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Sliding mode control with disturbance estimation for underwater robot.

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Sliding Mode Control with Disturbance Estimation for Underwater Robot

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***Abstract*—This paper proposes a sliding mode control with a disturbance estimation for an underwater robot. The mobility performance of an underwater robot is influenced by modeling error, observation noise, and several disturbances such as ocean current and tidal current. Therefore, a robust control system is needed for precise motion control of an underwater robot. This paper uses a sliding mode control, which is one of the robust control methods. In a sliding mode control, chattering tends to occur, if the switching gain is set to a high value. On the other hand, it is desirable to set the switching gain high from the viewpoint of robustness. Therefore, there is a trade-off between the switching gain and robustness. In the proposed method, the disturbance is estimated in real-time, and this estimated value is added to the control input. Most of the disturbances are compensated by this estimated value, and the sliding mode control is used for the rest of the disturbances. As a result, the robust control system is achieved by using the proposed method, even if the switching gain is set to a low value. The validity of the proposed method was confirmed from the simulation and experimental results.**

***Index Terms*—Underwater robot, ROV, AUV, position control**

I. Introduction

In recent years, it is desirable to excavate seabed resources. Seabed resources such as methane hydrate are expected as future energy resources. In addition, the seabed resources include several mineral resources such as rare metals. From this viewpoint, the technologies for the mining of the seabed resources have been developed [1].

For the mining of the seabed resource, underwater robots have been widely used. The underwater robots are roughly classified into two groups; one is a remotely operated vehicle (ROV) and the other is an autonomous underwater vehicle (AUV). ROV is controlled by the operator boarded in the mother ship. In addition, ROV can be equipped with a manipulator. By using this manipulator, several manipulation tasks such as the sample collection and the maintenance of the submarine plant are conducted [2]. On the other hand, AUV moves autonomously by using sensor information. AUV is used for seafloor topography exploration with an ultrasonic sounder and a still camera [3], and a pipeline inspection [4]. For these underwater tasks, position control for station keeping, and trajectory following is one of the key technologies.

Focused on the position control for the underwater robots, there are several disturbances such as ocean current and tidal current. There is the modeling error, since the structure of the underwater robot is complicated. In addition, the accuracy of the self-estimation for the robot position is not good, since the inertial measurement unit (IMU), which has observation noise, has to be used. Therefore, the mobility performance in the underwater robot is influenced by modeling error, observation noise, and disturbances.

From this viewpoint, it is necessary for the underwater robot to implement the robust position control method. Alamdari *et al.* developed the robust predictive control approach for underwater robotic vehicles [5]. Gan *et al.* showed the model predictive adaptive constraint tracking control for underwater vehicles [6]. Wang *et al.* proposed the neuroadaptive sliding mode formation control of AUV with uncertain dynamics [7]. Mancini *et al.* described the sliding mode control method and artificial potential field for dynamic collision avoidance [8]. Teo *et al.* developed the robust fuzzy AUV docking approach for unknown current disturbances [9]. Cui *et al.* proposed the adaptive neural network control of AUVs with the control input nonlinearities using reinforcement learning [10]. Gao and Guo investigated the fixed-time sliding mode formation control of AUVs based on a disturbance observer [11].

This paper proposes a robust position control system against disturbances such as ocean current and tidal current. For the robust control system, the sliding mode control is used. Generally speaking, the sliding mode control may occur chattering. In the proposed method, the disturbance is estimated in real-time, and this estimated value is added to the control input. Most of the disturbances are compensated by this estimated value, and sliding mode control is used for the rest of the

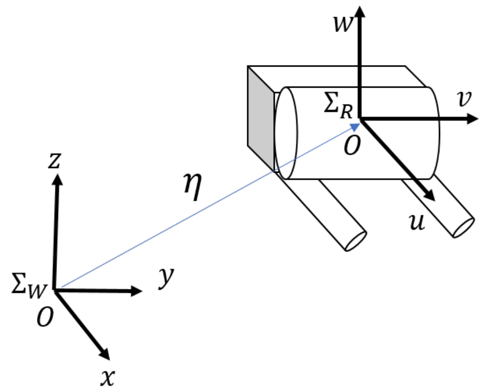
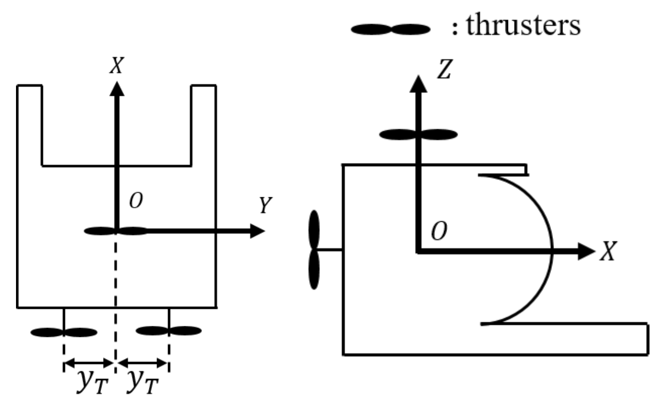


Fig. 1. Coordinate system



(a) Plan view

(b) Side view

Fig. 2. Thruster Arrangement

disturbances. Therefore, the control gain of the sliding mode control, which causes chattering, can be set to a low value. As a result, the robust control system is achieved by using the proposed method. The validity of the proposed method was confirmed from the simulation and experimental results.

The rest of this paper is described as follows. Section II explains the modeling of the underwater robot. Section III proposes the sliding mode control with the disturbance estimation. Section IV and V shows simulation and experimental results to confirm the validity of the proposed method. Finally, this paper is concluded in section VI.

II. Modeling of Underwater Robot

This section shows the modeling of the underwater robot [12]. In general, an underwater robot is regarded as a rigid body with 6 degrees of freedom. This motion is defined as surge, sway, heave, roll, pitch, and yaw.

A. Coordinate System

This subsection shows the modeling of the underwater robot. As shown in Fig. 1, there are two coordinate systems; One is the world coordinate system Σ_W, and the other is the robot coordinate system Σ_R. The origin of the world coordinate system Σ_W is fixed, and defined as the initial position of the underwater robot. The origin of the robot coordinate system Σ_R is set to the center of the underwater robot. The directions of the X-axis, Y-axis, and Z-axis are directed from aft to fore, to starboard, and from top to bottom, respectively.

The position vector $\boldsymbol{\eta}_1$ and orientation vector $\boldsymbol{\eta}_2$ in Σ_W are defined as follows.

$$\boldsymbol{\eta}_1 = [x\ y\ z]^{\mathrm{T}} \tag{1}$$
$$\boldsymbol{\eta}_2 = [\phi\ \theta\ \psi]^{\mathrm{T}} \tag{2}$$
$$\boldsymbol{\eta} = [\boldsymbol{\eta}_1\ \boldsymbol{\eta}_2]^{\mathrm{T}} \tag{3}$$

where x, y and z represent for the position of the underwater vehicle. ϕ, θ, and ψ mean Euler angles; roll, pitch and yaw.

The linear velocity vector $\boldsymbol{\nu}_1$ and angular velocity vector $\boldsymbol{\nu}_2$ in Σ_R are defined as follows.

$$\boldsymbol{\nu}_1 = [u\ v\ w]^{\mathrm{T}} \tag{4}$$
$$\boldsymbol{\nu}_2 = [p\ q\ r]^{\mathrm{T}} \tag{5}$$
$$\boldsymbol{\nu} = [\boldsymbol{\nu}_1\ \boldsymbol{\nu}_2]^{\mathrm{T}} \tag{6}$$

where u, v, w, p, q and r represent for the translation and angular velocities. The transformation form Σ_R to Σ_W is expressed as follows.

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J_{aco}}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{7}$$

where $\boldsymbol{J_{aco}}$ means the Jacobian matrix.

B. Equation of Motion

The motion equation of the underwater robot is simplified with the following assumptions:

- The origin of the robot coordinate system is coincident with the position of the vehicle's center of mass.
- Port/starboard, fore/aft and bottom/top are symmetrical.
- The underwater robot is moving at a slow speed.

The forces $\boldsymbol{\tau}_1$ and moments $\boldsymbol{\tau}_2$ acting on the underwater robot are defined as follows.

$$\boldsymbol{\tau}_1 = [F_x\ F_y\ F_z]^{\mathrm{T}} \tag{8}$$
$$\boldsymbol{\tau}_2 = [T_\phi\ T_\theta\ T_\psi]^{\mathrm{T}} \tag{9}$$
$$\boldsymbol{\tau} = [\boldsymbol{\tau}_1\ \boldsymbol{\tau}_2]^{\mathrm{T}} \tag{10}$$

where F_x, F_y, F_z, T_ϕ, T_θ and T_ψ represent for the forces and moments acting on the underwater vehicle.

The motion equation of a rigid body is expressed as follows.

$$\boldsymbol{M}_{RB}\dot{\boldsymbol{\nu}} + \boldsymbol{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau} \tag{11}$$

where $\boldsymbol{M}_{RB}$, and $\boldsymbol{C}_{RB}(\boldsymbol{\nu})$ represent for the inertia matrix and the matrix of Coriolis force and centrifugal force.

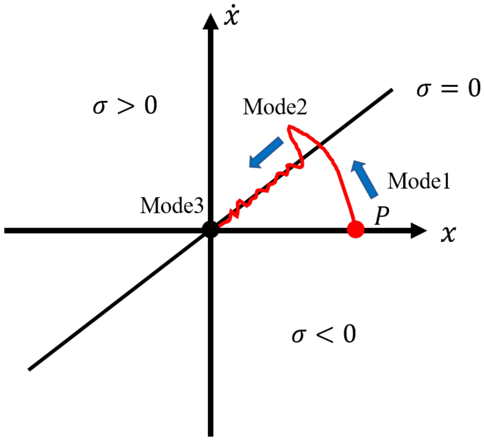


Fig. 3. Concept of sliding mode control

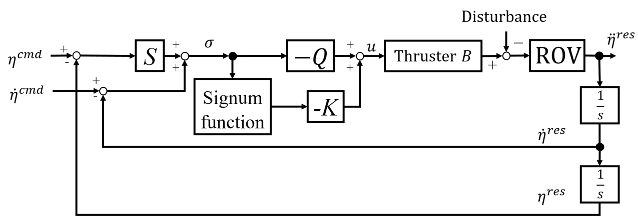


Fig. 4. Block diagram of sliding mode control

For the motion in a fluid, the dynamics is influenced from buoyancy and the hydrodynamic effects. Therefore, the motion equation of the underwater vehicle is expressed as follows.

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{\tau}_{gr} = \boldsymbol{\tau}_t \tag{12}$$

where $\boldsymbol{M}$, $\boldsymbol{C}(\boldsymbol{\nu})$ and $\boldsymbol{D}(\boldsymbol{\nu})$ represent for the inertia matrix including added mass, the matrix of Coriolis and centripetal terms including added mass and the fluid resistance matrix. $\boldsymbol{\tau}_g$, and $\boldsymbol{\tau}_t$ indicate the vector of gravitational and buoyant forces and moments.

C. Thruster Arrangement

Fig. 2 shows the thruster arrangement. In this research, the underwater robot has four thrusters; two are surge, one is sway, and the other is heave. y_T is the distance of surge thrusters from the X-axis. The thrust force and moment $\boldsymbol{\tau}_t$ is obtained as follows.

$$\boldsymbol{\tau}_t = \boldsymbol{B}\boldsymbol{u} \tag{13}$$

where $\boldsymbol{B}$ is the matrix of thruster coefficients considering the thruster arrangement, $\boldsymbol{u}$ represents for the control input vector.

III. Proposed Method

This section describes the sliding mode control with the disturbance estimation for the underwater robot.

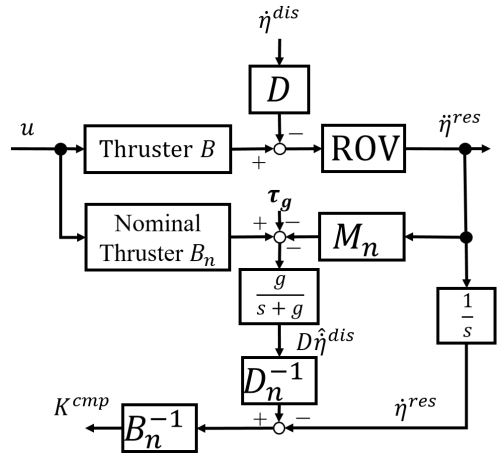


Fig. 5. Block diagram of disturbance estimation

A. Sliding Mode Control

Underwater robots are influenced by several disturbances such as ocean current and tidal current, and observation noise. In addition, there is the modeling error, since the structure of the underwater robot is complicated. Therefore, it is necessary to implement a robust controller for precise motion control.

This paper uses the sliding mode control as one of the robust controllers. Figs. 3-4 show the concept of the sliding mode control, and block diagram. As shown in Fig. 3, the sliding mode control converges the locus starting from an arbitrary point P to the origin in the phase plane.

The error between the command and response values are described as follows.

$$\boldsymbol{e} = \boldsymbol{\eta}^{cmd} - \boldsymbol{\eta}^{res} \tag{14}$$

where $\boldsymbol{e}$, $\boldsymbol{\eta}^{cmd}$, and $\boldsymbol{\eta}^{res}$ represent for the position error, position command, and position response. Switching function $\boldsymbol{\sigma}$ is calculated from switching surface $\boldsymbol{S}$ and $\boldsymbol{e}$.

$$\boldsymbol{\sigma} = \boldsymbol{S}\boldsymbol{e} + \dot{\boldsymbol{e}} \tag{15}$$

The control input $\boldsymbol{u}$ is obtained by using the sliding mode control.

$$\boldsymbol{u} = -\boldsymbol{Q}\boldsymbol{\sigma} - \boldsymbol{K}\mathrm{sgn}(\boldsymbol{\sigma}) \tag{16}$$

where $\boldsymbol{Q}$ and $\boldsymbol{K}$ represent for the proportional gain, and switching gain. sgn means the signum function.

As shown in Fig. 3, the control mode switches with the switching surface $\boldsymbol{S}$ as the boundary.

- Mode1: State to approach from an arbitrary point P to the switching surface $\boldsymbol{S}$
- Mode2: State to approach the origin along the switching surface $\boldsymbol{S}$
- Mode3: Steady state

By using this sliding mode control, robust motion against the disturbance is achieved.

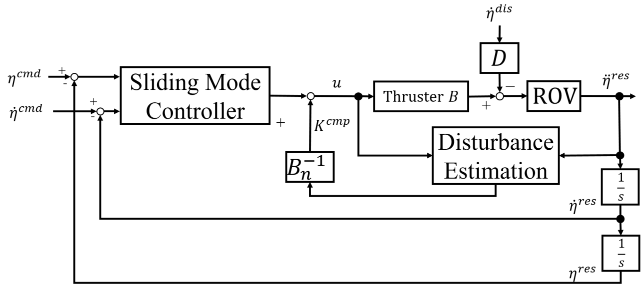


Fig. 6. Block diagram of proposed controller

B. Disturbance Estimation

This subsection describes the disturbance estimation. Several disturbances such as ocean current and tidal current influence the performance of underwater robots. In addition, since these disturbances are time-varying, it is difficult to create the disturbance model. Therefore, this paper proposed the disturbance estimation method to compensate these disturbances. This concept of this estimation is the same as disturbance observer (DOB) [13].

The equation of motion in the underwater robot is expressed as (12). The disturbances in the velocity dimension such as ocean current and tidal current are defined as $\dot{\boldsymbol{\eta}}^{dis}$. This research is assumed as the underwater robot is moving at a slow speed. Therefore, the Coriolis force is smaller than the fluid resistance. In this subsection, the fluid resistance $\boldsymbol{D}\dot{\boldsymbol{\eta}}^{dis}$ is treated as disturbance.

This paper is assumed that the thrust coefficient $\boldsymbol{B}$ is constant as $\boldsymbol{B}_n$. The driving force of the propeller is calculated from control input $\boldsymbol{u}_s$ and $\boldsymbol{B}_n$. The fluid resistance calculated from (12).

$$\boldsymbol{D}_n\dot{\boldsymbol{\eta}}^{dis} = \boldsymbol{\tau_t} - \boldsymbol{M}_n\ddot{\boldsymbol{\eta}}^{res} - \boldsymbol{g}(\boldsymbol{\eta}) + \boldsymbol{D}_n\dot{\boldsymbol{\eta}}^{res} \quad (17)$$
$$= \boldsymbol{B_n u} - \boldsymbol{M}_n\ddot{\boldsymbol{\eta}}^{res} - \boldsymbol{g}(\boldsymbol{\eta}) + \boldsymbol{D}_n\dot{\boldsymbol{\eta}}^{res} \quad (18)$$

where $\boldsymbol{M}_n$ and $\boldsymbol{D}_n$ represent for the nominal inertia matrix, and nominal fluid resistance coefficient. For noise reduction, the law-pass filter (LPF) is implemented.

$$\boldsymbol{D}_n\hat{\dot{\boldsymbol{\eta}}}^{dis} = \frac{g}{s+g}\boldsymbol{D}_n\dot{\boldsymbol{\eta}}^{dis} \quad (19)$$

where g and s represent for the cut-off frequency and Laplace operator. $\hat{\dot{\boldsymbol{\eta}}}^{dis}$ means the estimated disturbance in the velocity dimension.

The additional input $\boldsymbol{K^{cmp}}$ is calculated.

$$\boldsymbol{K^{cmp}} = \boldsymbol{B_n}^{-1}\hat{\dot{\boldsymbol{\eta}}}^{dis} \quad (20)$$

The additional input is added to the control input to compensate for the disturbance.

C. Whole Control System

This subsection describes the sliding mode control with disturbance estimation as the whole control system. For the robust control, the value of the switching gain $\boldsymbol{K}$ in (16) should be increased. However, if the value of the switching gain $\boldsymbol{K}$ sets to a high value, chattering may occur. There is the trade-off between chattering and robustness.

Fig. 6 shows the block diagram of the proposed controller. The proposed controller consists of the sliding mode control and disturbance estimation. The disturbance is estimated in real-time, and this estimated value is added to the control input.

$$\boldsymbol{u} = -\boldsymbol{Q\sigma} - \boldsymbol{K}\mathrm{sgn}(\boldsymbol{\sigma}) + \boldsymbol{K^{cmp}} \quad (21)$$

By using the disturbance estimation, the disturbance is compensated. Therefore, the disturbance to the underwater robot is treated as small. In other words, it is possible to set $\boldsymbol{K}$ a low value. As a result, a robust control system is achieved.

TABLE I
MECHANICAL PARAMETERS

m	Robot mass	$2.6[kg]$
$C_{\dot{u}}$	Additional mass (X)	$1.0[kg]$
$C_{\dot{v}}$	Additional mass (Y)	$2.0[kg]$
$C_{\dot{w}}$	Additional mass (Z)	$2.0[kg]$
$I_x + C_{\dot{p}}$	Inertia moment and additional mass (Roll)	$1.0[kg/m^2]$
$I_y + C_{\dot{q}}$	Inertia moment and additional mass (Pitch)	$1.0[kg/m^2]$
$I_z + C_{\dot{r}}$	Inertia moment and additional mass (Yaw)	$1.0[kg/m^2]$
B	Thruster coefficients	0.5
y_T	Thruster distance	$0.1[m]$
V	Underwater robot volume	$0.1[m^3]$

TABLE II
CONTROL PARAMETERS

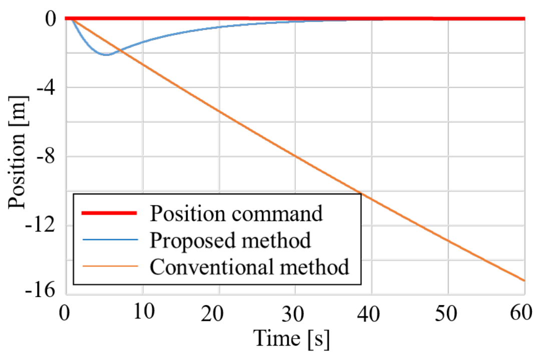
Q	Proportional gain	1.0
K	Switching gain	0.5
S	Switching surface	0.1
ΔT	Sampling time	$10[ms]$
g	Cut-off frequency	$5[Hz]$

IV. SIMULATION RESULTS

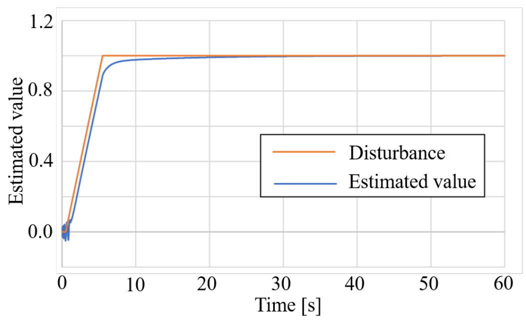
This section shows the simulation results by using the proposed method to confirm the validity of the proposed method. Table I and Table II shows the mechanical parameters and control parameters. The simulation environment was built with Webots [14]. In this simulation, the robot motion was assumed to be in one axis direction.

Two control methods were implemented; one is the sliding mode control (conventional method), and the other is the sliding mode control with the disturbance estimation (proposed method). The station keeping control was simulated. The position command is set to 0 [m]. The disturbance with a flow velocity of 1.0 [m/s] from 0.5[s] was given to the robot.

Fig. 7(a) and (b) show the position response and disturbance estimation in the simulation results. Fig. 8 shows the snapshot of this simulation. In Fig. 8, the blue line is the position command. The red square is the object to show the fluid force, and this object flew from the bottom to the top direction. In Fig. 7(a), the robot by using the conventional method was swept away by the flow. On the other hand, the station keeping was realized by using the proposed method. In Fig. 8(a), the

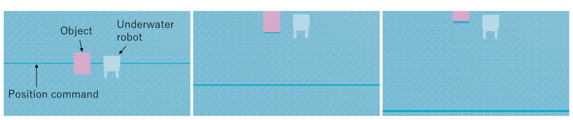


(a)Position response

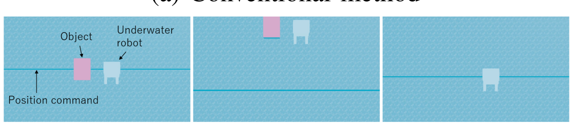


(b) Disturbance estimation

Fig. 7. Simulation results



(a) Conventional method



(b) Proposed method

Fig. 8. Snapshots of simulation results

underwater robot was swept by the fluid force. On the other hand, the underwater robot achieved station keeping as shown in Fig. 8(b). From Fig. 7(b), the disturbance was estimated in real-time. This estimation value was added to the control input to compensate for the disturbance. From these results, the validity of the proposed method was confirmed.

V. Experimental Results

This section shows the experimental results to confirm the validity of the proposed method. Fig. 9 shows the underwater robot which was used [15]. This underwater robot has IMU and depth sensor. In the water tank, the station keeping control was performed in the depth direction by using the depth sensor. The position command was set to -0.2 [m]. A 100g weight was used for the disturbance, and is attached to the robot

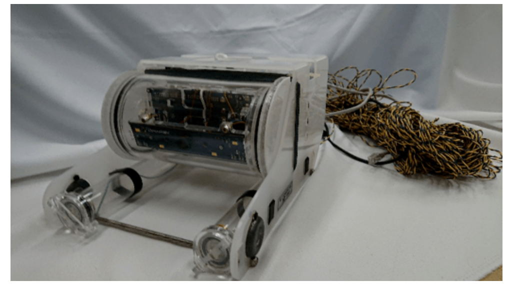


Fig. 9. Open ROV

body. Two control methods were implemented; one is the sliding mode control (conventional method), and the other is the sliding mode control with the disturbance estimation (proposed method).

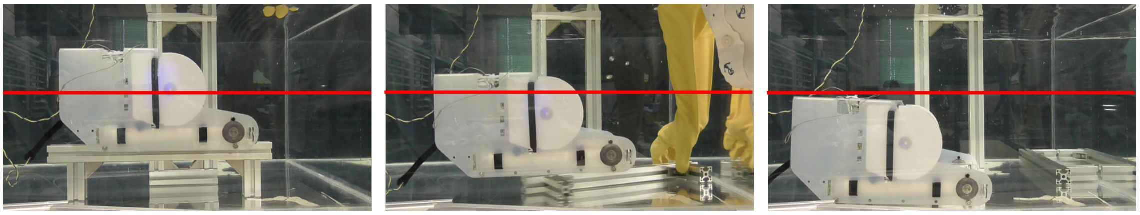
Fig. 10 and Fig. 11 show the experimental snapshots and experimental results. In Fig. 10, the red line means the position command. Left snaps were in the initial state, and the underwater robot stopped on the support frame. The center and right snaps show the scenes of experiments, and the underwater robot is controlled. As shown in Fig. 10(a), the underwater robot was sunk under the influence of the weight. As shown in Fig. 10(b), the underwater robot kept the constant position. Therefore, the station keeping control was achieved by using the proposed method.

Fig. 11(a) shows the estimation values, when several weights were attached to the underwater robot. The heavier the weight as the disturbance was, the higher the estimated value was. Therefore, the disturbance was estimated properly. Fig. 11(b) shows the experimental position response. -0.3[m] means the bottom of the water tank. By using the proposed method, the position response almost kept the position command. From these experimental results, the validity of the proposed method was confirmed.

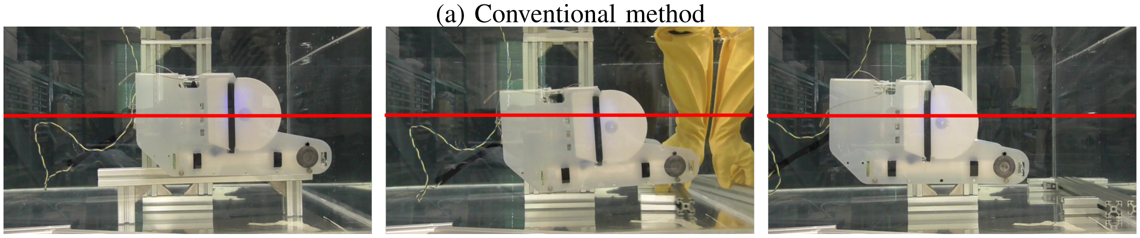
VI. Conclusions

This paper proposed the sliding mode control with the disturbance estimation. In the water, there are several disturbances such as ocean current and tidal current. Therefore, the sliding mode control which is one of the robust control methods is applied. In the sliding mode control, chattering tends to occur, if the switching gain K is set to a high value. On the other hand, it is desirable to set K high from the viewpoint of robustness. By using the proposed method, the robust control system was achieved even if K is set to a law value. Most of the disturbances were compensated by the disturbance estimation, and the sliding mode control was used for the precise motion. The validity of the proposed method was confirmed from the simulation and experimental results.

As future works, the underwater robot motion will be expanded to 3D motion. In addition, the experiments in the sea will be conducted.

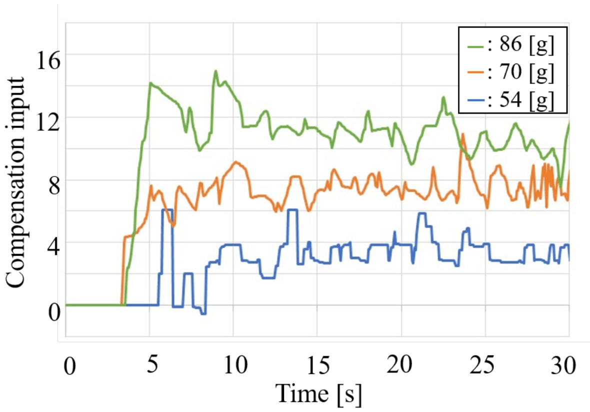


(a) Conventional method

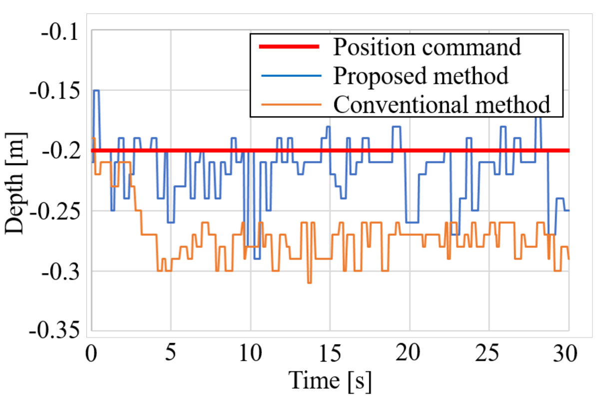


(b) Proposed method

Fig. 10. Snapshots of experimental results



(a) Disturbance estimation



(b) Position response

Fig. 11. Experimental results

ACKNOWLEDGMENT

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