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A ship berthing system design with four tug boats †

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Abstract

In harbor areas, precise ship steering is the most important operation. This requires a set of adequate thrust devices taking into account surge, sway and yaw motions precisely. However, the effectiveness of actuators during low-speed maneuvering is reduced, making it necessary to use tugboats to ensure safe berthing. In this paper, we present a mathematical model of a system describing the interaction between an unactuated ship and tugboats. Thrust allocation is solved by using the redistributed pseudo-inverse (RPI) algorithm to determine the thrust and direction of each individual tugboat. The main goal of this method is to minimize the power supplied to tugboats and increase their controllability. The constraints are twofold. First, the tugboat can only exert a limited pushing force, and second, it can only change directions slowly. Additionally, an adaptive control law is proposed to capture the draft coefficients of the ship, which are known as uncertainty parameters. The controller guarantees that the ship follows a given path (geometric task) with desired velocities (dynamic task). The specifications of Cybership I, a model ship, are used to evaluate the efficiency of the proposed method through Matlab simulations.

Keywords: Adaptive control; Control allocation; Redistributed pseudo-inverse algorithm; Ship berthing; Ship model

1. Introduction

Based on a marine literature review, ship berthing maneuvers are considered to be the most complex procedure, with high pressure for the shipmaster to ensure safe operation. Compared with other maneuvers such as autopilot for steering, position tracking (which includes trajectory tracking and path following), dynamic positioning or station keeping, ship berthing requires the shipmaster to carry out many tasks. When the vessel moves from open seas into confined waters, the ship velocity must be kept at dead slow, which significantly reduces the controllability of actuators (main propeller, rudder, etc.). Furthermore, when the ship comes near a jetty, the shipmaster must precisely know the ship's position, and predict her movement so as to prevent a collision. A large amount of information, including maneuvering conditions, actuator characteristics, wind effects, wave and current disturbances as well as the condition of tugboats, have to be considered.

For these reasons, automatic berthing approaches have been investigated since the early 1990s. Given the difficulties in capturing changes in hydrodynamic coefficients, it is not surprising that recent research efforts have focused on developing intelligent control strategies independent of the dynamic model. These include fuzzy control [1, 2] and neural network techniques [3, 4]. Although these approaches have the advantage of embedded human experience and knowledge about ship behavior in the control strategies, the limits of actuator controllability under dead-slow velocity conditions have not yet been solved. Thus, it is too dangerous to apply these methods in actual ship berthing operations. Despite the introduction of new navigation technologies such as the differential global positioning system (DGPS) and camera sensing, and advances in propulsion manufacturing, large ship maneuvering in harbor areas is still done manually with the assistance of tugboats as shown in Fig. 1.

To overcome these drawbacks and to develop a fully automated solution, we propose a new approach for ship berthing using autonomous tugboats. In this paper, we assume that none of the ship's actuators are used, the ship is thus considered as an unactuated system. The movement of the ship is controlled by autonomous tugboats. The mathematical model of the system describing the interaction between the ship and four tugboats is presented. Thrust allocation for this overactuated system is formulated to determine the thrust and direction of each tugboat. We consider the allocation as an optimization problem and solve it by using the RPI algorithm [5].

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Fig. 1. Ship berthing with assistance of tugboats.

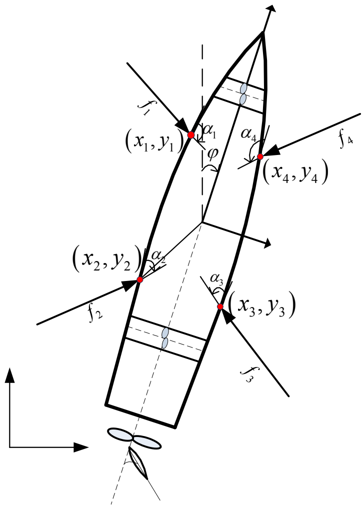

Fig. 2. Ship motion with the assistance of four tugboats.

One objective is to minimize the power supplied to the tugboats and to increase their controllability knowing that a tugboat can only exert a limited pushing force and that it can only change directions slowly. Furthermore, constraints due to limitations of contact angles between the ship and the tugboats are also considered.

Additionally, when the ship moves from open seas to confined waters, its hydrodynamic coefficients change significantly. This, in turn, considerably influences the ship's handling. To overcome this drawback, an adaptive controller that considers the change of draft coefficients is proposed.

The remainder of this paper is structured as follows. In Section II, we provide the second order dynamic system of ship considered in the horizontal plane. The thrust configuration matrix is studied through force decomposition analysis. In Section III, the adaptive controller is presented. Control allocation based on the RPI algorithm is proposed in Section IV. In Section V, the efficiency of the proposed approach is evaluated through model ship control simulations. Conclusions and plans for future study are summarized and discussed in Section VI.

2. System model

The kinematic and linear dynamic equation describing low-speed maneuvering of an unactuated vessel manipulated by four external tugboats in the horizontal plane can be written as follows [6]:

$$\begin{aligned} \dot{\boldsymbol{\eta}} &= \boldsymbol{R}(\varphi)\boldsymbol{v} , \\ \boldsymbol{M}\dot{\boldsymbol{v}} + \boldsymbol{D}\boldsymbol{v} &= \boldsymbol{\tau} \end{aligned} \tag{1}$$

where $\boldsymbol{\eta} = [x, y, \varphi]^T \in R^3$ represents the inertial position (x, y) and the heading angle φ in the earth-fixed coordinate frame, $\boldsymbol{v} = [u, v, r]^T \in R^3$ describes the surge, sway and yaw rates of the ship in a body fixed coordinate frame. The rotation matrix $\boldsymbol{R}(\varphi)$, which translates the body fixed coordinate frame into the earth fixed coordinate frame, is defined as

$$\boldsymbol{R}(\varphi) = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} . \tag{2}$$

$\boldsymbol{M} \in R^{3\text{x}3}$ represents a mass/inertia matrix. $\boldsymbol{D} \in R^{3\text{x}3}$ is a linear damping matrix assumed to be uncertain and continuously differentiable. These matrices can be determined, respectively, as follows:

$$\begin{aligned} \boldsymbol{M} &= \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & -Y_{\dot{r}} \\ 0 & -N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix} \\ \boldsymbol{D} &= \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & 0 \\ 0 & 0 & -N_r \end{bmatrix} . \end{aligned} \tag{3}$$

If we consider the assistance of tugboats, the control input vector $\boldsymbol{\tau} = [\tau_X, \tau_Y, \tau_Z] \in R^3$ (whose components are the surge force τ_X , sway force τ_Y and yaw moment τ_Z) is the result of combined efforts of four tugboats as shown in Fig. 2. Vector $\boldsymbol{\tau}$ is defined as

$$\boldsymbol{\tau} = \boldsymbol{B}(\alpha)\boldsymbol{f} \tag{4}$$

where the vector $\boldsymbol{f} = [f_1\, f_2\, f_3\, f_4]^T \in F$ represents the unidirectional thrust produced by each individual tugboat.

The set of F is described as $0 < f_i \le f_{\max}, \forall i \in (1,...,4)$. The geometrical configuration matrix $\boldsymbol{B}(\alpha) \in R^{3\text{x}4}$ captures the relationship between all four tugboats and the ship. The i-th column of matrix $\boldsymbol{B}(\alpha)$ is defined as follows:

$$\boldsymbol{B_i}(\alpha) = \begin{bmatrix} \cos(\alpha_i) \\ \sin(\alpha_i) \\ -l_{yi}\cos(\alpha_i) + l_{xi}\sin(\alpha_i) \end{bmatrix} . \tag{5}$$

Here, the angle α_i defines the force direction of the *i-th* tugboat. It is measured clockwise and is relative to the x-axis of body fixed coordinate frame. The location of the *i-th* contact point in the body fixed coordinate system is at (l_{xi}, l_{yi}). The control input vector $\boldsymbol{\tau}$ can thus be expressed in the form of the geometric configuration matrix $\boldsymbol{B}(\alpha)$ and thrust vector $\boldsymbol{f}$ by:

$$\boldsymbol{\tau} = \begin{bmatrix} c\alpha_1 & s\alpha_1 & -l_{y1}c\alpha_1 + l_{x1}s\alpha_1 \\ c\alpha_2 & s\alpha_2 & -l_{y2}c\alpha_2 + l_{x2}s\alpha_2 \\ c\alpha_3 & s\alpha_3 & -l_{y3}c\alpha_3 + l_{x3}s\alpha_3 \\ c\alpha_4 & s\alpha_4 & -l_{y4}c\alpha_4 + l_{x4}s\alpha_4 \end{bmatrix}^T \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{6}$$

where $s\alpha_i = \sin(\alpha_i)$ and $c\alpha_i = \cos(\alpha_i)$.

3. Adaptive control design

The primary control objective is to design the control input vector such that the unactuated vessel is forced to follow a desired trajectory with an uncertainty of draft coefficients of the damping matrix $\boldsymbol{D}$. The controller development is based on the assumption that all states of the vessel are measureable.

To simplify the development of the controller design, the system model presented in Eq. (1) is rewritten as

$$\boldsymbol{M}^*\ddot{\boldsymbol{\eta}} + \boldsymbol{D}^*\dot{\boldsymbol{\eta}} = \boldsymbol{\tau}^* \tag{7}$$

where the transformation $\boldsymbol{v} = \boldsymbol{R}^T(\varphi)\dot{\boldsymbol{\eta}}$ and $\dot{\boldsymbol{v}} = \boldsymbol{R}^T(\varphi)\ddot{\boldsymbol{\eta}} - \boldsymbol{S}(\dot{\varphi})\boldsymbol{R}^T(\varphi)\dot{\boldsymbol{\eta}}$ are utilized. The skew symmetric matrix $\boldsymbol{S}(\dot{\varphi}) \in R^{3x3}$ is given by

$$\boldsymbol{S}(\dot{\varphi}) = \begin{bmatrix} 0 & -\dot{\varphi} & 0 \\ \dot{\varphi} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{8}$$

The transformed system matrices $\boldsymbol{M}^* \in R^{3x3}$, $\boldsymbol{D}^* \in R^{3x3}$ and $\boldsymbol{\tau}^* \in R^{3x1}$ are calculated, respectively, as follows:

$$\begin{aligned} &\boldsymbol{M}^* = \boldsymbol{R}(\varphi)\boldsymbol{M}\boldsymbol{R}^T(\varphi), \\ &\boldsymbol{D}^* = \boldsymbol{R}(\varphi)(\boldsymbol{D}\boldsymbol{R}^T(\varphi) - \boldsymbol{M}\boldsymbol{S}(\dot{\varphi})\boldsymbol{R}^T(\varphi)), \\ &\boldsymbol{\tau}^* = \boldsymbol{R}(\varphi)\boldsymbol{\tau}. \end{aligned} \tag{9}$$

We noticed that the transformed system matrix $\boldsymbol{M}^*$ is non-negative matrix. We describe the position and orientation of the desired trajectory in the Earth-fixed coordinated frame by the vector $\boldsymbol{\eta}_d = [x_d, y_d, \varphi_d]^T$. Without any loss of generality, the selected trajectory is assumed to be both sufficiently smooth and bounded $\boldsymbol{\eta}_d, \dot{\boldsymbol{\eta}}_d, \ddot{\boldsymbol{\eta}}_d \in L_\infty$. The tracking error denoted by $\boldsymbol{e}(t) \in R^{3x1}$ is defined as

$$\boldsymbol{e} = \boldsymbol{\eta} - \boldsymbol{\eta}_d. \tag{10}$$

In order to simplify the error signals and to facilitate the stability analysis, the filtered tracking error, $\boldsymbol{r}(t) \in R^{3x1}$, is introduced as

$$\boldsymbol{r} = \dot{\boldsymbol{e}} + \boldsymbol{K}\boldsymbol{e}. \tag{11}$$

Here, $\boldsymbol{K} \in R^{3x3}$ is the constant control gain. It is defined as a diagonal positive matrix.

The time derivative of *r(t)* can be obtained as follows:

$$\dot{\boldsymbol{r}} = \ddot{\boldsymbol{\eta}} - \ddot{\boldsymbol{\eta}}_d + \boldsymbol{K}\dot{\boldsymbol{e}}. \tag{12}$$

By substituting Eq. (12) into Eq. (7), the open-loop dynamics for the filtered tracking error signal $\boldsymbol{r}(t)$ can be expressed as follows:

$$\begin{aligned} \boldsymbol{M}^*\dot{\boldsymbol{r}} &= \boldsymbol{\tau}^* - \boldsymbol{D}^*\dot{\boldsymbol{\eta}} - \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_d + \boldsymbol{M}^*\boldsymbol{K}\dot{\boldsymbol{e}} \\ &= \boldsymbol{\tau}^* - \boldsymbol{R}(\varphi)\boldsymbol{D}\boldsymbol{v} + \boldsymbol{R}(\varphi)\boldsymbol{M}\boldsymbol{S}(\dot{\varphi})\boldsymbol{R}^T(\varphi)\dot{\boldsymbol{\eta}} - \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_d + \boldsymbol{M}^*\boldsymbol{K}\dot{\boldsymbol{e}} \\ &= -\boldsymbol{Y}(\varphi,\boldsymbol{v})\boldsymbol{\Theta} + \boldsymbol{\tau}^* + \boldsymbol{R}(\varphi)\boldsymbol{M}\boldsymbol{S}(\dot{\varphi})\boldsymbol{R}^T(\varphi)\dot{\boldsymbol{\eta}} - \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_d + \boldsymbol{M}^*\boldsymbol{K}\dot{\boldsymbol{e}}, \end{aligned} \tag{13}$$

where the regression matrix $\boldsymbol{Y}(\varphi, v)$ and the unknown parameter vector $\boldsymbol{\Theta}$ are defined by the following expression:

$$Y(\varphi,\boldsymbol{v}) = \boldsymbol{R}(\varphi)\begin{bmatrix} u & 0 & 0 \\ 0 & v & 0 \\ 0 & 0 & r \end{bmatrix}, \quad \Theta = \begin{bmatrix} X_u \\ Y_v \\ N_r \end{bmatrix}. \tag{14}$$

Based on the open-loop dynamics of the filtered tracking error, the transformed control input vector $\boldsymbol{\tau}^*$ is specified to be

$$\begin{aligned} \boldsymbol{\tau}^* = &\boldsymbol{Y}(\varphi,\boldsymbol{v})\hat{\boldsymbol{\Theta}} - \boldsymbol{R}(\varphi)\boldsymbol{M}\boldsymbol{S}(\dot{\varphi})\boldsymbol{R}^T(\varphi)\dot{\boldsymbol{\eta}} + \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_d \\ &- \boldsymbol{M}^*\boldsymbol{K}\dot{\boldsymbol{e}} - \boldsymbol{e} - \boldsymbol{K}_r\boldsymbol{r}, \end{aligned} \tag{15}$$

where $\boldsymbol{K}_r$ is defined as a positive definite, diagonal gain matrix. The update law, based on the projection presented below, is defined to generate the bounded parameter estimate vector $\hat{\boldsymbol{\Theta}}(t)$ [7]:

$$\dot{\hat{\boldsymbol{\Theta}}} = \begin{cases} 0 & \text{if } \hat{\boldsymbol{\Theta}} = \bar{\Theta}, \ -\boldsymbol{Y}^T(\varphi,\boldsymbol{v})r > 0, \\ 0 & \text{if } \hat{\boldsymbol{\Theta}} = 0, \ -\boldsymbol{Y}^T(\varphi,\boldsymbol{v})r < 0, \\ -\boldsymbol{Y}^T(\varphi,\boldsymbol{v})r & \text{otherwise.} \end{cases} \tag{16}$$

Here, $\bar{\Theta}$ denotes the upper bound values for the draft coefficients (assumed to be known). The closed-loop dynamics of the filtered tracking error signal $\boldsymbol{r}(t)$ can be obtained as follows:

$$\boldsymbol{M}^*\dot{\boldsymbol{r}} = -\boldsymbol{Y}(\varphi,\boldsymbol{v})\tilde{\boldsymbol{\Theta}} - \boldsymbol{e} - \boldsymbol{K}_r\boldsymbol{r} \tag{17}$$

where $\tilde{\boldsymbol{\Theta}} = \boldsymbol{\Theta} - \hat{\boldsymbol{\Theta}}$ denotes the difference between the actual and estimated draft coefficients.

The non-negative control Lyapunov function is chosen to

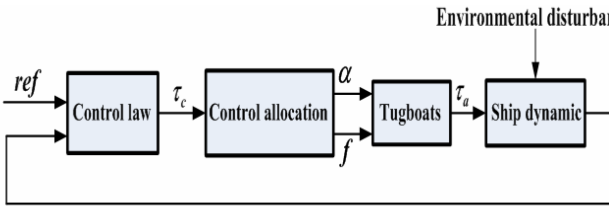

Fig. 3. Control allocation for unactuated ship using thrusts of tugboats.

analyze the stability of the system:

$$V = \frac{1}{2}\boldsymbol{e}^T\boldsymbol{e} + \frac{1}{2}\tilde{\boldsymbol{\Theta}}^T\tilde{\boldsymbol{\Theta}} + \frac{1}{2}\boldsymbol{r}^T\boldsymbol{M}^*\boldsymbol{r}\ . \tag{18}$$

By differentiating Eq. (18) and substituting Eqs. (11) and (17) into the derivative of *V(t)*, we obtain

$$\dot{V} = -\boldsymbol{e}^T\boldsymbol{K}\boldsymbol{e} - \boldsymbol{r}^T\boldsymbol{K}_r\boldsymbol{r}. \tag{19}$$

Eq. (19) gives the non-positive time derivative of the Lyapunov function candidate. Based on the Lyapunov stability, it is possible to conclude that the control system is asymptotically stable. Therefore, the tracking error and its derivative will converge to zero in a finite amount of time.

4. Formulation of control allocation

4.1 Control allocation problem

In this paper, the control allocation is formulated as shown in Fig. 3. It determines the direction α_i and the required force f_i for each individual tugboat from the desired control input vector $\boldsymbol{\tau}_c$, which is produced from the controller. In this case, the control allocation is optimized [8, 9] with the constraints of contact angles, slowly varying direction and limited pushing force such that

(1) $\|\boldsymbol{\tau}_c - \boldsymbol{\tau}_a(\alpha_i, f_i)\|$ is small to minimize the error between the actual thrust and the desired signal from the controller.
(2) $\|\boldsymbol{\tau}_a(\alpha_i, f_i)\|$ is small to minimize the power is supplied to tugboats.
(3) $\alpha_i(t)$ changes slowly to match the dynamic response of tugboats and to minimize the wear and tear on the thrust devices.

The approach presented in this paper can be outlined as described below:

First, calculate the angles α_i to determine the direction of the tugboats. The generated angles must satisfy $\alpha_{\min} \le \alpha \le \alpha_{\max}$. This limitation should be chosen so as to avoid any slips. Furthermore, the angles should be subject to the slowly varying constraint $\dot{\alpha}_i < \dot{\alpha}$. These requirements can be combined as $\underline{\alpha} \le \alpha_i \le \bar{\alpha}$, where

$$\begin{cases} \underline{\alpha} = \max(\alpha_{\min}, \alpha_{i-1} - \Delta t\dot{\alpha}), \\ \bar{\alpha} = \min(\alpha_{\max}, \alpha_{i-1} + \Delta t\dot{\alpha}). \end{cases} \tag{20}$$

The geometric configuration matrix $\boldsymbol{B}(\alpha)$ is then calculated based on the given α_i. Finally, the thrust vector f is chosen for minimal power consumption.

4.2 Solution for varying direction

Determining suitable directions for each tugboat is achieved by using extended control force decomposition. The thrust of each tugboat is separated into two elements relative to *x*- and *y*-directions within the body-fixed coordinate frame. The thrust vector $\boldsymbol{f}$ is then represented by the vector $\boldsymbol{f}'$ as follows:

$$\boldsymbol{f}' = [f_{1x}, f_{1y}, f_{2x}, f_{2y}, f_{3x}, f_{3y}, f_{4x}, f_{4y},]^T \tag{21}$$

where $f_{ix} = f_i\cos\alpha_i$ and $f_{iy} = f_i\sin\alpha_i$. The geometric configuration matrix $\boldsymbol{B}(\alpha)$ is then extended to give $\boldsymbol{B}'$:

$$\boldsymbol{B}' = \begin{bmatrix} 1 & 0 & \dots & 1 & 0 \\ 0 & 1 & \dots & 0 & 1 \\ -l_{y1} & l_{x1} & \dots & -l_{y4} & l_{x4} \end{bmatrix}. \tag{22}$$

The vector $\boldsymbol{f}'$ is computed using the Moore Penrose pseudo-inverse matrix [10], a special case of the pseudo-inverse matrix (presented later in more detail):

$$\boldsymbol{\tau}_c = \boldsymbol{B}'\boldsymbol{f}' \Rightarrow \boldsymbol{f}' = \boldsymbol{B}'^*\boldsymbol{\tau}_c \tag{23}$$

where $\boldsymbol{B}'^* = \boldsymbol{B}'^T(\boldsymbol{B}'\boldsymbol{B}'^T)^{-1}$. The direction of the tugboats can then be found with:

$$\alpha_i = \begin{bmatrix} \underline{\alpha} \text{ if } \alpha_i < \max(\alpha_{\min}, \alpha_{i-1} - \Delta t\dot{\alpha}), \\ \tan^{-1}\left(\dfrac{f_{iy}}{f_{ix}}\right) \text{ if } \underline{\alpha} \le \alpha_i \le \bar{\alpha} \quad \forall i \in (1,\dots,4), \\ \bar{\alpha} \text{ if } \bar{\alpha} > \min(\alpha_{\max}, \alpha_{i-1} + \Delta t\dot{\alpha}). \end{bmatrix} \tag{24}$$

Note that with the limitation on the rate of direction change, we can decrease the jump in the direction of a tugboat at each sample.

4.3 Solution for limited pushing force

In this paper, the control force optimization problem is solved by using the RPI approach. This approach is a constrained optimization technique. The objective of minimizing the power supplied to tugboats can be written as follows:

$$\min_f J = \min_f \frac{1}{2}(\boldsymbol{f} + \boldsymbol{c})^T\boldsymbol{W}(\boldsymbol{f} + \boldsymbol{c}) \tag{25}$$

subject to

$$\begin{aligned} &\boldsymbol{\tau}_c - \boldsymbol{B}(\alpha)\boldsymbol{f} = 0 \\ &f_{\min} \le f_i \le f_{\max}, \end{aligned} \tag{26}$$

where $W \in R^{nxn}$ is the weighting matrix and $c \in R^n$ is the offset vector. To solve this problem, we find the Hamiltonian (H):

$$H = \frac{1}{2}(f^T W f + c^T W f + f^T W c + c^T W c) + \\ +\xi(B(\alpha) f - \tau_c), \tag{27}$$

where $\xi \in R^n$ is an undetermined Lagrange multiplier. Taking the partial derivative of H and setting the results to zero, we obtain the following relations:

$$\frac{\partial H}{\partial f} = Wf + \frac{1}{2}(c^T W)^T + \frac{1}{2}Wc + (\xi B(\alpha))^T = 0 \\ \Rightarrow Wf = -Wc - B(\alpha)^T \xi^T, \tag{28}$$

and

$$\frac{\partial H}{\partial \xi} = B(\alpha) f - \tau = 0 \Rightarrow B(\alpha) W^{-1} W f = \tau_c \\ \Rightarrow B(\alpha) W^{-1}[-Wc - B(\alpha)^T \xi^T] = \tau_c. \tag{29}$$

Solving Eq. (29), we find that

$$\xi^T = -(B(\alpha) W^{-1} B(\alpha)^T)^{-1}(\tau_c + B(\alpha) c). \tag{30}$$

Substituting Eq. (30) into Eq. (28), we obtain the following:

$$Wf = -Wc + B(\alpha)^T (B(\alpha) W^{-1} B(\alpha)^T)^{-1}(\tau_c + B(\alpha) c) \\ \Rightarrow f = -c + W^{-1} B(\alpha)^T (B(\alpha) W^{-1} B(\alpha)^T)^{-1}(\tau_c + B(\alpha) c). \tag{31}$$

If we set $B^* = W^{-1} B(\alpha)^T (B(\alpha) W^{-1} B(\alpha)^T)^{-1}$, Eq. (31) is simplified as follows:

$$f = -c + B^*(\tau_c + B(\alpha) c). \tag{32}$$

Note that if W is the identity matrix, B^* is called the Moore–Penrose pseudo-inverse matrix.

After solving the force distribution problem using Eq. (32) with c initially a zero vector, if no element of the thrust vector f exceeds the minimum or maximum value, the process stops. However, if one of the elements exceeds the limits, the problem is solved again with Eq. (31) modified as follows:

(1) The zero vector is set to all the elements of the *i-th* column of matrix $B(\alpha)$, which corresponds to the position of the saturated f_i.
(2) The i-th element of vector c is set as the negative of the saturated value.

5. Simulation results

The primary focus of the simulation is to investigate the performance of the controlled system, as well as tugboats dynamics using the mathematical model along with the control approach described above.

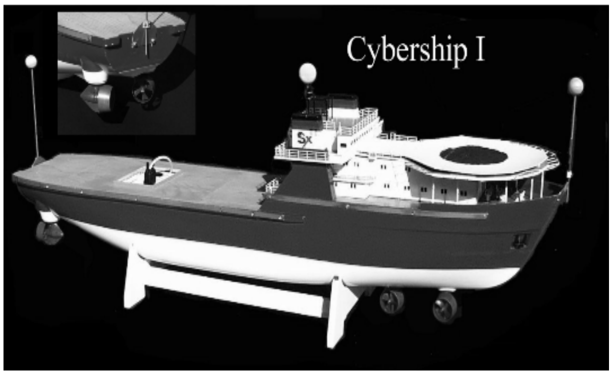

Fig. 4. Cybership I [11], supply vessel scale 1:70.

Cybership I [11], scale 1:70, which is a model of an offshore supply vessel with four thrusters in the configuration as shown in Fig. 4, is used in the simulation. It is noted that these actuators are not used and the motion of ship is done by tugboats. The model ship has a mass of 17.6[kg] and a length of 1.19[m]. The center of gravity is located at x_g=-0.04[m]. This is also the origin in the body fixed coordinate system. Hydrodynamic coefficients of the ship are described as follows:

$$M = \begin{bmatrix} 19[\text{kg}] & 0 & 0 \\ 0 & 35.2[\text{kg}] & \text{-0.7}[\text{kg}\cdot\text{m}^2] \\ 0 & \text{-0.7}[\text{kg}] & 1.98[\text{kg}\cdot\text{m}^2] \end{bmatrix}, \\ D = \text{diag}\ \{4[\text{kg/s}], 6[\text{kg/s}], 1[\text{kg}\cdot\text{m}^2/\text{s}]\}. \tag{33}$$

The configuration of the tugboats around the ship are described as

$$(l_{1x}, l_{1y}) = (0.41, -0.15),\ (l_{2x}, l_{2y}) = (-0.41, -0.15), \\ (l_{3x}, l_{3y}) = (-0.41, 0.15),\ (l_{4x}, l_{4y}) = (0.41, 0.15). \tag{34}$$

The slowly varying direction constraint emphasizes that the set of initial directions $\alpha_{10}, \alpha_{20}, \alpha_{30}, \alpha_{40}$ considerably affect the direction and control force of the tugboats. In this simulation, varying direction constraint is:

$$\dot{\alpha} = \frac{\pi}{90}[\text{rad/s}]. \tag{35}$$

Constraints about limitation of pushing force and contact angle of each tugboat are chosen as follows:

$$f_{\min} = 0, f_{\max} = 0.5[\text{N}], \\ \alpha_{1\min} = \alpha_{2\min} = \frac{\pi}{6},\ \alpha_{1\max} = \alpha_{2\max} = \frac{5\pi}{6}, \\ \alpha_{3\min} = \alpha_{4\min} = \frac{-5\pi}{6},\ \alpha_{3\max} = \alpha_{4\max} = \frac{-\pi}{6}. \tag{36}$$

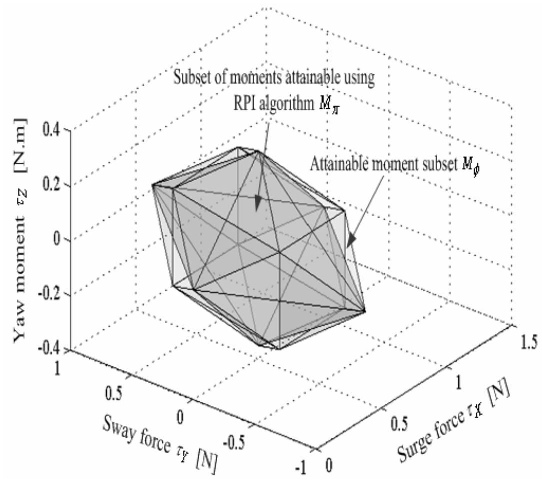

Fig. 5. Subset of moments attainable using the redistributed pseudo-inverse (RPI) algorithm.

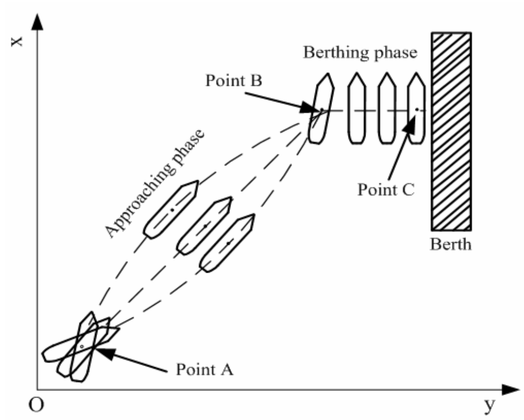

Fig. 6. Planning route for ship berthing.

Fig. 5 shows the attainable moment subset (M_ϕ) in the case $\alpha_1 = \alpha_2 = \pi/3$ and $\alpha_3 = \alpha_4 = -\pi/3$, namely, the result of mapping the limited pushing force constraint of all four tugboats in 4-D onto the control input vector in 3-D. This subset is a hyper cube. The subset of moments attainable using the RPI approach (M_π) is located inside the M_ϕ. The RPI approach exhibits good efficiency with a high ratio between volumes M_π and M_ϕ. We notice that, if the vector $\boldsymbol{\tau}_c$ is located inside the volume M_π, the error between the actual control input vector $\boldsymbol{\tau}_a$ and the desired control input vector $\boldsymbol{\tau}_c$ is zero.

For safety berthing, the planning route is separated into two phases as shown in Fig. 6. The first, where the ship moves from point A to point B is called approaching phase and the second, from point B to C is the berthing phase.

In this simulation, firstly, the ship is operated to move on the straight line from starting point A (0,0) where the initial heading angle is $\pi/3$ and stop at the point B (10,10) where the desired heading angle is $\pi/4$. The initial directions of tugboats in this phase are $\alpha_1 = \alpha_2 = \pi/3$ and $\alpha_3 = \alpha_4 = -\pi/3$. After that, the ship is maneuvered from the point B (10, 10) to point C (10, 15) in the berthing phase. In

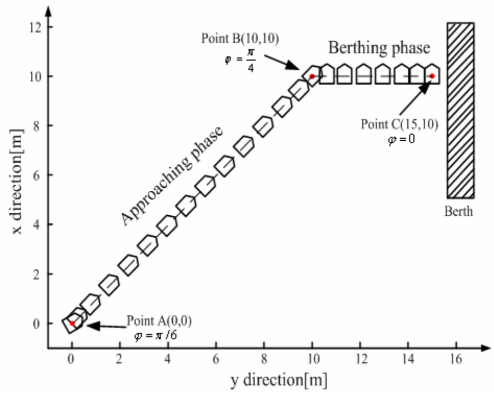

Fig. 7. Ship motion for berthing.

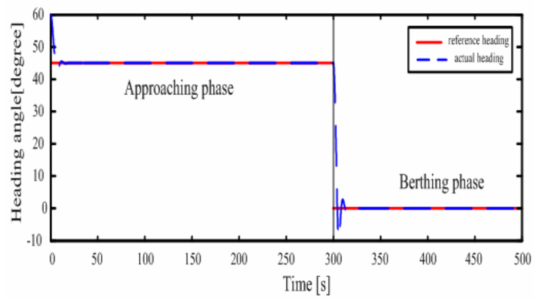

Fig. 8. Ship heading response.

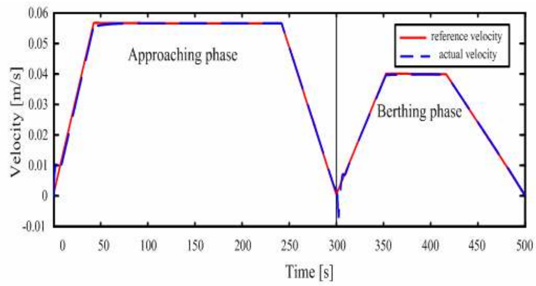

Fig. 9. Ship velocity response.

this phase, the directions of tugboats are fixed as $\alpha_1 = \alpha_2 = \pi/2$ and $\alpha_3 = \alpha_4 = -\pi/2$.

The control input vector $\boldsymbol{\tau}_c$ is calculated from the proposed adaptive controller. This system is simulated with $\boldsymbol{K} = \text{diag}\{1,1,1\}$ and $\boldsymbol{K}_r = \text{diag}\{0.3,0.3,0.3\}$. These matrices are chosen to match the subset of attainable moments as described above.

Figs. 7-9 show the responses during berthing. It is clearly shown that good performances achieved in both geometric task and dynamic task. The designed controller and proposed control allocation approach guarantee that the ship follows a given trajectory as well as achieves the desired velocity. In both phase, the heading angle changes from the initial value to desired value in the limited time by combination of tugboat thrusts. After that, the heading angle is kept and the ship follows defined trajectory with high accuracy. Based on the ship performance, it is ensured that the ship can move to the berth

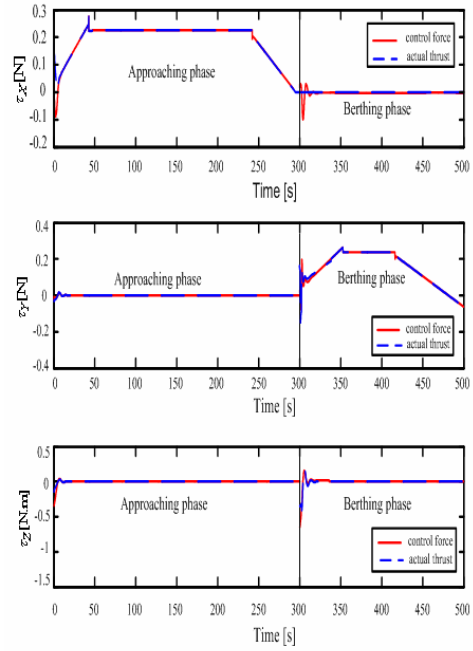

Fig. 10. Thrust force comparison: solid lines depict forces commanded by the controller, dashed line represents actual thrusts supplied to the ship.

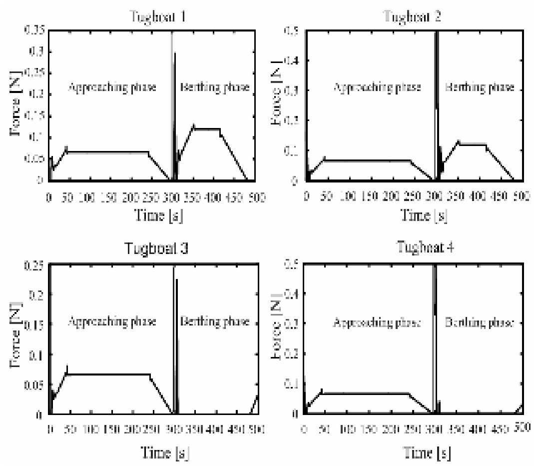

Fig. 11. Tugboat thrusts during berthing.

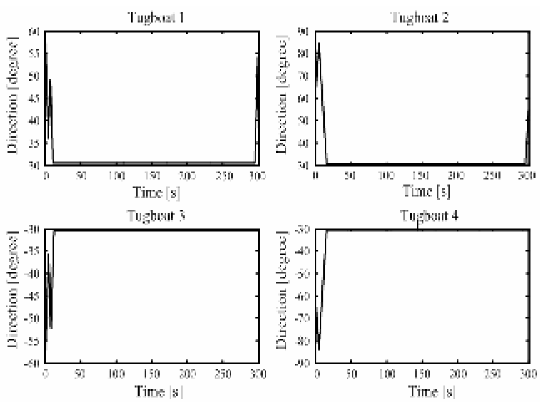

Fig. 12. Tugboat directions in approaching.

without collision between ship and the others located in the harbor as well as between ship and the berth.

Fig. 10 evaluates the efficiency of the proposed control allocation approach. Furthermore, it shows the forces and moment supply to ship by combination of four tugboats. Based on this figure, it is clearly to see that the proposed approach can minimize the error between the actual thrust and the desired signal from the controller. Additionally, it is shown that, in the approaching phase, to maneuver ship in the straight line from A to B, 4 tugboats just maintain the surge force τ_x. The sway force τ_Y and yaw moment τ_z are reduced to zero to avoid the undesired motion in Y direction as well as heading angle variation. In the berthing phase τ_X and τ_z are decreased to zero.

Figs. 11 and 12 depict the performance of four tugboats during berthing. The resulting thrusts and directions of tugboats satisfy the constraint about limited pushing force and slow change direction shown in Eqs. (35) and (36). In the approaching phase, the force supplied to ship is produced from the 4 tugboat thrusts synchronously to pass up the actuator saturation. However, in the berthing phase, the tugboat 1 and 2 are used as main actuators, tugboat 3 and 4 are just used to avoid the collision between the ship and berth.

6. Conclusion

In this paper, we proposed a new approach for ship berthing with the assistance of autonomous tugboats. An adaptive controller was presented to take into account the uncertainty of system parameters. The control allocation was considered as an optimization problem under the constraints that a tugboat can only exert a limited pushing force and that it can only slowly change directions. The efficiency of the proposed approach was evaluated through using a model ship in a Matlab simulation. It exhibited good performance and revealed the possibility of extending these results to future studies by testing a model ship under actual conditions. The combination of tunnel thrusters and the assistance of one, two or more tugboats will be studied to determine suitable solutions for various ship berthing situations.

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