# Nautical traffic simulation with multi-agent system

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***Abstract*—This paper describes a microscopic 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 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.**

***Keywords*—AIS Data; ODD protocol; Artificial force**

## 1. INTRODUCTION

This contribution is based on a paper sent to the 16th International IEEE Conference on Intelligent Transportation Systems. It is reproduced here for discussions on the IWNGNT symposium.

Ship collisions, groundings and other accidents are a part of risk assessment for the design of ships, offshore infrastructures and waterways (Wang et al., 2006). The probabilities of those kinds of accidents are the prime drivers for the risk assessment. When ship traffic intensifies, safety standards become increasingly important for ships and infrastructures (e.g. bridges and berths). In the past, analytical methods were developed to calculate accident rates and risk levels; for instance the AASHTO (1998) model. Unfortunately, these models lack detailed descriptions of real-life ship movements (Li et al., 2012, Xiao et al., 2010). 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.

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. With small modifications or add-on functions, the simulation model can be used for a number of purposes. (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.

## 2. 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. (Davis et al., 1980), 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 (Hasegawa et al., 2000). 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 (Goerlandt and Kujala, 2011). 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 (Webster, 1992). Other cheaper options are simulation of ship movements based on Fuzzy Logic (Priadi et al., 2012), Bayesian Networks (Szwed et al., 2006), and Neural Networks (Łącki et al., 2012). 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 (Zhang et al., 2005) and pedestrians (Murakami et al., 2002). Those models showed advantages for 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 (Xiaoyingjie et al., 2009, Statheros et al., 2008). However, the details of models and how good these represent the reality are barely mentioned.

## 3. 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 (Wilensky, 1999). It is designed to be suitable for modeling “complex systems developing over time”. Railsback studied the advantages and disadvantages in more detail (Railsback et al., 2006).

There are 4 types of built-in agents in the NetLogo world, Turtles, Patches, Links, and the Observer (Fig. 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) (Harati-Mokhtari et al., 2007). 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. (Xiao et al., 2012) 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 (Grimm et al., 2010, Grimm et al., 2006) . 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.

## 4. 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. 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. 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). In addition, the behavior of ships also conforms to regulations and common practices.

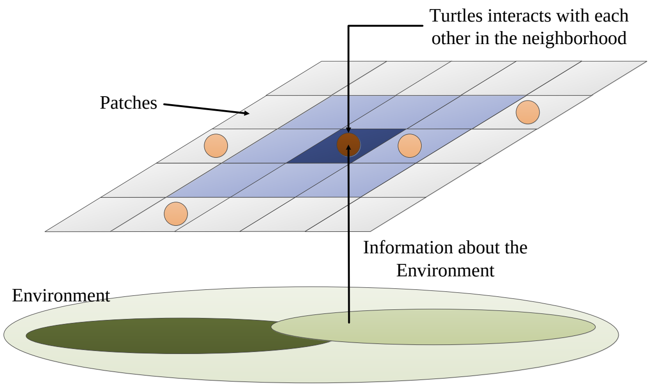



Fig. 1. The structure of NetLogo model, based on (Macal and North, 2010)

### *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.

### *C. ODD element 3: Process Overview and Scheduling*

This element includes the crucial processes in the simulation. Other processes in Netlogo program which are not mentioned here are setup procedure, procedures for additional information (e.g. generating graphs) and additional functions (e.g. information report function).

- 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).
- 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).
- 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). The sequence of events is shown in Fig. 2. In this graph, the relationships between events and the function of events are mentioned.

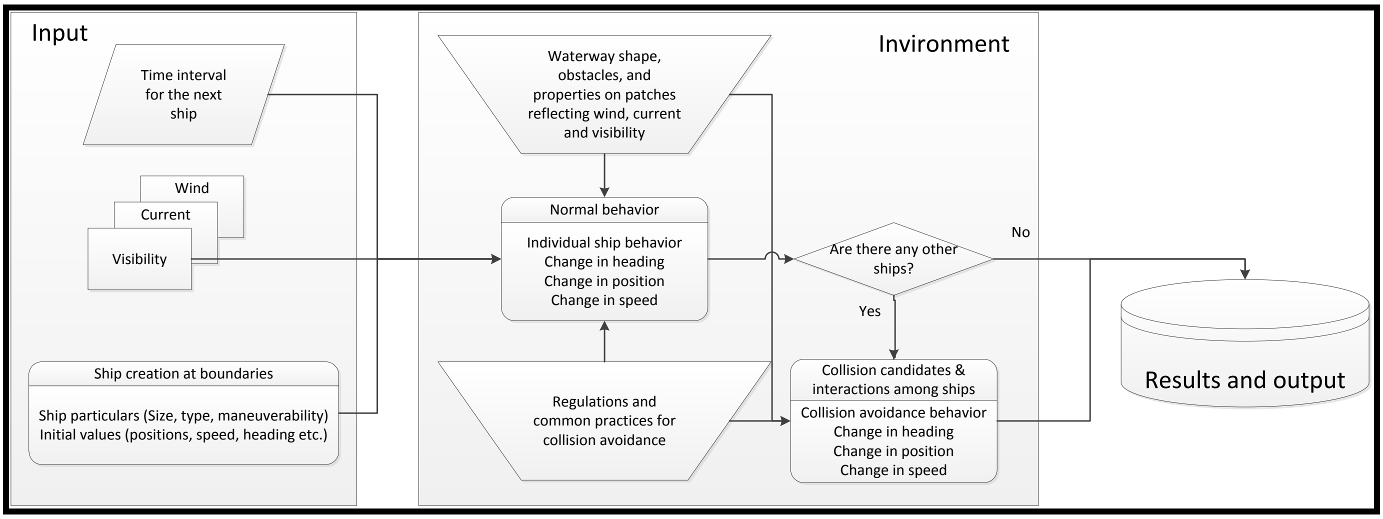



Fig. 2. The relationships and processes of events during each time step

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 |
| Visibility | Distance | Parameter for different visibility conditions |
| Wind | Direction | Wind direction |
| | Speed | Wind speed |
| Current | x component & y component of velocity | Current velocities |

## *D. ODD element 4: Design Concepts*

### *1) 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.

### *2) 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.

#### *3) 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.

#### *4) 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.

#### *5) Stochasticity*

There are many variables in the model. 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.

#### *6) Collectives*

Different types and sizes of ships behave differently in the simulation, according to behavior that is derived from statistical analysis of AIS data.

#### *7) 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 file.

### *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, current, and visibility.

### *G. ODD element 7: Submodels*

#### *1) 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 (Kawaguchi et al., 2004). This model uses time steps. The parameters include: ship maneuverability, rudder position, ship heading, and speed.

### 2) *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 (Mingming and Chaojian, 2007). 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. Here, a ship moves through its environment under the influence of artificial forces of various origins (see Fig. 3). 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 (Fb, Fhead-on, and Fovertaking) determine the rudder angle for the ship to change the course (using the Nomoto model) and avoid collision. In order to reflect regulations, the direction of ship turning under the forces conforms to the COLREGs and common practices for collision avoidance.

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 (Karamouzas et al., 2009). In this case, the first approximation of the repulsive force is defined as:

$$\begin{cases} F_i = n_i \dfrac{k_{obst}}{{d_i}^k}, & \text{if } d_i < d_s \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

Where the constant k 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.

## 5. 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 (Fig. 4). In the Dutch case (located in the Port of Rotterdam), the waterway is not separated, and overtaking is allowed (Fig. 6).

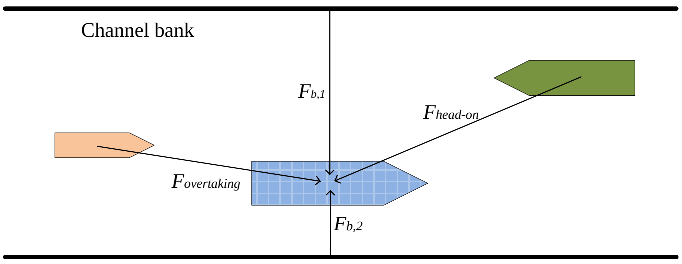



Fig. 3. Schematic of artifical forces on a ship

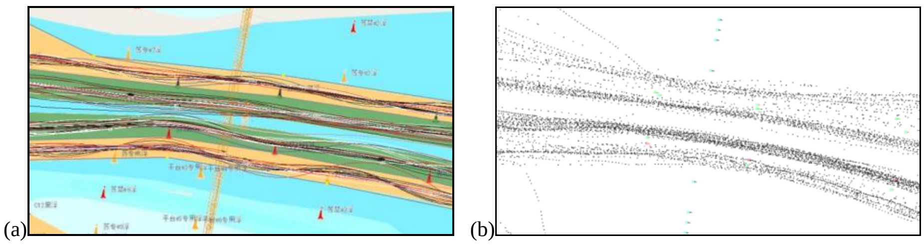



Fig. 4. Simulated result of ship tracks (a) and real ship tracks (b)

### 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 (Fig. 4). We can see the simulated tracks are similar to the AIS ship tracks. The ship spatial distribution across waterway is obtained from the simulations, which shows a qualitative resemblance with reality (Fig. 5). This shows 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.

### B. *Simulation Results of Collision Avoidances (Dutch case)*

Ship encountering cases should also be similar to the tracks derived from AIS. Fig.6 shows an overtaking situation as produced by the model. 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.

## 6. 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 (5). 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.

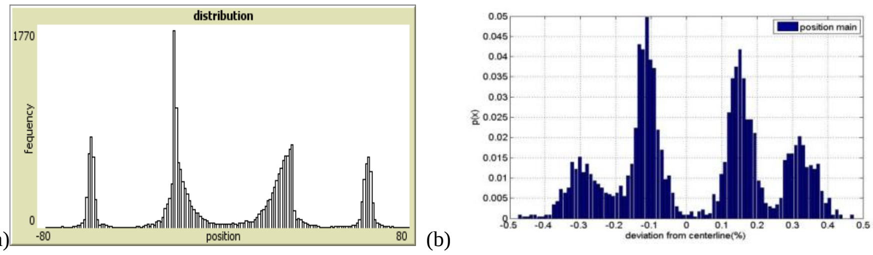
(a)  (b)


Fig. 5. Comparing the simulation results to the real data: (a)Simulated ship spatial distribution at the waterway crossing which is perpendicular to the river flow (incoming and outgoing with 20990 simulated vessel passages) ; (b)Non-dimentional ship spatial distribution at the waterway crossing (incoming and outgoing vessels in 6 days from AIS data)

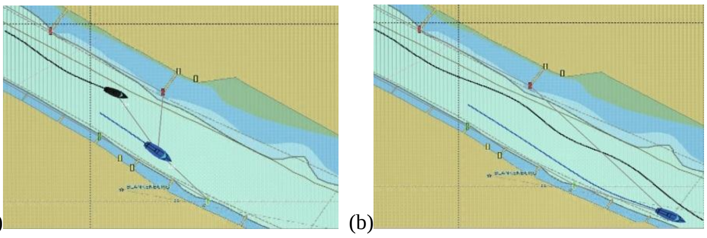
(a)  (b)

Fig. 6. Overtaking process in simulation

We implemented the artificial force field model in the simulation for collision avoidance behavior. The overtaking process in the simulation shows that the artificial force works. However, the artificial force field model needs to be tuned for complex situations and human decisions.

A ship maneuvering model and regulations are 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. 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 (Reynolds, 1999) 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.

## 7. 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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