Nautical traffic simulation with multi-agent system*

Fangliang Xiao, Han Ligteringen, Coen van Gulijk, Ben Ale

Abstract— **This paper describes a microscopic scale (less than 10 km waterway) nautical traffic simulation model based on multi-agent system. The ship traffic is produced from the behavior of autonomous agents that represent ships. Especially, we look at the behaviors for collision avoidance in different encountering situations with different local environmental conditions. The behavior of the ships is simulated with a dynamic ship maneuvering model, taking into account the movements in different local circumstances. And we utilize AIS (Automatic Identification System) data for input in simulation, model validation, and model verification. Moreover, we use the ODD (Overview, Design concepts, Details) protocol as a framework for the detailed description of the model.**

I. Introduction

Ship collisions, groundings and other accidents are a part of risk assessment for the design of ships, offshore infrastructures and waterways [1]. The probabilities of those kinds of accidents are the prime drivers for the risk assessment. When ship traffic intensifies with time, safety standards become increasingly important for ships and infrastructures (e.g. bridges and berths), with perspective of decades. Taking Su-tong Changjiang Highway Bridge in China (Su-tong Bridge) for example, the bridge has a span of 1088 meters wide. It was designed to fulfill the navigational needs for 50,000t container ships and 48,000t convoys, which seldom appear in the waterway at present. However, the standardized ships of those dimensions could be the main force for shipping 50 years later. In order to anticipate the risks, models should take into account of current situations as well as the future situations with larger ships and intensified traffic density.

In the past, analytical methods were developed to calculate accident rates and risk levels; for instance the AASHTO [2] model. Unfortunately, these models lack detailed descriptions of real-life ship movements [3, 4]. To overcome that and other deficiencies, simulation models were introduced. They showed advantages in describing dynamic ship movements. In addition, it is easier to include environmental elements and randomly occurring incidents in simulations.

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This paper proposes a nautical traffic simulation model based on multi-agent simulation and artificial force fields. This simulation model provides realistic individual ship movements and interactions between ships. The realistic simulation model can be used for a number of purposes with small modifications or add-on functions. (i) It can be used for risk analysis; the probability of accidents can be derived from the simulations. (ii) It can be used to simulate geometrical changes such as new bridges; the simulation then becomes part of the design process of marine waterways solving the bottleneck problems of the confined waterway. (iii) It can be used to simulate safe and efficient ship traffic and thereby help design methods to improve the traffic safety and efficiency in normal circumstances and dangerous situations.

The main purpose of this paper is proposing multi-agent system in nautical traffic simulations, taking wind and current influence into account. This paper provides key elements for the agent based nautical traffic model and shows the advantages in providing stochastic traits for realistic ship interactions and including environmental elements, which are seldom included in the existing models. Section II treats the theoretical background for nautical traffic simulations. Section III treats the Netlogo platform for simulation, the use of AIS (Automatic Identification System) data, and the ODD (Overview, Design concepts, Details) protocol which is used as a framework for the detailed description of the model. Section IV describes the model details using ODD protocol. Section V treats some preliminary simulation results. And sections VI and section VII present the discussion and conclusion, respectively.

II. Theory in Nautical Simulation Models

A. *Ship Simulation Models for Safety*

The simulation models for ships have been developing over three decades. Following the first simulation approach by Davis et al. [5], in recent years there are two different kinds of simulation models, one is for ship traffic simulation and the other one is for individual ship simulation.

For ship traffic, Hasegawa et al. developed SMARTS (Marine Traffic Simulation System) for ship traffic in port [6]. However the routes and waypoints are predetermined and dynamic collision avoidance behavior was not the focus. A simulation model with dynamic ship movements with different ship types and ship sizes has been developed for the Gulf of Finland [7]. However, the behavior of individual ships is simplified to implement the collision avoidance. This is because the hydrodynamic behavior of the individual ships and the human influences are very complex.

For individual ships, the interaction with other ships and the role of human interventions are important. Dynamic ship movements can be simulated with manned ship-handling simulators (e.g. the Mermaid 500 at MARIN). One of the drawbacks is that normally only scenarios with certain extreme circumstances are simulated using the system. Another disadvantage is that the interactions between ships are based on expert judgment. And different traffic patterns and uncertainties in the waterway are difficult to be reflected by this system, because the simulations are time consuming and the equipment is expensive [8]. Other cheaper options are simulation of ship movements based on Fuzzy Logic [9], Bayesian Networks [10], and Neural Networks [11]. But these methods remain dependent on expert opinions or other human interventions.

B. Nautical Traffic Simulation with Multi-agent system

The use of agent-based models is a logic step for realistic nautical traffic simulations, because ship traffic is a complex self-organizing system with autonomous entities. Firstly, the approach has been applied to other traffic modes such as road traffic [12] and pedestrians [13]. Those models showed advantages on both the individual agent level and the traffic level. At agent level, the individual behavior is realistic and reflects the proper characteristics of the agent, e.g. the mathematical equations make the car agent behave as a car. At traffic level, the simulation results showed the statistical characteristics of the traffic. Secondly, the multi-agent system has the potential to reflect interactions (e.g. evasive behavior), emergent behaviors (e.g. collision avoidance in different situations), and uncertainties (a number of random variables to describe uncertain incidences like human behavior or human preferences), which are lacking in most of the existing ship traffic simulation models. The concept design of the multi-agent simulation for ship traffic is described in [14, 15]. However, the details of models and how good these represent the reality are barely mentioned. Methods in agent based modeling for ship traffic

III. METHODS IN AGENT BASED MODELING FOR SHIP TRAFFIC

A. The NetLogo Platform for Multi-agent Simulation

The Netlogo platform is used for these simulations. NetLogo is an open source software platform for multi-agent simulations [16]. It is designed to be suitable for modeling "complex systems developing over time". Railsback studied the advantages and disadvantages in more detail [17].

There are 4 types of built-in agents in the NetLogo world, Turtles, Patches, Links, and the Observer (Figure 1). Turtles are agents moving around within the environment. These agents represent ships. Patches are agents that provide the environment with coordinate systems. Within the coordinate system, each patch is a squared piece of ground on which turtles can move around. We use these Patches to represent the geographical shape of the waterway. Links connect two agents together. We use these agents to represent the artificial forces to calculate the bearings and distances between two ships in the simulation. The Observer agent represents a person who is supervising the simulated "world".

B. Use of AIS Data

The AIS (Automatic Identification System) provide field data in obtaining boundary input data, model verification and validation for simulations. AIS data includes ship positions (from GPS), ship course, ship heading, ship rotation angle, ship speed, loading status, location and altitude of AIS antenna, ship type, navigation status, destination, time stamp, together with an unique Identification Number MMSI (Maritime Mobile Service Identity) [18]. The signals are sent with an interval of few seconds for each ship. After interpretation of ship tracks provided by AIS data, we derive information of ship traffic behavior that is characterized by the mean values and statistical distributions of position, speed, heading, and time interval for different types and sizes of ships. The details for obtaining the statistical characteristics are described by Xiao et al. [19] Moreover, the AIS tracks and statistical properties can be used to verify mathematical models built in simulation to get more accurate and realistic results.

C. ODD protocol for Describing Agent Based Nautical Traffic Model

The model description follows the ODD protocol [20, 21] . The application of this protocol is necessary because the content is complex. It involves several inputs, equations, which are integrated into a complex structure. Standard protocol is needed to better organize the elements of the model and to structure detailed descriptions. We use the ODD protocol to divide the model into three blocks (Overview, Design concepts, and Details), which are subdivided into seven elements: Purpose, State variables and scales, Process overview and scheduling, Design concepts, Initialization, Input, and Submodels. These elements are addressed explicitly below because the method is followed closely. We recommend the ODD protocol to be used in detailed descriptions of agent based nautical traffic models.

IV. ODD PROTOCOL FOR DETAILED DESCRIPTION OF THE MODEL

A. ODD element 1: Purpose

This paper provides a nautical traffic model based on multi-agent system. The model specifically explores the interactions between ships and the emergence of different encountering situations in straight waterway. We also look at how ship traffic density affects the interactions between ships, and consequently their safety. External meteorological influences and current influence on ship traffic are also taken into consideration to reproduce reality. The ships are represented by intelligent autonomous agents. The movements can be reflected in time during the simulation, including changes in position, course, and speed for each ship.

B. ODD element 2: State Variables and Scales

The model has been applied in two cases with straight channels, one in the Netherlands and one in China. Moreover, the scales of the geographic space are less than 10 kilometers. The state variables are listed in Table I. The variables provides geographical positions of ships, ship dimensions and other characteristics, moving status, the distances for safe navigation (outcome of sharp lookout), ship maneuverability, the steering order (which have an impact on navigational status in the next step), and external conditions which have an impact on ship movements.

C. ODD element 3: Process Overview and Scheduling

This element includes the crucial processes in the simulation. The sequence of events is shown in Figure 2.

Other processes in Netlogo program which are not mentioned here are setup procedure for maps, navigational aids, procedures for additional information (e.g. generating graphs) and additional functions (e.g. information report function for monitoring outcome and statistics).

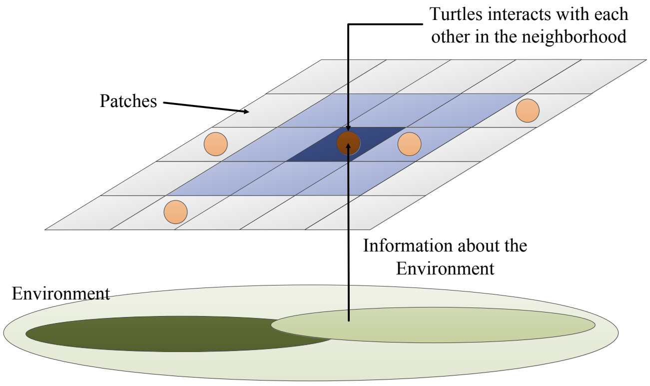


Figure 1. The structure of NetLogo model, based on [22]

TABLE I. STATE VARIABLES USED TO DESCRIBE MODEL ENTITIES

Entity	State variable	State variable description
Global	Ships-dist-total-left	Ship types distributions
	Ships-dist-total-right	Ship types distributions
Ship	Who (Identity)	Identity number of agent
	Ship type (in color)	Describing the ship type
	Positions	Position in coordinate system
	Shape	Shape of ship
	Size	Ship size
	Heading	Ship heading
	Velocity	Ship speed
	Rudder-angle	Rudder angle
	Rotation speed	Rate of turning
	Adapt-heading	The desired heading
	Distances to waterway banks and other agents	The distances calculation for artificial force
	K&T	Maneuverability indices
Patches	Positions	Positions in coordinate system
	Color	Color of the patch
	x component & y component of velocity	Local current velocities
Links	End1 & End2	Both ends of a link
Wind	Direction	Wind direction
	Speed	Wind speed
Current	x component & y component of velocity	Current velocities

- Creating a ship at the boundary of the simulation area: the ships are created at each boundary of the waterway. Each ship is assigned with a size, ship type (represented by different colors), speed, heading, and initial position at the boundaries.
- Generating time interval for the next ship: the time interval between the passages of two ships reflects the traffic density in the simulation. If the time intervals are small, we can expect more interactions between ships, and therefore more collision avoidance behavior can be observed. The time interval is generated as a random number of statistical distributions of ship arrivals from field study (AIS data analysis).
- Ship collision avoidance behavior: the moving ships try to stay in the waterway and to avoid grounding (path following). And when they encounter with ("sense") other ships, they try to avoid collision with one another based on regulations and common practices. The avoidance behavior is reflected in rudder angle (the extent of the turning).

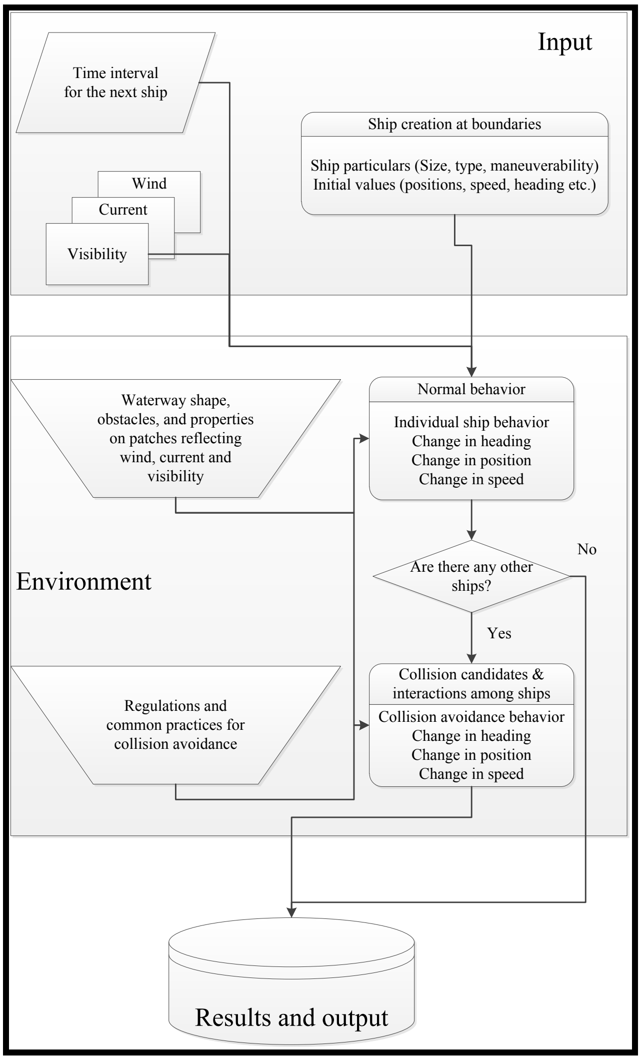


Figure 2. The relationships and processes of events during each time step

- Change in heading: the ships change their headings based on rudder angle and time. This process involves a simple ship maneuvering model to reflect the response of course change to rudder angles.
- Change in position: the movements of ships are based on the speeds and courses, together with the current velocities on patches.

Time is represented by continuous time steps. Each time step stands for 1 second of time. In this sense, the position, heading, and speed of each ship are updated at each time step. Therefore, we can provide very detailed ship movements in simulation. As a result, one day of traffic simulation can be finished in minutes of time (3000 ship passages in 6 minutes for the Chinese case) on a personal computer (Intel(R) Core(TM) I5 CPU 3.33 GHz). In this graph, the relationships between events and the function of events are mentioned.

D. ODD element 4: Design Concepts

Emergence

The interactions and behavior in different encountering situations are the emergent behaviors which result in position change and speed change of ships throughout the waterway. Especially, when multiple encounters happen at the same time, we are looking at the whole collision avoidance process, the reaction of the ships, and the deviation from the original path. The multiple encounters include different types, sizes, speeds, and bearings of ships.

Adaptation

A simple adaptive behavior built in the simulation is that the ship can always adapt its heading according to the geographical shape of the waterway. In other words, the ships should be able to maintain the relative position to the starboard side to keep on navigating without grounding. This function includes calculating the geographical shape of the waterway by navigational aids and adapting the shape by calculating the difference between ship heading and two adjacent local navigational aids in the waterway.

Sensing

The ships are able to identify the navigational aids along the waterway. And they are also able to sense the obstacles and other ships in the waterway for collision avoidance. The assumption is that the obstacles and the other ships are always observed by sharp lookout on board. The way to represent sensing is using links to connect the ships and the objects observed. In the program, the link lengths can be observed by each ship connected by the links agents, and the ship avoidance behaviors are based on the distances and bearings of the objects connected by the links.

The behavior of ships conforms to COLREGs (International Regulations for Preventing Collisions at Sea). The sensing and decision-making mechanisms are mimicked based on regulations and common practices (observed by AIS ship tracks analysis). First of all, the ships can be able to sense the other ships in the simulation, and they create link agents to each other. Second, if criterion on distance and bearing between two ship agents are met, encountering situations (head-on encounter and overtaking encounter) are determined based on COLREGs. And then "give way" vessels and "stand on" vessels are determined at the same time. Third, based on common practice, the ships take actions (by rudder angle) according to regulations at critical distances by experience (based on statistical observations of AIS tracks).

Other than the obstacles, the ships are able to observe the environmental conditions like wind and currents (with direction and velocities), see Figure 3. And the ship behaviors are influenced by the environmental conditions. The individual ship behavior is simulated with a dynamic ship maneuvering model, taking into account the movements in different local circumstances. The individual behavior is based on different internal conditions (vessel characteristics, maneuverability), external conditions (local environment and encounters). Mathematical models are built in the simulation to reflect the ship movements in different wind and currents.

Interactions

There are two different kinds of interactions. One is the ships' evasive behavior from the fixed objects and waterway banks. The other one is the ship avoidance behavior with respect to other ships in different encounters based on COLREGs and common practices (Figure 4).

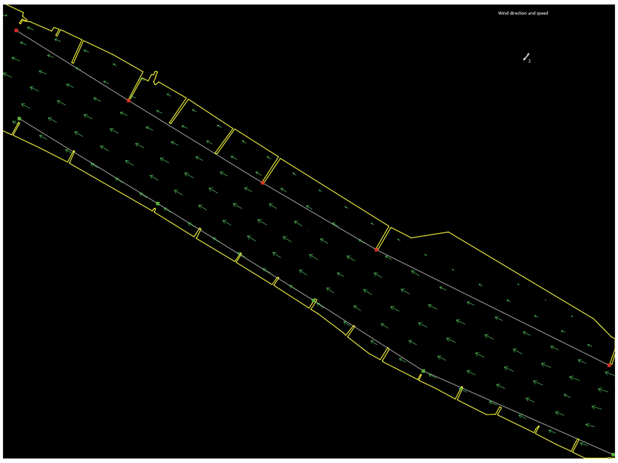


Figure 3. A snapshot of current field in the simulation

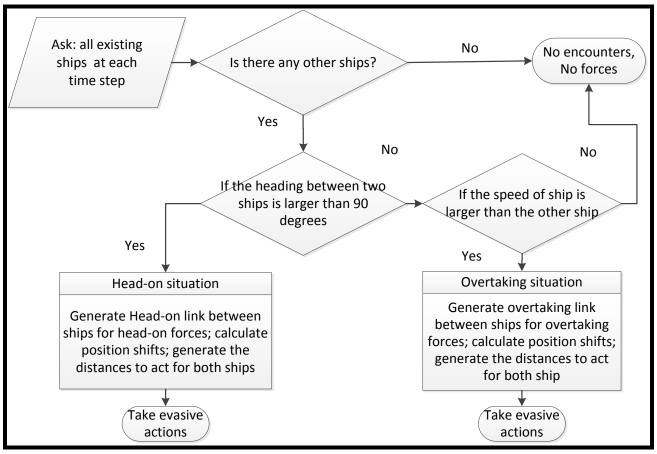


Figure 4. Algorithms for ship interactions

The evasive behaviors from the fixed objects are very simple. The ships always keep a certain distance from the waterway bank. The default critical distance in the program for the evasive behavior is 20 m. This default value is set irrespective of ship dimensions and types. However, larger ships keep further away from the waterway banks in real practice. Further AIS data analysis should be done to further understand the critical values for evasive behavior.

The ship avoidance behavior in the straight waterway means behaviors in head-on encounter and behaviors in overtaking encounter. Critical distances values for taking actions are provided by random values from normal distributions, which are based on AIS data observations. And the behavior taken by the ships conform to COLREGs and common practices. The common practices like the magnitudes of deviations from the original lateral positions and the rudder angles are determined by artificial force field model, which are developed by AIS data analysis. Lateral position means the position on waterway crossing which is perpendicular to the river flow. Statistical analysis of all the positions on crossing can derive the Lateral spatial distribution of ship positions. The ODD element 7 introduces the artificial force field model with more detail.

Since COLREGs is an important element for the decision making algorithm for ship interactions, the relevant regulations are provided and interpreted to understand ship behaviors in the waterway:

- "Every vessel must at all times maintain a proper look-out by sight and hearing, as well as by all available means in order to make a full assessment of the situation and risk of collision." (Article 5 in COLREGs)

  Interpretations: In the simulation, ships are able to observe each other within the capability limit of radar or other forms of look-out, as what is happening in reality. However, extreme weather conditions, human errors, or mechanical errors may result in accidents.

- "Actions taken to avoid collision should be: positive; obvious; made in good time" (Article 8 in COLREGs)

  Interpretations: The action taken should be obvious, which means small changes of ship movements should be avoided. The obviousness and proper time for action should be reflected in simulation. However, the actions should be restricted in confined waterways.

- "A vessel proceeding along a narrow channel must keep to starboard. Small vessels or sailing vessels must not impede (larger) vessels which can navigate only within a narrow channel." (Article 9 in COLREGs)

  Interpretations: Ships in simulation must keep to starboard side. However, from observations of overtaking situations, the overtaking ship may navigate to the port side to avoid collisions. This normal practice should be reflected in simulation.

- "An overtaking vessel must keep out of the way of the vessel being overtaken." (Article 13 in COLREGs)

  Interpretations: "Keep out of the way" should be implemented in simulation. The regulation did not tell the exact distance for keeping "out of the way" in overtaking. However, the AIS data analysis manifests the common practices in this situation. So, we can analyze the AIS ship tracks and make use of artificial forces to implement the overtaking behavior.

- "When two power-driven vessels are meeting head-on both must alter course to starboard so that they pass on the port side of the other." (Article 14 in COLREGs)

  Interpretations: Similar to actions in overtaking, it should be observed from AIS ship tracks that the extent of course altering, extent of lateral position shift to starboard, and the distance between the two ships for the evasive behaviors to begin with.

Stochasticity

There are many variables in the model, and those variables result in stochastic emergent events in the simulation. First, when we create a ship at the boundary of the simulation, the positions, headings, and speeds are generated by random numbers from (normal) distributions with mean and variance. Second, the sizes and types are also randomly generated from predefined categories and classes. Third, the time differences between two consecutive ships are generated by random numbers from an (exponential) distribution. In the collision avoidance behavior, we also use random choices of critical distances to take action and extant of the deviations from the original positions. All those stochastic variables and ship behaviors provides different situations which could happen in real practice. These further evolve different encountering situations involving two different ships (or multi-encountering situations with more than two ships) with different positions, dimensions, type, speed, behavior, human factors. Those various groups of emergent situations are hardly represented or included in the previous traffic simulations of ship handling simulators. The autonomous ships in the multi-agent system can be able to perceive the surrounding ships and assess the local situations based on COLREGs, and take action to avoid collision in different emergent situations.

Collectives

Different types and sizes of ships behave differently in the simulation. Those different characteristics are represented according to behaviors that are derived from statistical analysis of AIS data. An example is that the larger ships navigate closer to the center of the waterway, while the small ships make full use of the entire space in the waterway.

Observation

During the simulation, the spatial distribution of ship positions and speeds at selected places can be presented in a graph. We can also display the distributions for different categories of ship type and size to show differences. And the distributions can be printed in a graph as well. Other than that, we can print the intermediate values and final results in a separate file, which can be further analyzed with statistical tools.

Prediction

In this stage of the model, the ship agent cannot be able to predict the actions of the other ships, while appropriate prediction of the other ships in encounter is very important for ship navigation. However, as a straight waterway is very simple geographical condition, prediction of action from other ship becomes less important. As long as it is known beforehand that the ships follow the relative straight path, the actions of the other ships for the own ships are relative simple to predict.

E. ODD element 5: Initialization

Patch sizes and the coordinate system are the initial setup values for the patches. The proportions of different ship types and sizes are the initial setup for the ships. The size of patch does not affect the result of the simulation. However, it affects observers' visual perception during the simulation process. So, the patch size should be reasonably large. The coordinate system determines the number of patches, which affects the size of the simulated "world". The proportions of ship types and ship sizes are derived from statistical analysis of AIS data.

F. ODD element 6: Input

The input values are created by random numbers from statistical AIS data analysis or from other real world data collected. The values include, ship particulars, initial positions and speed, the time interval between two consecutive ships, wind, and current.

G. ODD element 7: Submodel

There are several submodels in the simulation. The Nomoto model makes the ship position and heading respond to rudder angle and ship speed. The perception of threats from multiple objects is the motive force for evasive behavior in encounters. Artificial forces serve in the same way with this motive force, and act as the key element for ship interactions in the simulation. Influences from wind and currents are taken into account. Nomoto model and Artificial Force Field model will be further introduced in the following texts.

For each submodel, the following details are illustrated. First, the mathematical equations inside the model are provided. Second, the stochastic characteristics for ship interactions are provided by statistical analysis based on AIS data. Third, the conditions for the formulas to take effect are described for different submodels.

Nomoto model

The Nomoto model that originates from Kawaguchi's research provides the basis for the maneuvering simulation of each ship in this simulation with maneuverability indices of K and T [23]. This model uses time steps. The parameters include: ship maneuverability, rudder position, ship heading, and speed.

$$x_{i+1} = x_i + S_p * cos\Phi_i * \Delta t \quad (1)$$

$$y_{i+1} = y_i + S_p * sin\Phi_i * \Delta t \quad (2)$$

$$\Phi_{i+1} = \Phi_i + \gamma_i * \Delta t \quad (3)$$

$$\gamma_{i+1} = \gamma_i + (K\delta - \gamma_i) * \Delta t \,/\, T \quad (4)$$

In ship navigation, larger K means a good ability to change the course of the ship. And larger T indicates the ship to have better ability to keep its course. The value of K and T depends on rudder angle, ship dimensions, and ship type. Δt is the time step in the simulation. S_p stands for the speed of the ship. Φ is the heading of the ship. γ indicates the rate of turning. And δ means rudder angle. So, in every time step Δt, the equations above will applied to determine the new ship position and course.

For indices of K and T, there are non-dimensional forms:

$$K' = K(L/V) \quad (5)$$

$$T' = T(V/L) \quad (6)$$

In which L is length of ship, V is speed of ship. 47 ships with non-dimensional K, T, ship types, loading condition and dimensions are found for regression analysis to derive K′ and T′ for simulation [24, 25]. Thereafter, T′ can be derived by L.

There are strong correlation between K′ and T′, as shown in Figure 5. After regression analysis, the relationship between K′ and T′ is:

$$K' = 0.31 * T' + 0.99 \quad (7)$$

For oil tanks, after regression analysis between T′ and ship Length:

$$T' = 0.0165 * L + 0.54 \quad (8)$$

For the ships other than oil tanks, the correlation between T′ and ship Length is week. So, for any ship length, T′ is a random number generated by exponential distribution with $\lambda = 1.74$:

$$T' \sim Exp(1.74),\ T' > 0.5 \quad (9)$$

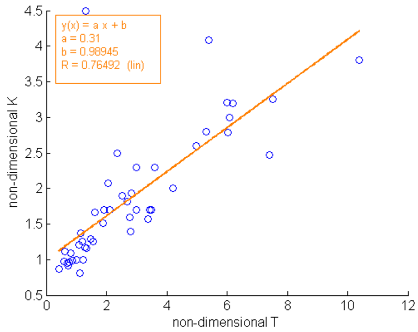


Figure 5. Regression analysis between K′ and T′

Artificial force field model

Artificial force field model provides the basis for the evasive behavior and collision avoidance behavior of ship interactions. A method of artificial potential field for collision avoidance in shipping was also proposed before [26]. 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. A ship moves through its environment under the influence of artificial forces of various origins. The forces should be based on properties of the agents and their environments such as the dimensions of the ship, loading conditions, speed, ship types, and the shape of the water channel. The artificial forces (F_b, $F_{head\text{-}on}$, and $F_{overtaking}$) determine the rudder angle for the ship to change the course (using the Nomoto model) 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 based on pedestrians model [27]. In this case, the first approximation of the repulsive force is defined as:

$$\begin{cases} F_i = n_i \frac{k_{obst}}{{d_i}^k}, \text{if } d_i < d_s \\ 0 \qquad \text{otherwise,} \end{cases} \quad (10)$$

Where the constant k_{obst} indicates the steepness of the repulsive potential, n_i is the number of obstacles, k_{obst} is a scaling constant, d_i defines the shortest distance between ships to other obstacles and agents, d_s denotes the distance that the force start to effect. Agents which are further away than d_s are not included in the obstacle avoidance behavior.

After statistical analysis of AIS ship tracks with encounters, it was found that d_s for head-on encounter conforms to normal distribution:

$$d_{s-headon} \sim N(1548, 706^2) \quad (11)$$

And it was also found that d_s for overtaking encounter:

$$d_{s-overtaking} \sim N(384,\ 358^2) \qquad (12)$$

V. SIMULATION RESULTS

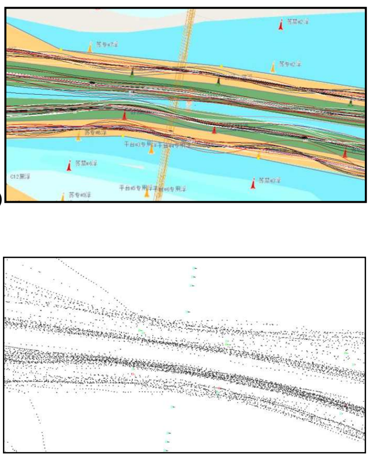
The simulation results described here are taken from both the Chinese case and the Dutch case. In the Chinese case (located near the Su-Tong Bridge), the waterway is separated into 4 traffic lanes by Traffic Separation Scheme, which is why 4 separated traffic flows are shown (Figure 6). In the Dutch case (located in the Port of Rotterdam), the waterway is not separated, and overtaking is allowed (Figure 9).

A. Simulation Result of Ship Tracks and Distribution (Chinese case)

After running the trial model, we simulated 20990 ship passages in both directions for incoming and outgoing vessels. We can see the simulated tracks are similar to the AIS ship tracks (Figure 6). The ship spatial distribution across waterway is obtained from the simulations (Figure 7), which shows a qualitative resemblance with reality (Figure 8). First, the ships are separated in the four traffic lanes. And the autonomous ship can be able to find its specific traffic lane to navigate in. Second, the ships in each lane as normally distributed, and most of ships are sailing close to the center of each lane, while there are ships observed at the boundaries of the lanes, which might be caused by ship interactions. However, the probability density functions are not the same. This shows that the simulation is able to reproduce key parameters of the waterway configuration.

These show that the simulation is able to reproduce stochastic characteristics of ship traffic. However, the differences in the distributions and the oscillations in ship tracks show that the simulated ship behavior does not represent reality precisely. This means that the parameters in the equation of the artificial force have to be further optimized through calibration. Nevertheless, the results confirmed that the basic assumptions of the current model lead to approximate reproduction of the real world. A detailed statistical analysis for the ships in the waterway needs 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.

(a)



(b)

Figure 6. Simulated result of ship tracks (a) and real ship tracks (b)

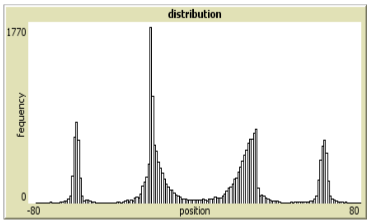


Figure 7. Simulated ship spatial distribution at the waterway crossing which is perpendicular to the river flow (incoming and outgoing with 20990 simulated vessel passages)

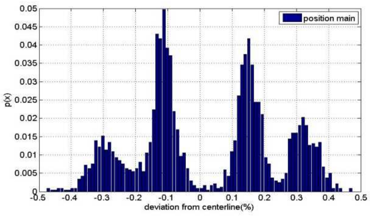
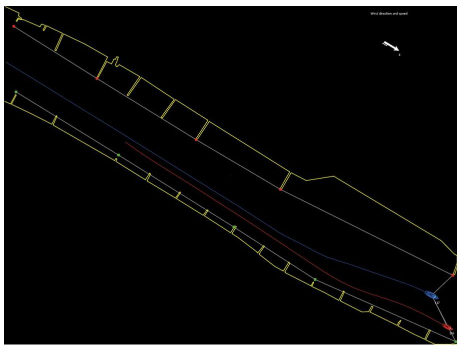


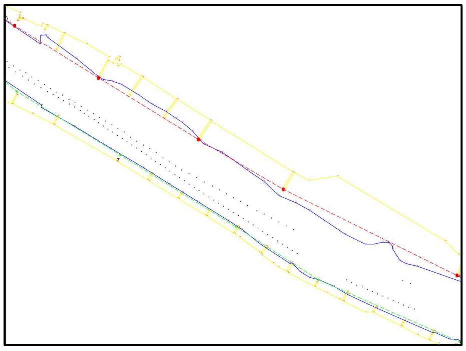
Figure 8. Non-dimentional ship spatial distribution at the waterway crossing which is perpendicular to the traffic flow (incoming and outgoing vessels in 6 days from AIS data)

B. Simulation Results of Collision Avoidances (Dutch case)

Ship encountering cases should also be similar to the tracks derived from the AIS. Figure 9 shows an overtaking situation as produced by the model. In this scenario, the container ship is overtaking the chemical ship. At first, the two ships are far away from each other, and they are both navigating in the right side of the waterway. At a critical point in the middle of the Figure 9(a), the chemical ship which is closer to the starboard side of the waterway starts to maneuver to even closer to the starboard side. This is a signal for the container ship to start the overtaking maneuvering (ships overtake from portside in this section of waterway). Then the container ship navigates to the left side of the waterway to avoid collision with the chemical ship. And finally, both of the ships move to the positions shown at the bottom right of Figure 9(a). Although there is AIS information missing in the Figure 9(b), the trend of the positions in the figure shows that the simulated ship tracks and the AIS ship tracks are very similar.

(a)





(b)

Figure 9. Ship tracks of overtaking encounter in simulation (a) and AIS data (b)

VI. DISCUSSIONS

The results of the simulations show similarity to the real world data. First, the simulated tracks are similar to the real ship track from AIS data. However, we need more evidence from statistical analysis of AIS data to determine the parameters in equation (10). A method for that analysis is currently being developed. Also, the oscillations of ship tracks need to be dampened by fine-tuning the model. Second, the spatial distributions of ship positions are similar to the AIS data. This shows that the simulation is able to reproduce real-life variances in ship's position with the basic assumptions made for the model. The model shows this as stochastic distribution. This distribution is an important parameter for the analysis because many behaviors are stochastic in nature. They can be verified against AIS data.

The artificial force field model was implemented in the simulation for collision avoidance behavior. The overtaking process in the simulation shows that the artificial force works. The force field model substitutes the human decision part on collision avoidances, functioning together with regulations. Stochastic magnitude of forces provides various maneuvering behavior of ships on the extents of deviations from original path, which reflect the common practices in collision avoidance for different dimensions of ships. However, the artificial force field model needs to be modified for complex situations and human decisions.

A ship maneuvering model is provided for realistic movements of agents. However, the hydrodynamic model is very simple compared to a ship handling simulator. We speculate that a more complex hydrodynamic model can be implemented which takes into account the effects of shallow water, the bank, etc. This will also help to describe the ship behaviors in close encounter (with effect of ship suction) and behavior after collisions, taking into account all the hydrodynamic effects. But the limited computational capacity may be a problem for implementing a complex hydrodynamic model for ship movements.

The ODD protocol has been a great support for the development of the model. It helped presenting many elements in the model in a standard form. Beyond the scope of ODD protocol, the steering behaviors by Reynolds [28] could further improve the precision of the results by introducing some steering behaviors for ships. Those steering behaviors for ships can be: Seeking (the ship should be able to seek a specific position as a goal to arrive at with "desired speed" and "desired course"); Offset pursuit (the pursuing ship sets the other moving ship as target, and the pursuing ship keeps a certain distance to the pursued ship); Arrival (ships behavior to slow down and make special maneuvering to adapt to another local environment condition); Path following (this behavior allows a ship to deviate from the track and the ship should be able to correct its position and resume to a limited distance from the track); Flow field following (this behavior represents the influence from dynamic effects of wind and currents). The individual steering behaviors are components of more complex patterns of ship traffic behaviors, some behaviors are blended together and happen parallel in actions. For example, the flow field following behavior is always happening in parallel with the other behaviors when there are currents.

VII. CONCLUSIONS

This paper demonstrates a multi-agent model for nautical traffic simulation. The ODD protocol was used successfully to design a simulation model based on the Netlogo platform that was partly based on AIS information. This model takes into account stochastic events and emergent behaviors to generate different encountering situations and collision avoidances. The current model represents real-life ship traffic in a qualitative way, even without fine-tuning of the model. This means that the model can be applied in risk analysis methods based on simulation. It is clear that fine tuning remains an important task, AIS data and Reynolds' rules are currently introduced to achieve that goal.

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