International Review of Mechanical Engineering (I.RE.M.E.), Vol. 12, N. 11
ISSN 1970 - 8734 November 2018

Design of Motion Control Using Proportional Integral Derivative for UNUSAITS AUV

Teguh Herlambang, Subchan, Hendro Nurhadi

Abstract – *Robotics technology for the defense of a country today is a necessity. One of such defense technologies is an unmanned underwater vehicle or Autonomous Underwater Vehicle (AUV). It is a type of underwater robots operated for underwater exploration or underwater defense system equipment. AUV is controlled and able to move with six degrees of freedom (6-DOF). To control AUV requires a motion control system to move as expected. In this research, the motion control system was developed by applying a linear 6-DOF model to UNUSAITS AUV, resulted from linearization of the nonlinear model with 6-DOF, that is, surge, sway, heave, roll, pitch and yaw with Proportional Integral Derivative (PID) method. Specifically, this study is a make comparison the simulation between result of PID method and those of Proportional control system without integral and derivative was made. The contribution of this paper is numeric study regarding the performance of PID compared to proportional applied to AUV linear model. The simulation results show that the PID method could be used as the motion control system of the linear model 6-DOF with an error of 0.4 % - 13% and globally asymthotically stable with analysis of stability using Lyapunov method, whereas the proportional controller still had a considerably significant error.*

***Keywords**: AUV, Control System, PID, 6-DOF, Linear Model*

Nomenclature

AUV	Autonomous Underwater Vehicle
DOF	Degree of Freedom
EFF	Earth Fixed Frame
BFF	Body Fixed Frame
PID	Proportional Integral Derivative
$\eta = [\eta_1^T, \eta_2^T]^T$	The position and orientation vector in the earth-fixed coordinates
$\eta_1 = [x, y, z]^T$	The linear position vector in the earth-fixed coordinates
$\eta_2 = [\emptyset, \theta, \Psi]^T$	The angular position vector in the earth-fixed coordinates
$v = [v_1^T, v_2^T]^T$	The linear and angular velocity vector in the body-fixed coordinates
$v_1 = [u, v, w]^T$	The linear velocity vector in the body-fixed coordinates (surge,sway and heave)
$v_2 = [p, q, r]^T$	The angular velocity vector in the body-fixed coordinates (roll, pitch and yaw)
$\tau = [\tau_1^T, \tau_2^T]^T$	The forces and moments acting on the vehicle in the body-fixed coordinates
$\tau_1 = [X, Y, Z]^T$	The forces acting on the vehicle in the body-fixed coordinates
$\tau_2 = [K, M, N]^T$	The moments acting on the vehicle in the body-fixed coordinates
$[x_G, y_G, z_G]$	The AUV's center of gravity in body fixed coordinates
$[I_x, I_y, I_z]$	The moments of inertia about the X, Y, Z axes respectively
$f_1, f_2, f_3, f_4, f_5, f_6$	Surge, Sway, Heave, Roll, Pitch and Yaw for function in Jacobian matrix
$a_1, a_2, \dots, g_6$	Component of matrix *A* (Result of linearization using Jacobian matrix for equation of motion with 6-DOF)
$A_1, A_2, \dots, G_6$	Component of matrix *B* (Result of linearization using Jacobian matrix for equation of motion with 6-DOF)
$X_{res}, Y_{res}, Z_{res}, K_{res}, M_{res}, N_{res}$	Hydrostatic force for surge, sway, heave, roll, pitch and yaw
$X_{uu}, Y_{vv}, N_{vv}, Y_{rr}, N_{rr}, Z_{ww}, M_{ww}, M_{qq}, K_{pp}$	Drag force for surge, sway, heave, roll, pitch and yaw
$X_{\dot{u}}, X_{wq}, X_{qq}, X_{vr}, X_{rr}$	Added Mass for surge
$Y_{\dot{v}}, Y_{\dot{r}}, Y_{ur}, Y_{wp}, Y_{pq}$	Added Mass for sway
$Z_{\dot{w}}, Z_{\dot{q}}, Z_{uq}, Z_{vp}, Z_{rp}$	Added Mass for heave
$K_{\dot{p}}$	Added Mass of inertia moment for roll
$M_{\dot{w}}, M_{\dot{q}}, M_{uq}, M_{vp}, M_{rp}$	Added Mass of inertia moment for pitch

https://doi.org/10.15866/ireme.v12i11.15758

$N_{\dot{v}}, N_{\dot{r}}, N_{ur}, N_{wp}, N_{pq}$	Added Mass of inertia moment yaw
N_{uv}	Body and lift moment
$N_{uu\delta_r}$	Fin lift moment
Y_{uv}	Body Lift Force and Fin Lift
$Y_{uu\delta_r}$	Fin Lift Force
δ_r	Rudder Angle

I. Introduction

Robotics technology for the defense of a country, today is a necessity. One of the defense underwater technologies is an unmanned underwater vehicle or Autonomous Underwater Vehicle (AUV) [1], [2]. AUV was first created by Applied Phyics Laboratory (APL) at the University of Washington, USA, in the late 1950s because of the need for oceanographic data [3]. Some AUVs developed include HUGIN AUV, HUGIN 1, and REMUS AUV [4], and NPS ARIES AUV was developed at the AUV research center [5]. AUV technology has developed in several directions [19]-[20]. Its application area has expanded gradually, covering areas such as sea floor mapping, oceanographic monitoring, underwater structural inspection, and underwater defense system equipment [6]. Considering the usefulness and benefits of AUV above, Indonesia really needs to develop AUV, because more than 70% of Indonesian territory is ocean, therefore AUV is an effective technology to maintain the sea potential of Indonesia. AUV is indispensable to assist Indonesia's undersea exploration survey [7], because AUV is relatively flexible for ocean exploration without having to use cables so that it can swim freely without barriers [8]. Several AUV control system studies that have been conducted within the period of the 1990s up to now can be described as follows. Jalving and Storkersen (1994) examined AUV motion control by using Proportional Integrator Derivative (PID) focusing on 3 (three) subsystem speed, steering and diving [9], then Li and Lee (2005) used adaptive non-linear control method based on Lyapunov theory and backstepping technique [10].

Wu et al (2008) used the Genetic Algorithm (GA) method for several AUVs [11]. Oktafianto et al (2015) used the Sliding Mode Control (SMC) method on a 6-DOF linear model [12]. Jebelli et al (2013) used the fuzzy controller for design and construction AUV [13].

In this research, the motion control system was developed by applying a linear 6-DOF model to UNUSAITS AUV, resulted from linearization of the nonlinear model with 6-DOF, that is, surge, sway, heave, roll, pitch and yaw with Proportional Integral Derivative (PID) method. Specifically, this study is a make comparison the simulation between result of PID method and those of Proportional control system without integral and derivative was made.

The contribution of this paper is numeric study regarding the performance of PID compared to proportional applied to AUV linear model.

This study began with formulation of equation model of non-linear motion with 6-DOF, and it was linearized with Jacobi matrix to get the linear model with 6-DOF.

Then, Proportional Integral Derivative (PID) method and the proportional control method were applied to control the 6-DOF motion to be stable at the desired set-point assuming no disturbance at the time of moving AUV.

II. Autonomous Underwater Vehicle

There are two important things to analyze AUV, the axis system consisting of Earth Fixed Frame (EFF) and Body Fixed Frame (BFF) as shown in Fig. 1 [3]. EFF is used to explain the position and orientation of AUV, where the x-axis position leads northward, the y-axis to the east and the z-axis toward the center of the earth.

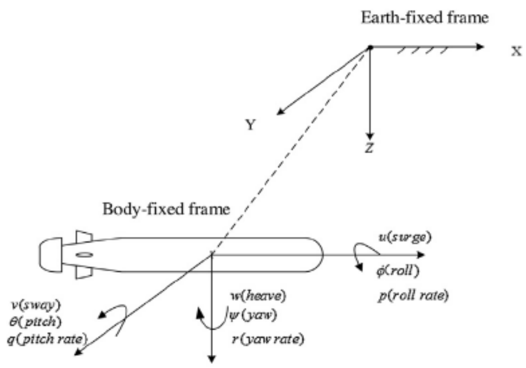


Fig. 1. AUV motion with six degrees of freedom [15]

While the BFF defines the positive x-axis leading to the prowess of the vehicle, the positive y-axis leads to the right side of the vehicle, and the positive z-axis points downward [14].

The BFF system is used to explain the speed and acceleration of AUV with the starting point at the center of gravity. The profile of UNUSAITS AUV is shown in Fig. 2.

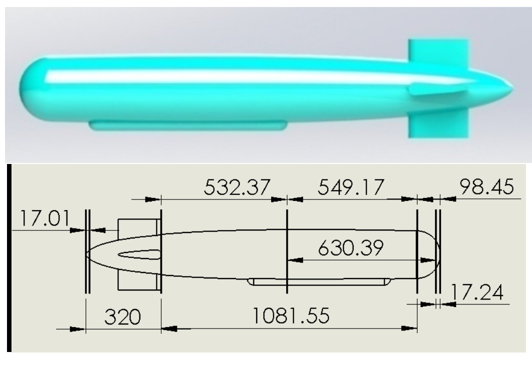


Fig. 2. Profile of UNUSAITS AUV [16], [17]

Fig. 1 and Table I show that AUV has six degrees of freedom (6-DOF) consisting of surge, sway, heave, roll, pitch and yaw. The equation of AUV motion is influenced by the outer force as follows:

$$\tau = \tau_{hidrostatis} + \tau_{addedmass} + \tau_{drag} + \tau_{lift} + \tau_{control} \quad (1)$$

TABLE I
SPECIFICATION OF UNUSAITS AUV [16], [17]

Weight	16 kg
Overall Length	1500 mm
Beam	200 mm
Controller	Ardupilot Mega 2.0
Communication	Wireless Xbee 2.4 GHz
Propulsion	12V motor DC
Propeller	3 Blades OD : 50 mm
Speed	3.1 knots (1.5m/s)

The movement of UNUSAITS AUV has 6 degrees of freedom (6 DOF) consisting of 3 (three) degrees of freedom for the direction of translational motion on the x-axis (surge), y-axis (sway), and z-axis (heave) and the other 3 (three) degrees of freedom for rotational motion on x-axis (roll), y-axis (yaw), and z-axis (pitch). The UNUSAITS AUV specifications cover, among others, weight of 16 kg, length of 1.5 m, a diameter of 20 cm [18].

The general description of AUV with 6 DOF can be expressed in the equation [14]:

$$\begin{aligned} \eta &= [\eta_1^T, \eta_2^T]^T, \eta_1 = [x, y, z]^T, \eta_2 = [\emptyset, \theta, \Psi]^T; \\ v &= [v_1^T, v_2^T]^T, v_1 = [u, v, w]^T, v_2 = [p, q, r]^T; \\ \tau &= [\tau_1^T, \tau_2^T]^T, \tau_1 = [X, Y, Z]^T, \tau_2 = [K, M, N]^T \end{aligned} \quad (2)$$

in which η shows the vector position and orientation on EFF, and, τ denotes the force vector and moment working on AUV on BFF, surge (u), sway (v), heave (w), roll (p), pitch (q) and yaw (r). The total force and moment working on AUV can be obtained by combining hydrostatic force, hydrodynamic force and thrust force. In this case it is assumed that the diagonal inertia tensor (I_o) is zero, to obtain the total force and moment of the whole model as follows [3]:

Surge:

$$\begin{aligned} & m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) \\ & \quad + z_G(pr + \dot{q})] \\ & \quad = X_{res} + X_{|u|u}u|u| + X_{\dot{u}}\dot{u} \\ & \quad + X_{wq}wq + X_{qq}qq + X_{vr}vr \\ & \quad + X_{rr}rr + X_{prop} \end{aligned} \quad (3)$$

Sway :

$$\begin{aligned} & m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) \\ & \quad + x_G(pq + \dot{r})] \\ & \quad = Y_{res} + Y_{|v|v}v|v| + Y_{r|r|}r|r| + Y_{\dot{v}}\dot{v} \\ & \quad + Y_{\dot{r}}\dot{r} + Y_{ur}ur + Y_{wp}wp + Y_{pq}pq \\ & \quad + Y_{uv}uv + Y_{uu\delta_r}u^2\delta_r \end{aligned} \quad (4)$$

Heave :

$$\begin{aligned} & m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rp - \dot{q}) \\ & \quad + y_G(rq + \dot{p})] \\ & \quad = Z_{res} + Z_{|w|w}w|w| + Z_{q|q|}q|q| \\ & \quad + Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} + Z_{uq}uq + Z_{vp}vp \\ & \quad + Z_{rp}rp + Z_{uw}uw + Z_{uu\delta_s}u^2\delta_s \end{aligned} \quad (5)$$

Roll:

$$\begin{aligned} & I_x\dot{p} + (I_z - I_y)qr \\ & + m[y_G(\dot{w} - uq + vp) \\ & - z_G(\dot{v} - wp + ur)]\, K_{res} \\ & + K_{p|p|}p|p| + K_{\dot{p}}\dot{p} + K_{prop} \end{aligned} \quad (6)$$

Pitch:

$$\begin{aligned} & I_y\dot{q} + (I_x - I_z)rp + m[z_G(\dot{u} - vr + wq) \\ & \quad - x_G(\dot{w} - uq + vp)] \\ & \quad = M_{res} + M_{w|w|}w|w| + M_{q|q|}q|q| \\ & \quad + M_{\dot{w}}\dot{w} + M_{\dot{q}}\dot{q} + M_{uq}uq + M_{vp}vp \\ & \quad + M_{rp}rp + M_{uw}uw + M_{uu\delta_s}u^2\delta_s \end{aligned} \quad (7)$$

Yaw:

$$\begin{aligned} & I_z\dot{r} + (I_y - I_z)pq \\ & + m[x_G(\dot{v} - wp + ur) \\ & - y_G(\dot{u} - vr + wq)] \\ & = N_{res} + N_{v|v|}v|v| + N_{r|r|}r|r| \\ & + N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{ur}ur + N_{wp}wp \\ & + N_{pq}pq + N_{uv}uv + N_{uu\delta_r}u^2\delta_r \end{aligned} \quad (8)$$

III. Linearization

In this paper the AUV non-linear model can be linearized by Jacobi matrix, and the common equations of the AUV non-linear model are as follows:

$$\dot{x}(t) = f(x(t), u(t), t), y(t) = g(x(t), u(t), t) \quad (9)$$

and Jacobi Matrix as follows [6]:

$$\frac{\partial f(\bar{x}, \bar{u}, t)}{\partial x} = \begin{bmatrix} \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_2} & \cdots & \frac{\partial f_1(\bar{x}, \bar{u}, t)}{\partial x_n} \\ \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_2} & \cdots & \frac{\partial f_2(\bar{x}, \bar{u}, t)}{\partial x_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_1} & \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_2} & \cdots & \frac{\partial f_n(\bar{x}, \bar{u}, t)}{\partial x_n} \end{bmatrix} \quad (10)$$

If Jacobi matrix as expressed in equation (10) is implemented to the linearization of AUV equation of motion with 6-DOF, then the following equations are obtained:

$$\frac{\partial f(\bar{x},\bar{u},t)}{\partial x}=\begin{bmatrix}\frac{\partial f_1(\bar{x},\bar{u},t)}{\partial u} & \frac{\partial f_1(\bar{x},\bar{u},t)}{\partial v} & \frac{\partial f_1(\bar{x},\bar{u},t)}{\partial w} & \frac{\partial f_1(\bar{x},\bar{u},t)}{\partial p} & \frac{\partial f_1(\bar{x},\bar{u},t)}{\partial q} & \frac{\partial f_1(\bar{x},\bar{u},t)}{\partial r}\\ \frac{\partial f_2(\bar{x},\bar{u},t)}{\partial u} & \frac{\partial f_2(\bar{x},\bar{u},t)}{\partial v} & \frac{\partial f_2(\bar{x},\bar{u},t)}{\partial w} & \frac{\partial f_2(\bar{x},\bar{u},t)}{\partial p} & \frac{\partial f_2(\bar{x},\bar{u},t)}{\partial q} & \frac{\partial f_2(\bar{x},\bar{u},t)}{\partial r}\\ \frac{\partial f_3(\bar{x},\bar{u},t)}{\partial u} & \frac{\partial f_3(\bar{x},\bar{u},t)}{\partial v} & \frac{\partial f_3(\bar{x},\bar{u},t)}{\partial w} & \frac{\partial f_3(\bar{x},\bar{u},t)}{\partial p} & \frac{\partial f_3(\bar{x},\bar{u},t)}{\partial q} & \frac{\partial f_3(\bar{x},\bar{u},t)}{\partial r}\\ \frac{\partial f_4(\bar{x},\bar{u},t)}{\partial u} & \frac{\partial f_4(\bar{x},\bar{u},t)}{\partial v} & \frac{\partial f_4(\bar{x},\bar{u},t)}{\partial w} & \frac{\partial f_4(\bar{x},\bar{u},t)}{\partial p} & \frac{\partial f_4(\bar{x},\bar{u},t)}{\partial q} & \frac{\partial f_4(\bar{x},\bar{u},t)}{\partial r}\\ \frac{\partial f_5(\bar{x},\bar{u},t)}{\partial u} & \frac{\partial f_5(\bar{x},\bar{u},t)}{\partial v} & \frac{\partial f_5(\bar{x},\bar{u},t)}{\partial w} & \frac{\partial f_5(\bar{x},\bar{u},t)}{\partial p} & \frac{\partial f_5(\bar{x},\bar{u},t)}{\partial q} & \frac{\partial f_5(\bar{x},\bar{u},t)}{\partial r}\\ \frac{\partial f_6(\bar{x},\bar{u},t)}{\partial u} & \frac{\partial f_6(\bar{x},\bar{u},t)}{\partial v} & \frac{\partial f_6(\bar{x},\bar{u},t)}{\partial w} & \frac{\partial f_6(\bar{x},\bar{u},t)}{\partial p} & \frac{\partial f_6(\bar{x},\bar{u},t)}{\partial q} & \frac{\partial f_6(\bar{x},\bar{u},t)}{\partial r}\end{bmatrix} \quad (11)$$

Equations (3)-(8) can be changed into $f_1, f_2, f_3, f_4, f_5, f_6$ as follows:

$$f_1 = \frac{\begin{gathered}X_{res} + X_{|u|u}u|u| + X_{wq}wq + X_{qq}qq + X_{vr}vr + \\ X_{rr}rr + X_{prop} - \\ m[-vr + wq - x_G(q^2 + r^2) + pqy_G + prz_G]\end{gathered}}{m - X_{\dot{u}}} \quad (12)$$

$$f_2 = \frac{\begin{gathered}Y_{res} + Y_{|v|v}v|v| + Y_{r|r|}r|r| + Y_{\dot{r}}\dot{r} \\ +Y_{ur}ur + Y_{wp}wp + Y_{pq}pq + Y_{uv}uv + \\ Y_{uu\delta_r}u^2\delta_r - \\ m[-wp + ur - y_G(r^2 + p^2) + qr\, z_G + pq\, x_G]\end{gathered}}{m - Y_{\dot{v}}} \quad (13)$$

$$f_3 = \frac{\begin{gathered}Z_{res} + Z_{|w|w}w|w| + Z_{q|q|}q|q| + \\ Z_{\dot{q}}\dot{q} + Z_{uq}uq + Z_{vp}vp + Z_{rp}rp + \\ Z_{uw}uw + Z_{uu\delta_s}u^2\delta_s - \\ m[-uq + vp - z_G(p^2 + q^2) + rp\, x_G + rq\, y_G]\end{gathered}}{m - Z_{\dot{w}}} \quad (14)$$

$$f_4 = \frac{\begin{gathered}K_{res} + K_{p|p|}p|p| + K_{prop} - \\ \left(\left(I_z - I_y\right)qr + m\begin{bmatrix}y_G(-uq + vp) - \\ z_G(-wp + ur)\end{bmatrix}\right)\end{gathered}}{I_x - K_{\dot{p}}} \quad (15)$$

$$f_5 = \frac{\begin{gathered}M_{res} + M_{w|w|}w|w| + M_{q|q|}q|q| + M_{\dot{w}}\dot{w} \\ +M_{uq}uq + M_{vp}vp + M_{rp}rp + \\ M_{uw}uw + M_{uu\delta_s}u^2\delta_s - \\ \left(\left(I_x - I_z\right)rp + m\begin{bmatrix}z_G(-vr + wq) \\ -x_G(-uq + vp)\end{bmatrix}\right)\end{gathered}}{I_y - M_{\dot{q}}} \quad (16)$$

$$f_6 = \frac{\begin{gathered}N_{res} + N_{v|v|}v|v| + N_{r|r|}r|r| + N_{\dot{v}}\dot{v} \\ +N_{ur}ur + N_{wp}wp + N_{pq}pq + \\ N_{uv}uv + N_{uu\delta_r}u^2\delta_r \\ -\left(\left(I_y - I_z\right)pq + m\begin{bmatrix}x_G(-wp + ur) \\ -y_G(-vr + wq)\end{bmatrix}\right)\end{gathered}}{I_z - N_{\dot{r}}} \quad (17)$$

The linear model can be obtained as follows [2]:

$$\dot{x}(t) = A\,x(t) + Bu(t), y(t) = Cx(t) + Du(t) \quad (18)$$

with:

$$A = J_x = \begin{bmatrix} 1 & 0 & 0 & 0 & \frac{mz_G}{m - X_{\dot{u}}} & \frac{-my_G}{m - X_{\dot{u}}} \\ 0 & 1 & 0 & -\frac{mz_G}{m - Y_{\dot{v}}} & 0 & \frac{(mx_G - Y_{\dot{r}})}{m - Y_{\dot{v}}} \\ 0 & 0 & 1 & \frac{my_G}{m - Z_{\dot{w}}} & -\frac{(mx_G + Z_{\dot{q}})}{m - Z_{\dot{w}}} & 0 \\ 0 & -\frac{m\,z_G}{I_x - K_{\dot{p}}} & \frac{m\,y_G}{I_x - K_{\dot{p}}} & 1 & 0 & 0 \\ \frac{m\,z_G}{I_y - M_{\dot{q}}} & 0 & -\frac{(m\,x_G + M_{\dot{w}})}{I_y - M_{\dot{q}}} & 0 & 1 & 0 \\ -\frac{my_G}{I_z - N_{\dot{r}}} & \frac{(mx_G - N_{\dot{v}})}{I_z - N_{\dot{r}}} & 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} a_1 & b_1 & c_1 & d_1 & e_1 & g_1 \\ a_2 & b_2 & c_2 & d_2 & e_2 & g_2 \\ a_3 & b_3 & c_3 & d_3 & e_3 & g_3 \\ a_4 & b_4 & c_4 & d_4 & e_4 & g_4 \\ a_5 & b_5 & c_5 & d_5 & e_5 & g_5 \\ a_6 & b_6 & c_6 & d_6 & e_6 & g_6 \end{bmatrix}$$

$$B = J_u$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & \frac{mz_G}{m - X_{\dot{u}}} & \frac{-my_G}{m - X_{\dot{u}}} \\ 0 & 1 & 0 & -\frac{mz_G}{m - Y_{\dot{v}}} & 0 & \frac{(mx_G - Y_{\dot{r}})}{m - Y_{\dot{v}}} \\ 0 & 0 & 1 & \frac{my_G}{m - Z_{\dot{w}}} & -\frac{(mx_G + Z_{\dot{q}})}{m - Z_{\dot{w}}} & 0 \\ 0 & -\frac{m\,z_G}{I_x - K_{\dot{p}}} & \frac{m\,y_G}{I_x - K_{\dot{p}}} & 1 & 0 & 0 \\ \frac{m\,z_G}{I_y - M_{\dot{q}}} & 0 & -\frac{(m\,x_G + M_{\dot{w}})}{I_y - M_{\dot{q}}} & 0 & 1 & 0 \\ -\frac{my_G}{I_z - N_{\dot{r}}} & \frac{(mx_G - N_{\dot{v}})}{I_z - N_{\dot{r}}} & 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} A_1 & B_1 & C_1 & D_1 & E_1 & G_1 \\ A_2 & B_2 & C_2 & D_2 & E_2 & G_2 \\ A_3 & B_3 & C_3 & D_3 & E_3 & G_3 \\ A_4 & B_4 & C_4 & D_4 & E_4 & G_4 \\ A_5 & B_5 & C_5 & D_5 & E_5 & G_5 \\ A_6 & B_6 & C_6 & D_6 & E_6 & G_6 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

and:

$$D = 0$$

IV. Computational Result

Before the application a PID control system, the system was tested without a controller with a block diagram of Matlab simulink as shown in Figs. 3 and 4.

After the block diagram was formed, the results of the AUV system simulation without a control system was seen in Figs. 5 and 6. The design of PID control system was made to overcome the instability of translational and rotational motions of AUV. Here is a block diagram of AUV using PID and proportional control system in Fig. 7. The method used to determine the proportional, integral and derivative values was a trial and error method.

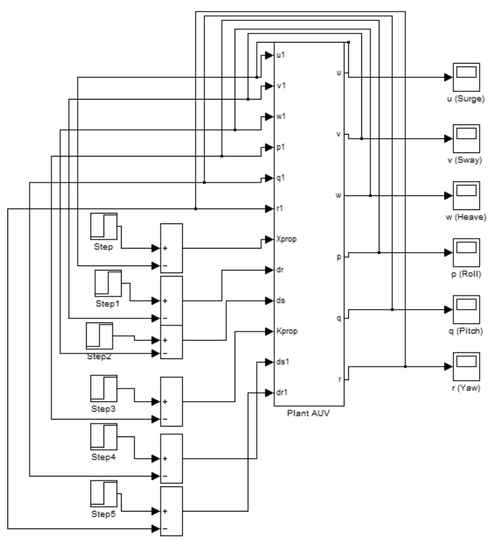


Fig. 3. Block diagram of AUV

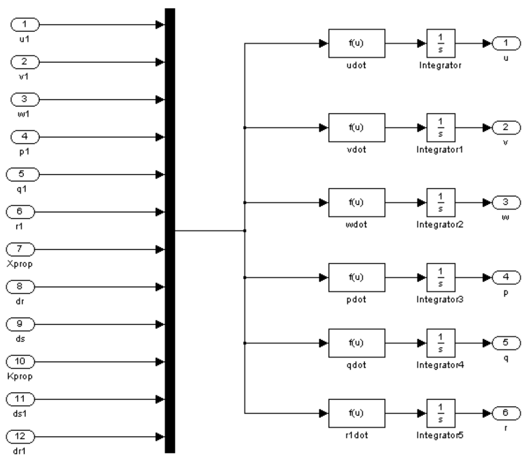


Fig. 4. Block diagram of AUV subsystem

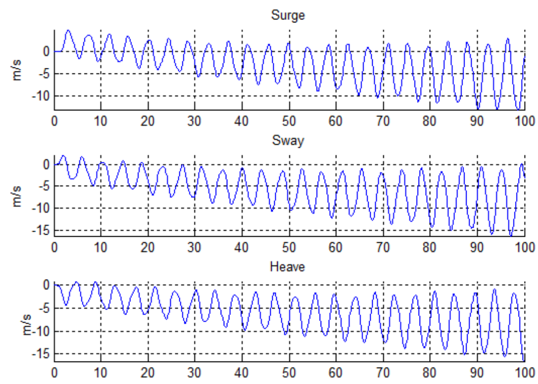


Fig. 5. Responses of the translational motion of AUV without control system

In the PID simulation, some comparisons between simulation result of the PID and those of the proportional controller were made. Here are the proportional, integral and derivative values of both PID and proportional control. After the block diagram was formed, the simulation was carried out. We got the simulation results of AUV system with PID control system. Discussion on the comparison of the responses of the control systems by PID and proportional control was made as the block diagram made and simulated resulting in the responses of the translational motion (surge sway, heave) as shown by

Figs. 8 and those of the rotational motion (roll, pitch and yaw) as shown by Figs. 9.

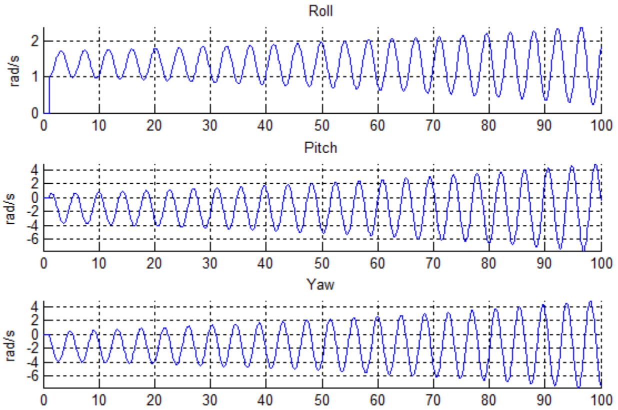
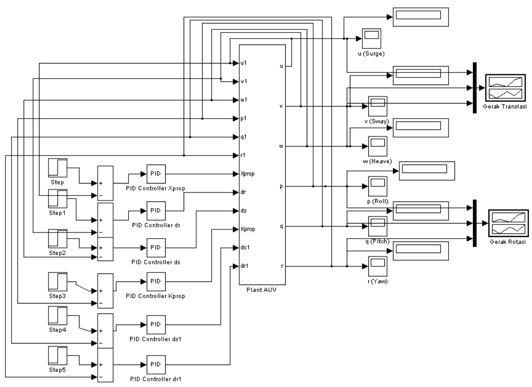
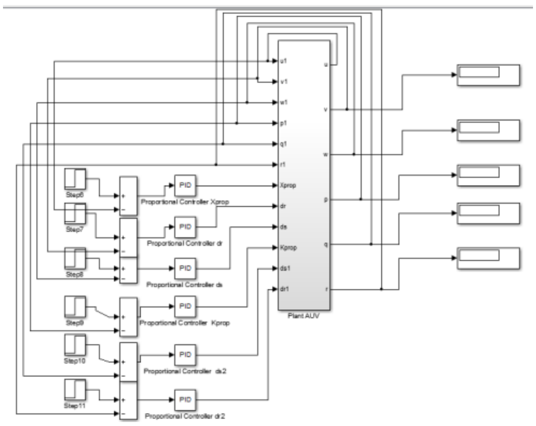


Fig. 6. Responses of rotational motion of AUV without control system



(a)

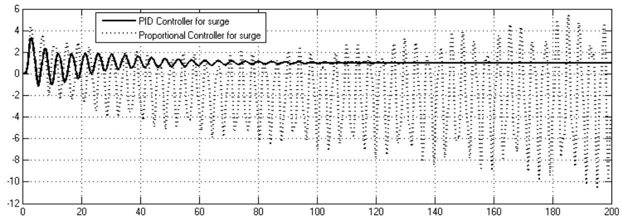


(b)

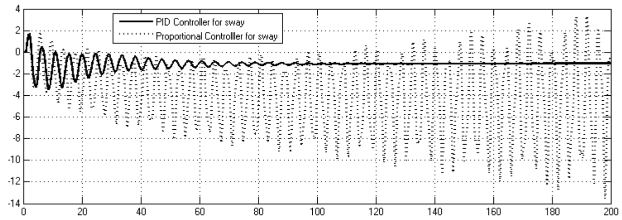
Figs. 7. Block Diagram of AUV using (a) PID method and (b) Proportional method Control System

TABLE II
PROPORTIONAL, INTEGRAL AND DERIVATIVE VALUES OF BOTH PID CONTROLLER AND PROPORTIONAL CONTROLLER

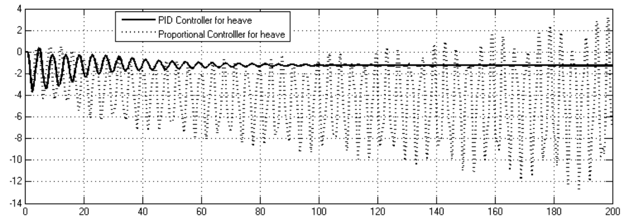
	PID			Proportional		
	K_p	K_i	K_d	K_p	K_i	K_d
Surge	10	1.8	3	2.4	0	0
Sway	2	8	2	2.05	0	0
Heave	3	1.5	2	2.05	0	0
Roll	2	1.2	0.01	2.05	0	0
Pitch	4	1	0.01	2.2	0	0
Yaw	2	1	0.01	2.3	0	0



(a)



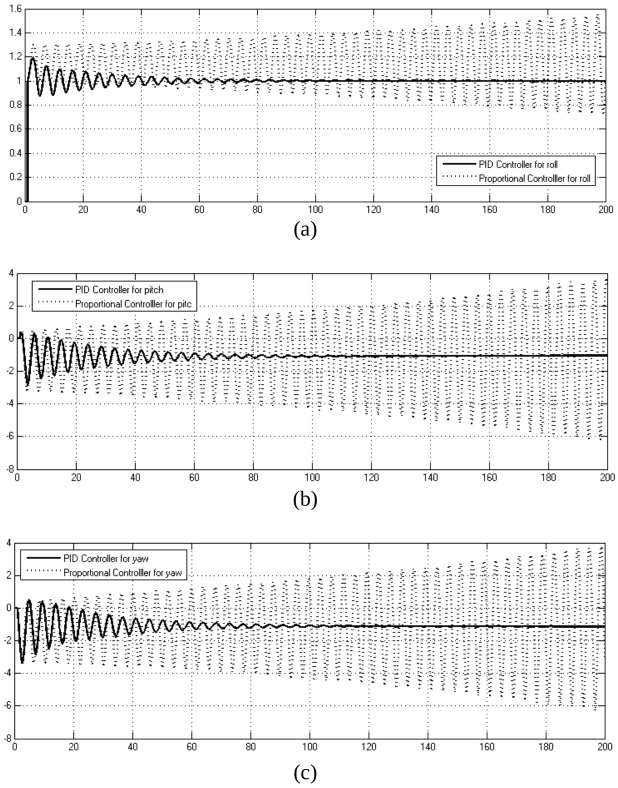
(b)



(c)

Figs. 8. The results of the simulation by both PID and Proportional Control System for (a) surge, (b) sway and (c) heave

In the comparison of the surge responses in Figure 8(a), the result shows that the surge responses by the PID were more stable at a set-point of 1 m/s, managed to reach a settling time of 80 seconds with a maximum overshoot of 3.4 m / s, and had an error of 4.2%. While in Figure 8(b), the result shows that the sway responses by the PID were more stable at setpoint of -1 m / s, managed to reach a settling time of 76 seconds with maximum overshoot of -3.4 m / s, and had an error of 12%. And in Figure 8(c), the result shows the heave responses by the PID were more stable at setpoint of -1 m / s, managed to reach a settling time of 80 seconds with maximum overshoot of -3,6 m / s, and had an error of 13%. For the responses by the PID in surge, sway, and heave motion, the results show the responses were unstable and did not reach a settling time at the setpoint. In this case, overshoot was not the main priority setting for autonomous platform performance. The preferred ones were the settling time and the resulting error. The simulation results for rotational motion can be seen in Figs. 9. In the comparison of the roll responses in Fig. 9(a), the result of the simulation by PID shows that the roll responses were more stable at setpoint of 1 rad/s, managed to reach a settling time of 40 seconds with maximum overshoot of 1.2 rad/s, and had an error of 0.4%. While in Fig. 9(b), the result shows that the pitch responses by the PID were more stable at setpoint of -1 rad/s, managed to reach a settling time of 70 seconds with maximum overshoot of -2.8 rad/s, and had an error of 8.9%. In Fig. 9(c), the result shows that yaw responses by PID were more stable at set-point of -1 rad/s, managed to reach a settling time of 60 seconds with maximum overshoot of -3.4 rad/s, and had an error of 5.8%.



Figs. 9. The result of the simulation by both PID and Proportional Control System for (a) roll, (b) pitch, and (c) yaw

For responses by proportional controller in roll, pitch, and yaw, the results show that the responses were not yet stable and did not reach a settling time at set-point. The comparison of delay time, rise time, peak time, maximum overshoot, settling time, and error shows responses of each by either PID or proportional controller for translational motion, that is, surge, sway and heave can be seen in Table III.

TABLE III
SPECIFICATIONS OF THE TRANSIENT RESPONSES IN SURGE, SWAY, AND HEAVE MOTIONS

	Surge		Sway		Heave	
	PID	Proportional	PID	Proportional	PID	Proportional
Delay Time (s)	1.6	1.8	1.2	2.6	1.6	1.5
Rise Time (s)	1.8	2.2	1.5	3	1,8	1.8
Peak Time (s)	3	3	2	3.5	2.8	2.2
Maximum Peak (s)	3.4	4.2	-3.4	-3.5	-3.6	-3.8
Settling Time (s)	80 s	Inf	80	inf	80	inf
Error (%)	4,2	Inf	12	inf	13	inf

Based on the response comparison, it could be concluded that the best control system for AUV shall rely on the error and settling time observation. The specification comparison between the transient responses in surge by PID and those by proportional controller in Table III shows that the results by proportional controller had an error of infinity due to the inability to be stable.

Those by PID had an error of 4.2 %. For sway motion, the results by proportional controller had an error of infinity due to the inability to be stable, and those by PID had an error of 12%. For heave motion by proportional controller, the results show an error of infinity due to the inability to be stable, while those by PID had an error of 15%. The specification comparison between the *transient* responses in roll motion by PID and those by proportional controller in Table IV shows that the results by proportional controller had an error of infinity due to the inability to be stable, whereas those by PID had an error of 0.4 %. For pitch motion, the results by proportional controller had an error of infinity due to the inability to be stable, whereas those by PID had an error of 8.9 %. For heave motion by proportional controller, the results show an error of infinity due to the inability to be stable, whereas those by PID had an error of 5.8 %.

TABLE IV
SPECIFICATION OF THE TRANSIENT RESPONSES IN ROLL, PITCH, AND YAW MOTIONS

	Roll		Pitch		Yaw	
	PID	Proportional	PID	Proportional	PID	Proportional
Delay Time (s)	1.05	1	2.2	2.2	1.25	1.2
Rise Time (s)	1.3	1.1	2.5	2.5	1.4	1.4
Peak Time (s)	2.8	3	3.8	3.5	2.8	2.5
Maximum Peak (s)	1.2	1.3	-2.8	-3.2	-3.4	-3.4
Settling Time (s)	40	Inf	70	inf	60	Inf
Error (%)	0,4	Inf	8,9	Inf	5,8	Inf

V. Stability Analysis

Analysis of Stability, for PID method, employing Lyapunov stability analysis, shall meet 1 definition and 2 theorema as follows.

Definition 1. Function $V(x)$ is said to be a Lyapunov function if on a ball B_R, $V(x)$ is positive definite and has a partial derivative of negative semi definite $\dot{V}(x) \leq 0$

Theorem 1. If on a ball B_R, there is a scalar function $V(x)$of which the first partial derivative is continuous in which:

1. $V(x)$ is positive definite (local on B_R)
2. $\dot{V}(x)$ negative semi definite (local on B_R)

Then the system equilibrium point is stable, if $\dot{V}(x)$ is negative definite (local on B_R). Then the system is asymptotically stable.

Theorem 2. If on a ball B_R, there is a scalar function $V(x)$ of which the first partial derivative is continuous in which:

1. $V(x)$ is positive definite (local on B_R)
2. $\dot{V}(x)$is negative semi definite (local on B_R)
3. $V(x) \to \infty$ and$\|x\| \to \infty$

Then the system equilibrium pouint is globally, asymptotically stable.

Candidate Function of Lyapunov for AUV linear system with 6-DOF is:

$$V(u,v,w,p,q,r) = \frac{1}{2}u^2 + \frac{1}{2}v^2 + \frac{1}{2}w^2 + \frac{1}{2}p^2 + \frac{1}{2}q^2 + \frac{1}{2}r^2 \quad (19)$$

Showing that the function:

$$V(u,v,w,p,q,r) = \frac{1}{2}u^2 + \frac{1}{2}v^2 + \frac{1}{2}w^2 + \frac{1}{2}p^2 + \frac{1}{2}q^2 + \frac{1}{2}r^2$$

is a Lyapunov function conforming to definition 1 and the stability criteria in accordance with Theorem 1 and Theorem 2. The candidate Lyapunov function in equation (19) will be proved that the candidate function with the SMC control system in the linear model is Lyapunov function and asymptotically stable.

1. For $(u,v,w,p,q,r) = (0,0,0,0,0,0)$, $V(u,v,w,p,q,r) = 0$, whereas for $(u,v,w,p,q,r) \neq (0,0,0,0,0,0)$, $V(u,v,w,p,q,r) > 0$.
   It is proved that $V(u,v,w,p,q,r)$ positive definite
2. Function V is continuous and has its first partial derivative mwhich is continuous on S. Function $V(u,v,w,p,q,r) = \frac{1}{2}u^2 + \frac{1}{2}v^2 + \frac{1}{2}w^2 + \frac{1}{2}p^2 + \frac{1}{2}q^2 + \frac{1}{2}r^2$ is a quadratic function, it is clear that the quadratic function is continuous. Then the partial derivative is also continuous.
3. $\dot{V}(u,v,w,p,q,r) = \frac{\partial V}{\partial u}\dot{u} + \frac{\partial V}{\partial v}\dot{v} + \frac{\partial V}{\partial w}\dot{w} + \frac{\partial V}{\partial p}\dot{p} + \frac{\partial V}{\partial q}\dot{q} + \frac{\partial V}{\partial r}\dot{r}$

$$\dot{V}(u,v,w,p,q,r) = u\dot{u} + v\dot{v} + w\dot{w} + p\dot{p} + q\dot{q} + r\dot{r} \quad (20)$$

$$\begin{aligned}\dot{V}(u,v,w,p,q,r) = {} & u\big(aa_1\,u + bb_1\,v + cc_1\,w + dd_1\,p + ee_1\,q + gg_1\,r + AA_1X_{prop} + BB_1\,\delta_{r_1} + CC_1\delta_{s_1} \\ & + DD_1K_{prop} + EE_1\,\delta_{s_2} + GG_1\delta_{r_2}\big) + \cdots \\ & v\big(aa_2\,u + bb_2\,v + cc_2\,w + dd_2\,p + ee_2\,q + gg_2\,r + AA_2X_{prop} + BB_2\,\delta_{r_1} + CC_2\delta_{s_1} + DD_2K_{prop} + EE_2\,\delta_{s_2} \\ & + GG_2\delta_{r_2}\big) + \cdots \\ & w\big(aa_3\,u + bb_3\,v + cc_3\,w + dd_3\,p + ee_3\,q + gg_3\,r + AA_3X_{prop} + BB_3\,\delta_{r_1} + CC_3\delta_{s_1} + DD_3K_{prop} + EE_3\,\delta_{s_2} \\ & + GG_3\delta_{r_2}\big) + \cdots \\ & q\big(aa_5\,u + bb_5\,v + cc_5\,w + dd_5\,p + ee_5\,q + gg_5\,r + AA_3X_{prop} + BB_5\,\delta_{r_1} + CC_5\delta_{s_1} + DD_5K_{prop} + EE_5\,\delta_{s_2} \\ & + GG_5\delta_{r_2}\big) + \cdots \\ & r\big(aa_6\,u + bb_6\,v + cc_6\,w + dd_6\,p + ee_6\,q + gg_6\,r + AA_6X_{prop} + BB_6\,\delta_{r_1} + CC_6\delta_{s_1} + DD_6K_{prop} + EE_6\,\delta_{s_2} \\ & + GG_6\delta_{r_2}\big)\end{aligned} \quad (21)$$

choosing:

$$X_{prop} = K_{p1}u + K_{i1}\frac{1}{2}\,u^2 + K_{d1}\dot{u}$$
$$\delta_{r_1} = K_{p2}v + K_{i2}\frac{1}{2}\,v^2 + K_{d2}\dot{v}$$
$$\delta_{s_1} = K_{p3}w + K_{i3}\frac{1}{2}\,w^2 + K_{d3}\dot{w}$$
$$K_{prop} = K_{p4}p + K_{i4}\frac{1}{2}\,p^2 + K_{d4}\dot{p}$$
$$\delta_{s_2} = K_{p5}q + K_{i5}\frac{1}{2}\,q^2 + K_{d5}\dot{q}$$
$$\delta_{r_2} = K_{p6}r + K_{i6}\frac{1}{2}\,r^2 + K_{d6}\dot{r}$$

so that the following eq. (22) are obtained:

$$\dot{V}(u,v,w,p,q,r) = u\left(\frac{aa_1\,u + bb_1\,v + cc_1\,w + dd_1\,p + ee_1\,q + gg_1\,r + AA_1\left(K_{p1}u + K_{i1}\frac{1}{2}\,u^2\right)}{1 - AA_1\,K_{d1}} + \frac{BB_1\,\delta_{r_1} + CC_1\delta_{s_1} + DD_1K_{prop} + EE_1\,\delta_{s_2} + GG_1\delta_{r_2}}{1 - AA_1\,K_{d1}}\right) + \cdots$$

$$v\left(\frac{aa_2\,u + bb_2\,v + cc_2\,w + dd_2\,p + ee_2\,q + gg_2\,r + AA_2X_{prop}}{1 - BB_2\,K_{d2}} + \frac{BB_2\,\left(K_{p2}v + K_{i2}\frac{1}{2}\,v^2\right) + CC_2\delta_{s_1} + DD_2K_{prop} + EE_2\,\delta_{s_2} + GG_2\delta_{r_2}}{1 - BB_2\,K_{d2}}\right) +$$

$$w\left(\frac{aa_3\,u + bb_3\,v + cc_3\,w + dd_3\,p + ee_3\,q + gg_3\,r + AA_3X_{prop}}{1 - CC_3\,K_{d3}} + \frac{BB_3\,\delta_{r_1} + CC_3\left(K_{p3}w + K_{i3}\frac{1}{2}\,w^2\right) + DD_3K_{prop} + EE_3\,\delta_{s_2} + GG_3\delta_{r_2}}{1 - CC_3\,K_{d3}}\right) +$$

$$p\left(\frac{aa_4\,u + bb_4\,v + cc_4\,w + dd_4\,p + ee_4\,q + gg_4\,r + AA_4X_{prop}}{1 - DD_4\,K_{d4}} + \frac{BB_4\,\delta_{r_1} + CC_4\delta_{s_1} + DD_4\left(K_{p4}p + K_{i4}\frac{1}{2}\,p^2\right) + EE_4\,\delta_{s_2} + GG_4\delta_{r_2}}{1 - DD_4\,K_{d4}}\right) +$$

$$q\left(\frac{aa_5\,u + bb_5\,v + cc_5\,w + dd_5\,p + ee_5\,q + gg_5\,r}{1 - EE_5K_{d5}} + \frac{AA_3X_{prop} + BB_5\,\delta_{r_1} + CC_5\delta_{s_1} + DD_5K_{prop} + EE_5\,\left(K_{p5}q + K_{i5}\frac{1}{2}\,q^2\right) + GG_5\delta_{r_2}}{1 - EE_5K_{d5}}\right) +$$

$$r\left(\frac{aa_6\,u + bb_6\,v + cc_6\,w + dd_6\,p + ee_6\,q + gg_6\,r}{1 - GG_6K_{d6}} + \frac{AA_6X_{prop} + BB_6\,\delta_{r_1} + CC_6\delta_{s_1} + DD_6K_{prop} + EE_6\,\delta_{s_2} + GG_6\left(K_{p6}r + K_{i6}\frac{1}{2}\,r^2\right)}{1 - GG_6K_{d6}}\right)$$

Since the value of $1 - AA_1\,K_{d1} < 0$, $1 - BB_2\,K_{d2} < 0$, $1 - CC_3\,K_{d3} < 0$, $1 - DD_4\,K_{d4} < 0$, $1 - EE_5K_{d5} < 0$ dan $1 - GG_6K_{d6} < 0$, then it is obtained that $\dot{V}(u, v, w, p, q, r) \le 0$.

Meeting the condition above and the requirements by Theorem 1, then the function is as follows:

$$V(u, v, w, p, q, r) = \frac{1}{2}u^2 + \frac{1}{2}v^2 + \frac{1}{2}w^2 + \frac{1}{2}p^2 + \frac{1}{2}q^2 + \frac{1}{2}r^2$$

is a Lyapunov function and asymtotically stable.

In Theorem 2 there is one requirement $V(x) \to \infty$ with $\|x\| \to \infty$ if fulfilled, the Lyapunov function is globally, asysmthotically stable. Lyapunov Function above is:

$$V(u, v, w, p, q, r) = \frac{1}{2}u^2 + \frac{1}{2}v^2 + \frac{1}{2}w^2 + \frac{1}{2}p^2 + \frac{1}{2}q^2 + \frac{1}{2}r^2$$

It will be proved that:

$$V(u, v, w, p, q, r) \to \infty$$

with:

$$\|u\| \to \infty, \|v\| \to \infty, \|w\| \to \infty, \|p\| \to \infty, \|q\| \to \infty, \|r\| \to \infty$$

Since:

$$V(u, v, w, p, q, r) = \frac{1}{2}u^2 + \frac{1}{2}v^2 + \frac{1}{2}w^2 + \frac{1}{2}p^2 + \frac{1}{2}q^2 + \frac{1}{2}r^2$$

is quadratic function, so if $\|u\| \to \infty, \|v\| \to \infty, \|w\| \to \infty, \|p\| \to \infty, \|q\| \to \infty$ and $\|r\| \to \infty$, then $V(u, v, w, p, q, r) \to \infty$. So, Lyapunov Function:

$$V(u, v, w, p, q, r) = \frac{1}{2}u^2 + \frac{1}{2}v^2 + \frac{1}{2}w^2 + \frac{1}{2}p^2 + \frac{1}{2}q^2 + \frac{1}{2}r^2$$

is globally asymthotically stable

VI. Conclusion

Based on the computational results and discussion on the design of the Proportional, Integral, and Derivative (PID) Control System, regarding the linear model of 6-DOF, it can be concluded that the PID method can be used as a motion control system of 6-DOF linear model with a significant accuracy. For translational motions (surge, sway and heave) the PID method has an error of 0.4% - 8.9%, and for rotational motions (roll, pitch and yaw) it has an error of 4.2% - 13%. Whereas, the Proportional control remains to have a considerably big error. If viewed in term of its stability analysis, the PID is considered globally asymptotically stable by employing Lyapunov method of stability analysis. In Conclusion, the PID method can be used as the motion control system of AUV.

Acknowledgements

High appreciation to the Ministry of Research and High Education (Kemenristekdikti), Republic of Indonesia for the fund for my research conducted in the year of 2018. And appreciation to The Center of Excellence for Mechatronics and Industrial Automation (PUI-PT MIA-RC ITS) Kemenristekdikti, Republic of Indonesia.

References

[1] Herlambang, T., Nurhadi H and Subchan., 2014, Preliminary Numerical Study on Designing Navigation and Stability Control Systems for ITS AUV, *Applied Mechanics and Materials* Vol. 493 (2014) pp 420-425 Trans Tech Publications, Switzerland.

[2] Herlambang, T., Djatmiko E.B and Nurhadi H., 2015, Navigation and Guidance Control System of AUV with Trajectory Estimation of Linear Modelling, *Proc. of International Conference on Advance Mechatronics, Intelligent Manufactre, and Industrial Automation*, IEEE, ICAMIMIA 2015, Surabaya, Indonesia, pp. 184-187, Oct 15 – 17.

[3] Yang, C. 2007. *Modular Modelling and Control for Autonomous Vehicle (AUV)*. Department of Mechanical Engineering National University of Singapore.

[4] Prestero, T., 2001, *Verification of Sic-Degee of Freedom Simulation Model for the REMUS Autonomous Uderwater Vehicle*, Massachusetts Intitute of Technology.

[5] Healey, A. J., 2002, Guidance and Control, For Small AUVs Using DGPS and Dopples Aided Inertial Underwater Navigation, *AAIA Guidance Navigation and Control Conference and Exhibit*, Monterey, California, Aug. 5-8.

[6] Herlambang, T., Djatmiko, E., Nurhadi, H., Ensemble Kalman Filter with a Square Root Scheme (EnKF-SR) for Trajectory Estimation of AUV SEGOROGENI ITS, (2015) *International Review of Mechanical Engineering (IREME)*, 9 (6), pp. 553-560. doi:https://doi.org/10.15866/ireme.v9i6.6341

[7] Ermayanti, E., Aprilini, E., Nurhadi H, and Herlambang T, 2015, Estimate and Control Position Autonomous Underwater Vehicle Based on Determined Trajectory using Fuzzy Kalman Filter Method, *International Conference on Advance Mechatronics, Intelligent Manufactre, and Industrial Automation (ICAMIMIA)*-IEEE Surabaya Indonesia, 15–16 Oktober 2015.

[8] Kondo, H., and Ura, T., 2004, Navigation of an AUV for Investigation of Underwater Structures, *Control Engineering Practice*, Elsevier, Vol. 12, pp. 1551–1559

[9] Jalving, B., and Storkersen, N., 1994, The Control System of an Autonomous Underwater Vehicle, *Proc. of the Third IEEE Conference*, Vol. 2, pp. 851 – 856, Aug. Glasgow, Scotland

[10] Li, J. H., and Lee, P. M., 2005, Design of an Adaptive Non-linear Controller for Depth Control of an Autonomous Underwater Vehicle, *Ocean Engineering*, vol. 32 Issues 17-18, pp. 2165-2181

[11] Wu, X., Feng, Z., Zhu, J., and Allen, R., 2008, “GA-Based Path planning for multiple AUVs, *International Journal of Control*. Vol. 80, Issue-7, pp. 1180-1185.

[12] Oktafianto, K., Herlambang T., Mardlijah, Nurhadi H., 2015, “Design of Autonomous Underwater Vehcle Motion Control Using Sliding Mode Control Method”, *International Conference on Advance Mechatronics, Intelligent Manufactre, and Industrial Automation (ICAMIMIA)*-IEEE Surabaya Indonesia, 15–16 October 2015.

[13] Jebelli, A., Yagoub, M., Rahim, R., Kazemi, H., Design and Construction of an Underwater Robot Based Fuzzy Logic Controller, (2013) *International Review of Mechanical Engineering (IREME)*, 7 (1), pp. 147-153.

[14] Fossen, T. I. 2005, A Nonlinear Unified State-space Model for Ship Maneuvering and Control in A Seaway. *International Journal of Bifurcation and Chaos*, Vol. 5, pp. 2717-2746, Aug.

[15] Nie, W and Feng, S., 2016, Planar path-following tracking control for an autonomous underwater vehicle in the horizontal plane, *Optik* 127, page 11607 – 11616.

[16] Herlambang, T., Nurhadi, H., and Subchan 2018 Trajectory Estimation of UNUSAITS AUV Based on Dynamical System with Ensemble Kalman Filter Square Root for Building Platform of Navigation and Guidance Control System, *Proc. of International conference on Engineering Technology, Advance Science, and Industrial Application,* IEEE, ICETASIA 2018, Surakarta, Indonesia, Sep 06 – 07.

[17] Herlambang, T., Subchan and Nurhadi H., 2018 Design of UNUSAITS AUV Motion Control Using Sliding PID (SPID), *Proc. of International conference on Engineering Technology, Advance Science, and Industrial Application,* IEEE , ICETASIA 2018, Surakarta, Indonesia, Sep 06 – 07.

[18] Nurhadi. H., Herlambang, T., and Subchan., 2018 Navigation and Guidance System of Autonomous Underwater Vehicle with Trajectory Estimation of Nonlinear Modeling using Ensemble Kalman Filter, *Proc. of International conference on Engineering Technology, Advance Science, and Industrial Application,* IEEE , ICETASIA 2018, Surakarta, Indonesia, Sep 06 – 07.

[19] Mohd Aras, M., Abdullah, S., Baharin, K., Mohd Nor, A., Mohd Zambri, M., Model Identification of an Underwater Remotely Operated Vehicle Using System Identification Approach Based on NNPC, (2015) *International Review of Automatic Control (IREACO)*, 8 (2), pp. 149-154. doi:https://doi.org/10.15866/ireaco.v8i2.5525

[20] Hernández Beleño, R., Mora Gonzales, P., Avilés Sánchez, O., Ferreira, J., Dynamic Modeling and PID Control of an Underwater Robot Based on the Hardware-in-the-Loop Method, (2016) *International Review of Mechanical Engineering (IREME)*, 10 (7), pp. 482-490. doi:https://doi.org/10.15866/ireme.v10i7.9037

Authors' information

Teguh Herlambang is currently Lecturer at the Department of Information System, Nahdlatul Ulama Surabaya University (UNUSA) Surabaya, Indonesia. He received his B.Sc and M.Sc. degree from Department of Mathematics at Institute of Technology Sepuluh Nopember (ITS) in 2010 and 2012. He receive his Ph.D degree from Department of Ocean Engineering at Institute of Technology Sepuluh Nopember (ITS). He is currently is a Head of Research Department of UNUSA, also assigned as researcher in Center of Excellence for Mechatronics and Industrial Automation (PUI-PT MIA-RC ITS) Kemenristekdikti. His area of interest is modelling, navigation, guidance and control of dynamics system.

Subchan is currently Associate Professor at the Department of Mathemathics, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia. He received Ph.D (2006) from Cranfield University, UK, Master Degree from TU-Delft the Netherland and B.Sc Form ITS Surabaya. Subchan currently is the Vice Rector on Academic Affair of Kalimantan Institute of Technology. He has published numerous paper in his field. His interest is mathematical modeling, optimization, navigation, guidance and control.

Hendro Nurhadi Received the Dipl.Ing.(FH) degree from the University of Applied Science Georg-Simon-Ohm Fachhochshule Nuremberg, Nuremberg, Germany, in 2001 and the Ph.D degree from the National Taiwan University of Science and Technology (NTUST), Taipei, Taiwan, in 2009. He is currently with the Department of Mechanical Engineering at Institute of Technology Sepuluh Nopember (ITS), Surabaya, Indonesia, in charged as a Head of Mechatronics Laboratory, also assigned as a coordinator of national consortium for mechatronics for defense, unmanned systems and industrial machineries. He also assigned as researcher in Center of Excellence for Mechatronics and Industrial Automation (PUI-PT MIA-RC ITS) Kemenristekdikti. He has authored numerous international journal papers and International conferences, as well as reviewer and editor for various international journal papers and international proceedings. His research interests and consulting activities are in the areas of control system, robotics and automation, advanced mechatronics, automated optical inspection (AOI), machine tools, dynamic systems, automation of manufacturing processes, computer-aided design and manufacturing, optimization applications, digital signal processing, artificial intelligence and related fields.

