A Computerized Navigation Support for Maneuvering Clustered Ship Groups in Close Proximity

Akira Kawaguchi* *and* **Xiozhen Xiong**
The City College of The City University of New York
New York, New York 10031

Masaaki Inaishi *and* **Hayato Kondo**
Tokyo University of Marine Science & Technology
Etchyujima, Tokyo 135–8533

ABSTRACT

The aim of this research is to realize a computerized, intelligent, and autonomous system to support navigation for multiple ocean-going vessels that share the same sailing course like a transport convoy. Detecting and evading other clusters in close proximity is one of the most important tasks in navigation as contacting these will potentially cause serious risks to the ship. Focus of this paper is to investigate computational capabilities added to the so-called ship cluster behavior model of our previous work. Enhancement is made to predict a risky situation and to guide for multiple ship clusters, enabling them to move safely and avoid contact with each other. Such improvement is critical, especially when the traffic becomes congested with a number of clustered ship groups moving to distinctive directions. Foundations for and preliminary experimental results of this study are presented.

Keywords: ship navigation control, collision avoidance, cluster behavior model, ship maneuverability.

1 INTRODUCTION

Navigation technology is a branch of autonomous and intelligent systems [1, 2, 3, 4, 5, 6] which is steadily gaining in importance and is being recognized by government, funding agencies, and industry both in the U.S. and Japan. Development of effective tools to assist commercial vessels in navigating safely through waterways is vitally important for global commerce [6, 7, 8]. Minimizing the risk of distress in the sea is not only for yielding ship firm's immediate commercial profit, but also for protecting marine resources and global environment in a long range. A study gathered in this paper aims to develop a computerized, intelligent, and autonomous system to assist group-wise vessel navigation in the open sea.

Specifically, this paper presents a progress on an ongoing research effort that makes use of a system designed to simulate a group-based ship navigation according to the so-called *ship cluster behavior model* [9, 10, 11, 12, 13, 14, 15, 16, 17]. The model interprets the overall navigation behaviors and the effects of interferences of multiple ocean-going vessels when these vessels share the same sailing course like a transport convoy, with or without constantly exchanging navigation decisions among them.

A motivation of this research is to identify a computation model of a physical system that is suitable to capture the dynamics of group-based navigation of ocean-going vessels, in order to assess the maneuverability of ships and predict hazardous operation conditions. The focus of this paper is to study and analyze the result obtained from our extensions made to the ship cluster behavior model. The cluster model in our previous work attempts to characterize movement of a *single* ship cluster. In real circumstances, a large number of clusters exist in the sea within a close range, in which case many clusters in motion to distinctive directions may need to pass thought an identical point at the same time, often making their navigation extremely difficult. For instance, several ship groups need to meet and pass through restricted areas such as a narrow water channel. A ship group maneuvering a congested port entry or departure often encounters other groups. A hazardous weather condition found en-route to the destination also forces many ship groups to gather in a limited area and to maneuver on the restricted courses.

Detecting and evading other clusters in close proximity is one of the most important tasks in navigation as contacting these will potentially cause serious risks to the ship. In this paper, computational capabilities are added to the model to predict a risky situation and to guide for *multiple* ship clusters' safe movement to avoid contacting with each other. This enhancement and improvement is important, especially when the traffic becomes congested with a number of clustered ship groups that are moving towards distinctive directions. We will describe foundations for and experimental results of this improvement. We also discuss the approach to investigate the model's abilities in finding risks and taking safety navigation actions to avoid collisions for various cases appropriate to the prevailing circumstances and conditions.

Recently, the International Maritime Organization mandated the use of an Automatic Identification System (AIS) to help improve safety at sea by enabling the tracking of vessels by shore-based stations and other vessels (SOLAS Chapter V, regulation 19) [18, 19]. The AIS is a shipboard broadcast system, operating in the VHF maritime band, which is capable of handling well over 4,500 reports per minute and updates as often as every two seconds [18]. This emerging technology, even though requiring more time for full implementation across the world, is expected to ensure reliable ship-to-ship operation by allowing the ship crew to learn about every AIS-equipped ship,

*This work has been partly supported by New York State Department of Transportation and New York City Department of Environment Protection.

such as the ship name, course and speed, classification, call sign, registration number, etc.

Most studies on marine traffic analysis focus on a limited scope of group behavior [4, 9]. Traditional approach is mainly based on a hierarchical reduction in the way of decomposing a complex marine system into various subcomponents to characterize ship operations and to reconstruct specific navigation behaviors [7, 20, 21]. Group-oriented navigation control is not well understood in this way. Restructuring a set of individual navigation processes does not necessarily reproduce complex behaviors resulted from the decisions taken by member ships in a group. A goal of the study presented in this paper aims to overcome the shortcomings of conventional analysis, by means of extending the constructive approach studied in [4, 9].

As a summary, contributions of this paper are threefold: First, the ship cluster behavior model is enhanced with the ship's kinematics to reflect true movement of the various types of ships. Second, the cluster model is extended further to incorporate a proactive course change to avoid collision with other clusters in close proximity. Third, an experimental performance study is presented based on a comprehensive simulation system that implements all these concepts (simulation system is publicly accessible at `http://wikiwiki.engr.ccny.cuny.edu/~akira/ShipNav`).

The significance of this research for the longer-term goals lies in its implications for adaptation of our intelligent ship cluster model into the future AIS. In particular, aided with an automatic radar plotting, it is likely that the crew can learn about the membership and scale of a ship cluster in the vicinity more accurately and timely. Consequently, the development of more advanced computerized decision making tools will become feasible to assist greater use of the AIS technology, which also leads to the wide scale marine traffic assessment and management in the open sea.

Paper Organization: The rest of the paper is organized as follows: Section 2 defines a ship cluster behavior model and introduces an extended ship cluster model that accounts on our approach for introducing the ship's kinematics and maneuverability as well as the way to identify other ship clusters in the sea and to take appropriate decisions to avoid contact. Section 4 presents experimental approach and preliminary experimental performance study. Section 5 discusses related work, and Section 6 concludes our work.

2 A SHIP CLUSTER BEHAVIOR MODEL

2.1 Principles

Suppose that a group of vessels, depicted as $V = \{V_1, V_2, \ldots, V_n\}$, is navigating towards an identical destination. The group V is a transport convoy. A position of each ship in the group is expressed using a (x, y) coordinate of a plane in an Euclidean space. Following conventions, upward of the y-axis of the plane mapped from a sea region indicates the North. The navigation direction is a ship's compass degree. The aim of each ship V_i is to make an autonomous decision to avoid collision with the ships nearby, to maintain the sailing speed as others, and to follow the planned course without deviating much from the group's movement.

Suppose also that a vessel V_i in the group is sailing with a speed of Sp (sea miles per hour). A coordinate of the geometric center C of the group V is trivially obtained from the positions of the ships in the group. We consider the next four *forces* to characterize a ship movement with regard to the vessel V_i (see Figure 1):

$\overrightarrow{F}_{ga}$: a force for V_i to navigate toward a planned goal destination, called a *goal achievement force*.

$\overrightarrow{F}_{cf}$: a force for V_i to keep closer to the central position C of the group V, called a *centripetal force*.

$\overrightarrow{F}_{ca}$: a force for V_i to avoid a possible collision with another vessel in the group V, called a *collision avoidance force*.

$\overrightarrow{F}_{ff}$: a force for V_i to keep up with the closest vessel V_j in the group V, called a *following force*.

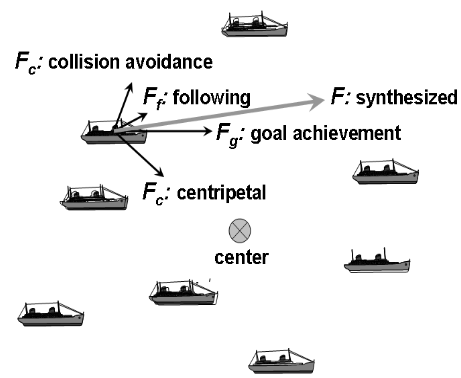


Figure 1. Conceptual view of the cluster model

When V_i is in motion at position (x_i, y_i), V_i's *collision avoidance force* $\overrightarrow{F}_{ca}$ becomes effective against V_i's nearest ship V_j sailing at (x_j, y_j) where $x_j - x_i > 0$ and $y_j - y_i < 0$. This means that the position of V_j is found forehead of V_i and in the viewing scope of 0 to 90 degree relative to the V_i's current compass degree. The collision avoidance force will effect V_i, in compliance with a navigation rule, to change its navigation course to prevent possible collision with V_j. The *following force* $\overrightarrow{F}_{ff}$ of V_i attempts to express seaman's general practice to harmonize the group-wise navigation. This force and the centripetal force will effect V_i for stabilizing the group movement, induced by the nearest ship V_k found at (x_k, y_k) where $x_k - x_i > 0$, i.e., the ship running forehead of V_i.

In addition, we introduce a scope range S as a threshold to activate or deactivate some of these forces based on the following distances defined between V_i and V_j.

L_{cf} : a distance from V_i to the center C of the group V.

L_{ca} : a distance from V_i to the vessel V_j to which the collision avoidance should be enforced.

L_{ff} : a distance from V_i to the vessel V_j to follow.

The ship cluster behavior model with regard to the vessel V_i is defined by the next set of weighting functions when a set of constants $\{w_{ga}, w_{cf}, w_{ca}, w_{ff}\}$ are specified as parameter, so that V_i will be able to determine its direction to move in response to the movement of other ships in the group:

$$f_{ga} = w_{ga} \cdot S_p \quad (1)$$

$$f_{cf} = w_{cf} \cdot S_p \cdot L_{cf}^2 \quad (2)$$

$$f_{ca} = w_{ca} \cdot \frac{S_p}{S_{ca}^2} \cdot (L_{ca} - S_{ca})^2 \quad (3)$$

$$f_{ff} = w_{ff} \cdot S_p \cdot \frac{1}{2} \cdot (\sin(\frac{2\pi}{S_{ff}} \cdot L_{ff} - \frac{\pi}{2}) + 1) \quad (4)$$

With the above scope range S, the force element f_{ca} or f_{ff} (or both) will become zero (or zeros) when $L_{ca} > S_{ca}$ or $L_{ff} > S_{ff}$. In other words, both f_{ca} and f_{ff} with regard to V_i become effective only if V_i finds other vessels within the given range of scope.

The previous work of [9] and others has investigated various weighting schemes. For instance, consider the configuration of vessels moving toward 90 degree in the speed of 15 knots. The weighting parameter is set as $\{w_{ga}, w_{cf}, w_{ca}, w_{ff}\} = \{\ 500,\ 35,\ 50,\ 10\ \}$. The scope ranges for S_{ca} and S_{ff} are set respectively 6 and 10 sea miles. Figure 2 shows a functional relationship of the magnitude of weight and a hypothetical distance between the position of a certain ship and others in a group.

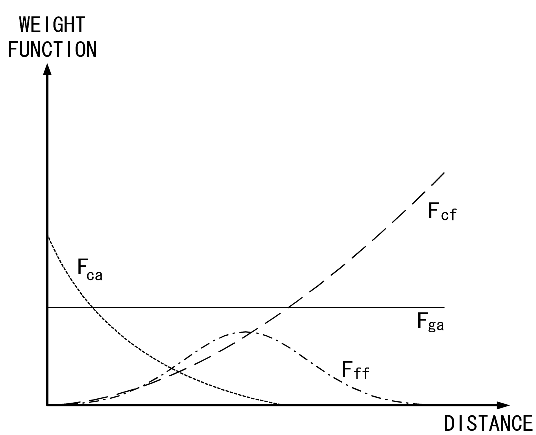


Figure 2. Weighting scheme characteristics

The weighting function f_{ca} effects highest in a close range in the presence of other ships and gradually decreases as a risk of collision decreases, whereas the weighting function f_{cf} gradually increases as the distance to the center increases. The weighting function f_{ff} has a peak over the range the ship can find another to follow. Weighting function f_{ga} only depends on the speed.

Finally, a vector synthesis of the forces expressed as $\vec{F}_{ga} + \vec{F}_{cf} + \vec{F}_{ca} + \vec{F}_{ff}$ reflects the movement of the ship V_i. The x element, F_x, and y element, F_y, are defined respectively as:

$$\begin{aligned} F_x &= f_{ga} \cdot \sin(Co) + f_{cf} \cdot \sin(\theta_{cf}) + f_{ca} \cdot \sin(\theta_{ca}) \\ &\quad + f_{ff} \cdot \sin(\theta_{ff}) \quad (5) \\ F_y &= f_{ga} \cdot \cos(Co) + f_{cf} \cdot \cos(\theta_{cf}) + f_{ca} \cdot \cos(\theta_{ca}) \\ &\quad + f_{ff} \cdot \cos(\theta_{ff}) \quad (6) \end{aligned}$$

where Co is the current compass setting, θ_{cf} is a direction to the group center, θ_{ca} is a direction to the ship to avoid collision, and θ_{ff} is a direction to the ship to follow, all measured in clockwise from the North (i.e., absolute direction) in terms of ship V_i. The compass direction of V_i is determined accordingly as $\sin^{-1}(F_x/\sqrt{F_x^2 + F_y^2}) = \cos^{-1}(F_y/\sqrt{F_x^2 + F_y^2})$.

2.2 Enhancement with Vessel Motion Equations

Equations (5) and (6) adjust ship's courses for group movement. In real circumstances, ships cannot move into new directions right away, but rather drift off before getting into the right tracks. Large deviation may occur due to the momentum inherent to the ship's speed, rotational performance, and maneuverability, which will in turn affect the overall behavior of the cluster model.

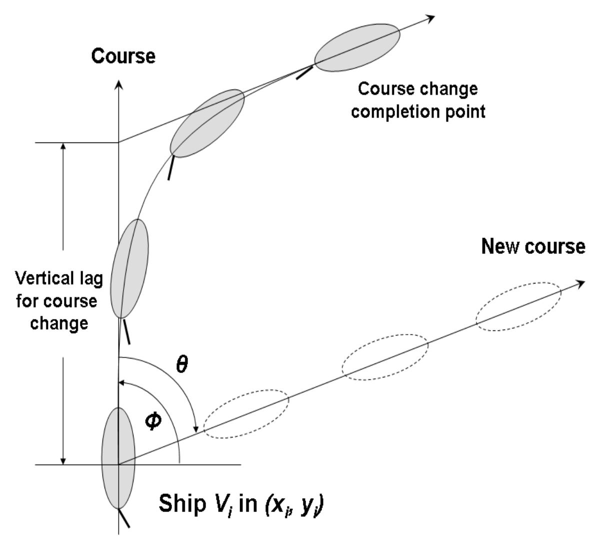


Figure 3. Vessel movement in the sea

Figure 3 illustrates the difference: a ship changes direction by turning its rudder, 5 to 15 degrees in most cases. The ship follows an arc-like path, and then stabilizes into a target course. As a result, the position completing the course change swerves much from the one computed by the equations (5) and (6). This kind of turning lag can be characterized by so-called *vessel motion equations* [1, 3].

Suppose that, at time t, a vessel V_i located in (x_i, y_i) and running toward Φ with a speed of Sp chooses a new course θ by taking "starboard 10" (right rudder of +10 degrees) or "port 10" (left rudder of -10 degrees). Notice that by following convention Φ is measured in counter clockwise as opposed to θ (see Figure 3). If the rudder is kept $\delta = \pm 10$ degrees, the next differential equations compute V_i's motion:

$$\frac{dx}{dt} = Sp \cdot \cos\Phi \quad \text{and} \quad \frac{dy}{dt} = Sp \cdot \sin\Phi \qquad (7)$$

$$\frac{d\Phi}{dt} = r \quad \text{and} \quad \frac{dr}{dt} = \frac{K\delta - r}{T} \qquad (8)$$

where r is a *rotation speed* (from Φ to θ) measured at time t, and K and T are so-called *maneuverability indices* that indicate rotational abilities specific to V_i—given V_i's length l, the values of K and T can be obtained by the next formulas and approximated linearly for the nominal ranges listed in Table 1:

$$T = \frac{T' \cdot l}{Sp} \quad \text{and} \quad K = \frac{K' \cdot Sp}{l} \qquad (9)$$

Table 1. Values for K' and T' when $\delta = 10$ is set

Type	*l (m)*	*Sp*	$T'(sec.)$	$K'(sec.^{-1})$
Cargo ships	100–150	18–20	1.5–2.5	1.5–2.0
Oil tankers	150–200	12–17	3.0–6.0	1.7–3.0

Furthermore, the following iterative evaluation initiating at the position (x_i, y_i) of the ship V_i with maneuverability of K and T not only approximates equations (7) and (8), but also produces a trace of V_i's motion:

$$x_{i+1} = x_i + Sp \cdot \cos\Phi_i \Delta t \qquad (10)$$

$$y_{i+1} = y_i + Sp \cdot \sin\Phi_i \Delta t \qquad (11)$$

$$\Phi_{i+1} = \Phi_i + r_i \Delta t \qquad (12)$$

$$r_{i+1} = r_i + \frac{K\delta - r_i}{T} \Delta t \qquad (13)$$

For the accuracy of evaluation, value of Δt must be small enough, say 0.5 (second). The iteration ends when Φ reaches θ. The goal of this research is to build a real-time system to support computerized navigation, whose first approximation requires a function that generates navigation decisions in a periodic manner. The iterative evaluation of the equations (10) through (13) will determine the exact point for the ship to complete the course change, from which the ship keeps moving toward θ in speed Sp until the next round of the decision will take place.

Incorporating vessel motion equations into the cluster model makes it possible for us to compute the ship's movement based on the ship's kinematics characterized by the maneuverability indices. This improves an overall group behavior as well.

3 DEALING CLUSTER INTERFERENCES

Pro-active course change may often be required for a ship to avoid contact with other ships found outside its group. Group movement needs to be maintained as well. When finding another group in close proximity, alteration of course of the entire group alone would be the effective action to avoid a close-quarters situation. In general, however, deciding group membership of those ships found beyond own presumed boundary is not easy. For instance, unpredictable conflict situations may arise when a group, say a cargo convoy, needs to approach the region occupied by a number of small ships engaged in fishing with nets, lines, trawls, etc. Because these ships, even formed as a group, are rather independent, and in many cases they force their ways, knowingly or unknowingly, into courses of other ships. This kind of situation, especially in the absence of the fully installed AIS environment, makes navigation extremely difficult.

Detecting and avoiding contact with other clusters found in the close proximity is an important task in navigation. The cluster model needs to be enhanced with a good strategy to predict risky situations and to guide the group's movement for the safe direction to prevent close contact with other clusters found nearby.

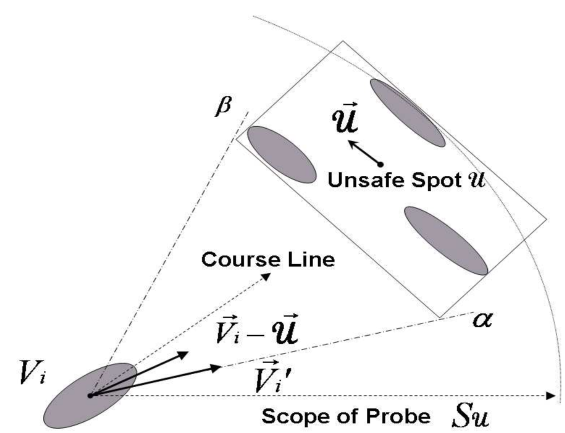


Figure 4. Collision detection and evasion

An *unsafe spot*, $\mathcal{U}$, with regard to a ship V_i in motion is informally defined as an area approximated with a rectangular or square region that encloses a collection of ships found ahead of that ship. Coverage of the unsafe spot may be a portion of ships in another cluster, or simply a number of ships moving towards distinctive directions. This region can be obtained from conventional radar output—the position and speed of the ships outside group boundary are measured through the use of the AIS output and/or radar-based surveillance method. Let a *course line* be a straight line extended toward the sight of ship's compass course. A ship will constantly probe the area ahead of its course, with the angles $\pm\Delta\psi$, spanning to the left and right of the course line. A scope of the probe, denoted $S_{\mathcal{U}}$, complies with the normal capability of commercial ships, usually slightly more than 2 sea miles.

Let a *group velocity* be a velocity (i.e., a vector consisting of direction and speed) of the movement of the center of a ship group, that is, an average velocity of each ship in the group. A group velocity of unsafe spot, denoted $\overrightarrow{\mathcal{U}}$, can be computed by gathering the speed of each ship found in that spot. In Figure 4, a ship V_i has found an unsafe spot $\mathcal{U}$ on its course, where the marked rectangular region $\mathcal{U}$ in the figure contains collection of ships. Then, the relative velocity of ship V_i with regard to unsafe spot $\mathcal{U}$ is expressed with $\overrightarrow{V_i} - \overrightarrow{\mathcal{U}}$, where $\overrightarrow{V_i}$ and $\overrightarrow{\mathcal{U}}$ are the respective (group) velocities of the ship and the unsafe spot.

A collision possibility is identified by inspecting the relative speed of a ship and an unsafe spot being detected along the ship's course line. Specifically, consider a ship's *viewing angle* that spans between two straight lines, each pointing to a corner of the unsafe spot. The ship has a risk to contact the unsafe spot that is found within the ship's viewing angle. As for the example shown in Figure 4, the viewing angle obtained by the ship V_i spans between two dashed lines marked α and β. These lines can be thought of as the line segments in the image projected from the ship's sensor and/or radar equipment. Accordingly, V_i has a risk to contact $\mathcal{U}$ as the direction of its relative velocity with respect to the spot $\mathcal{U}$, denoted $\overrightarrow{v_i} = \overrightarrow{V_i} - \overrightarrow{\mathcal{U}}$, is within V_i's viewing angle.

For the safety measure, the ship V_i would need to adjust its relative velocity into the course along one of the dashed lines, the α line for the case shown in Figure 4. Thus, the desired absolute velocity of the ship V_i to apply this course change, $\overrightarrow{V_i'}$, can be determined through its relation to the relative velocity, $\overrightarrow{v_i'} = \overrightarrow{V_i'} - \overrightarrow{\mathcal{U}}$, which can be expressed in the following canonical representation on the standard coordinate system:

$$
\begin{aligned}
v_i' \cos\alpha &= V_i \cos Co' - \mathcal{U} \cos Co_{\mathcal{U}} &(14)\\
v_i' \sin\alpha &= V_i \sin Co' - \mathcal{U} \sin Co_{\mathcal{U}} &(15)
\end{aligned}
$$

Each of v_i', V_i, and $\mathcal{U}$ in the formula is the speed of $\overrightarrow{v_i'}$, $\overrightarrow{V_i}$, and $\overrightarrow{\mathcal{U}}$, respectively. Notice that our objective is to apply pro-active course change, that means that $\overrightarrow{V_i'}$ maintains the same speed as $\overrightarrow{V_i}$ but changes the direction. The above two equations characterize V_i's new direction, denoted Co', in conjunction with the course taken by the unsafe spot, denoted $Co_{\mathcal{U}}$.

Solving for unknown v_i' and Co' results in the next set of equations:

$$
\begin{aligned}
v_i' &= -V_i \cdot \cos(Co_{\mathcal{U}} - \alpha) \\
&\quad + \sqrt{V_i^2 - \mathcal{U}^2 \cdot \sin^2(Co_{\mathcal{U}} - \alpha)} &(16)\\
cos(Co') &= \frac{v_i'}{V_i} \cos\alpha + \frac{\mathcal{U}}{V_i} \cos(Co_{\mathcal{U}}) &(17)\\
\sin(Co') &= \frac{v_i'}{V_i} \sin\alpha + \frac{\mathcal{U}}{V_i} \sin(Co_{\mathcal{U}}) &(18)
\end{aligned}
$$

The extended ship behavior cluster model utilizes the same vector synthesis: $\overrightarrow{F}_{ga} + \overrightarrow{F}_{cf} + \overrightarrow{F}_{ca} + \overrightarrow{F}_{ff}$. We incorporate the above consideration by way of adjusting the goal achievement force of $\overrightarrow{F}_{ga}$. Let an *adjusted goal achievement force*, denoted $\overrightarrow{F'}_{ga}$, be the force with the direction of $\overrightarrow{V_i'}$ and with the magnitude f_{ga} expressed with $f_{ga} = w_{ga} \cdot Sp$, as shown in the next formula:

$$
\overrightarrow{F} = \overrightarrow{F}_{cf} + \overrightarrow{F}_{ca} + \overrightarrow{F}_{ff} + \begin{cases} \overrightarrow{F}_{ga} \\ \overrightarrow{F'}_{ga} \end{cases} \qquad (19)
$$

Recall from the previous section that $\overrightarrow{F}_{ga}$ has a direction of $\theta_{ga} = Co$ and a magnitude of $f_{ga} = w_{ga} \cdot Sp$. Recall also that the unsafe spot will be probed within the scope range of $S_{\mathcal{U}}$. The model will replace $\overrightarrow{F}_{ga}$ with $\overrightarrow{F'}_{ga}$ for any ship finding an unsafe spot in its vicinity and in its viewing angle. Consequently, the ship's direction will be altered to $\theta_{ga} = Co'$ (derived from equations (16) through (18)), resulting a new dynamics for ships in a cluster to follow.

The intuition behind this extension is to take the advantage of group velocity, an important navigation quantity characterizing group behavior, so that the model would effectively regulate the group movement for safer direction to avoid conflict with other clusters, emphasized with the same weight of w_{ga}.

4 EXPERIMENTAL RESULTS

A time-driven simulation system is built using a Java programming language and a Java Web Start utility. The main objective of this development is to visualize the real-time movement of the ships in clusters, by mapping ship positions in the ocean or in the harbor mouse into pixel positions in a simulator's viewing window. Simulation experiments help us examine the model's effectiveness and assess the practical usability in supporting computerized navigation.

This section describes a summary of implementation, an experimental design, and preliminary experimental results.

4.1 Implementation

A choice of Java programming language enhanced with Web-oriented software distribution is to minimize the implementation-dependent parts and to maximize the portability of our product—the current release runs with up-to-date Java runtime environments of all operating systems (the simulator can be obtained from `http://wikiwiki.engr.ccny.cuny.edu/~akira/ShipNav`).

Figure 5 shows a simulator's graphic user interface. Its main window represents portion of the sea, and ships can be placed manually by pointing desired locations on a virtually unlimited area of the waterway. By selecting a scale of, say 5 pixels per mile (5 PPM), the height and width of the viewable area of the window covers 100 and 200 sea

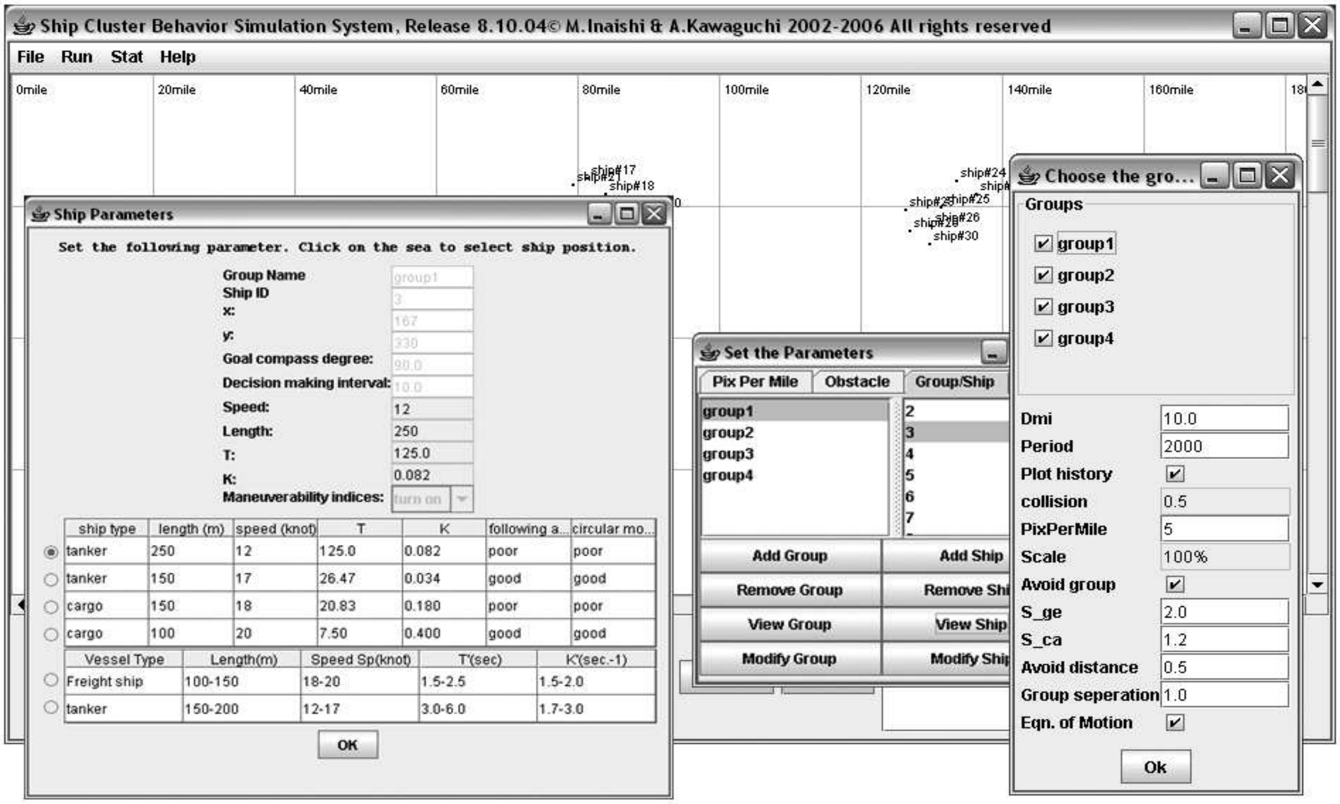


Figure 5. Comprehensive simulation system for ship cluster model

miles, respectively. Window's grid indicates 20 × 20 miles. (Figure 5's window size is adjusted for this paper presentation). Ships can move to any directions for any distances, as the window scrolls.

The simulator is installed into the user's machine via Web browser and is automatically upgraded (whenever ready) by the Java Web Start utility. At its start, the user can either create a new navigation environment or open a saved parameter set by selecting options in `File` menu. To create an environment, (1) choose an initial scale (default 5 PPM), (2) define groups by selecting its name and group parameter in the `Group/Ship` pane, and (3) specify set of ships for each group. Along the course, the weights $(w_{ga}, w_{cf}, w_{ca}, w_{ff})$ and scope ranges $(S_{ca}, S_{ff}, S_{\mathcal{U}})$ for the ship cluster behavior model are determined.

The ship's initial position can be set by clicking the water area. Each click pops up a `Ship Parameter` pane to assign the ship's performance. Note that the ship ID will be generated automatically (an unlimited number of ships can be placed). As in Figure 5, the pane has two parts: one to choose from a typical collection of ship configurations and another to fill in the specific values for the length and speed of the ship (maneuverability indexes for T and K are automatically computed). The user can fine tune the ship's starting position (by adjusting coordinate values of x and y) as well as its destination. Selecting a `Save` option from the `File` menu allows to save the present settings into persistent store for the later use.

Prior to the execution, simulation conditions are set by selecting a `SetUp` option of the `Run` menu. For instance, the user can choose a specific set of ship groups to run. Then, pressing a `Start` button presents the movement of ships. Buttons of `Pause` and `Step` are for step-by-step execution, and a `Scale` button produces a magnified view of the water area—when pressed, double clicks will zoom in 200%.

Furthermore, several statistics can be collected to analyze the ship movement. After pushing a `Pause` button, select `New` from the `Stat` menu to initialize, and press `Begin` to start collecting the statistics from the present step. Pressing an `End` button will terminate the collection.

4.2 Experimental Design

The convention on the international regulations for preventing collisions at sea (Collision Regulations or COLREGs [22]) is a navigation principle to determine safe speed, the risk of collision, and the conduct of vessels operating in or near traffic separation schemes. The regulations consist of general steering and sailing rules based on any condition of visibility and specific rules applied to vessels in sight of one another.

The purpose of this experiment is to examine the

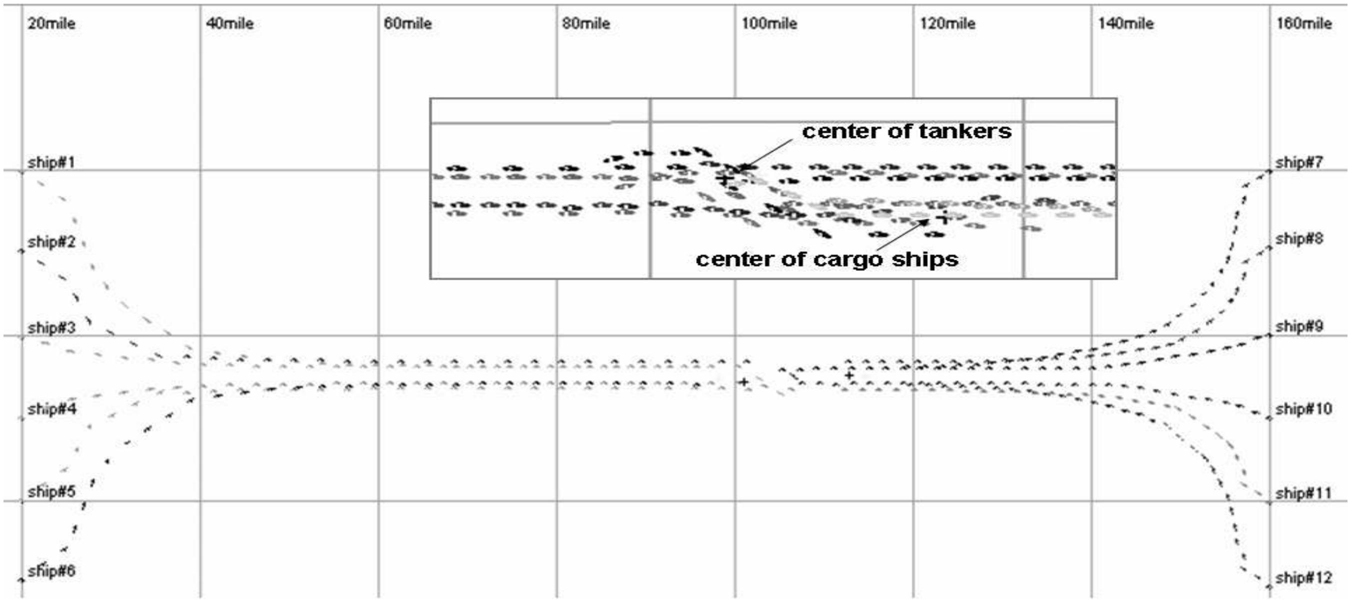


Figure 6. Experimental result for head-on situation

model's abilities to comply with these regulations when multiple groups of ships meet in the sea: we would like to investigate the model's response for typical conflicting navigation situations classified by COLREGs. We are particularly interested in the following situations:

Head-on situation: when two vessels are meeting on (nearly) reciprocal courses so as to involve risk of collision, each shall alter her course to starboard so that each shall pass on the port side of the other. Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.

Overtaking: any vessel overtaking any other shall keep out of the way of the vessel being overtaken. A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5 degrees abaft her beam, that is, in such a position with reference to the vessel she is overtaking, that at night she would be able to see only the sternlight of that vessel but neither of her sidelights.

Crossing situation: when two vessels are crossing with risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall avoid crossing ahead of the other vessel.

The COLREGs also rule general action to avoid collision: (1) if there is sufficient sea-room, alteration of course alone may be the most effective action to avoid conflict if it is made in good time and does not result in another conflict situation, (2) action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance. The effectiveness of the action shall be carefully checked until the other vessel is finally past and clean, and (3) if necessary to avoid collision or allow more time to assess the situation, a vessel shall slacken her speed or take all way off by stopping or reversing her means of propulsion. Finally, every give-way vessel which is directed to keep out of the way of another vessel shall take early and substantial action to keep well clear.

4.3 Preliminary Experimental Results

We show several experimental results to summarize our observations on the model's abilities to identify ship clusters in close proximity and to take appropriate navigation decisions to avoid contact.

4.3.1 Head-on Situation

Method of experiment: we simulate two groups that consist of six cargo ships (Group 1) and six tankers (Group 2). Group 1 and Group 2 are 140 miles away, moving to the East in 18 knots and the West in 12 knots respectively with relatively poor maneuverability. Ships are positioned vertically in every 10 miles to make sure if the groups are formed appropriately. Parameters are set with $\{w_{ga}, w_{cf}, w_{ca}, w_{ff}\} = \{500, 0.3, 20, 2\}$, suitable for forming a stable cluster [10, 11]. Every ship adjusts its course in every 10 minutes.

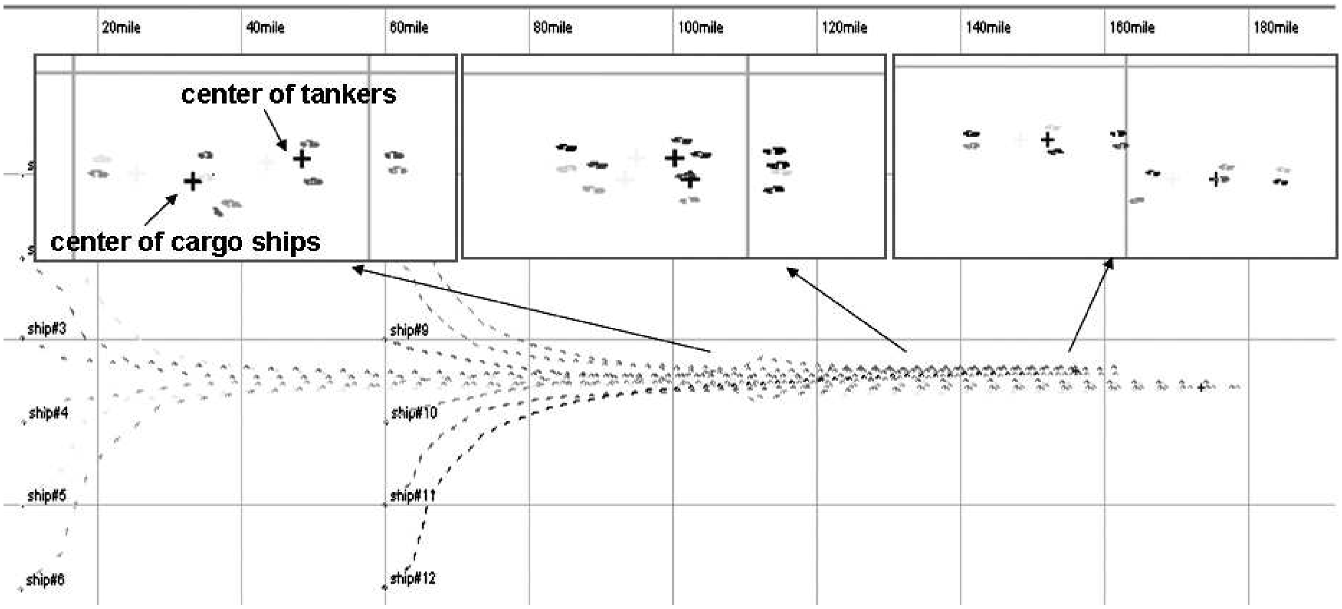


Figure 7. Experimental result for overtaking situation

Analysis: see Figure 6 for the plot of the ship movement that shows the moment before the two groups meet in the head-on situation. The inset of the figure shows a zoomed up image of the trace immediately after the encounter. Cargo ships (left side) and tankers (right side) formed group in 30 miles of navigation. With the scope of probe, $S_{\mathcal{U}} = 6.0$, the two groups alter courses to starboard so that each passes on the port side of the other. Notice that a cargo ship in Group 1 has a better maneuverability. Thus, Group 1's pro-active course change (to the South-east) is more responsive than that of Group 2.

4.3.2 Overtaking

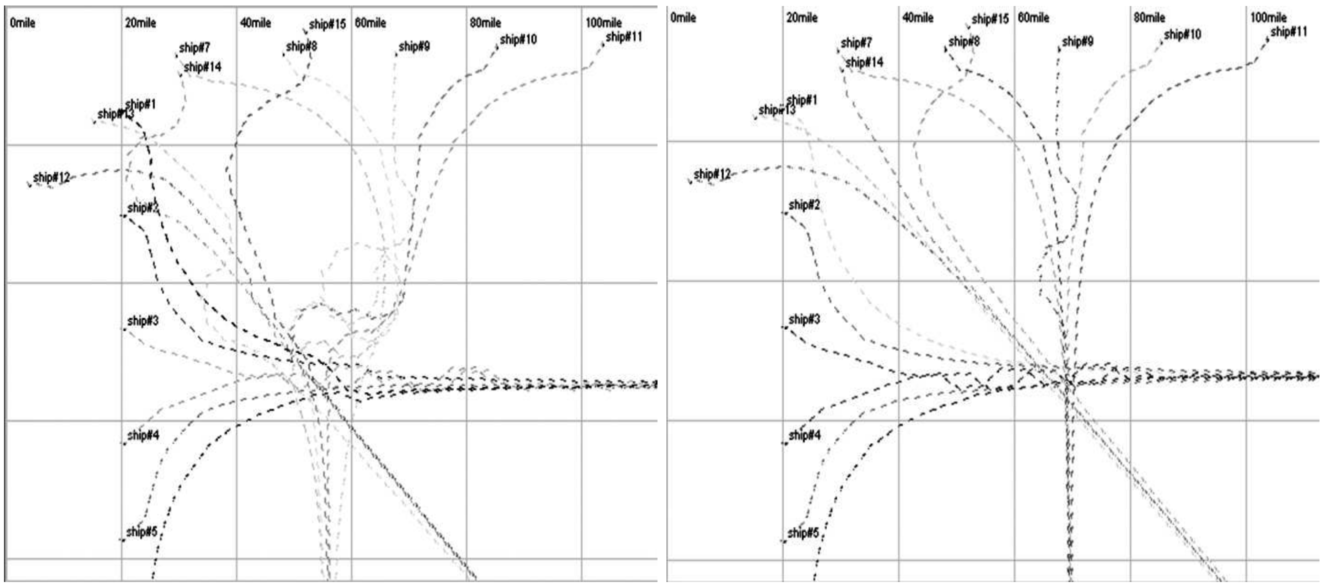
Method of experiment: similar to the previous experiment, we place two groups that consist of six cargo ships (Group 3) and six tankers (Group 4). Group 3 and Group 4 are 50 miles away, both moving to the East in 20 knots and 12 knots respectively. The cargo ship in Group 3 has a good maneuverability, and will overtake Group 4. Parameters are set with $\{w_{ga}, w_{cf}, w_{ca}, w_{ff}\} = \{500, 0.3, 20, 2\}$, and each ship adjusts its course in every 10 minutes. The scope of probe is set $S_{\mathcal{U}} = 2.0$, smaller than the previous experiment.

Analysis: see Figure 7 for the plot of the ship movement. The cargo ships overtake tankers in 100 miles of navigation. Three insets show the moment before the two groups meet, in midst of overtaking, and after passing through. Based on the model definition, the cargo ships (left side) must be sensitive to the other clusters found ahead. This can be observed in this experiment. The tankers (right side) do not change the course until they are overtaken by the cargo group, which follows from the rule such that any vessel overtaking any other shall keep out of the way of the vessel being overtaken. The tanker group slightly moves up to the North when finding out the cargo cluster ahead. The reaction that occurs after overtaken by another cluster becomes more apparent with a larger probe scope.

4.3.3 Crossing Situation

Method of experiment: We place three ship groups consisting of six tankers (Group 5), five cargo ships (Group 6), and four tankers (Group 7), each heading to the East, South, and Southeast direction, respectively. Each of the two groups of tankers moves 12 knots together and the group of cargo ships moves 17 knots. The latter group has better maneuverability and thus capable of responding to course changes relatively quickly. The ships are placed to come across others approximately within 10 miles after about 50 miles of their movement. Parameters are again set with $\{w_{ga}, w_{cf}, w_{ca}, w_{ff}\} = \{500, 0.3, 20, 2\}$, and navigation course adjustment of each ship occurs in every 10 minutes.

Analysis: The difference of Figure 8(a) and (b) is that the former is obtained with the use of a relatively large scope range (10 miles) to probe unsafe spots, and the latter is with a smaller scope range (2 miles). In both cases, three groups are formed within about 40 miles of navigation. Figure 8(a) indicates that the cargo group (Group 6) takes evasive actions to avoid close-encounter with other groups. Deviations from the course are discernible. On the other hand, Figure 8(b) shows little course change of the ship in



(a) Large setting of $S_{\mathcal{U}}$ (b) Small setting of $S_{\mathcal{U}}$

Figure 8. Experimental result for three-way crossing situation

each group. Both experiments show no collision and near-miss incident, as counted when any of the two ships are in the range of 0.5 mile (specified as parameter).

These experiments demonstrate the abilities of the extended ship cluster behavior model to achieve multicluster-based group navigation. The proposed model allows proactive course change to prevent potential collisions. Additional performance measures such as width and height of the group, frequency of direction changes, etc., need to be collected to guide us carrying out more rigorous and comprehensive analysis. These measures will help us develop a profile set to identify the range of effective parameter values to characterize ship convoy structures such as speed, scale, number, and heterogeneity of the ships. These will be gathered in our future work.

5 RELATED WORK

A significant amount of effort has been made for the development of simulation systems for the marine traffic assessment. This is especially true in Japan, and survey and outlook of the work are found in [7, 20, 21]. The work of [20] attempts to categorize architectural types of the simulation system, in terms of the combinations of ship motion control method, space slicing method, terrain selection, and simulation language selection. [7] also classifies the simulation models into a *macro* type and a *micro* type based on the level of precision required for the model's output analysis. The macro model applies series of statistical analysis for the simulation result to derive metrics (e.g., accident probability estimate) that serve to guide harbor and port (re)design. The micro model reproduces a navigation environment for a specific ship, by decomposing ship's operation characteristics under approximated marine environment and terrain and by assembling simulated cause-and-event responses. A survey and overview of various micro models is gathered in [21]. Execution of micro models generally necessitates a large amount of computational resources. The question of practical usability of the micro type simulators often remains unclear as the capacity of the simulation system (e.g., the number of ships and the scale of area to simulate) depends on the availability of computational power.

Most studies on marine traffic analysis consider a limited scope of group behavior [24, 25], and little attention has been paid for characterizing the mutual effect produced by multiple ships navigating in the same waterway. Some of the early work may be extended to capture complex group behavior, by composing a set of individual ship navigation processes into a group. For instance, [6] studies one-to-one based ship collision detection and prevention method, which may be refined for the one-to-n method as introduced in this paper. The challenge is to establish a computation model suitable to assimilate the movement of hybrid group of ships, in which each ship has specific motion characteristics different from others.

The work gathered in this paper is to respond these, In [9], the model called *a ship cluster behavior model* is proposed to analyze a group behavior that is characterized by the dynamics defined over a set of abstract forces, as well as the synthetic effect of such forces. This model attempts to capture the correlations and interactions of the member ships in a group and to predict group-wise movement as a whole. This development is motivated by the sea-man's ship operation practice and empirical knowledge that indicates a group-oriented behavior in the way a group of commercial vessels following the same destination takes an identical or similar navigation course, regardless of whether such a group exchanges information among ships or not [1, 2]. The simulation analysis performed in [9, 10, 11] has successfully identified various sets of parameters that characterize group navigation formations and collision possibilities for a homogeneous group of vessels. However, the abilities to handle a group of *heterogeneous* vessels are missing. A group consisting of hybrid types of ships, such as tankers and cargo ships, needs to be explored for more comprehensive analysis as the ship's maneuverability depends on the type. Grouping formation may become different in this case. Furthermore, the simulation system should be available for many users to conduct experiments. Accordingly, a good interface to set simulation configurations and to show visual effects of the simulation activities need to be developed.

This research is rather inspired by the philosophy and concept to realize a distributed behavioral model of [26] that explores an approach based on simulation as an alternative to scripting the paths of each "bird" individually. Each simulated bird is implemented as an independent actor that navigates according to its local perception of the dynamic environment, the laws of simulated physics that rule its motion, and a set of behaviors programmed into it by the "animator." The aggregate motion of the simulated flock is the result of the dense interaction of the relatively simple behaviors of the individual simulated birds. We take a similar approach, in the context of marine traffic analysis, for developing a distributed ship behavioral model. This type of complex motion is rarely studied in the past [27].

Preliminary work of the ship cluster behavior model goes back to the study of [9]. This work also gathers the first attempt to realize a computerized system that reflects a group navigation model. This effort demonstrated implementability of the model using PVM (Parallel Virtual Machine). However, the system needs to have functionalities to collect additional performance measures (e.g., collision counts, etc.) and a good user interface to set and adjust execution parameter. The system also needs to have an ability to visualize the real-time progress of the simulated ship group's movement.

6 CONCLUSIONS

In this paper, we have presented an extension of our previous study of a ship cluster model, to predict a risky situation and to guide for multiple ship clusters in close proximity, enabling them to move safely and avoid contact with each other. A group-based navigation has an important behavioral aspect, and the assessment scheme used to investigate the ship interferences can be applied to evaluate navigation planning to give information and offer advice to mariner, risk assessment, navigation training, and traffic lane and port planning. A simulator being developed for this research may be used to regulate vessel movements, for surveillance and monitor to identify discrepancy or suspicious behavior around narrow channel or strait. We plan to extend this work with more comprehensive experiment and analysis.

We plan to extend this research into several directions; in particular, the next issues are deemed important. First, additional performance measures such as width and height of the group, frequency of direction changes, etc., need to be collected for more rigorous and comprehensive analysis in order to classify ship convoy structures. Second, we would like to investigate more complex cases such as ships with different decision intervals and maneuvering complex water channels. The model's effectiveness in the presence of these factors needs to be studied carefully for the enhancement. Third, the simulator needs to be able to run under a real geographic environment, that is, the user should be able to scan the chart image of the region e.g., gulf, port, water channel, etc., into the simulation system. This can be done by adapting well-known image fusion algorithms into the system.

We hope in the future that the simulator will be applied for more strategic use to facilitate terrain surveillance and intelligence gathering through sensor or radar devices implanted in a region, for the purpose to identify unusual patters of activity in the terrain to predict accidents.

References

[1] C.L. Crane. Maneuvering Safety of Large Tankers: Stopping, Turning, and Speed Selection. In *SNAME*, Vol.83, 1973.

[2] G.L. Danton. The theory and practice of Seamanship. Routeledge & Kegan Paul, 1974.

[3] J.P. Hooft. Maneuvering Large Ship in Shallow Water. In *Journal of Navigation*, Vol.26, No.2, 1973

[4] M. Inaishi and X. Bai. Knowledge Acquisition using Distributed Autonomous Navigation Simulation Model. In *Journal of Navigation in Japan*, 1999.

[5] A.C. Landsburg. Design and Verification for Adequate Ship Maneuverability In *SNAME*, Vol.91, 1983.

[6] A. Nagasawa. Marine Traffic Simulation Including Collision Avoidance. In *Navigation, Japan Institute of Navigation*, Vol.80, pp 28–34, Jan. 1984.

[7] Y. Okuyama. An Outlook of the Marine Traffic Simulation in Japan. In *Navigation, Japan Institute of Navigation*, Vol.80, pp 2–7, Jan. 1984.

[8] Japan Marine Transportation White Paper (Government Document) Ministry of Land, Infrastructure and Transport, 2002, 2004.

[9] M. Inaishi and T. Imashiku. Marine Traffic Simulation with an Autonomous Ship Cluster Behavior Model. In *Journal of Japan Institute of Navigation*, 2001.

[10] M. Inaishi and A. Kawaguchi. Ship Group Navigation Assessment. *Best session paper in the 9th International Conference on Information Systems Analy-*

sis and Synthesis (ISAS '03), Orlando, Florida, July 2003, pp. 410–415.

[11] M. Inaishi and A. Kawaguchi. Ship Cluster Behavior Characteristics Investigation. *The Journal of Japan Institute of Navigation, Vol. 109*, September 2003, pp. 89–96.

[12] M. Inaishi and A. Kawaguchi. A Ship Behavior Cluster Model for Maneuverability and Marine Traffic Assessment. *In the first Hawaii International Conference on Computer Sciences, Honolulu Hawaii*, January 2004, pp. 53–60.

[13] M. Inaishi, H. Kondo, and A. Kawaguchi. Multiple Ship Cluster Navigation Investigation. *Japan Institute of Navigation, Vol. 110*, March 2004, pp. 1–7.

[14] M. Inaishi, H. Kondo, and A. Kawaguchi. Research on the Group Navigation Using Estimate Type Agents. *Japan Institute of Navigation, Vol. 111*, September 2004, pp. 243–249.

[15] M. Inaishi, H. Kondo, and A. Kawaguchi. Influence on the Information Search Space in Ship Cluster Behavior Model. *Japan Institute of Navigation, Vol. 112*, April 2005, pp. 29–34.

[16] M. Inaishi, H. Kondo, M. Kondo, and A. Kawaguchi Simulation of Cluster Merge and Separation Using a Ship Cluster Behavior Model. *To appear in Japan Institute of Navigation, Vol. 114*, April 2006.

[17] A. Kawaguchi, X. Xiong, M. Inaishi, and H. Kondo. A Computerized Navigation Support for Maneuvering Clustered Ship Groups in Close Proximity. *Best session paper in the 10th International Conference on Information Systems Analysis and Synthesis (ISAS '04), Orlando, Florida*, July 2004, pp. 313–318.

[18] U.S. Coast Guard Navigation Center Automatic Identification System. Accessible at `http://www.navcen.uscg.gov`.

[19] Transportation Research Board. Shipboard Automatic Identification System Displays: Meeting the Needs of Mariners. In *TRB Special Report 273*, May, 2003.

[20] A. Sugisaki. General Description of Marine Traffic Simulator. In *Navigation, Japan Institute of Navigation*, Vol.80, pp 8–13, Jan. 1984.

[21] A. Sugisaki. On the Marine Traffic Simulation with a Microscopic Model. In *Navigation, Japan Institute of Navigation*, Vol.80, pp 14–19, Jan. 1984.

[22] International Marine Organization Convention on the International Regulations for Preventing Collisions at Sea, 1972. Accessible at `http://www.imo.org`.

[23] T. Kaneko and S. Okamoto. View Interpolation with Range Data for Navigation Applications. In IEEE proc. *Image Processing*, 1996.

[24] D.H. .MacElrevey. Shiphandling for the Mariner, In *Cornell Maritime Press*, 1983.

[25] B. Chopard, A. Dupis, and P. Luthi. A Cellular Automaton Model for Urban Traffic and its Application to the City of Geneva In *Workshop on Traffic and Granular Flow*, 1997.

[26] C.. Reynolds. Flocks, Herds and Schools: A Distributed Behavioral Model. In *Computer Graphics, 21, 4*, pp 25–34, 1987.

[27] J. Yamashita, Y. Yamauchi, M. Mochmaru, and K. Yokoyama. Real-time 3-D Model-based Navigation System for Endoscopic Paranasal Sinus Surgery. In *IEEE Transactions on Biomedical Engineering*, vol.46, no.1, pp.107-116, Jan. 1999.