Development of Comprehensive Simulation System for Autonomous Ships

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1. INTRODUCTION

Interest in Maritime Autonomous Surface Ships (MASS) has increased in recent years, and efforts to realize MASS are also underway in Japan. The roadmap for practical use of autonomous ships released by Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) proposes realization of highly automated autonomous ships (Phase III), in which the system makes some final decisions, targeting the year 2025. The Nippon Foundation's unmanned ship project, MEGURI 2040, also aims at practical use of unmanned ships in 2025 through demonstration experiments and other activities. In autonomous ships and unmanned ships, prevention of accidents due to human factors and improvement of safety by support by the autonomous system are demanded. On the other hand, not only technological development but also social acceptance is necessary for operation of autonomous ships. In order to gain social acceptance, it is necessary to show that autonomous ships are safe, that is, the assumed risks have been reduced to the allowable range. The National Maritime Research Institute (NMRI) is studying methods for evaluating safety and construction of the system necessary in such evaluations. This paper reports on a comprehensive simulation system consisting of multiple simulation systems, beginning with a ship handling simulator, and an evaluation method using simulations.

2. FLOW OF DEVELOPMENT AND CERTIFICATION OF AUTONOMOUS MANEUVERING SYSTEMS

Figure 1 shows the process of commercialization of unmanned automated driving services in the automotive sector, where automation advanced from an earlier date. The figure shows that the series of processes consisting of 1) Setting of the use case, 2) Setting of the traveling environment and operating conditions, 3) Vehicle technologies, development and selection of automated systems, development and improvement of infrastructure and peripheral technologies, 4)Demonstration of technology in a simulated environment, test course and public roads and 5) Demonstration of services, is carried out while conducting reviews based on the issues identified in the course of these processes [1). In 4) Demonstration of technology and 5) Demonstration of services, problems are identified and test scenarios are confirmed through cooperation between the developer and the certifying entity, and the performance standards, etc. necessary for certification are studied simultaneously with development. It is thought that study of commercialization and certification of automatic operation systems for ships will be carried out by a similar process, and in the process of demonstration of technology by test course operation and simulations, a comprehensive simulation system which can be used in place these demonstrations will be necessary. Moreover, since these verifications are carried out in cooperation with the developer, providing the functions necessary in development was also one purpose of the system discussed in this paper.

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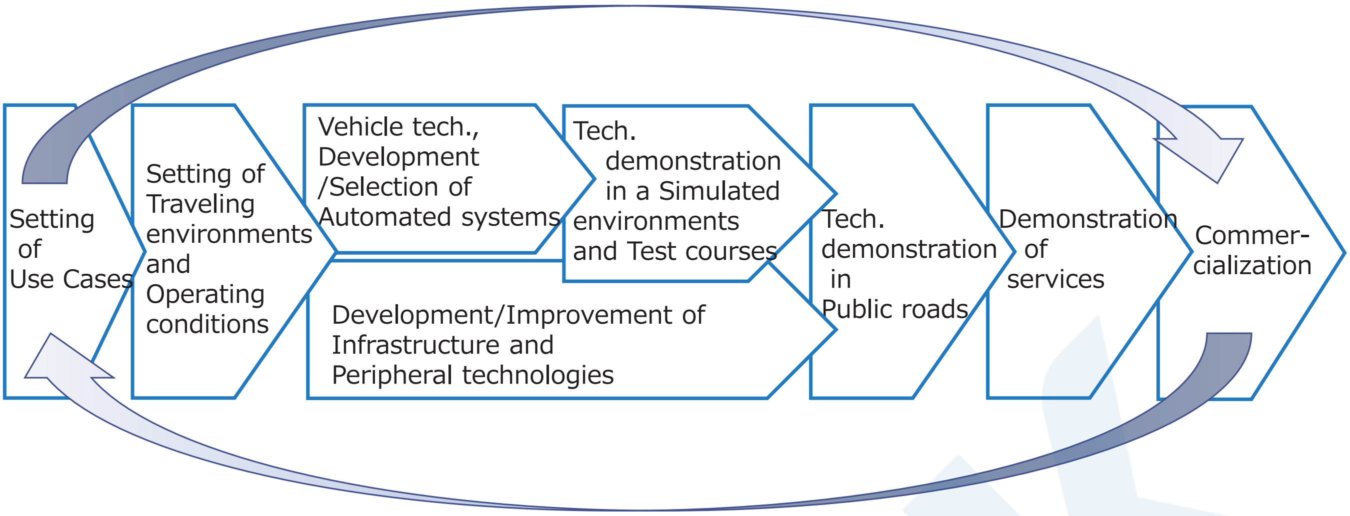

Figure 1　Process of commercialization of automated driving services (source: "Progress report on efforts to support the development of autonomous driving technologies and create adequate policies Version 5.0")

3.　OVERVIEW OF COMPREHENSIVE SIMULATION SYSTEM

Configuration of the comprehensive simulation system utilizing the following five systems is under study.

1) Ship Handling Simulator (SHS)
   This is a full mission-type ship handling simulator. Various types of evaluations considering human involvement are possible, including evaluation of the human machine interface (HMI), evaluation of the timing of transfer of ship operation authority to the crew in emergencies, evaluation of maneuvering actions in waters shared with existing ships, etc.
2) Fast Time Ship Simulator (FTSS)
   This system makes it possible to conduct simulations in a significantly shorter time than the actual time, and conduct comprehensive verifications under set conditions.
3) Sensor verification system
   Enables verification of the detection performance of the system that detects the condition of navigation by other ships, which is connected to the automation system.
4) Evacuation simulation
   Enables verification of the evacuation condition under abnormal conditions such as fires, etc.
5) Engine remote monitoring system

Enables monitoring of the engine condition from shore.

Here, general names which indicate the system function are used as the names of these systems, except for the FTSS. The following discussion will center on the SHS and FTSS, as study of the concepts (e.g., clarification of verification targets, etc.) of the sensor verification system, the evacuation system and the engine remote monitoring system began in FY 2021. In addition, the work on shipboard is diverse, and the evaluation methods differ depending on the target. The evaluation targets for the SHS and FTSS are items related to ship handling, and comprise the following functions.

1) Automatic ship handling (berthing/deberthing, collision avoidance, ship handling during stormy weather)
2) Remote monitoring and maneuvering
3) Emergency (transfer of ship handling from system to crew)

In order to use the SHS or FTSS in development and certification, it is necessary to connect the target automation system (algorithms for automatic collision avoidance maneuvering, etc. or the system incorporating algorithms). A standard interface called a functional mock-up interface (FMI) is used for this purpose. In addition, we are also studying the creation of a maneuvering operation model database to reproduce target ships and creation of a scenario database that generates scenarios considering information such as on the target sea area, etc.

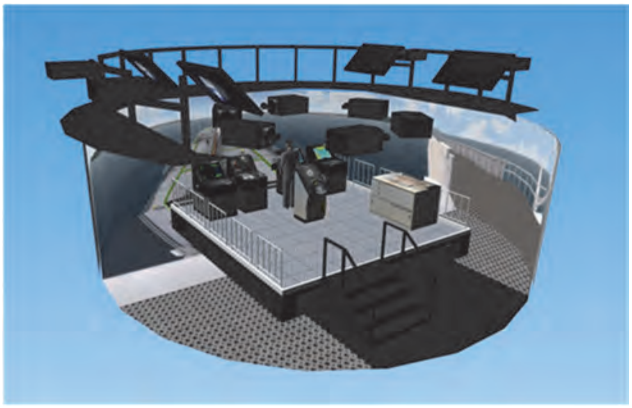

Figure 2　Image of ship handling simulator (prepared in March 2021)

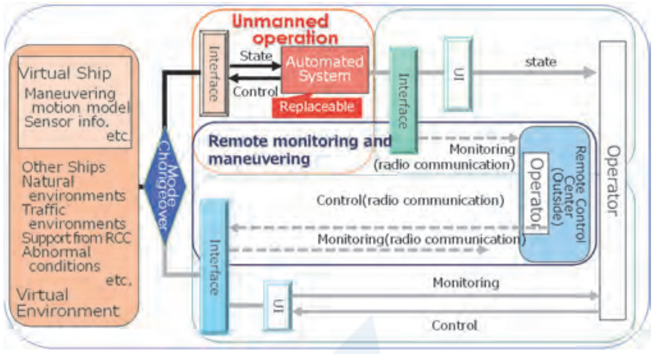

Figure 3　Conceptual diagram of ship handling simulator

4.　FUNCTIONS OF SIMULATION SYSTEM

4.1　Ship Handling Simulator (SHS) (Fig. 2)

Regarding the levels of MAAS or automation systems, it can be thought that there are several steps from the current level, where seafarers make judgments and carry out ship handling and the system supports those activities, to the level of a fully autonomous automated ship which navigates without the need for human involvement, and development will advance based on those steps. In particular, in the stage of development where work on the ship's bridge reaches fully autonomous, automated ship operation, it will be necessary to conduct a safety evaluation that considers the involvement of the crew. For example, it will be necessary to verify that the necessary time and information can be secured when it is judged that the system is unable to respond in an emergency, etc. and ship operation is transferred to the crew. Regardless of the development stage of the ship, it is necessary to consider coexistence with existing ships operating under human control. In this case, the target of evaluation is operation that does not cause feelings of unease to operators on those ships.

One distinctive feature of the SHS is the fact that evaluations considering this kind of human involvement are possible. This is also necessary in order to verify various conditions, including trouble and environments which are difficult to reproduce in actual-sea experiments.

The functions required in the SHS are as follows, and are also shown schematically in Fig. 3.

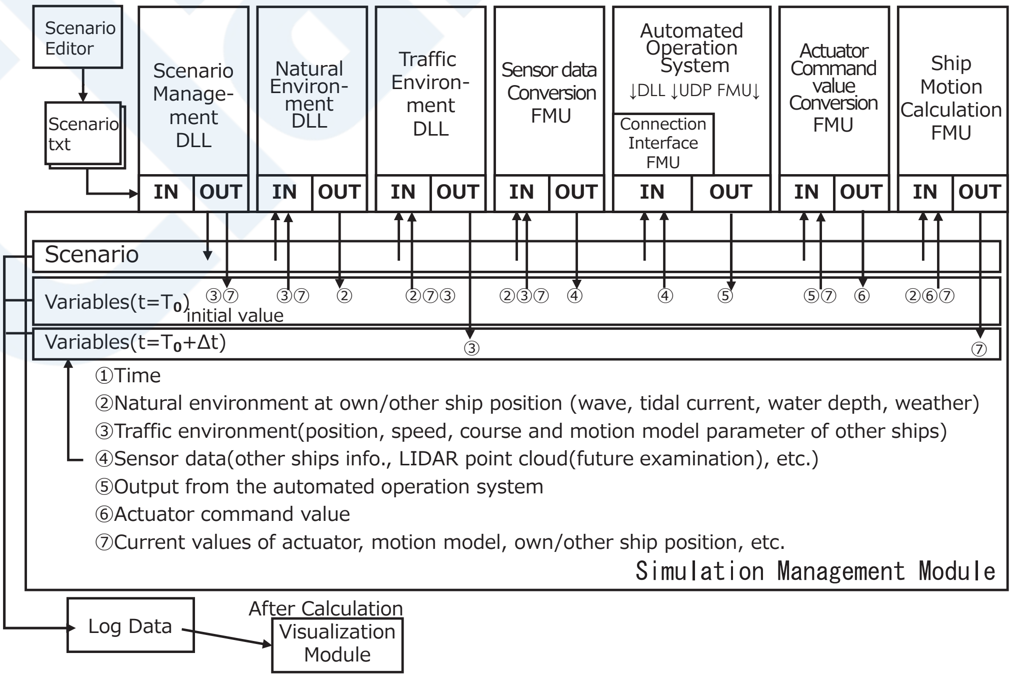

Figure 4　Overview of operation of fast time ship simulator

1) Automatic ship operation
- Connection of arbitrary automatic ship operation program
- Incorporation of ship motion model corresponding to evaluation target

2) Remote monitoring and maneuvering
- Remote telecommunication system
- Reproduction of information presentation function
- Reproduction of telecommunication speed, lack of data, etc.

3) Transfer of ship operation to crew, evaluation of HMI
- Reproduction of information provision function
- Reproduction of ship operation switching device and functions
- Reproduction of display and operation devices corresponding to evaluation target
- Free layout of navigation equipment, function for connection with equipment brought in from outside

4) Incorporation of various types of information
- Incorporation of own ship’s collision avoidance function in other ships
- Preparation of various types of sensor information
- Formation of sensor information suited to the evaluation object
- Reproduction of information accuracy (noise, lack of data, updating interval, etc.)
- Incorporation of engines, thrusters, steering gear
- Function for expression of abnormal events
- Reproduction of malfunction of sensors, engine, power supply, etc.

5) Testing environment
- Test case creation function
- Display of ship operation results and results of analysis of various types of indexes

The SHS also includes new functions not available in existing ship handling simulators, and we are conducting a study aiming at implementation of those functions.

4.2 Fast Time Ship Simulator (FTSS)

In safety evaluations by the SHS, simulations under a diverse range of conditions are necessary. In cases where it is not necessary to consider human involvement, use of the Fast Time Ship Simulator (FTSS) is effective, as calculations are executed at high speed, and output is not limited to real time.

Figure 4 shows the outline of the FTSS. The SHS and the simulation modules that operate on the FTSS, including the environment, other ship, sensor, ship motion calculation modules, are connected with the simulation management module as DLL (Dynamic Link Library) through FMI as an FMU (Functional Mock-up Unit), and function as an FTSS in which the total system tests the operation of the autonomous ship. The outline of the respective modules is as follows.

1) Simulation management module

   This is module performs the series of operation including starting the modules that comprise the simulator, initializing the modules based on the scenario, executing the modules, controlling the data output from the modules, outputting logs, outputting for visualization, judging completion based on the scenario, time update, etc., and manages the operation of the FTSS.

2) Scenario management DLL

   This module is in charge of scenario management. It prepares scenarios in response to the simulation management module and is used when executing simulations. The purpose of the scenario management DLL is to read the setting items necessary to execute a simulation from the scenario file, and load the scenario information so it can be used by the simulation management module.

3) Natural environment calculation DLL

   The purpose of this module is to output ocean surface winds and tidal currents, which change depending on the time and position of the own ship and other ships. It outputs information on ocean surface winds, tidal currents, the water depth, weather and night or day conditions based on the time and the coordinates of the own ship and other ships. In order to improve the calculation speed, it has a function which prepares datasets by calculating the grid data for these items in advance for 24-hour time periods.

4) Traffic environment DLL

Based on the values set by the scenario, this module generates a set number of other ships and performs navigation and automatic collision avoidance for each of the other ships.

5) Sensor data conversion FMU

Based on the real values obtained by the own ship state, other ship state and natural environment simulation calculations, this module creates and supplies sensor data which are consistent with the input of the SHS by superimposing noise simulating the measurement error of measuring instruments and performing processing in a form that simulates the output of the ship’s navigation equipment.

6) Ship operation system connection interface

This is an interface for connecting ship operation automation systems constructed with interfaces other than FMI to the simulation system by FMI. Because ship operation automation systems were thought to have diverse execution forms and input formats, easy revamping of this interface is necessary. At present, connection via networks other than FMI connection is assumed.

7) Actuator command value conversion FMU

This device converts the maneuvering commands received from the ship operation automation system by way of a FMI, etc. to a form that the actual actuators can receive as inputs, simulates the mechanical response of the actuators, and outputs the results to the ship motion calculation FMU as the present values of the actuators (rotation speed, rudder angle, etc.).

8) Ship motion calculation FMU

In the ship motion calculation FMU, the ship operation information and quantities of state of the natural environment calculated by the actuator command value conversion FMU and the natural environment calculation DLL are input via an FMI, and the module performs time update calculations of the quantities of state of the own ship and outputs the results to the simulation management module by way of an FMI. We are also studying the creation of a maneuvering motion simulation tool which outputs the maneuvering motion parameters necessary in setting the maneuvering motion model based on the main items and actuator composition, and use of the parameters generated by that tool by this FMU in evaluations of collision avoidance maneuvering, etc.

9) Visualization module

A function for more detailed analysis of the execution results is provided by visualizing the visualization log output from the simulation by display of electronic charts, 3D display and evaluation indexes, as shown in Fig. 5. The evaluation indexes are described in Chapter 5.

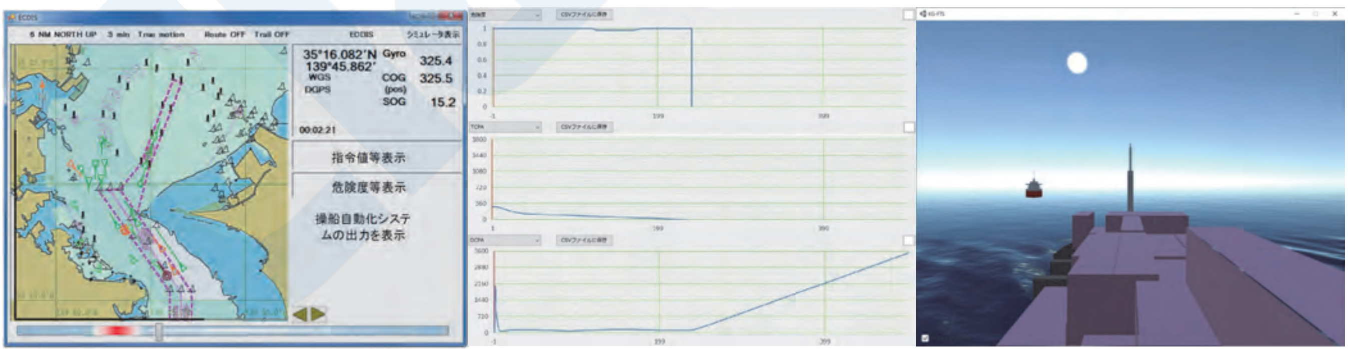

Figure 5　Visualization of results

Left: Display of electronic chart, middle: display time-series indexes, right: 3D display

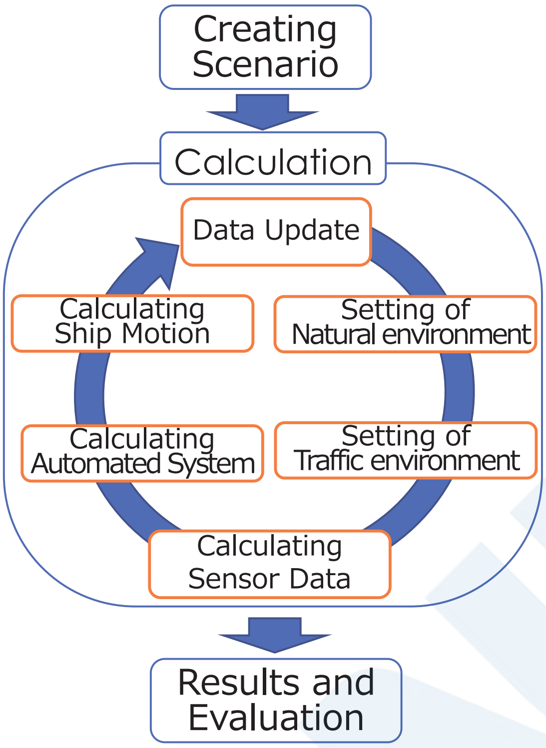

Figure 6　Simulation execution procedure

4.3　Simulation Execution Procedure

Figure 6 shows the simulation execution procedure using the FTSS as an example. When a calculation is executed in the SHS, this procedure also includes the creation of data for display items such as scenery images and displays of the ship's navigation equipment; however, the basic flow is the same.

1) Scenario creation

In scenario creation, the initial conditions of the simulation are set. The items set here include the own ship's state, position and planned course (information on course change points), the traffic flow, such as the position, speed and other information concerning other ships, the conditions of the natural environment, such as waves, wind, day or night, etc., and geographical conditions such as the water depth, obstacles to navigation and the like. A text file is created using the scenario creation editor. The scenario management DLL mentioned in Section 4.2 2) is in charge of loading the scenario file.

2) Calculation execution

In simulation calculations, the data are updated in each cycle, as shown in Fig. 6, and calculations are continued until the results satisfy the condition for completion of the simulation. Although the condition for completion is determined by the scenario, cases such as arrival at the final course change point, etc. may be used. The modules described in Section 4.2 3) to 8) are responsible for this operation.

3) Analysis and evaluation of results

In addition to the course track, heading and speed of the own ship and other ships, the output of the autonomation system, etc. is also recorded, making it possible to evaluate the ship operation results. We are also studying construction of a debugging environment which enables easy feedback to the target system during development, for example, by making it possible to reproduce the results from any arbitrary timing.

4.4　Standard Interface (FMI)

FMI is a free standard that defines the container and interface for the exchange of dynamic models using a combination of XML files, binary and C code zip-compressed into 1 file. The code and documents are publicly available [2].

Development and use have been promoted in the automotive sector. In system development, it is difficult to connect models described with the various simulation tools of each development company, but unification of the simulation tools would be unrealistic. Therefore, FMI was constructed as a public project in Europe with the aim of standardizing a common interface for model connection which does not depend on the tool and exchanging and connecting models between different simulation tools.

Construction of a simulation platform applying FMI has also been promoted in the maritime sector, centering on Norway, and a specialized code is publicly available [3].

In the NMRI simulation system, the automation system, sensor data, actuator and ship motion modules, which differ depending on the developer and development target, as mentioned previously, were also constructed by using FMI, enabling connection of any desired system.

5. STUDY OF EVALUATION METHODS USING SIMULATIONS

5.1 SHS and FTSS

The SHS is mainly used to obtain subjective evaluations by ship operators and ship operation results for limited scenarios. In evaluations of the collision avoidance maneuvering function, it is used in evaluations of the appropriateness of the condition of collision avoidance by the own ship and other ships, and in evaluations of the HMI with the automatic collision avoidance maneuvering function. In case collision avoidance maneuvering is not possible and ship operation is transferred to the human ship operator, it is also used to evaluate whether this transfer can be carried out properly.

In evaluations by the SHS, the results of evaluations corresponding to more realistic navigational environments are obtained together with subjective evaluations based on use experience, but it would be difficult to evaluate all of the possible scenarios for encounter situations. For this reason, the FTSS is used in evaluations for confirmation of the system safety validation based on a validation plan and validation tests under comprehensive environmental conditions set by the certifying entity. It is thought that efficient and effective evaluations can be carried out by targeting verification of scenarios that are difficult to judge in an evaluation by FTSS for verification by experienced ship operators using the SHS.

Table 1 Degree of collision risk

Target	Evaluation index	Outline
Degree of collision risk	CJ [12]	The degree of collision risk is calculated based on the relative heading with the other ship and its rate of change, and the distance between the 2 ships and its rate of change.
	SJ [13]	The changes in the relative distance and relative heading with the other ship are given in fuzzy representations in 3 levels, considering encounter situations, and the degree of collision risk of the 2 ships calculated based on a combination of the two variables is shown by an index system ranging from 3 (safe) to −3 (dangerous).
	CR [14]	Using TCPA and DCPA as variables, the degree of collision risk of 2 ships is shown by fuzzy inference, considering the ship lengths and maneuvering performance.
Degree of maneuvering difficulty	BC [15]	The degree of maneuvering difficulty is evaluated by obtaining the degree of obstruction by ships existing in the surrounding waters (collision avoidance space obstruction) by multiplying the degree of risk of a collision by another ship by a weight corresponding to the preference of the means of collision avoidance by speed change or course change.
	ES [16]	The magnitude of the load borne by the ship operator is shown by quantification, by substituting the time margin until the risk of collision with an obstacle or another ship becomes manifest for the sense of risk felt by the ship operator.
	OZT [11]	The region where the direction of progress of the own ship is obstructed by the presence of other ships is defined as an OZT (Obstacle Zone by Target), and the margin for collision avoidance maneuvering by the own ship is evaluated based on the distribution of the OZT.

5.2 Scenarios for Use in Evaluations

In certification of automation systems such as an automatic collision avoidance function, etc., the reliability and appropriateness of the software is set as a test item by designating hazards, and a simulation is carried out under those conditions to confirm that there are no problems. As hazards, scenarios are set under comprehensive environmental conditions, considering encounters with other ships, judgment of an encounter situation, lost signals and the like, and are then used in the test.

The evaluation scenarios when evaluation of a collision avoidance algorithm is to be carried out by FTSS are considered to comprise scenarios for verifying the basic functions in 1 to 1 encounter and in multiple overlapping encounters with other ships, which are assumed to occur in congested waters. For 1 to 1 encounter, the number of necessary scenarios is limited by restricting the range to the area where watchkeeping is performed, and the scenarios are created by comprehensively setting the arrangement, course and speed of the other ship. However, an infinite number of scenarios can be prepared for multiple overlapping encounters. Therefore, when the collision avoidance maneuvering function is the subject of verification, the scenarios are prepared from the following viewpoints:

1) Random setting of other ships encountered by the own ship
2) AIS (Automatic Identification System): Encounter situations which occur frequently and encounter situations in which maneuvering seems difficult are extracted from the tracks recorded in data, etc.
3) Collection of scenarios used in evaluations of the collision avoidance maneuvering function from the literature on collision avoidance maneuvering, etc. [4]
4) Extraction of scenarios from cases of maritime accidents [5]

Regarding preparation of scenarios using AIS data, in the automotive sector, a data storage/classification type scenario-based approach [6] has been proposed, in which a scenario database is created by classifying and storing the accumulated traffic flow observation data in systematic categories. Since AIS data includes information such as ship positions, ground speeds, headings, MMSI, IMO number, destination(s) and the like [7], the individual data can be assigned to each ship based on information specific to the ship, such as MMSI, etc., and course tracks can then be obtained by sorting in time order. Therefore, the construction of a scenario database by using a similar technique is under study. In particular, we are also studying the creation of models that reflect the current condition and addition of scenarios to reproduce ships that are not equipped with AIS. For coastal ships with displacements of less than 500 GT, this would be based on estimation from data acquired by AIS-equipped ships, use of radar data, etc., and for fishing boats, surveys of the condition of navigation in the targeted waters would be conducted through interviews with fishing cooperatives and others.

5.3 Study of Evaluation Indexes

The conceivable evaluation indexes for collision avoidance maneuvering include a combination of the distance to the closest point of approach (DCPA) and time to the closest point of approach (TCPA) using course track and ship operation records obtained during experiments and conventional quantitative evaluations of the degree of collision risk, as shown in Table 1. A method for evaluating the suitability of this approach for legal compliance has also been advocated, particularly by Norway [8) 9)]. In this evaluation method, an evaluation of collision avoidance is conducted for head-on, crossing and overtaking encounters, which are the three types of ship encounter situations mentioned in The Convention on the International Regulations for Preventing Collision at Sea (COLREGs). Several other evaluation methods have also been proposed, for example by the subjective degree of risk and subjective evaluation of collision avoidance of ship operators [10], and evaluation utilizing OZT, [11], among others.

Although compliance with the rules of navigation by autonomous ships is important for preventing maritime accidents, quantitative evaluation is difficult because the existing rules include ambiguity premised on human ship operation [7]. In the method proposed by Norway, the rules are evaluated by a mathematical formula using multiple parameters which were derived from papers described past accidents or collision avoidance. While there is room for further study, the proposed method is extremely interesting as a quantitative evaluation method. Furthermore, in encounters where multiple ships interact, compliance with good seamanship by the seafarers is demanded. For encounters where a clear relationship exists, evaluation in accordance with the rules is necessary, and for complex encounters, an evaluation index corresponding to the target is required, for example, evaluation utilizing subject viewpoints. However, either type of evaluation must satisfy the system requirements.

6. CONCLUSIONS

This paper has presented an overview of the comprehensive simulation system which is now under development by the National Maritime Research Institute (NMRI), and has described evaluation methods for automatic collision avoidance maneuvering. Safety evaluation will be indispensable in realizing practical use of autonomous ships, and those standards will also provide a guideline for future development. The authors hope to improve the comprehensive simulation system, which will support that development, and the standards for safety evaluations in cooperation with the related companies, beginning with developers that participated in the MEGURI 2040 Project.

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