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선박위치제어를 위한 슬라이딩모드 제어기 설계

Design of Sliding Mode Controller for Ship Position Control

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Abstract: This paper addresses the trajectory tracking problem for ship berthing by using sliding mode technique. With significant potential advantages: insensitivity to plant nonlinearities, parameter variations, remarkable stability and robust performance with environmental disturbances, the multivariable sliding modes controller is proposed for solving trajectory tracking of ship in harbor area. In this study, the ship position and heading angle are simultaneously tracked to guarantees that the ship follows a given path (geometric task) with desired velocities (dynamic task). The stability of the proposed control law is proved based on Lyapunov theory. The proposed approach has been simulated on a computer model of a supply vessel with good results.

Keywords: control allocation, trajectory tracking, sliding mode control, ship model

I. INTRODUCTION

The trajectory tracking problem in the field of vessel maneuvering has been concerned from decades ago. Because of the nonlinear hydrodynamic properties of marine vessel, the control design tends to concentrate on the nonlinear control. Nonlinear controllers can overcome some limitations comparing with linear control design. For example, conventional ship control systems are designed under the assumption that the kinematic and dynamic equation of motion can be linearised such that gain-scheduling techniques and optimal control theory can be applied [1,2]. It is not good in the condition that the surge, sway and yaw motion of ship are controlled simultaneously. Additionally, in the linear control design, the gain adjustment is a very complicated task with requires time consuming tests. Moreover, the controller performance varies with the environmental and loading conditions. Nonlinear controller has been applied to vessel maneuvering to overcome problems [3,4]. Fossen and Berge [5] applied the nonlinear backstepping controller for global exponential tracking of marine vessel in the presence of actuator dynamics with very good results. Zhang [6] proposed a sliding mode control for path following of the surface ship in restricted water.

This paper proposes the multivariable nonlinear sliding mode control (SMC) for ship maneuvering in the harbor area. By using the SMC controller, we can cope with the uncertainties such as the environmental disturbances, modeling error and the change of hydrodynamic coefficients. In addition, to overcome the dead slow velocity phenomenon of main propellers in maneuvering condition at harbor area, we propose the automatic tugboat control technique.

The remainder of this paper is structured as follows. In Section II, we express the dynamic system in the presence of environmental disturbance. The thrust configuration matrix is studied through force decomposition analysis. In section III, the multivariable nonlinear SMC is presented. In section IV, the efficiency of the proposed approach is evaluated through model ship control simulation. Conclusion is summarized and discussed in the Section V.

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II. SYSTEM MODEL

1. Ship Model

The low frequency motion of a large class of surface ship can be described by following model [7].

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

The inertia matrix $\boldsymbol{M} \in R^{3\mathrm{x}3}$ which includes hydrodynamic added inertia can be written:

$$\boldsymbol{M} = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & -Y_{\dot{r}} \\ 0 & -N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{2}$$

where m is the vessel mass and I_z is the moment of inertia about

그림 1. 터그보트에 의한 선박접안 모습.
Fig. 1. Ship berthing by using tugboats.

the vessel fixed z-axis. For control application, the motion of ship is restricted to low frequency. The wave frequency can be assumed independence from added inertia. This implies that $\dot{\boldsymbol{M}} = \mathbf{0}$.

For a straight-line stable ship, $\boldsymbol{D} \in R^{3\text{x}3}$ will be a strictly positive damping matrix due to linear wave drift damping and laminar skin. The linear damping matrix is defined as

$$\boldsymbol{D} = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix} \tag{3}$$

and $\boldsymbol{\eta} = [x, y, \varphi]^T \in R^3$ 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 rate of ship motion in body fixed coordinate frame. The rotation matrix in yaw $\boldsymbol{R}(\varphi)$ is used to describe the kinematic equation of motion, that is

$$\boldsymbol{R}(\varphi) = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

The slow varying external forces and moment due to winds, currents and waves are lumped together into a bias term $\boldsymbol{b} \in R^3$. $\boldsymbol{\tau} \in R^3$ is the control of forces and moment provided by the propulsion system, that is main propellers of ship, bow and stern thrusters. In this paper, to prevent ship collisions, the propulsion system is replaced by tugboats. The vector forces and moment $\boldsymbol{\tau}$ is the result of combined efforts of four tugboats as shown in Fig. 2. Vector $\boldsymbol{\tau}$ is defined as follows:

$$\boldsymbol{\tau} = \boldsymbol{B}(\alpha)\boldsymbol{f} \tag{5}$$

where the vector $\boldsymbol{f} = [f_1\, f_2\, f_3\, f_4]^T \in F$ presents thrusts produced

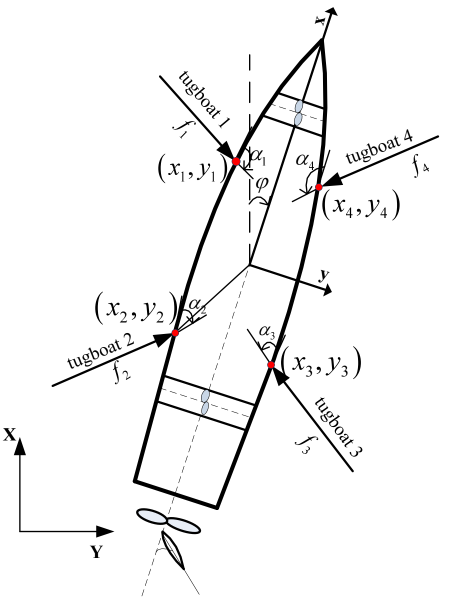

그림 2. 4척의 터그보트에 의한 선박운동제어 개념도.
Fig. 2. Ship motion by manipulation of 4 tugboats.

by tugboats. The set of F is described as $0 \le f_i \le f_{\max}$, $\forall i \in (1,...,4)$.

The geometric configuration matrix $\boldsymbol{B}(\alpha) \in R^{3\text{x}4}$ captures relationship between all four tugboats and ship. The *i-th* column of matrix $\boldsymbol{B}(\alpha)$ is defined as follows:

$$\boldsymbol{B}_i(\alpha) = \begin{bmatrix} \cos(\alpha_i) \\ \sin(\alpha_i) \\ -l_{yi}\cos(\alpha_i) + l_{xi}\sin(\alpha_i) \end{bmatrix} \tag{6}$$

where the angle α_i defines the force direction of the *i-th* tugboat. It is measured clockwise and is relative to 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}). So 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:

$$\boldsymbol{\tau} = \begin{bmatrix} c\alpha_1 & s\alpha_1 & -l_{y1}c\alpha_1 + l_{x1}s\alpha_1 \\ c\alpha_2 & s\alpha_2 & -l_{y2}c\alpha_2 + l_{x2}s\alpha_2 \\ c\alpha_3 & s\alpha_3 & -l_{y3}c\alpha_3 + l_{x3}s\alpha_3 \\ c\alpha_4 & s\alpha_4 & -l_{y4}c\alpha_4 + l_{x4}s\alpha_4 \end{bmatrix}^T \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix} \tag{7}$$

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

In this paper, we assume that the contact positions between ship and tugboats are fixed. The adequate set (α_i, f_i) is solved by redistributed pseudo-inverse algorithm.

2. Environmental Disturbances

The effect of environmental disturbances is the sum of the low frequency motion components and wave frequency motion components. The wave frequency components describe the oscillatoric motion of the ship and should be ignored in the control design. The forces and moment due to slow varying wind, current and waves are lumped together in to Earth-fixed bias term $\boldsymbol{b} \in R^3$. A frequently used bias model for marine control application is the first-order Markov process

$$\dot{\boldsymbol{b}} = -\boldsymbol{T}^{-1}\boldsymbol{b} + \boldsymbol{\psi}\boldsymbol{n} \tag{8}$$

where $\boldsymbol{b} \in R^3$ is the vector of bias forces and moment, $\boldsymbol{n} \in R^3$ is the vector of zero-mean Gaussian white noise. $\boldsymbol{T} \in R^{3\text{x}3}$ is the diagonal positive bias time constants matrix and $\boldsymbol{\psi} \in R^{3\text{x}3}$ is the diagonal matrix scaling the amplitude of white noise disturbance $\boldsymbol{n}$.

This model can be used to describe slow varying environmental forces and moment due to:

- second order wave drift
- ocean current
- wind
- unmodelled dynamics

III. SLIDING MODE CONTROL DESIGN

In this section, the SMC method is developed to design the controller. With significant potential advantages: insensitivity to plant nonlinearities, parameter variations, remarkable stability and performance robustness with environmental disturbances, this method satisfies the trajectory tracking requirements in the harbor area. The design of SMC includes two steps:

- First, choosing a set of switching surfaces that represent some sort of a desired motion

- Second, designing a discontinuous control law that guarantees the attractiveness of the switching surfaces and ensure convergence to the switching surfaces.

Definition 1: The measure of tracking is defined as:

$$\boldsymbol{s} = \dot{\tilde{\boldsymbol{\eta}}} + \boldsymbol{\Lambda}\tilde{\boldsymbol{\eta}} \tag{9}$$

where $\boldsymbol{\Lambda} \in R^{3x3}$ is diagonal positive design matrix, $\tilde{\boldsymbol{\eta}} = \boldsymbol{\eta} - \boldsymbol{\eta}_d$ is the Earth-fixed tracking error. The desired trajectory in the Earth fixed coordinated frame is denoted by vector $\boldsymbol{\eta}_d = [x_d, y_d, \varphi_d]$. Without any lose of generality, the selected trajectory is assumed to be both sufficiently smooth and bounded $\boldsymbol{\eta}_d, \dot{\boldsymbol{\eta}}_d, \ddot{\boldsymbol{\eta}}_d \in L_\infty$. It can be seen that the convergence of $\boldsymbol{s}$ to zero implies that the tracking error $\tilde{\boldsymbol{\eta}}$ converges to zero.

Definition 2: The virtual reference trajectory in body fixed and Earth-fixed coordinates are defined as

$$\dot{\boldsymbol{\eta}}_r = \dot{\boldsymbol{\eta}}_d - \boldsymbol{\Lambda}\tilde{\boldsymbol{\eta}} \tag{10}$$

From Eqs. (9) and (10), $\boldsymbol{s}$ can be rewritten as following

$$\boldsymbol{s} = \dot{\boldsymbol{\eta}} - \dot{\boldsymbol{\eta}}_r \tag{11}$$

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

$$\boldsymbol{M}^*\ddot{\boldsymbol{\eta}} + \boldsymbol{D}^*\dot{\boldsymbol{\eta}} = \boldsymbol{\tau}^* \tag{12}$$

Notice that the bias term can be deal as uncertain disturbances and it is ignored in SMC design. The transformed system matrices $\boldsymbol{M}^* \in R^{3x3}$, $\boldsymbol{D}^* \in R^{3x3}$ and $\boldsymbol{\tau}^* \in R^3$ are calculated as follows

$$\begin{aligned} &\boldsymbol{M}^* = \boldsymbol{R}(\varphi)\boldsymbol{M}\boldsymbol{R}^T(\varphi), \\ &\boldsymbol{D}^* = \boldsymbol{R}(\varphi)(\boldsymbol{D}\boldsymbol{R}^T(\varphi) - \boldsymbol{M}\boldsymbol{S}(\dot{\varphi})\boldsymbol{R}^T(\varphi)), \\ &\boldsymbol{\tau}^* = \boldsymbol{R}(\varphi)\boldsymbol{\tau} \end{aligned} \tag{13}$$

where, the skew symmetric matrix $\boldsymbol{S}(\dot{\varphi}) \in R^{3x3}$ is defined as follows:

$$\boldsymbol{S}(\dot{\varphi}) = \begin{bmatrix} 0 & -\dot{\varphi} & 0 \\ \dot{\varphi} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{14}$$

The differential equation of the sliding mode is derived as following:

$$\boldsymbol{M}^*\dot{\boldsymbol{s}} = -\boldsymbol{D}^*\boldsymbol{s} + (\boldsymbol{\tau}^* - \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_r - \boldsymbol{D}^*\dot{\boldsymbol{\eta}}_r) \tag{15}$$

Let $\dot{\boldsymbol{s}} = 0$, then the equivalent control can be obtained as

$$\boldsymbol{\tau}_{eq} = \boldsymbol{D}^*\boldsymbol{s} + \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_r + \boldsymbol{D}^*\dot{\boldsymbol{\eta}}_r \tag{16}$$

The control input of SMC is defined as

$$\boldsymbol{\tau}^* = \boldsymbol{\tau}_{eq} + \boldsymbol{\tau}_{sw} \tag{17}$$

where $\boldsymbol{\tau}_{sw}$ is switching control part. To guarantee that the sliding mode $\boldsymbol{s}$ tends to zero in finite time, the dynamic of sliding mode is chosen to have the following form:

$$\dot{\boldsymbol{s}} = -\boldsymbol{W}\boldsymbol{s} - \boldsymbol{K}\mathrm{sgn}(\boldsymbol{s}) \tag{18}$$

where $\boldsymbol{W} \in R^{3x3}$ and $\boldsymbol{K} \in R^{3x3}$ are the designed diagonal positive matrices.

Based on Eq. (18), the $\boldsymbol{\tau}_{sw}$ can be chosen as

$$\boldsymbol{\tau}_{sw} = -\boldsymbol{M}^*(\boldsymbol{W}\boldsymbol{s} + \boldsymbol{K}\mathrm{sgn}(\boldsymbol{s})) \tag{19}$$

Totally, the control input is designed as

$$\boldsymbol{\tau}^* = \boldsymbol{D}^*\boldsymbol{s} + \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_r + \boldsymbol{D}^*\dot{\boldsymbol{\eta}}_r - \boldsymbol{M}^*(\boldsymbol{W}\boldsymbol{s} + \boldsymbol{K}\mathrm{sgn}(\boldsymbol{s})) \tag{20}$$

The non-negative control Lyapunov function is chosen to analyze the stability of system:

$$V = \frac{1}{2}\boldsymbol{s}^T\boldsymbol{s} \tag{21}$$

The derivative of V along the trajectory of system is

$$\dot{V} = \boldsymbol{s}^T\dot{\boldsymbol{s}} = \boldsymbol{s}^T\boldsymbol{M}^{*-1}\{-\boldsymbol{D}^*\boldsymbol{s} + (\boldsymbol{\tau}^* - \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_r - \boldsymbol{D}^*\dot{\boldsymbol{\eta}}_r)\}.$$

Substituting the control input $\boldsymbol{\tau}^*$ in Eq. (20) to (21), we have

$$\dot{V} = -\boldsymbol{s}^T\boldsymbol{W}\boldsymbol{s} - \boldsymbol{s}^T\boldsymbol{K}\,\mathrm{sgn}(\boldsymbol{s}) \le \boldsymbol{0} \tag{22}$$

Equation (22) 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.

The control input of SMC controller presented by Eq. (20) contents the discontinuous signum function and generates the chattering on the surface vector $\boldsymbol{s} = \boldsymbol{0}$. In order to eliminate this chattering phenomenon, the signum function should be replaced by the saturation function. The control law can be represented as follows

$$\boldsymbol{\tau}^* = \boldsymbol{D}^*\boldsymbol{s} + \boldsymbol{M}^*\ddot{\boldsymbol{\eta}}_r + \boldsymbol{D}^*\dot{\boldsymbol{\eta}}_r - \boldsymbol{M}^*(\boldsymbol{W}\boldsymbol{s} + \boldsymbol{K}\mathrm{sat}(\boldsymbol{s}/\delta)) \tag{23}$$

where δ is a boundary layer thickness and the saturation function is defined as:

$$\begin{cases} \mathrm{sat}(\gamma) = \gamma & \text{if } |\gamma| < 1 \\ \mathrm{sat}(\gamma) = \mathrm{sgn}(\gamma) & \text{otherwise} \end{cases} \tag{24}$$

IV. SIMULATION RESULTS

Computer simulations have been done with model ship to evaluate the performance of controlled system. In this study, SMC controller is compared with traditional PID in two cases. First, the system is simulated by circle trajectory tracking without the presence of environmental disturbances. Second, the disturbances are considered to estimate the robustness of the SMC controller.

We have used the CybershipI [8], which is the model of an offshore supply vessel scale 1:70. The motion of ship is maneuvered by four tugboats. The model ship has the mass of 17.6[kg] and a length of 1.19[m]. The center of gravity is located at $x_g = -0.04$[m]. It is chosen as the body fixed coordinate original. Hydrodynamic coefficients of model are described as follows:

$$\begin{aligned} M &= [19[\text{kg}]\ 0\ 0; 0\ 35.2[\text{kg}]\ -0.7[\text{kg.m}^2] \\ &\quad ; 0\ -0.7[\text{kg}]\ 1.98[\text{kg.m}^2]] \\ D &= diag\{4[\text{kg/s}], 6[\text{kg/s}], 1[\text{kg.m}^2/\text{s}]\}; \end{aligned} \tag{25}$$

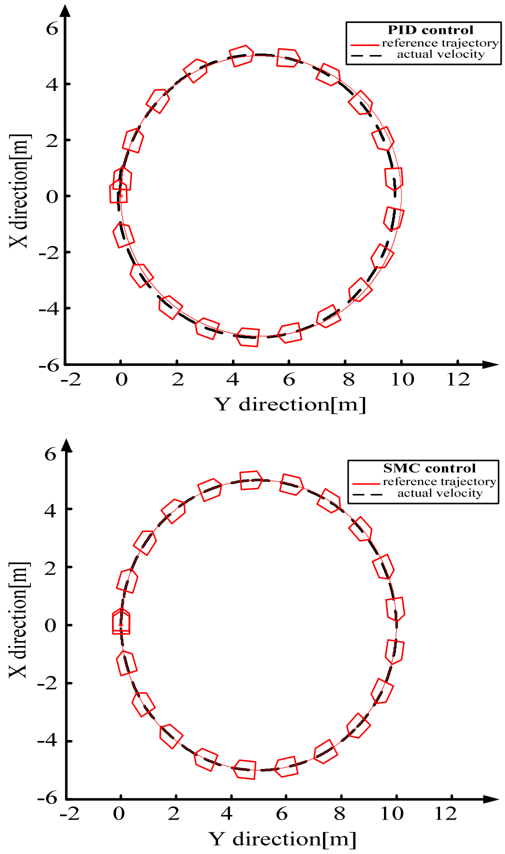

그림 3. 외란이 존재하지 않는 경우의 항로추종제어성능.

Fig. 3. Ship performance without external disturbances.

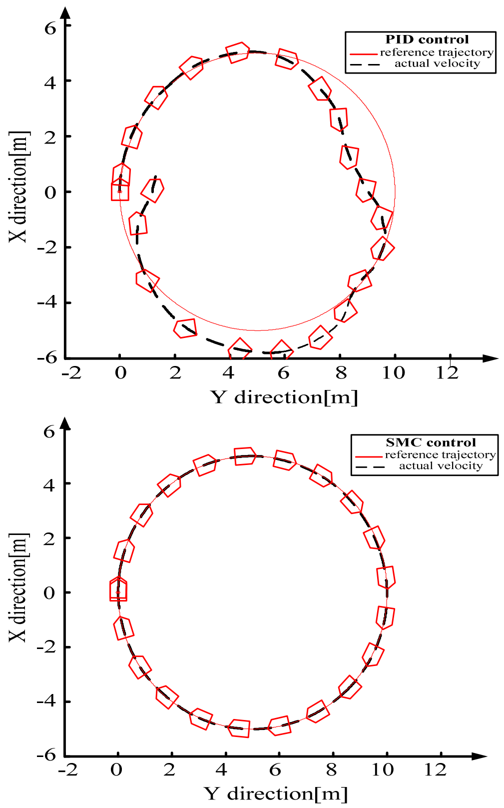

그림 4. 외란이 존재할 경우의 항로추종제어성능.

Fig. 4. Ship performance with environmental disturbances.

The tugboats configuration are described as

$$(l_{1x}, l_{1y}) = (0.41, -0.15), \quad (l_{2x}, l_{2y}) = (-0.41, -0.15),$$
$$(l_{3x}, l_{3y}) = (-0.41, 0.15), \quad (l_{4x}, l_{4y}) = (0.41, 0.15). \tag{26}$$

The SMC control law is simulated with

$$\mathbf{\Lambda} = \text{diag}\{0.1,\ 0.1,\ 1\}, \quad \mathbf{W} = \text{diag}\{0.5, 1, 1\},$$
$$\mathbf{K} = \text{diag}\{1, 1, 1\}\text{x}10^{-3}.$$

The parameters of PID controller are chosen as follows

$$\begin{aligned} K_P &= (0.1)^2 \times [19\ 0\ \ 0;\ \ 0\ \ 35.2\ \ -0.7;\ \ 0\ \ -0.7\ \ 1.98\ ] \\ K_I &= (0.1)^4 \times [19\ 0\ \ 0;\ \ 0\ \ 35.2\ \ -0.7;\ \ 0\ \ -0.7\ \ 1.98\ ] \\ K_D &= 0.16 \times [19\ 0\ \ 0;\ \ 0\ \ 35.2\ \ -0.7;\ \ 0\ \ -0.7\ \ 1.98\ ] \end{aligned} \tag{27}$$

Constraints about limitation of thrust, contact angle as well as slowly varying direction are chosen as follows

$$\begin{aligned} &f_{\min} = 0, && f_{\max} = 0.5[\text{N}] \\ &\alpha_{1\min} = \frac{\pi}{2}, && \alpha_{1\max} = \frac{5\pi}{6} \\ &\alpha_{2\min} = \frac{\pi}{6}, && \alpha_{2\max} = \frac{\pi}{2} \\ &\alpha_{3\min} = \frac{-\pi}{2}, && \alpha_{3\max} = \frac{-\pi}{6} \\ &\alpha_{4\min} = \frac{-5\pi}{6}, && \alpha_{4\max} = \frac{-\pi}{2} \\ &\dot{\alpha} = \frac{\pi}{18}[\text{rad/s}] \end{aligned} \tag{28}$$

In simulations, the trajectory for ship tracking is given as circle line. The radius is 5m. This model ship is maneuvered from the starting point (0, 0) with 0 degree heading angle. Fig. 3 shows the performance of ship by using PID and SMC controllers. Notice that external disturbances are not included in this case. Based on this figure we can see that both of controllers satisfy the given tracking mission. However, the performance of SMC is better than PID controller without position and direction errors.

Next, to estimate the robustness of controlled system, slow varying disturbances is considered. The bias matrix $\boldsymbol{T}$ and scale amplitude matrix $\boldsymbol{\psi}$ in Eq. (8) are defined as following:

$$\boldsymbol{T} = \text{diag}\{100, 100, 100\},\ \boldsymbol{\psi} = \text{diag}\{0.05, 0.05, 0.01\} \tag{29}$$

In Fig. 4, it clearly sees that the PID controller could not guarantee tracking task. Position and direction of ship are too different than desired trajectory. Inversely, a good control performance is obtained by using SMC controller with high accuracy. The robustness is verified in the environmental disturbance condition.

Figs. 5~6 depict the performance of four tugboats by using SMC controller in the presence of environmental disturbances cases. The resulting thrust and directions of tugboats satisfy the constraints about limited pushing force and varying direction.

V. CONCLUSION

In this paper, we proposed the approach for ship trajectory tracking by using SMC controller. Especially, four tugboats control were used to replace the main propulsion for maneuvering in harbor area. The modeling of system was figured out. The

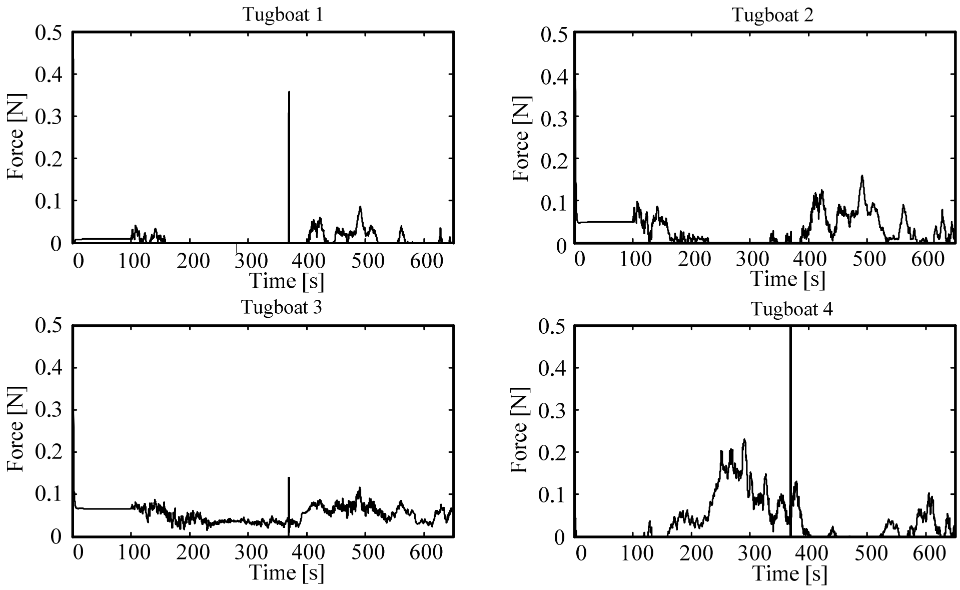

그림 5. 각 터그보트 추력.

Fig. 5. Tugboat thrusts.

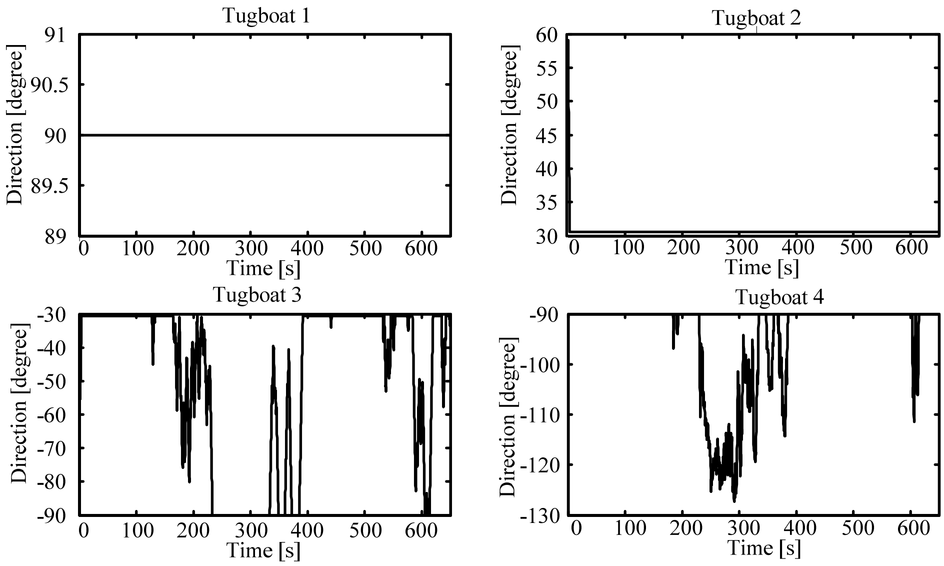

그림 6. 각 터그보트 운동방향.

Fig. 6. Tugboats directions.

efficiency of proposed approach was evaluated through trajectory tracking simulation of the model ship .SMC controller showed better performance than PID controller in the presence of environmental disturbances. It revealed the possibility of extending these results to future studies.

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