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Artificial force fields for multi-agent simulations of maritime traffic: a case study of Chinese waterway

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Abstract

Collisions are an important factor in probabilistic risk modeling of waterway infrastructures. Especially in the design of bridges and terminals, the probability of ship collision is important. Researchers are looking for simulations that mimic ship behavior and estimate accident probabilities rather than using probabilistic accident models. AIS (Automatic Identification System) data forms a valuable basis for development of such simulation models. The data is a valuable asset for the validation and calibration of accident simulation models. Hence, a detailed analysis of AIS data is being undertaken as part of current research on ship collision simulations. Based on AIS data analysis, we developed a primary application of multi-agent simulation for ship traffic in the Yangtze River, which provides a realistic representation of the shipping traffic. Visual comparisons between AIS data and simulation data show comparable ship movements. More importantly, many different simulations show that the output of the simulation reproduces the behavior of real ships according to AIS data. Further down the road, ship failures will also be simulated, which results in a probability of ship accidents. Rather than the existing mathematical methods to estimate the risks of maritime accidents, multi-agent simulations provide a realistic ship behavior and all the details of ship movement. The model provides detailed information on how ships go wrong, and forms a useful tool in the design of waterways, design of bridges, and in traffic management.

Keywords: Muiti-agent Simulation; safety; shipping; AIS.

Nomenclature

K	index of steady state turning ability
T	index of response to helms

1. Introduction

This work was inspired by the increasing number of collisions in busy waterways of China and elsewhere [1]. In this work a probabilistic simulation model is developed to model the occurrence of shipping accidents on waterways. This paper treats the development of an artificial force field model to simulate ship's behavior in the Yangtze River in China and its calibration with AIS (Automatic Identification System) data of China.

In recent years, simulation models have been developed to describe the movement of ships in all kinds of situations [2-4]. Dynamic ship movement can be simulated with a uniquely built manned ship-handling simulator (the Mermaid 500) real-time navigation simulators at MARIN, but it requires experts to operate it and the equipment is expensive [5]. The cheaper

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option is to simulate ship movements that are based on Fuzzy Mathematics Methods [6], Bayesian Networks [7] and Neural Networks [8]. However, these methods are still dependent on expert decision or human intervention.

This work uses an alternative approach to simulating ship behavior. Rather than using expert opinion we use the actual behavior of ships and their crews from historical data of the AIS database for the simulation. The historical information can be transferred to the simulation model by multi-agent simulation and artificial force field theory. This paper reports the progress of that work. Here, trial simulations are used to demonstrate the current capabilities. In the last section of the paper, a trial simulation is provided as an indication of the capabilities of the future model.

2. Simulation method

Fig. 1 shows the simulation schematically and shows the information that is used to perform the simulation. The input parameters like ship particulars, route, time interval, initial heading, initial speed, and initial positions are retrieved from the AIS database. When ships enter the simulation, collision candidates are selected. And subsequently, the ship movements are simulated and the output is stored.

The Nomoto model that originates from Kawaguchi's research [9] provides the basis for the maneuvering simulation of ships in this simulation with maneuverability indices of K and T. This model uses time-steps. The position of the ship at one time step (usually in the order of seconds) is calculated from parameters from the preceding time step. These parameters include: the size of the ship, its maneuverability, rudder position, ship heading, and speed. Ship to ship interaction is simulated by multi-agent simulation. The maneuvering behavior of an agent (in this case, a ship) is simulated separately from other agents. The flow of agents in a given space (in this case a confined waterway) simulates shipping traffic in the waterway. For each agent different rules apply depending on for instance the type and size of ship.

Artificial force field algorithm was used to simulate agent behavior in air traffic [10]. A slightly different method of artificial Potential Field for collision avoidance in shipping was also proposed before [11]. In this work, the artificial force field functions in the same fashion as charged particles through an electrical field according to the rules of electrical forces. In this case the forces are built up from quite different sources than electrical forces. Here, a ship moves through its environment under the influence of artificial forces of various origins (see Fig. 2). Firstly, there are the physical parameters that play a role. They are based on properties of the agents and their environments such as the dimensions of the ship, loading conditions, speed, and types of cargo, and the shape of the water channel. Secondly, there is a set of forces that originates from regulatory rules for shipping, for instance the International Regulations for Preventing Collisions at Sea (COLREGS) which is also valid in inland channels. And then, there are parameters that are difficult to measure, such as the behavior of maritime staff. Simulating the application of the rules from first principles is extremely difficult, so an alternative route is followed: the effect of all the influences is calibrated with historic data from the AIS database that contains information about ships and how they maneuver in complex situations. One of the most efficient ways to capture the historic data is by using an artificial force field.

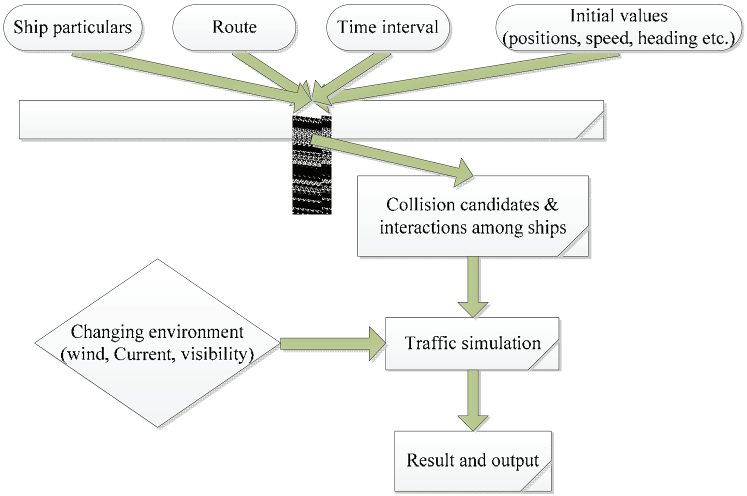

Fig. 1. General graph for simulation model.

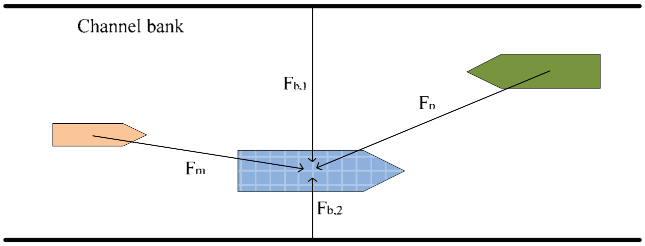

Fig. 2. Application of force field theory.

In the simulation, after the ships are generated at the model boundary, the artificial field applies to the ships. The artificial forces apply to the ship by a force link. There are three kinds of artificial forces, which apply in a similar way. The first one (F_b) originates from the channel boundaries, which exert an artificial force on the ship and represent the effect of activities on the ship that makes it stay in the waterway. This force is also used to represent the effect of activities when the ship is encountering with other fixed objects in the waterway. The second artificial force ($F_{head-on}$) originates from ships in a head-on situation. In this case a link connects the two ships and makes the two ships to turn starboard (as shipping rules dictate) and avoid collision. Once the two ships are clear from each other, then the inter-ship link breaks, and the force becomes zero. The last force ($F_{overtaking}$) originates from ships in an overtaking situation. Again, a link connects the two ships, which forces the overtaking ship to turn port, and the overtaken ship to turn starboard to cooperate. These three kinds of forces or links make the ship navigate realistically in the simulation.

Fig. 2 demonstrates how the artificial force field affects the ships behavior. Arrows represent the artificial forces. Together they make up an artificial force field for the ship, this works as follows:

$$F_b = f_{b,1} + f_{b,2} \tag{1}$$

$$F_{head-on} = \sum_{i=1}^{n} f_i \tag{2}$$

$$F_{overtaking} = \sum_{i=1}^{m} f_i \tag{3}$$

Forces with the suffix b represent the two forces that originate from the channel bank. In our simulation we use navigational buoys along the waterway. In this stage of model development, there are always two forces from the bank; one to the right side of the ship and one to the left ($f_{b,1}$ and $f_{b,2}$). The suffix head-on indicates ships and other objects (such as bridge piers) in the front, while suffix overtaking indicates the number of ships that could overtake the ship. The most important parameters for determining the artificial forces are distance to object, course to the object, gross tonnage of the object and relative velocity. The relative importance of these parameters is investigated by means of statistical analyses of AIS data, which is still ongoing. So for any artificial force:

$$f_i = f(D_i, C_i, G_i, V_i \ldots) \tag{4}$$

The artificial forces (F_b, $F_{head-on}$, and $F_{overtaking}$) determine the rudder angle for the ship to change the course and avoid collision. That means even every force can result in rudder angle to function the ship turning in simulation with calculation using the Nomoto model in each time-step.

However, for the trial model, we set some approximate values by coarse optimization of the formulae, to get some simulation results that mimic reality. We will plot the AIS ship tracks to further investigate the formulae and further calibrate the model. And the final simulation output should be compared with the original dataset.

The force field will be calibrated with AIS data to represent the interactions among the ships and the environment in which they navigate. This calibration, however, is not a straightforward task. In this work we use a step-wise calibration process where we start developing a force-field by analyzing various encounters in a simple shipping situation and then increase its complexity with ever more challenging situations in several steps. And with the statistical analysis of AIS data, we simulate the ship behaviors, which have a similar pattern compared to the result of AIS data analysis, which proves that the simulation is a reproduction of reality.

3. Data Extraction from the AIS Database

3.1. General guidelines for the preparation of your text

In this case, a nearly straight waterway close to the Su-Tong Bridge is chosen. The Su-Tong Bridge is located in Nantong city of Jiangsu Province, China, 108 kilometers to the mouth of Yangtze River. The river crossing perpendicular to the river flow is 8146 meters wide and the main waterway passes under the Su-Tong Bridge, which has a span of is 1088 meters wide and is 62 meters in height. The navigable waterway clearance is 890 meters, which is then separated into 4 traffic lanes and a 100-meter wide separation zone. It was designed to fulfill the navigational needs for 50,000t container ships and 48,000t convoys. The characteristics of the waterway and the bridge are shown in Fig. 3(a).

China MSA (Maritime Safety Administration of the People's Republic of China) provided the AIS data for the case study and was kind enough to provide other related information such as positions of navigational aids.

Fig. 3(b) shows that the ship traffic under the Su-tong Bridge is quite busy. The ships are within 500m range with each other. So it is an interesting test case for the force field theory. Relevant local ordinances include the following. According to the separation scheme of Jiangsu Waterway, the ship traffic is separated into 4 lanes, 2 incoming and 2 outgoing. There is a 500m wide "deep-waterway" in the middle, which is separated into 2 traffic lanes, incoming and outgoing, with a 100m wide separation zone. And the two "suggested waterways" are 200m wide traffic lanes (if available), which are separated from the "deep-waterway" by navigational aids on both sides. The "deep-water way" is specifically navigable for "very large ships" and "large ships", the "suggested waterways" are specific for "small ships". According to the local regulations, "very large ships" are the ships (convoys) which have a fresh water draught more than 9.7m or length more than 205m, or ships (convoys) with maximum height above water which is close to the span clearance of the bridge and overhead cables, or ships (convoys) with restricted maneuverability. And "large ships" are the ships (convoys), which have a fresh water draught between 4.5m and 9.7m or length between 50m and 205m in the regulation. "Small ships", also defined in the regulations, are the ships (fleet) with dimensions smaller than the "very large ships" and "large ships". An important ordinance factor is that overtaking is not allowed in the waterway near the bridge area. Those regulations should be reflected in the simulation.

We extracted data at the main span of the bridge, position of ships, speed of the ships, and time intervals between the ships. Those data are variables, which are constantly changing. The representations of those changing variables are the key elements to judge whether the simulation is realistic or not. The static information, such as length of ships, tonnage of ships, width of ships, and K, T values are static values, which influence the artificial forces and the calculation.

Fig. 3. (a) Characteristics of the waterway and the bridge and (b) pictures of Su-Tong Bridge.

3.2. General guidelines for the preparation of your text

Fig. 4 shows the AIS data about ship distributions under the main span. The x-axis is the proportion of width from the center of waterway, and the y-axis stands for the proportion of ship numbers. We use this histogram to show the ships' preference of position perpendicular to the waterway. The histogram shows that the ship traffic conforms to the separation scheme as a whole. The ship traffic is distributed in 4 traffic lanes, and there are more ships in the center of each lane compared to the sides. Note that many "small ships" are not equipped with AIS, and we cannot take them into account. We expect those to navigate in the "small ships" channels so that the number of ships may be underestimated there.

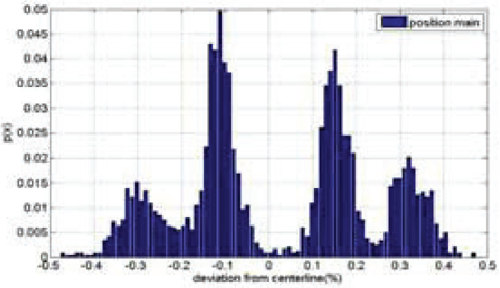

Fig. 4. Ship special distribution under the main span (incoming and outgoing vessels in 6 days).

The speed of ships is different in the waterway. Sea-going ships have a larger speed than the inland ships. And convoys normally have even smaller speed. The speed of vessels depends on all varying circumstances on the water but that is hard to detect in these compound data sets. On the whole, the speed of ships fits well to a normal distribution, ranging from 3 knots to about 18 knots, see Fig. 5.

The time interval between ships conforms to lognormal distribution based on one day of AIS data (426 ship passages), see Fig. 6. In the AIS database, we can derive the arrival time of every ship, and we record it as [t_1, t_2 … t_n]. Then we calculate the time interval between subsequent ships. Hence, we generate ships with a time interval (seconds) based on lognormal distribution, which is a function of μ and σ:

$$F(x) = f(\mathrm{x} \mid \mu, \sigma) \tag{5}$$

In the formula, μ is 5.0204 and σ is 0.886. In this graph, we can see that the ship intervals is neither too small to be generated frequently, nor to be too far away, which is similar in the reality.

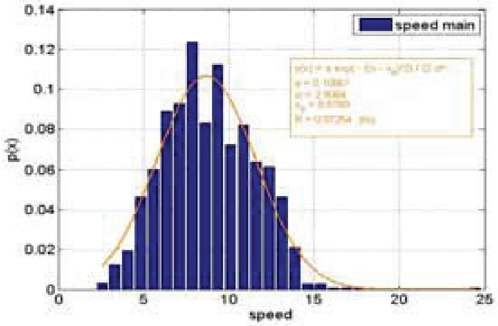

Fig. 5. Speed distribution.

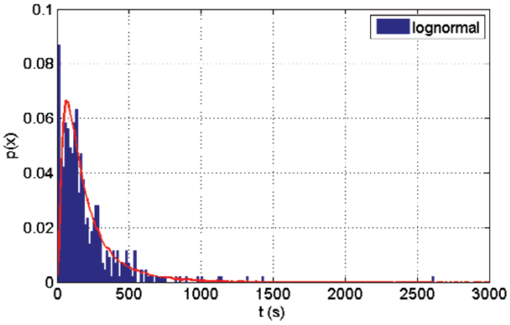

Fig. 6. Time interval distribution (real distributions and generated distributions).

4. Trial of Simulation as an Example

The artificial forces in the simulation are calculated based on preliminary values and a preliminary formula, which are based on personal experience to make the simulation work. Every single artificial force has a value, which influences the rudder angle of each individual ship.

For simplicity of the simulation, head-on situation forces are neglected as the ships are sailing in the individual lanes. Overtaking situations, however, are included and they can be found very frequently in the simulation. So, in this case, if a ship wants to overtake another ship, the overtaking ship will turn starboard giving 5 degrees rudder angle to the left and the overtaken ship will give 5 degree of rudder angle to the right to assist in the maneuvering. The boundaries of each lane will exert additional forces on the ships to ensure the ships are sailing in the designated lanes. Based on our preliminary analysis of the AIS data we have taken this force as 250/d2, where d is the distance from the ship to one of the boundaries. With these preliminary values, we find that the ship not only can have a good distribution in the waterway, but also have relatively straight trajectories. The courses of the ships follow with the channel bends during simulation. A more accurate formula of those forces will be based on a statistical study from the AIS data, which is the next step of our study.

4.1. Simulation Result of Ship Traffic

The ship tracks as a whole should be similar to the tracks that are derived from the AIS data. As can be seen in Fig. 7(a), the ship tracks are generated as the result of the simulation, which represented in colored lines, and those lines are situated in those four traffic lanes. The simulated ship tracks in the simulation are similar to the tracks from the AIS database, which are separated in 4 traffic lanes. Note that some unrealistic harmonic oscillations still appear in the simulation. This is the result of the coarse initial force parameters and remains to be solved in future work. The green lanes are the “deep-waterways” and the yellow lanes are the “suggested waterways”. The black dots in Fig. 7(b) are the ship positions and the blue ones are bridge piers and navigation aids. These results mean the traffic as a whole is simulated reasonably well. This is remarkable since only a coarse optimization was performed.

4.2. Simulation Result of Ship Distribution on Each Traffic Lane

After running the trial model, we simulated 20990 ship passages on both directions for incoming and outgoing vessels. The ship spatial distributions in the whole waterway as well as the ship spatial distributions in each separated lane are obtained from the simulations. The simulated spatial distribution in the whole waterway is shown in Fig. 8. We observe that Fig. 8 is similar to Fig. 4, showing the ships in each lane as normally distributed. However, the probability density functions are not the same. This shows that the simulation is able to reproduce key parameters of the waterway configuration, but does not yet simulate the ship behavior adequately. This means that the same K & T value in the Nomoto model for all the ships have to be further optimized through calibration. The details of the maneuvering behavior are just confirmed with major principles, such as regulations and mechanical movements of ships on speed and turning. A detailed statistical analysis for the ships in the waterway need to be done to build a more detailed model, then a more realistic and accurate spatial distribution can be derived, which is our next step of study.

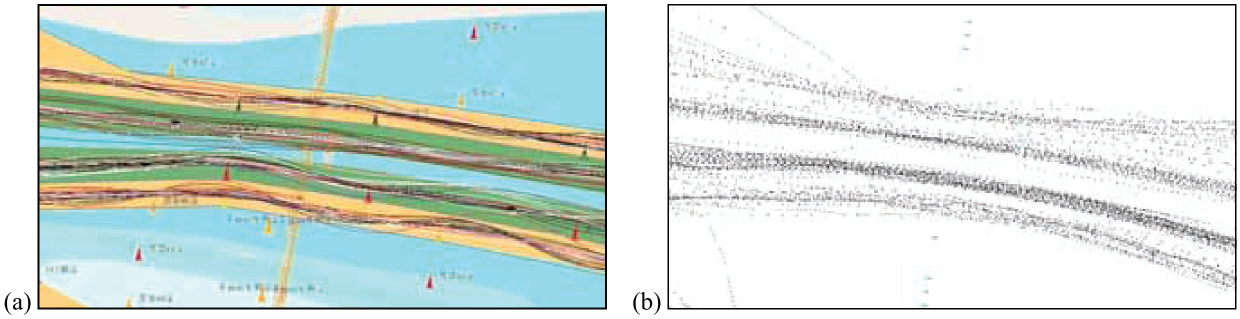

Fig. 7. (a) Simulated result of ship tracks and (b) AIS Ship Tracks.

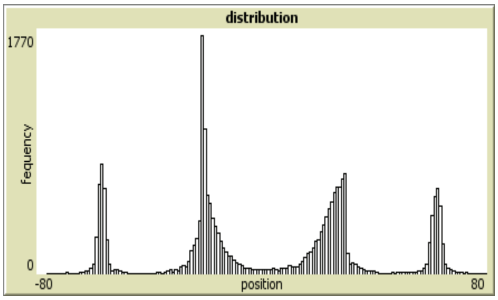

Fig. 8. Simulated ship spacial distribution under the main span of the bridge (incoming and outgoing with 20990 vessel passages).

4.3. Simulation Result of Ship Distribution on Each Traffic Lane

An overtaking process is simulated in the trial (see Fig. 9). Two "large ships" are navigating downstream of the traffic lane, and one can find in Fig. 9(a), the white ship (13 kn) is faster than the black ship (6 kn), so there will be an overtaking situation. After a while they come across the Su-Tong Bridge. So the overtaking process stopped and the white ship had to reduce speed to maintain certain distance to the black ship ahead, because overtaking is not allowed in the bridge area based on local regulation for the safety of the bridge, see Fig. 9(b) and Fig. 9(c). After crossing the bridge the white ship overtook the black ship, as shown in the Fig. 9(d).

4.4. Simulation Result of Ship Distribution on Each Traffic Lane

In Fig. 10, a case of engine failure was simulated. The engine failure was initiated on an outgoing vessel, which was navigating in the "deep-waterway" before passing under the bridge. The consequence was that it could only drift under the forces of wind and current (which were calculated rather schematically in this first attempt) in a state of out of control. Eventually, it crossed the bridge without control and goes beyond the waterway. The green line behind the black vessel is the simulated trajectory for the ship with engine failure.

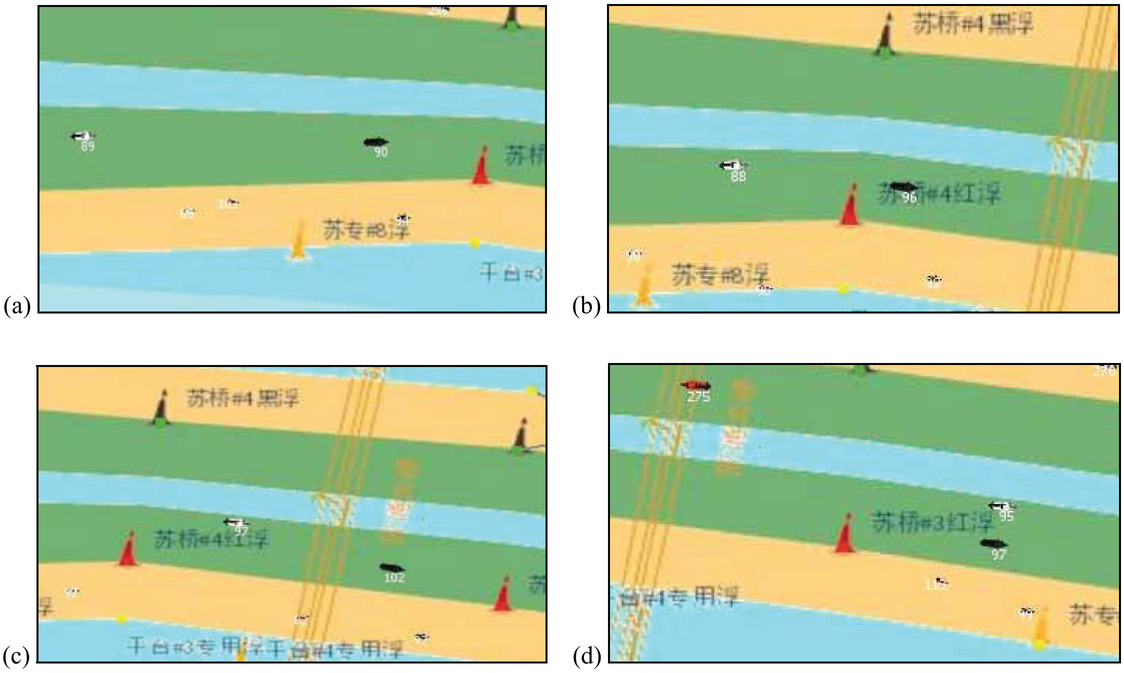

Fig. 9. Simulated results of when (a) the faster ship was about to overtake, (b) the white ship slowed down due to local regulation, (c) the ships kept their speed under the bridge and (d) overtaking happened after crossing the main span of the bridge.

Fig. 10. A simulated situation with engine failure on board

Likewise, if the probabilities of failures, like engine breakdown, rudder failure or human failure are known, then the probability of accidents can be simulated. And this model can be used to anticipate the accident rates in concerned area.

5. Conclusion

This paper describes the concept and early application of artificial force fields to simulate maritime traffic in confined waterways. The case study shows that the separation scheme also can be applied with even the most simplistic artificial force field models to simulate the ship traffic, and AIS data is a good source in both studying the ship traffic and verifying the simulation. More importantly, many different simulations show that the output of the simulation is similar to the AIS data, and the ships in the simulation act in conformity with the regulations. The influence of the waterway geometry is well reproduced, we see normal distributions, but the average and standard deviation of the simulated distributions do not match AIS distributions. Moreover, the agent based simulation reproduces individual ship decisions in realistic conditions. These prove that the method provides a solid basis for the realistic modeling of the ship traffic.

These results are the first step in developing an improved nautical traffic model that allows simulating accidents in shipping. Yet many challenges remain. First, we have to calibrate the model to derive a more accurate artificial force field based on a thorough statistical analysis of AIS data. Second, most of the AIS ship data on gross tonnage, ship length and ship type are missing and we have to find solutions to circumvent this shortcoming. Third, some ships are not equipped with AIS system on board, which is another obstacle for AIS data analysis. The influence of wind and current is very simple in this case study but they may be important in other situations. And last but not least, the risks with complex traffic and bridges have to be simulated to derive design rules for safer bridges in the future. However, the initial success with the simulation model shows that the principle of artificial potential forces works and that further development of the model is worth the effort.

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