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Control Systems

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# Non Linear DP Controller

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## ABSTRACT

In the dynamic positioning control and thrust allocation system of the vessels, it is difficult to obtain an optimal solution in real time because of inherent non-linearity, and development of a reliable real-time calculation method for the optimal control has been waited for. The control system we have developed realizes a real-time optimal control. This paper presents examples of application of the real-time nonlinear receding horizon (RH) control for route-tracking and real-time algorithm for optimal thrust allocation for redundant actuators. The effectiveness of the method applied to the systems is verified by computer simulation and experimental study conducted at a model test basin.

## INTRODUCTION

In recent years, demand has been growing for new applications of the dynamic positioning system (DPS) to support the maneuvering operations such as berthing operations to the side-by-side offloading LNG-FPSO and maneuvering in harbor of conventional ships.

As key technologies to implement these automatic systems, the improvements in accuracy and reliability of positioning sensors such as the advanced system with Real Time Kinematic (RTK) GPS and the state-of –the-art optimal control system would be emphasized. The former has been developed and already in practical use. The latter is, however, still waiting to be improved.

There is a study[1] in which minimal time control is used for automatic maneuvering control in harbor as two-point boundary-value problem. But what truly demanded in maneuvering control in harbor is minimizing thrust powers, avoiding to enter the restricted water area, moving to the specified position, and stopping there with the specified heading angle. In the conventional study, at first a tracking route is calculated by the minimal time control in advance. Next the ship is controlled to track the calculated route. But this approach is impractical because it needs trial-and-error offline work to make proper maneuvering plan and thus sometimes uses much time. Moreover, it cannot cope with the real situation of changing disturbances.

Our method reported in this paper carries out an on-line non-linear optimization in which ship's dynamics and complicated thruster models are treated. Since it minimizes an evaluation function, which is composed of ship's position, heading angle, and speed deviations from desired values, thrust powers, etc., and avoids to enter restricted water areas, the proposed method must be more practical and reliable.

In addition, for ships with redundant actuators such as multi-thrusters or multi-rudders, somewhat heuristic allocation methods have been used in the conventional DPS. However, as they do not necessarily employ optimal control techniques, neither power minimization nor relocation of redundant actuators in case of failure can be properly achieved. In particular, when the latter case takes place in the conventional system, a large number of combinations of allocation ratios are to be required beforehand in preparation to assumable troubles or other emergencies. To these issues, even in case of actuators' failure, we develop a system that can always realize an appropriate thrust allocation by applying an on-line optimization method.

Our developed online nonlinear optimal control system is based on the receding horizon (RH) control algorithm that minimizes the multi-objective function with constraints by changing the evaluation zone time by time.

In this report, we discuss the control logic through simulations and experiments and show some results for typical operation scenarios to verify the effectiveness of our proposed method.

## CONTROLLED OBJECT

As a controlled object, a model ship, is shown in Fig.1. The dimensions of the model are length: 3.5 [m], width: 0.59 [m], draft: 0.17 [m], and mass: 200 [kg]. It has five actuators which consist of two propellers, two rudders, and one side thruster as shown in Fig.2.

The configuration of the experimental equipment is shown in Fig.3. We set a computer on shore (PC1) the control device. Position of the model ship is measured by an automatic tracking light rangefinder and angle of direction by a gyrocompass on the model ship. A notebook computer (PC2) is installed on the ship. It sends and receives data, such as commands to the actuators and direction of the ship, with PC1 through wireless LAN. The control period is set 0.1 [sec] in all experiments.

Fig.1 Controlled object (model ship)

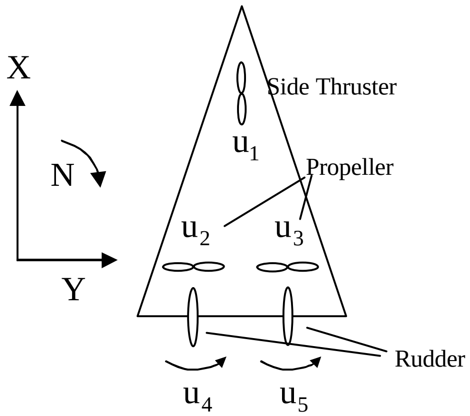


Fig.2 Arrangement of Actuators

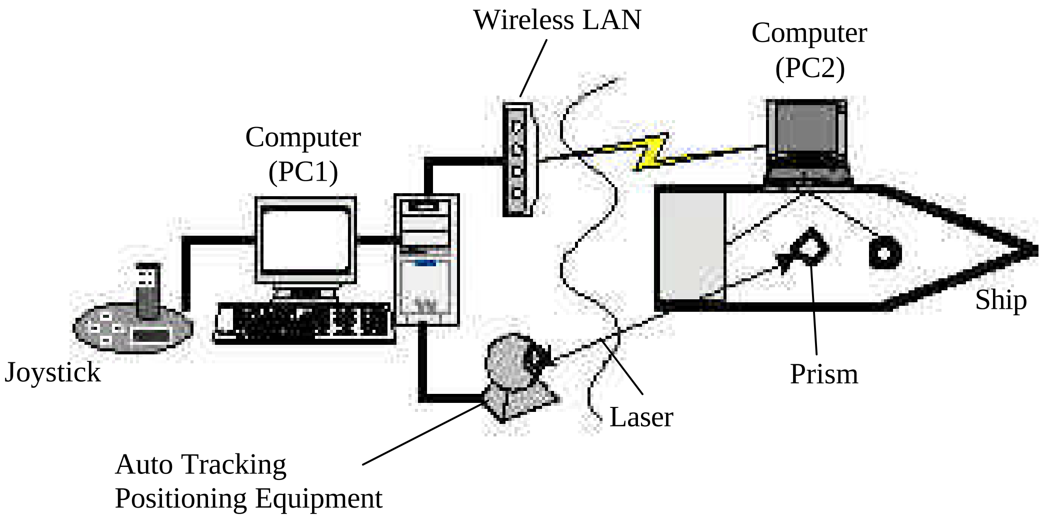


Fig.3 Experimental setup

# OPTIMAL THRUST ALLOCATION

## Model of the Object

Fig.2 shows the configuration of actuators of the model. Normalized propeller thrusts are described $u_1$, $u_2$, and $u_3$; rudder angles $u_4$ and $u_5$, consequently, port and starboard side rudder forces are expressed by $u_2$?$u_4$ and $u_3$?$u_5$, respectively ($u_2$>0, $u_3$>0).

When the normalized forces ($X_r$, $Y_r$) and moment, and $N_r$ are given by DPS or the joystick, equations of balance of each thruster can be expressed in equations (1), (2), and (3).

$$\mathrm{k}_{11}u_2 + k_{12}u_3 = Xr \tag{1}$$

$$\mathrm{k}_{21}u_1 - \left\{ k_{22}\, u_2\, u_4 + k_{23}\, u_3\, u_5 \right\} = Yr \tag{2}$$

$$\mathrm{k}_{31}u_1 + \left\{ k_{32}\, u_2\, u_4 + k_{33}\, u_3\, u_5 \right\} + \left( k_{34}u_2 - k_{35}u_3 \right) = Nr \tag{3}$$

But we should take the thrust loss of the propeller caused by the interaction with the rudder into consideration in equation (1). In this case $u_2$ and $u_3$ in the equation are assumed to be proportional to the rudder angle. Thus, the revised equations of balance are $\boldsymbol{C}=\mathbf{0}$ expressed in (4).

$$C = \begin{bmatrix} \mathrm{k}_{11}\left\{ u_2 - k_{r1}\mathrm{u}_2 |\mathrm{u}_4| \right\} + \mathrm{k}_{12}\left\{ u_3 - k_{r2}\mathrm{u}_3 |\mathrm{u}_5| \right\} - Xr \\ \mathrm{k}_{21}u_1 - \left\{ k_{22}\, u_2\, u_4 + k_{23}\, u_3\, u_5 \right\} - Yr \\ \mathrm{k}_{31}u_1 + \left\{ k_{32}\, u_2\, u_4 + k_{33}\, u_3\, u_5 \right\} + \left( k_{34}u_2 - k_{35}u_3 \right) - Nr \end{bmatrix} \tag{4}$$

where $k_{r1}$ and $k_{r2}$ are coefficients of the thrust loss rate to the rudder angle.

## Optimal Design

Let us consider a allocation for $u_1,\ldots, u_5$ that minimizes the evaluation function (5) under the condition that equation of balance (4) equals to zero.

$$\mathrm{J} = \frac{1}{2}\left( r_1\, u_1{}^2 + r_2\, u_2{}^2 + r_3\, u_3{}^2 + r_4\, u_4{}^2 + r_5\, u_5{}^2 \right) \tag{5}$$

where $r_1,\ldots, r_5$ are weight coefficients that adjust importance of each actuator's role.

By selecting this evaluation function, an optimal allocation of thrusts to each actuator can be realized for the command of the forces and moment $X_r$, $Y_r$, and $N_r$. Moreover, by tuning the weight coefficients related to each actuator, it is possible to make the output of a particular actuator be small. This optimization is realized in real time, and the weight coefficients can be changed dynamically in terms of time.

## Experimental Results

Under an assumption that the ship make a simulated failure in the port side propeller, calculation of the rest thrust allocation are executed as soon as the failure is detected. The situation adopted is the ship is moving with keeping 30 degree between the ship's head and the moving direction under position and direction control. The parameters of the evaluation function are set $R$=diag[1.0, 1.0, 1.0, 5.0, 5.0].

The test results of the effectiveness of the automatic recovering are shown in Fig.4 and Fig.5. As shown in Fig.4, the model ship with the conventional allocator traveled changing the heading angle largely. On the other hand, the model ship with the optimal allocator traveled without large deviation from the original course and the heading angle as shown in Fig.5. In this case, the output command for the failed actuator sets to zero by making its weight coefficient in the evaluation function large quickly but smoothly soon after the failure detection.

## Consideration

The ship cannot keep its position and direction in Fig.4. On the other hand, it tracks the trajectory correctly after the failure detection of the port side propeller in Fig.5. Thus, we can verify that this optimal method redistributes thrusts of the rest undamaged actuators.

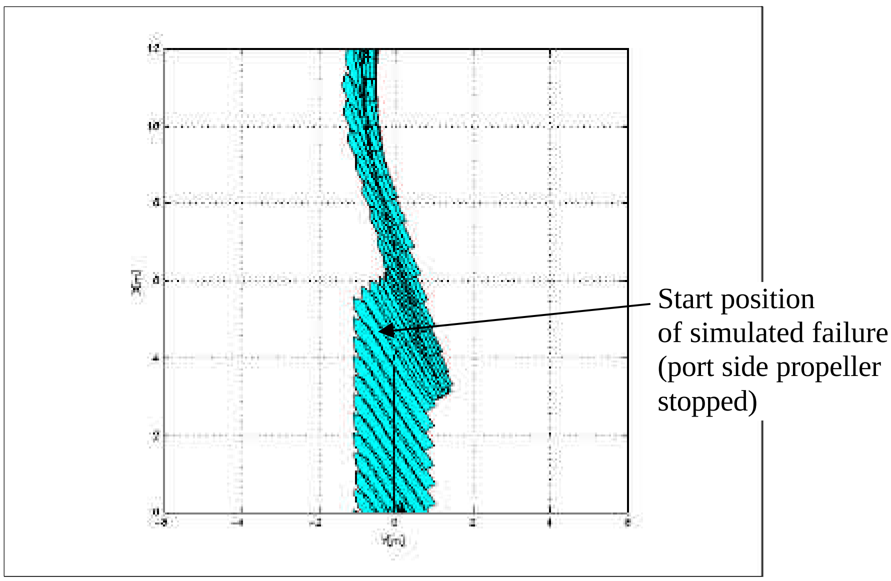


Fig.4 Trajectory of the model ship (thrust allocation was not re-calculated)

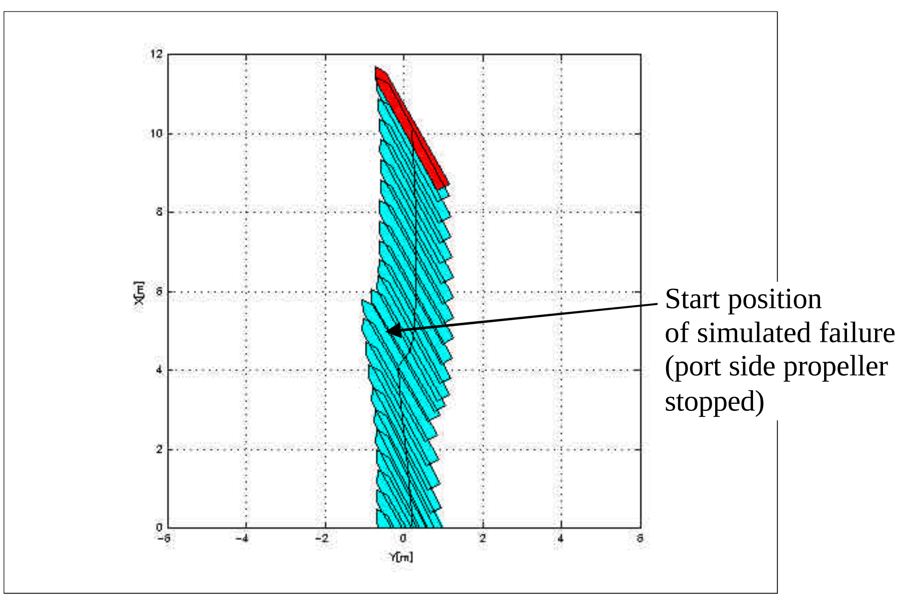


Fig.5 Trajectory of the model ship (thrust allocation was re-calculated)

# ROUTE TRACKING

## Model of the Object

Route tracking simulations and experiments are executed by using the model ship in Fig.1. Equations of motion about this object are described in equations (6) ~ (14). Parameters used in these equations are as follows; $(X, Y)$: position of center of the ship, ? : angle of direction, $u$, $v$, $r$: velocity or angular velocity to each direction, $X$, $Y$, $N$: thrust, $X_r$, $Y_r$, $N_r$: thrust command, $M$: mass of the model ship (200kg), $mx$: added mass to cross direction (5.9kg), $my$: added mass to horizontal direction (159.8kg), $I_{zz}$: moment of inertia (178.9kgm$^2$), $J_{zz}$: added moment of inertia (116.6kgm$^2$), $x_G$: distance between center of the ship to center of gravity (0.166m), $X_H$, $Y_H$, $N_H$: fluid force to each direction. These fluid forces depend on the model proposed by Karasuno et. al [4]. In the design of the control system, we use approximated fluid forces as functions of velocity and angular velocity to each direction. Dynamic character of thrust is, also, approximated as a first order time lag. Actual commands to actuators are calculated at the thrust distributor from thrust commands.

$$(M + mx)\dot{u} = M v r + M x_G r^2 + X_H + X \tag{6}$$

$$(M + my)\dot{v} + M x_G \dot{r} = -M u r + Y_H + Y \tag{7}$$

$$\left(Izz + M x_G{}^2 + Jzz\right)\dot{r} + M x_G \dot{v} = -M x_G u r + N_H + N \tag{8}$$

$$\dot{x} = u \cos y - v \sin y \tag{9}$$

$$\dot{y} = u \sin y + v \cos y \tag{10}$$

$$\dot{y} = r \tag{11}$$

$$X = \frac{Kx}{Tx\, s + 1} Xr \tag{12}$$

$$Y = \frac{Ky}{Ty\, s + 1} Yr \tag{13}$$

$$N = \frac{Kn}{Tn\, s + 1} Nr \tag{14}$$

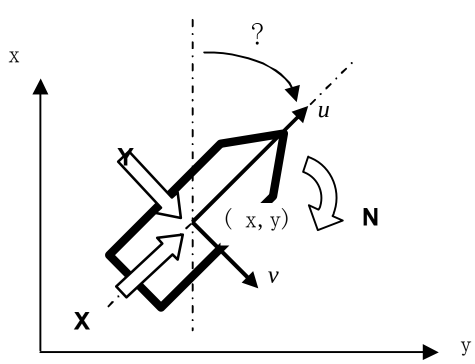


Fig.6 Coordinates of the model ship

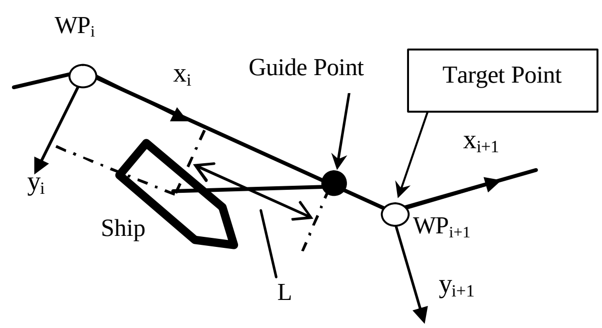


Fig.7 Waypoint and tracking route

## Design of Control System

Definition of the Route and Abstracts of Control:

Let us define a route by a broken line that connects waypoints (WP) by a straight line.

The ship is controlled by calculating an optimal moving trajectory from current position and state to the targeted WP, and by calculating thrusts acting on the ship by using RH control method.

Moreover, degree of constraint to the defined route is decided by adjusting weight of coefficients in the evaluation function explained below.

When arriving a targeted WP, the next WP is selected as a new targeted WP. In that case, decision if the ship has already arrived to the targeted WP should be made, this can be achieved by setting a guide point which moves in advance the distance L to the ship with the same velocity. When the guide point arrives to the WP, the target changes to the next WP.

The state vector is expressed as $\boldsymbol{x}=[x\ u\ y\ v$ ? $r\ X\ Y\ N]^T$, the control input vector as $\boldsymbol{u}=[X_r\ Y_r\ N_r]^T$, the desired state vector as $\boldsymbol{x}_{ref}$, the weight matrix in the evaluation function as $\boldsymbol{Sf}$, $\boldsymbol{Q}$, $\boldsymbol{R}$, respectively. Then we choose the evaluation function as follows. As for the state, $x$, $y$, and ? are measured directly; and others are estimated with using an observer.

$$
\begin{aligned}
J &= \frac{1}{2}\left[\mathbf{x}(t+T)-\mathbf{x}_{\mathbf{ref}}\right]^{\mathbf{T}}\ \mathbf{Sf}\ \left[\mathbf{x}(t+T)-\mathbf{x}_{\mathbf{ref}}\right] \\
&\quad + \frac{1}{2}\int_{t}^{t+T}\left\{(\mathbf{x}-\mathbf{x}_{\mathbf{ref}})^{\mathbf{T}}\ \mathbf{Q}\ (\mathbf{x}-\mathbf{x}_{\mathbf{ref}}) + \mathbf{u}^{\mathbf{T}}\mathbf{R}\,\mathbf{u}\right\}dt
\end{aligned}
\tag{15}
$$

When the evaluation function is chosen as shown in equation (15), the command to the actuators can be obtained in order to tracking the optimal trajectory from the current position to the targeted WP.

In this system, RH control applying C/GMRES[3] is used in order to calculate in real time.

## Simulation Results and Experimental Results

After setting the route shown in Fig.8, simulations and actual experiments using the model ship are executed. Parameters on the evaluation function are set as follows; evaluation interval $T$: 30 (sec), weights on WP0-WP1 $\boldsymbol{Sf}$=diag[1.0, 0.0, 1.0, 0.0, 1.0, 0.0, 0.0, 0.0, 0.0], $\boldsymbol{Q}$=diag[5.0, 1.0, 5.0, 1.0, 3.0, 1.0, 0.0, 0.0, 0.0], and $\boldsymbol{R}$=diag[10.0, 20.0, 20.0], and weights on WP1-WP2 $\boldsymbol{Sf}$=diag[1.0, 0.0, 5.0, 0.0, 1.5, 0.0, 0.0, 0.0, 0.0], $\boldsymbol{Q}$=diag[2.0, 1.0, 20.0, 1.0, 5.0, 1.0, 0.0, 0.0, 0.0], and $\boldsymbol{R}$=diag[10.0, 20.0, 20.0].

Simulation results are shown in Fig.9 and experimental results are in Fig.10.

## Consideration

The ship moves from the starting point (WP0) to the end point (WP2) via the middle point (WP1). By using the given desired state and the weight matrices on the evaluation function at each waypoint, the ship moves on the route that is optimally calculated under the given condition.

The experimental result and simulation result are not completely the same but qualitatively identified. The reasons why they are not the same are thought to be followings; at first the model of fluid force, which is an effect of water flow around the moving ship, used in designing the control system and actual one are not the same. Secondly, parameters in calculating the fluid force are not perfectly correct. Above all, difference of horizontal fluid force is thought to be especially large. Probably there are other reasons.

From these experimental and simulation results, therefore, we can conclude that effectiveness of the algorithm using RH control method in route tracking is proven.

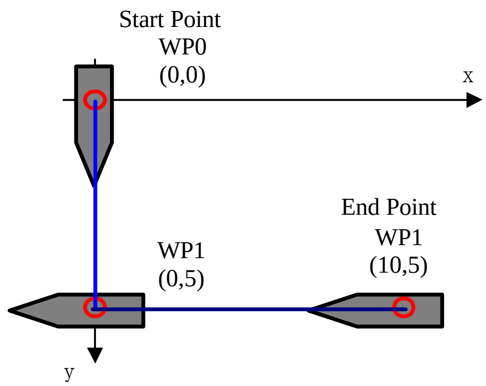


Fig.8 Waypoint setup

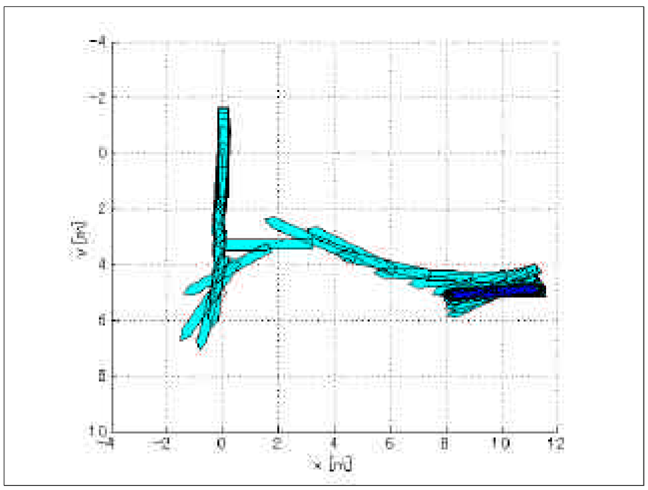

Fig.9 Trajectory of the model ship (simulation)

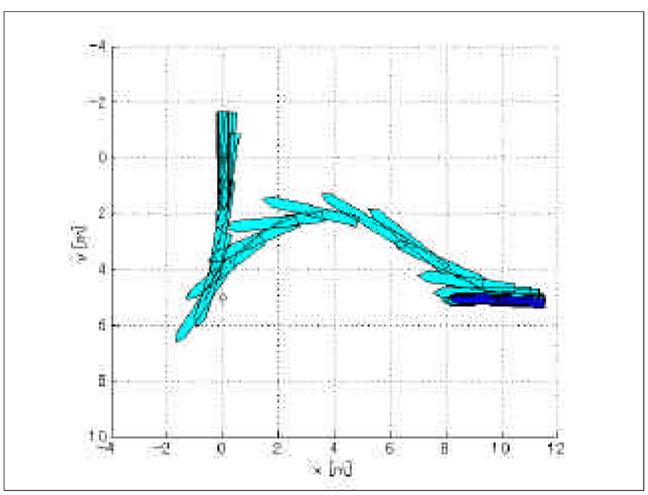

Fig.10 Trajectory of the model ship (experiment)

## CONCLUSION

A system is developed that uses an on-line optimal method for optimal thrust allocation and that uses RH control method for route tracking.

In optimal thrust allocation, real-time thrust reallocation logic is verified for the ship whose actuator has a simulated failure.

In route tracking, logic for the predefined route is verified through simulation and actual experiments using the model ship.

In both cases, desired performance is obtained in real time, therefore, we can verify the effectiveness of these system.

## ACKNOWLEDGEMENT

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