Autopilot system design on monohull USV- LSS01 using PID-based sliding mode control method

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Abstract. The Autopilot system for Unmanned Surface Vehicle (USV) can be applied by Sliding Mode Control which is a high frequency switching based control method and has discontinuous control action causing chattering on the system. Therefore, the Sliding Mode Control with natural control signal using a PID controller structure is applied to the USV. By using Sliding Mode Control, USV is expected to move accurately from the expected waypoint without any chattering on the system. The stability of the whole loop of system regulation is ensured using the Lyapunov stability function. The simulation results for autopilot system validate that the control parameters fit the time constant controller design specification and have zero steady-state errors. Further, autopilot system with waypoint navigation relatively generates small Mean Square Error (MSE) of waypoint.

1. Introduction
Unmanned surface vehicle (USV) or the unmanned vessel, currently has a very rapidly developing role, including in the fields of industry, military, and scientific research. In its development, USV requires a sophisticated control system, sensor systems, communication systems, and weapon systems to be able to complete several missions, such as sea patrol, environmental monitoring, and explorers. To achieve those needs, marine vehicles are required to move automatically without operator supervision. Automatic movement of vessel requires an autopilot system algorithm [1]. The autopilot system is the control of a vessel to move in a certain direction at a predetermined track point, which is named as waypoint.

To maneuver, USV requires propulsion devices and steering devices. The propulsion most used is the thruster using the electric BLDC motor and the steering device using a rudder. USV modeling generally using three approaches degree of freedom which consists of three axes, namely surge, sway, and yaw [2].

USV will face external disturbance including winds, waves, and currents when move at sea. Control action is required to investigate the different both moving without disturbance and with disturbance. Then, USV is expected to maneuver well in both conditions.

One way to apply the autopilot system which can overcome the external disturbance is by designing a Sliding Mode Control method. Sliding Mode Control Method is a control technique which can be used in the nonlinear plant [3]. The basic principle for Sliding Mode Control consists of displacement or movement state of the track toward the sliding surface and keep it around its area with a sliding function [4].

However, Sliding Mode Control Method has the disadvantage that generating of chattering or high frequency switching in the control signal caused by the discontinuous of the natural control signal in the system. Therefore, in this research the PID controller is used as a natural input system which can reduce
the effects of chattering [5]. By designing PID-based Sliding Mode Control it is expected that USV can move at the sea and capable to move through waypoints that have been predetermined, either without external disturbance or with external disturbance.

2. USV LSS01

2.1 Overview

The USV-LSS01 type unmanned surface vehicle is the name of the USV Monohulls owned by the Laboratory of Systems and Cybernetics, Department of Electrical Engineering, ITS. It uses thruster as a propulsion and rudder as the steering device. The thruster machine is used to give a thrust to the USV and the steering device is used to set the direction of the USV for turning [6].

2.2 Mathematical Model

The mathematical model of USV was obtained by following the 6-dof model of unmanned surface vehicles[7]. However, the model was adjusted to the following assumptions:

1. Roll, pitch, dan heave movements are ignored.
2. The vessel has the homogenous mass distribution on xz-plane.
3. The center of gravity and center of buoyancy placed vertically on z-axis.

Based on the above assumptions, then the mathematical model of USV-LSS01 could be expressed in 3 degrees of freedom (surge, sway, and yaw) as follows:

\[
\begin{align*}
\dot{\eta} &= J(\eta) \nu \\
M \dot{\nu} &= -C(\nu) \nu - (D + D_n(\nu)) \nu + \tau + \tau_E
\end{align*}
\]

where \( \eta = [x \ y \ \psi]^T \) is the position and orientation vector with coordinates in the earth fixed frame and \( \nu = [u \ v \ r]^T \) is the linear and angular velocity vector with coordinates in the body-fixed frame. 

\( J(\eta) \) is a transformation matrix defined as follows:

\[
J(\eta) = \begin{bmatrix}
\cos(\psi) & -\sin(\psi) & 0 \\
\sin(\psi) & \cos(\psi) & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\( M \) is a sum of the rigid body system inertia matrix and the added mass matrix defined as follows:

\[
M = \begin{bmatrix}
m - X_\ddot{u} & 0 & 0 \\
0 & m - Y_\dot{v} & mx_g - Y_r \\
0 & mx_g - Y_r & I_z - N_r
\end{bmatrix}
\]

\( C(\nu) \) is a sum of the rigid body Coriolis and centripetal matrix and the hydrodynamic Coriolis and centripetal matrix defined as follows:

\[
C(\nu) = \begin{bmatrix}
0 & 0 & -m(x_g r + v) + Y_\dot{v} v + Y_r r \\
0 & 0 & m u - x_\ddot{u} u \\
m(x_g r + v) - Y_\dot{v} v - Y_r r & -m u + x_\ddot{u} u & 0
\end{bmatrix}
\]
$D$ and $D_n(v)$ each is the linear damping matrix and the nonlinear damping matrix defined as follows:

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

(6)

$$D_n(v) = \begin{bmatrix} X_{|u|u}|u| & 0 \\ 0 & Y_{|v|v}|v| + Y_{|r|r}|r| \\ 0 & N_{|v|v}|v| + N_{|r|r}|r| \end{bmatrix}$$

(7)

Input force of $\tau$ for the vessel’s system has only two components, which are input forces in the direction of surge and yaw. Force vector of input $\tau$ defined as follows:

$$\tau = \begin{bmatrix} \tau_u \\ 0 \\ \tau_r \end{bmatrix}$$

(8)

External disturbances (current, wave, and wind) forces and moments vector, $\tau_E$, defined as follows:

$$\tau_E = \begin{bmatrix} \tau_{uE} \\ \tau_{vE} \\ \tau_{rE} \end{bmatrix}$$

(9)

$$\tau_{uE} = \tau_{uE}^{CI} + \sum_{i=1}^N \rho g B L T \cos(\beta) s_i(t) + \frac{1}{2} \rho_a V_w^2 C_x(yw) A_f w$$

(10)

$$\tau_{vE} = \tau_{vE}^{CI} + \sum_{i=1}^N -\rho g B L T \sin(\beta) s_i(t) + \frac{1}{2} \rho_a V_w^2 C_y(yw) A_l w$$

(11)

$$\tau_{rE} = \tau_{rE}^{CI} + \sum_{i=1}^N \frac{1}{24} \rho g B L (L^2 - B^2) \sin(2\beta) s_i^2(t) + \frac{1}{2} \rho_a V_w^2 C_N(yw) A_l w H_L w$$

(12)

where $\beta$ is vessel’s heading angle and $V_w^2$ is the wind speed. The wave slope $s_i(t)$ for the wave component $i$ is defined as:

$$s_i(t) = A_i \frac{2\pi}{\lambda_i} \sin(\omega_{ei} t + \phi_i)$$

(13)

where $A_i$ is the wave amplitude, $\lambda_i$ is the wavelength, $\omega_{ei}$ is the encounter frequency and $\phi_i$ is a random phase corresponding to the wave component $i$. The body parameter of USV LSS01 is explained by Table 1.

| Table 1. Nomenclature of USV-LSS01 |
|------------------------------------|
| Symbols               | Explanation                                                                 |
| $Y_v$              | Y-axis added mass caused by $\dot{v}$                                      |
| $X_u$              | X-axis added mass caused by $\dot{u}$                                      |
| $Y_u$              | Y-axis added mass caused by $\dot{u}$                                      |
| $N_r$              | N-axis added mass caused by $\dot{r}$                                      |
| $X_r$              | X-axis linear damper caused by $\dot{u}$                                   |
| $Y_r$              | Y-axis linear damper caused by $\dot{r}$                                   |
| $I_z$              | Inertial moment with respect to $O_b Z_b$                                   |
| $X_{|u|u}$          | X-axis non-linear damper caused by $u$                                      |
| $Y_{|v|v}$          | Y-axis non-linear damper caused by $v$                                      |


Thus, the state space equation is obtained as follows:

\[
\dot{x} = f(x) + g(x,u) + d(t); \quad x = [x_1, ..., x_3]^T
\]  

(14)

where, state variables are defined as follows:

\[
\begin{align*}
    x_1 &= x_B \\
    x_2 &= \dot{x}_1 = u \\
    x_3 &= y_B \\
    x_4 &= \dot{x}_3 = v \\
    x_5 &= \psi x_6 = r
\end{align*}
\]  

(15)

thus, the state space equation is obtained as follows:

\[
\begin{align*}
    \dot{x}_2 &= \frac{(m - Y_p)}{(m - X_0)} x_2 x_3 - \frac{X_u}{(m - X_0)} x_1 - \frac{X_{u|u}}{(m - X_0)} |x_1| x_1 + \frac{1}{(m - X_0)} \tau_u \\
    \dot{x}_3 &= \frac{(X_{u|u} - m)}{(m - X_0)} x_3 - \frac{X_{u|u}}{(m - X_0)} x_2 - \frac{Y_v}{(m - Y_p)} |x_2| x_2 - \frac{Y_{v|v}}{(m - Y_p)} |x_2| x_2 - \frac{Y_{v|r}}{(m - Y_p)} |v| x_3 \\
    \dot{x}_4 &= \frac{(Y_v - X_0)}{(m - Y_p)} x_1 x_3 - \frac{N_r}{(I_z - N_r)} x_3 - \frac{N_{r|v}}{(I_z - N_r)} |x_2| x_2 - \frac{N_{r|r}}{(I_z - N_r)} |v| x_3 - \frac{1}{(I_z - N_r)} \tau_r
\end{align*}
\]  

(16)

Coefficients of equation (16) is supposed to be in equation (17):
\[
\begin{align*}
\dot{x}_1 &= u \\
\dot{x}_2 &= A_1x_2x_3 - A_2x_1 - A_3|x_1| + A_4U_1 \\
\dot{x}_3 &= v \\
\dot{x}_4 &= A_5x_1x_3 - A_6x_2 - A_7|x_2|x_2 - A_8|x_3| - A_9x_3 \\
\dot{x}_5 &= r \\
\dot{x}_6 &= A_{10}x_1x_2 - A_{11}x_3 - A_{12}|x_2|x_2 - A_{13}|x_3|x_3 - A_{14}|x_2|x_2 - A_{15}|x_3|x_3 + A_{16}U_2
\end{align*}
\]

where \(U_1 = \tau_u\) and \(U_2 = \tau_r\). Further, the coefficients of equation (17) are all outlined in Table 2, namely the USV Body Parameter[6]:

| Parameters | Value  |
|------------|--------|
| \(A_1\)    | -0.0152|
| \(A_2\)    | 0.1305 |
| \(A_3\)    | 0      |
| \(A_4\)    | 0.0508 |
| \(A_5\)    | 0.6245 |
| \(A_6\)    | -0.0075|
| \(A_7\)    | 0.1831 |
| \(A_8\)    | -0.0111|
| \(A_9\)    | 0.0139 |
| \(A_{10}\) | 0.0194 |
| \(A_{11}\) | 0.0505 |
| \(A_{12}\) | 0.0268 |
| \(A_{13}\) | -0.4451|
| \(A_{14}\) | 0.7005 |
| \(A_{15}\) | 106.4701|
| \(A_{16}\) | 0.0385 |

3. USV Autopilot System Design

The design of the autopilot system is a design to create USV maneuvering at sea with certain velocity and direction of heading angle following a predetermined waypoint including control of the velocity and heading angle of USV. The autopilot system design in this research includes the autopilot system design for controller validation and autopilot system design with waypoint navigation.

The system design for controller validation is illustrated in Figure 1. Controller validation is performed by a maneuvering test on the USV to determine that the vessel’s response after obtaining the control signal corresponds to the desired performance criteria. The velocity controller is given a constant value input and the heading controller is given a heading input with a change at a certain second.

![Figure 1. Block diagram of autopilot system](image)

To determine the propulsion and steering device in Figure 1 conversion is required from the USV drive input (\(\tau_u, \tau_r\)) to the thruster engine input on the surge axis and rudder on the sway axis and to facilitate the operator to design the system, the thruster engine is converted to % throttle [6].
The block diagram of waypoint navigation is illustrated in Figure 2. The input of waypoint navigation is desired waypoints \((X_w, Y_w)\) and present position \((x, y)\) of USV in the earth-fixed frame reference. The output of waypoint navigation is heading angle reference \((\phi_R)\) which is the input of controller. Then controller set the moment of thrust \((\tau_r)\) to direct USV moving to desired waypoints with certain angle and velocity. USV is given in a fixed reference velocity value.

**Figure 2. Block diagram of waypoint navigation**

### 4. Sliding Mode Control Design

The Sliding Mode controller design includes the design of the translation velocity control and design of the USV heading angle control. After obtaining the control design, then a desired design specification is defined using experiment response system without controller.

#### 4.1 Controller Design

Objective of controller design is to obtain the control signals of SMC, which consist of an equivalent control signal and natural control signal. The task of equivalent control signal is to set the state movement at the sliding surface boundary \(s(x) = 0\) and natural control signal is to keep the state trajectory around the sliding surface[5].

The first controller design is USV translational velocity. The USV’s translation velocity control is represented by the velocity control of surge axis. Velocity of surge axis illustrated in the state of \(x_2\). State of \(\dot{x}_2\) represents an equation for USV acceleration in body-fixed reference frame, which were obtained from USV mathematic model on Equation (5).

USV state equation for translational velocity can be written as follows:

\[
\dot{x}_2 = A_1 x_2 x_3 - A_2 x_1 - A_3 |x_1| x_1 + A_4 U_1
\]

The desired system specification is a first-order shown as follows:

\[
Y_c(s) = \frac{1}{\tau s + 1} Y_r(s)
\]

with the position tracking error at the body-fixed frame is defined as follows:

\[
e_1 = x_{1ref} - x_1
\]

Then, equation error is defined to determine the sliding surface that is shown as follows:
\[ e_1 + \frac{1}{r} \dot{e}_1 = 0 \]  
(21)

and the sliding surface is obtained as follows:

\[ s = \lambda e_1 + \dot{e}_1 \]  
(22)

where, \( \lambda = \frac{1}{r} \). If Equation (10) is derived with respect to time:

\[ \dot{s} = \lambda \dot{e}_1 + \ddot{e}_1 = 0 \]  
(23)

Substitution of Equation (18), Equation (20) and Equation (23) gives a control signal equivalent \((U_{1eq})\) to the equation (24).

\[ U_{1eq} = \frac{\lambda \dot{e}_1 - \ddot{x}_{1\text{ref}} - A(1)x_2x_3 - A(2)x_1 - A(3)|x_1|x_1}{A(4)} \]  
(24)

A natural control signal of SMC considering Lyapunov Stability is defined in Equation (25) [8,9].

\[ V_i = \frac{1}{2} s^2 \]  
(25)

The first derivative of the Lyapunov is as follows:

\[ \dot{S}S < 0 \]  
(26)

From the condition of stability in Equation (14) the equation of natural control signal \((U_{1N})\) is obtained as follows:

\[ U_{1N} = a. \text{sign}(s) \]  
(27)

Where:

\[ \text{sign}(s) = \begin{cases} -1, & s < 0 \\ 1, & s > 0 \end{cases} \]

Because equation (15) produces a high frequency switching phenomenon, the signum function in equation (15) is replaced by the PID control structure in Equation (28).

\[ U_{1N} = (k_p s + k_i \int s \, dt + k_d \frac{ds}{dt}) \]  
(28)

where the value \( k_p, k_i, k_d > 0 \).

From the equation of the equivalent control signal and the natural control signal that represent the control of USV translational velocity, the equation \(U_1\) is obtained as follows:

\[ U_1 = U_{1eq} + U_{1N} \]  
(29)
The second controller design is the design of heading yaw control angle which sets the direction of the USV heading in a predetermined direction. The design of heading controller in yaw axis has the same method with the design of the translational velocity controller on the surge axis. USV state equation for translational velocity can be written as follows:

\[
x_6 = A_{10}x_1x_2 - A_{11}x_3 - A_{12}|x_2|x_2 - A_{13}|x_3|x_2 - A_{14}|x_2|x_3 - A_{15}|x_3|x_3 + A_{16}U_2
\]  

(30)

a tracking error is defined between the reference yaw angle and USV yaw angle as follow:

\[
e_5 = x_{5\text{ref}} - x_5
\]  

(31)

Sliding surface is defined in equation (19)

\[
s = \lambda e_5 + \dot{e}_5
\]  

(32)

if equation (32) is derived with respect to time then it gives as follows:

\[
\dot{s} = \lambda \dot{e}_5 + \ddot{e}_5 = 0
\]  

(33)

then, the heading angle control is obtained as follows:

\[
U_{2\text{eq}} = (\lambda \dot{e}_5 + \dot{x}_{5\text{ref}} + A(10)x_1x_2 + A(11)x_3 + A(12)|x_2|x_2 + A(13)|x_3|x_2 + A(14)|x_2|x_3 \\
+ A(15)|x_3|x_3)/A(16)
\]  

(34)

The procedure design of natural control is the same with the design of natural control signal \(U_N\) to regulate the velocity of translation. From the equation of the equivalent control signal and the natural control signal that represent the control signal of USV heading angle, the equation \(U_2\) is obtained as follows:

\[
U_2 = U_{2\text{eq}} + U_{2N}
\]  

(35)

4.2 Open Loop Response

The design specifications of USV are obtained from the characteristics of USV without controller. To obtain this it requires the simulation of open loop response. The throttle is initially rated 40% for 150 seconds and the rudder is initially given 0 rad for 50 seconds. At 51 to 150 seconds, USV is deflected by 0.1 radians or 5.73 degrees.

Figure 3 illustrates the movement of the USV from its initial coordinates \((0,0)\) to form a straight line then turn to form an oval path. Figure 4 shows the USV velocity response in the coordinates of the x, y, \(\psi\) in the reference body coordinate of USV or in the direction of surge, sway, and yaw. The characteristic response of USV is all outlined in Table 3.
Table 3. Characteristics of USV system without controller

| USV velocity  | Value       |
|---------------|-------------|
| Surge Velocity| 39.91 seconds|
| Sway Velocity | 20.33 seconds|
| Yaw Velocity  | 20.33 seconds|

From the characteristic of the first order system, the design specifications with time constant ($\tau$) can then be obtained as shown in Table 4.

Table 4. Design specification of translational velocity

| Design specifications | Translational Velocity | Heading Angle |
|-----------------------|------------------------|---------------|
| Time constant ($\tau$) | 2 seconds              | 2 seconds     |
| Error steady state    | 0%                     | 0%            |
| % overshoot           | 0%                     | 0%            |

5. Experiment Results and Analysis

As referred to in Section 3, the experiment results are divided in two parts. Part one is the control validation design which consists of control of translational velocity experiment and control of heading angle response experiment. Part two is autopilot system experiment with waypoint navigation.

5.1 Autopile System Validation with the SMC

5.1.1 Response of translational velocity with the SMC

The translational velocity response is given reference velocity of 3 m/s. Velocity translation response with SMC-Signum is shown in Figure 5. The results in Table 5 illustrate that simulation with gain of $\alpha$ equal to 0.5 is adequate to generate the velocity response of the USV satisfying the desired design specifications. Simulation result in figure 5 illustrate increasing gain of $\alpha$ which is too large can cause the system response to be slower to reach the steady state. Conversely, the selection of gain $\alpha$ which is too small will lead to an overshoot.

Simulation result in figure 6 illustrate that the control signal gives rise to chattering or high-frequency switching. It is caused by the discontinuous element of the system. Therefore, for reducing it the Signum function is replaced by the PID controller structure. Velocity Translation Response with SMC PID is illustrated in Figure 7.
Table 5. SMC-Sigmun testing for translational velocity

| Specification | Gain $a$ | Settling time | %ESS | %OS  |
|---------------|---------|---------------|------|------|
| 1             | 0.05    | 10.105 s      | 0    | 1.37%|
| 2             | 0.5     | 6.439 s       | 0    | 0%   |
| 3             | 5       | 10.94 s       | 3.71%| 0%   |

Figure 5. Translational velocity response with SMC-Sigmun

Figure 6. Control signal of throttle with SMC-Sigmum

The simulation results in Table 6 illustrates gain of $K_p = 15; K_i = 0.0001; \text{ and } K_d = 4$, successfully generating a response satisfying the desired design specifications. Simulation results in Figure 7 illustrate that the selection of $K_p$ and $K_i$ gain which do not match causes overshoot in the system response. It should be noted that selection of $K_d$ gain must consider to the value of $K_p$. Figure 8 illustrates the control signal of throttle with the parameter of $K_p = 15, K_i = 0.0001$, and $K_d = 4$.

Table 6. SMC-PID simulation for translational velocity

| Simulation | $K_p$ | $K_i$ | $K_d$ | Settling time | %ESS | %OS  |
|------------|-------|-------|-------|---------------|------|------|
| 1          | 1.5   | 3.5   | 0.001 | 8.97 s        | 0    | 5.2% |
| 2          | 6.5   | 0.0001| 15    | 6.69 s        | 0    | 1.2% |
| 3          | 15    | 0.0001| 4     | 7.95 s        | 0    | 0%   |

Figure 7. Translational velocity response with SMC-PID

Figure 8. Throttle control signal with SMC-PID

5.1.2 Heading angle response USV with the SMC

The heading angle response is given with heading angle reference of 0.3 radians. Heading angle response with SMC-Signum is shown in Figure 9. From the three simulation results in Table 7 show that the response of the heading angle of USV causing different oscillation gain in each simulation. However, the closest USV design specification is the first simulation with gain of equal to 0.006. The simulation
results in Figure 9 illustrates that the addition of gain of $\alpha$ which is too large causes the oscillation on system response.

**Table 7. SMC-PID simulation for translational velocity**

| Simulation | Gain $\alpha$ | Settling time | %ESS | %OS |
|------------|---------------|---------------|------|-----|
| 1          | 0.006         | 8.93 s        | 0.3% | 0%  |
| 2          | 0.009         | 8.8 s         | 1%   | 0%  |
| 3          | 0.6           | 7.78 s        | 1%   | 0%  |

**Figure 9.** Heading angle response with SMC-Signum

**Figure 10.** Rudder control signal to the SMC-Signum

The simulation result in Figure 10 illustrates that the control signal gives rise to chattering or high frequency switching. It is caused by the discontinuous elements of the system. The solution to reduce chattering is to replace the SMC output with the saturation function with a certain gain value. With the same characteristic plant on the case study of Ball and Plate System results in a reduction in chattering from an amplitude of 0.07 m to 1.7615e-04 m. This shows a high reduction in chattering even at increased SMC gain. The presence of this level of chattering in the controller is undesirable as it could also lead to the problems associated with it, making the controller unrealistic to implement. Therefore, a further reduction of chattering is required [10]. The PID is an appropriate natural control for resolving this problem.

The simulation result in Heading Response Testing with SMC PID shown in Figure 11. The third test with the parameters $K_p = 1.5$, $K_i = 0.0001$, and $K_d = 0.001$, managed to make a response to meet the desired design specifications.

**Table 8. SMC-PID Simulation for translational velocity**

| Simulation | $K_p$ | $K_i$ | $K_d$ | Settling time | %ESS | %OS |
|------------|-------|-------|-------|---------------|------|-----|
| 1          | 0.15  | 0.0001| 0.01  | 4.2 s         | 0.001| 0%  |
| 2          | 1.5   | 0.0001| 0.001 | 3.98 s        | 0    | 0%  |
| 3          | 6.5   | 0.001 | 0.001 | 3.6 s         | 0.002| 0%  |

The simulation result in Figure 11 illustrates that the selection of $K_p$ gain will affect the small errors which occur at system response and for a larger $K_i$ selection will generate overshoot in the system. Figure 12 shows the control signal from the rudder using the parameter gain $K_p = 1.5; K_i = 0.0001; K_d = 0.001$. 
Figure 11. Heading angle response with the SMC-PID

Figure 12. Rudder signal control with the SMC-PID

5.2 Autopilot System with Waypoint Navigation

The simulation results of autopilot system with waypoint navigation have been discussed in Section 2. It uses the validation controller of autopilot system which has resulted in sub-section 5.1. The scenario is USV have to move through the predetermined waypoints either with disturbance or without disturbance. The parameters of external disturbances including wind, current and wave are shown in Table 9.

Table 9. Parameter of external disturbance

| Disturbance | Value | Direction |
|-------------|-------|-----------|
| Wind        | 1 m/s | -0.1 radian |
| Current     | 0.5 m/s | -0.1 radian |
| Wave        | 1 m   | -0.1 radian |

Figures 13, 14, and 15 illustrate the USV position response with difference form of waypoints, including straight waypoint, wave waypoint, and circle waypoint. Figure 16 illustrate the rudder control signal with sinus waypoint form.
The comparison of navigation errors between USV response with disturbance and without disturbance is shown in Table 10. By using the Root Mean Square Error (RMSE) obtained that the difference error depends on the form of waypoint. By using PID-Based Sliding Mode Controller can relatively generate small Mean Square Error (MSE) of waypoint. Therefore, USV able to drive at the sea with various of waypoints, either with disturbance or without disturbance.

6. Conclusions and Recommendations

6.1 Conclusions

From the results of the discussions, several conclusions can be taken as follows:

1. The design of autopilot system with the Sliding Mode Control Method is able to produce translational velocity response and heading angle response in USV which are in accordance with the desired design specifications. The control validation of the translational velocity response results in the gain of $\alpha = 0.5$ and for heading angle responses result in the gain of $\alpha = 0.06$. But the control signal produces a chattering so that the natural signum control is replaced by the PID structure.

2. The design of autopilot system using the PID-Based Sliding Mode method is able to produce translational speed responses and heading angle responses in USV which are in accordance with the desired design specifications and be able to reduce the chattering in the control signal. The control validation of the translation velocity response results in the gain of $K_p = 15$, $K_i = 0.0001$, and $K_d = 4$ and the heading angle response result in the gain of $K_p = 1.5$, $K_i = 0.0001$, and $K_d = 0.001$.

3. The design of autopilot system with the navigation waypoint using the PID-Based Sliding Mode method can direct the USV to the desired waypoint, either with disturbance or without disturbance.

6.2 Recommendations

For further development, the following are recommended:

1. To help design a better system requires detailed modeling and understanding of unmanned surface vehicle.

2. $K_p$, $K_i$, and $K_d$ values should be adjusted adaptively to maintain system stability.
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