

ROS-Based Depth Control for Hybrid-Driven Underwater Vehicle-Manipulator System

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Abstract: This paper presents an algorithmic solution for depth control. Depth control for Underwater Vehicle-Manipulator System (UVMS) is essential to complete a specific underwater manipulation. A large number of algorithms have been designed to tackle the depth control problem. However, because of water currents, algorithm for depth control is required strong robustness. This work describes an adaptive sliding mode control (SMC) method to implement the depth control. The designed SMC method combining the proposed adaptive algorithm can alleviate influence of uncertain parameters of system and external disturbances. The stability is proven by a Lyapunov function. Then, we build a ROS-based underwater simulation environment-UWSim. Real-time depth and velocity of UVMS can be obtained by depth gauge and IMU via ROS nodes. Finally, we conduct a depth control simulation with our proposed hybrid-driven underwater vehicle-manipulator system (HD-UVMS). A comparative simulation is also implemented to verify the effectiveness of the proposed method.

Key Words: Depth Control, Adaptive SMC, Underwater Vehicle-Manipulator System, ROS

1 Introduction

With the further development and utilization of ocean resources, an autonomous Underwater Vehicle-Manipulator System (UVMS) plays an important role in many applications which clearly demands intervention capabilities, such as archaeology research, recovery, and military operation[1]. Depth control for UVMS is particularly significant to execute accurate intervention manipulations. Depth sensors are deployed to help UVMS avoid underwater hazards. The depth control for UVMS is challenging because there are external disturbances in underwater environment[2]. In general, an accurate model of UVMS is hardly achievable. Evaluation the value of added mass and hydrodynamic damping force that acting on an underwater vehicle is tough[3]. In order to solve these problems, some researchers have raised a series of solutions.

Many control strategies have been adopted for depth control of UVMS, such as fuzzy logic control, back-stepping control, and multivariable sliding mode control. D. Gao proposed an optional internal model control (OIMC) with respect to the quadratic performance indexes to control depth of an underactuated autonomous underwater vehicle (AUV), which demonstrated effectiveness and robustness of the controller[4]. A back-stepping controller based on nonlinear disturbance observer was implemented to track the desired depth of AUV. The back-stepping controller could suppress uncertain hydrodynamic parameters and unknown disturbances effectively[5]. In Ref.[6], a nonlinear PID depth controller with adaptive compensation was given to overcome the response speed of the actuator in depth control with external bounded interference and model parameter uncertainties. It is well known that sliding mode control in nonlinear system has good performance, which can drive the

error dynamic towards a predefined surface. An expanded adaptive fuzzy sliding mode controller based on the decomposition method was applied in the underwater flight vehicle (UFV) depth control system[7]. A numerical simulation verified its performance. Besides UVMS, depth control for robotic fishes also capture many interests. A hybrid controller combining sliding-mode control (SMC) with a fuzzy strategy to regulate the vertical displacement of a bioinspired robotic dolphin was built[8]. Some experimental results showed that the proposed control strategy successfully steered the robot toward and along the desired depth.

The Robot Operating System (ROS) has been applied in many underwater research, and it also play a key role in this work. It is of utmost importance for UVMS to conduct simulation before sea experiments. To facilitate the development and application of UVMS, ROS provides many packages to implement underwater dynamics simulation[9]. UWSim is a software tool for visualization and simulation of UVMS missions. UWSim software is visually realistic through OpenSceneGraph (OSG) and osgOcean, and can allow users configure important parameters about underwater environment. A simulation scene can be loaded in UWSim as long as it is exported to any of the OSG formats[10]. Note that UWSim do the interface with external control programs through ROS.

This paper is organized as follows: Section II briefly describes our proposed platform and the ROS-based simulation environment. Section III presents an overview of the depth control based on adaptive sliding mode control. Depth control simulation in UWSim is described in Section IV and finally, Sections V concludes this paper.

2 The Design of HD-UVMS and Simulation Environment

This section mainly presents the structure of HD-UVMS and the construction process for building a ROS-based underwater simulator.

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2.1 The Structure of HD-UVMS

The proposed HD-UVMS is equipped with a hybrid-driven system, a 4-DOF underwater manipulator with unique electrical design, and some sensors, such as depth gauge, IMU, binocular cameras. HD-UVMS adopts a hybrid-driven strategy to accomplish underwater manipulation in sea environment. The hybrid-driven system mainly consists of four thrusters and two long fin propulsors, which can implement high efficiency cruise with thrusters and stably approach to targets with long fin propulsors. Note that the two vertical thrusters can change the depth of HD-UVMS while the two horizontal thrusters perform in-plane maneuvers such as going forward, backward, turning to the left and right. Similarly, the two long fin propulsors can assistant HD-UVMS carry out planar motion with sinusoidal wave, which is efficient for hovering. PC 104 in the control cabin can receive and decode the signals from thruster control board, and send corresponding control signals to the control board to enable thrusters. Depth gauge can measure the distance between HD-UVMS and water surface. Two binocular cameras can capture pictures of underwater environment to navigate HD-UVMS. The 4-DOF manipulator can grasp marine products, such as sea cucumber, scallop, and sea urchin. The detailed structure of HD-UVMS is depicted in Fig. 1.

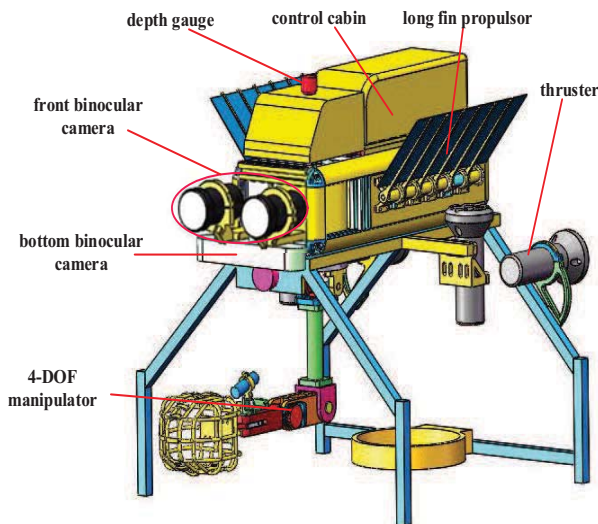


Fig. 1: The structure of HD-UVMS

2.2 ROS-based Underwater Simulation Environment

Underwater simulation test plays an important role in underwater manipulation before real sea environment. ROS provides a software package UWSim for developing underwater physical simulation test. The virtual underwater environment can be built with 3ds MAX and be shown via Open Source Graph (OSG). As shown in Fig. 2, the structure of UWSim mainly consists of ROS-interface, dynamic model, UWSim configuration, and osgOcean. Basically, UWSim is a core module in charge of loading the main scene and its simulated robots. The interfaces module provides communication with external architectures. The dynamics module contains underwater vehicle dynamics. The osgOcean is in charge of rendering the ocean surface. Three-dimensional model of HD-UVMS can be translated into URDF file,

which can be imported into the UWSim, as shown in Fig. 3. In the UWSim, HD-UVMS can accomplish basic motion modes with dynamic models. In the process of real underwater manipulation, the two vertical thrusters mainly offer function of depth control. So, in the following section, the proposed depth control method is implemented by the two vertical thrusters.

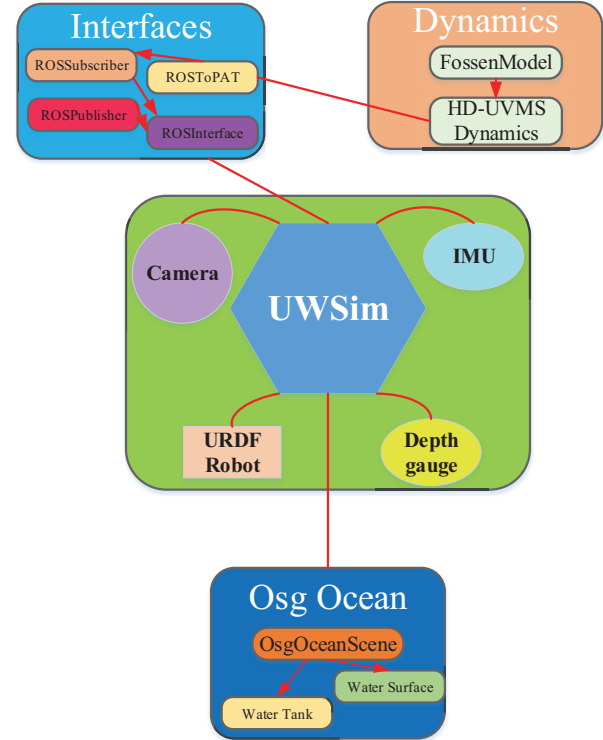


Fig. 2: A diagram of UWSim

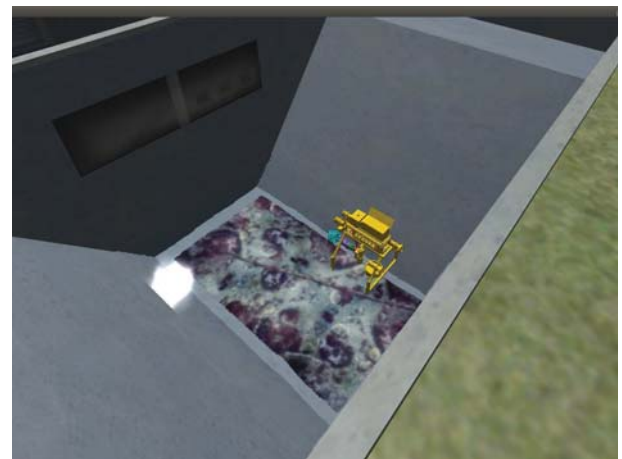


Fig. 3: UWSim enviroment of the HD-UVMS

3 Depth Control of HD-UVMS Based on Adaptive Sliding Mode Control

In this section, adaptive SMC for depth control of HD-UVMS is presented and a comparative PID method performances are compared. The real depth measured by the depth gauge can be regarded as feedback of loop-control method.

3.1 The Dynamic Modeling of HD-UVMS and Adaptive Sliding Mode Control Method

Considering we only care about the control of the depth (Z-direction), the dynamic modelling of depth for HD-UVMS can be described as[11]:

$$\begin{cases} \dot{z} = w \\ \dot{w} = \frac{1}{m_{33}}\tau_w + \frac{1}{m_{33}}\tau_{dw} - \frac{d_{33}}{m_{33}}w \end{cases} \quad (1)$$

where z stands for depth, w denotes the velocity in heave, m_{33} denotes the element of inertia matrix in heave, τ_w represents the input control value of system, τ_{dw} denotes the external disturbances in heave. In order to simplify the dynamic model, (1) can be presented as :

$$\begin{cases} \dot{z}(t) = w(t) \\ m_{33}\dot{w}(t) = \tau_w(t) + \delta(t) \end{cases} \quad (2)$$

where $\delta(t) = \tau_{dw}(t) - d_{33}w(t)$ stands for external disturbances and the system parameter variations.

Generally speaking, there are many disturbances in the movement process of underwater robots. SMC is commonly favored as a powerful robust control method for dynamic positioning and motion control owing to its insensitivity to model mismatches. We adopt an adaptive SMC algorithm to design a feedback control law that can drive HD-UVMS track depth to desired value. The adaptive SMC manifold can be described as:

$$s(t) = \dot{e}(t) + c e(t) \quad (3)$$

where $e(t) = z(t) - z_d(t)$, $z_d(t)$ represents the desired depth, $z(t)$ denotes the actual depth, $e(t)$ denotes the tracking error, and $\dot{e}(t)$ represents the derivative of tracking error.

According to (3), the following equation can be derived:

$$m_{33}\dot{s}(t) = m_{33}(\dot{w}(t) - \ddot{z}_d(t) + c\dot{e}(t)) \quad (4)$$

Lyapunov-function candidate can be chosen as:

$$V(t) = \frac{1}{2}m_{33}s^2(t) + \frac{1}{2\eta}\tilde{m}_{33}^2 \quad (5)$$

where $\tilde{m}_{33} = \hat{m}_{33} - m_{33}$, \hat{m}_{33} denotes the estimation of the m_{33} , $\eta > 0$.

Differentiate $V(t)$ with respect to time t , we can obtain the following equation:

$$\begin{aligned} \dot{V}(t) &= m_{33}s(t)\dot{s}(t) + \frac{1}{\eta}\tilde{m}_{33}\dot{\tilde{m}}_{33} \\ &= s(t)[m_{33}\dot{w}(t) - m_{33}\ddot{z}_d(t) + m_{33}c\dot{e}(t)] + \frac{1}{\eta}\tilde{m}_{33}\dot{\tilde{m}}_{33} \\ &= s(t)[\tau_w(t) + \delta(t) - m_{33}(\ddot{z}_d(t) - c\dot{e}(t))] + \frac{1}{\eta}\tilde{m}_{33}\dot{\tilde{m}}_{33} \end{aligned} \quad (6)$$

The control law can be presented as follows by the SMC method:

$$\tau_w(t) = \hat{m}_{33}(\ddot{z}_d(t) - c\dot{e}(t)) - ks(t) - \mu \text{sign}(s(t)) \quad (7)$$

where $k > 0$ and $\mu > 0$.

Combining (6) and (7), the following equation can be obtained:

$$\dot{V}(t) = -ks^2(t) - \mu|s(t)| + \delta(t)s(t) + \tilde{m}_{33}\left[s(t)(\ddot{z}_d(t) - c\dot{e}(t)) + \frac{1}{\eta}\dot{\tilde{m}}_{33}\right] \quad (8)$$

According to (8), adaptive law can be concluded as:

$$\dot{\hat{m}}_{33} = -\eta s(t)(\ddot{z}_d(t) - c\dot{e}(t)) \quad (9)$$

To sum up, we can get the following conclusion:

$$\begin{aligned} \dot{V}(t) &= \delta(t)s(t) - ks^2(t) - \mu|s(t)| \\ &\leq ks^2(t) \\ &\leq 0 \end{aligned} \quad (10)$$

Only when $s(t)=0$, $\dot{V}(t)=0$. So, the proposed system is asymptotically stable.

In order to avoid the big error of \hat{m}_{33} to cause inappropriate value of $\tau_w(t)$, we design a projection-based adaptive law algorithm to revise the value of \hat{m}_{33} in range of $[m_{33 \min}, m_{33 \max}]$. The algorithm is presented as follows:

$$\dot{\hat{m}}_{33} = \text{Pr}_{o_{\hat{m}_{33}}}(-\eta s(t)(\ddot{z}_d(t) - c\dot{e}(t))) \quad (11)$$

where

$$\text{Pr}_{o_{\hat{m}_{33}}}(\varepsilon) = \begin{cases} 0 & \text{if } (\hat{m}_{33} \geq m_{33 \max}) \&\& (\varepsilon > 0) \\ 0 & \text{if } (\hat{m}_{33} \leq m_{33 \min}) \&\& (\varepsilon < 0) \\ \varepsilon & \text{otherwise} \end{cases} \quad (12)$$

In order to verify the convergence of the method, we built a Matlab-Simulink simulation for adaptive SMC combining the HD-UVMS dynamics, as shown in Fig. 4.

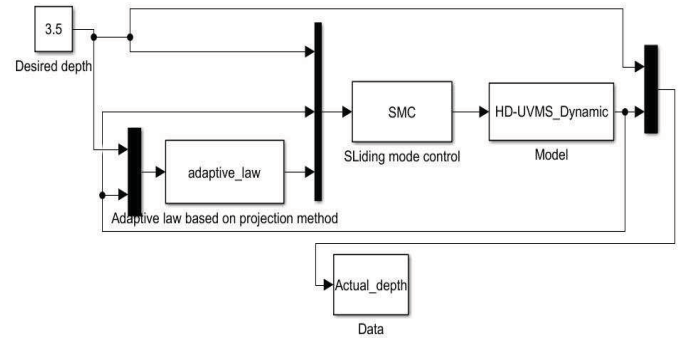


Fig. 4: Block diagram of Matlab-Simulink for adaptive SMC.

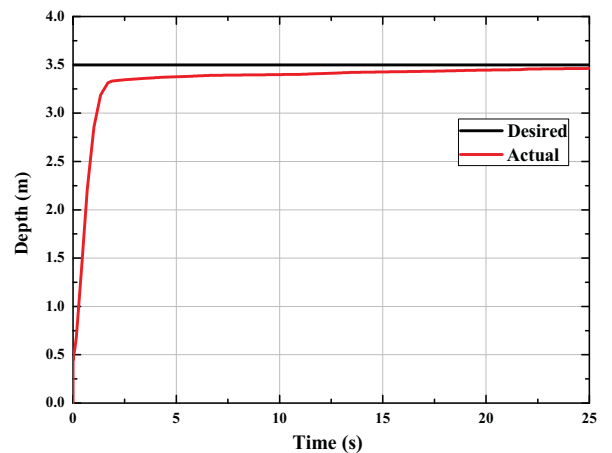


Fig. 5: Time evolution of feedback law.

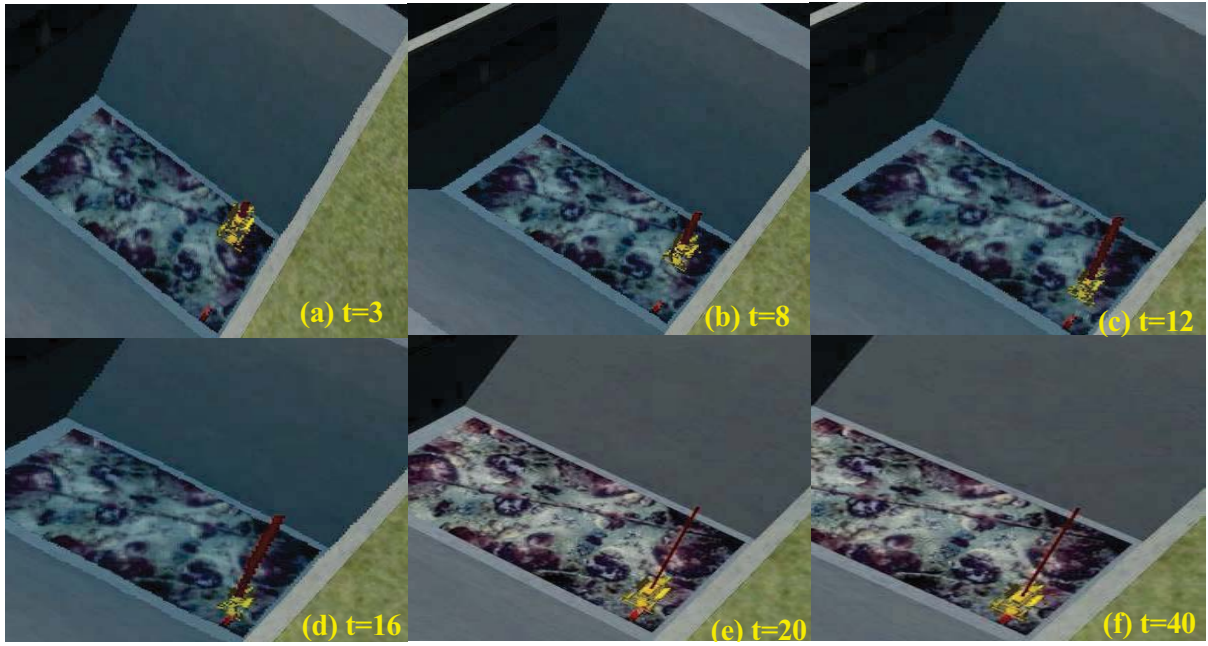


Fig. 7: Snapshot sequences of depth control for HD-UVMS

Fig. 5 presents the actual depth can converge to the desired value with adaptive SMC. The convergence time depends on the characteristics of system.

In Fig. 6, the time evolution of feedback law τ_{dw} illustrates that it can converge to zero when the actual depth reaches the desired value.

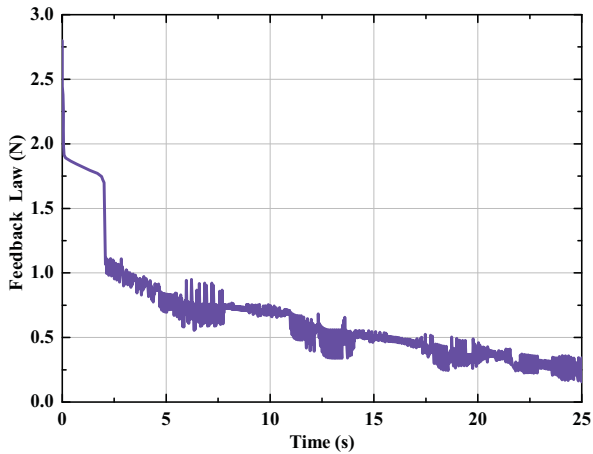


Fig. 6: Time evolution of feedback law.

4 Depth Control Simulation and Analysis

In order to verify the effectiveness of proposed algorithm, we conducted numerical simulations in ROS-based environment. First of all, we import the Unified Robot Description Format(URDF) file of HD-UVMS into UWSim and the scene will be shown. Then, we set the dynamic parameters of HD-UVMS, and the dynamic modelling for UWSim is built. Finally, the depth control with adaptive SMC method is conducted. Meanwhile, the comparative experiment with PID method is implemented.

4.1 Depth Control with Adaptive SMC Method

According to the above mentioned adaptive SMC method, we designed a control framework as shown in Fig. 8. The depth of HD-UVMS can be obtained by depth gauge, which is designed in UWSim with the characteristics measuring water pressure. Similarly, the IMU is also created in UWSim to measure the motion state of HD-UVMS. With the aids of virtual sensors, the implemented algorithm is tested on HD-UVMS in the proposed simulation environment.

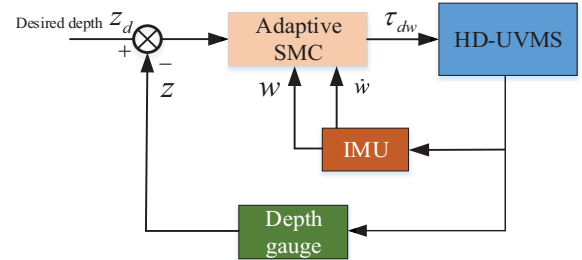


Fig. 8: Framework of depth control with adaptive SMC

The snapshot sequences of depth control with adaptive SMC are shown in Fig. 7. This test lasts approximately 40 s. The HD-UVMS can maintain the desired depth from 20 s to 40 s corresponding to Fig. 7(e)-(f). According to the real-time depth and velocity by ROS nodes, HD-UVMS gradually approach to the desired depth. The adaptive SMC can guarantee the tracking error converge to zero. A comparative experiment was formulated to verify the performance of the adaptive SMC method compared to that of a cascaded PID controller, as is illustrated in Fig. 9.

Fig. 10 depicts the corresponding depth of HD-UVMS. The reference depth is set as 3.5m, and the results indicated that both controllers are able to converge to the desired depth. However, the adaptive SMC controller is more stable than the PID controller.

As clearly displayed in Fig. 11, the feedback law τ_{dw}

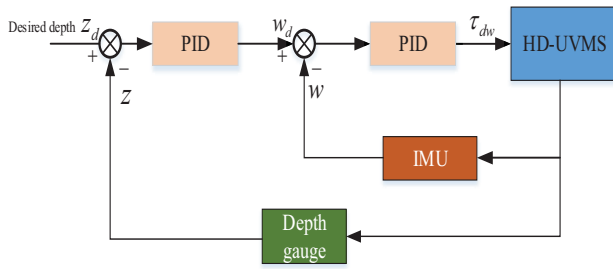


Fig. 9: Cascaded PID controller. The position PID outputs a velocity setpoint that is then followed with the velocity PID.

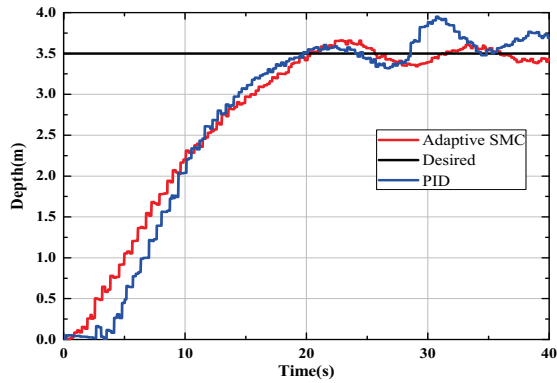


Fig. 10: Time evolution of depth with adaptive SMC and PID, respectively. The black line denotes the desired depth, the red line denotes the change of depth with adaptive SMC, and the blue line denotes the change of depth with PID controller.

gradually converges to zero with the change of depth. However, the feedback law shows small oscillation owing to the noisy of depth gauge and IMU from 20 s to 40 s.

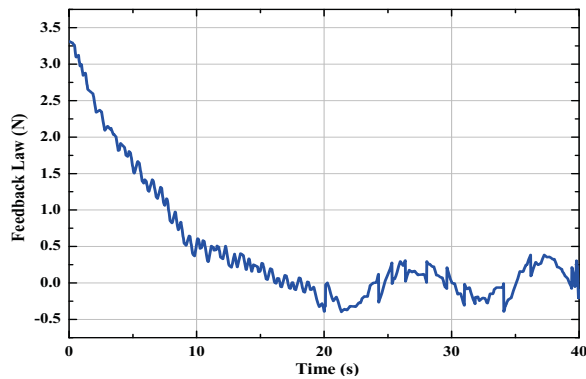


Fig. 11: Time evolution of feedback law.

5 Conclusion

In this paper, we have designed an adaptive SMC algorithm to achieve depth control for HD-UVMS. The HD-UVMS can implement heave motion with two vertical thrusters. The depth gauge and IMU in the UWSim can measure motion state of HD-UVMS, which can be collected through ROS nodes. Based on the collected data, an adaptive SMC method is described and the stability of proposed system is analytically proved using Lyapunov stability theory. Finally, the

performance of the proposed method is investigated based on UWSim environment. A comparative simulation is conducted with PID controller. The simulation results confirm the validity of the proposed methods.

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