all directions and cannot show the real scale characteristics of the ship. In reality, there is an elliptical domain of the ship, so we introduce the ship domain into the social force model, construct the dynamic safety domain of the ship using the generalized centrifugal force model (Chraibi et al., 2010), and use the ship safety domain instead of the circular domain of the social force model.

In the 1970s, Fujii first proposed the concept of ship domain when he studied the traffic capacity of the sea off Japan and gave the elliptical ship domain model and corresponding dimensions through traffic survey and probability statistics (Fujii and Tanaka, 1971). In this section, based on the ship domain model, the dynamically adjusted scaling factor is added to construct the dynamic safety domain. The shape of the safety domain is considered with the change of speed based on the generalized centrifugal force model. When the ship speed is 0, the dynamic safety domain is the ship domain. The ship domain and dynamic safety domain are shown in Fig. 3.

The Fujii ship domain model is shown in Fig. 3(a) (Fujii and Tanaka, 1971). R_i is the major semiaxis of ship domain, $R_i = 4L_i$. Si is the minor semiaxis of ship domain, $S_i = 1.6L_i$. Li is the length of ship$i$.

The dynamic safety domain is shown in Fig. 3(b).

$$A_i = R_i + v_i\tau_i, \tag{5}$$

$$\alpha_i = \frac{v_i\tau_i}{R_i}, \tag{6}$$

$$B_i = S_i \times \alpha_i, \tag{7}$$

where A_i is the major semiaxis of the dynamic safety domain. B_i is the minor semiaxis of the dynamic safety domain. α_i is the scale factor. τ_i is the response time. v_i is the speed of the ship$i$.

The individual self-driving force is the intrinsic force of the ship towards the navigational goal. This force allows the ship to adjust its behavior during the voyage to achieve the purpose of navigation. A schematic diagram of ship individual self-driving force is shown in

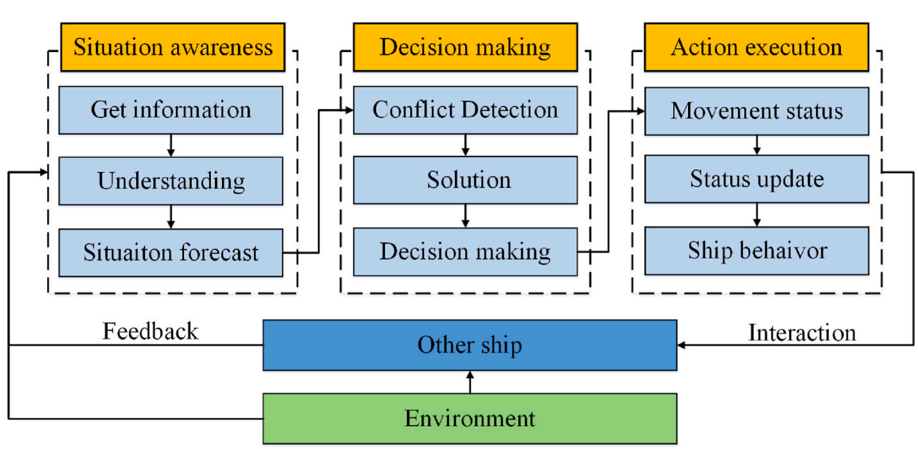

Fig. 2. The hierarchical diagram of the ship-ship interaction.

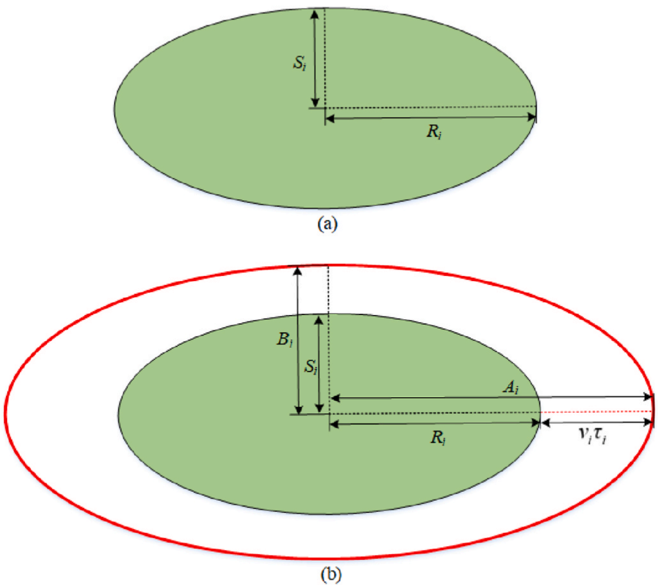

Fig. 3. Ship domain and dynamic safety domain.

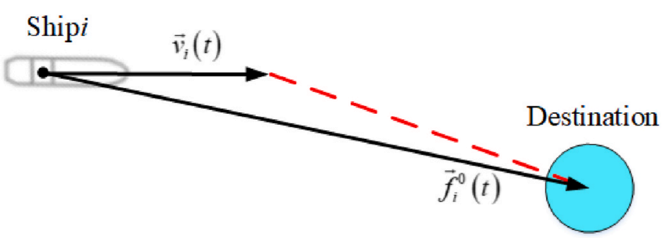

Fig. 4. Schematic diagram of ship individual self-driving force.

Fig. 4.

The expression of the individual self-driving force is as follow:

$$\vec{f}_i^{\,0}(t) = m_i \frac{v_i^0(t)\vec{e}_i^{\,0}(t) - \vec{v}_i(t)}{\tau_i}, \tag{8}$$

where $v_i^0(t)$ is the desired speed value of ship*i* at *t*. $\vec{v_i}(t)$ is the actual speed of ship*i* at *t*. m_i is the displacement volume of the ship*i*, the unit is 100 kiloton. τ_i is the response time of the ship*i*.

The repulsive force between ships is the degree of interaction between a ship and its surrounding ships in the process of ship motion. In addition to the impact on the environment, the ship will also be affected by other ships in the water area. During the collision avoidance operation, the ship needs to turn, accelerate and decelerate, which shows that there is a relationship of mutual influence between the ships. This relationship is expressed by repulsive force between ships. The repulsive force between ships is shown in Fig. 5.

The expression of the repulsive force is as follow:

$$f_{ij}(t) = -m_i k_{ij} \frac{(\lambda v_{ij})^2}{d_{ij}} \vec{n}_{ij}, \tag{9}$$

where v_{ij} is the relative speed of ship*i* and ship*j*. λ is an adjustable parameter. $\vec{n}_{ij}$ denotes the unit vector of the ship*j* pointing to the ship*i*. d_{ij} is the distance from the safety domain boundary of ship*j* away from the safety domain boundary of ship*i* (Zhang et al., 2016), see Fig. 5 k_{ij} is the approaching coefficient. The k_{ij} is determined by the approaching rate r_{ij}. If the approaching rate is greater than or equal to 0, it means that the two ships are sailing in a divergence trend, $k_{ij} = 0$. If the approaching rate is less than 0, it indicates that there is a convergence trend between ships, $k_{ij} = 1$. The calculation procedures of k_{ij} are as follows.

$$k_{ij} = \begin{cases} 1 & \text{if } r_{ij} < 0 \\ 0 & \text{otherwise} \end{cases}, \tag{10}$$

$$r_{ij} = \frac{\vec{d}_{ij} \bullet \vec{v}_{ij}}{\left\|\vec{d}_{ij}\right\|} = \left\|\vec{v}_{ij}\right\| \bullet \cos\left(\vec{d}_{ij}, \vec{v}_{ij}\right), \tag{11}$$

The calculation procedures of d_{ij} are as follows.

$$\theta_i = \arccos\left(\frac{y_2 - y_1}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}\right) - \varphi_i, \tag{12}$$

$$l_i = \left(\frac{1 + \tan^2\theta_i}{\frac{1}{B_i^2} + \frac{\tan^2\theta_i}{A_i^2}}\right)^{½}, \tag{13}$$

The calculations in this study are carried out in a Cartesian coordinate system, so the Euclidean distance is chosen to measure the ship

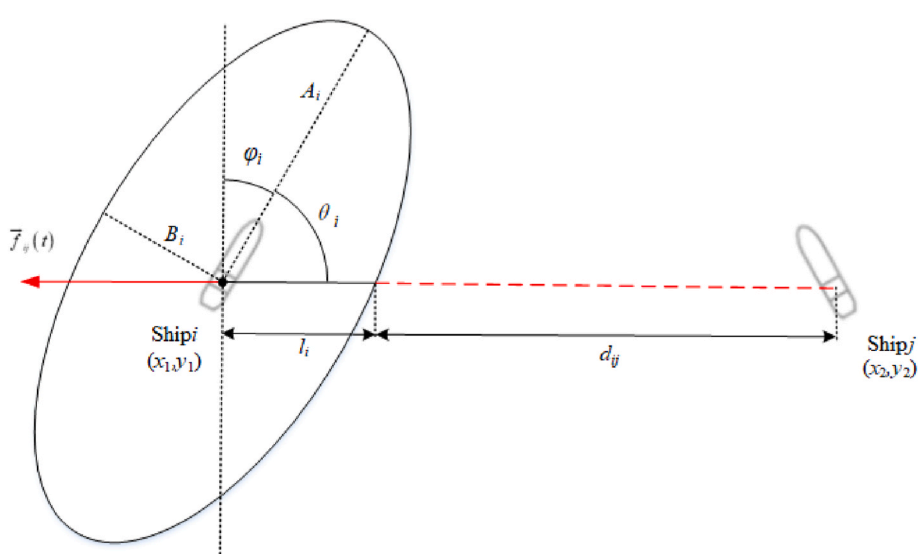

Fig. 5. Schematic diagram of the repulsive force.

distance. So, the d_{ij} can be obtained by equations (14) and (15).

$$d_{ij} = D_{ij} - l_i, \tag{14}$$

$$D_{ij} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}, \tag{15}$$

3.3. Analysis of multi-ship behavior based on complex network

In maritime traffic system, ships are individuals with basic intelligence, and the emergence of multi-ship behavior is achieved through the interaction between ships. Multi-ship behavior is a process of behavior replication, diffusion and evolution, which is the interaction between multiple individuals. The evolution of multi-ship behavior with time can be naturally described by the dynamic model. Based on this view, this research argues that it is possible to link multi-ship situation to complex network and to measure the marine traffic situation based on structure entropy in complex system.

The stochastic and non-linear behavior of individual ships will inevitably lead to the complexity of maritime traffic systems, so that multi-ship behavior can be modeled as a dynamic set of different individuals evolving under certain rules. In the field of traffic, complex networks theory has been widely used (Zanin et al., 2014; Lordan et al., 2015; Sui et al., 2020, 2021 and 2022). We have adopted Marine Traffic Situation Complex Network (MTSCN) (Sui et al., 2020) and improved it for the ship behavior research. The ship is regarded as a node, the influence between ships determines the edge, which is measured by distance and approaching rate. And the weight is measured by the repulsive force between ships. The schematic of MTSCN structure is shown in Fig. 6.

The network average degree is used to describe the conflict rate of the system. Degree k is the number of connections it has to other nodes. In MTSCN, the degree of nodes represents the number of ships conflicted with a ship. The average degree can be defined as follows.

$$\bar{k} = \frac{1}{N}\sum_{i=1}^{N} k_i, \tag{16}$$

where N is the number of ship, k_i is the degree of node i, $\bar{k}$ is the average degree of a complex network.

Entropy is used as a unit of measure in thermodynamics to describe the disorder of the individuals of a system that can well measure the order level of a large number of individuals in the system. Therefore, this study uses the structure entropy of MTSCN to measure the changes of multi-ship behavior. Then structure entropy E is given by:

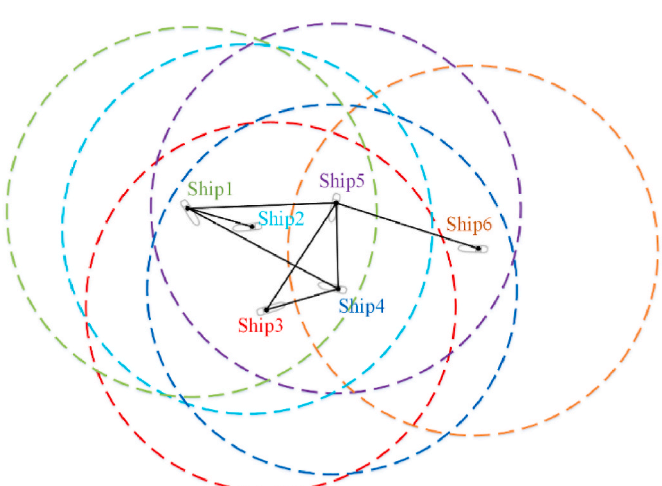

Fig. 6. Schematic of network structure.

$$E = -\sum_{i=1}^{N} I_i \bullet \ln I_i, \tag{17}$$

$$I_i = \frac{k_i}{\sum_{j=1}^{N} k_j}, \tag{18}$$

4. Case study

This section includes two parts, three test scenarios and random scenarios. Scenarios are designed to explain the ship-ship behavior interaction and multi-ship behavior in maritime navigation based on the improved social force model. In the case study, response time is the time for turning and calculated by the method proposed by Huang (2020). The principal particulars of the ship are identified with simulations of KVLCC2 (The second variant of Kriso Very Large Crude Carrier). The details can be found in the literature (Yasukawa and Yoshimura, 2015).

4.1. Test scenarios on ship-ship interaction

4.1.1. Test scenarios construction

The ship's fundamental parameters in three test scenarios are shown in Table 2, nm represent nautical mile. The desired speed for all ships is 15 knots. Scenario 1 is a crossing situation. Ship1 sails from west to east and ship2 sails from south to north. In scenario 2, four ships in a crossing situation. The course of ship3, ship4, ship5 and ship6 are 045, 315, 135 and 225 respectively. In scenario 3, three ships are traveling in the same direction. Change the course of ship7 and observe the behavior change of ship8 and ship9. Fig. 7 (a), (b) and (c) depicts the results in three scenarios. Then we have calculated the repulsive force between ships at each time tag. The change of course and the repulsive force can be seen in Fig. 7 (d), (e) and (f).

4.1.2. Results and analysis

In scenario 1, two ships are in a crossing situation. The change of course and the repulsive force can be seen in Fig. 7 (d). At the moment T5, a repulsive force is generated between the two ships, creating a behavioral interaction. As the behavior of the ships changes, the repulsive force between ships is also changed (T5-T22). At the moment T23, the repulsive force between ships drops to 0. At this moment, the ship is only driven by individual self-driving forces. Similar to scenario1, the four ships are in a crossing situation in scenario 2. As shown in Fig. 7 (e). Ships are subjected to repulsive forces from other ships at the moment T5. The repulsive force between ships of this process increases substantially. When the conflict is resolved, ships are only driven by the individual self-driving force to keep adjusting course toward the destination. In scenario 3, three ships sail in the same direction. As shown in Fig. 7 (f). At the moment T3, a force is applied to ship7, ship7 turns to starboard under the repulsive force. At the moment T4, ship8 is influenced by ship7 and turns to starboard. Now, ship7's behavior spread to ship8. At the moment T4, ship behavior keeps spreading. Ship9 starts to

Table 2
Parameters in simulated test scenarios.

Simulation scenarios	Ship	Origin/[nm]	Destination /[nm]	Initial course/[°]
Scenario 1	1	(0, 5)	(10, 5)	090
	2	(5, 0)	(5, 10)	000
Scenario 2	3	(0, 0)	(10, 10)	045
	4	(10, 0)	(0, 10)	315
	5	(0, 10)	(10, 0)	135
	6	(10, 10)	(0, 0)	225
Scenario 3	7	(0.5, 3.5)	(6.5, 9.5)	045
	8	(1, 3)	(8, 10)	045
	9	(2, 2)	(10, 10)	045

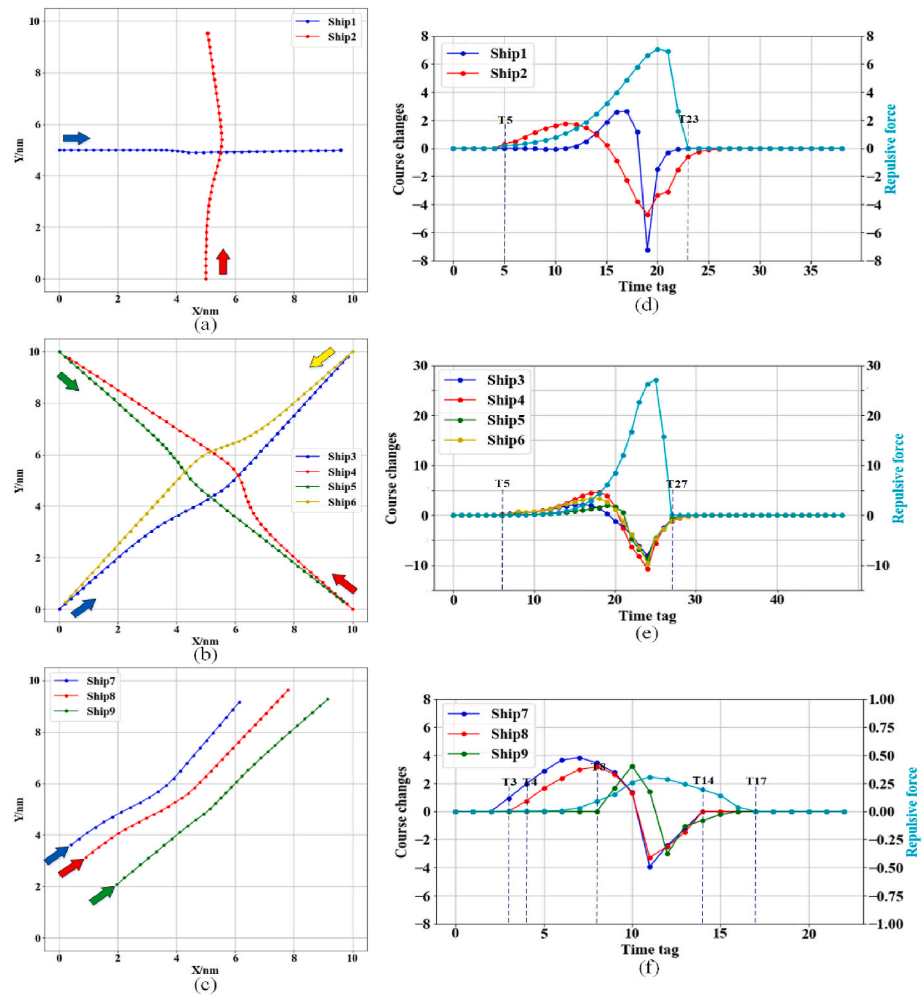

Fig. 7. Trajectories of ships in three scenarios and changes of course and the repulsive force. (a) Ship trajectories in scenario1. (b) Ship trajectories in scenario2. (c) Ship trajectories in scenario3. (d) Change of the ship course and repulsive force in scenario1. (e) Change of the ship course and repulsive force in scenario2. (f) Change of the ship course and repulsive force in scenario3.

adjust the course slightly. At the moment T17, ship7, ship8 and ship9 return to the same course without interfering with each other. At this point, there is no repulsive force between the ships.

4.2. Random scenarios on multi-ship behavior

In philosophy and systems theory, emergence occurs when an entity is observed to have behaviors its parts do not have on their own, behaviors that emerge only when the parts interact in a wider whole (Mueller et al., 2019). When a ship enters a busy water area, it tends to be very affected by a complex navigational environment and has to take a series of actions to ensure navigation safety. In the process, ships have been forced to respond and adapt. These are phenomena that cannot be generated by a single ship's navigation.

4.2.1. Random scenarios construction

To analyze the characteristics of multi-ship behavior in a different marine traffic situation, we designed the following experimental scenarios. The experimental area is set as open water and the area is established as 30nm × 30 nm. We take the longitude and latitude of the ship as two independent variables, and Random distribution is used to simulate the ship position. The evolutionary process of the multi-ship behavior in traffic system will be analyzed based MTSCN. In random scenarios case study, the infectious period is related to the average speed of ships, so we focus on the impact of traffic density on the multi-ship behavior. 30 ships, 50 ships, 80 ships and 100 ships are generated to build a random scenario respectively and MTSCNs are constructed. The speed of all ships is set to 10 knots and the ship course is generated to adopt random distribution. In order to simulate the difference of perception ability of different ships, the detection range of the ship is obey 3~5 nm Gaussian distribution. Improved social force models are used to model the interaction behavior between ships. Four simulation scenarios in one of the experiments can be seen in Fig. 8.

4.2.2. Measurement of multi-ship behavior

Group behavior is a kind of emergence of complex system in the process of interaction between a large numbers of individuals. Therefore, complexity is an important measurement index of intelligence behavior emergence. As a concept of complexity measurement, structural entropy can describe the group behavior of the multi-agent system. Change of structure entropy and conflict rate in different scenarios is shown in Fig. 9. It can be seen in Fig. 10 that the larger the number of ships, the higher the complexity of the system, and the more likely it is to produce the emergence of multi-ship behavior. It is congenial with reason and common sense. This phenomenon can be explained by the system theory.

When the structure entropy decreases continuously, the overall system toward the priority structure of a low-energy state, which means that the conflict in the system is decreasing. The cyan line represents the conflict rate in the maritime traffic system. When the structure entropy

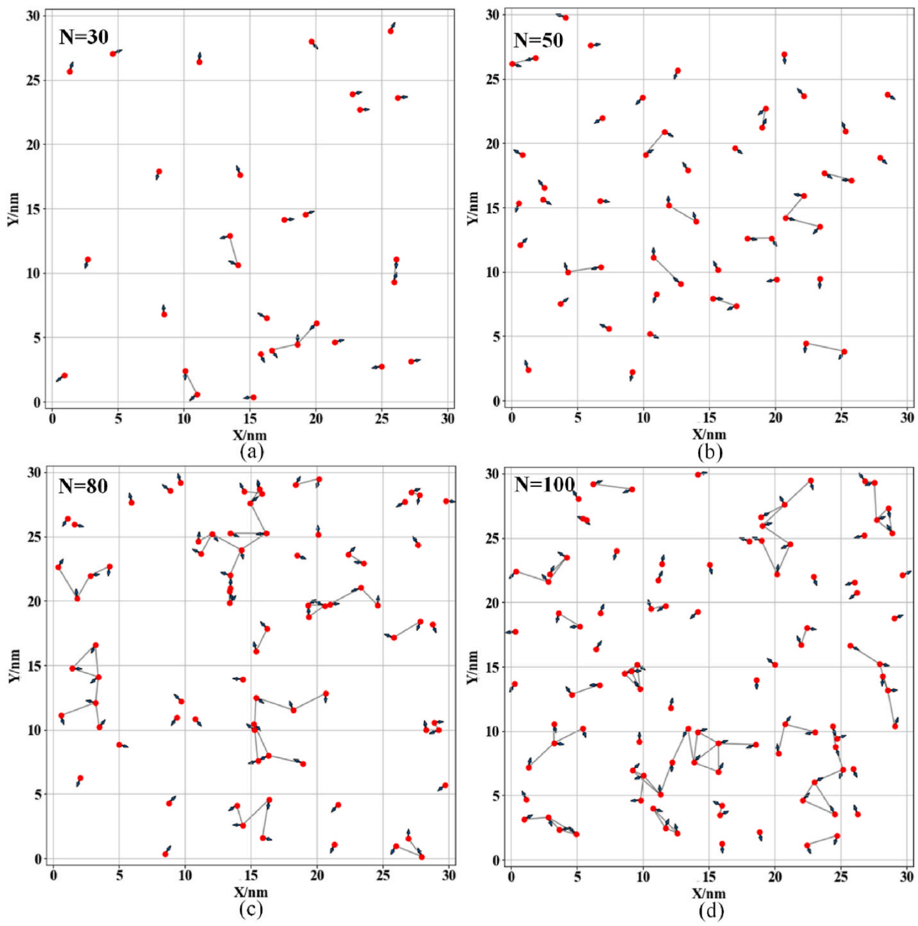

Fig. 8. Random scenarios with different number of ship. (a) Random sceanrio1, number of ship is 30. (b) Random sceanrio2, number of ship is 50. (c) Random sceanrio3, number of ship is 80. (d) Random sceanrio4, number of ship is 100.

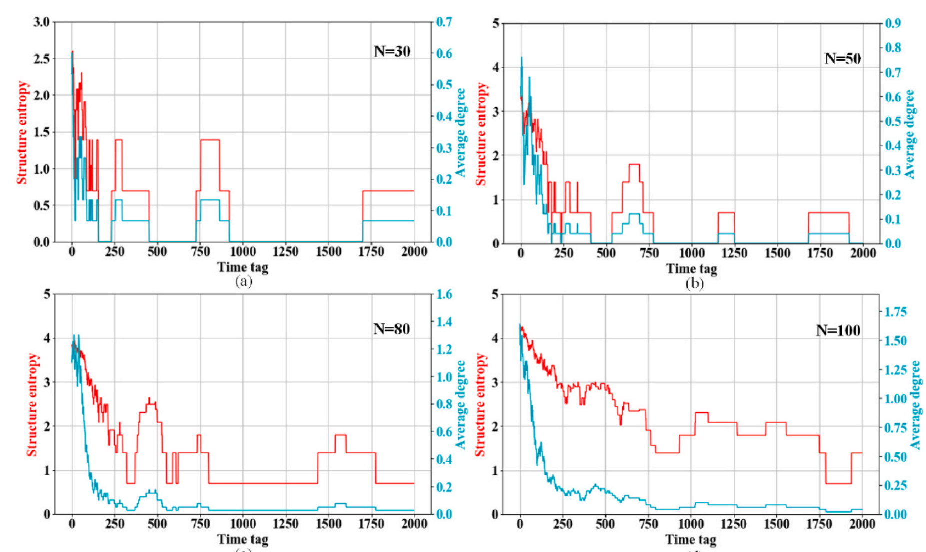

Fig. 9. Changes of structure entropy in different scenarios. (a) Change of structure entropy and average degree in scenario1. (b) Change of structure entropy and average degree in scenario2. (c) Change of structure entropy and average degree in scenario3. (d) Change of structure entropy and average degree in scenario4.

increases, the individuals in the maritime traffic system are in a state of excitation and interactive coupling under the condition of micro-scale. When the structure entropy fluctuates, the system is in the state of an intelligent emergence game and will repeatedly produce group intelligence.

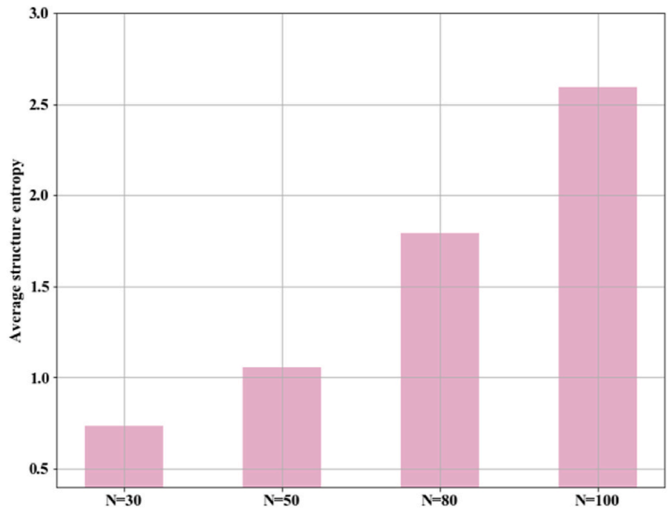

Fig. 10. Average structure entropy in different scenarios.

5. Discussion

5.1. Comparison of improved SFM with related works

Current ship traffic modeling is divided into two main types: macro modeling and micro-individual dynamics modeling. In general, macro models focus on the macroscopic characteristics of the traffic flow (e.g. velocity, density and volume). Micro-individual dynamics models focus on the behavioral characteristics of the individual.

At present, cellular automata is widely used in macro traffic flow modeling. In contrast to the macroscopic movement characteristics, the microscopic movement characteristics of a ship are not directly observable and are mainly reflected in the intrinsic decision-making level of the ship. Ships undergo judgments at the strategic, tactical and executive levels respectively when executing decisions. The strategic and tactical decisions are susceptible to change due to the influence of the surrounding environment. It is more valuable to study ship behavior at the executive level using social forces model. Therefore, in the current method, the dynamics of the ship behavior have been analyzed from a microscopic point of view.

In the field of maritime traffic, simulation studies of the ship's microscopic behavior are mainly focused on collision avoidance. Ship collision avoidance methods are only applicable to specific scenarios and mostly consider local ship behavior, which cannot achieve the traffic characteristics analysis from microscopic to macroscopic. Social force model is derived from crowd psychology. So it can accurately model the motion state of multi-ships. This characteristic makes that the improved SMF not only can be used to simulate individual ship dynamics, but can also reflect the self-organizing characteristics of the water area.

5.2. Limitations of this research

The maritime traffic system is extremely complex. The research on maritime traffic situation is just in its infancy, and it is necessary to accurately analyze and describe the traffic behavior of ships. Even though the presented method is bound by some idealizations and assumptions, the results seem reasonable. Nevertheless, more validation is needed. Due to the time, technical reasons and the limited knowledge available, the following issues need to be further investigated and supplemented in future research of this research. Constructing a multi-scale ship behavior model from time and space to analyze ship behavior. The experimental scenarios in this research are set up in a rather idealized manner, causing certain limitations to the analysis results of the mechanism of ship behavior. In the subsequent research, relevant factors contained in the actual traffic scenarios can be added to the research model, such as environment and rules, to establish a more suitable model.

6. Conclusion

For the ship behavior of major three-pronged approach to research, ship individual behavior, ship-ship interaction and multi-ship behavior. A dynamic model of ship behavior based on social force model which takes into account the ship domain is proposed. Motion information, such as the ship domain, the neighbors and safe distance, is defined according to principal particulars of the ship. The ship is modeled as the node of the MTSCN. The influence between ships determines the edge, which is measured by distance and approaching rate. MTSCN structure entropy is used to describe the changes in group behavior in macroscopic view. The innovative points of this paper are as follows. The social force model is proposed to analyze the forces acting on a ship during its movement, and this is used as a basis for constructing an analytical model of ship water traffic behavior and analyzing the evolutionary mechanisms of multi-ship behavior. The multi-ship behavior model is constructed based on complex network theory to demonstrate the complexity and emergence of multi-ship behavior in maritime traffic situation, providing new ideas for the analysis of the evolution mechanism of maritime traffic systems.

CRediT authorship contribution statement

Yuanqiao Wen: Conceptualization, Methodology, Writing – original draft, Visualization, Formal analysis, Funding acquisition, Project administration. **Wei Tao:** Writing – review & editing, Data curation, Visualization, Formal analysis. **Zhongyi Sui:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Formal analysis. **Miquel Angel Piera:** Supervision, Writing – review & editing. **Rongxin Song:** Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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