Artificial Force Fields for Multi-agent Simulations of Maritime Traffic
and Risk Estimation

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Abstract: A probabilistic risk model is designed to estimate probabilities of collisions for shipping accidents in busy waterways. We propose a method based on multi-agent simulation that uses an artificial force field to model ship maneuvers. The artificial force field is calibrated by AIS data (Automatic Identification System). The artificial force field is capable of dealing with many different kinds of navigational environment simultaneously, such as channel shape, wind and maneuvering by the crew.

Keywords: ship traffic; collision; risk; traffic simulation.

1. INTRODUCTION

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

Busy traffic in confined waterways yields complex maneuvering situations for ships. So the modeling of these situations is also complicated. In recent years, simulation models have been developed to describe the movement of ships in all kinds of situations [2,3,4]. Dynamic ship movement can be simulated with a manned ship handling simulator (such as the Mermaid 500 type real-time navigation simulators at MARIN), but it requires experts to operate it and the equipment is expensive [5]. The cheaper options of ship simulation 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 simulation model by multi-agent simulation and artificial force field theory. This work shows the progress of the development of that program. Here, trial simulations are used to demonstrate the current capabilities. In last section of the paper, a trial simulation is provided as an indication of the future model, because the final simulation is not yet finished as the simulation process is rather complicated.

2. SIMULATION METHOD

Figure 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 more ships enter the simulation, collision candidates are selected. Then the movement is simulated and the outcome is stored.

The Nomoto model [9] that originates from Kawaguchi’s research [10] provides the basis for the maneuvering simulation of ships in this simulation. This model is based on time-stepping and the position of the ship in the following time step (usually in the order of seconds), which is dependent on parameters such as: 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 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.

Hoekstra et al have used an artificial force field algorithm to simulate agent behavior in air traffic simulations [11]. Zhang Mingming et al proposed artificial Potential Field for collision avoidance in shipping
[12]. The artificial force field functions in the same way as charged particles through an electrical field according to the rules of electrical forces. Similarly, a ship moves through its environment under the influence of a set of rules for shipping, for instance the International Regulations for Preventing Collisions at Sea (COLREGS). These rules include parameters that are based on properties of the agents such as the exact dimensions of the ship, loading conditions, speed, and types of cargo, and the shape of the water channel. And finally these rules include parameters that are difficult to measure such as the behavior of maritime staff. Simulating the aggregation of the rules is extremely difficult, so an alternative route is followed in this work: the effect of the rules 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.

Figure 1. General Graph for Simulation Model

3. Data extraction from the AIS database

The force field is calibrated with AIS data to represent the interactions among the ships and the environment in which they sail. 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 increasing its complexity with ever more challenging situations in several steps. In this work we explain how relevant data is extracted from the AIS database based on a simple situation: a straight channel with calm weather.

Figure 2. Maassluis waterway
In this case, a nearly straight waterway in the port of Rotterdam is used. The Maassluis waterway is used, which is 1 mile upstream and downstream of coordinates (+51° 54' 13.77", +4° 16' 19.07"), also see Figure 2. The Dutch maritime research institute MARIN provided the data and was kind enough to allow the use of their software “Show Route” for the data analysis. Data that was gathered for the input parameters (see Figure 1) include: spatial distribution of ships in the width of the channel (see Figure 1); temporal distance between ships on a fixed point in the channel (not shown); types of ships and number of ships (not shown); ship dimensions; ship heading and speed.

Figure 3 shows data that was extracted from the AIS database. The x axis is latitude, and the y axis stands for the number of ships. The two blue lines are the 10 meter depth contour on both sides, and the red line in the center shows the middle of the waterway. We can find that most of the ships were navigating in the right side of the waterway. And most of the traffic prefers to stay closer to the centerline rather than the boundary. The distribution can be modeled with a normal distribution.

In the simulation, after the ships are generated at the boundary, the artificial field applies to the ships. The artificial forces apply to the ship by a force link. There are three kinds of forces, which apply in a similar way. So, there are three kinds of artificial links. The first force ($F_b$) comes from the river boundaries, which exert a force on the ship and make it stay in the waterway, this force also applies when the ship is encountering with other fixed objects in the waterway. The second force ($F_n$) comes from another ship with head-on situation. Then a link connects the two ships and makes the two ships to turn starboard and avoid collision. After the two ships are clear from each other, then the link will break, and so are the forces. The last force ($F_m$) comes from another ship with overtaking situation. Then a link connects the two ships, which makes the overtaking ship to turn port, and at the same time making the overtaken ship to turn starboard to cooperate. Those three kinds of forces or links will make the ship navigate realistically in the simulation.
Figure 4 shows how the artificial force field affects the ship behavior. The artificial forces are represented by arrows. Together they make up an artificial force field for the ship, this works as follows:

\[
F_b = F_{b,1} + F_{b,2}
\]  
(1)

\[
F_n = \sum_{i=1}^{n} f_i
\]  
(2)

\[
F_m = \sum_{i=1}^{m} f_i
\]  
(3)

Forces with the suffix \( b \) represent the two forces that originate from the river bank. In our simulation we use navigational buoys. 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 \( m \) includes ships and other objects (such as bridge piers) in the front, while \( n \) are the number of ships that could overtake the ship. The most important parameters for determining the artificial forces are distance to object, course, gross tonnage and velocity. Their relative importance of these contributors is investigated statistical analyses of AIS data but that work is still ongoing. So for any artificial force:

\[
f_i = f(D, C, G V ...)
\]  
(4)

All those forces constitute artificial forces (\( F_b, F_n, \) and \( F_m \)) which are used to determine the rudder angle for the ship to change the course and avoid collision. 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 to see the similarities.

4. TRIAL OF SIMULATION AS AN EXAMPLE

The traffic tracks as a whole should be similar to the tracks that are found in the AIS data. As can be seen in Figure 5, the results of traffic tracks in the simulation are similar to the tracks from the AIS databases, which are always straight like lines as similar in shape. This means the traffic as a whole is simulated reasonably well. This is remarkable since only a coarse optimization was performed.

![Figure 5. Ship Traffic Tracks Derived by Simulation and Real Ship Track](image)

Ship encountering cases should also be similar to the tracks derived from AIS. Figure 6 (a&b) shows an overtaking situation. In the left graph, the container ship (black) is overtaking the general cargo ship (blue) ahead of it. The black ship deviates from normal route to port, and the blue ship deviates to the starboard side to cooperate in the overtaking process. In the end, the overtaking process is finished, and then both of the ships intend to resume their original positions in the cross-section. Figure 6-c shows a real encountering situation of two ships derived from the AIS, where one of the ships deviates while the other does not.
In Figure 7, a case of rudder failure is simulated. In the left graph, rudder failure happened on the brown ship, leading to an abnormal course, which needs correction. But it does not have the ability to turn because of the rudder problem. So it continues its course and finally collides on the embankment. If the probability of rudder failure is known, then the probability of accidents can be simulated.
5. CONCLUSION

This paper describes the design and primary application of artificial force fields to simulate maritime traffic in an attempt to simulate the probabilities of accidents. Visual comparisons between AIS data and simulation data show comparable ship movements. More importantly, many different simulations show that the output of the simulation is identical to the AIS data. This shows that the method provides a realistic representation of the shipping.

These are the first step for simulating accidents in shipping. Yet many challenges remain. First, we have to calibrate the artificial force field to handle complex situations by analyzing ship tracks details. Second, the mathematical model has to be tested with historic accident databases. Third, the effects of wind and current need to be further investigated, and the influence of reduced visibility will also be amply reflected in the simulation. 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.

References