Developing the Autonomous Control for Navigation

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1. Introduction

Domestic maritime transportation in Japan is responsible for transporting about 80% of the basic materials for domestic industry. Recently, the decreasing number of seafarers in domestic maritime service and aging of them is an urgent issue to improve the working environment and ensure the safety of navigations while reducing the workload of them.

In response, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and the Nippon Foundation are promoting projects to automate and autonomously operate ships utilizing the rapid development of IoT and artificial intelligence technologies. In particular, the Nippon Foundation has started the unmanned ship project "MEGURI 2040" in 2020. It aims to realize the practical unmanned ships by 2025. In this paper, the autonomous navigation control system which has been developed in these projects are described.

2. Autonomous System Development

2.1 Study of Autonomous System

Based on our knowledge and ship's control technology obtained through the development of automatic ship control systems since 1985, we started research and development of autonomous ship control technology in 2017.

At first, we investigated current domestic rules and regulations. We also analyze the tasks of onboard works, and define the level of autonomy and technical concepts in the MLIT project with the Tokyo University of Marine Science and Technology, the National Maritime Research Institute, the Japan Ship Technology Research Association, Nippon Kaiji Kyokai, and Mitsui O.S.K. Lines, Ltd. In this project, six levels of autonomous was defined as from Level 0 to 5. Level 0 is the most common ship at present, and Level 5 is the most autonomous ship in future. Additionally, we also studied which level is best for autonomous system in order to put to practical use as soon as possible. As the result, we decided to develop the Level 3 system, "semi-autonomous ship", which means that the ship will be navigated automatically in limited conditions under the supervision of an operator.

We first focused on the tasks related to behaviors at bridge for ship navigation as shown in Fig.1, and we decided to study specific systems for automatic / autonomous functions related to decision making, execution, check, and planning.

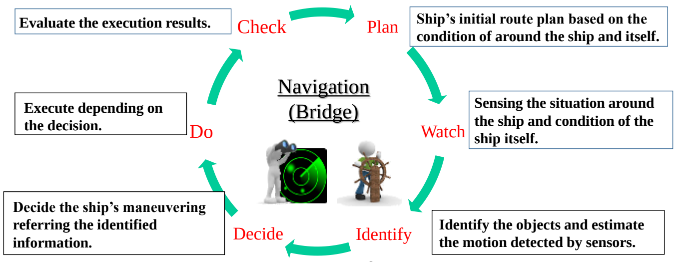


Fig.1 Behaviors at bridge for Ship Navigation

2.2 Design of Autonomous System

In order to study the specific autonomous control system, the operations for the ship from departure to arrival in port of the destination are organized into the following three phases.

a. Operation for Departure in Port
b. Operation in Offshore (Out of Port)
c. Operation for Arrival in Port

In these phases, the effects of not only disturbance and topography but also the characteristics of ship's motion are different. Therefore, it is not reasonable to use a same control logic in all phases. In addition, when a ship maneuvers in port, it is required to navigate strictly along the predetermined course. Accordingly, a control logic for the course keeping was designed to be suitable for a wide range of speed in each phase except for berthing / un-berthing in port. The control block diagram is shown in Fig. 2.

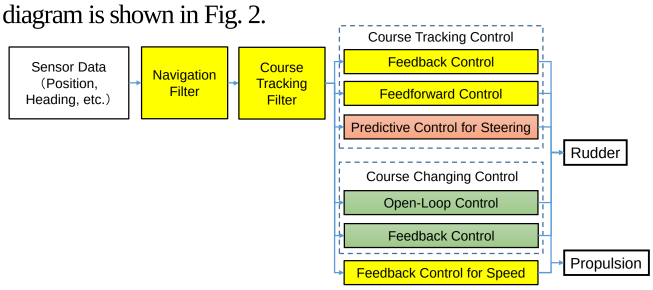
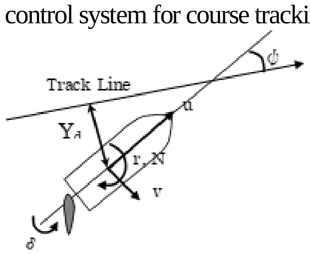


Fig.2 Block Diagram for Course Tracking Control System

The blocks shown in yellow are always used in any operation phases. On the other hand, the red one is used only in the phase in port. The green blocks are for the operations out of port.

2.2.1 Navigation for Course Tracking Control

Fig.3 shows the coordinate systems which is defined to design the navigation control system for course tracking.



u, v, r	: Speed and Rate of Turn
ϕ	: Heading Deviation from the Course Direction
Y_d	: Deviation from the Tracking Line
δ	: Rudder Angle

Fig.3 Coordinate Systems for Navigation Control

(i) Navigation Filter

The linear Kalman filter was used as the navigation filter to estimate the stable ship's motion based on the input data from the sensors.

(ii) Course Tracking Filter

In this control system, the discretized linear equation of ship's motion is shown in (1) and (2). The state variables are defined as shown in (3) to take into account the constant effects of external disturbances by including $d_Y(n)$, velocity of Y_d.

$$\mathbf{\Phi} = e^{A\Delta t}, \Gamma = B\int_0^{\Delta t} e^{A\Delta t}\, dt \tag{1}$$

$$\mathbf{x}(n+1) = \mathbf{\Phi}\mathbf{x}(n) + \mathbf{\Gamma}\mathbf{u}(n) \tag{2}$$

$$\mathbf{x}(n) = [v(n) \quad r(n) \quad \varphi(n) \quad Y_d(n) \quad d_Y(n)]^t \quad (3)$$

(iii) Feedback Control for Course Tracking

The rudder angle $\boldsymbol{u}$ is obtained by multiplying the estimated state variables $\mathbf{x}$ and control gains $\boldsymbol{L}$ as shown in (4).

$$\mathbf{u}(n) = -\mathbf{L}(n)\mathbf{x}(n) \qquad (4)$$

The control gains $\boldsymbol{L}$ is decided to minimize the evaluation function J_N as shown in (5).

$$J_N = \sum_{n=1}^{N} [\mathbf{x}^t(n)\mathbf{Q}\mathbf{x}(n) + \mathbf{u}^t(n-1)\mathbf{R}\mathbf{u}(n-1)] \qquad (5)$$

(iv) Feedforward Control for Course Tracking

It becomes possible to perform the feedforward control against the effects of external disturbances by considering ϕ_s which is the direction of the composite velocity U in controlling heading as shown in Fig.4.

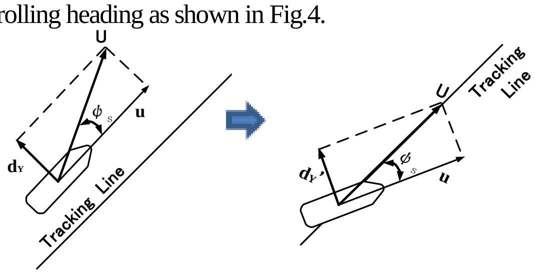


Fig.4 Image of Feedforward Control for Course Tracking

(v) Predictive Control for Steering

Generally, ship operators predict not only the deviation from the current maneuvering target, but also the ship's position and heading in tens of seconds to several minutes. In this control system, shooting method is used as the predictive control for steering because this method incorporates a maneuvering motion model and does not require a large amount of data collection.

Fig. 5 shows the image to calculate the optimal rudder angle to return to the course by changing the rudder angle multiple times from the starting point at regular intervals.

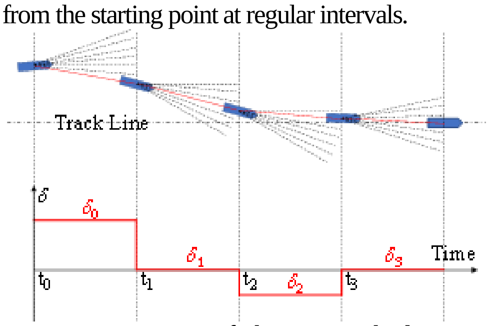


Fig.5 Image of Shooting Method

In this method, the value of the evaluation function J shown in (6) is considered to search for the optimum rudder angle which minimize the value of J.

$$J = \sum_{i=0}^{n} (q^{n-i}(W_y Y_{d,i}^2 + W_\psi \Delta\psi_i^2 + W_r r_i^2) + W_\delta \delta_i^2) \qquad (6)$$

q : Attenuation Coefficient

W : Weight

r_i, δ_i : Rate of Turn, Rudder Angle

2.2.2 Navigation Control for Course Changing

The navigation control for course changing is designed as the combination of open-loop control, which outputs a predetermined rudder angle, and feedback control for heading.

(i) Open-Loop Control for Course Changing

When changing the course, the distance from the way point to start steering is calculated with reference to the ship's speed and course changing angle based on the information obtained from the results of sea trial experiments.

(ii) Feedback Control for Course Changing

If the heading angle while course changing differs from the calculated target one, the rudder angle is adjusted by feedback control according to the amount of deviation.

3. Demonstration of Technology

We conducted technical demonstrations for the following three ships in MEGURI 2040 project.

- Small Passenger Ship : G.T. 19(ton), Lpp 17(m)
- Coastal Container Ship : G.T. 749(ton), Lpp 83(m)
- Large Car Ferry : G.T. 11,410(ton), Lpp 175(m)

As examples of the results of the demonstration, Fig.8 shows the sample of trajectory of the small passenger ship navigated autonomously over a course of approximately 2km.

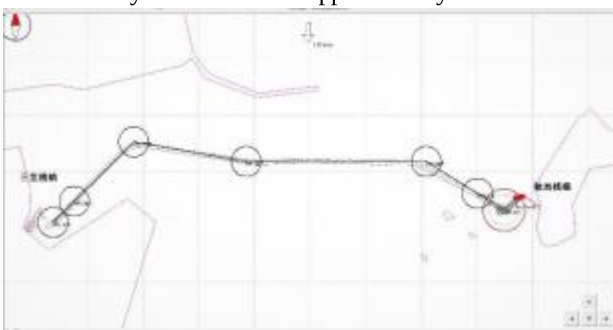


Fig.8 Trajectory of Autonomous Control from Port to Port

4. Conclusion

In this paper, we presented the course tracking control function which is one of the most important functions of the autonomous system for ship's navigation.

In MEGURI2040 project, we carried out demonstration on three ships of different sizes, types, and operating areas. We have also developed and confirmed the collision avoidance function that allows the ship to automatically avoid navigation according to the movements of other ships at offshore area.

We will continue to further develop the technology for early commercialization, taking advantage of these experiences.

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