Abstract

The main problem for autonomous underwater vehicle (AUV) is not only how to make a stable underwater vehicle but also how to keep the AUV form its desire trajectory. Some perturbations such as wind, waves, and ocean currents are the crucial factors to disturb the AUV. Those will move AUV's position from for the desired track. To cope with this problem, sliding mode control (SMC) is used to make a robust AUV under a range of ocean disturbances. Moreover, the chattering effect which is produced by SMC will be overcome by fuzzy logic control (FLC). A simulation is presented to analyse the effectiveness of proposed control under some deterministic condition. However, the results show that the movement of AUV under high value of disturbances cannot be solved by the proposed control.

1. Introduction

The development of AUV have been getting immerse issues due to its important functions in undersea mission such as cable inspection and installation, oil and gas exploration, science data collection, and more. However, ocean natural factors (wind, waves, ocean currents) cannot be neglected. Those perturbations can move AUV's position from its determined trajectory even though in a small value [1].

Therefore, developing an advanced controller to obtain successful missions including stabilization and trajectory tracking is a challenging task [2]. Researchers have proposed a range of control method, for instance, PID control, fuzzy logic control, adaptive control, robust control, neural network (NN), and combined two or three control methods [3]. Besides stabilization and trajectory tracking, the most crucial goal is robustness of AUV. Hence, many researchers studied how to deal with uncertainty and nonlinearities by expanding various robust control schemes [4].

SMC is one of the control systems which is commonly applied in robust control scheme, especially for dynamic positioning and motion control of underwater vehicles under external disturbances. In SMC, it is developed a close-loop control system to remove the requirement for linearization. However, during to reach the sliding surface, SMC tends to be sensitive to the unstructured parametric uncertainties and inaccurate mathematical model of the system. During this time, chattering effect will appear and sometimes cause the system performance to be unstable [5].

To eliminate these problems, researchers combined SMC with other control. Kim and Shin elaborated SMC with expanded adaptive fuzzy to apply to UFV depth control [6]. The simulation results indicated satisfying performances in term of robustness and adapted control parameters. Furthermore, it used simple fuzzy rule to solve the problems. However, disturbance influences were not involved in this simulation. Whereas natural disturbance is one of big problems which will affect the stability and robustness of AUV [7].

This paper discusses a fuzzy sliding mode control based on a tracking line for 6 DOF holonomic AUV under various deterministic disturbances. SMC is used to make a robust AUV to external disturbances. Due to its chattering effect which may make the system to be unstable, fuzzy logic control is added and used to adjust the gain of the proposed controller. A simulation is presented to analyse the proposed control under some determine disturbances.

2. Modelling of 6 DOF AUV

AUV involves the study of two kinds of modelling. One is kinematic model and another is dynamic model. Kinematic model concerns the equilibrium of the body both at rest and moving with certain velocity. While dynamic model concerns the body's acceleration of motion.

2.1 Kinematic model

The kinematic model has a correlation between inertial and body-fixed vehicle velocity. It can be described by using the Jacobian matrix \( J(\eta_2) \) in the following form [8]

\[
\begin{bmatrix}
\eta_1 \\
\eta_2
\end{bmatrix} = \begin{bmatrix}
J_1(\eta_2) & 0_{3x3} \\
0_{3x3} & J_2(\eta_2)
\end{bmatrix} \begin{bmatrix}
v_1 \\
v_2
\end{bmatrix} \iff \eta = J(\eta_2) v
\]

where \( \eta_1 = [x \ y \ z]^T \in \mathbb{R}^3 \) and \( \eta_2 = [\phi \ \theta \ \psi]^T \in \mathbb{R}^3 \) denote the position and the orientation of the vehicle, respectively, expressed in the inertial-fixed frame. \( J_1 \) and \( J_2 \) are the transformation matrices expressed in terms of the Euler angles. The linear and angular velocity vectors, \( v_1 = [u \ v \ w]^T \in \mathbb{R}^3 \) and \( v_2 = [p \ q \ r]^T \in \mathbb{R}^3 \), respectively, are described in terms of the body-fixed frame.

2.2 Dynamic model

The study of dynamic equation of motion for an underwater vehicle has been previously reported in [8]. The
underwater vehicle dynamic equation can be expressed in closed form as

\[
M \ddot{v} + C(v)v + D(v)v + g(\eta) = \tau 
\]

where \( v \in \mathbb{R}^6 \) is the velocity state vector with respect to the body-fixed frame, \( M \) is the inertia matrix including the added mass, \( C(v) \) represents the matrix of the coriolis and centripetal terms including the added mass, \( D(v) \) denotes the hydrodynamic damping and lift force, \( g(\eta) \) is the restoring force and \( \tau \) is the vector of generalized forces acting on the vehicle and can be written as the sum of estimated dynamics disturbances (control input). The dynamic equation (2) preserves the following properties [8].

- **Property 1**: The inertia matrix \( M \) is symmetric and positive definite i.e.: \( M = M^T > 0 \).
- **Property 2**: \( C(v) \) is the skew-symmetric matrix such that \( C(v) = -C^T(v) \).
- **Property 3**: The hydrodynamic damping matrix \( D(v) \) is positive definite, i.e.: \( D(v) = D^T(v) > 0 \).

3. Control System

SMC design consists of two parts. First, determine the equivalent control law. Second, design a sliding surface or switching control.

Determination of appropriate equivalent control law is needed to track the system performance with desired trajectory or to achieve a condition for the trajectory to remain on the sliding surface \( s \). On the other hand, the system has a function to keep the initial state lying off \( S \) would remain hit \( s \) \((s = 0) \). First, it is necessary to define a feedback control law. Feedback control law can be designed as

\[
\tau = -ks + \tau_0 
\]

where \( k \) is feedback gain control. In order to define \( \tau_0 \), it is necessary to know the sliding surface \( s \) related to the tracking error.

\[
s = v - v_r 
\]

If AUV starts in the position \( s > 0 \), it will move toward \( s = 0 \). When \( s = 0 \), it will continue to move on the line track. After that, differentiate Eq. (4) and substitute Eq. (2) into it. The step can be seen as

\[
\dot{s} = \dot{v} - \dot{v}_r \\
M \ddot{v} + C(v)v + D(v)v + g(\eta) = -ks + \tau_0 \\
M \ddot{s} + M \dot{v}_r + C(v)v + D(v)v + g(\eta) = -ks + \tau_0 
\]

Next problem is choosing the Lyapunov function. The following Lyapunov function is available.

\[
V = \frac{1}{2}Ms^2 
\]

Then, differentiating \( V \) along trajectories \( s \) we obtain

\[
\dot{V} = s M \dot{s} \\
\dot{V} = s(\tau_0 - M \dot{v}_r - C(v)v - D(v)v + g(\eta) - ks) 
\]

If \( \dot{V} = 0 \), then

\[
\tau_0 = M \dot{v}_r + C(v)v + D(v)v + g(\eta) - ks\text{sgn}(s) 
\]

Hence, Eq. (8) is not a perfect function because the signum formula causes the chattering effect which is produced by the control input. To cope with this problem, \( sgn(s) \) is replaced by saturation function such as

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

Then, fuzzy system is used in the term of constant gain. It is applied because if the switching gain increases, the sliding surface will be approached rapidly but it tends to produce chattering effect, and vice versa. So, the equation will be proposed as

\[
\tau = M \dot{v}_r + (C(v) + D(v))v + g(\eta) - K_s \text{sat}(s) 
\]

The scheme of fuzzy controller can be seen in Fig. 1.
Here $N$, $Z$, $P$, $L$, $M$, and $S$ stand for negative, zero, positive, large, medium, and small, respectively. The general rule of fuzzy control can be expressed as shown in Table 1.

| $K_{\text{fuzzy}}$ | S       |
|---------------------|---------|
|                      | NL      |
|                      | NM      |
|                      | NS      |
|                      | Z       |
|                      | PS      |
|                      | PM      |
|                      | PL      |
| N                   | L       |
| L                   | L       |
| L                   | L       |
| Z                   | M       |
| M                   | S       |
| S                   | L       |
| P                   | M       |
| M                   | S       |
| S                   | M       |
| M                   | L       |
| L                   | L       |

Block diagram of the proposed control is shown in Fig. 2.

4. Simulation Results

This section performs the evaluation of control system performance by using a simulation. The AUV has to follow a certain trajectory. To test the efficiency of the proposed fuzzy sliding mode controller, the simulation is done under various disturbance.

An ODIN with full 6-DOF holonomic system is chosen as autonomous underwater vehicle model for numerical simulation. Technical descriptions of the simulation are described below:

- initial position of AUV = $[3 \ 0 \ -1]^T m$
- initial velocity of AUV = $[0 \ 0 \ 0]^T m/s$
- desired trajectory = straight line
- disturbances = $[w_x \ w_y \ w_z]^T m/s$

where $w_x = \text{wind}$, $w_y = \text{waves}$, $w_z = \text{ocean current}$.

The simulation results are shown in Fig. 3.
There are three figures for the simulation result. Figure 3(a) is the result for the proposed control applied under $w_x = [0.1 \ 0 \ 0] \frac{m}{s}$. Figure 3(b) is the result under $w_x$ and $[0.1 \ 0.1 \ 0.1] \frac{m}{s}$. While Fig. 3(c) is the result under $w_x, w_y, w_z = [0.1 \ 0.1 \ 0.1] \frac{m}{s}$. Red line depicts the desired trajectory, where blue line for AUV's the tracking result. X mark is the initial position.

5. Conclusion

This paper has proposed a sliding mode control based on fuzzy tuning gain for AUV. In the simulation, the AUV had to follow a straight line as a trajectory. Some deterministic disturbances were arranged to observe the movement of proposed control and those values were adjusted. SMC was used to make a robust AUV, while fuzzy controller was employed to set a gain value so the chattering effect could be reduced.

This control technique enabled an AUV to track desired trajectory under deterministic disturbances in a small value. However, the data showed more imperfect condition by increasing the value of disturbances. In other word, high deterministic disturbances could not be solved by the control proposed. Another control should be designed for better results for AUV.

References

[1] H. R. Koofigar: Robust adaptive motion control with environmental disturbance rejection for perturbed under-

water vehicles, Journal of Marine Science and Technology, Vol. 22, No. 4, pp. 455–462, 2014.

[2] K. D. Do and J. Pan: Robust and adaptive path following for underactuated autonomous underwater vehicles, Proc. American Control Conference 2003, Vol. 3, pp. 1994-1999, June 2003.

[3] Z. H. Ismail: Region boundary-based control scheme for an underwater vehicle with an edge-based segmentation approach, Proc. Robotics and Biomimetics (ROBIO), pp. 2137-2142, Dec. 2011.

[4] X. Bin, et al.: Robust nonlinear controller for underwater vehicle-manipulator systems, Proc. Advanced Intelligent Mechatronics, pp. 711-716, July 2005.

[5] G. V. Lakhekar: Tuning and analysis of sliding mode controller based on fuzzy logic, International Journal of Control and Automation, Vol. 5, No. 3, pp. 93-110, 2012.

[6] K. Hyun-Sik and S. Yong-Ku: Expanded adaptive fuzzy sliding mode controller using expert knowledge and fuzzy basis function expansion for UFV depth control, Ocean Engineering, Vol. 34, Issues 8–9, pp. 1080-1088, 2007.

[7] A. Budiono: Model predictive control for autonomous underwater vehicle, Indian Journal of Geo-Marine Sciences, Vol. 40, No. 2, pp. 191-199, 2011.

[8] T. I. Fossen: Handbook of Marine Craft Hydrodynamics and Motion Control, First Edition, New York, John Wiley and Sons, 2011.