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Responsive surging, heading and diving controls of autonomous underwater vehicle based on brute forcing and smoothing of controllers

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There are many types of controllers had been used to control Autonomous Underwater Vehicle (AUV) such as Proportional Integral Derivative (PID), Linear Quadratic Regulator (LQR), state feedback linearization, integrator back-stepping, and Sliding-Mode Control (SMC). However, for PID and SMC in particular, it is difficult to determine the optimal control design parameters. The objective of this study is to design and develop a responsive motion control system with optimal parameters for an AUV. The contribution of this paper is in term of introducing a filter to smooth reference signal and proposing a brute forcing technique to find optimal controller parameters. The methodology starts with modeling the AUV, estimating the unknown parameters from a real AUV model, designing a control system based on PI and SMC methods, and finally optimizing the controller parameters. The controller design was onto controlling surge speed using PI, heading using SMC, and diving using SMC. Simulation-wise, the developed control system has an average value of 93.89 % of responsiveness to track desired trajectory while 82.33 % of responsiveness without using the smoothing filter. The tested input signals were unit step, ramp, parabolic, and sinusoidal.

[**Keywords**: Autonomous underwater vehicle, Brute force optimization, Control system, Proportional integral derivative, Sliding mode control, Surging heading diving]

Introduction

Some of the challenges presence when controlling an Autonomous Underwater Vehicle (AUV) are nonlinearity of hydrodynamics, coupling effects, and in dealing with uncertain disturbances such as flow of current. There are many control methods had been proposed on AUV over the years. In this paper, more emphasis is given to popular control methods specifically Proportional-Integral-Derivative (PID) and Sliding-Mode Control (SMC).

The PID is a linear type of control system. The basic principle of using PID is tuning its proportional, integral, or derivative terms to achieve a desirable transient and steady-state response. Among the recent research works that utilize PID to control the motion of AUV are Genetic Algorithm (GA) based PID[1], fuzzy PID[2], and fully-actuated AUV PID control[3]. The GA based PID optimizes the terms for controlling the heading of an AUV, the fuzzy PID tune the terms based on inference or forming rules for depth control, and the fully-actuated AUV PID control focuses on speed control. Implementing a PID controller is simple. However, to get an optimal performance by changing the parameters' values is difficult. Also, it has low robustness to disturbances and unable to compensate the behavioral change of the system.

A SMC is a robust nonlinear controller with the ability to handle model uncertainties and unexpected disturbances. The controller objective is to make a sliding variable goes to zero as time approaches infinity. SMC had been used on AUV for depth control[4], yaw control[5,6], tracking control under ocean currents[7], and tracking control for under-actuated AUV system[8]. SMC has a simple design principle yet there are some issues such as finding suitable desired poles for closed-loop system and configuring the tuning parameter of switching term gain to get the right balance between performance and robustness.

For controlling a robot in an underwater environment, the robustness aspect is the most important factor. This is due to the nonlinear hydrodynamic properties and randomness of current that affect the AUV movement. In that sense, SMC is selected as the most suitable control method for the purpose of this study. For a simpler model such as speed of the AUV, a Proportional-Integral (PI) based controller is more appropriate. In one aspect of control design, finding value for nonlinear controller parameters to produce optimum response is difficult. Therefore, a brute force controller design parameters optimization is proposed to obtain optimum value for the designed nonlinear controllers. Additionally, a smoothing filter is also introduced to make the reference trajectory smoothly responsive.

Materials and Methods

The process of designing a proper control system for an AUV starts with modeling. The AUV modeling is based on both kinematics and dynamics. After the equations of motion had been derived, there would be some parameters that are difficult to determine due to the nonlinearity of hydrodynamics properties. So, it is required to estimate these unknown parameters by using a system identification approach. Once the unknown parameters are estimated, control systems are designed to control the AUV's motion for each subsystem of the AUV. Then, the controllers' parameters are optimized by using a brute force optimization. Finally, the controllers are then combined altogether into one system.

Note that all of the symbols used for modeling and control in this paper are based from Fossen, 2021[ref. 9]. The kinematics equation is given as:

$$\begin{aligned}
\dot{x}_n &= u\,c(\psi)c(\theta) + v\left[c(\psi)s(\theta)s(\phi) - s(\psi)c(\phi)\right] \\
&\quad + w\left[s(\psi)s(\phi) + c(\psi)c(\phi)s(\theta)\right] \\
\dot{y}_n &= u\,s(\psi)c(\theta) + v\left[c(\psi)c(\phi) + s(\phi)s(\theta)s(\psi)\right] \\
&\quad + w\left[s(\theta)s(\psi)c(\phi) - c(\psi)s(\phi)\right] \\
\dot{z}_n &= -u\,s(\theta) + v\,c(\theta)s(\phi) + w\,c(\theta)c(\phi) \\
\dot{\phi} &= p + q\,s(\phi)t(\theta) + r\,c(\phi)t(\theta) \\
\dot{\theta} &= q\,c(\phi) - r\,s(\phi) \\
\dot{\psi} &= q\frac{s(\phi)}{c(\theta)} + r\frac{c(\phi)}{c(\theta)}, \theta \neq \pm\frac{\pi}{2}
\end{aligned} \quad \dots (1)$$

As for the dynamics, the AUV model can be divided into 3 subsystems specifically surging subsystem, heading subsystem (combination of swaying and yawing), and diving subsystem (combination of heaving and pitching). They are given as:

$$\dot{u} = \frac{\left(X_u + X_{u|u|}|u|\right)u + f_3 + f_4}{m - X_{\dot{u}}} + \mathbf{T}_{loss\_\dot{u}} \quad \dots (2)$$

$$\begin{aligned}
\dot{v} &= \frac{\left(Y_v + Y_{v|v|}|v|\right)v}{m - Y_{\dot{v}}} + \mathbf{T}_{loss_\dot{v}}; \\
\dot{r} &= \frac{\left(N_r + N_{r|r|}|r|\right)r + N_v v - f_3 l_{y3} + f_4 l_{y4}}{I_z - N_{\dot{r}}} + \mathbf{T}_{loss_\dot{r}}
\end{aligned} \quad \dots (3)$$

$$\begin{aligned}
\dot{w} &= \frac{\left(Z_w + Z_{w|w|}|w|\right)w + Z_q q + f_1 + f_2 + f_5}{m - Z_{\dot{w}}} + \mathbf{T}_{loss_\dot{w}}; \\
\dot{q} &= \frac{\left(M_q + M_{q|q|}|q|\right)q + M_w w + W z_b s(\theta) + \dots + f_1 l_{x1} + f_2 l_{x2} - f_5 l_{x5}}{I_y - M_{\dot{q}}} + \mathbf{T}_{loss_\dot{q}}
\end{aligned} \quad \dots (4)$$

For system identification, Table 1 shows all of the initially guessed values, similarity percentage of responses between experimentation and simulation, and final estimated values for all parameters for BlueROV prototype. From Table 1 as well, *sim* stands for simulation, *nlgreyest* stands for nonlinear grey estimate function, and *pem* stands for prediction error minimization function.

For control system design, the formula for PI controller to produce surge thrust X is

$$X = K_p e + K_i \int_0^t e\, dt \quad \dots (5)$$

Let the error dynamics be of a second order mass-spring-damper model and matching to (5), the pole placement algorithm is

$$\frac{K_p - X_u}{m - X_{\dot{u}}} = 2\zeta_s \omega_{ns}; \quad \frac{K_i}{m - X_{\dot{u}}} = \omega_{ns}^2 \quad \dots (6)$$

The heading thrust N needed to track desired yaw angle ψ_d using SMC is

$$\begin{aligned}
N &= -u_{eqh} + u_{swh} \\
&= -k_{h1}v - k_{h2}r + \frac{1}{h_{h2}b_h}\left[h_{h2}\dot{r}_d + h_{h3}\dot{\psi}_d - \eta\tanh(s_h)\right]
\end{aligned} \quad \dots (7)$$

While, the thrust needed to track desired depth for diving Z using SMC is

$$\begin{aligned}
Z &= -u_{eqd} + u_{swd} \\
&= -k_{d1}w - k_{d2}q - k_{d3}\theta - k_{d4}z_n + \frac{1}{h_{d1}b_d}\left[h_{d1}\dot{w}_d + h_{d3}\dot{z}_{nd} - \eta\tanh(s_d)\right]
\end{aligned} \quad \dots (8)$$

Then, the block diagram for the combined control systems is shown in Figure 1. The important part about the block diagram is the thrust allocation block.

Table 1 — All estimated parameters for BlueROV

Motion	Initial guessed values	Similarity percentage based on NRMSE (%)			Final estimated values
		sim	*nlgreyest*	*pem*	
Surge	$X_u = -3, X_{\dot{u}} = 3$	-16.8	99.7	99.7	$X_u = -5, X_{\dot{u}} = 2$
Heave	$Z_w = -1, Z_{\dot{w}} = 1$	-20.3	87.0	95.0	$Z_w = -3, Z_{\dot{w}} = 3.5$
Roll	$z_b = 0.015, I_x = 0.0003,$ $K_p = 0.1, K_{\dot{p}} = 0.3$	35.1	48.4	97.0	$z_b = 0.002, I_x = 0.001,$ $K_p = 0.3, K_{\dot{p}} = 0.4$
Pitch	$I_y = 0.025, M_q = 0.13,$ $M_{\dot{q}} = 0.13$	27.2	55.6	95.3	$I_y = 0.001, M_q = 0.35,$ $M_{\dot{q}} = 0.35$
Yaw	$I_z = 0.5, N_r = 1,$ $N_{\dot{r}} = 1$	5.8	93.1	95.6	$I_z = 0.015, N_r = 1.3,$ $N_{\dot{r}} = 0.5$
Heading (sway and yaw)	$Y_r = 0.1, Y_v = 0.1,$ $Y_{\dot{v}} = 0.1, I_z = 0.015,$ $N_v = 0.1, N_r = 1.3,$ $N_{\dot{r}} = 0.5$	9.3	88.6	92.2	$Y_r = -1, Y_v = -10,$ $Y_{\dot{v}} = 6, I_z = 0.015,$ $N_v = 10, N_r = 1.3,$ $N_{\dot{r}} = 0.5$
Diving (pitch and heave)	$z_b = 0.002, Z_q = 1,$ $Z_w = -3, Z_{\dot{w}} = 3.5,$ $I_y = 0.001, M_w = 0.01,$ $M_q = 0.35, M_{\dot{q}} = 0.35,$	-15.7	77.4	91.0	$z_b = 0.002, Z_q = 1,$ $Z_w = -3, Z_{\dot{w}} = 3.5,$ $I_y = 0.001, M_w = 0.0001,$ $M_q = 0.35, M_{\dot{q}} = 0.35,$

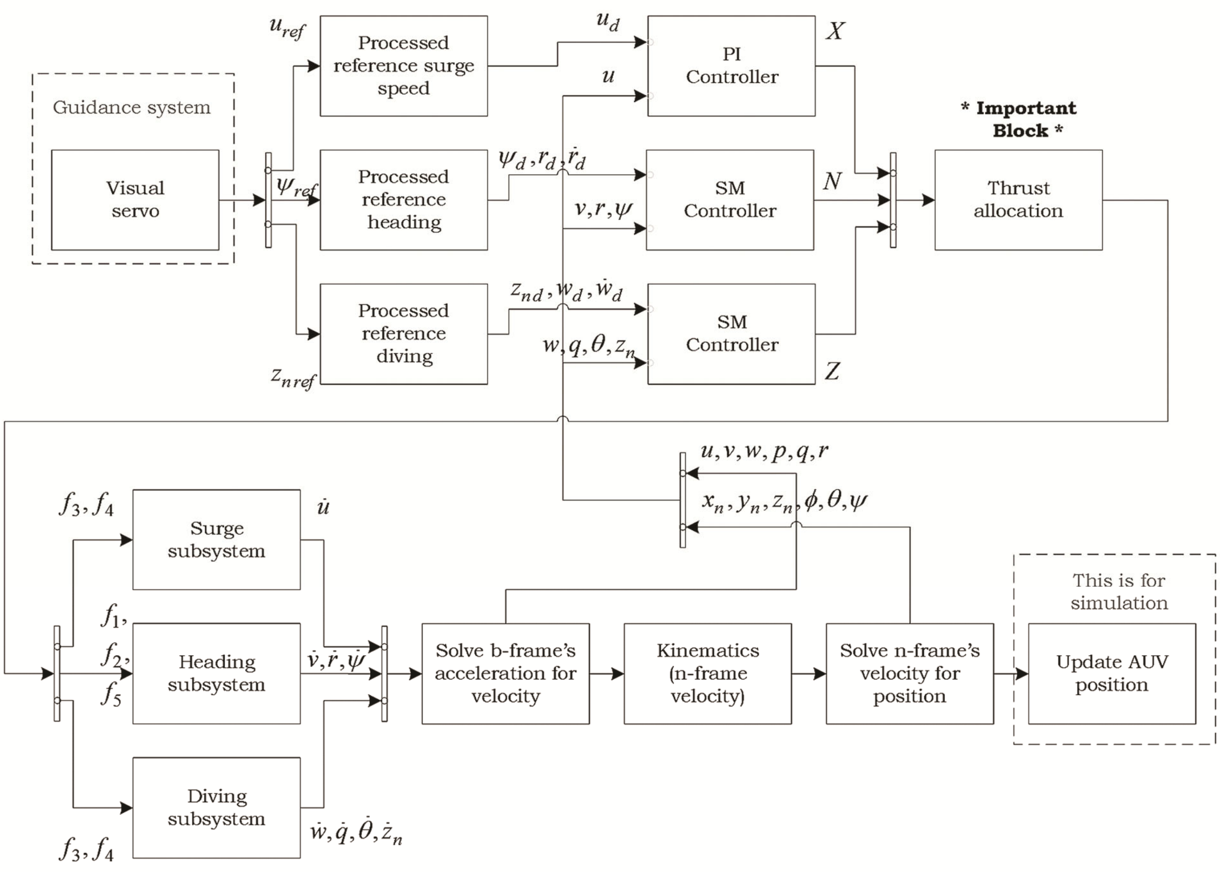

Fig. 1 — Block diagram for combined control systems

It is used to transform resultant forces and moments from controllers into actuator forces. The formula for the block is given by

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & 0 & 0 & -1 \\ l_{y1} & -l_{y2} & 0 & 0 & 0 \\ -l_{x1} & -l_{x2} & 0 & 0 & l_{x5} \\ 0 & 0 & -l_{y3} & l_{y4} & 0 \end{bmatrix}^{-1} \begin{bmatrix} X \\ 0 \\ Z \\ 0 \\ 0 \\ N \end{bmatrix} \quad \ldots (9)$$

Where, $l_{y1} = l_{y2} = l_{y3} = l_{y4} = 0.11$ m and $l_{x1} = l_{x2} = l_{x5} = 0.17$ m.

The designed controllers need to produce desirable response as required by a guidance system. This can be achieved by optimizing the parameters for each controller. The design parameters to be optimized are damping ratio ζ_s, natural frequency ω_{ns}, both for speed control, eigenvalues h_{h1}, h_{h2} and h_{h3} for heading control, and eigenvalues h_{d1}, h_{d2}, h_{d3}, and h_{d4} for diving control. The proposed brute force optimization technique is resource extensive but it is applicable to any type of problem to find the desired control parameters. The technique is performed by the following steps which focus on the heading control system as an example:

1. Determine control design parameters: the eigen values are h_{h1}, h_{h2} and h_{h3}.
2. Set the parameter accuracy and range: accuracy is set to 1 and range is set from -0 to -40.
3. Determine the pattern or a set of waypoints for reference signal.
4. Determine the type of error between desired and acquired signals: sum of absolute error.
5. Generate a list for all combination of parameters in step 2.
6. Prepare first set of parameters: $h_{h1} = 0$, $h_{h2} = -1$, and $h_{h3} = -2$.
7. Configure the controller with the set of parameters and get the response from the system.
8. Calculate the error signal based from step 4.
9. Save the set of parameters and its respective error in a database.
10. Repeat step 7 to step 9 for subsequent sets of parameters.
11. When all sets of parameters had been tested, sort the errors ascendingly.

Table 2 listed the configuration and optimized values for each controller's parameters when using the proposed optimization technique.

Results and Discussion

The performance metric used to analyze the result is known as responsiveness. In this study, responsiveness is defined as the ability of an AUV to react quickly to follow a desired input signal. The

Table 2 — Configuration and values from proposed optimization technique

Designed controller	Accuracy and range	Reference signal	Minimum sum of absolute error	Optimized parameters
PI for surging	1; 0 to 40	$u_{ref} = \begin{cases} 0 & t=0 \\ 1.5 & 0<t\le 6 \\ 1 & 6<t\le 12 \\ 0.5 & 12<t\le 18 \\ 1.8 & 18<t\le 24 \\ 0 & 24<t\le 30 \end{cases}$	0.45	$[\zeta_s, \omega_{ns}] = [2, 40]$
SMC for heading	1; -0 to -40	$\psi_{ref} = \begin{cases} 0 & t=0 \\ \pi/4 & 0<t\le 6 \\ \pi/9 & 6<t\le 12 \\ -\pi/18 & 12<t\le 18 \\ -\pi/4 & 18<t\le 24 \\ 0 & 24<t\le 30 \end{cases}$	2.98	$[h_{h1}, h_{h2}, h_{h3}] =$ [-0, -39, -40]
SMC for diving	0.00001; -0 to -10	$z_{n\,ref} = \begin{cases} 0 & t=0 \\ 1.3 & 0<t\le 6 \\ 0.3 & 6<t\le 12 \\ 1.7 & 12<t\le 18 \\ 0.2 & 18<t\le 24 \\ 2 & 24<t\le 30 \end{cases}$	5.46	$[h_{d1}, h_{d2}, h_{d3}, h_{d4}]$ =[-10, -0, -0.00001, -1]

responsiveness is determined by the designed controller because controller produces actuator signal which makes the AUV responsive. The formula to calculate the responsiveness is

$$R_t = 100\left(1 - \frac{1}{N}\sum_{n_S=1}^{N}\left|\frac{\delta_d(n_s) - \delta_a(n_s)}{\delta_d(n_s)}\right|\right) \quad \dots (10)$$

Where, n_s is the sample number, N is the total number of samples, and $\delta_d(n_s)$ and $\delta_a(n_s)$ are the desired and actual values for sample n_s, respectively. The variable δ could be surge speed u, heading angle ψ, or depth z_n.

There are four types of input signals used to evaluate the responsiveness of the AUV. They are unit step, ramp, parabolic, and sinusoidal. These reference signals can be smoothed to create another set of desired signals. The smoothing filter is of second order mass-spring-damper system where ζ is set to 1 and ω_o is set to 2. So, there are two sets of input signals used as tracking sources for the designed controllers. All initial conditions of the AUV are set to zero. The sampling interval was set to 0.01 s. Figure 2 shows the heading sample response and thrust of the AUV when the controller tracks the desired reference signals.

Overall, the responsiveness is populated in Table 3. For non-smooth signals, PI controller shows excellent responsiveness for all input signals and as for the SMC specifically heading and diving, the results are acceptable. For smoothed signals, the responsiveness is all above 85 % for all controllers. Quantitatively, the PI controller has an average responsiveness of 97.87 % to track smoothed reference signals while the SMC for heading and diving shown to have 96.09 and 87.72 %, respectively. Also from the result output, the thrust for desired reference input signal fluctuates steeply while the thrust for desired smoothed input signal changes gradually. Thus, using the desired reference signal strains the thruster more while using the desired smoothed signal preserves the thruster better.

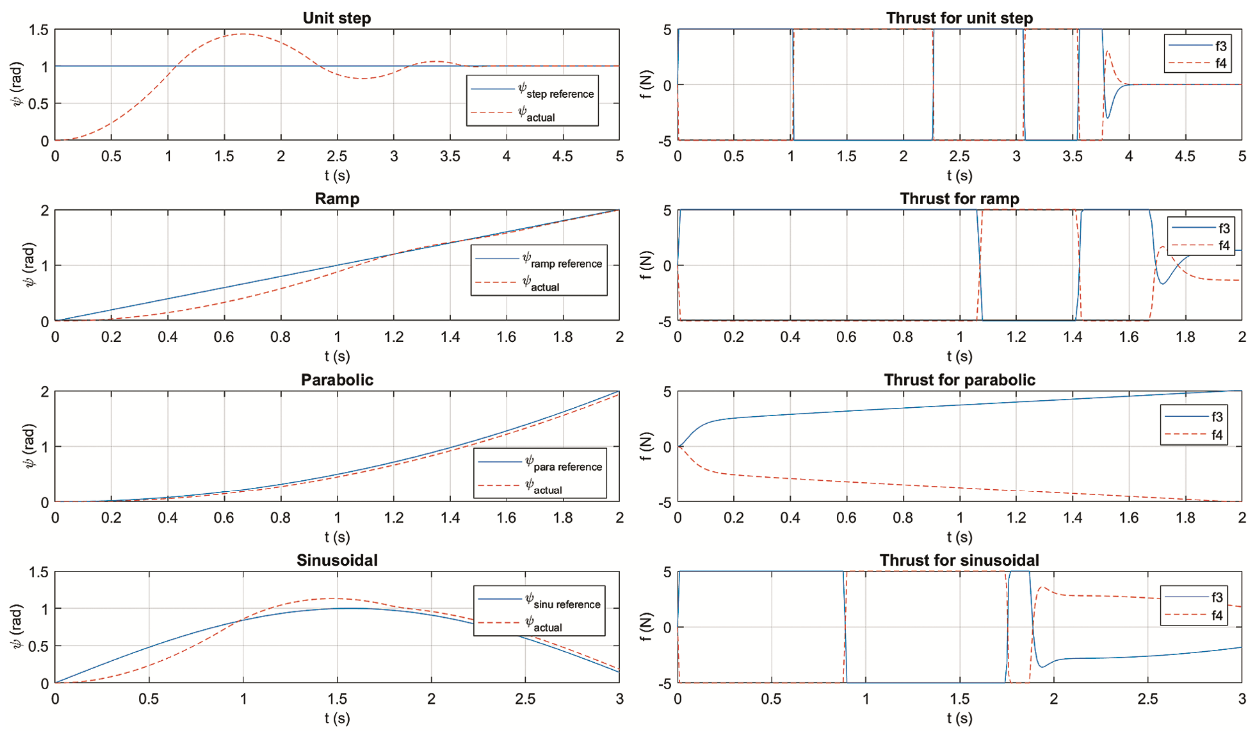

Fig. 2 — Response of AUV and thrust produced by SMC for heading motion based on desired reference input signals

Table 3 — Responsiveness of AUV based on desired reference input

Designed controllers	Responsiveness, R_t (%)							
	Non-smooth signals				Smoothed signals			
	Unit step	Ramp	Parabolic	Sinusoidal	Unit step	Ramp	Parabolic	Sinusoidal
PI for surging (speed u)	89.59	96.34	94.36	99.26	99.34	97.43	96.41	98.30
SMC for heading (yaw ψ)	78.05	70.89	78.05	77.79	95.55	96.32	94.95	97.52
SMC for diving (depth z_n)	76.77	66.46	60.13	69.93	91.22	87.65	86.33	85.67

Conclusion

A control system based on PI to control surge speed, SMC to control heading, and another SMC to control diving had been designed and developed for an AUV. In order to optimize the controller performance, a brute force controller design parameters optimization is introduced. The optimization technique is capable to solve the issue of determining the better configuration of all developed controllers. Qualitatively, the designed control system has high responsiveness to track smooth desired trajectory and good responsiveness for non-smoothed trajectory.

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Conflict of Interest

There is no conflict of interest.

Author Contributions

MFY: writing, methodology, simulation, experimentation; MRA: supervision, review, validation; and MHAM: article organization, proofreading.

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