Development of Maneuvering System for Realizing Autonomous Ships

— Preliminary Report on Approach Maneuvering Control and Automatic Berthing —

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1. INTRODUCTION

1.1 Background

Accompanying higher speeds in ship-to-shore communications in recent years, there have also been active moves toward digitalization in maritime industries utilizing information and telecommunication and processing and control technologies such as the Internet of Things (IoT) and artificial intelligence (AI). Together with this growing momentum, technology development related to automated and autonomous ship operation has accelerated, resulting in increasingly active concrete moves toward practical application. Particularly in Europe, the ambitious concept of realizing unmanned ships by autonomous ship operation has been proposed, and multiple technology development initiatives are in progress. Various technology development projects are also underway in Japan.

Looking at domestic-trade shipping, which supports approximately 80 % of the transportation of basic industrial materials and products in the Japanese domestic economy, the number of veteran seafarers is decreasing, and their average age is increasing. As shown in Fig. 1, Composition of domestic seafarers by age [1], the percentage of persons over 50 years old exceeds 37 %, and the largest age group of sailors is shifting to 60 years and older. Moreover, since 70 % to 80 % of maritime accidents in the waters around Japan are caused by human factors, reducing the risk of accidents at sea by preventing human error is critical for securing transportation quality.

Thus, in view of the current shortage of seafarers and the rapidly aging, prevention of human error by improving the working environment and reducing the workload on sailors is an urgent challenge.

Technology development aimed at realizing autonomous ships is one effort to address this social situation. The start of the Nippon Foundation's MEGURI 2040 Project [2], which aims at the future goal of completely unmanned ship operation, has accelerated technology development for automated and autonomous ship operation.

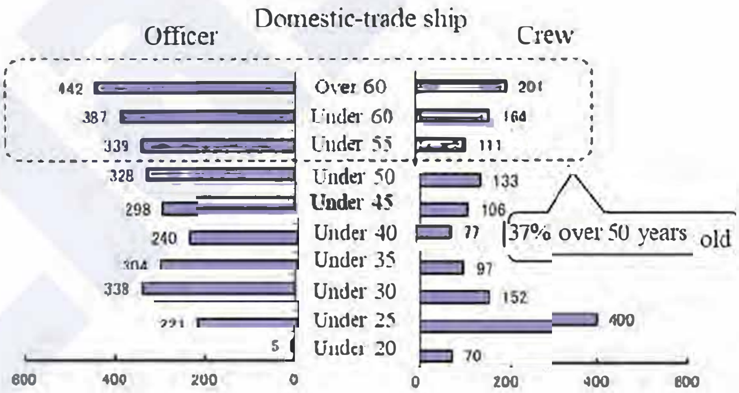

Figure 1 Composition of domestic seafarers by age

1.2 Overview

The Mitsui E&S Group, of which the authors are members, Mitsui O.S.K. Lines, Ltd. and the Tokyo University of Marine Science and Technology, jointly carried out the "Safety of Automatic Berthing and Un-Berthing Demonstration Project" of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) under a 3 year plan beginning in 2018. The Mitsui E&S

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Group was also involved in the development of an autonomous maneuvering system as part of the two consortia "Autonomous navigation at Sarushima, Yokosuka" and "Verification testing of unmanned technologies using coastal container vessels and car ferries" in the MEGURI 2040 Project of the Nippon Foundation (Public Interest incorporated Foundation).

In ship operation, maneuvering always requires a total evaluation, judgment of the situation, and decision-making based on information on the waters and ships navigating nearby, which is acquired by visual observation, radar, AIS (Automatic Identification System) and instruments, as well as various other information, including weather and marine meteorological conditions, the operating condition of the ship's engines and related laws and regulations. In particular, when maneuvering in a port, it is necessary to simultaneously operate multiple steering devices (including the rudder, propellers, and thrusters) based on topographical restrictions such as the water depth, course, etc.It is also especially important to consider the control characteristics of the ship at reduced speeds because the effects of external disturbances are relatively larger under these conditions.

The Mitsui E&S Group was involved in the development of the joystick maneuvering control system, the Mitsui Ship Maneuver Control System (hereinafter, MMS) and the Dynamic Positioning System (DPS) [3],, which has been installed on approximately 100 ships. Possessing a high level of maneuvering motion, control technology, and particularly technology related to maneuvering motion control a at low speeds. Utilizing these technologies, we are developing a maneuvering control system for realizing autonomous ships.

This paper presents an overview of the development of the maneuvering system and automated approach maneuvering control, which is the most difficult process in port maneuvering systems, and a preliminary report describing some of the results of approach and berthing maneuvering control in a demonstration test conducted at an actual quay using an actual ship.

2. OVERVIEW OF DEVELOPMENT OF AUTONOMOUS MANEUVERING SYSTEM

2.1 Condition Setting

In order to construct a maneuvering system, which is indispensable for realizing autonomous ships, various conditions were set, including the purpose and targets of the system and the operating conditions and requirements of the developed system. The conditions summarized below.

- System shall realize automation and autonomous operation of work for ship navigation which is performed from the bridge.
- The purpose of the system shall be hands-free berth-to-berth navigation based on the given voyage plan.
- The crew shall be able to understand the conditions of the own ship and its surroundings at all times.
- The crew shall perform fallback when conditions are outside the limit region of the system or when safe navigation cannot be maintained.
- The system shall also function without support from land.
- The system shall consider commercialization.
- Fallback is required, because redundancy in case of equipment failure is not considered in order to hold down the product cost.
- Installation on ordinary ships and retrofitting on existing ships shall be possible.
- It shall be possible for the crew to maneuver with the existing maneuvering devices by one action.
- In particular, the control right of the actuators shall be clear, preconditioned on input from the existing sensors and devices and output to the existing actuators.
- The system shall be connected considering the safety of the shipboard equipment.
- Regions limited by weather and marine meteorology shall be set based on the performance of the individual ship and the waters of each voyage.

2.2 Functions Required in Maneuvering System

In order to identify the functions required in an autonomous maneuvering system for realizing autonomous ships, the work performed by the crew on the bridge was investigated. Next, the functions required in the autonomous maneuvering system were extracted from the investigated work, considering the set conditions mentioned in the previous section. Focusing on the flow of information for realizing those functions, four main tasks were formulated below. The representative tasks classified in each function are shown in Table 1.

- Navigation state control
- Situational awareness
- Automatic collision avoidance (navigation and course plan management)
- Maneuvering control

Table 1 Tasks and functions required in maneuvering system

Task	Subtask Level 1	Subtask Level 2
1. Navigation state control	1.2 Judgment of possibility of autonomous maneuvering control	1.2.2 Judgment by system
	1.3 Mode control	1.3.1 Target WP control
		1.3.2 Mode transition (deberthing maneuvering → in-port maneuvering)
		1.3.3 Mode transition (in-port maneuvering → out-of-port maneuvering)
		1.3.4 Mode transition (out-of-port maneuvering → in-port maneuvering)
		1.3.5 Mode transition (in-port maneuvering → berthing maneuvering)
		1.3.6 Collision avoidance maneuvering control
2. Situational awareness	2.1 Watchkeeping	2.1.1 Grasp of other ships as moving or stopped
		2.1.2 Grasp of navigated waters
		2.1.3 Grasp of drifting objects, etc.
		2.1.4 Judgment of danger of grounding
	2.2 Situational awareness of ship navigation	2.2.1 Own ship's position
		2.2.2 Grasp of own ship's motion
	2.3 Weather and marine meteorology observation	2.3.1 Wind direction and speed
	2.4 Situational awareness of ship operation	2.4.1 Grasp of condition of main engine operation
		2.4.2 Grasp of condition of electric power on ship
	2.5 Evaluation of actuator response	2.5.1 Grasp of condition of actuators
		2.5.2 Evaluation of response values
	2.6. System soundness control	2.6.1 Monitoring of system operating condition (monitored by the system)
	3.2 Confirmation of course	3.2.1 Confirmation of appropriateness and safety
		3.2.4 Control of executed planned course
4. Automatic collision avoidance	4.1 Navigation space (waters) risk calculation	4.1.1 Setting of course environment
		4.1.2 Setting of topographical/water surface environment
		4.1.3 Calculation of risk of collision with other ships
		4.1.4 Calculation of total navigation risk
	4.2 Collision avoidance plan	4.2.1 Setting of collision avoidance plan
		4.2.2. Setting of collision avoidance course
		4.2.3 Evaluation of set course
5. Maneuvering control	5.1 Berthing and un-berthing maneuvering (berthing)	5.1.1 Calculation of maneuvering plan
		5.1.2 Maneuvering control
	5.2 In-port maneuvering (disapproach, approach)	5.2.1 Calculation of maneuvering plan
		5.2.2 Maneuvering control
	5.3 Out-of-port maneuvering	5.3.1 Maneuvering control
	5.4 Estimation of external force	5.4.1 Estimation of fore/aft external force
		5.4.2 Estimation of lateral external force
		5.4.3 Estimation of turning direction external force
		5.4.4 Estimation of steady course deviation component
		5.5.5 Estimation of wind pressure
	5.5 Situational awareness/evaluation of control	5.5.1 Evaluation of control results
		5.5.2 Prediction of control results
		5.5.3 Evaluation of GNSS error factors

2.3 System Configuration

In constructing the autonomous maneuvering system, the Mitsui Ship Maneuver Control System (MMS) mentioned in Chapter 1 was used in order to reduce the cost and time of development. The MMS has already received ship classification and has a linkage function with nautical instruments and functions for safely controlling maneuvering devices (propellers, rudder, thrusters, etc.). Because this system realizes various control functions, including joystick maneuvering, heading-keeping and dynamic positioning, it was thought that development time and costs could be substantially reduced, while simultaneously constructing a highly reliable control system.

In addition, the system also enables maneuvering by a single operator using only a joystick and dial, which is extremely effective when transferring control from the system to a human ship operator.

As shown in Fig. 2, Configuration of autonomous maneuvering system, a maneuvering system for realizing autonomous maneuvering was developed by providing a function that connects the autonomous maneuvering control system, which performs the control calculations for autonomous maneuvering, to the MMS.

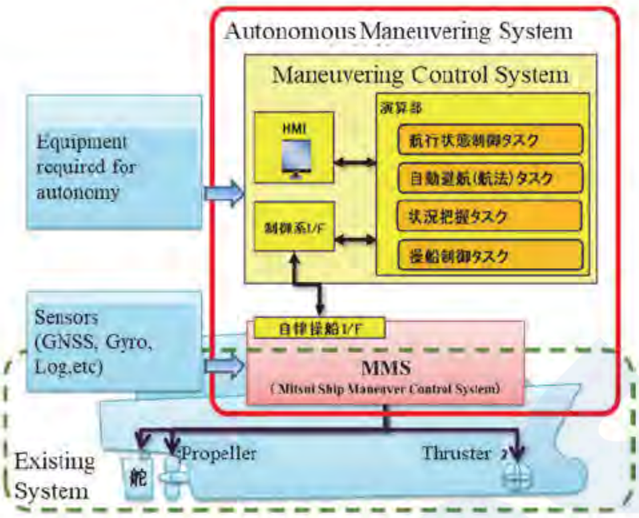

Figure 2 Configuration of autonomous maneuvering system

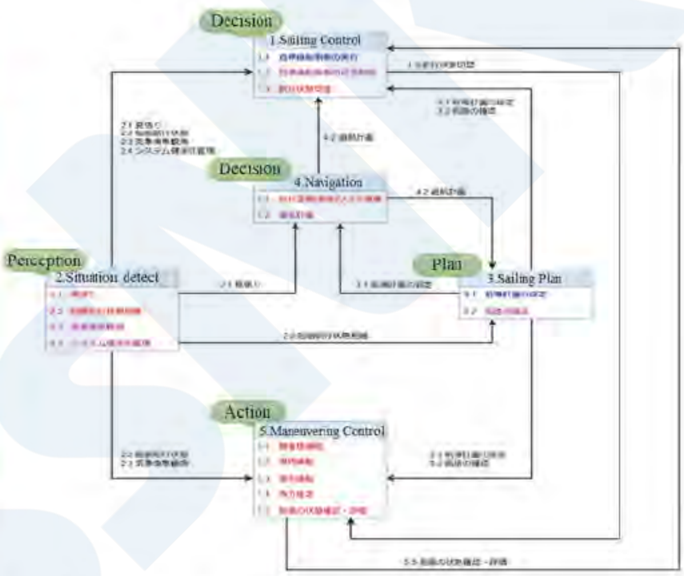

Figure 3 Task block diagram of autonomous maneuvering control functions

The autonomous maneuvering system comprises the "Autonomous Maneuvering Control System," which performs the control calculations for autonomous maneuvering, and the MMS, which is equipped with an interface with the newly-developed autonomous maneuvering system. The system realizes autonomous maneuvering by transferring the sensor and other information input by the MMS to the Autonomous Maneuvering Control System, and controlling the various actuators, that is, the rudder, propellers and thrusters, from the MMS in accordance with the control commands calculated by the Autonomous Maneuvering Control System.

Next, the tasks for realizing the functions required in the maneuvering system, as analyzed in the previous section 2.2, and the dataflow between the tasks are shown in Fig. 3, Task block diagram of autonomous maneuvering control functions.

3. MANEUVERING CONTROL SYSTEM

3.1 Overview of Maneuvering Control System

Depending on the phase of ship operation, maneuvering can be classified as out-of-port maneuvering, which includes navigation in open waters and along coastlines, and in-port maneuvering, which means navigation inside a port or harbor. In-port maneuvering can be subclassified as unberthing, disapproach, navigation at steady speed (including narrow waterways), approach and berthing. Because the content and motion considered in each of these phases differ greatly, it is not realistic to control all operations by the same logic. Therefore, control logics suited to the respective phases are used. In this paper, we will explain approach maneuvering control, as this phase has a high degree of difficulty among the above-mentioned phases, and thus has a high possibility of resulting in a maritime accident.

3.2 Approach Maneuvering Control

As features of approach maneuvering, a ship generally must be navigated in waters with topographical restrictions such as channels or breakwaters, while controlling the ship position and bow heading toward the berthing point during deceleration.

In particular, the challenges for realizing approach maneuvering control include the fact that approach must be successful on the first attempt, as redoing the approach is difficult under the above-mentioned topographic restrictions, and the ship's motion characteristics continue to change significantly due to deceleration, and at the same time, the relative effects of external disturbances become larger due to the decreased speed of the ship.

3.2.1 System Configuration

Approach maneuvering cannot be automated by a simple control function because it is not possible to redo the approach and the ship's motion characteristics and influence of external disturbances change due to deceleration. Therefore, a combination of multiple algorithms was developed, referring to the shiphandling of actual ship operators, in order to realize approach maneuvering control.

A list of the control algorithms is shown below, and a block diagram is presented in Fig. 4.

- Navigation filter
- Track Control filter(TCS Filter)
- Feedback track control(TCS F.B. Control)
- Feedforward to steady external force
- Predicted maneuvering feedforward control
- Ship velocity control

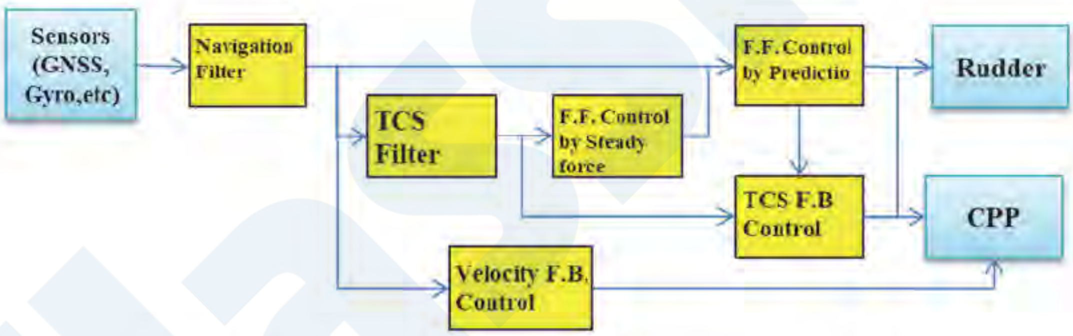

Figure 4 Block diagram of approach maneuvering control functions

3.2.2 Navigation Filter

Positioning error is small in this system because a RTK (Real Time Kinematic) positioning GNSS receiver is used. However, because the positioning signals contain a noise component, which is considered to have a significant effect, it is necessary to differentiate the position information when calculating ship's ground speed (absolute speed). In order to estimate the ship's probable position and speed smoothly, a linear Kalman filter called a navigation filter was adopted. This filter was also used by Imamura [4] and Tamaru [5].

As shown in Fig. 5, a 2 dimensional coordinate system fixed with respect to the earth is defined, in which the origin is the reference waypoint (WP), and the northerly and easterly directions are the positive directions of the X axis and Y axis, respectively. The ship's position x_n is defined as follows by using the ship's position, speed and acceleration on the defined coordinate system at time t_k as state variables in Eq. (1). (In the following, the superscript T denotes a transposed matrix.)

$$x_n = \left[p_x(n), p_y(n), v_x(n), v_y(n), a_x(n), a_y(n)\right]^T \tag{1}$$

The state space expression, comprising the state equation and observation equation, are obtained from the above, as follows:

State equation = $x(n+1) = \mathrm{F}x(n) + G\omega(n)$
Observation equation = $y(n) = \mathrm{H}x(n) + v(n)$ (2)

$$\mathbf{F} = \begin{bmatrix} 1 & 0 & \Delta T & 0 & \Delta T^2/2 & 0 \\ 0 & 1 & 0 & \Delta T & 0 & \Delta T^2/2 \\ 0 & 0 & 1 & 0 & \Delta T & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

F, G and H are the state transition matrix, driving matrix and observation matrix, respectively. Here, the first element of $y(n)$ is the latitude information obtained from the Kalman filter, and the second element is the longitude. When these two signals have been obtained by using the Kalman filter, the estimated values of the ship's position, speed and acceleration are obtained in the internal expression in Eq. (2), and the smoothed ship position and speed can be obtained.

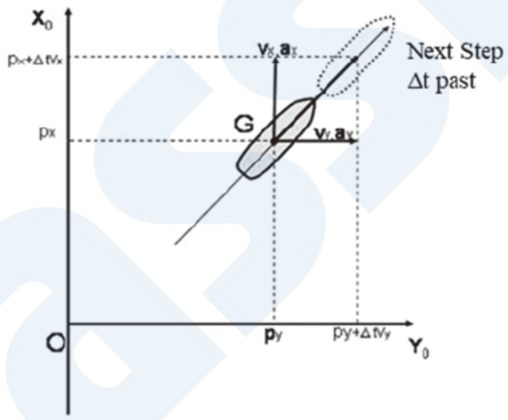

Figure 5　Coordinate system in navigation filter

3.2.3　Track Filter

In order to realize approach maneuvering control, approach maneuvering is defined as a track control problem for keeping the set approach line, and a Kalman filter is used in estimation of the state variables in the state space expression obtained from the maneuvering motion model, as in the optimal tracking control proposed by Miyoshi [6) 7)].

In the track control filter, the ship's lateral velocity: v, angular velocity (yaw rate): r, error of bow heading from the target course (yaw angle): φ, cross track error: Y_d (as the deviation of the own ship's position from the target course) and the rudder angle: δ shown in the coordinate system in Fig. 6 are adopted, and the motion model for control shown in Eq. (3 is used. Here, the technique for obtaining a_{11}, a_{12}, a_{21}, a_{22}, b_{11} and b_{21} in Eq. (3) from the linearized maneuvering motion model according to Miyoshi [6) 8)] was also adopted because it is possible to obtain the motion model from the ship's principal particulars, which is an advantage from the viewpoint of generalization and commercialization.

$$\begin{pmatrix} \dot{v} \\ \dot{r} \\ \dot{\varphi} \\ \dot{Y}_d \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & 0 & 0 \\ a_{21} & a_{22} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & U_0 & 0 \end{pmatrix} \begin{pmatrix} v \\ r \\ \varphi \\ Y_d \end{pmatrix} + \begin{pmatrix} b_{11} \\ b_{21} \\ 0 \\ 0 \end{pmatrix} \delta \qquad (3)$$

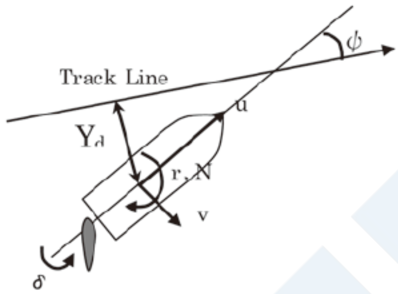

Figure 6 Coordinate system of motion model in track control

From the continuous linear model shown in Eq. (3), the discretized model at a sampling time Δt is calculated by Eq.(4):

$$\mathbf{\Phi} = e^{\mathbf{A}\Delta t} \qquad \mathbf{\Gamma} = \mathbf{B}\int_0^{\Delta t} e^{\mathbf{A}\Delta t} dt \qquad (4)$$

As a result, the following discrete expression is obtained in Eq. (5).

$$\mathbf{x}(n+1) = \mathbf{\Phi}\mathbf{x}(n) + \mathbf{\Gamma}\mathbf{u}(n)$$

$$\mathbf{\Phi} = \begin{pmatrix} \Phi_{11} & \Phi_{12} & 0 & 0 \\ \Phi_{21} & \Phi_{22} & 0 & 0 \\ \Phi_{31} & \Phi_{32} & 1 & 0 \\ \Phi_{41} & \Phi_{42} & \Phi_{42} & 1 \end{pmatrix}, \quad \mathbf{\Gamma} = \begin{pmatrix} \Gamma_{11} \\ \Gamma_{21} \\ \Gamma_{31} \\ \Gamma_{41} \end{pmatrix}, \qquad (5)$$

$$\mathbf{x}(\mathbf{n}) = [v \quad r \quad \phi \quad \mathrm{Y_d}]^t, \quad \mathbf{u}(n) = \delta(n)$$

In order to treat steady external force, the lateral displacement velocity d_Y from the target course is added to the state variable in Eq. (6).

$$\mathbf{x}(n) = [v(n) \quad r(n) \quad \phi(n) \quad \mathrm{Y_d}(n) \quad d_Y(n)]^t \qquad (6)$$

As shown in the state equation in Eq. (7), in the final line of the system expression, the cross track error is expressed as having a steady nature.

State equation

$$\mathbf{x}(n+1)=\begin{pmatrix}\Phi_{11} & \Phi_{12} & 0 & 0 & 0\\ \Phi_{21} & \Phi_{22} & 0 & 0 & 0\\ \Phi_{31} & \Phi_{32} & 1 & 0 & 0\\ \Phi_{41} & \Phi_{42} & \Phi_{43} & 1 & \Delta t\\ 0 & 0 & 0 & 0 & 1\end{pmatrix}\begin{pmatrix}v(n)\\ r(n)\\ \psi(n)\\ Y_d(n)\\ d_y(n)\end{pmatrix}+\begin{pmatrix}\Gamma_{11}\\ \Gamma_{12}\\ \Gamma_{13}\\ \Gamma_{14}\\ 0\end{pmatrix}\delta(n)+\boldsymbol{\varepsilon}(n) \qquad (7)$$

Observation equation

$$\mathbf{y}(n)=\mathbf{H}\mathbf{x}(n)+w \quad \mathbf{H}=\begin{pmatrix}0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0\end{pmatrix} \qquad (8)$$

H: observation matrix, ε: system noise, w: observation noise

Ship motion related to tracking was estimated by estimating the state variables in this state space expression by using the Kalman filter.

However, because the model includes terms that depend on the ship's speed, it cannot be adapted to the problem of approach maneuvering in its present form, since a ship's speed changes greatly from the start to the end of approach. Therefore, a tracking model using multiple ship speeds was designed, and the estimated values of the state variables for the corresponding speeds were obtained by using a model in which the models for each speed are treated as membership functions.

3.2.4 Feedback Track Control

To realize approach maneuvering control, feedback control was performed by using the state variables mentioned in the previous section. Concretely, the amount of rudder action u(n) was obtained by multiplying the state variable x(n) by the control gain L(n), as shown in Eq. (9).

$$\mathbf{u}(n)=-\mathbf{L}(n)\mathbf{x}(n) \qquad (9)$$

Here, the general technique is to obtain the optimal value of L(n) by using an evaluation function. However, in the present study, L(n) was decided by trial-and-error by performing simulations due to the large number of uncertain elements such as changes in the ship's speed.

3.2.5 Feedforward For Steady External Force

As discussed up to this point, it is also important to consider the external force acting on a ship in approach maneuvering control because the effect of external forces increases as the ship's speed decreases. Therefore, feedforward control for steady external force [8] was added to this control method by using the lateral displacement rate from the target course d_Y, which was calculated by the Kalman filter as described in section 3.2.3.

As shown at the left in Fig. 7, a ship which is underway with tracking as a speed U in the composite direction of the lateral speed d_Y and the longitudinal speed u. Under this condition, the ship's direction shifts to a direction having an angle of φ_S from the bow heading. Because φ_S is very small at this time, it can be assumed that $d_Y \fallingdotseq d_Y'$, and it is possible to reduce the steady course error, as shown at the right in Fig. 7, by considering the φ_S when the declination φ of the bow heading from the target course changes to the optimal control law. Concretely, it is possible to consider steady external forces by considering this φ_S by predictive maneuvering feedforward control, as described in the following section.

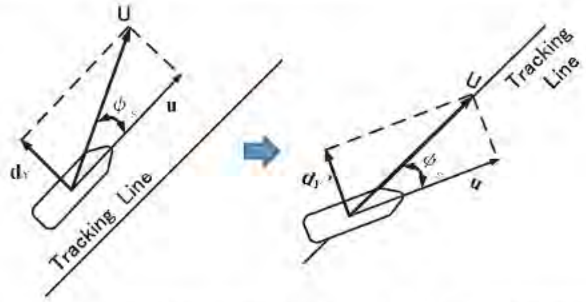

Figure 7 Image of control for steady external force

3.2.6 Predictive Maneuvering Feedforward Control

A ship operator generally performs maneuvering not only considering the current deviation from the target course, but also by predicting the own ship's position and heading several 10 s to several minutes in the future. To date, a number of studies [9) 10) 11)] have been done on berthing maneuvering, but all of those studies proposed that it is necessary to apply feedforward control considering the predictive maneuvering normally performed by ship operators in the maneuvering phase of approaching the berth while reducing speed.

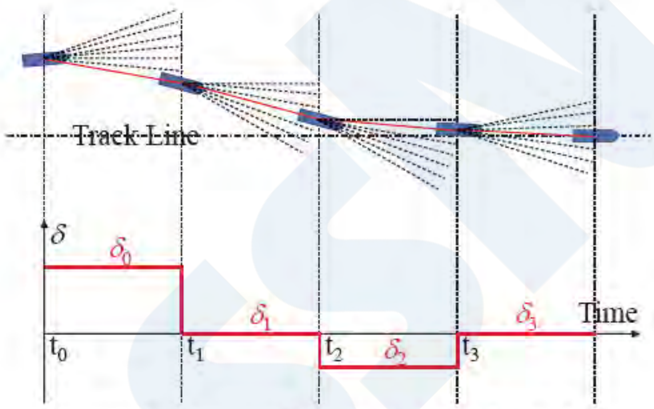

Figure 8 Image of shooting method search

In this type of predictive control, the deep learning method [12)] or similar techniques are conceivable. However, due to the long time required to collect the teaching data, the authors decided to obtain the optimal steering plan by using the shooting method in consideration of practical application.

As shown in the image of this search method in Fig. 8, the optimal rudder angle for returning to the target course is calculated while changing the rudder angle multiple times from the starting point. In this image, the optimal rudder angle for returning to the target course is searched by changing the rudder angle at set time steps from the state when the cross track error on the left edge of Fig. 8 occurs.

The procedure of this search technique using the shooting method is as follows.

① Prepare a high speed simulation using an MMG (Maneuvering Modeling Group) model.

② Prepare combinations of n times of changes for candidate rudder angles δ while maintaining a time of T seconds.
(Example)
δ [deg] = {±15.0, ±10.0, ±5.0, ±2.5, 0.0}
T [s] = 30, n = 4

③ Search for the optimal combination by using the high speed simulation.
Definition of "optimal": To minimize the evaluation function shown in Eq. (10)

$$J = \sum_{i=0}^{n} (q^{n-i}(W_y Y_{d,i}^2 + W_\psi \Delta\psi_i^2 + W_r r_i^2) + W_\delta \delta_i^2) \qquad (10)$$

q: damping factor
W: weightings
$Y_{d,i}$: cross track error at completion of i-th step
$\Delta_{\psi i}$: heading error (yaw) at completion of i-th step
r_i: turning angular velocity at completion of i-th step
δ_i: rudder angle in i-th step

At this time, the heading considering φ_S, which was obtained in the previous section, was used as the reference course heading when obtaining $\Delta_{\psi i}$.

4. DEMONSTRATION TEST

A demonstration of the approach and berthing control was carried out with an actual ship at an actual berth by using a port maneuvering control system which combined the approach control described up to this point and berthing control applying DPS, *etc*. This chapter presents an overview of the demonstration test as a preliminary report on the demonstration.

This demonstration test was conducted jointly with Mitsui O.S.K. Lines and Tokyo University of Marine Science and Technology, which participated in the "Safety of Automatic Berthing and Un-Berthing Demonstration Project" of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Prior to the test at the actual quay, a virtual quay was set outside the port, and the actual test was carried out after verifying that the control functions of the system were sufficient.

4.1 Test Conditions

4.1.1 Test Ship

The ship used in the demonstration was the car ferry *Sun Flower Shiretoko*, which is owned and operated by MOL Ferry Co., Ltd. The principal particulars of the test ship are shown in Table 2, and a photograph is shown in Fig. 9.

Table 2 Principal particulars of *Sun Flower Shiretoko*

• Gross tonnages	11 410 t
• Length overall (LOA)	190.0 m
• Length between perpendiculars (LBP)	175.0 m
• Breadth moulded	26.4 m
• Depth moulded	20.5 m
• Draft (designed full load)	6.85 m
• Maximum speed in test operation	25 Kts
• Maximum passenger capacity	180
• Main engines	4 cycle medium speed diesel × 2 units 14 580 kW × 400 rpm (/unit)
• Propellers	CPP × 2 shafts
• Thrusters	Bow × 2 units Stern × 1 unit

Figure 9 General view of car ferry *Sun Flower Shiretoko*

4.1.2 Test Waters and Maneuvering Scenarios

The test was conducted at the Port of Oarai, Ibaraki Prefecture and Central West Quay berth. The maneuvering scenario used in the test is shown in Fig. 10. The target berthing point was before the berthing point used in normal service, and was set so as to secure clearances with the wharf of 25 m at the front of the ship and 10 m on the starboard side.

Figure 10 Maneuvering scenario used in demonstration test

4.1.3 Test Conditions

Table 3 shows the weather and marine meteorological conditions, etc. when the demonstration test was conducted. The test was started at an initial speed of 12.0 kts from a point 1.0 miles before the initial WP (waypoint) near the tip of the offshore breakwater at the Port of Oarai, as shown in Fig. 10.

Table 3 List of conditions of demonstration test

Weather and marine meteorology conditions	
Weather	Clear
Visibility	Good (approx. 12 miles)
Wind	NE to ENE
Wind speed (outside port)	10.0 to 14.0 m/s
Wind speed (inside port)	4.5 to 10.0 m/s
Wave height (outside port)	1.5 m
Wave direction (outside port)	NE
Other conditions	
Test time	Afternoon
Draft	6.4 m

4.2 Test Results

A total of 4 demonstration tests were carried out at the actual quay. The results of all the tests confirmed that course-keeping and deceleration in accordance with the predetermined maneuvering scenario were possible, and the ship could stop (ship speed < 0.1 kts) with an accuracy of 0.5 to 2.0 m from the target berthing point.

As one example, Fig. 11 shows the ship track chart and Fig. 12 shows time-series screens of the test system. Because this paper is a preliminary report, the explanation of the time-series information will be omitted here.

As can be understood from the track chart, it was found that the ship meanders when passing between the offshore breakwater, the port breakwater and the breakwater on the inner side. This phenomenon was not observed in the simulation or the test with the virtual breakwater outside the port. The cause of meandering in the actual test is considered to be the large effect of environmental changes, including the large change in the wind speed due to the shielding effect of the breakwaters, and local currents generated between the breakwaters.

4.3 Discussion

The effectiveness of the maneuvering control system developed up to this point could be confirmed in this demonstration test. On the other hand, the results also showed anew that ship motion is greatly influenced by changes in external forces due to the effects of topography at an actual port and actual quay, and at the same time, a control system which is capable of adapting quickly to changes in external forces is required.

The results confirmed that some differences appeared between predictive maneuvering (results of shooting) and in actual ship motion during the demonstration test. Where this is concerned, it is thought that the maneuvering motion model itself had changed due to the effect of shallow water because the water depth becomes shallow and under keel clearance (UKC) decreased to only 0.8 to 1.5 m when the ship entered the port. Thus, the results of this test confirmed the need to study countermeasures.

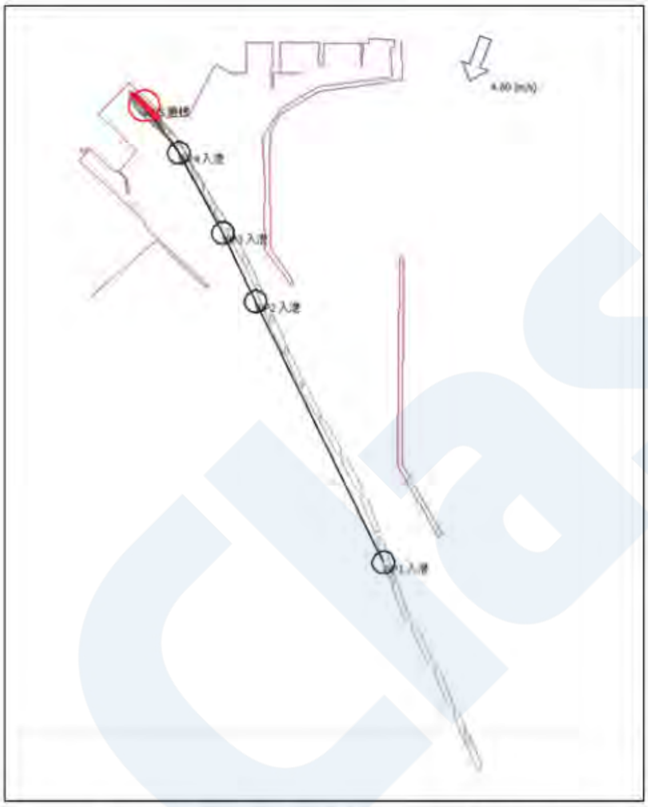

Figure 11 Track of demonstration test

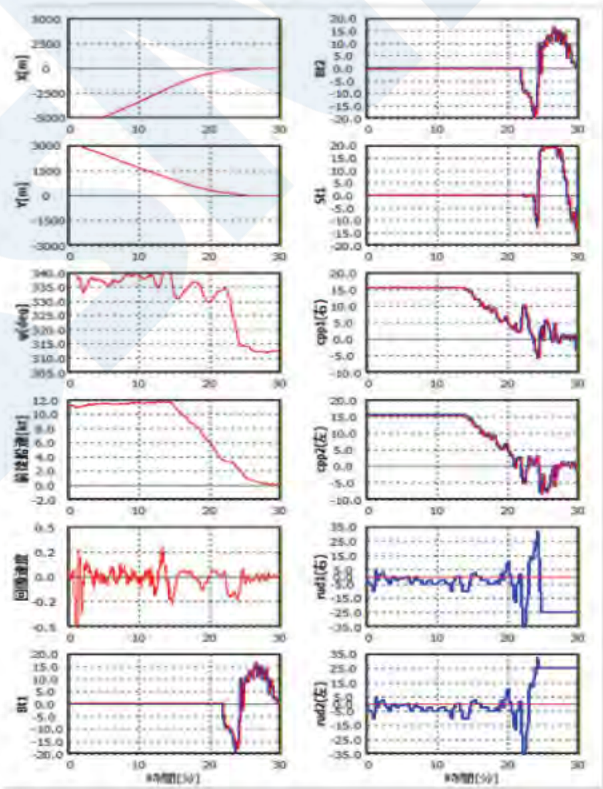

Figure 12 Time-series screens of test system

5. CONCLUSION

An automated maneuvering system is indispensable for realizing autonomous ship operation. In this paper, the requirements of this system were presented, followed by an overview of the conceptual design and basic design.

The automated maneuvering control system which controls the movement of the ship is a key function of the maneuvering system. Next, therefore, the composition and technology of the maneuvering control system are explained, with a particular focus on approach maneuvering control.

Finally, as a preliminary report, the results of a demonstration test of approach and berthing maneuvering control at an actual quay by an actual car ferry using the in-port maneuvering control system incorporating the approach maneuvering control and berthing maneuvering control functions explained previously are presented.

This study confirmed the effectiveness of the maneuvering system which is currently being developed with the aim of realizing autonomous ship operation. However, at the same time, various problems also became clear.

In the future, the authors will continue to conduct technology development for practical application of an automated maneuvering system for autonomous ship operation by conducting technology development centering on maneuvering control and clarifying the problems for safety and practical application by simulations and actual ship tests. We also hope to contribute to the maritime industry of Japan by realizing practical application of autonomous ships at the earliest possible date through cooperation with companies that possess related technologies, including manufacturers of navigation instruments.

ACKNOWLEDGMENT

A portion of this research and development was conducted with the support of the MEGURI 2040 Project. We wish to express our appreciation to the Nippon Foundation, which is the sponsor of the Project, for providing this opportunity for research and development. We would also like to thank Prof. Tadatsugi Okazaki of Tokyo University of Marine Science and Technology for his generous guidance in connection with the technology development, and the MOL Ferry Co., Ltd. and the crew of the *Sun Flower Shiretoko* for their cooperation in the demonstration test. In particular, since the cooperation of Capt. Yoshida of the *Sun Flower Shiretoko* was indispensable for the success of the demonstration test, we would like to take this opportunity to thank him once again.

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