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Positioning Control of an Underwater Robot with Tilting Thrusters via Decomposition of Thrust Vector

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Abstract: Positioning control of an underwater robot is a challenging problem due to the high disturbances of ocean flow. To overcome the high disturbance, a new underwater robot with tilting thrusters was proposed previously, which can compensate for disturbance by focusing the thrusting force in the direction of the disturbance. However, the tilting motion of the thrusters makes the system nonlinear, and the limited tilting speed sometimes makes the robot unstable. Therefore, an optimized controller is necessary. A new positioning controller is proposed for this robot using a vector decomposition method. Based on the dynamic model, the nonlinear force input term of the tilting thrusters is decomposed in the horizontal and vertical directions. Based on the decomposition, the solution is determined by a pseudo-inverse and null-space solution. Using the characteristics of the decomposed input matrix, the final solution can be found by solving a simple second-order algebraic equation to overcome the limitations of the tilting speed. The positioning was simulated to validate the proposed controller by comparing the results with a switching-based controller. Tracking results are also presented. In future work, a high-level control strategy will be developed to take advantage of the tilting thrusters by focusing the forcing direction toward the disturbance with a limited stability margin.

Keywords: Decomposition, positioning control, tilting thruster, underwater robot.

1. INTRODUCTION

Coastal underwater work is becoming increasingly important as the marine industry develops. Underwater work such as welding, cutting, and surface repair is very dangerous for divers because of the harsh underwater environment. In the water, divers cannot see well, and decompression sickness can occur because of the water pressure and even lead to death. Strong currents are another issue. Underwater robots have thus been developed, and it is important for them to be stably and reliably controlled for performing various underwater tasks [1]. Positioning control of an underwater robot is a challenging problem due to the high disturbances of ocean flow. To overcome the disturbances, a new underwater robot with tilting thrusters was proposed previously, as shown in Fig. 1. This robot can compensate for disturbance by focusing the thrusting force in the direction of the disturbance [2].

Most underwater robots are overactuated systems or designed with fixed thrusters to move with six degrees of freedom (DOF) [3]. ODIN has eight bi-directional thrusters that are positioned symmetrically around its spherically shaped hull [4]. Tri-Dog1 is equipped with six fixed thrusters on the front, rear, left, right, top, and bottom. DEPTHX has four horizontal thrusters and two vertical thrusters for 6-DOF motion [5,6].

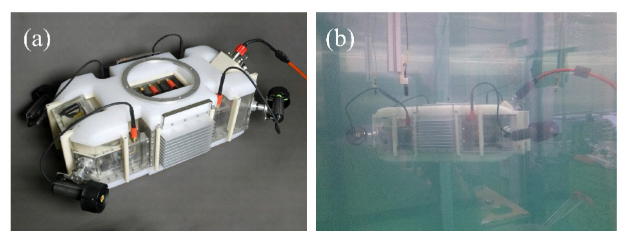

Fig. 1. (a) Underwater robot. (b) Experiment in a water tank.

To minimize the size of the robot and the number of actuators, our platform has only four thrusters that are capable of tilting. The robot also has two servomotors in the front and rear, which allow the thrusters to rotate and change the direction of the thrust force. The thrusters are arranged at the four corners of the platform, and they are tilted synchronously by servomotors in sets of two. This

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can reduce the power consumption and the size of the system, but it makes the system nonlinear. Quadrotors with a tilting angle [7] and mobile robots with a steering wheel [8] are also nonlinear and difficult to control for similar reasons.

In a previous study [2], we applied a selective switching control method to the robot because of the complexity resulting from the nonlinear system. The switching controller was designed to select one of two linear subsystems based on a horizontal mode and a vertical mode, depending on the error. All four tilting angles are 0 degree in horizontal mode or 90 degree in vertical mode and each 3-DOF mode is controlled separately. However, this method has trouble with endless vibration, and the robot sometimes diverges when a large disturbance is applied because there are only two configurations, all four tilting angles of 0 degree or 90 degree.

For more stable positioning control, the robots need a suitable control method that uses continuous tilting angles instead of one that uses two modes with tilting angles of 0 degrees or 90 degrees. Therefore, we applied a backstepping method [9], which is widely used in nonlinear system control [10, 11]. However, the robot could not maintain stability in experiments. The tilting angle control input is highly oscillated and the velocity of the servo motor could not follow the change of the tilting angle exactly. The tilting speed cannot be increased because of the required torque, motor size, and wear of the rotary seal [12].

We tried to apply another control method to this robot that uses a continuous tilting angle and includes the motor dynamics. It is common for the complex dynamics to be simply converted by decoupling [13], and the variables are optimized using a null space method [14]. To solve the complex thrust vector map, the thrust vector is decomposed, and the constraints of the robot structure are added to the null space of the decomposed vector. An algorithm to select the better solution was added to the controller to reduce the amount of change in the tilting angle.

In this paper, we propose a new control design to address the nonlinearity and limitations of the tilting thruster model. Section 2 presents the dynamic model of the robot platform and the tilting mechanism. Section 3 describes the design of the proposed controller and the derivation of the stability criterion. A simulation of the positioning motion and trajectory tracking are shown in Section 4. Finally, concluding remarks are given in Section 5.

2. SYSTEM MODELING

2.1. Dynamics equation

The 6-DOF underwater robot is shown in Fig. 2. Two coordinate systems are commonly used for a 6-DOF underwater robot: the earth-fixed frame (E-frame) and the body-fixed frame (B-frame). The nonlinear dynamics of

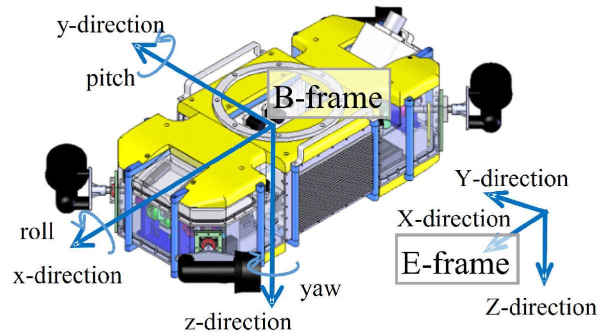

Fig. 2. B-frame and E-frame of the robot platform.

the robot in the B-frame are given by:

$$\mathbf{M}\dot{v} + \mathbf{C}(v)v + \mathbf{D}(v)v + \mathbf{g}(\eta) = \tau, \quad (1)$$

$$v = \mathbf{J}^{-1}(\eta)\dot{\eta}, \quad (2)$$

where $eta = [x\ y\ z\ \phi\ \ \theta\ \ \psi]^T$ is the position and orientation vector in the E-frame; $v = [u\ v\ w\ p\ q\ r]^T$ is the linear and angular velocity in the B-frame, $\tau = [X\ Y\ Z\ K\ M\ N]^T$ is the force and moment vector in the B-frame, $\mathbf{J}(\eta)$ is the transformation matrix between the B-frame and the E-frame; $\mathbf{M}$ is the inertial matrix including added mass; $\mathbf{C}(v)$ is a matrix of the Coriolis, centripetal, and velocity-dependent terms due to added mass; $\mathbf{D}(v)$ is the damping matrix, which includes drag forces terms; $\mathbf{g}(\eta)$ is the gravitational force and buoyant force; and τ is the control input. Fossen provides a detailed description of these equations [15]. Substituting (2) into (1), the equation of motion in the E-frame becomes:

$$\mathbf{M}_\eta(\eta)\ddot{\eta} + \mathbf{C}_\eta(v,\eta)\dot{\eta} + \mathbf{D}_\eta(v,\eta)\dot{\eta} + \mathbf{g}_\eta(\eta) = \tau_\eta(\eta), \quad (3)$$

where

$$\mathbf{M}_\eta(\eta) = \mathbf{J}^{-T}(\eta)\mathbf{M}\mathbf{J}^{-1}(\eta),$$
$$\mathbf{C}_\eta(v,\eta) = \mathbf{J}^{-T}(\eta)[\mathbf{C}(v) - \mathbf{M}\mathbf{J}^{-1}(\eta)\dot{\mathbf{J}}(\eta)]\mathbf{J}^{-1}(\eta),$$
$$\mathbf{D}_\eta(v,\eta)\dot{\eta} = \mathbf{J}^{-T}(\eta)\mathbf{D}(v)\mathbf{J}^{-1}(\eta),$$
$$\mathbf{g}_\eta(\eta) = \mathbf{J}^{-T}\mathbf{g}(\eta),$$
$$\tau_\eta(\eta) = \mathbf{J}^{-T}(\eta)\tau.$$

2.2. Tilting mechanism

The four thrusters are attached to each corner of the rectangular robot platform and the configuration of the thrust vector is expressed in Fig. 3. Each one can rotate about an axis, but the two front thrusters rotates at the same angle simultaneously, as do the two rear thrusters. For 6-DOF motion using the 6 actuators, a structure was designed in which each of the two tilting angles has the same value. The force and moment vector τ is determined

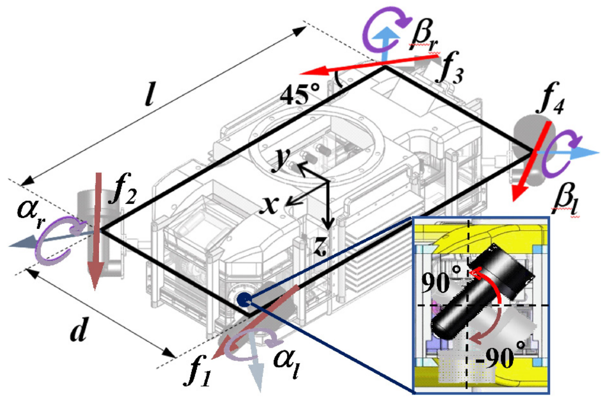

Fig. 3. Configuration of thrust vector.

from the revolution of the thruster and calculated as follows:

$$\tau = \begin{bmatrix} \frac{1}{\sqrt{2}}(f_1\cos\alpha + f_2\cos\alpha + f_3\cos\beta + f_4\cos\beta) \\ \frac{1}{\sqrt{2}}(f_1\cos\alpha - f_2\cos\alpha + f_3\cos\beta - f_4\cos\beta) \\ -f_1\sin\alpha - f_2\sin\alpha - f_3\sin\beta - f_4\sin\beta \\ \frac{d}{2}(f_1\sin\alpha - f_2\sin\alpha - f_3\sin\beta + f_4\sin\beta) \\ \frac{l}{2}(f_1\sin\alpha + f_2\sin\alpha - f_3\sin\beta - f_4\sin\beta) \\ \frac{l+d}{2\sqrt{2}}(f_1\cos\alpha - f_2\cos\alpha - f_3\cos\beta + f_4\cos\beta) \end{bmatrix}, \tag{4}$$

where f_1, f_2, f_3, and f_4 are the thrust forces generated by each thruster, while α and β are the tilting angles of the thrusters. l and d are the length and width of the robot platform. The tilting angles are involved sine and cosine functions and thrust vector is represented by multiplication of it and thrust forces f_i. The tilting thruster needs a more complicated control design than a fixed thruster model because of the complex nonlinear structure.

3. CONTROL DESIGN

The proposed controller is a new hierarchical PD controller. The desired force and moment are found by using a PD control scheme in the high-level controller. In the low-level controller, the forces and angles of each thruster are needed to generate the required control input τ. However, these are difficult to obtain because of the nonlinearity of the tilting mechanism, and the actual thruster does not follow the derived control input. Therefore, we designed the hierarchical controller while considering these problems.

3.1. Decomposition of thrust vector using null space

To solve the nonlinear problem, we divided each of the thruster forces into the horizontal and vertical directions.

$$\tau = \mathbf{A}q, \tag{5}$$

where

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -1 & -1 & -1 & -1 & 0 & 0 & 0 & 0 \\ \frac{d}{2} & -\frac{d}{2} & -\frac{d}{2} & \frac{d}{2} & 0 & 0 & 0 & 0 \\ \frac{l}{2} & \frac{l}{2} & -\frac{l}{2} & -\frac{l}{2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{l+d}{2\sqrt{2}} & -\frac{l+d}{2\sqrt{2}} & -\frac{l+d}{2\sqrt{2}} & \frac{l+d}{2\sqrt{2}} \end{bmatrix},$$

$$q = \begin{bmatrix} f_1\sin\alpha \\ f_2\sin\alpha \\ f_3\sin\beta \\ f_4\sin\beta \\ f_1\cos\alpha \\ f_2\cos\alpha \\ f_3\cos\beta \\ f_4\cos\beta \end{bmatrix}.$$

The complex thrust vector is divided into two a constant matrix $\mathbf{A} \in \Re^{6\times 8}$ and an input column vector $q \in \Re^8$. Solving for q,

$$q = \mathbf{A}^{-1}\tau, \tag{6}$$

where $\mathbf{A}^{-1}$ is the inverse of $\mathbf{A}$. The thrust forces, f_1, f_2, f_3, and f_4 and the tilting angles α and β are obtained as follows:

$$\begin{aligned} f_1 &= sign(q_5)\sqrt{q_1^2+q_5^2}, \\ f_2 &= sign(q_6)\sqrt{q_2^2+q_6^2}, \\ f_3 &= sign(q_7)\sqrt{q_3^2+q_7^2}, \\ f_4 &= sign(q_8)\sqrt{q_4^2+q_8^2}, \end{aligned} \tag{7}$$

$$\begin{aligned} \alpha_l &= \arctan\frac{q_1}{q_5}, \quad \alpha_r = \arctan\frac{q_2}{q_6}, \\ \beta_l &= \arctan\frac{q_3}{q_7}, \quad \beta_r = \arctan\frac{q_4}{q_8}, \end{aligned} \tag{8}$$

where α_l and α_r are the left and right front tilting angles, respectively, β_l and β_r the rear tilting angles, and q_i is the i-th component of input q. Each of the four tilting angles is derived as shown in equation (8) and Fig. 3. However, the front and rear tilting angles must have the same values because of designed tilting mechanism, and q should satisfy the following two constraints:

$$\begin{aligned} q_1q_6 &= q_2q_5, \\ q_3q_8 &= q_4q_7. \end{aligned} \tag{9}$$

Considering that the size of matrix $\mathbf{A}$ is 6×8, we can add two constraints in the null space of $\mathbf{A}$:

$$q = \mathbf{A}^+\tau + \mathbf{N}\boldsymbol{\xi}, \tag{10}$$

$$q = \begin{bmatrix} c_1 - \xi_2 \\ c_2 + \xi_2 \\ c_3 - \xi_2 \\ c_4 + \xi_2 \\ c_5 - \xi_1 \\ c_6 - \xi_1 \\ c_7 + \xi_1 \\ c_8 + \xi_1 \end{bmatrix}, \tag{11}$$

where $\mathbf{A}^+$ is the pseudo inverse of $\mathbf{A}$, and $\mathbf{N}$ is the null space of $\mathbf{A}$. $c = \mathbf{A}^+\tau \in \mathbb{R}^8$ and $\boldsymbol{\xi} = [\xi_1\ \xi_2]^{\mathrm{T}}$ are defined to insert the two constraints in (9). Substituting (11) into (9) yields the following simultaneous quadratic equation of $\boldsymbol{\xi}$:

$$\begin{aligned} 2\xi_1\xi_2 \ &+ \ (-c_1+c_2)\xi_1 + (-c_5-c_6)\xi_2 \\ &+ (c_1c_6 - c_2c_5) = 0, \\ 2\xi_1\xi_2 \ &+ \ (-c_3+c_4)\xi_1 + (c_7+c_8)\xi_2 \\ &+ (c_4c_7 - c_3c_8) = 0. \end{aligned} \tag{12}$$

By subtracting these equations, we have:

$$\xi_1 = b_1\xi_2 + b_2, \tag{13}$$

$$\bar{a}\xi_2^2 + \bar{\mathrm{b}}\xi_2 + \bar{c} = 0, \tag{14}$$

$$\xi_2 = \frac{-\bar{b} \pm \sqrt{\Delta}}{2\bar{a}}, \tag{15}$$

where

$$\begin{aligned} b_1 &= \frac{c_5+c_6+c_7+c_8}{-c_1+c_2+c_3-c_4}, \\ b_2 &= \frac{-c_1c_6+c_2c_5+c_4c_7-c_3c_8}{-c_1+c_2+c_3-c_4}, \\ \bar{a} &= 2b_1, \\ \bar{b} &= 2b_2 + (-c_1+c_2)b_1 + (-c_5-c_6), \\ \bar{c} &= (-c_1+c_2)b_2, \\ \Delta &= \bar{b}^2 - 4\bar{a}\bar{c}. \end{aligned}$$

These equations are used to determine ξ_2. We now have to find the 8 variables of q, and we already have 8 equations such that $\mathrm{rank}(\mathbf{A}) = 6$ and the two equations in (9). Therefore, the problem is very simple and can be solved explicitly.

3.2. Choosing the solution

In the general case of a simultaneous quadratic equation, two solutions are always existed. However we consider the existence and the number of a solution can be changed as a discriminant since we deal with the robot in the real number domain. To overcome the limitations of the actual tilting thrusters, it is better to minimize the movement of the thruster posture using the following cases:

1) $\Delta > 0$

As shown in (13) and (14), for real numbers $\bar{a}$, $\bar{b}$, and $\bar{c}$, if Δ is positive, ξ_2 can be two values according to (15), which are determined by choosing a plus or minus sign in front of the root of the equation. When comparing previous tilting angles, ξ_2 is determined so as to minimize the change of the tilting angles.

2) $\Delta = 0$

There is no choice because the solution of (15) is only one when Δ is zero. Therefore, ξ_2 is obtained by choosing the only result.

3) $\Delta < 0$

When Δ is negative, a solution does not exist, and we have no choice but to choose an arbitrary value. We can select a certain value only in that case, so we assume that $\boldsymbol{\xi}$ is zero. When $\boldsymbol{\xi}$ is zero, homogeneous solution to create the required force and moment is still calculated, however, tilting angles of the left and right are different since the constraints is not considered. When comparing previous tilting angles, the better tilting angles is selected for the left or right angles, and the thrust force is also determined. A better value can reduce the variation of the tilting angles. However, the solution is a pseudo solution because it does not consider the two constraints.

3.3. Stability of the controller

The design of the high-level PD control begins with finding the desired force and moment vector τ. In this system, the tracking error vector is defined as $e = \eta_d - \eta$ in the E-frame, and the time differentiation of the error state is $\dot{e} = -\dot{\eta} = -\mathbf{J}(\eta)v$, which is derived from the body velocity using the transformation matrix. The control system was designed based on a PD control law for the tracking error as follows:

$$\tau = \mathbf{J}^T[\mathbf{K}_p e + \mathbf{K}_d \dot{e}], \tag{16}$$

where $\mathbf{K}_p$ and $\mathbf{K}_d$ are constant gain matrices. From this, we define the following Lyapunov function candidate for the PD controller :

$$V(v,e) = \frac{1}{2}(v^T\mathbf{M}v + e^T\mathbf{K}_p e), \tag{17}$$

where the time differentiation is given by:

$$\frac{dV}{dt} = v^T[\mathbf{M}\dot{v} - J^T(\eta)\mathbf{K}_p e]. \tag{18}$$

Substituting (1) into (16) yields:

$$\frac{dV}{dt} = v^T[\tau - \mathbf{C}(v)v - \mathbf{D}(v)v - J^T(\eta)\mathbf{K}_p e]. \tag{19}$$

Note that $v^T\mathbf{C}(v)v$ is zero for all v, and (15) can be substituted into (19). If $\mathbf{K}_p > 0$ and $\mathbf{J}^T\mathbf{K}_D\mathbf{J} > 0$, the following is ensured:

$$\frac{dV}{dt} = -v^T[\mathbf{D}(v) + \mathbf{J}^T(\eta)\mathbf{K}_D\mathbf{J}(\eta)]v \le 0. \tag{20}$$

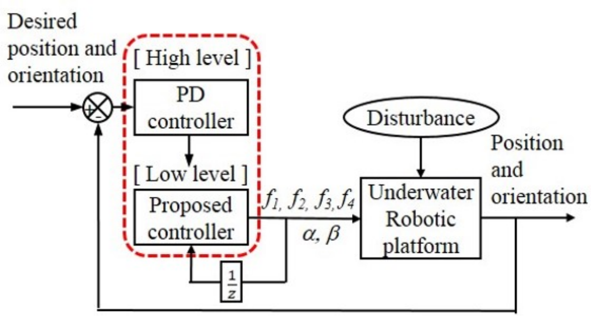

Fig. 4. Block diagram of the proposed hierarchical PD control.

The fact that the time derivative of V is less than or equal to zero means that $V(t) \leq V(0)$, d^2V/dt^2 is bounded, and d^2V/dt^2 is uniformly continuous. Using Barbalat's lemma [16], we verified that $v \to 0$ when $t \to \infty$. We should ensure that $dV/dt = 0$ is not true when $e \neq 0$, and (1) and (16) can be used for the proof.

$$\dot{v} = \mathbf{M}^{-1}\mathbf{J}^T(\eta)\mathbf{K}_P e. \tag{21}$$

The time derivative of the Lyapunov function dV/dt is zero only if the error e is zero, which means that the whole system is always stable [15].

4. SIMULATION AND DISCUSSION

We performed two simulations of the control design. A block diagram of the design can be seen in Fig. 4. All of the simulations are performed with MATLAB Simulink (Mathworks Co.). The sampling time of the simulation is 10 ms, and that of the controller is 50 ms, which is the control cycle of the actual robot controller.

4.1. Positioning with pitch angles

In the first simulation, the positioning motion with a pitch angle was simulated. The robot changes pitch angle in only 30 sec and keeps -30 degrees of pitch angles after that. While changing the posture of the robot, we commanded the robot to maintain its initial position of 0 m in the x direction, 0 m in the y direction, and 0 m in the z direction. The roll and yaw angles of the robot were to be kept at 0 degrees. The positioning motion with this posture is widely used for various underwater tasks.

Modeling error caused by inaccurate actual robot model generates a restoring force and it can be a disturbance that interferes with maintaining the position and orientation of the robot. Modeling error about the center of mass is applied as a disturbance [17]. Fig. 5 shows the position and orientation error in the simulation with the proposed hierarchical PD control and the selective switching control from a previous study. Although the robot vibrated slightly when the input was applied, the results converge

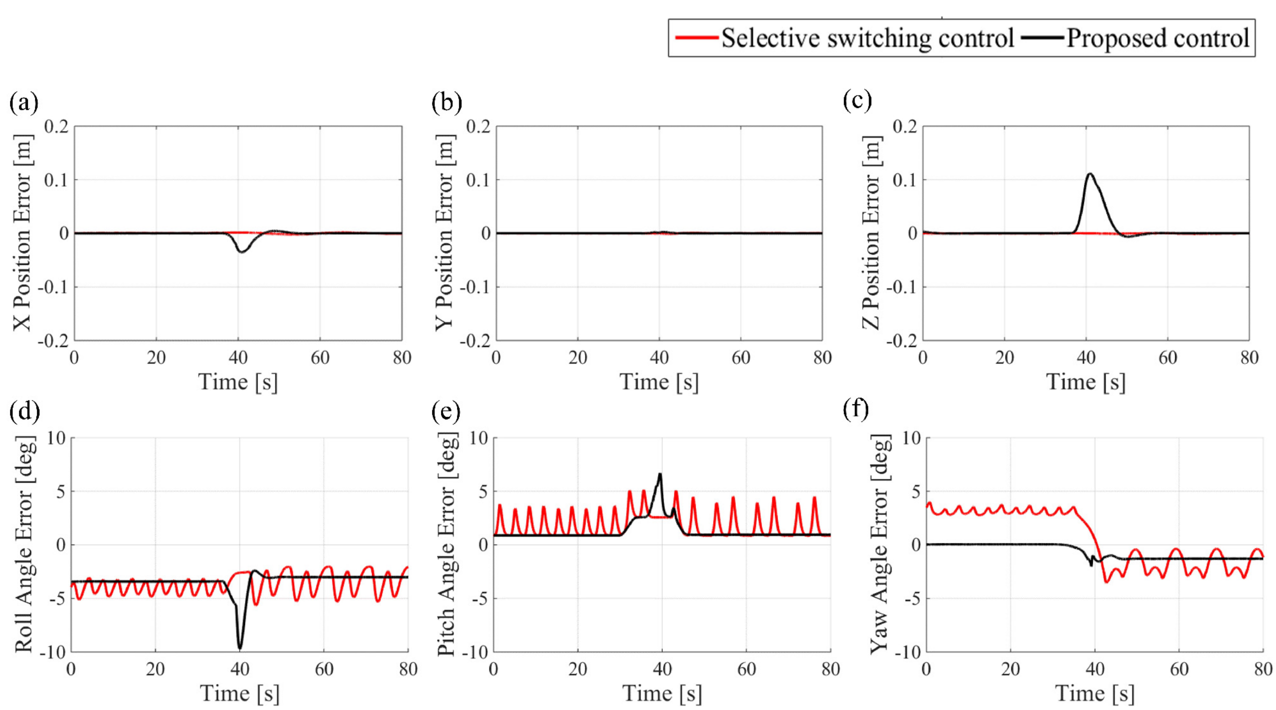

Fig. 5. Simulation results of the position and orientation error with pitch of -30 degrees using proposed control and selective switching control: (a) x-position, (b) y-position, (c) z-position, (d) roll angle, (e) pitch angle, and (f) yaw angle.

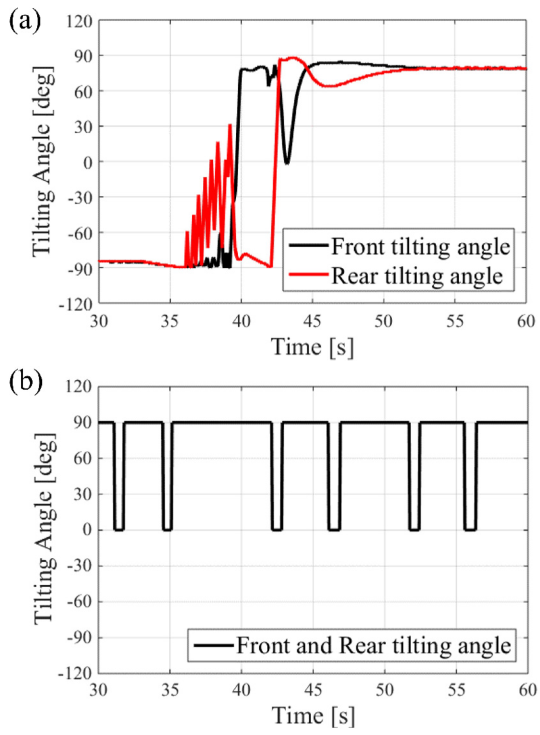

Fig. 6. Tilting angles in simulation: (a) proposed control and (b) selective switching control.

well. Since the selective switching controller cannot control all 6 DOF of the motion at the same time, the orientation of the robot vibrated endlessly. However, the oscillation of the robot posture disappeared when the new controller was applied.

As shown in Fig. 6, the tilting angles of the proposed controller have continuous values, unlike the previous controller. The tilting angles of the proposed hierarchical control change only when the input is applied, and they converge to an appropriate value for positioning, unlike the selective switching control. The simulation results clearly show that the control performance is improved in steady state by the proposed design.

4.2. Trajectory tracking

The second simulation in Fig. 7 shows that the robot platform follows a given path well when using the designed controller. Trajectory tracking was simulated without changing the posture of the robot. The robot was allowed to go from 0 m to 1 m in the x direction and to and -1 m in the z direction, and it was commanded to draw a sine wave with amplitude of 0.4 m and frequency of 0.025π rad/sec for 120 sec. As with the previous simulation, the disturbances caused by the modeling error about the center of mass were again applied to reflect an actual environment. We can see that the robot follows the desired value with little error, and the vibration phenomenon of

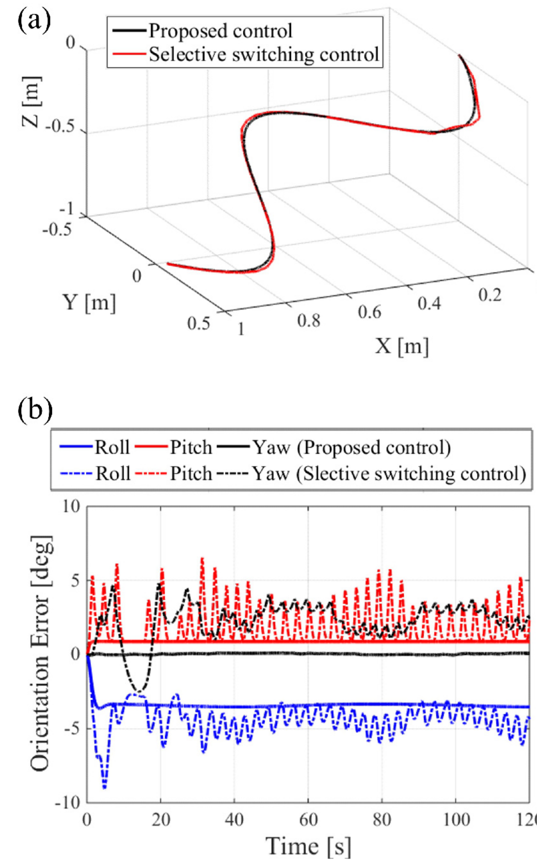

Fig. 7. Simulation results of trajectory tracking: (a) position and (b) orientation error with the proposed control and the selective switching control in simulation.

the robot orientation is reduced compared to the previous study.

5. CONCLUSION

We proposed a new hierarchical controller design to obtain the continuous tilting angle for an underwater robot. Due to the tilting mechanism, the thrust vector consists of a complex nonlinear equation, and the robot has difficulty with the error of the actual working model. In order to overcome this weakness, the new control algorithm was developed by decomposition of the thrust vector. The control algorithm was verified through convergence of the position and orientation of the robot, which showed enhanced control performance compared with the previous control algorithms. However, this controller has no solution when Δ is negative. The simulation results showed the feasibility of this controller, but this algorithm should be more robust. In future work, a modified complementary controller will be applied to the robot platform by analyzing this case.

$$J = \begin{bmatrix} \cos\psi\cos\theta & -\sin\psi\cos\phi+\cos\psi\sin\theta\sin\phi & \sin\psi\sin\phi+\cos\psi\cos\phi\sin\theta & 0 & 0 & 0 \\ \sin\psi\cos\theta & \cos\psi\cos\phi+\sin\phi\sin\theta\sin\psi & -\cos\psi\sin\phi+\sin\theta\sin\psi\cos\phi & 0 & 0 & 0 \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & 0 & 0 & 0 & \cos\phi & -\sin\phi \\ 0 & 0 & 0 & 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta} \end{bmatrix}, \tag{A.1}$$

$$M = \begin{bmatrix} 96.3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 133.04 & 0 & 0 & 0 & 0 \\ 0 & 0 & 168.57 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4.47 & 0 & 0 \\ 0 & 0 & 0 & 0 & 9.26 & 0 \\ 0 & 0 & 0 & 0 & 0 & 8.1 \end{bmatrix}, \tag{A.2}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 168.57w & -133.04v \\ 0 & 0 & 0 & -168.57w & 0 & 96.30u \\ 0 & 0 & 0 & 133.04v & -96.30u & 0 \\ 0 & 168.57w & -133.04v & 0 & 8.10r & -9.26q \\ -168.57w & 0 & 96.30u & -8.10r & 0 & 4.47p \\ 133.04v & -96.30u & 0 & 9.26q & -4.47p & 0 \end{bmatrix}, \tag{A.3}$$

$$D = \begin{bmatrix} 34.55\,|u| & 0 & 0 & 0 & 0 & 0 \\ 0 & 104.40\,|v| & 0 & 0 & 0 & 0 \\ 0 & 0 & 146.50\,|w| & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.68\,|p| & 0 & 0 \\ 0 & 0 & 0 & 0 & 5.34\,|q| & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.07\,|r| \end{bmatrix}. \tag{A.4}$$

APPENDIX A

The matrices in the motion equations of the underwater robot can be derived by rigid body dynamics and hydrodynamics [1].

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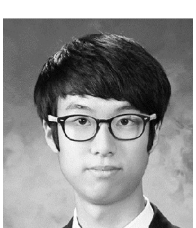

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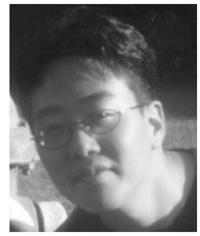

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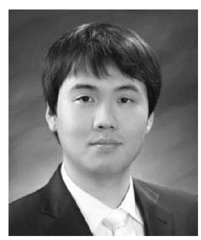

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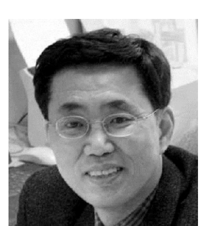

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