RESEARCH ARTICLE

An optimization model of tugboat operation for conveying a large surface vessel

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Abstract

In general, tugboats are used to convey many kinds of surface vessels, including unactuated vessels, such as barge ships and offshore structures. This requires an adequate model for tugboat operation to precisely take into account surge, sway, and yaw motions. We present an optimization method of tugboat operation for conveying a large surface vessel in the shipyard. An optimization problem that includes the interactions between the vessel and the tugboats is mathematically formulated. The procedure to solve this problem is composed of three steps. The desired control input, which should act on the vessel to track the desired path in the presence of environmental disturbances, is calculated every control interval. Second, the optimization problem is solved by using an optimization algorithm to find the thrust force and tug force direction for each tugboat. Finally, based on the three-degrees of freedom (DOF) horizontal model, the position and velocity of the vessel in the next step are calculated. There are three advantages to this study. First, the proposed method considers the thrust force and the direction of the tugboats at the same time, and the number of tugboats can also be changed. Second, it is possible to control the tugboats through realistic time intervals. Finally, the practical external force is considered in the application. The proposed method is applied to the conveying of a mega floating crane, one of the large surface vessels, in various environmental conditions, such as waves, winds, and currents, and the applicability of the method was evaluated.

Keywords: tugboat operation; sliding mode control; optimization method; offshore floating crane

1. Introduction

The maneuvering of large surface vessels in crowded harbors requires delicate motion control at slow velocity to avoid a collision. However, the maneuvering of a vessel along the desired path in this environment is very difficult due to the following two reasons. First, the controllability reduction of the actuator of the vessel occurs at a slow velocity. Second, when the vessel moves, the exciting force, which is acting on the vessel as disturbance, is also changed because the heading angle is changed. When the vessel cannot be maneuvered by its own actuator
in this environment, the vessel must be conveyed by providing thrust from the outside. Therefore, the conveying of a vessel by tugboats can be proposed as a feasible solution. Figure 1 shows examples of a large surface vessel and tugboats that perform conveying operations.

Tugboats are generally used to convey surface vessels that do not have self-propulsion. Also, even if they have self-propulsion, tugboats assist them in ports where movement is limited due to their size. For this type of conveying operation, the use of tugboats is made according to the relevant regulations set by each port rather than a specific size limitation (Thorndike, 2004). Multiple tugboats are used to convey a large surface vessel in a harbor area, and the overall control performance depends on how the tugboats cooperate. However, in actual practice, conveying with assistance from tugboats is conducted manually, and the overall control performance of the vessel depends on the experience of the operators of the tugboats. All tugboats should be strategically operated to improve the overall control performance through cooperation. The thrust forces of the tugboats should be coordinated, such that their total input conveys the vessel along the desired path. Therefore, a theoretical tugboat operation method that considers the number of tugboats used for the conveying, the position of the tugboats, the thrust force of each tugboat, and the tug force direction during the conveying is required.

2. Related Works

In the last decade, different types of control strategies using tugboats have been proposed. Braganza et al. (2007) presented control strategies for the positioning of an unactuated vessel by multiple, autonomous tugboats. An adaptive control strategy was designed, and thrust forces of tugboats arranged in opposite pairs were obtained from this strategy. The tug force directions remained fixed throughout the maneuver, and the number of tugboats used was also fixed at six. Esposito et al. (2008) presented a strategy that allowed a swarm of autonomous tugboats to move a large object on the water. A tracking controller and force allocation strategy were suggested and verified using a 1:36 scale model of a U.S. Navy ship. The thrust allocation was performed by solving the linearly constrained least-squares problem to obtain the thrust forces and tug force directions of the tugboats. Bidikli et al. (2016) proposed a robust controller for an unactuated surface vessel manipulated by autonomous tugboats. The stability of the novel control methodology was investigated via Lyapunov stability analysis. They used tug force direction as a fixed average value that changes over time as a sinusoidal function.

Studies using optimization techniques were conducted to allocate the thrust force of tugboats. Bui et al. (2011) and Bui and Kim (2013) proposed an approach for ship berthing with the assistance of autonomous tugboats. An adaptive controller and sliding mode controller were presented to cope with the uncertainty of the system. The thrust force and tug force direction were determined by using a redistributed pseudo-inverse (RPI) algorithm in these studies, and the number of tugboats used was also fixed at four. Similarly, Gao et al. (2019) used the optimization technique for controlling the thrusters of a ship. They controlled the ship with three azimuth thrusters and one tunnel thrust using an optimization method to follow a specific trajectory. Also, Kamil et al. (2019) analysed ship berthing, which is similar to this study.

Table 1 shows a comparison of the characteristics of this study and other studies. From investigating the related studies, the theoretical background of the tugboat operation was studied. However, no study has yet been performed on the tugboat operation for conveying using the optimization method that simultaneously considers thrust force and tug force direction. Therefore, a method for the tugboat operation is proposed for conveying a surface vessel.

3. Method of Tugboat Operation

A method for tugboat operation based on the optimization technique and control design is proposed. Figure 2 shows a flowchart of the proposed method.

The procedure for obtaining the optimal operation of the tugboats is as follows. First, input data are used to initialize the information of the vessel and the tugboats (Fig. 2-①). These data include the initial position and velocity of the surface vessel, the principal dimensions and location of each tugboat, and the allowable thrust and tug force direction. The control input is changed only if Δt is greater than the control interval ΔtInterval, otherwise update the motion containing the vessel’s position and velocity with the same control input as the previous time step (Fig. 2-②). Δt refers to the updated time duration without changing the control input. The control interval can be freely set to a multiple of the time step. The update of the control input is performed through a process that includes the calculation of the desired control input and optimization. The tracking error in the position and velocity at the current time step are calculated (Fig. 2-③), and the desired control input is calculated using the
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Table 1: Summary of related works and comparison with this study.

| Studies               | Control methodology | Optimization method | Optimization of thrust forces | Optimization of tug force directions | Optimization algorithm | Tugboat number          |
|-----------------------|----------------------|---------------------|-------------------------------|--------------------------------------|------------------------|-------------------------|
| Braganza et al. (2007)| Adaptive control     | Not applied          | Not applied (Fixed)           | Not applied                          | Fixed (6)             |
| Esposito et al. (2008)| Adaptive control     | Not applied          | Not applied (Fixed)           | Not applied                          | Fixed (6)             |
| Bui et al. (2011)     | Adaptive control     | Applied              | RPI algorithm                 | Fixed (4)                            |
| Bui and Kim (2011)    | Robust control       | Applied              | Applied                       | RPI algorithm                        | Fixed (4)             |
| Bidikli et al. (2016) | Robust control       | Not applied          | Not applied                   | Fixed (6)                            |
| Gao et al. (2019)     | Optimization technique| Applied              | Applied                       | Genetic algorithm                     | Arbitrary number      |
| This study            | Robust control       | Applied              | Applied                       | Genetic algorithm                     | Arbitrary number      |

Figure 2: Overall procedure of the method of tugboat operation.

sliding mode control based on these values (Fig. 2-5). Next, the optimization method for solving the problem for tugboat operation is performed (Fig. 2-6). The problem has objective functions and constraints to find an optimal solution for the tugboat operation. The desired control input is used to calculate the objective function of the problem. As a result of the optimization, the thrust force and tug force direction of the tugboats are updated (Fig. 2-7). Finally, the motion of the vessel is computed for the changed control input (Fig. 2-7), the time step is updated, and the same process is repeated. The ‘tracking error’ calculated in...
The mass/inertia matrix that includes hydrodynamic added mass, $M$

The mass of the vessel $m$

$I_{xy}$

$D$
The linear damping matrix that includes the linearized damping forces and moment of the vessel,

$\epsilon_0$
The set of thrust forces $f$

$f_{thrust}$ The thrust force produced by the $i$-th tugboat

$f_{max}$ The upper limit value of the thrust force

$f_{min}$ The lower limit value of the thrust force

$f_{tuple}$ The tug force at the previous time $f$

The allowable magnitude of the time derivative of the thrust force $|f|$ at time $t$

$l_i$ The $i$-th axis location of the position and orientation of the desired trajectory in the Earth-fixed coordinate frame $R$

$x_{d}$ The surge, sway, and yaw rates of the vessel in a body-fixed coordinate frame $\dot{x}$

$V(t)$ The wind/current speed at time $t$

$\Delta t$ The operation hour of tugboats

$\eta$ The inertial position and the heading angle in the Earth-fixed coordinate frame $R$

$\eta_d$ The position and orientation of the desired trajectory in the Earth-fixed coordinate frame $R$

$\Lambda$ The diagonal positive design matrix, $\epsilon_0^{3 \times 3}$

$\rho$ The air density

$\rho_{water}$ The water density $\epsilon$

$\tau_c$ The control input vector

$\tau_s$ The surge force of the control input $\tau$

$\tau_y$ The sway force of the control input $\tau$

$\tau_r$ The yaw moment of the control input $\tau$

$\psi$ The heading angle $\psi$

$s(z)$ The sliding surface $s$

$s_g(\psi)$ The skew-symmetric matrix, $\epsilon_0^{3 \times 3}$

$u = [u, v, \tau]^T$ The surge, sway, and yaw rates of the vessel in a body-fixed coordinate frame, $\epsilon_0^3$

$V(t)$ The wind/current speed at time $t$

$\Delta t$ The operation hour of tugboats

$\eta = [x, y, \psi]^T \in \epsilon_0^3$

$\eta_d = [x_d, y_d, \psi_d]^T$

$\Lambda$ The diagonal positive design matrix, $\epsilon_0^{3 \times 3}$

$\rho_{air}$ The air density

$\rho_{water}$ The water density $\epsilon$

$\tau_c$ The control input vector

$\tau_s$ The surge force of the control input $\tau$

$\tau_y$ The sway force of the control input $\tau$

$\tau_r$ The yaw moment of the control input $\tau$

$\psi$ The heading angle $\psi$

$\text{sgn}(s)$ The signum function with $s$, and $G \in \epsilon_0^{3 \times 3}$ and $K \in \epsilon_0^{3 \times 3}$ are diagonal positive design matrices

this study refers to the difference between the trajectory (position and velocity of the vessel) determined in advance for the operation of a specific time step and the vessel’s position and velocity calculated by the equations of motion. The proposed method mainly consists of three parts: the dynamic motion analysis of the surface vessel, the calculation of control input, and the optimization method. Dynamic motion analysis is performed to calculate the motion of the surface vessel by the control input. Section 3.1 constructs the three-DOF horizontal model consisting of the vessel and tugboats, and proposes a linear dynamic equation describing low-speed maneuvering of a mega surface vessel. In addition, considering the geometrical relationship between the vessel and tugboats, it formulates a method of calculating the resultant of the thrust force and the thrust force direction of each tugboat. Section 3.2 develops a control system that is capable of calculating the desired control input that allows the surface vessel to track the desired path. Sliding mode control is used to perform good tracking in modeling uncertainty. Finally, Section 3.3 proposes the optimization method for the tugboat operation. The main component of the proposed method is the optimization method. A problem for the tugboat operation is mathematically formulated as an optimization problem. The optimal values of the design variables (independent variables) of the problem are found in the optimization method. A summary of the variables used for the equations covered in Section 3 is shown in Table 2.

### 3.1. Motion analysis for conveying a large surface vessel

Tugboats can manipulate the motion of a large surface vessel by providing horizontal force, so the dynamics system should be modeled to describe the conveying by tugboats. Figure 3 shows that conveying a surface vessel can be simplified to a system that includes a model of the surface vessel and the tugboats.
The three-DOF horizontal model for a large surface vessel considering surge, sway, and yaw motion is used to represent the motion of a surface vessel. This implies that the dynamics associated with the motion in heave, roll, and pitch are neglected. This assumption is appropriate for a large surface vessel because the roll and pitch angles of the vessel in slow maneuvering are usually very small (Fossen, 2002). Therefore, the linear dynamic equation describing low-speed maneuvering of a large surface vessel manipulated by external tugboats in the horizontal plane can be written as equation (1) (Fossen, 2002; Bui et al., 2011; Ham et al., 2018). The transformation relating the linear velocity vector in an initial reference frame to a velocity in the body-fixed reference frame can be expressed as equation (2).

\[
M \dot{v} + Dv = r_c + b \tag{1}
\]

\[
\dot{\eta} = R(\phi)v \tag{2}
\]

When analysing the six-DOF motion of the vessel, the damping force of the vessel does not have a linear relationship with the velocity of the vessel, but may have a proportional relationship with the square of the velocity or more complicated relationship (Wassermann et al., 2016). However, a floating crane that has a larger and simpler shape compared to a ship was designated as a control target here. In general, the floating crane works in a calm sea condition, so its movement is relatively small. Therefore, the motion of the floating crane was analysed as three-DOF equations. Generally, in the three-DOF equations of motion in moderate sea conditions, the damping force term is proportional to the velocity of the vessel (Bui et al., 2011). Therefore, the equations of motion of the floating crane were solved under the assumption that the damping force has a linear relation with the velocity. \( \eta \) represents the inertial position \((x, y)\) and the heading angle \( \phi \) in the Earth-fixed coordinate frame, while \( v \) describes the surge, sway, and yaw rates of the vessel in a body-fixed coordinate frame. The heading angle \( \phi \) is measured counterclockwise about the \( x \)-axis of the Earth-fixed coordinate frame, as shown in Fig. 4. The rotation matrix \( R(\phi) \), which translates the body-fixed coordinate frame into the
Figure 5: Configuration of the thrust force and tug force direction of each tugboat.

Earth-fixed coordinate frame, is defined as follows:

\[
R(\phi) = \begin{bmatrix}
\cos \phi & -\sin \phi & 0 \\
\sin \phi & \cos \phi & 0 \\
0 & 0 & 1
\end{bmatrix}.
\]

(3)

The matrix \( M \) can be determined as follows:

\[
M = \begin{bmatrix}
m + a_{11} & 0 & 0 \\
0 & m + a_{22} & a_{26} \\
0 & a_{62} & I_z + a_{66}
\end{bmatrix}.
\]

(4)

For a low-speed vessel with \( xz \)-symmetry, linear damping in surge is decoupled from sway and yaw, so the damping matrix \( D \) can be determined as follows:

\[
D = \begin{bmatrix}
d_{11} & 0 & 0 \\
0 & d_{22} & d_{26} \\
0 & d_{62} & d_{66}
\end{bmatrix}.
\]

(5)

The control input \( r_c \) is the result of the thrust forces acting on the vessel by all tugboats. The thrust forces produced by each individual tugboat are combined, as shown in Fig. 5.

In Fig. 5, \( i \) is an index for the tugboat. Each individual tugboat acts on the vessel with a unidirectional thrust force. The direction angles are measured counterclockwise about the \( x \)-axis of the body-fixed coordinate frame. The position \((l_{x_i}, l_{y_i})\) represents the location of the contact point of the \( i \)-th tugboat in the body-fixed coordinate frame. When the number of tugboats conveying the surface vessel is \( N \), the control input vector \( r_c \) is defined as equation (6).

\[
r_c = B(\alpha)f
\]

(6)

The i-th column of matrix \( B(\alpha) \) is defined as follows:

\[
B_i(\alpha) = \begin{bmatrix}
\cos(\alpha_i) \\
\sin(\alpha_i) \\
l_{x_i} \sin(\alpha_i) - l_{y_i} \cos(\alpha_i)
\end{bmatrix}.
\]

(7)

It is assumed that the tugboat’s thrust force and direction act directly at the local position of the tugboat, not connected using the joint. The thrust force applied by the tugboat actually causes delay or loss due to joints. However, this study assumes that these effects are reflected in the calculated thrust force and direction.

The causes of environmental disturbances that induce the vector \( b \) acting on the vessel are wind, current, wave, and so on. The hydrodynamic force induced by waves is considered as the cause of environmental disturbances. Ham et al. (2017) described the hydrodynamic force due to time-varying vessel motions using the formulation given by Cummins (1962) and Journee and Massie (2001). Cummins’ equation is an equation of six-DOF; hence, the hydrodynamic force was calculated by assuming the remaining terms excluding three-DOF (surge, sway, and yaw) as 0. And, it was used by substituting it into \( b \) in equation (1). For an accurate analysis, the waves reflected by the quay and the waves disturbed by tugboats should be considered. However, since the operation is generally carried out under moderate conditions, this effect can be negligible. Therefore, only the effect of the external forces directly acting on the surface vessel is considered here. By applying winds and currents, simple equations are used according to Ham et al. (2017) as follows:

\[
F_{\text{current}_x} = C_{\text{current}_x} \frac{1}{2} \rho_{\text{water}} V(t)^2 \text{current}_x A_x,
\]

(8)

\[
F_{\text{current}_y} = C_{\text{current}_y} \frac{1}{2} \rho_{\text{water}} V(t)^2 \text{current}_y A_y.
\]

(9)
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\[ F_{\text{wind}, x} = C_{\text{wind}, x} \frac{1}{2} \rho_{\text{air}} V(t)^2 \omega_{x}, \]  
\[ F_{\text{wind}, y} = C_{\text{wind}, y} \frac{1}{2} \rho_{\text{air}} V(t)^2 \omega_{y}. \]

The wind's fluctuation is calculated from the NPD (Norwegian Petroleum Directorate) wind spectrum by ISO 19901-1 (2005).

3.2. Sliding mode control design for conveying a large surface vessel

The control system should be designed to calculate the desired control input that allows the vessel to track the desired path. We developed a control system that can successfully perform trajectory tracking (Selma et al., 2020; Lee et al., 2021), even in the presence of model uncertainty. Model uncertainty may come from the uncertainty of the parameter of the control or from the system's dynamics (Slotine & Li, 1991; Misaghi & Yaghoobi, 2019).

The simplification of the three-DOF horizontal model in Section 3.1 and the environmental disturbance acting on the floating crane cause model uncertainty.

Two major approaches to dealing with model uncertainty are robust control and adaptive control. The adaptive control method is used to handle uncertainties in constant or slowly varying parameters. However, the adaptive control method does not provide sufficient performance when there are uncertainties associated with environmental disturbance, rapidly varying parameters, and unmodeled dynamics. The sliding mode control method can successfully perform trajectory tracking in the face of the abovementioned model uncertainties. Compared with the adaptive control method, the sliding mode control method has significant advantages of insensitivity to parameter variations, remarkable stability, and performance robustness in environmental disturbances (Slotine & Li, 1991; Bidikli et al., 2016). Therefore, a control system for conveying a floating crane was developed by using sliding mode control.

To simplify the design of the control system, the linear dynamic equation is rewritten as an equation for the Earth-fixed coordinate frame using the rotation matrix presented in equation (2). Since the rotation matrix is an orthogonal matrix, equation (2) can be rewritten as equation (12), and the time derivative of vector \( v \) can be derived as equation (13), as follows:

\[ v = R(\psi)^T \dot{\eta} \]  
\[ \dot{v} = R(\psi)\dot{\eta} - S(\psi)R(\psi)^T \eta. \]

where the skew-symmetric matrix \( S(\psi) \) is given by

\[ S(\psi) = \begin{bmatrix} 0 & -\psi & 0 \\ \psi & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \]

By substituting equations (12) and (13) into equation (1), the dynamic equation is transformed as follows:

\[ M^* \ddot{\eta} + D^* \dot{\eta} = r^*, \]

where the transformed system matrices \( M^* \in R^3 \times 3 \), \( D^* \in R^3 \times 3 \), and \( r^* \in R^3 \times 3 \), and \( \eta^* \in R^3 \times 1 \) are calculated, respectively, as follows:

\[ M^* = R(\psi)MR(\psi)^T, \]
\[ D^* = R(\psi)(DR(\psi) - MS(\psi)R(\psi)^T). \]

The position and orientation of the desired trajectory in the Earth-fixed coordinate frame are defined as the vector \( \eta_d = [x_d, y_d, \psi_d]^T \). It can be assumed that the vectors \( \eta_d, \dot{\eta}_d, \text{ and } \ddot{\eta}_d \) that describe the selected trajectory satisfy both the smooth and bounded conditions. In a second-order system, position and velocity cannot jump, so that the desired trajectory at the initial time should be the same position and velocity as those of the vessel. Therefore, the initial conditions for the desired trajectory are defined as follows:

\[ \eta_d(0) = \eta(0), \]
\[ \dot{\eta}_d(0) = \dot{\eta}(0), \]
\[ \ddot{\eta}_d(0) = \ddot{\eta}(0). \]

The tracking error vector in variable \( \eta \) is defined as equation (18). It is the objective of control design to calculate the control input vector \( r_c \), achieving the problem of tracking \( \ddot{\eta} = 0 \).

\[ \ddot{\eta} = \eta - \eta_d \]

The sliding surface, which is a time-varying surface, is defined by the vector equation, as shown in equation (19). Given the initial condition of equation (17), the problem of tracking is equivalent to that of remaining on the sliding surface \( s(t) \) for all \( t > 0 \); indeed, \( s = 0 \) represents a linear differential equation whose unique solution is \( \eta = \dot{\eta} = 0 \), given the initial condition of equation (17). Thus, the problem of tracking the vector \( \eta_d \) can be reduced to that of maintaining the vector \( s \) at zero.

\[ s = \dot{\eta} + \Lambda \ddot{\eta} \]

The differential equation for a sliding surface \( s \) can be derived by substituting equations (18) and (19) into equation (15), as follows:

\[ M^* \dot{s} = -D^* s + [r^* - M^*(\ddot{\eta}_d - \Lambda \dot{\eta}_d) - D^*(\dot{\eta}_d - \dot{\eta}_d)]. \]

The stability of the control system and the tracking result can be illustrated through Lyapunov analysis, by defining the following non-negative scalar function \( V(t) \), as follows:

\[ V(t) = \frac{1}{2} s^T s. \]

Based on Lyapunov stability, the control system is asymptotically stable, if the time derivative of function \( V(t) \) is less than or equal to zero (Anderson & Moore, 1971). Therefore, in order to satisfy these conditions, the time derivative of the sliding surface is defined as follows:

\[ \dot{s} = -G s - K sgn(s). \]

Then, the time derivative of function \( V(t) \) along the trajectory of the system can be derived as follows:

\[ \dot{V} = -s^T G s - s^T K sgn(s) \leq 0. \]

Equation (23) gives the non-positive time derivative of the Lyapunov function candidate. The control system is asymptotically stable, according to the mentioned Lyapunov stability. Therefore, the tracking error and its time derivative will converge to zero in a finite amount of time. The desired control input is designed as follows:

\[ r^* = D^* s + M^*(\ddot{\eta}_d - \Lambda \dot{\eta}_d) + D^*(\dot{\eta}_d - \dot{\eta}_d) - M^*(G s + K sgn(s)) \]

\[ r_d = R(\psi)^T r^*. \]
### Table 3: Input data of the optimization problem for tugboat operation.

| Item                              | Information                                                                 |
|----------------------------------|-----------------------------------------------------------------------------|
| Desired path                     | Desired position and yaw angle \((\eta_d)\), desired velocity and yaw rate \((\dot{\eta}_d)\) |
| Principal dimensions of the vessel | Mass \((m)\), size (length, breadth, and height), mass/inertia matrix \((M)\), linear damping matrix \((D)\) |
| Position and velocity of the vessel | Position and yaw angle \((\eta)\), velocity and yaw rate \((\dot{\eta})\) |
| Desired control input            | Desired control input calculated by sliding mode control \((\tau_d)\) |
| Group of tugboats                | Number \((N)\), local positions \((l_{xi}, l_{yi})\) |
| Tugboat operation in the previous step | Thrust force of the \(i\)-th tugboat in the previous step \((f_{tug,i}^{\text{previous}})\), Tug force direction in the previous step \((\alpha_{tug,i}^{\text{previous}})\) |
| Allowable thrust force            | Upper limit of thrust force \((f_{\text{max}})\), lower limit of thrust force \((f_{\text{min}})\), allowable magnitude of time derivative of thrust force \((|\dot{f}_i|)\) |
| Allowable tug force direction     | Upper limit of tug force direction \((\alpha_{\text{max}})\), lower limit of tug force direction \((\alpha_{\text{min}})\), allowable magnitude of time derivative of tug force direction \((|\dot{\alpha}_i|)\) |

### Table 4: Design variables for the optimization of the tugboat operation.

| Design variables | Description |
|------------------|-------------|
| \(f_i\)          | The thrust force produced by the \(i\)-th tugboat \((i = 1, \ldots, N)\) |
| \(\alpha_i\)     | The tug force direction of the \(i\)-th tugboat \((i = 1, \ldots, N)\) |

#### 3.3. Mathematical formulation of the optimization problem for the tugboat operation

This section presents an optimization problem for the tugboat operation. The tugboat operation, which updates the thrust force and tug force direction of each tugboat, is performed every control interval, as shown in Fig. 2. The problem for finding the angle and thrust of tugboats that have to follow the desired control input for tracking the route should be solved for every control interval. As mentioned in Section 3.2, the desired control input can be calculated based on the tracking error in the position and velocity of the vessel.

To formulate the optimization problem, input data on the components of the system model should be given. Table 3 shows the input data for optimization.

The tugboat operation determines the thrust forces generated by each tugboat and the tug force directions with the vessel. The desired control input for conveying the surface vessel along the desired path should be generated by the tugboats. Thus, they are set up as design variables of the optimization problem. Table 4 shows the design variables for the tugboat operation. The number of design variables is twice the number of tugboats \(N\).

An objective function in the optimization problem is used as a criterion to select an optimum among many alternatives. In this problem for the tugboat operation, two objective functions are used, and the control performance and efficiency of the operation process are considered. The first objective function is to minimize the difference between the desired control input and the control input acting on the vessel by the tugboats. The second objective function involves maximizing the efficiency of the tugboat operation. In order to increase the efficiency of the tugboat operation for conveying the vessel, the total amount of fuel used by the tugboats should be minimized. In general, the fuel consumption of a ship such as a tugboat is expressed as the product of her main engine power \((\text{BHP})\), specific fuel oil consumption \((\text{SFOC})\), and operation hour, as shown in equation (26) (Gusti & Semin, 2016).

\[
\text{FOC} = \text{BHP} \cdot \text{SFOC} \cdot \Delta t \quad (26)
\]

The thrust force of a tugboat can generally be regarded as the resistance acting on a ship in a calm sea (Nitonye et al., 2017). Since the product of the ship’s resistance and velocity can be expressed as the effective power required for the ship, it can generally be assumed that the fuel consumption is proportional to the thrust force of a tugboat. Since the tugboats’ thrust is a vector value, in general, the objective function can be taken as the absolute value of the thrust force. However, as a result of using both the absolute value and the square of the thrust force as the objective function, it was confirmed that when the square was used as the objective function, the sensitivity of the objective function to the thrust force increased, and the optimization was performed more smoothly. Therefore, in this study, the square of the thrust force was used as the objective function. Table 5 summarizes the objective functions for the optimization of the tugboat operation.

The optimization problem for tugboat operation is a kind of multi-objective problems (Kaveh & Mahdavi, 2019; Nahvi et al., 2019; Sahu & Andhare, 2019). This type of problem has many optimal called a Pareto optimal set, depending on different weight factors for objective functions. Thus, each objective function was normalized, and a weight factor that is relatively higher than \(F_2\) is used for \(F_1\).

For realistic optimization, eight constraints were selected. In general, there are constraints that bind the upper and lower limits for the thrust force of a tugboat. The limitation of the thrust force depends on the specifications of the tugboat used for vessel conveying. Similarly, there are also constraints that bind the upper and lower limits for the tug force direction with the vessel. The limitation of the tug force direction should be considered so as to prevent the tugboat from slipping. Time-varying constraints are used to avoid sudden changes in the thrust force and the tug force direction, and there is a limitation in dramatically reducing or increasing the thrust force of the tugboat in actual operation. Summarizing the above constraints can be expressed in Table 6.

The problem for tugboat operation has multi-objective functions, and the variables organize non-linear equations to account for the geometrical relationship between the tugboats and
Table 5: Objective functions for the optimization of the tugboat operation.

| Objective functions                                      | Type     | Mathematical representation |
|---------------------------------------------------------|----------|----------------------------|
| The difference between the desired control input and the control input by the tugboats | Minimize | $F_1 = \| \tau_d - B(\alpha) \| f $ |
| Total thrust force of the tugboats                      | Minimize | $F_2 = f^T f $             |

Table 6: Constraints for the optimization of the tugboat operation.

| Constraints                                      | Mathematical representation |
|--------------------------------------------------|-----------------------------|
| The upper limit for the tug force of a tugboat    | $g_1 = f_{\text{min}} - f_i \leq 0$ |
| The lower limit for the tug force of a tugboat     | $g_2 = f_i - f_{\text{max}} \leq 0$ |
| The upper limit for the tug force direction of a tugboat | $g_3 = \alpha_{\text{min}} - \alpha_i \leq 0$ |
| The lower limit for the tug force direction of a tugboat | $g_4 = \alpha_i - \alpha_{\text{max}} \leq 0$ |
| The time-varying constraint for the tug force     | $g_5 = f_{\text{before},i} \cdot f_i - f_i \leq 0$ |
| The time-varying constraint for the tug force direction | $g_6 = f_i - (f_{\text{before},i} + \Delta t \cdot | f_i |) \leq 0$ |
|                                                   | $g_7 = (\alpha_{\text{before},i} - \Delta t \cdot | \alpha_i |) - \alpha_i \leq 0$ |
|                                                   | $g_8 = \alpha_i - (\alpha_{\text{before},i} + \Delta t \cdot | \alpha_i |) \leq 0$ |

Figure 6: The mega floating crane (source: Hyundai Heavy Industries Co., Ltd).

Table 7 summarizes the principal particulars of the floating crane.

| Item                         | Value       |
|------------------------------|-------------|
| Length overall               | 183 m       |
| Length between perpendiculars| 182 m       |
| Breadth                      | 70 m        |
| Depth                        | 11 m        |
| Operation draft              | 6 m         |
| Number of hooks              | 8 EA        |
| Total lifting capacity (one hook capacity) | 10,000 ton (1250 ton) |

4. Application of the Proposed Method

4.1. Description of examples

To check the applicability of the proposed method to the tugboat operation, it is applied to a mega floating crane with a capacity of 10,000 tons (Ham et al., 2017). Figure 6 shows the floating crane selected as an example.

Table 7 summarizes the principal particulars of the floating crane.

Figure 7 shows the tugboat selected as an example. The total power of this tugboat is 1440 HP, and Table 8 summarizes its principal dimensions.

The floating crane is generally moored in a quay wall when there is no operation. While operation, the floating crane is conveyed in the quay area inside the shipyard and put it into the necessary operation. In general, the quay has a very complex polygonal shape. To avoid collision with the quay when conveying the floating crane for other operations, it is conveyed at a
certain distance from the quay. A scenario similar to the actual conveying of the floating crane is constructed, and the proposed method of tugboat operation is applied to this scenario. Figure 8 shows schematics of the floating crane near the quay, the tugboats for conveying them, and the process of the scenarios used in this study. The figure shows that the goal of the scenario is to convey the floating crane to the destination on the quay. The scenario consists of three steps. The first step is to move the marine crane far from the quay to an intermediate position close to the quay. The second step is to rotate the floating crane by 90 degrees, so that the jib of the floating crane is facing the quay. Finally, the third step is to move the floating crane to the precise target location on the wall. The regulation velocity of surge, sway motion, and yaw rate are defined as 0.75 m/s and 1.5 degree/s, respectively.

To compare the tracking error and total thrust force of the tugboats, the four cases are selected as the problems of tugboat operation. Initially, the heading angle of the wave is set at 45 degrees (quartering sea). Therefore, between Step 1 and Step 2, the heading angle is changed from 45 degrees to −45 degrees.

Table 8 summarizes the information for cases.

| Item                  | Value  |
|-----------------------|--------|
| Length overall        | 21.19 m|
| Breadth               | 9.43 m |
| Depth                 | 4.00 m |
| Operation draft       | 3.90 m |
| Installed power       | 2600 HP|

There is no specific guideline for the reaction time to operate a tugboat, as if driving a car, taking into account various situations such as the sea condition, the condition of the floating crane, the state of the tugboat, and the pilot’s indicator. In order to assume a more realistic situation, Case 1 was performed for various control intervals to find the maximum value of the control interval.

Case 1 consists of a total of nine cases, from Case 1–1 with the control interval equal to the simulation time step, to Case 1–9 with the control interval of 500 times the simulation time step. Figures 9, 10, and 11 compare the surge, sway, and yaw motion, respectively, of the crane in Case 1. The blue line (solid line) is Case 1–1, and the red line (dash-single dotted line) is Case 1–8. In some graphs, the results of Cases 1–1 and 1–8 are almost overlapped. Table 10 summarizes the results for Case 1. It can be seen that the tracking error is almost similar until it diverged. However, in Case 1–9, the tracking error diverged, and tracking was not performed properly.

Figures 12, 13, and 14 represent the initial surge, sway, and yaw motion, respectively, of the crane in Case 1–9. It can be seen that the velocity of the sway motion diverged while oscillating. This is because the control interval in Case 1–9 is too long to converge the tracking error to zero. There is an upper limit to the increase of the control interval. Therefore, the control interval of Case 1–8 (2.5 s) was applied to the other cases, because the tracking results, in this case, are almost similar to the results with shorter control intervals.

Figure 7: The tugboat used in the analysis (source: Damen Shipyards Co., Ltd).
4.2.2. Case 2: consideration of the minimum total thrust force of the tugboats

Case 2 shows the comparison of the tracking results of the conveying of the crane according to whether the minimum total thrust force of the tugboats is considered. Case 2 consists of a total of two cases. In Case 2–1, the difference between the desired control input and the control input by the tugboats is minimized as the only objective function. In Case 2–2, two objective
| Case | Control interval       | Objective function | Type of environmental disturbance | Beaufort scale | Number of tugboats |
|------|------------------------|--------------------|-----------------------------------|----------------|-------------------|
| 1    | 1–1 Same as time step  (0.01 s) | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 1–2 ×5 (0.05 s)        | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 1–3 ×10 (0.1 s)        | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 1–4 ×20 (0.2 s)        | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 1–5 ×50 (0.5 s)        | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 1–6 ×100 (1 s)         | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 1–7 ×200 (2 s)         | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 1–8 ×250 (2.5 s)       | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 1–9 ×500 (5 s)         | Applied            | Applied                           | Irregular waves | 5 4              |
| 2    | 2–1 ×250 (2.5 s)       | Applied            | Not applied                       | Irregular waves | 5 4              |
| 3    | 3–1 ×250 (2.5 s)       | Applied            | Applied                           | Regular waves   | 5 4              |
|      | 3–2 ×250 (2.5 s)       | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 3–3 ×250 (2.5 s)       | Applied            | Applied                           | Irregular waves, winds, and currents | 5 4 |
|      | 3–4 ×250 (2.5 s)       | Applied            | Applied                           | Irregular waves | 5 4              |
| 4    | 4–1 ×250 (2.5 s)       | Applied            | Applied                           | Irregular waves | 5 4              |
|      | 4–2 ×250 (2.5 s)       | Applied            | Applied                           | Irregular waves | 5 5              |
|      | 4–3 ×250 (2.5 s)       | Applied            | Applied                           | Irregular waves | 5 6              |

Figure 9: Comparison of the surge motion of the crane in Case 1.

Figure 10: Comparison of the sway motion of the crane in Case 1.
Figure 11: Comparison of the yaw motion of the crane in Case 1.

Table 10: Comparison of the tracking results and average thrust force in Case 1.

| Case | Control interval | Average tracking error (%) | Maximum tracking error (%) | Average thrust force of all tugboats (kN) |
|------|------------------|-----------------------------|---------------------------|------------------------------------------|
| 1    | 1–1 Same as time step (0.01 s) | 0.697                       | 3.453                     | 2427                                     |
|      | 1–2 Per 5 time steps (0.05 s)  | 0.685                       | 3.805                     | 2703                                     |
|      | 1–3 Per 10 time steps (0.1 s)  | 0.654                       | 2.970                     | 2596                                     |
|      | 1–4 Per 20 time steps (0.2 s)  | 0.754                       | 2.714                     | 2386                                     |
|      | 1–5 Per 50 time steps (0.5 s)  | 0.632                       | 3.047                     | 2717                                     |
|      | 1–6 Per 100 time steps (1 s)   | 0.644                       | 3.140                     | 2758                                     |
|      | 1–7 Per 200 time steps (2 s)   | 0.730                       | 3.909                     | 2685                                     |
|      | 1–8 Per 250 time steps (2.5 s) | 0.855                       | 4.516                     | 4516                                     |
|      | 1–9 Per 500 time steps (5 s)   | 6.622                       | 14.774                    |                                          |

Figure 12: Initial surge motion of the crane in Case 1–9.

Figure 13: Initial sway motion of the crane in Case 1–9.
functions are considered, and the total thrust force of tugboats is minimized, along with the objective function in Case 2–1. Figures 15, 16, and 17 compare the surge, sway, and yaw motion, respectively, of the crane in Case 2. Table 11 summarizes the results for Case 2. Table 11 shows that the average thrust force of the tugboats in Case 2–2 was reduced by 18.51%, compared to that in Case 2–1.

Figures 18 and 19 show the thrust force and tug force direction of each tugboat during crane conveying in Cases 2–1 and 2–2. Figure 18 shows that each tugboat in Case 2–2 carried the crane with a smaller thrust force than that in Case 2–1. Figure 19 shows that the tug force direction of each tugboat satisfied the time-varying constraint introduced in Section 3.3.4 and fluctuated slowly. Therefore, it can be seen from the results of Case 2 that using both objective functions is not only economical but also superior in control.

4.2.3. Case 3: different environmental disturbances
Case 3 compares the tracking results of the conveying of the crane in different environmental disturbances. Table 9 shows that Case 3 consists of four cases, with each case considering a different type of environmental disturbance. Figures 20, 21, and 22 compare the surge, sway, and yaw motion, respectively, of the crane in Case 3. The blue line (solid line) is the result of Case 3–3, indicating the motion of the crane in irregular waves. The red line (dash-single dotted line) is the result of Case 3–4, showing the motion of the crane in irregular waves with winds of 19 knots and currents of 1 m/s. As can be seen, overall, the tracking was performed similarly in both cases. Table 12 summarizes the results for Case 3. As can be seen from the results, the influence on the wave condition is not large. However, since it is greatly affected by winds and currents, it is judged that the two influences should be considered larger during the operation.
4.2.4. Case 4: a different number of tugboats

Case 4 shows the comparison of the tracking results of the conveying of the crane for a different number of tugboats. Case 4 consists of a total of three cases; the number of tugboats used for conveying in Cases 4–1, 4–2, and 4–3 is four, five, and six, respectively. Figure 23 shows the arrangement according to the number of tugboats.

Figures 24, 25, and 26 compare the surge, sway, and yaw motion, respectively, of the crane in Case 4. The blue line (solid line) is the result of Case 4–2, indicating the motion of the crane carried by five tugboats. The red line (dash-single dotted line) is the result of Case 4–3, and shows the motion of the crane carried by six tugboats. As can be seen, overall, the tracking was performed similarly in both cases. However, in Case 4–2, the yaw

Table 11: Comparison of the tracking results and average thrust force in Case 2.

| Case | Objective function | Average tracking error (%) | Maximum tracking error (%) | Average thrust force of all tugboats (kN) |
|------|--------------------|---------------------------|---------------------------|------------------------------------------|
| 2    | 2–1 Applied        | 0.818                     | 4.134                     | 3295                                     |
| 2–2  | Applied            | 0.697                     | 3.453                     | 2685                                     |
Figure 19: Comparison of the tug force direction of each tugboat in Case 2.

Figure 20: Comparison of the surge motion of the crane in Case 3.

Figure 21: Comparison of the sway motion of the crane in Case 3.
rate of the crane fluctuated, and an error occurred. The reason is considered to be that the direction of the thrust force of the tugboats is not symmetric. Table 13 summarizes the results for Case 4. The smallest tracking error can be seen in Case 4–3 using six tugboats. The total thrust force in Case 4–3 was smaller than that in Case 4–2, although the number of tugboats used was greater.

Additionally, the tracking results in severe conditions according to the number of tugboats are compared. It is common not to operate the floating crane in bad weather. According to the industry’s statement, it is reasonable to operate the floating crane under the Beaufort scale 5 or less. In bad weather more than that, the operation is stopped for safety reasons. The severe cases presented in this study are cases to check whether the proposed method is applicable in any situation. Through this, we tried to confirm the controllable range of the floating crane. Table 14 shows four severe cases with four and six tugboats, respectively, in the severe condition. Figures 27, 28, and 29 compare the surge, sway, and yaw motion, respectively, of the crane in Severe cases 1 and 2. Figures 30, 31, and 32 compare the
motion of the crane in Severe cases 3 and 4. As can be seen, in Severe cases 3 and 4, a very large tracking error occurred due to bad weather. On the other hand, in Severe cases 1 and 2, the tracking error was not much different from Case 4–3. Table 14 summarizes the results for severe cases. As seen in Case 4, there is no significant difference in tracking error due to the number of tugboats in a calm sea. However, as shown in Severe cases of Table 14, when the external force is large, more thrust force is required to follow the trajectory. Therefore, it is possible to check the effect according to the number of tugboats. In case of Severe

Table 13: Comparison of the tracking results and the thrust forces in Case 4.

| Case | Number of tugboats | Average tracking error (%) | Maximum tracking error (%) | Average thrust force of all tugboats (kN) | Total thrust force of all tugboats (kN) |
|------|---------------------|----------------------------|-----------------------------|------------------------------------------|----------------------------------------|
| 4    | 4–1                 | 0.697                      | 3.453                       | 2685                                     | 10 741                                 |
|      | 4–2                 | 0.820                      | 4.162                       | 2531                                     | 12 654                                 |
|      | 4–3                 | 0.719                      | 4.132                       | 1943                                     | 11 660                                 |
Figure 27: Comparison of the surge motion of the crane in Severe cases 1 and 2.

Figure 28: Comparison of the sway motion of the crane in Severe cases 1 and 2.

Figure 29: Comparison of the yaw motion of the crane in Severe cases 1 and 2.

Figure 30: Comparison of the surge motion of the crane in Severe cases 3 and 4.
Table 14: Comparison of the tracking results and the thrust forces in severe cases.

| Case            | Type of environmental disturbance | Beaufort scale | Number of tugboats | Average tracking error (%) | Maximum tracking error (%) | Average thrust force of all tugboats (kN) | Total thrust force of all tugboats (kN) |
|-----------------|-----------------------------------|----------------|--------------------|---------------------------|---------------------------|------------------------------------------|----------------------------------------|
| Severe case 1   | Irregular waves                   | 10             | 4                  | 0.927                     | 4.749                     | 2801                                     | 11 203                                 |
| Severe case 2   | Irregular waves                   | 10             | 6                  | 0.768                     | 3.997                     | 2364                                     | 14182                                 |
| Severe case 3   | Irregular waves, winds, and currents | 10          | 4                  | 25.294                    | 54.372                    | 4779                                     | 19117                                 |
| Severe case 4   | Irregular waves, winds, and currents | 10          | 6                  | 8.539                     | 16.087                    | 5007                                     | 30 044                                |

Figure 31: Comparison of the sway motion of the crane in Severe cases 3 and 4.

Figure 32: Comparison of the yaw motion of the crane in Severe cases 3 and 4.

cases 3 and 4, when using four tugboats, the vessel gets off the trajectory. On the other hand, using six tugboats, the vessel can follow the trajectory relatively well.

5. Conclusions and Future Works

This study proposed the optimal method of tugboat operation for the conveying of a large surface vessel. To achieve that, a system of a surface vessel and tugboats was simplified to a three-DOF horizontal model. Next, a control method to calculate the desired control input was designed using sliding mode control. The genetic algorithm was used to optimize the thrust force and tug force direction of each tugboat, to bring the desired control input to the minimum total thrust force. Then, to check the feasibility and applicability of the proposed method, it was applied to a mega floating crane with a capacity of 10 000 tons.

In order to confirm the effectiveness of the proposed method, a total of four case studies were conducted. Through Case 1, it was confirmed that the appropriate control interval was 2.5 s. Through Case 2, the effect of two objective functions of the optimization formulation proposed in this study was confirmed, and as a result, the best results were obtained using both objective functions. Through Case 3, the influence on various environmental disturbances was demonstrated, and as a result, it was confirmed that the operation was affected more by winds and currents than by wave conditions. Finally, through Case 4 and Severe cases, the efficiency of the work according to the number of tugboats was confirmed. As a result, it is economical to have a smaller number of tugboats under normal
circumstances. However, it was confirmed that it is safe to operate more tugboats when the environmental condition for the operation is rough.

As future works, the improvement of this study will be made. First, the dynamics system, including the motion of the tugboats, will be made, considering the realistic intersection of the surface vessel and the tugboats. Minimizing the operation time is not recommended for the safe conveying operation of the vessel. However, in the case of ship berthing, which is similar to this study, it is also necessary to minimize the time. If the operation time is tight, it seems that it can be a more practical problem, requiring additional consideration of the operation time. Therefore, second, we plan to take this into account in the future and revise the problem. The proposed method was applied to the floating crane and followed the advice of workers in the field. However, for confidential issues, it is difficult to obtain information about the actual operation. Therefore, third, we plan to conduct additional research on the problem that the proposed method is practically applicable through joint research with shipbuilding companies, including various problems of controlling the path on land of the shipyard (Man et al., 2020).

Acknowledgements
This work is an expansion of our previous study (Lee et al., 2017) and supported by (a) the Research Institute of Marine Systems Engineering of Seoul National University, Republic of Korea and (b) the Institute of Engineering Research of Seoul National University, Republic of Korea.

Conflict of interest statement
None declared.

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