Control design of motion of Autonomous Underwater Vehicle (AUV) with Active Ballast using Sliding Mode Control

Mardlijah*, A Chandra, D Adzkiya
Department of Mathematics, Institut Teknologi Sepuluh Nopember, Kampus ITS
Sukolilo-Surabaya 60111, Surabaya, Indonesia
E-mail: mardlijah@matematika.its.ac.id

Abstract. Autonomous Underwater Vehicle (AUV) is an unmanned submarine that is currently being developed. In this research, a sliding mode controller will be designed to adjust the following motion of an AUV: surge, heave and yaw. We developed a mathematical model for an AUV with active ballast at a certain depth. The results showed that the hitting time for surge, heave, yaw motions is less than 12.7 seconds, 9.8 seconds and 6.9 seconds, respectively. Steady state error on surge, heave and yaw motion is less than 0.0003%, 0.0005% and 0.0003%. Finally, overshoot of the response of each motion is 0%.

1. Introduction
Indonesia is a country with a fairly large area which is mostly consists of oceans. With the existence of a vast ocean, there are a lot of natural resources available in Indonesia. Therefore, as humans who need natural resources, it is appropriate to care for, monitor, protect and preserve them. In monitoring natural resources in the oceans, we must be careful because the depth of the sea in Indonesia itself is different. Therefore, we need a tool to overcome this. The underwater technology that has been developed recently is the Autonomous Underwater Vehicle (AUV) [1].

AUV is an unmanned underwater vehicle that can move in 6 degrees of freedom and travel in the water using a propulsion system, controlled and then steered by the operator with the help of a computer on board a support vessel based on a navigation, guidance and control system. AUV is very important in underwater activities because it has a higher speed, endurance and diving ability than humans. The AUV application contributes to the science, environment, oil and gas industry, as well as the military. Some examples of the advantages of using AUV, namely seabed mapping, environmental improvement of underwater structures including pipelines and dams, construction and maintenance of underwater structures, and search and disposal of shallow water mines [2].

There are so many components which certainly play an important role in the operation of the AUV. One of the important components in the AUV is an active ballast. The active ballast is a tool used to adjust the mass of water at AUV. The ballast tanks are intended as a counterweight and active ballast system on the AUV to be able to dive and float as needed [3]. It is also necessary to have an optimal speed input which later can be used for better AUV control. To serve an optimal speed input, it is necessary to control the motion of AUV.
One of the best methods to solve this problem is sliding mode control. Sliding Mode Control (SMC) is a high-speed switching feedback control that can be applied to both linear and nonlinear systems [4]. The working principle of sliding mode control is to force the trajectory state of a system to a certain sliding surface and maintain it on the sliding surface. SMC has several advantages, namely that it is very robust, and works well on nonlinear systems that have model or parameter uncertainties [5]. There are many works on SMC in the literature. We will mention some of them here. First of all, Mardlijah et al. designed a controller for a solar panel system using Fuzzy SMC in [6]. Then, Mardlijah et al. combined Type 2 Fuzzy SMC and the firefly algorithm to design a controller for a mobile inverted pendulum in [7] and a solar panel system in [8]. After that, Mardlijah et al. proposed a Modified Type 2 SMC method and its applications to solar panel systems in [9]. In this paper, we discuss control design of surge, heave and yaw motions of UAV with active ballast by using sliding mode control.

2. AUV Model with Active Ballast

The AUV motion equation consists of translational and rotational motion. The translational motion consists of surge, sway and heave, while rotational motion consists of roll, pitch and yaw. Since we focus on an AUV under the low speed condition, some translational motions are ignored, such as sway, pitch and roll motion. We obtained the following surge, heave and yaw acceleration:

\[
\dot{q} = \frac{Xqq + X_{qq}|q| + X_{prop}}{m - X_q}, \\
\dot{w} = \frac{Z_{ww} + Z_{ww}|w| - (ballast) + Z_{qqw}q + Z_{qqq}qw}{m - Z_w}, \\
\dot{r} = \frac{N_{rr}r + N_{rr}|r| + N_{qqr}qr}{I_{zz} - N_r},
\]

where

\[
ballast = \left( \rho ag \int_{-h}^{0} A(h) dh \right) - \left( \rho bg \int_{-h}^{L-h} A(h) dh \right).
\]

A linear equation is formed as follows:

\[
\dot{x}(t) = \begin{bmatrix} -0.2448 & 0 & 0 \\ 0.0344 & 0.1579 & 0 \\ 0 & 0 & 0.3881 \end{bmatrix} \begin{bmatrix} q \\ w \\ r \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1.92 & 0 \\ 0 & 0 & -1.92 \end{bmatrix} \begin{bmatrix} X_{prop} \\ \delta_s \\ \delta_r \end{bmatrix},
\]

\[
y(t) = \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ w \\ r \end{bmatrix} + [0][u],
\]

where \(X_{prop}\) is the propeller thrust, \(\delta_s\) is the control for sway and yaw, and \(\delta_r\) is the control for heave and roll.

3. Motion control design with Sliding Mode Control method

In designing a motion control system using the Sliding Mode Control (SMC) method, the procedure will be divided into three steps, namely the design of a motion control system for surge, heave, and yaw motion.
3.1. Surge motion control system design

In designing the input control of the surge motion, the first step is to determine the tracking error of the surge as follows:

\[ \tilde{q} = q - q_d, \]

where \( q_d \) is a constant. Because the system is of order 1, the following switching function is formed:

\[ S_1(q,t) = \left( \frac{d}{dx} + \lambda \right)^{n-1} \tilde{q}, \]

where \( n = 1 \). The derivative of \( S_1 \) is

\[ \dot{S}_1(q,t) = \dot{q} - \dot{q}_d. \] (2)

Because \( q_d \) is a constant then \( \dot{q}_d = 0 \). By substituting equation (1) to equation (2), we obtain:

\[ \dot{S}_1(q,t) = -0.2448q + X_{\text{prop}}. \] (3)

Furthermore, the value of \( \dot{X}_{\text{prop}} \) is determined by substituting \( \dot{S}_1(q,t) = 0 \), in order to obtain:

\[ \dot{X}_{\text{prop}} = 0.2448q. \] (4)

Based on the control law, the equation that fulfills the sliding conditions is:

\[ X_{\text{prop}} = \dot{X}_{\text{prop}} - K_1 \text{sgn}(S_1). \] (5)

So from equations (4) and (5), we obtained:

\[ X_{\text{prop}} = 0.2448q - K_1 \text{sgn}(S_1). \] (6)

By substituting equation (3) to (6), we get:

\[ \dot{S}_1(q,t) = -K_1 \text{sgn}(S_1). \] (7)

Then the value of \( K_1 \) will be designed by substituting equation (7) into equation (8) so that it meets the sliding conditions, namely:

\[ S_1 \dot{S}_1 \leq -\eta |S_1|. \] (8)

So we get:

\[ -K_1 \text{sgn}(S_1) \leq -\eta. \] (9)

From equation (9), we obtained that the value of \( K_1 \) is:

\[ K_1 = \max |\eta|. \] (10)

Then a boundary layer is used to minimize chattering by changing the sign function to a saturation function as follows:

\[ X_{\text{prop}} = \dot{X}_{\text{prop}} - K_1 \text{sat} \left( \frac{S_1}{\phi} \right). \] (11)

With this, the control design obtained from substituting equations (4) and (10) into equation (11) is as follows:

\[ X_{\text{prop}} = 0.2448q - \max |\eta|. \text{sat} \left( \frac{S_1}{\phi} \right) \]
3.2. Heave and yaw motion system control design

The steps used in designing the heave and yaw motion are the same as the design of the surge motion control, so that the heave motion control system design is obtained as follows:

$$\delta_s = 0.0344q + 0.1579w - (-\eta - 1) \cdot \text{sat} \left( \frac{S_2}{\phi} \right),$$

where

$$K_2 = -\eta - 1.$$  

Meanwhile, the yaw motion control system design is as follows:

$$\delta_r = 0.3881r - (-\eta - 1) \cdot \text{sat} \left( \frac{S_3}{\phi} \right),$$

where

$$K_3 = -\eta - 1.$$  

4. Simulation and results

After the design of the SMC control system on the 3-DOF linear model is obtained, we implement the closed-loop system by using SIMULINK. The purpose of the implementation is to measure the performance of the obtained closed-loop system via conducting some simulations. Figure 1 is a block diagram of the AUV once given the controls.

The 3-DOF AUV Motion block represents the AUV motion with 3-DOF expressed in equation (1). The SMC controller contains the control law derived in the previous section. There are three set-points, i.e. for surge, heave and yaw motions. Furthermore, observe that there is a feedback mechanism in order to determine the controller. The three blocks on the right are used to display the results.

![Figure 1. The closed-loop system block diagram using the SMC method.](image)

The detailed implementation of SMC control law is shown in Figure 2. The detailed implementation of the 3-DOF AUV model is displayed in Figure 3. Next, we describe the scenario in the simulations in detail.
Figure 2. The sliding mode controller subsystem.

Figure 3. The 3-DOF AUV model block diagram.

For the surge motion, two set points are used, each with value of 0.5 m/s and 1 m/s. Figure 4 (left) shows the response of the surge motion with set point value 0.5 for the first time to reach stability (settling time) at 14.3 seconds, a steady state error of 0.0003% and overshoot 0%. Figure 4 (right) is the result of the response of the surge motion with set point value 1 with the SMC method, where the response of the surge motion reaches a settling time at 13.3 seconds, a steady state error of 0.0001% and overshoot 0%.

For heave motion, two set points are used, each with value of 1 m/s and 4 m/s. Figure 5 (left) shows the response of the heave motion with the first set point value 1 reaching stability (settling time) at 7.3 seconds, a steady state error of 0.0005% and overshoot of 0%. Figure 5 (right) is the result of the heave response with set point value 4 with the SMC method, where the heave motion response reaches a settling time at 3.8 seconds, a steady state error of 0% and overshoot 0%.

Meanwhile, for the yaw motion, three set points are used with each of the values 0.78 rad/s (45°) and -0.78 rad/s (-45°). Figure 6 (left) shows the response of the yaw motion with set point value 0.78 for the first time to reach stability (settling time) at 6.5 seconds, a steady state
Figure 4. Surge response when the set point is 0.5 m/s and 1 m/s.

Figure 5. Heave response when the set point is 1 m/s and 4 m/s.

error of 0% and overshoot 0%. Figure 6 (right) is the result of the response of yaw motion with set point value -0.78 with the SMC method, where the response of the yaw motion reaches a settling time at 6.9 seconds, a steady state error of 0% and overshoot 0%.

Figure 6. Yaw response when the set point is 0.78 rad/s (45°).
5. Conclusions

Based on simulation result, we can conclude that the control law for surge, heave and yaw motion on Autonomous Underwater Vehicle (AUV) by using Sliding Mode Control (SMC) is

\[ X_{prop} = 0.2448q - \max|\eta| \cdot \text{sat} \left( \frac{S_1}{\phi} \right) \]

\[ \delta_s = 0.0344q + 0.1579w - (-\eta - 1) \cdot \text{sat} \left( \frac{S_2}{\phi} \right) \]

\[ \delta_r = 0.3881r - (-\eta - 1) \cdot \text{sat} \left( \frac{S_3}{\phi} \right) \]

The performance of the Autonomous Underwater Vehicle motion control using the Sliding Mode Control method shows that the surge, heave and yaw motion is stable towards the given set point values. Surge response is given two set points resulting in settling time less than 14.3, steady state error less than 0.0003% and overshoot 0%. The response of heave motion is given two set points resulting in a settling time of less than 9.8, a steady state error of less than 0.0005% and an overshoot of 0%. For the response of yaw motion given two set points resulting in settling time less than 6.9, steady state error less than 0.0003% and overshoot 0%. This shows that the SMC method works well on AUV motion systems with active ballasts.

References

[1] Puspita S 2019 Model regresi linear dari ballast aktif pada autonomous underwater vehicle (auv)
[2] Yang C 2008 Modular modeling and control for autonomous underwater vehicle (AUV) Ph.D. thesis National University of Singapore
[3] Hatinoto R 2018 Analisa sistem ballast aktif desain auv-militus (autonomous underwater vehicle multi purpose intelligent tandem unmanned system)
[4] Mursyitah D 2014 Jurnal Teknik Elektro 3 112–116
[5] Cahyani N D 2018 Perbandingan metode smc dan pid pada rancangan sistem kontrol gerak autonomous surface vehicle (asv) terhadap pengaruh lingkungan
[6] Mardlijah M, Ismanto W and Usadha I R 2009 Limits: Journal of Mathematics and Its Applications 6 35–50
[7] Mardlijah, Jazidie A, Widodo B and Santoso A 2013 International Review of Automatic Control (IREACO) 6 431–440
[8] Mardlijah M and Zuhri Z 2018 TELKOMNIKA (Telecommunication Computing Electronics and Control) 16 2988–2998
[9] Mardlijah, Zhai G, Adzkiya D, Mardianto I and Ikhwan M 2019 Systems Science & Control Engineering 7 189–197