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HIGHLY RESPONSIVE HEADING CONTROL OF UNDERACTUATED MODIFIED BLUEROV USING SLIDING-MODE CONTROLLER

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The control of Autonomous Underwater Vehicle (AUV) presents some challenging tasks such as dealing with the nonlinearity of AUV dynamics, coupling effects, and taking into consideration the hydrodynamics uncertainties and disturbances such as current. One of the more robust control method for controlling a nonlinear system is Sliding-Mode Control (SMC). In literature, SMC had been used to control the depth and yaw of an underactuated AUV. However, the switching term of the SMC had to be tuned to get a proper balance between performance and robustness and it has low responsiveness to track desired reference signal. This paper introduces the usage of smoothing filter to make the SMC more responsive to track desired heading motion. The methodology starts with deriving heading model of an AUV, then estimating the parameters in the AUV model, followed by designing the heading controller based on SMC, and finally optimizing the controller parameters. The design model is based on underactuated modified BlueROV. Results shown that when the reference heading signal is smoothed, the SMC is able to achieve 95.55% responsiveness compared to only just 78.05% responsiveness without smoothing. The thrusts produced by the AUV is also less strained when the smoothing filter is applied. Therefore, to get a highly responsive SMC and to preserve the longevity of the thrusters of an AUV, a smoothing filter had to be considered in controller design of an underactuated AUV.

1. Introduction

According to National Oceanic and Atmospheric Administration (NOAA), over 1000 ship wrecks lie off at the Florida Keys. To investigate each one of them manually is a tedious job which is better performed by Autonomous Underwater Vehicle (AUV). Apart from the shipwreck investigation, an AUV has the potential to perform underwater cave exploration and studying coral reefs, all of which requires sophisticated motion control. The control of AUV presents some challenging tasks such as dealing with the nonlinearity of AUV dynamics, coupling effects, and taking into consideration the hydrodynamics uncertainties and disturbances such as flow of current.

One of the more suitable controller for controlling a nonlinear system is Sliding-Mode Control (SMC). The SMC aims to make a sliding variable goes to zero as time approaches infinity. The sliding variable is defined as the tracking error times eigenvector of a closed-loop system. SMC had been used on AUV for depth control [1], yaw control [2,3], tracking control under ocean currents [4], and tracking control for under-actuated system [5]. Apart from its normal usage, there are several improvements made for controlling an AUV. In one study, the switching term of SMC was tuned using extreme learning machine (ELM) [6]. In another study, a combination of method consisting of backstepping and SMC are used to control an autonomous underwater glider [7]. In addition, this combination of method has been used on an AUV with a neural network added on top of the controller to tune SMC switching term [8]. Basically, higher switching term gain adds robustness to the controller at the cost of performance while lower switching term gain make the controller performs better but lacks robustness to handle disturbances.

In all, SMC has a simple design principle yet very robust to handle model uncertainties and unexpected disturbances. On the other hand, there are some issues such as configuring the tuning parameter of switching term gain to get the desirable balance between performance and robustness, and it has low responsiveness to desired reference signal.

In this paper, the objective is to design and develop a responsive and robust controller based on SMC for an underactuated hovering AUV. The focus of the controller is on heading motion. Heading refers to the capability of the robot to turn left or right and it is one of the most important motion to control. The scope covers the applicability of the control only for a modified BlueROV prototype and some of the test was conducted at diving pool with calm water instead of at sea.

2. Methodology

The process of designing a proper heading control system for an AUV starts with modeling. Modeling means a simple description of a system. In this research, the AUV's heading is described by its heading equation of motion. After the heading equations of motion had been derived, there would be some parameters in the model that is hard to determine due to the nonlinearity of hydrodynamics properties. So, estimation of these unknown parameters by system identification is required. Next, a heading control system based on SMC is designed. Then, the SMC controller parameters are optimized to get desired response. Once the controller had been optimized, the response of the robot is evaluated based on certain metrics. In all, the flowchart of the methodology is shown in Figure 1.

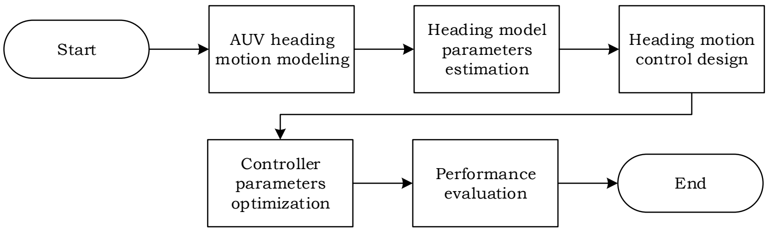


Figure 1. Methodology

2.1. *Heading Model of AUV*

The prototype to be modeled is a modified BlueROV. The modified BlueROV is chosen because it is lightweight, small-sized, and has high maneuverability. Figure 2 shows the design of the robot as well as motion variables, *u*, *v*, *w*, *p*, *q*, and *r* in m/s. Although the main usage of the robot is as a Remotely-Operated Vehicle (ROV), it is used primarily as an AUV in this study. Focus is also given to thrusters T_3 and T_4 which produces heading motion.

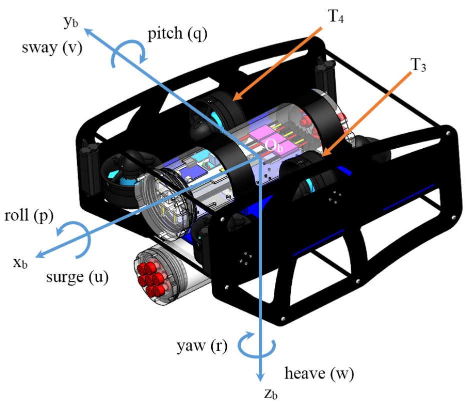


Figure 2. Modified BlueROV design with motion variables

The modeling derivation of the robot is based on [9]. The heading model of the robot in state space is given as follow

$$\begin{bmatrix} \dot{v}(t) \\ \dot{r}(t) \\ \dot{\psi}(t) \end{bmatrix} = \begin{bmatrix} \frac{Y_v}{m-Y_{\dot{v}}} & \frac{Y_r}{m-Y_{\dot{v}}} & 0 \\ \frac{N_v}{I_z-N_{\dot{r}}} & \frac{N_r}{I_z-N_{\dot{r}}} & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v(t) \\ r(t) \\ \psi(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{I_z-N_{\dot{r}}} \\ 0 \end{bmatrix} N(t) \tag{1}$$

where v is swaying speed, r is yawing speed, ψ is yawing angle, Y_v is linear damping force coefficient with respect to swaying, m is mass of the modified BlueROV, $Y_{\dot{v}}$ is added mass with respect to swaying, Y_r is linear damping force coefficient with respect to yawing, N_v is linear damping force coefficient with respect to swaying, I_z is inertia about z_b-axis, $N_{\dot{r}}$ is added mass with respect to yawing, N_r is linear damping force coefficients with respect to yawing, and N is moment about z_b-axis produces by thrusters T_3 and T_4 (both of T100 model thruster).

2.2. *Parameter Estimation of Heading AUV Model*

Although the equations of motion had been derived, some of the components in the equations are unknown. The unknown components consist of hydrodynamics and inertial parameters. These unknown parameters need to be estimated using system identification. Gray-box system identification is used because the modeling and prototype are available. The process to estimate parameters based on gray-box system identification is firstly to perform experiment, secondly to run simulation, and thirdly to estimate parameters by comparing the 2 sets of collected data.

For experimentation, let the AUV submerged in a pool for 1 meter and let it stabilized (neutrally buoyant). Then, starts to record the yawing angle, ψ. When t is equal to 2, 8, and 14 seconds, T_3 and T_4 are supplied with an instantaneous force of 1.37 N but with different direction so that the AUV produces rotation about z_b-axis. The duration of test is set to 20 s and the experiment is repeated 3 times to get average value. Figure 3 shows the illustration of the experiment.

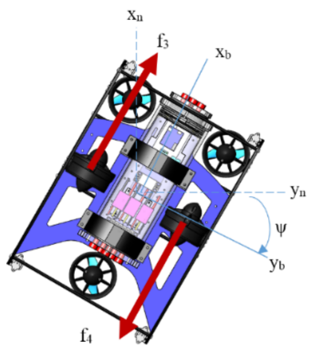


Figure 3. System identification experiment for heading

For simulation, the known value is the mass m which is 6.2 kg and the initially guessed values are Y_r = 0.1 kg/s, Y_v = 0.1 kg/s, $Y_{\dot{v}}$ = 0.1 kg, I_z = 0.015 kg m^2/s^2, N_v = 0.1 kg m/s, N_r = 1.5 kg m/s, and $N_{\dot{r}}$ = 0.5 kg m^2/s^2. The simulation is conducted for 20 s similar to experiment duration and the yawing angle, ψ is recorded.

Based from the 2 yawing angle data sets (experiment and simulation), the initially guessed values are estimated using *nlgreyest* function from MATLAB and the estimation is further improved using *pem* function. The final estimated values are Y_r = -1 kg/s, Y_v = -10 kg/s, $Y_{\dot{v}}$ = 6 kg, I_z = 0.015 kg m^2/s^2, N_v = 10 kg m/s, N_r = 1.3 kg m/s, and $N_{\dot{r}}$ = 0.5 kg m^2/s^2. Note that the Normalized Root Mean Squared Error (NRMSE) percentage for simulation, *nlgreyest* function, and *pem* function are 9.3%, 88.6%, and 92.2% respectively.

2.3. *Heading Motion Control Design*

The block diagram of the designed heading control system using SMC is shown in Figure 4. There are four significant blocks denoted by the bolded text and number.

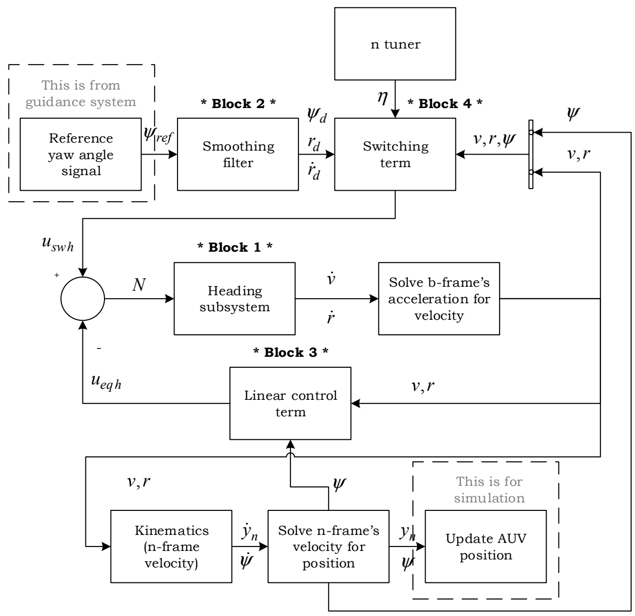


Figure 4. Block diagram of the designed heading control system

The first block (Block 1) is about heading subsystem and the equation is given as in Eq. (1). Then, the second block (Block 2) is about the smoothing filter. It smooths the reference input so that the signal appears analogous rather than digital. The smoothing filter is of second order mass-spring-damper system given by

$$\ddot{\psi}_d + 2\zeta\omega_o\dot{\psi}_d + \omega_o^2\psi_d = \omega_o^2\psi_{ref} \tag{2}$$

with

$$\begin{aligned} \dot{\psi}_d &= r_d \\ \ddot{\psi}_d &= \dot{r}_d \end{aligned} \tag{3}$$

where ψ_{ref} is reference yaw angle, ψ_d is desired yaw angle, r_d is desired yaw angular velocity, and $\dot{r}_d$ is desired yaw angular acceleration. The damping ratio ζ is set to 1 and the natural frequency ω_o is set to 2 to get a combination of critically damped and quicker response signal.

Next, Block 3 is a linear control term block. The input to the block is state variables consisting of sway velocity v, yaw angle rate r and yaw angle ψ. So, there will be three parameters for linear control term such that

$$\mathbf{k}_h = [k_{h1}, k_{h2}, k_{h3}]^T \tag{4}$$

where k_{h1}, k_{h2} and k_{h3} are poles placed on the closed-loop system to control the v, r and ψ terms respectively. The output for the equivalent linear controller block is

$$u_{eqh} = \mathbf{k}_h^T \mathbf{x}_h = [k_{h1}, k_{h2}, k_{h3}] \begin{bmatrix} v \\ r \\ \psi \end{bmatrix} \tag{5}$$

The objective of the linear controller block is not just to control the state variables, but to also find the eigenvalues for the switching term. This is done by decomposing the eigenvalues of a closed-loop system matrix. The closed-loop system matrix for the heading subsystem $\mathbf{A}_{ch}$ with the respective linear controller can be modeled by

$$\mathbf{A}_{ch} = \begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} - b_h k_{h1} & a_{22} - b_h k_{h2} & -b_h k_{h3} \\ 0 & 1 & 0 \end{bmatrix} \tag{6}$$

Let $\mathbf{h}_h$ be an eigenvector to the heading switching term and according to [9]

$$\lambda_h \mathbf{x}_h^T \mathbf{h}_h = 0 \text{ if } \mathbf{h}_h \text{ is a right eigenvector of } \mathbf{A}_{ch}^T \text{ for } \lambda_h = 0 \tag{7}$$

where $\lambda_h = 0$ is an eigenvalue for the pure integrator of r producing ψ. So, $\mathbf{h}_h$ is found by decomposing eigenvalues based from $\mathbf{A}_{ch}^T$. Therefore,

$$\mathbf{h}_h = [h_{h1}, h_{h2}, h_{h3}]^T \tag{8}$$

are to be optimized SMC parameters.

The final block or Block 4 is about switching term. The output of the switching block is given as follow

$$\begin{aligned} u_{swh} &= \left(\mathbf{h}_h^T \mathbf{b}_h\right)^{-1} \left[\mathbf{h}_h^T \dot{\mathbf{x}}_d - \mathbf{h}_h^T \hat{\mathbf{f}}(\mathbf{x}, t) - \eta \operatorname{sgn}(s_h)\right] \\ &= \frac{1}{h_{h2} b_h} \left[h_{h2} \dot{r}_d + h_{h3} \dot{\psi}_d - \eta \tanh(s_h)\right], \ \eta > 0 \end{aligned} \tag{9}$$

where s_h is the heading sliding surface such that

$$s_h = \mathbf{h}_h^T \tilde{\mathbf{x}} = \mathbf{h}_h^T (\mathbf{x}_h - \mathbf{x}_{hd}) = h_{h1} v + h_{h2} (r - r_d) + h_{h3} (\psi - \psi_d) \tag{10}$$

Therefore, the heading thrust needed to track desired yaw angle ψ_d is

$$N = -u_{eqh} + u_{swh} = -k_{h1} v - k_{h2} r + \frac{1}{h_{h2} b_h} \left[h_{h2} \dot{r}_d + h_{h3} \dot{\psi}_d - \eta \tanh(s_h)\right] \tag{11}$$

N can be transformed into actuator forces by summing the resultant forces and moments so that

$$\begin{aligned} f_3 + f_4 &= 0 \\ -f_3 l_{y3} + f_4 l_{y4} &= N \end{aligned} \tag{12}$$

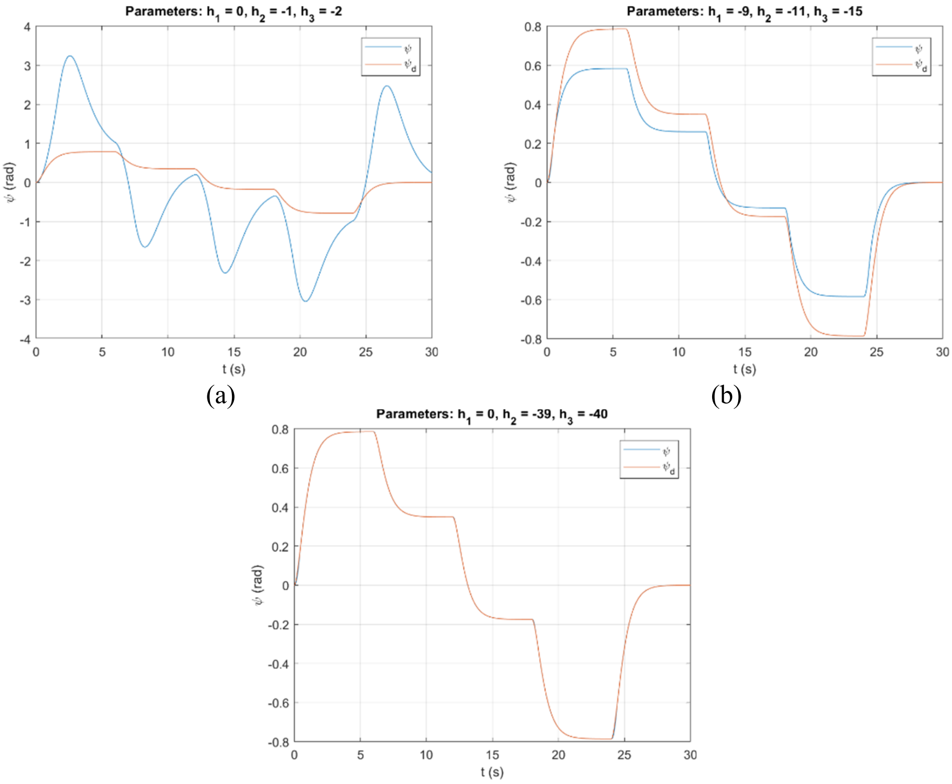
where $l_{y3} = l_{y4} = 0.11$ m are distance from origin of body frame to T_3 and T_4 origins respectively.

2.4. *Controller Parameters Optimization*

The controller parameters are optimized using trial and error method by means of brute force. The parameters values tested are from -1 to -40 with decrement of -1. Combination of parameters values which produces minimum sum of absolute error is selected. So, let the waypoint be

$$\psi_{ref} = \begin{cases} 0 & t = 0 \\ \pi/4 & 0 < t \le 6 \\ \pi/9 & 6 < t \le 12 \\ -\pi/18 & 12 < t \le 18 \\ -\pi/4 & 18 < t \le 24 \\ 0 & 24 < t \le 30 \end{cases} \tag{13}$$

Figure 5 shows the response of heading using the worst, mediocre and best (optimized) controller parameters values. For the optimized controller parameters values (h_1 = 0, h_2 = -39, h_3 = -40), the sum of absolute error is 2.98. Note that the switching gain η is fixedly set to 100.



(a) (b) (c)

Figure 5. Heading responses using different sets of controller parameters

3. Results and Discussions

The performance metric used to conduct the analysis of the results is responsiveness to unit step input. The formula to calculate the responsiveness to unit step is given by

$$R = 100\left(1 - \frac{1}{N}\sum_{n_s=1}^{N}\left|\frac{\psi_d(n_s) - \psi_a(n_s)}{\psi_d(n_s)}\right|\right) \tag{14}$$

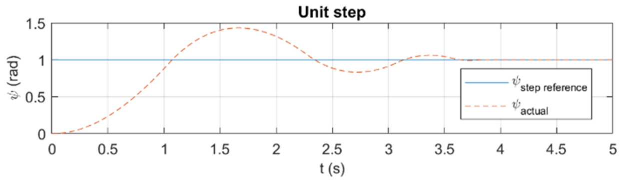
where n_s is the sample number, N is the total number of samples, and $\psi_d(n_s)$ and $\psi_a(n_s)$ are the desired and actual yaw values for sample n_s respectively. The formula for unit step is given as

$$\psi_d(n_s) = 1 \tag{15}$$

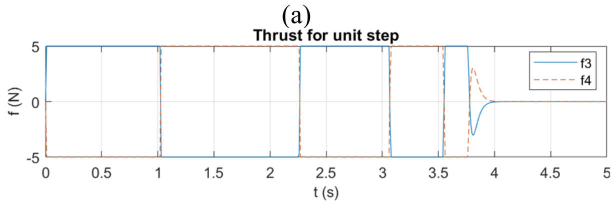
The reference signal can be smoothed to create another type of desired signal. The desired smoothed signal using mass-spring-damper system as suggested during the design of control system is given as

$$\psi_d(n_s-2)+2\zeta\omega_o\psi_d(n_s-1)+\omega_o^2\psi_d(n_s)=\omega_o^2\times 1 \tag{16}$$

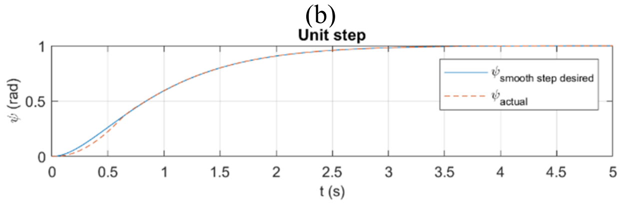
So, there are two input signals used as tracking sources for the designed controller. Figure 6 shows the responses of the robot when the heading controller tracks the desired reference and desired smoothed signals. Also shown are the thrusts needed to perform the maneuver. Note that the lower limit of thrust is set to -5N and upper limit of thrust is set to 5N.



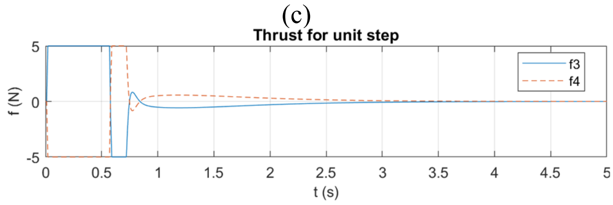
(a)



(b)



(c)



(d)

Figure 6. Response of robot and thrust produced by SMC for heading control, (a) and (b) for desired reference input signal, (c) and (d) for desired smoothed input signal

Figure 6 (a) shows the response of the robot based from the thrust produced by SMC for heading using desired reference input signal. Based from the figure, for unit step signal, the response is oscillating at the beginning, but became steady after 4 s. It is observed that the thrusts as in Figure 6 (b) that produce this response are alternating steeply at about 1 s, 2.25 s, 3.1 s, 3.6 s, and 3.75 s before they stabilize. Then, Figure 6 (c) shows the response of the robot based on desired smoothed input signal using SMC. There are no overshoot and the controller shows excellent tracking performance. The corresponding thrust as shown in Figure 6 (d) changes gradually instead of steeply for a longer period of time compared to Figure 6 (b). Evidently, from Figure 6 (a) and (c), the designed SMC produces stable heading output response patterns. In all, the responsiveness of the heading based on the desired reference input is 78.05% while desired smoothed input gives 95.55%. In addition, using the desired reference signal strains the thruster more while using the desired smoothed signal preserves the thruster better. Therefore, it is necessary to smooth the reference input signal so that the AUV performs better responsively and to preserve the longevity of the thrusters.

4. Conclusions and Future Works

In conclusion, a heading control system based on SMC had been designed and developed for a modified BlueROV. In order to make the controller more responsive, a smoothing filter is introduced to the reference signal so that the controller is able to track the signal with reduced tracking error. Quantitatively, the controller shown to have 95.55% responsiveness with smoothing filter and 78.05% responsiveness without the smoothing filter. Qualitatively, the controller has excellent responsiveness to follow smoothed reference signal and acceptable responsiveness to follow non-smoothed reference signal.

The future works could include updating the estimated parameters from the heading model with sea water instead of pool water or introducing lateral disturbance (current) or developing an algorithm to further optimize controller parameters to get an even better heading response.

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