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Original Paper

Preliminary study on the docking control of a large ship using tugboats

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Abstract: In this study, we aim to automate the docking operation by manipulating a (disabled) large ship using multiple tugboats. To this end, as a preliminary study, we attempt to incorporate the dynamics of the ship and tugboats into the manipulation control. Assuming that the contact between the ship and each tugboat is a point contact, the velocity constraints at the contact points yield a reduced dynamic equation that can be expressed using independent variables, e.g., ship variables (surge, sway, and yaw rates), and that excludes contact force terms; this allows us to treat the ship and multiple tugboats as a single system to control the independent variables. We formulate the reduced dynamic equation of a ship and *n* number of tugboats and present a controller to manipulate the ship to track a straight-line path while maintaining a desired heading angle. However, a separate controller is required when using a single tugboat because a singular point appears when the contact point is aligned with the two centers of mass of the ship and tugboat. We conduct simulations of cases of using one, two, and three tugboat(s) to verify the effectiveness of the proposed control method based on the reduced dynamics.

Keywords: Tugboat, Docking, Ship, Reduced dynamic equation, Path-tracking control

1. Introduction

Operation of a ship in harbors, including the docking operation, is a tense task for onboard members because of the risk of collisions with other ships and harbor facilities. In particular, a large ship typically has powerful propellers that have poor maneuverability at a low speed; thus, it becomes difficult for the ship to move with a delicate motion, despite having a dynamic positioning system. Therefore, tugboats play an active role in maneuvering such large ships in harbors **[1]**.

Meanwhile, pushing or pulling motion enables us to move a large object easily in our daily activities, and it can be more effective on the sea because the frictional force in sea is less than that on land. A tugboat utilizes this advantage to move large floating objects, such as (disabled) large ships, barges, oil platforms, caissons, etc. Moreover, multiple tugboats can cooperatively perform more delicate tasks like docking a large ship in a narrow space. However, the radio communications by humans between tugboats often interrupt the smooth flow of the operation, and operators are required to have considerable skills; this has encouraged researchers to automate the maneuvering operation of a large ship through multiple tugboats.

The research group in **[2]**-**[5]** investigated the manipulation problem of a large (disabled) ship using swarms of autonomous marine surface vehicles (tugboats). Each tugboat in contact with the ship was considered to be a three-degree-of-freedom (3-DOF) azimuth thruster of the ship, and its influence was treated as a pushing force to the ship. Ship dynamics were used to develop control strategies. Robust control methods based on the aforementioned concept have also been studied by other researchers **[6][7]**.

The manipulation of a large ship by multiple surface vehicles is worth investigating as indicated in **[2]** and there are few related works. However, in robotics, there is a significant amount of research on the manipulation of a large object by multi-robot cooperation **[8]**-**[16]**. Related works were reviewed in **[8].** Approaches using pushing **[9]**-**[12]**, formation **[13]**, grasping **[14]**, caging **[15]**, and object closure **[16]** have been investigated; these robotics technologies can be applied to marine robotics.

This study involves pose (position and orientation) control of a large ship by multiple tugboats with the aim of automating docking operation. To this end, we first challenge to incorporate the dynamics of both the ship and tugboats as a preliminary study; the previous research in **[2]**-**[7]** considered only the ship dynamics. The contact between the ship and each tugboat is assumed to be a point contact. The velocity constraints at the contact points yield a reduced dynamic equation that is ex-

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pressed by independent variables, e.g., ship variables (surge, sway, and yaw rates), and excludes contact force terms; this allows us to treat the ship and multiple tugboats as a single system to control the independent variables. Section 2 of this paper formulates the reduced dynamic equation inspired by multi-fingered robot hand dynamics **[17]**. In Section 3, a controller to manipulate the ship to track a straight-line path while maintaining a desired heading angle is presented; a separate controller is, however, required for a single tugboat because a singular point appears when the contact point is aligned with two centers of mass of the ship and tugboat. Section 3 further considers a controller for this case. Lastly, Section 4 conducts simulations to verify the effectiveness of the presented control method based on the reduced dynamics.

2. Reduced dynamic equation

Consider a (disabled) ship manipulated by n number of tugboats as shown in **Figure 1**. To formulate the reduced dynamic equation, we use the following notations:

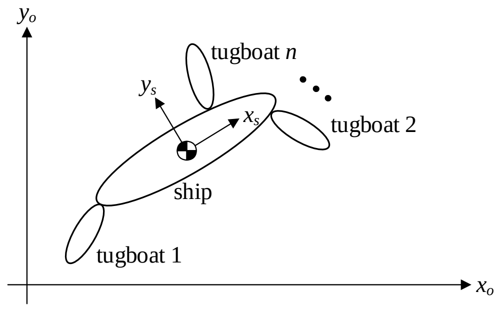

Figure 1: Ship manipulated by n number of tugboats

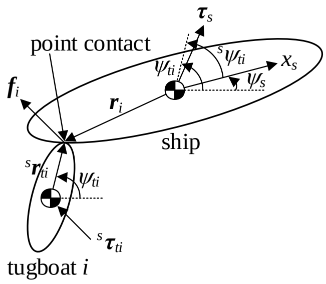

Figure 2: Force and moment relationships between the ship and the i-th tugboat

x_o-y_o coordinate system: the fixed frame

x_s-y_s coordinate system: the ship frame

u_s: the surge rate of the ship

u_{ti}: the surge rate of the i-th tugboat

v_s: the sway rate of the ship

v_{ti}: the sway rate of the i-th tugboat

ω_s: the yaw rate of the ship

ω_{ti}: the yaw rate of the i-th tugboat

${}^su_{ti}$, ${}^sv_{ti}$, ${}^s\omega_{ti}$: the rates expressed with respect to (w.r.t.) the ship frame

$\boldsymbol{V}_s = (u_s\ v_s\ \omega_s)^T \in \Re^3$

$\boldsymbol{V}_{ti} = (u_{ti}\ v_{ti}\ \omega_{ti})^T \in \Re^3$

${}^s\boldsymbol{V}_{ti} = ({}^su_{ti}\ \ {}^sv_{ti}\ \ {}^s\omega_{ti})^T \in \Re^3$

ψ_s: the yaw angle of the ship w.r.t. the fixed frame

ψ_{ti}: the yaw angle of the i-th tugboat w.r.t. the fixed frame

${}^s\psi_{ti}$: the yaw angle of the i-th tugboat w.r.t. the ship frame

$\boldsymbol{\tau}_s \in \Re^3$: the resultant forces and moment applied to the ship

$\boldsymbol{\tau}_{ti} \in \Re^3$: the forces and moment exerted by the i-th tugboat, which are expressed w.r.t. its body frame

${}^s\boldsymbol{\tau}_{ti} \in \Re^3$: $\boldsymbol{\tau}_{ti}$ expressed w.r.t. the ship frame

$\boldsymbol{f}_i \in \Re^2$: the contact force at the contact point of the i-th tugboat

$\boldsymbol{r}_i \in \Re^2$: the position vector pointing from the center of mass of the ship to the contact point of the i-th tugboat

$\boldsymbol{r}_{ti} \in \Re^2$: the position vector pointing from the center of mass of the i-th tugboat to the contact point with the ship, which is expressed w.r.t. its body frame

${}^s\boldsymbol{r}_{ti} \in \Re^2$: $\boldsymbol{r}_{ti}$ expressed w.r.t. the ship frame

From **Figures 1** and **2**, we obtain the dynamic equations of the ship and the i-th tugboat expressed w.r.t. the ship frame as follows:

$$M_s\dot{\boldsymbol{V}}_s + C_s(\boldsymbol{V}_s)\boldsymbol{V}_s + D_s(\boldsymbol{V}_s)\boldsymbol{V}_s = \boldsymbol{\tau}_s \tag{1}$$

$${}^sM_{ti}\,{}^s\dot{\boldsymbol{V}}_{ti} + {}^sC_{ti}(\boldsymbol{V}_{ti})\,{}^s\boldsymbol{V}_{ti} + {}^sD_{ti}(\boldsymbol{V}_{ti})\,{}^s\boldsymbol{V}_{ti} = {}^s\boldsymbol{\tau}_{ti} \tag{2}$$

$${}^sM_{ti} = RM_{ti}\mathrm{R}^T \in \Re^{3\times3} \tag{3}$$

$${}^sC_{ti}(\boldsymbol{V}_{ti}) = R(C_{ti}(\boldsymbol{V}_{ti}) - M_{ti}\mathrm{R}^T\dot{R})\mathrm{R}^T \in \Re^{3\times3} \tag{4}$$

$${}^sD_{ti}(\boldsymbol{V}_{ti}) = RD_{ti}(\boldsymbol{V}_{ti})\mathrm{R}^T \in \Re^{3\times3} \tag{5}$$

$${}^s\boldsymbol{\tau}_{ti} = R\boldsymbol{\tau}_{ti} \in \Re^3 \tag{6}$$

$$R \equiv R({}^s\psi_{ti}) \in \Re^{3\times3}\text{: the rotation matrix of } {}^s\psi_{ti} \tag{7}$$

where $M_s = M_{sRB} + M_{sA} \in \Re^{3\times3}$, M_{sRB} and M_{sA} are the rigid-body inertia matrix and the added inertia matrix, respectively, $C_s(\boldsymbol{V}_s) = C_{sRB}(\boldsymbol{V}_s) + C_{sA}(\boldsymbol{V}_s) \in \Re^{3\times3}$, $C_{sRB}(\boldsymbol{V}_s)$ and $C_{sA}(\boldsymbol{V}_s)$ are the rigid-body Coriolis and centripetal matrix, as well as the hydrodynamic Coriolis and centripetal matrix, respectively, and $D_s(\boldsymbol{V}_s) \in \Re^{3\times3}$ is the hydrodynamic damping matrix **[18]**; these are for the ship and M_{ti}, $C_{ti}(\boldsymbol{V}_{ti})$, and $D_{ti}(\boldsymbol{V}_{ti})$ represent the same things associated with the tugboat.

Assuming that the contact between the ship and each tugboat is a point contact, and considering the influence of the contact force to the ship and tugboat, as shown in **Figure 2**, **Equations (1)** and **(2)** can be rewritten as

$$M_s\dot{\boldsymbol{V}}_s + C_s(\boldsymbol{V}_s)\boldsymbol{V}_s + D_s(\boldsymbol{V}_s)\boldsymbol{V}_s = B_s^T\boldsymbol{f} \quad (8)$$

$${}^sM_{ti}\,{}^s\dot{\boldsymbol{V}}_{ti} + {}^sC_{ti}(\boldsymbol{V}_{ti})\,{}^s\boldsymbol{V}_{ti} + {}^sD_{ti}(\boldsymbol{V}_{ti})\,{}^s\boldsymbol{V}_{ti} = R\boldsymbol{\tau}_{ti} - {}^sB_{ti}^T\boldsymbol{f}_i \quad (9)$$

$$B_s^T = \begin{pmatrix} I_2 & \cdots & I_2 \\ \boldsymbol{r}_1^TE^T & \cdots & \boldsymbol{r}_n^TE^T \end{pmatrix} \in \Re^{3\times 2n} \quad (10)$$

$${}^sB_{ti}^T = \begin{pmatrix} I_2 \\ {}^s\boldsymbol{r}_{ti}^TE^T \end{pmatrix} \in \Re^{3\times 2} \quad (11)$$

$$\boldsymbol{f} = \begin{pmatrix} \boldsymbol{f}_1 \\ \vdots \\ \boldsymbol{f}_n \end{pmatrix} \in \Re^{2n} \quad (12)$$

$$E = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad (13)$$

where I_2 is a 2×2 identity matrix, and E is the orthogonal rotation matrix rotating an arbitrary vector 90° counterclockwise in a plane.

Combining **Equations (8)** and **(9)** for a ship and n number of tugboats, we obtain the following:

$$M\dot{\boldsymbol{V}} + C(\boldsymbol{V})\boldsymbol{V} + D(\boldsymbol{V})\boldsymbol{V} = T\boldsymbol{\tau}_t + B^T\boldsymbol{f} \quad (14)$$

$$\boldsymbol{V} = \begin{pmatrix} \boldsymbol{V}_s \\ {}^s\boldsymbol{V}_{t1} \\ \vdots \\ {}^s\boldsymbol{V}_{tn} \end{pmatrix} \in \Re^{3+3n} \quad (15)$$

$$M = \text{blockdiag}(M_s,\ {}^sM_{t1}, \cdots,\ {}^sM_{tn}) \quad (16)$$

$$C(\boldsymbol{V}) = \text{blockdiag}(C_s(\boldsymbol{V}_s),\ {}^sC_{t1}(\boldsymbol{V}_{t1}), \cdots,\ {}^sC_{tn}(\boldsymbol{V}_{tn})) \quad (17)$$

$$D(\boldsymbol{V}) = \text{blockdiag}(D_s(\boldsymbol{V}_s),\ {}^sD_{t1}(\boldsymbol{V}_{t1}), \cdots,\ {}^sD_{tn}(\boldsymbol{V}_{tn})) \quad (18)$$

$$M, C(\boldsymbol{V}), D(\boldsymbol{V}) \in \Re^{(3+3n)\times(3+3n)} \quad (19)$$

$$T = \begin{pmatrix} O_{3\times 3n} \\ \text{blockdiag}(R({}^s\psi_{t1}), \cdots, R({}^s\psi_{tn})) \end{pmatrix} \in \Re^{(3+3n)\times 3n} \quad (20)$$

$$\boldsymbol{\tau}_t = \begin{pmatrix} \boldsymbol{\tau}_{t1} \\ \vdots \\ \boldsymbol{\tau}_{tn} \end{pmatrix} \in \Re^{3n} \quad (21)$$

$$B^T = \begin{pmatrix} B_s^T \\ -\,{}^sB_t^T \end{pmatrix} \in \Re^{(3+3n)\times 2n} \quad (22)$$

$${}^sB_t^T = \text{blockdiag}({}^sB_{t1}^T, \cdots,\ {}^sB_{tn}^T) \in \Re^{3n\times 2n} \quad (23)$$

Let $\boldsymbol{v}_s = (u_s\ v_s)^T$, ${}^s\boldsymbol{v}_{ti} = ({}^su_{ti}\ \ {}^sv_{ti})^T$, and $\boldsymbol{v}_i$ be the velocity of the contact point with the i-th tugboat; moreover, let us assume that the contact point does not change during operation.

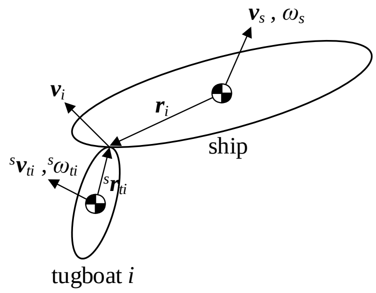

Figure 3: Velocity constraint at the contact point between the ship and the i-th tugboat

From **Figure 3**, the velocity constraint at the contact point can then be expressed as

$$\boldsymbol{v}_i = \boldsymbol{v}_s + E\boldsymbol{r}_i\omega_s = {}^s\boldsymbol{v}_{ti} + E\,{}^s\boldsymbol{r}_{ti}\,{}^s\omega_{ti} \quad (24)$$

Combining all the velocity constraints at n number of contact points, we have

$$B_s\boldsymbol{V}_s = {}^sB_t\,{}^s\boldsymbol{V}_t \Leftrightarrow B\boldsymbol{V} = \boldsymbol{0} \quad (25)$$

Here, selecting $\boldsymbol{V}_s$ as independent variables, we obtain the following:

$$\boldsymbol{V} = N\boldsymbol{V}_s \quad (26)$$

$$\dot{\boldsymbol{V}} = N\dot{\boldsymbol{V}}_s + \dot{N}\boldsymbol{V}_s \quad (27)$$

$$N = \begin{pmatrix} I_3 \\ {}^sB_t^{\#}B_s \end{pmatrix} \in \Re^{(3+3n)\times 3} \quad (28)$$

${}^sB_t^{\#}$: the pseudoinverse of ${}^sB_t$ (29)

Substituting **Equations (26)** and **(27)** into **Equation (14)** and eliminating the contact force terms because $BN = O_{2n\times 3}$ from **Equation (25)**, the reduced dynamic equation is finally expressed as follows:

$$\bar{M}\dot{\boldsymbol{V}}_s + \bar{C}(\boldsymbol{V})\boldsymbol{V}_s + \bar{D}(\boldsymbol{V})\boldsymbol{V}_s = N^TT\boldsymbol{\tau}_t \quad (30)$$

$$\bar{M} = N^TMN \in \Re^{3\times 3} \quad (31)$$

$$\bar{C}(\boldsymbol{V}) = N^T(C(\boldsymbol{V})N + M\dot{N}) \in \Re^{3\times 3} \quad (32)$$

$$\bar{D}(\boldsymbol{V}) = N^TD(\boldsymbol{V})N \in \Re^{3\times 3} \quad (33)$$

3. Path-tracking control

As a complex trajectory can be formed by combinations of straight lines, we discuss the straight-line path-tracking control of a ship using multiple tugboats while maintaining a certain yaw angle (heading angle) of the ship. **Figure 4** shows notations for tracking a particular straight-line path. $\boldsymbol{p}_s$, $\boldsymbol{p}_p$, and

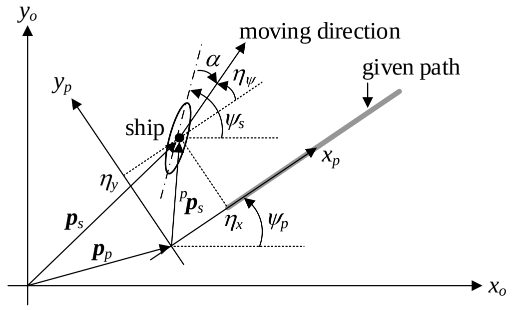

Figure 4: Tracking a straight-line path. The tugboats are omitted from the figure

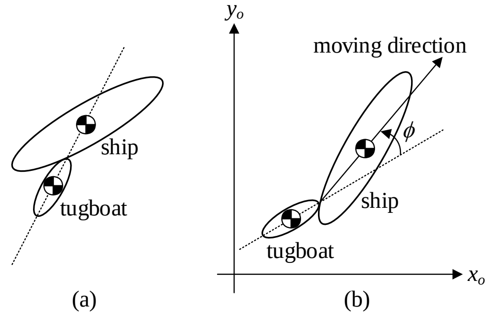

Figure 5: (a) Singular configuration. (b) Pushing the ship to track a given path by a single tugboat

${}^p\boldsymbol{p}_s = (\eta_x\ \eta_y)^T$ are the position vectors of the ship, the origin of the x_p-y_p frame (path frame) w.r.t. the fixed frame, and the ship w.r.t. the path frame, respectively, and ψ_p, α, and η_ψ are the angle of the x_p-axis from the x_o-axis, the angle from the front side of the ship to the moving direction, and the angle of the moving direction from the x_p-axis, respectively.

The control purpose ensures that η_y and η_ψ are zeros, and η_y and η_ψ are obtained by

$$ {}^p\boldsymbol{p}_s = \begin{pmatrix}\eta_x \\ \eta_y\end{pmatrix} = R^T(\psi_p)(\boldsymbol{p}_s - \boldsymbol{p}_p) \tag{34}$$

$$\eta_\psi = (\psi_s - \alpha) - \psi_p \tag{35}$$

Letting U_d and $\boldsymbol{V}_{sd}$ be the desired moving speed and the desired value of $\boldsymbol{V}_s$, respectively, we can set $\boldsymbol{V}_{sd}$ as

$$\boldsymbol{V}_{sd} = \begin{pmatrix} U_d cos\alpha \\ -U_d sin\alpha \\ -k_y\eta_y - k_\psi\eta_\psi \end{pmatrix} \tag{36}$$

From the reduced dynamic equation in **Equation (30)**, the forces and moments required to be exerted by the tugboats to achieve $\boldsymbol{V}_s \to \boldsymbol{V}_{sd}$ are obtained by

$$\boldsymbol{\tau}_t = \widetilde{M}K(\boldsymbol{V}_{sd} - \boldsymbol{V}_s) + \tilde{C}(\boldsymbol{V})\boldsymbol{V}_s + \widetilde{D}(\boldsymbol{V})\boldsymbol{V}_s \tag{37}$$

$$\widetilde{M} = (N^T T)^{-1}\overline{M} \in \Re^{3n\times 3} \tag{38}$$

$$\tilde{C}(\boldsymbol{V}) = (N^T T)^{-1}\bar{C}(\boldsymbol{V}) \in \Re^{3n\times 3} \tag{39}$$

$$\widetilde{D}(\boldsymbol{V}) = (N^T T)^{-1}\overline{D}(\boldsymbol{V}) \in \Re^{3n\times 3} \tag{40}$$

$$K = \mathrm{diag}(k_u, k_v, k_\omega) \in \Re^{3\times 3} \tag{41}$$

where K is a control gain matrix. Substituting **Equation (37)** into **Equation (30)** yields $\dot{\boldsymbol{V}}_s = K(\boldsymbol{V}_{sd} - \boldsymbol{V}_s)$, and $\boldsymbol{V}_s \approx \boldsymbol{V}_{sd}$ if the elements of K are sufficiently large.

Here, we should note that $\boldsymbol{\tau}_t$ in **Equation (37)** can be calculated if $N^T T$ is invertible; however, when using a single tugboat, i.e., n = 1, it cannot be invertible when the contact point is aligned with the two centers of mass of the ship and tugboat as shown in **Figure 5 (a)** (singular configuration); this situation usually occurs when a single tugboat pushes the ship to move. To address this problem, a kinematic control approach is written as follows:

$$\boldsymbol{\tau}_{t1} = K(\boldsymbol{V}_{sd} - \boldsymbol{V}_s) \in \Re^3 \tag{42}$$

$$\boldsymbol{V}_{sd} = \begin{pmatrix} U_d cos\alpha \\ -U_d sin\alpha \\ -k_y\eta_y - k_\psi\eta_\psi - k_\phi\phi \end{pmatrix} \in \Re^3 \tag{43}$$

where a control variable ϕ was added to the desired value of the yaw rate in **Equation (36)**, $\phi = (\psi_s - \alpha) - \psi_{t1}$ is the angle from the line passing through the center of mass of the tugboat and the contact point to the moving direction as shown in **Figure 5 (b)**, and α depends on the contact point here.

For more than two tugboats, singular configurations can also occur, e.g., when the lines passing through the contact points and the centers of mass of the tugboats intersect at a point; however, such singular configurations are difficult to occur in actual operations and thus this paper does not consider this issue.

4. Simulation

To verify the effectiveness of the path-tracking control method based on the reduced dynamics, simulations were conducted. It was assumed that the ship did not use its propulsive forces for movement (we can consider another floating object, e.g., barge, instead of a ship) and the tugboat can exert forces and moment for 3-DOF motion on a horizontal plane. The contact points were chosen arbitrarily to prove the correct functioning of the reduced dynamics.

Table 1: Parameter values of the ship and tugboats used for simulations. It is assumed that all tugboats are identical.

Parameter	Unit	Value		Parameter	Unit	Value	
		Ship	Tugboat			Ship	Tugboat
L× W	m	2×1	1×0.5	X_u	kg/s	-2	-1.2
m	kg	40	20	Y_v	kg/s	-20	-12
I_z	kgm^2	15.83	1.98	Y_ω	kg/s	-8.7	-5.2
$X_{\dot{u}}$	kg	-12.03	-6.02	N_v	kgm^2/s	-32	-19.2
$Y_{\dot{v}}$	kg	-24.98	-12.49	N_ω	kgm^2/s	-20	-12
$Y_{\dot{\omega}}$	kg	-0.14	-0.02	$X_{\|u\|u}$	kg/m	-3	-1.5
$N_{\dot{v}}$	kgm^2	-0.35	-0.04	$Y_{\|v\|v}$	kg/m	-30	-15
$N_{\dot{\omega}}$	kgm^2	-1.23	-0.15	$N_{\|\omega\|\omega}$	kgm^2	-30	-15

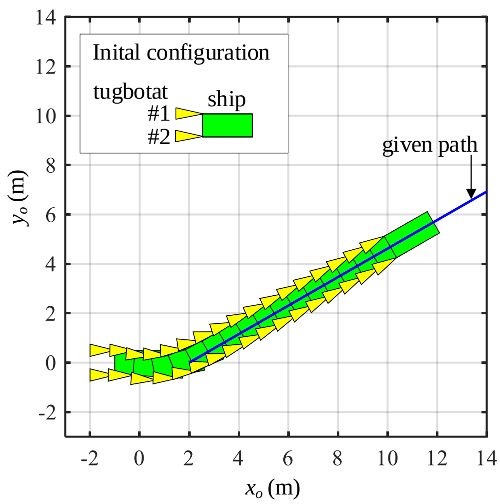

Figure 6: Tracking a given path using two tugboats while maintaining $\alpha = 0^{\text{o}}$

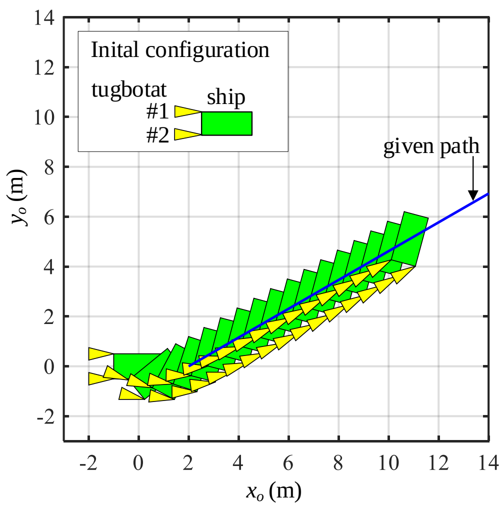

Figure 7: Tracking a given path using two tugboats while maintaining $\alpha = 45^{\text{o}}$

The parameter values of the ship and tugboats used for simulations are shown in **Table 1,** and they were determined for future lab-scale experiments. L, W, m and I_z are the length, width, mass, and moment of inertia, respectively. $X_{\dot{u}}$, $Y_{\dot{v}}$, $Y_{\dot{\omega}}$, $N_{\dot{v}}$, and $N_{\dot{\omega}}$ are the added mass and inertia derivatives, X_u, Y_v, Y_ω, N_v, and N_ω are the coefficients of the linear skin friction, and $X_{|u|u}$, $Y_{|v|v}$, and $N_{|\omega|\omega}$ are the coefficients of the quadratic drag (refer to **[18]**). I_z, $X_{\dot{u}}$, $Y_{\dot{v}}$, and $N_{\dot{\omega}}$ were obtained through calculations, and others were chosen by referring to the ship parameters in **[18]** and through simulations. Three cases were examined: the use of two tugboats, three tugboats, and a single tugboat.

First, we tested the case when two tugboats were used, i.e., n = 2. The two tugboats were initially in contact with the ship as shown in **Figure 6**. $\boldsymbol{r}_1 = (-1, 0.5)^T$, $\boldsymbol{r}_2 = (-1, -0.5)^T$, $\boldsymbol{r}_{t1} = \boldsymbol{r}_{t2} = (0.5, 0)^T$, and the origin and angle of the path frame were set as $(2, 0)^T$ and $\psi_p = 30^{\text{o}}$, respectively. The desired moving speed was $U_d = 1$ knot, α in **Figure 4** and **Equation (35)** is set as 0^{o}, and the control gains are $k_y = 1$, $k_\psi = 1.2$, $k_u = k_v = k_\omega = 1000$, i.e., $K = \text{diag}(1000, 1000, 1000)$. As observed in the figure, the ship tracks the given path well while maintaining the heading angle specified ($\alpha = 0^{\text{o}}$). **Figure 7** presents the case when a given path is tracked while maintaining $\alpha = 45^{\text{o}}$. The result proved the good performance in this case.

Figures 8 and **9** are the cases of using three tugboats, i.e., n = 3. First, the initial conditions for the case of **Figure 8** are $\boldsymbol{r}_1 = (1, 0.5)^T$, $\boldsymbol{r}_2 = (0, 0.5)^T$, $\boldsymbol{r}_3 = (-1, 0.5)^T$, $\boldsymbol{r}_{t1} = \boldsymbol{r}_{t2} = \boldsymbol{r}_{t3} = (0.5, 0)^T$, $\psi_s = 90^{\text{o}}$, and $\alpha = 135^{\text{o}}$. The origin and angle of the path frame, the desired moving speed, and the control gains are the same as those used in the previous simulations. For **Figure 9,** $\boldsymbol{r}_1 = (1, 0.5)^T$, $\boldsymbol{r}_2 = (0, 0.5)^T$, $\boldsymbol{r}_3 = (-1, 0)^T$, $\boldsymbol{r}_{t1} = \boldsymbol{r}_{t2} = \boldsymbol{r}_{t3} = (0.5, 0)^T$, $\psi_s = 90^{\text{o}}$, and $\alpha = 45^{\text{o}}$. The two simulation results verified that the controller worked correctly. **Figure 10** shows the changes of α in the simulations shown in **Figures 7**, **8**, and **9**.

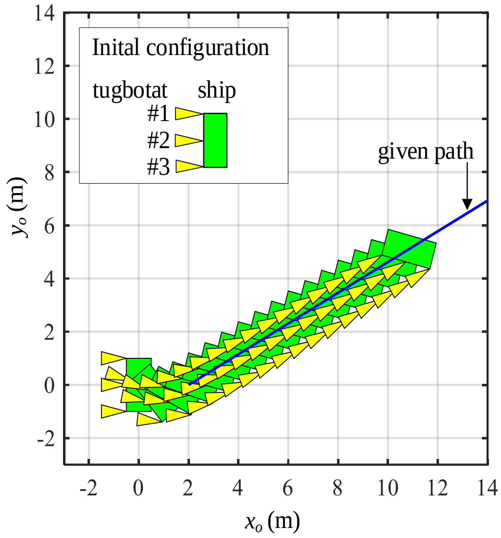

Figure 8: Tracking a given path using three tugboats while maintaining $\alpha = 135^{\circ}$

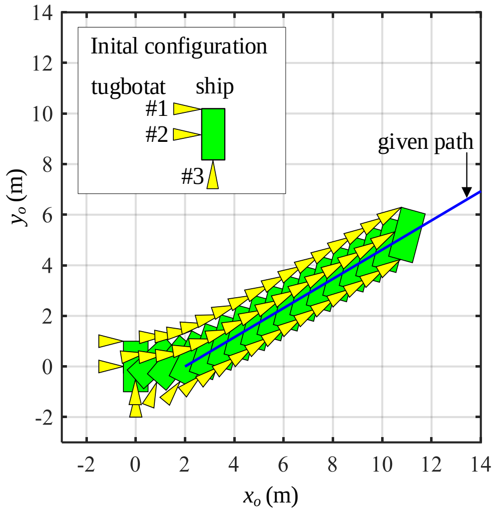

Figure 9: Tracking a given path using three tugboats while maintaining $\alpha = 45^{\circ}$

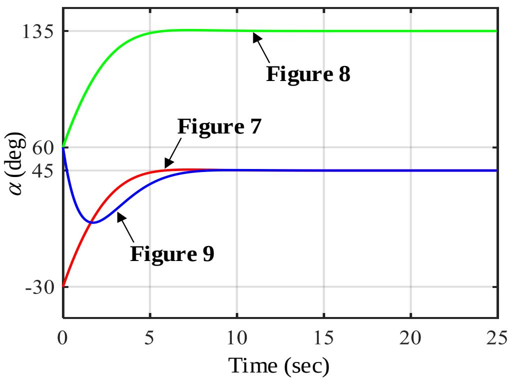

Figure 10: Changes of α in **Figures 7**, **8**, and **9**

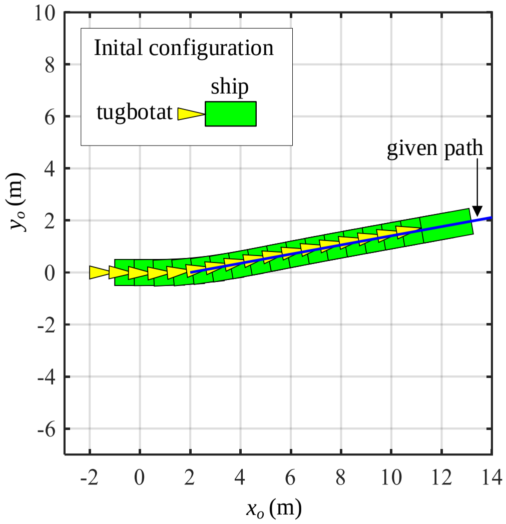

Figure 11: Tracking a given path using a single tugboat

In addition, simulation was conducted using a single tugboat, as shown in **Figure 11**. $\boldsymbol{r}_1 = (-1, 0)^T$, $\boldsymbol{r}_{t1} = (0.5, 0)^T$, $\psi_p = 10^{\circ}$, and $\alpha = 0^{\circ}$, and the control gains are $k_y = 1$, $k_\psi = 1.92$, $k_\phi = 2.55$, and $K = \mathrm{diag}(100, 100, 100)$. The figure shows that the ship tracks the given path well.

From these simulation results, it was confirmed that the reduced dynamics functioned correctly; however, this study did not consider the friction angle of the contact force that assures the pushing motion of the tugboat for manipulation of the ship. For future works, we aim to incorporate/combine the contact force constraints into/with the reduced dynamics.

5. Conclusion

In this study, the manipulation of a large ship was conducted using multiple tugboats. We formulated a reduced dynamic equation that incorporates the dynamics of the ship and n number of tugboats and excludes the contact force terms; this allowed us to treat the ship and n number of tugboats as a single system to manipulate the ship. A pose control method based on the reduced dynamics was presented, and its effectiveness was verified through simulations. Our future works will involve incorporating the contact force constraints, as mentioned in the last part of Section 4, and conducting lab-scale experiments.

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Author Contributions

Conceptualization, J.-K. Choi; Methodology, J.-K. Choi; Validation, J.-K. Choi; Formal Analysis, J.-K. Choi; Investigation, J.-K. Choi; Resources, J.-K. Choi; Data curation, J.-K. Choi; Writing-Original Draft Preparation, J.-K. Choi; Writing-Review & Editing, J.-K. Choi; Visualization, J.-K. Choi; Supervision, J.-K. Choi; Project Administration, J.-K. Choi; Funding Acquisition, J.-K. Choi.

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