Position Control System of Autonomous Underwater Vehicle using PID Controller

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Abstract* – Water covers most of the earth's surface compared to the land, including Indonesia. Such an area can be explored using an underwater robot, which is implemented in an autonomous underwater vehicle (AUV). The AUV control system requires a controller to be able to move properly. Thus, a PID controller that has a simple structure and yields great performance can be implemented in the AUV. This study was conducted to control the movement of the surge, heave, and yaw of the AUV using the PID. The AUV modeling simulations were carried out using Simulink to determine the PID gain values. The simulation results for surge movement were Kp = 38.41, Ki = 10.8 and Kd = 58.4, heave movement were Kp = 49.13, Ki = 2.56 and Kd = 107.12 and yaw movement were Kp = 3.18, Ki = 0.18 and Kd = 12.11. The results showed that AUV could perform well and maintain the position determined by the set point for 3-4 seconds.

Keywords: Autonomous Underwater Vehicle, PID, Control System, Simulink.

I. Introduction

Water makes up about 71% of the Earth's surface compared to the land, including in Indonesia. According to the Ministry of Marine Affairs and Fisheries, water covers about 3.25 million Km^2 of Indonesia [1]. Thus, underwater exploration can be carried out by the government or society for various purposes. However, underwater exploration carried out by humans has a high potential for accidents and death because of the quick environment changing.

To overcome it, nowadays, underwater exploration is done by using underwater robots [2][3]. The underwater robot is the right solution to replace humans in doing underwater tasks or missions. The underwater robot can perform simple to difficult tasks, such as underwater research, underwater resource search, underwater pipeline observation, port defense and security, and also application in the military area [4]. The most important thing while using an underwater robot is the control system for controlling the position and movement of the robot. The position control system on the robot is needed to specify the condition and position in the water.

In general, there are two kinds of underwater robots, namely Remotely Operated Vehicle (ROV) and Autonomous Underwater Vehicles (AUV). The AUV is an underwater robot that can automatically perform some tasks without an operator. The AUV needs controllers to control its movement. Various studies have been performed to control the AUV, such as Proportional Integral Derivative (PID) controller [5][6], self-adaptive Fuzzy-PID [7], Adaptive control [8], Neural Network-Fuzzy [2], Particle Swarm Optimization (PSO)-PID with derivative filter [9], and PID based on grey wolf optimizer [10]. Some of these controllers show great results in controlling the AUV, for example [5-10] which did a study about depth control, and [6-8] discussed the AUV simulation control systems.

However, the previous studies only implemented the simulation control system and only controlled the depth. Therefore, this study was conducted in simulation and AUV experimental test on navigation, position, and depth position using PID controller. The PID controller has a simple structure and yields great performance in various systems [6].

This paper is organized as follows, Section 2 describes the autonomous underwater vehicle, kinematic and dynamic equations of the AUV, and PID controller. Then, Section 3 presents the methods used in this work. The results and discussion are shown in Section 4. This work is then concluded in Section 5.

II. Literature Review

A. Autonomous Underwater Vehicle

Autonomous Underwater Vehicle (AUV) denotes a vehicle that can move automatically without a human as an operator. It can perform various tasks and missions in place or conditions that are difficult for humans. The AUV is equipped with several sensors as a control system, communication, and collecting data or required information, then proceed them to the operator.

B. AUV Kinematics

All degrees of freedom on world coordinate system (W) and body coordinate system (B) can be written in vector equation [11] as

$$\chi = [surge \quad sway \quad heave \quad roll \quad pitch \quad yaw]^T$$

$$= [x_B \quad y_B \quad z_B \quad \phi_B \quad \theta_B \quad \Psi_B]^T \quad (1)$$

$$\eta = [x \quad y \quad z \quad \varphi \quad \theta \quad \Psi]^T. \quad (2)$$

Equations (1) and (2) can determine the orientation, velocity, acceleration, and navigation of the world and body coordinate system of AUV [11].

Euler angle is used to relate the orientations of both coordinate systems. Euler angle equation can be written as

$$R^{BW}(\varphi,\theta,\Psi) = R_z(\Psi)R_y(\theta)R_x(\varphi). \quad (3)$$

Linear velocity or acceleration of coordinate system W can be calculated using this following equation:

$$J_1(V_W) = R^{BW}(V_W). \quad (4)$$

Angular velocity or acceleration of coordinate system W can be calculated as follows

$$J_2(\omega_W) = \begin{bmatrix} 1 & S(\varphi)T(\theta) & C(\varphi)T(\theta) \\ 0 & C(\varphi) & -S(\varphi) \\ 0 & S(\varphi)/C(\theta) & C(\varphi)/C(\theta) \end{bmatrix} \quad (5)$$

Every movement of the AUV can be shown in Fig. 1.

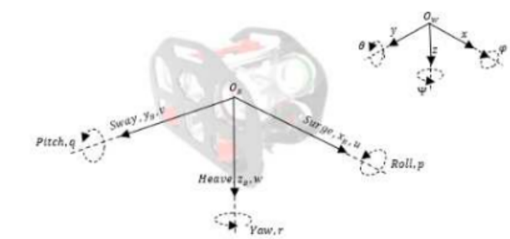

Fig 1. AUV Kinematics

C. AUV Dynamics

A dynamic model of the AUV can be used to determine the formula of control algorithm and simulation. The AUV dynamic equation can be calculated as [11]

$$M\dot{V} + C(V)V + D(V)V + g(\eta) = \tau. \quad (6)$$

Equation (9) is derived from Newton-Euler equation of rigid body in fluid [12], where $M = M_{RB} + M_A$ denotes inertia and added mass matrix, $C(V) = C_{RB}(V) + C_A(V)$ denotes the Coriolis and centripetal matrix for the rigid body and added mass, $D(V) = D_q(V) + D_l(V)$ denotes quadratic and linear drag matrix, $g(\eta)$ denotes weight and buoyancy matrix, and τ is force or torque vector from the thrusters.

D. PID Control System

PID controller can be used in the control system of AUV. Each parameter of the PID, such as Proportional, Integral, and Derivative has the constant values of Kp (Proportional constant), Ki (Integral constant), and Kd (Derivative constant), respectively. The equation of PID controller can be written as,

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt}, \quad (7)$$

where *u(t)* is the output from the system, *e* is error, *t* is the time, and τ is an integral variable with the value from 0 to *t*.

III. Research Method

This method performed in this study is divided into three parts, namely control system, hardware design, and system testing design. To test of AUV was conducted in a lake.

A. Control System

The block diagram of the control system performed in this study can be seen in Fig. 2. The setpoints for surge, heave, and yaw movement are x, z, Ψ, respectively while x*, z*, and Ψ* are the output of the control system. A bilge pump is the thruster of the AUV and the sensors are acceleration, gyroscope, and pressure sensor.

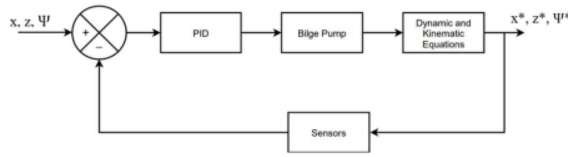

Fig 2. System design

B. Hardware Design

The design of the AUV can be seen in Fig. 3. The AUV uses 2 acrylic tubes with 5 mm width, an aluminum rod, an acrylic base, and 6 bilge pumps for the thrusters and buoy.

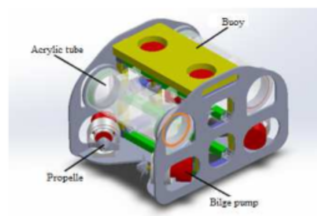

Fig 3. AUV Design

C. System Testing

The testing was conducted to know the success and errors of the system that has been designed. In the AUV testing process, a depth setpoint was given, then the AUV moved trying to reach a setpoint while maintaining its position and stability. The testing was also conducted to know some parameters, such as overshoot, delay time, peak time, settling time, and rise time. These parameters were used to analyze and declare whether the system was good.

IV. Results and Discussion

This section discusses testing and analysis of the AUV position control systems using the PID controller, and the prototype of AUV.

A. AUV Prototype

The AUV was manufactured before conducting the testing. In this research, the AUV was assembled by aluminum rod, acrylic, acrylic tube, and plastic bottles. The AUV that has been made is shown in Fig. 4.

Fig 4. AUV Prototype

B. AUV Design For Simulation

The simulation was conducted to the AUV design to know the values of linear drag, quadratic drag, and added mass of the AUV. Ansys Fluent and Ansys Aqwa were used for the simulation. Ansys Fluent was used to know the value of linear drag and quadratic drag for surge, heave, and yaw movement while Ansys Aqwa was used to know the value of added mass for surge, heave, and yaw movement. First, the design of AUV must be simplified as seen in Fig. 5.

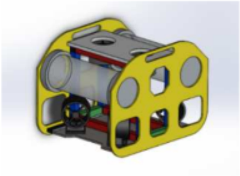

Fig 5. AUV Design For Simulation

Measurement and simulation results using Solidworks, Ansys Fluent, and Ansys Aqwa can be seen in Table I.

TABLE I. MEASUREMENT AND SIMULATION RESULTS OF AUV

Mass	9.12 kg
Volume	0.005 m^3
Length	40.2 cm
Width	29 cm
Height	27.1 cm
I_{xx} (Moment of inertia in x axis)	0.088 kg/m^2
I_{yy} (Moment of inertia in y axis)	0.110 kg/m^2
I_{zz} (Moment of inertia in z axis)	0.097 kg/m^2
Weight	89.4672 N
Buoyancy	48.9519 N
X_u(Linear drag surge)	2.80059 Ns/m
Z_w(Linear drag heave)	0.1416 Ns/m
N_r(Linear drag yaw)	0.0114290 Ns/m
$X_{u\|u\|}$ (Quadratic drag surge)	37.1787 Ns^2/m^2
$Z_{w\|w\|}$ (Quadratic drag heave)	18.758 Ns^2/m^2
$N_{r\|r\|}$ (Quadratic drag yaw)	0.9140965 Ns^2/m^2
$X_{\dot{u}}$ (Added mass surge)	6.267665 kg
$Z_{\dot{w}}$(Added mass heave)	18.93234 kg
$N_{\dot{r}}$(Added mass yaw)	0.00242 kg

C. AUV Simulation using PID Controller

The simulation and testing of the AUV using the PID controller were conducted in Simulink. There are some assumptions applied to simplify the control system of AUV. The assumptions are:

1. Buoyancy of AUV is neglected because AUV moves relatively slow.
2. Symmetric in 3 planes, x-z, y-z, and x-y plane.
3. Roll, Pitch, and Sway movements are neglected because the AUV in this research cannot do that movements.
4. The B-frame is positioned at the center of gravity, therefore $r_G = [0 \quad 0 \quad 0]^T$.
5. DOF (Degrees of Freedom) of the AUV can be decoupled, this assumes that motion along one DOF does not affect another DOF. When DOF are decoupled the Coriolis and centripetal matrix becomes negligible, since only diagonal terms matter [9], therefore the dynamic model of the AUV becomes

$$M\dot{V} + D(V)V + g(\eta) = \tau. \tag{8}$$

Based on the above assumptions, dynamic equation in the surge, heave, and yaw movements of the AUV become

Surge:

$$(m - X_{\dot{u}})\dot{u} = g_x + X_u u + X_{u|u|}u| + \tau_u, \tag{9}$$

Heave:

$$(m - Z_{\dot{w}})\dot{w} = g_z + Z_w w + Z_{w|w|}w| + \tau_w, \tag{10}$$

Yaw:

$$(I_{zz} - N_{\dot{r}})\dot{r} = g_\Psi + N_r r + N_{r|r|}r| + \tau_r, \tag{11}$$

where τ_u, τ_w, and τ_r are the thruster force in surge, heave, and yaw movement, respectively, while $\dot{u}$, $\dot{w}$, and $\dot{r}$ are AUV acceleration in surge, heave, and yaw movement, respectively. Kinematic equations for surge, heave, and yaw movement of the AUV become [13-14]

$$\dot{x} = u\cos(\Psi), \tag{12}$$

$$\dot{z} = w, \tag{13}$$

$$\dot{\Psi} = r. \tag{14}$$

where $\dot{x}$, $\dot{z}$, and $\dot{\Psi}$ are AUV velocity in surge, heave and yaw movement, respectively. Dynamic and kinematic equations were used in the simulation. The simulation was conducted in Simulink using some blocks, such as Matlab Function, Integrator, Derivative, Gain, Scope, Constant, Limit, and Sum. Fig. 6 shows the simulation model of AUV in the Simulink.

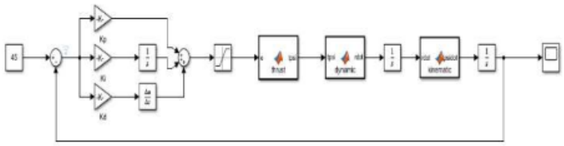

Fig 6. Model simulation of AUV in Simulink

The gain value of the PID controller was determined using trial and error method. Table II shows the gain value of the PID controller.

TABLE II. GAIN VALUE OF PID CONTROLLER

Movement	Kp	Ki	Kd
Surge	38.41	10.8	58.4
Heave	49.13	2.56	107.12
Yaw	3.18	0.18	12.11

Simulation was conducted by giving the setpoint of $x = 1$ m, $z = 0.5$ m, and $\Psi = 45°$. The simulation results using the PID gain value in Table II are shown in Figs. 7, 8, and 9 with surge, heave, and yaw movement, respectively.

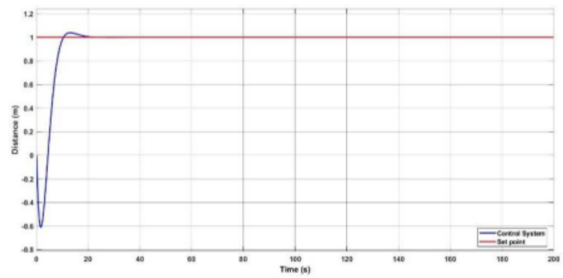

Fig 7. Simulation result in surge movement

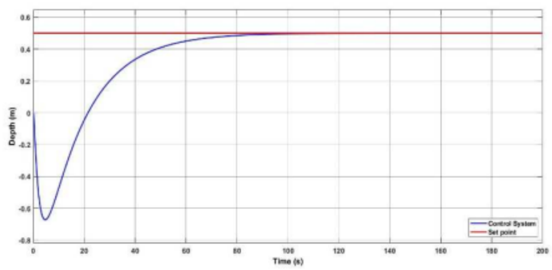

Fig 8. Simulation result in heave movement

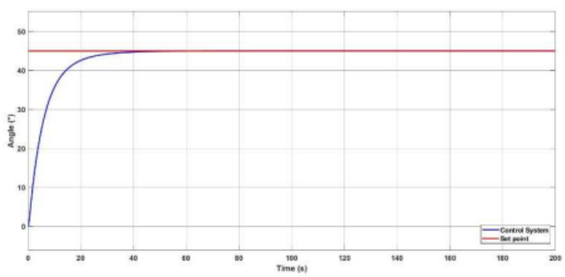

Fig 9. Simulation result in yaw movement

Table III shows more detail of simulation results shown in Figs. 7, 8, and 9.

TABLE III. SIMULATION RESULTS USING SIMULINK

Parameter	Surge	Heave	Yaw
Delay time	8.07 s	33.048 s	4.47 s
Rise time	10.51 s	174.012 s	88.91s
Settling time	19.68 s	73.164 s	17.65 s
Peak time	12.71 s	200 s	58.45 s
Overshoot	3.77 %	0.0035 %	0.015 %

D. AUV test using PID Controller

The gain values of the PID Controller in Table II are used in the testing. The testing was conducted in the lake, and the setpoints of the surge movement, heave movement, and yaw movement were 0 cm, 50 cm, and 0°, respectively. The test results are shown in Figs. 10, 11, 12 for surge, heave, and yaw movements.

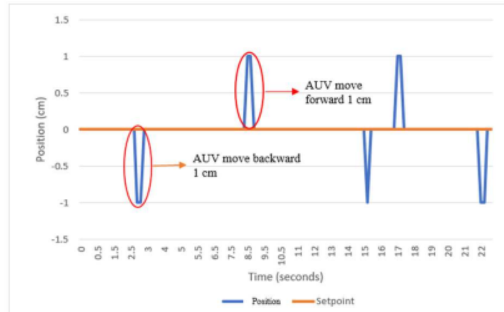

Fig 10. Surge movement test.

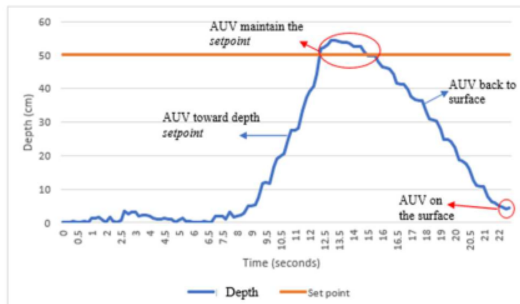

Fig 11. Heave movement test

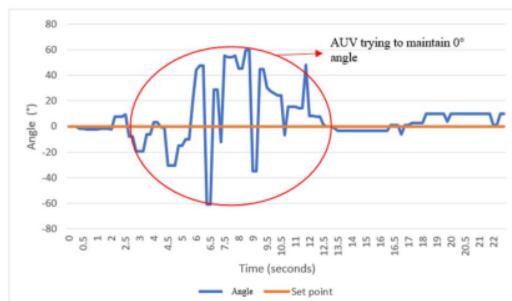

Fig 12. Yaw movement test

Based on Figs. 10, 11, and 12, the testing duration is 22.5 seconds. In surge movement, the AUV can maintain its position well, with an error of ± 1 cm. In heave movement, the AUV can reach the setpoint of 50 cm within 12 seconds and maintain its position about 3.5 seconds before the AUV went up to the surface in 7 seconds. In yaw movement, the error was a large error about -60° and 60°, this is due to the sensor poor in readings the values within a certain time. Even though it has a fairly large error value, the AUV can still move towards the specified setpoint.

V. CONCLUSION

Based on the simulation and test of the AUV, it can be concluded that the PID controller implemented on the AUV can work well. The gain values of the AUV were Kp = 38.41, Ki = 10.8, and Kd = 58.4 for surge movement, Kp = 49.13, Ki = 2.56, and Kd = 107.12 for heave movement, and Kp = 3.18, Ki 0.18, and Kd = 12.11 for yaw movement. The simulation results in Simulink showed that the settling time for surge movement was 19.68 seconds, for heave movement is 73.164 seconds, and for yaw movement in 17.65 seconds, while the AUV test showed that the AUV can maintain its position around 3 – 4 seconds at depth of 50 cm and able to maintain 0° for a few seconds.

For future works, the AUV simulation design should not be simplified to generate the best result in computation and simulation. Besides, an additional controller or use of another controller should be done to make the AUV navigation and position better.

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