Modelling and Simulation of Sea Traffic and a Visualization-based Collision Avoidance Support System

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Abstract: Safety of vessel transit in congested sea areas such as busy ports and coastal waters is a key issue for navigation officers and traffic operators. With performance improvement of observation devices and introduction of new information systems, vessel traffic service is expected to play a larger role in supporting the officers onboard. Increase in amount of available information demands higher ability of critical situation awareness and operational decision-making in complex situations. Computer support for these tasks is of the highest importance. However, the development and evaluation of support systems for marine traffic is challenging since existing ship manoeuvring simulators do not present rich scenarios involving interesting situations occurring in appropriate ambient traffic. In this paper, the work on a sea borne traffic model in the sea traffic simulation system SEATRAS and a visual support system for management of critical traffic situations has been reported. An algorithm to generate traffic flow from observation data and ship motion model has been developed to represent the movements of the vessels in congested areas. Visualization-based Collision Avoidance Support System (VCASS) calculates and displays the information of collision risks based on traffic flow data, which is shared with the simulation system using local area network. A case study of an actual collision incident in Tokyo Bay has been simulated to illustrate the capability of the proposed systems.

Keywords: Sea Traffic; Collision Avoidance; Sea Traffic Surveillance

1. INTRODUCTION

Safety of vessel transit in congested sea areas such as busy ports and coastal water is a key issue for ship navigation officers as well as operators of Vessel Traffic Services (VTS). Maintaining an overview of changing navigational conditions to maintain safe manoeuvre in these areas causes high workload, which can lead to unacceptable risk of misjudgment and mistakes.

With recent performance improvement of observation devices and introduction of new information systems, VTS is expected to play larger role in supporting the officers onboard. However, an increase in the volume of available information demands higher skills in critical situation awareness and operational decision-making in complex situations. Assessment of collision risks and evasive manoeuvres are still to a degree left to human individuals. Practical solutions so far include training and acquiring experience, although long-term experience does not guarantee that the right decisions will be reached.

Development and evaluation of support systems for sea traffic are also considered. A prototype system to support visual assessment by providing display of collision danger regions with surrounding vessels was proposed and tested in simulator test programmes by Pedersen et al. (2002a, 2002b). The scenarios were composed of various traffic densities and different ranges of own ship speed showed that the proposed system facilitates more homogeneous, precise, and safe evasive manoeuvres than utilizing conventional judgment techniques such as standard Automatic Radar Plotting Aid (ARPA) systems.

This paper presents the model formulation, architectural structure and core algorithm of sea borne traffic reproduced in the SEATRAS (Sea Traffic Simulation) system by Numano et al. (1987, 2001), visual navigation aid as provided by VCASS (Visualization-based Collision Avoidance Support System) system, and a simulation environment composed of these systems. An actual collision incident that occurred in Tokyo Bay in 1985 has been simulated to discuss the effectiveness of VCASS system as VTS support. Simulation results show that VCASS have the potential to become a useful judgment tool for the VTS operators.

2. MATHEMATICAL MODELLING

2.1. Representation of Sea Traffic

The route of a vessel, in general, is planned as a polygonal line that connects two ports. Vertices of the polygonal line are called waypoints. A vessel keeps its passage plan by changing its course to next waypoint when it arrives in the vicinity of a waypoint. In compliance with the navigation rules concerning two vessels approaching one another and traffic lanes that guide vessels to navigate orderly in the congested areas, they alter their courses according to the situation.

Vessel traffic is modelled as a set of entities that flow through links between Origin-Destination (OD) pairs, which represent part of connecting line between two ports. The modelling is organized as follows: 1) Retrieve pairs of OD gates from surveyed data of vessel tracks. Each gate is defined as a line segment. 2) Fix the shape of a fairway that represents the links for each set of gate pairs. As illustrated in Figure 1, a fairway is specified by a collection of line segments that indicate the location that vessels are required to pass through. The line segment is called fairway gate. 3) Determine parameters to calculate time intervals for entity generation at origin gates. Parameters are determined in accordance with the types of vessels for all the fairways.

SEATRAS calculates generation time of entities at origin gates every execution time using fairway parameters and pseudo-random numbers.

- for (int i=0; i < FairwayNum; i++) {
  - for (int j=0; j < ShipTypeNum; j++) {
    - calculate number of type-j entity to be generated in this time span
    - for (int k=0; k < EntityNum; k++) {
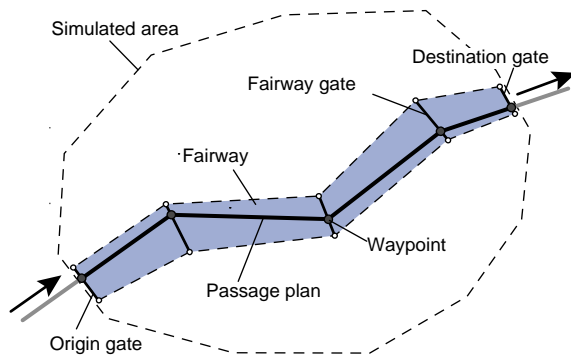   - calculate generation time of entity
    }
  }
}

In order to simulate or repeat simulation of specific patterns, a mechanism to incorporate XML-based scenario from text files, and definition of an XML scheme to represent a traffic flow, have been implemented. The scheme is defined to express a scene of simulation, characteristics of the vessels, and their passage plans. The traffic flow data generated by the above algorithm can be saved as well as data generated by hand. This static scenario can be applied in combination with the dynamically generated traffic flow.

The KT model by Nomoto et al. (1956) is implemented to calculate ship motion characteristics in the horizontal plane.

For each time step, motion of the ship is updated as follows; firstly, the turning (yaw) rate is calculated from,

$$\frac{\Delta r}{\Delta t} = \frac{r_{max} \cdot \delta / \delta_{max} \cdot u / u_{max} - r}{\tau_r}$$

where r and τ_r indicate yaw angle and response delay of turning speed, respectively, δ indicates rudder angle, u is ship speed, and subscript *max* denotes the upper limit of each parameter. The ship heading $\psi_{heading}$ and course ψ_{course} are according to;

$$\frac{\Delta \psi_{heading}}{\Delta t} = r$$

$$\frac{\Delta \psi_{course}}{\Delta t} = \frac{\psi_{heading} - \psi_{course}}{\tau_\psi}$$

where τ_ψ is the response delay for turning. Finally, the ship velocity is calculated from:

$$\frac{\Delta u}{\Delta t} = \frac{u_o - u}{\tau_u}$$

where τ_u denotes response delay of speed.

Figure 1. Fairway and passage plan.

2.2. Representation of Collision Avoidance Parameters and Collision Danger Regions

Consider the movement of two vessels, a reference vessel and an external target i, traveling on a plan sea surface in an Earth-fixed Cartesian co-ordinate system x-y. It is assumed that the vessels are mass points without extension and that the velocity vectors can be regarded as constant relative to the Earth-fixed co-ordinate. The movement vectors are furthermore considered as known at any time. The two vessel's encounter geometry is plotted in Figure 2.

Let $\mathbf{X}_0$ (L) = $[X_0 \; Y_0]^{\mathrm{T}}$ and $\mathbf{X}_T^i$ (L) $= [X_T^i \; Y_T^i]^{\mathrm{T}}$ be the respective position vectors of the vessels, $\mathbf{V}_0$ (LT^{-1}) = $[V_{0x} \; V_{0y}]^{\mathrm{T}}$ and $\mathbf{V}_T^i$ (LT^{-1}) = $[V_{Tx}^i \; V_{Ty}^i]^{\mathrm{T}}$ represent the corresponding true velocity vectors, and let ψ_0 and ψ_T represent the respective true courses. Furthermore, t (T) is time, Δt (T) is equivalent with the vector length in time scale, and α is the aspect angle (relative bearing). The relative vector $\mathbf{V}_R^i$ (LT^{-1}) is then, on component form, given by

$$\left\langle V_{Rx}^i, V_{Ry}^i \right\rangle = \left\langle V_{Tx}^i, V_{Ty}^i \right\rangle - \left\langle V_{0x}, V_{0y} \right\rangle$$

The time to, and minimum distance at, closest point of approach (referred to as $TCPA$ (T) and $DCPA$ (L), respectively) follows from minimizing the time derivative of the relative distance function,

$$\frac{\partial}{\partial t}\left| \mathbf{X}_T^i - \mathbf{X}_0 \right|_{t=0} = 0$$

and can be written as

$$TCPA_i = -\frac{\left(X_T^i - X_0\right)V_{Rx}^i + \left(Y_T^i - Y_0\right)V_{Ry}^i}{V_{Rx}^{i\,2} + V_{Ry}^{i\,2}}$$

and

$$DCPA_i = \left| \frac{\left(X_T^i - X_0\right)V_{Ry}^i - \left(Y_T^i - Y_0\right)V_{Rx}^i}{\sqrt{V_{Rx}^{i\,2} + V_{Ry}^{i\,2}}} \right|$$

The mathematical criteria for collision between the two approaching vessels can be formulated as,

$$V_0 \sin\alpha_0 = V_T^i \sin\alpha_T^i$$

It follows from Figure 2 and this analytical collision criteria that the Potential Point of Collision (PPC) can be moved along the external target's track line if V_0 is altered such that its end position touches the bold dashed line that is parallel to the in-sight line between the vessels and drawn from the tip of target's vector. Thus, any manoeuvre that deflects the end of the reference vessel's velocity vector away from the bold dashed line is a potential collision avoidance

manoeuvre. This line can therefore be regarded as a Collision Danger Line (CDL) in true motion. It is simply created by parallel displacement of the bearing line to the target, a distance equal to the length of $\mathbf{V}_T^i$, and is therefore independent of the reference vessel's motion parameters. The dotted line from the centre of reference vessel, parallel to $\mathbf{V}_T^i$, represents the course that would result in parallel movement. The interception point (B) between this line and the CDL can therefore be regarded as a limit for relevant anti-collision evaluation.

The general solution of the collision scenario is then obtained by considering a minimum passing distance ($DCPA$ limit) from which a cone-shaped collision region (dashed lines) can be imagined on a standard ARPA radar in relative motion display from the viewpoint of the reference vessel, and transformed to appear in the true motion display (shadowed sector) as shown in Figure 3. Thus, any manoeuvre that deflects the end of velocity vector away from the shadowed sector, referred to as Collision Danger Sector (CDS), is a potential evasive manoeuvre.

Let A and B refer to the end coordinates of the CDL, and let C and D refer to the points on the $DCPA$ limit circle that determines the position of the tangents through B, see Figures 2 and 3. The cone-shaped collision danger region in true motion display is determined by the position vectors $\mathbf{X}_k^i$ (L) = $\{ [X_k^i \; Y_k^i]^{\mathrm{T}} \}_{k=\{A,B,C,D\}}$ which can be formulated as,

$$\mathbf{X}_A^i = \mathbf{X}_T^i + V_T^i \Delta t \, \mathbf{I}\,\mathbf{\Psi}_i$$

and

$$\mathbf{X}_B^i = \mathbf{X}_0 + V_T^i \Delta t \, \mathbf{I}\,\mathbf{\Psi}_i$$

where $\mathbf{\Psi}_i = [\sin \psi_T^i \; \cos \psi_T^i]^{\mathrm{T}}$ for $0 \le \psi_T^i \le 2\pi$ and $\mathbf{I}$ is the 2×2 unit matrix,

$$\mathbf{X}_C^i = \mathbf{X}_B^i + \left(\left| \mathbf{X}_A^i - \mathbf{X}_B^i \right|^2 - DCPA_{\lim}^2 \right)^{1/2} \mathbf{\Omega}_i$$

and

$$\mathbf{X}_D^i = \mathbf{X}_B^i + \left(\left| \mathbf{X}_A^i - \mathbf{X}_B^i \right|^2 - DCPA_{\lim}^2 \right)^{1/2} \mathbf{\Phi}_i$$

where

$$\mathbf{\Omega}_i = \left[(-1)^m \cos\left(\gamma_i + (-1)^n \beta_i\right) \quad (-1)^p \sin\left(\gamma_i + (-1)^n \beta_i\right) \right]^{\mathrm{T}}$$

$$\mathbf{\Phi}_i = \left[(-1)^m \cos\left(\gamma_i + (-1)^q \beta_i\right) \quad (-1)^p \sin\left(\gamma_i + (-1)^q \beta_i\right) \right]^{\mathrm{T}}$$

$$\gamma_i = \left| \tan^{-1}\left(\frac{Y_A^i - Y_B^i}{X_A^i - X_B^i} \right) \right|_{X_A^i \neq X_B^i} \quad ; \quad \gamma_i = \frac{\pi}{2}\bigg|_{X_A^i = X_B^i}$$

$$\beta = \sin^{-1}\left(\frac{DCPA_{\lim}}{\left| \mathbf{X}_A^i - \mathbf{X}_B^i \right|} \right)\Bigg|_{DCPA_{\lim} < \left| \mathbf{X}_A^i - \mathbf{X}_B^i \right|}$$

m, n, p and q are integers (0 or 1) according to;

$Y_A^i \geq Y_B^i$ and $X_A^i \geq X_B^i$: $[m, n, p, q] = [0, 1, 0, 0]$

$Y_A^i \geq Y_B^i$ and $X_A^i < X_B^i$: $[m, n, p, q] = [1, 1, 0, 0]$

$Y_A^i < Y_B^i$ and $X_A^i \geq X_B^i$: $[m, n, p, q] = [0, 0, 1, 1]$

$Y_A^i < Y_B^i$ and $X_A^i < X_B^i$: $[m, n, p ,q] = [1, 0, 1, 1]$
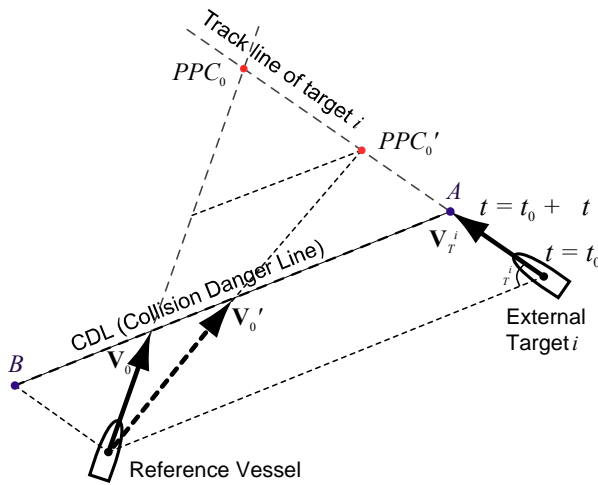
Figure 2. Reference vessel ($\mathbf{V}_0$ or $\mathbf{V}_0'$) and target ($\mathbf{V}_T^i$) on collision course(s).
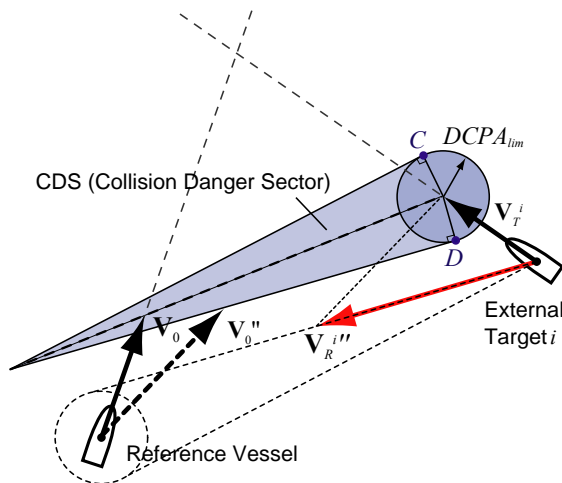

Figure 3. Cone-shaped collision danger regions as they appear in true (shadowed sector) and relative (dashed sector) motion displays.

3. SYSTEM ARCHITECTURE AND CORE ALGORITHM

The Borland C++ Builder development environment was utilized to develop the algorithm and user interfaces for SEATRAS and VCASS. Vessel position and movement data are broadcasted from SEATRAS through Ethernet and forms the key inputs. The anti-collision parameters and co-ordinates of the collision danger region to all vessels are calculated at every time step according to the following scheme that represents the core algorithm:

- read UDP data string containing traffic data

- get total number of vessels (ShipNum) and length of string (StringLength)

- set key control parameters and select reference target

- for (int j = 0; j < StringLength; j++){
  - get vessel i's data:
    Identification number, $\mathbf{X}_0$, $\mathbf{X}_T^i$, $\mathbf{V}_0$, $\mathbf{V}_T^i$
  }

- for (int i = 0; i < ShipNum; i++){
  - calculate relative velocity vector $\mathbf{V}_R^i$
  - calculate $TCPA_i$ and $DCPA_i$
  - calculate $\mathbf{X}_k^i$; $k = \{A, B, C, D\}$
  - if target within relevant anti-collision distance
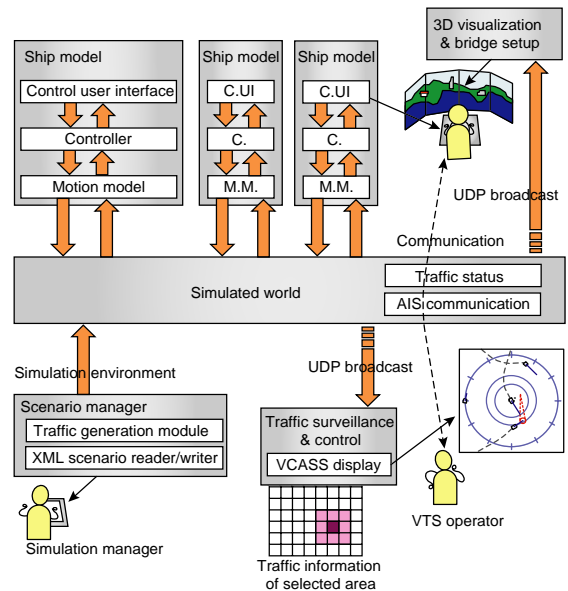   - display collision danger region
}

Figure 4. Simulation architecture of SEATRAS with VCASS.

4. CASE STUDY

Vessel Traffic Services (VTS) are shore-side systems that evolved as a response to the increased complexity of shipping and the need to prevent congestion by maintaining a safe traffic flow. The services are basically of two types; one is predominantly found in coastal areas or straits that are characterized by congested shipping lanes, such as for example the English Channel, while the other type is used to control the traffic movement in and out of ports.

VTS are designed to provide support to vessels by services that range from the provision of simple information messages, such as position of traffic in the vicinity, to extensive management of the traffic flow. In general, vessels entering a VTS covered area report to the authorities by radio, and are tracked by the VTS control centre. The vessels keep watch on a specific frequency for navigational or other warnings, while they may be contacted directly by the VTS operator if there is risk of an incident or, in areas where traffic flow is regulated, to be given advice on when to proceed.

VCASS can be applied to sea traffic surveillance purposes as the vessel from which collision risk is of interest to assess can be selected from any of the acquired targets. A case study involving ships on outbound courses in the innermost sector of Tokyo Bay has been simulated in order to illustrate the potential for efficient and safe collision avoidance management by VCASS. The case study is based on an actual collision incident that took place in 1985.

Figure 5 shows the sea traffic and topographical conditions for the four ships (1 – 4) that were involved in the actual incident when Ships 1 and 3 eventually collided. The speed, course and waypoint data of the ships are given in Appendix as an XML scheme identical to the scenario configuration format used in SEATRAS. Additional ships have been generated to provide a realistic traffic scenario in this busy sector of Tokyo Bay.

Figure 6 shows a VCASS screen shot from the viewpoint of Ship 1 a few minutes (260 seconds) prior to the point of collision. The collision danger sectors are displayed with a *DCPA* limit of 0.05 n. mile. The VTS operator can easily identify that Ship 1 is on collision course with Ships 2 and 3 as its vector terminates inside the corresponding collision danger sectors.
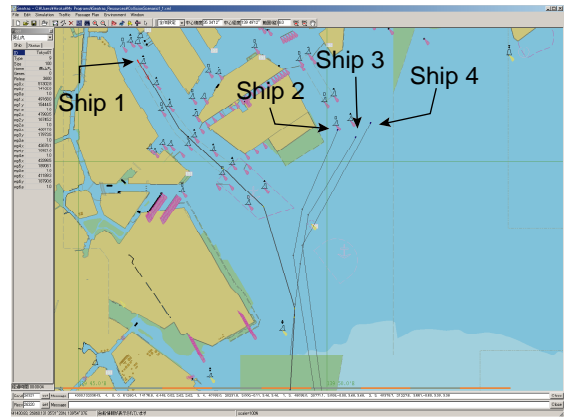

Figure 5. Positions and navigation tracks of the 4 ships involved in the collision incident in Tokyo Bay in 1985 when Ships 1 and 3 eventually collided. (Simulation time = 0 sec.)
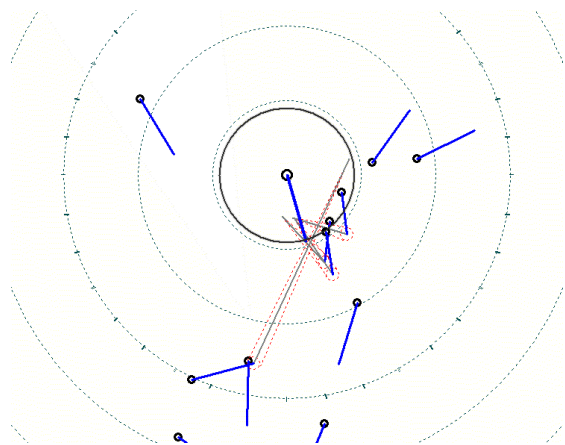

Figure 6. VCASS display (*DCPA* limit = 0.05 n.mile) from the viewpoint of Ship 1. The ship is on a collision danger course with Ships 2 and 3 as the tip of its vector terminates inside the respective collision danger regions. $TCPA_{Ship3} = 260$ sec. (Simulation time = 1190 sec.)
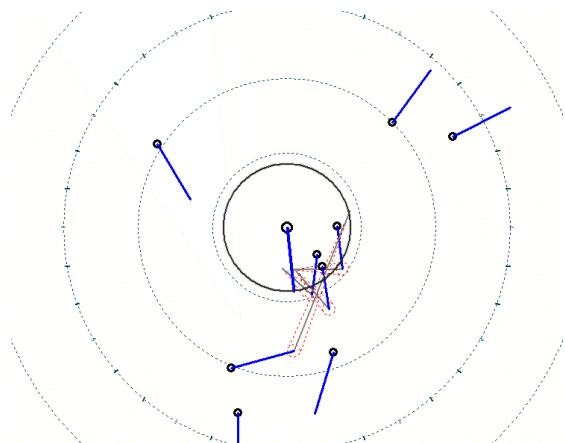

Figure 7. VCASS display after Ship 1 has executed an evasive manoeuvre by a course change to starboard. Ship 1 will overtake Ships 2 and 3 with a clear safety distance margin. (Simulation time = 1300 sec.)

The following feasible evasive manoeuvres can be identified from the VCASS display; 1) a course alteration to port, 2) a course alteration to starboard, 3) a decrease of speed or 4) a combination of 1) and 3) or 2) and 3). A change of course to port should be avoided due to the ship on the port side. Speed reduction normally has a significant time lag and is thus avoided as an evasive manoeuvre. The obvious choice for the VTS operator to communicate to Ship 1 is thus a course alteration of 10-15 deg. to starboard. Figure 7 shows the resulting effect of such a manoeuvre with a screen shot 2 minutes later, taking into account a 1 minute delay in response due to communication between VTS operator and the particular ship.

5. CONCLUSIONS

In this paper the model formulation, architectural structure and core algorithm of sea borne traffic reproduced in the sea traffic simulator SEATRAS, and a visual navigation aid provided by Visualization-based Collision Avoidance Support System (VCASS) are illustrated. The SEATRAS utilizes traffic flow dynamically generated from observation data and predefined static scenario in combination. The VCASS supports the navigators and VTS operators to identify feasible evasive manoeuvres by providing the display of cone-shaped collision danger regions to targets in the vicinity of a selected reference target, which represent collision risks to each of them. This enables judgment of collision risks and feasible evasive manoeuvres among vessels in congested waters. The simulation environment composed of these systems is also described.

A case study with congested traffic flow has been simulated to illustrate how the traffic in SEATRAS can be configured and how the VCASS interface can provide a simple and easy understandable judgment support for the VTS operator in cases where collision conflicts have the potential to arise. The results of this research indicate that VCASS display is beneficial for VTS control centres.

6. ACKNOWLEDGEMENTS

7. REFERENCES

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APPENDIX

```xml
<?xml version="1.0" encoding="Shift_JIS"?>
<scenario>
  <scenario_name>Collision incident in Tokyo Bay</scenario_name>
  <scenario_description>Collision in Tokyo Bay, March,1985</scenario_description>
  <scene_description id="0"><name>Northern part of Tokyo Bay</name>
   <latCenter>35.57</latCenter><lonCenter>139.82</lonCenter>
   <range>6</range></scene_description>
  <navigationplan_description id="0">
   <name>Ship 1</name><shipid>Tokyo01</shipid><type>9</type>
   <length>100</length><wpnum>7</wpnum>
   <role><gen_time>0</gen_time>
    <init_speed>12.6</init_speed><init_heading>150.0</init_heading>
    <init_psi>150.00</init_psi><init_thrust>1.1</init_thrust>
    <init_rudder>0</init_rudder><release_time>3600</release_time></role>
   <waypoint id="0">
    <latitude>35.6112</latitude><longitude>139.7698</longitude></waypoint>
   <waypoint id="1">
    <latitude>35.59197</latitude><longitude>139.78398</longitude></waypoint>
   <waypoint id="2">
    <latitude>35.5813</latitude><longitude>139.79837</longitude></waypoint>
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    <latitude>35.5201</latitude><longitude>139.821</longitude></waypoint>
  </navigationplan_description>
  <navigationplan_description id="1">
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   <length>23</length><wpnum>5</wpnum>
   <role><gen_time>0</gen_time>
    <init_speed>7.6</init_speed><init_heading>210.84</init_heading>
    <init_psi>210.84</init_psi><init_thrust>1.2</init_thrust>
    <init_rudder>0</init_rudder><release_time>3600</release_time></role>
   <waypoint id="0">
    <latitude>35.59</latitude><longitude>139.843</longitude></waypoint>
   <waypoint id="1">
    <latitude>35.56828</latitude><longitude>139.82704</longitude></waypoint>
   <waypoint id="2">
    <latitude>35.55483</latitude><longitude>139.82428</longitude></waypoint>
   <waypoint id="3">
    <latitude>35.54365</latitude><longitude>139.82255</longitude></waypoint>
   <waypoint id="4">
    <latitude>35.52963</latitude><longitude>139.82094</longitude></waypoint>
  </navigationplan_description>
</scenario>
```