Sliding mode control design for autonomous surface vehicle motion under the influence of environmental factor

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ABSTRACT

Autonomous Surface Vehicle (ASV) is a vehicle that is operated in the water surface without any person in the vehicle. Since there is no person in the ASV, a motion controller is essentially needed. The control system is used to make sure that the water vehicle is moving at the desired speed. In this paper, we use a Touristant ASV with the following specifications: the length is 4 meters, the diameter is 1.625 meters, and the height is 1.027 meters. The main contribution of this paper is applying the Sliding Mode Control system to the Touristant ASV model under the influence of environmental factors. The environmental factors considered in this work are wind speed and wave height. The Touristant ASV model is nonlinear and uses three degree of freedom (DOF), namely surge, sway and yaw. The simulation results show that the performance of the closed-loop system by using the SMC method depends on the environmental factors. If environmental factors are higher, then the resulting error is also higher. The average error difference between those resulted from the simulation without environmental factors and those with the influence of environmental factors is 0.05% for surge, sway and yaw motions.

1. INTRODUCTION

Indonesia is one of the countries in the world where approximately 70% of the area is sea [1, 2]. Such condition makes Indonesia a suitable place to develop marine and coastal tourism. There are many marine and coastal tourism services in Indonesia. One of them is Kenjeran Beach, that is located in Surabaya. At Kenjeran Beach, tourists can enjoy the view by riding a simple boat that is operated by humans. Boat operation by humans may cause accidents due to negligence, lack of professionalism and some other reasons. To reduce the number of accidents and along with technological developments, a vehicle called Autonomous Surface Vehicle (ASV) can be utilized as a support for marine and coastal tourism.

An Autonomous Surface Vehicle (ASV) is an unmanned on-water vehicle that is able to navigate automatically in water area [3, 4]. There are many works on ASV in the literature. We will mention some of
them here. ASV have been applied in many aspects, such as water quality monitoring [5], risk assessment [6] and network centric operations [7]. There are also some papers on modeling, control and estimation of ASV and autonomous unmanned vehicle [8], for example tracking control using neural network approach [9], adaptive dynamic surface control [10], path following [11], obstacle detection and avoidance [12, 13], target tracking [14], stability analysis [1], estimation using square root ensemble Kalman filter [2, 15], Proportional Integral Derivative (PID) control design [16], control design using Sliding Mode Control (SMC) [17–19], sliding PID control design [20, 21], using Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) for Optimizing PID Parameters on Autonomous Underwater Vehicle (AUV) [22], estimation using ensemble Kalman filter [23, 24] and estimation using fuzzy Kalman filter [25].

In this paper, we discuss control design for ASV by using SMC. There are many advantages of using SMC, for example it is robust and it can be applied to nonlinear systems. The ASV model discussed in this paper has three degrees of freedom, namely surge, sway and yaw. The disturbances considered are wind speed and wave height. This paper is structured as follows. The modeling of ASV is discussed in Section 2. Then the general control design using SMC is described in Section 3. The control design of ASV by using SMC is explained in Section 4. The simulation results are discussed in Section 5. Finally, the conclusions are written in Section 6.

2. AUTONOMOUS SURFACE VEHICLE

Autonomous Surface Vehicle (ASV) is equipped with Global Positioning System (GPS), sensors, gas, pH sensors, bluetooth, and telemetry. When the location has been determined, the vehicle will move automatically in real-time. Besides research water vehicle, ASV can also be used for other purposes, such as survey vehicle, inspection of river conditions, seismic surveys, rescue operations etc. The profile and specification of Touristant ASV are listed in Figure 1 and Table 1.

![Figure 1. Profile of Touristant ASV](image)

**Table 1. Specification of Touristant ASV**

| Length (m) | Beam (m) | Depth (m) | DWL (m) |
|------------|----------|-----------|---------|
| 4.12       | 1.625    | 1.027     | 0.3     |

In general, the water-vehicle motions are divided into two types, namely translational and rotational motions. Translational motion consists of surge, sway and heave, whereas rotational motion comprises of roll, pitch, and yaw [18]. In this paper, we use the equation of water-vehicle motions with 3 degrees of freedom (DOF), namely surge, sway and, yaw. The mathematical model for surge, sway and yaw motions is given by
In the following, we define three variables \( U \) on wave height, moment of wind speed and force on wave height. It follows that the equations are as follows

\[
(m - X_a)\dot{u} = X_{|u|}|u|u + (1 - h)X_{prop} + (m + X_{vr})vr + (mx_G + X_{rr})r^2 + X_{\delta\delta}\delta^2 + X_{ext},
\]
\[
(m - Y_a)v + (mx_G - Y_c)v = -(m - Y_{ur})ur + Y_{uw}uv + Y_{|v|}v + Y_{|v|}v|v|v + Y_{\delta} + Y_{ext},
\]
\[
(mx_G - N_c)v + (I_z - N_r)v = -(mx_G - N_{ur})ur + N_{uw}uv + N_{|v|}v + N_{|v|}v|v|v + N_{\delta}\delta + N_{ext}.
\]

From (1)-(3), \( X_{ext}, Y_{ext} \) and \( N_{ext} \) represent an interference from outside of the surge, sway and yaw motions.

In this study, the external interference or environmental factors considered are the force on wind speed, force on wave height, moment of wind speed and force on wave height. It follows that the equations are as follows

\[
X_{ext} = X_{wind} + X_{waves},
\]
\[
Y_{ext} = Y_{wind} + Y_{waves},
\]
\[
N_{ext} = N_{wind} + N_{waves}.
\]

From the description of \( X_{ext}, Y_{ext} \) and \( N_{ext} \), the following nonlinear equations are obtained:

\[
(m - X_a)\dot{u} = X_{|u|}|u|u + (1 - h)X_{prop} + (m + X_{vr})vr + (mx_G + X_{rr})r^2 + X_{\delta\delta}\delta^2 + X_{wind} + X_{waves},
\]
\[
(m - Y_a)v + (mx_G - Y_c)v = -(m - Y_{ur})ur + Y_{uw}uv + Y_{|v|}v + Y_{|v|}v|v|v + Y_{\delta}\delta + Y_{wind} + Y_{waves},
\]
\[
(mx_G - N_c)v + (I_z - N_r)v = -(mx_G - N_{ur})ur + N_{uw}uv + N_{|v|}v + N_{|v|}v|v|v + N_{\delta}\delta + N_{wind} + N_{waves}.
\]

In the following, we define three variables \( U_{surge}, V_{sway} \) and \( N_{yaw} \) which will be used later.

\[
U_{surge} = X_{|u|}|u|u + (m + X_{vr})vr + (mx_G + X_{rr})r^2 + X_{\delta\delta}\delta^2 + X_{wind} + X_{waves},
\]
\[
V_{sway} = -(m - Y_{ur})ur + Y_{uw}uv + Y_{|v|}v + Y_{|v|}v|v|v + Y_{\delta}\delta + Y_{wind} + Y_{waves},
\]
\[
N_{yaw} = -(mx_G - N_{ur})ur + N_{uw}uv + N_{|v|}v + N_{|v|}v|v|v + N_{\delta}\delta + N_{wind} + N_{waves}.
\]

Equations (7)-(9) are quite long and complicated. In order to simplify those three equations, we use the newly introduced \( U_{surge}, V_{sway} \) and \( N_{yaw} \), as follows

\[
(m - X_a)\dot{u} = (1 - h)X_{prop} + U_{surge},
\]
\[
(m - Y_c)v + (mx_G - Y_c)v = Y_{\delta}\delta + V_{sway},
\]
\[
(mx_G - N_c)v + (I_z - N_r)v = N_{\delta}\delta + N_{yaw}.
\]

The mathematical model of Touristant ASV is described in (13)-(15). In order to apply the sliding mode control design, it is better if the mathematical model is written in a state-space form. The state-space form of the mathematical model is as follows

\[
\dot{u} = T_1((1 - h)X_{prop} + U_{surge}),
\]
\[
\dot{v} = T_2(Y_{\delta}\delta + V_{sway}) + T_3(N_{\delta}\delta + N_{yaw}),
\]
\[
\dot{r} = T_4(Y_{\delta}\delta + V_{sway}) + T_5(N_{\delta}\delta + N_{yaw}),
\]

where \( T_1, T_2, \ldots, T_5 \) are constants, \( \delta_1 \) is the variable associated with sway and \( \delta_2 \) is the variable associated with yaw. The state variables are \( u, v, r \) and the input variables are \( X_{prop}, \delta_1 \) and \( \delta_2 \).

3. SLIDING MODE CONTROL

In order to apply the Sliding Mode Control (SMC), we follow the flowchart shown in Figure 2. The detailed stages of SMC implementation can be summarized as follows [17, 25]:

1. Determine switching function \( S(x, t) \) from the tracking error

At the stage of determining the switching function, each ASV motion state is associated with a switching function using the following equations:

\[
S(x, t) = \left( \frac{d}{dt} + \lambda \right)^{n-1} \tilde{x}(t),
\]

where tracking error can be expressed as \( \tilde{x}(t) = x(t) - x_d(t) \) and \( x_d \) is the desired state.
2. Determine the sliding surface
   The next step is to determine the sliding surface, namely $S(x, t) = 0$ from the switching function obtained.

3. Determine the controller estimation value $\hat{a}$
   The step to determine the controller estimation value $\hat{a}$ can be obtained from the equation $\dot{S} = 0$.

4. Use control law $a = \hat{a} - K \text{sgn}(S)$
   The next step is applying the control law by using the equation:
   \[
a = \hat{a} - K \text{sgn}(S)
   \]
   To satisfy the sliding condition, the signum function is defined as follows:
   \[
   \text{sgn}(x) = \begin{cases} 
   -1, & \text{if } x < 0 \\
   0, & \text{if } x = 0 \\
   1, & \text{if } x > 0
   \end{cases}
   \]

5. Substitute the value of $\hat{a}$
   Substitute the value $\hat{a}$ to control law so that new control input is obtained as the substitute of the previous control input.

6. Determine the value of $K$
   Determine the value $K$ from control law $a = \hat{a} - K \text{sgn}(S)$ that has been obtained.

7. Saturation function
   The last step is to change the signum function into a saturation function which aims is to minimize the chattering.

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Figure 2. The flowchart of sliding mode control
4. SLIDING MODE CONTROL DESIGN FOR AUTONOMOUS SURFACE VEHICLE MODELS

As mentioned in the previous section, the design of SMC for Nonlinear ASV model consists of three parts, namely for surge, sway and yaw motions.

4.1. SMC design for surge motion

In designing the control of surge motion, first of all notice that the tracking error of surge motion is \( \tilde{u} = u - u_d \), where the desired surge \( u_d \) is constant. Because the system has order 1, the switching function is formed from (19) by defining \( n = 1 \) as follows:

\[
S_1(u, t) = \tilde{u} = u - u_d.
\]

Since \( u_d \) is a constant function, \( \dot{u}_d = 0 \). It follows that the derivative of \( S_1(u, t) \) is

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

(20)

Then we substitute (16) to (20) to obtain the following equation:

\[
\dot{S}_1(u, t) = T_1((1 - h)X_{\text{prop}} + U_{\text{surge}}).
\]  

(21)

In order to compute the estimated value of \( X_{\text{prop}} \), denoted by \( \hat{X}_{\text{prop}} \), \( \dot{S}_1(u, t) \) is set to zero:

\[
0 = T_1((1 - h)\hat{X}_{\text{prop}} + U_{\text{surge}})
\]  

(22)

We obtain the following expression

\[
\hat{X}_{\text{prop}} = \frac{-U_{\text{surge}}}{1 - h}.
\]  

(23)

Based on the control law that meets the sliding condition, the relationship between \( X_{\text{prop}} \) and \( \hat{X}_{\text{prop}} \) shall be

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

(24)

By substituting (23) into (24), we obtain

\[
X_{\text{prop}} = \frac{-U_{\text{surge}}}{1 - h} - K_1 \text{sgn}(S_1).
\]  

(25)

Then we substitute (25) to (21), as follows

\[
\dot{S}_1(u, t) = T_1 \left((1 - h) \left( \frac{-U_{\text{surge}}}{1 - h} - K_1 \text{sgn}(S_1) \right) + U_{\text{surge}} \right),
\]

\[
= -T_1 (1 - h) K_1 \text{sgn}(S_1).
\]  

(26)

Then \( K_1 \) is chosen such that the sliding condition is fulfilled, that is

\[
S_1 \dot{S}_1 \leq -\eta |S_1|,
\]

where \( \eta \) is a tuning parameter. After some simple algebraic manipulations, we obtain

\[
K_1 \geq \frac{\eta}{T_1 (1 - h) \text{sgn}(S_1)}.
\]  

(27)

From (27), the value of \( K_1 \) is

\[
K_1 = \max \left| \frac{\eta}{T_1 (1 - h)} \right|.
\]  

(28)

Then, a boundary layer is used to minimize chattering by changing the signum function (sgn) into saturation function as follows:

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

(29)
where \( \phi \) is a tuning parameter. Finally the control input \( X_{\text{prop}} \) is defined in the following equation

\[
X_{\text{prop}} = \frac{-U_{\text{surge}}}{1 - h} - \max \left| \frac{\eta}{T_1 (1 - h)} \right| \text{sat} \left( \frac{S_1}{\phi} \right).
\]  \hspace{1cm} (30)

### 4.2. SMC design for sway motion

The procedure for designing sway input is similar with surge input. The switching function of sway motion is as follows:

\[
S_2(v, t) = v - v_d.
\]  \hspace{1cm} (31)

By performing the same steps as in the surge motion, the control system design for sway motion is as follows:

\[
\delta_1 = \frac{-(T_2 V_{\text{sway}} + T_3 N_{\text{yaw}})}{T_2 Y_\delta + T_3 N_\delta} - \max \left| \frac{\eta}{T_2 Y_\delta + T_3 N_\delta} \right| \text{sat} \left( \frac{S_2}{\phi} \right),
\]  \hspace{1cm} (32)

where \( \eta \) and \( \phi \) are tuning parameters.

### 4.3. SMC design for yaw motion

The procedure for designing yaw input has some similarities to that for surge inputs. The switching function of yaw motion is given by:

\[
S_3(r, t) = r - r_d.
\]  \hspace{1cm} (33)

By applying the same steps as for the surge motion, the design of the control system for yaw motion is as follows:

\[
\delta_2 = \frac{-(T_4 V_{\text{sway}} + T_5 N_{\text{yaw}})}{T_4 Y_\delta + T_5 N_\delta} - \max \left| \frac{\eta}{T_4 Y_\delta + T_5 N_\delta} \right| \text{sat} \left( \frac{S_3}{\phi} \right),
\]  \hspace{1cm} (34)

where \( \eta \) and \( \phi \) are tuning parameters.

### 5. RESULTS AND SIMULATION

After designing the motion control system using the SMC method, then we simulate the results on Matlab’s Simulink. This control system is arranged in the form of block diagrams on the motion system of Autonomous Surface Vehicle (ASV) in the form of a closed loop with \( \eta = 1 \) and \( \phi = 1 \). The block diagram of the nonlinear 3-DOF Autonomous Surface Vehicle (ASV) model using the SMC method is presented in Figure 3.

![ASV block diagram of the SMC method](image)

After the SMC control system is simulated, the response of surge, sway and yaw motions are displayed in Figure 4(a), Figure 4(b) and Figure 5, respectively. In the simulation, we compare the performance of SMC in the absence of environmental factors and in the presence of environmental factors.
Figure 4. Response of surge and sway motions for the disturbance-free case and in the presence of disturbance, (a) surge motion, (b) sway motion

From Figures 4 and 5, it can be seen that the higher wind speed and wave height, the steady-state error is higher and settling time is longer. But the level of the wind speed and the height of the wave has no effect on the overshoot. At a wind speed of 23 km/h and a wave height of 0.6 m, the graph shows that it goes away from the setpoint. It appears that the motion is stable and the steady-state error is very small with a setpoint of 4.6 m/s for surge, 1 m/s for sway and 1 rad/s for yaw. Figure 4 shows a surge motion response reaching the first time (settling time) at 11 seconds, a steady-state error of 0.17% and having a 0% overshoot by presenting an error between a setpoint and a stable position. Figure 4 is the result of a response by the SMC method for sway motion, where the sway motion response reaches settling time at 9.4 seconds, steady-state error of 0.2% and has a 0% overshoot. Figure 5 is the result of a response by the SMC method for yaw motion, where the yaw motion response reaches settling time in 8.1 seconds, steady state error 0.2% and has a 0% overshoot. The simulation results of the three conditions can be seen in Table 2.

Figure 5. Response of yaw motion for the disturbance-free case and in the presence of disturbance

| Table 2. Error and Settling Time for 3-DOF nonlinear model by using SMC |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|
| Without Environmental Factors | Wind Velocity 15 m/s & High Waves 0.4 m | Wind Velocity 23 m/s & High Waves 0.6 m |
| Error | Settling Time | Error | Settling Time | Error | Settling Time |
| Surge 0.12 % | 8.5 s | 0.15 % | 10.1 s | 0.17 % | 11 s |
| Sway 0.14 % | 6.4 s | 0.17 % | 8 s | 0.2 % | 9.4 s |
| Yaw 0.15 % | 6.5 s | 0.18 % | 7.2 s | 0.2 % | 8.1 s |
6. CONCLUSIONS

Based on the results and analysis related to the design of the ASV motion control system with the Sliding Mode Control (SMC) method for surge, sway and yaw motions, the study of 3-DOF nonlinear models came to the conclusion that if the environmental factor value is higher, then the error produced is also higher. The average error difference between the simulation without environmental factors and that using environmental factors is 0.05% for surge, sway and yaw motions.

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