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Simulation and Dynamics Analysis of Remotely Operated Vehicle (ROV) using PID Controller for Pitch Movement

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Abstract— ROV (Remotely Operated Vehicle) is a type of underwater robot that resembles a ship. The robot is controlled by a pilot who controls the remote control. In this ROV tether as a link robot with devices such as the sea surface energy source, remote control and sensing display. This study starts from the stage of modeling the body of the ROV using SolidWorks 2014. Estimation of added mass coefficient and estimation of damping hydrodynamics with manual calculation that very important to enter in the simulation. Thus construct equations of mathematical modeling to dynamics with MATLAB SIMULINK to generate 3 DOF motion of the ROV, and to analyze the stability of ROV using command and GUI in MATLAB with PID control. Creating a world in language VRML files using software V-Realm Builder 2.0 and connect it to the ROV dynamics conditions in MATLAB SIMULINK. Then simulation of the ROV using sl3d toolbox contained in MATLAB 2013b and dynamics analysis of the ROV vision of ROV thruster force is modeled as the input plots generated by Signal Builder with position and velocity about time.

Keywords— underwater robot, buoyancy, virtual reality

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I. Introduction

As we know, two-third surface area of Indonesian country is water. Being a maritime country, Indonesia's sea area is no less than 5.8 million km^2, which consists of 0.8 million km^2 of territorial sea area, 2.3 million km^2 of archipelagic sea, and 2.7 million km^2 of exclusive economic zone [1], a vast area awaiting to be explored but can be only be done economically and safely by underwater robots. Based on operation system, underwater robots are divided in two types: Remotely Operated Vehicle (ROV), and Autonomous Underwater Vehicle (AUV). ROV is underwater vehicle that is controlled by human directly using remote control from surface area, and is usually operated in the deep sea and controlled from ship using tether. Whereas AUV is underwater vehicle that can move without being controlled by human operator, it can be operated autonomously below the surface but not too deep [2].

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In this research, simulation will be made using toolbox sl3d in MATLAB 2013b, dynamics analysis of ROV using mathematical modeling and computational parameter. Simulation using Matlab Simulink is performed to obtain position and velocity plot about the time. The output of this research is an ROV design that is based on mathematical model.

A. ROV (Remotely Operated Vehicle)

A typical ROV consist of frame, thruster, control system/ box, camera.

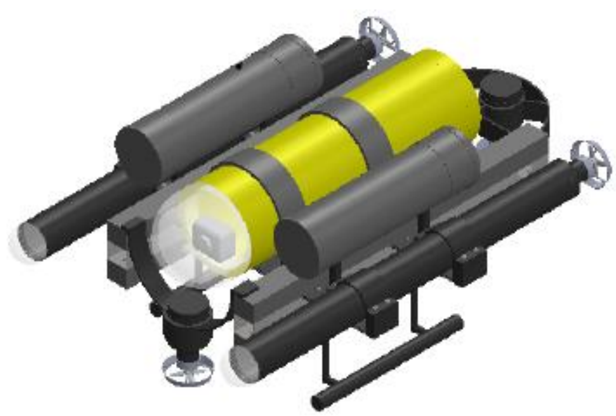

Figure 1 ROV Design

B. Coordinate System, Definition Kinematics and Position of ROV

Coordinate is important to explain the motion of underwater vehicle in six degrees of freedom (DOF) and to determine position and orientation in three dimensional volume and time. The 6 DOF motion is described as position and translation velocity as X, Y, Z, and ϕ, θ, ψ for orientation and rotation velocity. For underwater robots, those motion variables are termed as surge, sway, heave, roll, pitch, and yaw. Position or translational motion and orientation or rotational motion of a rigid body (a body in which the relative position of all its points is constant) can be described with respect to a reference position. For this purpose, some set of orthogonal coordinate axes are chosen and assumed to be rigidly connected to the arbitrary origin of the body to build up the reference frame.

Force and moment that work on the underwater vehicle must be referenced to the same frame as the motion variables. The notation that is used to explain 6 degree of freedom (DOF) summarized on the Table 1. Note that convention for underwater vehicle, x positive direction in front, y positive direction in right hand, z positive direction in bottom and rule of right hand used for angle [3].

Table 1 Notation standard motions [3]

DOF	Motions	Forces and Moments	Linear Velocities and Angular Velocities	Positions and Orientations
1	Surge	X	U	x
2	Sway	Y	V	y
3	Heave	Z	w	z
4	Roll	K	p	ϕ
5	Pitch	M	q	θ
6	Yaw	N	r	ψ

Figure 2 shows the determination of body-fixed coordinate and earth-fixed coordinate that are used as standard motion as summarized on the Table 1.

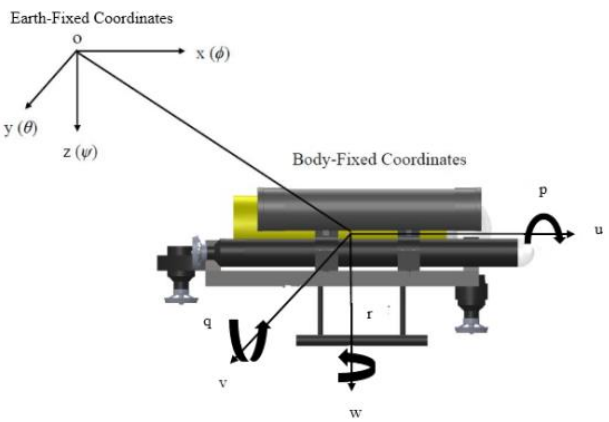

Figure 2 Body fix coordinate and earth fix coordinate

II. Dynamics Modeling of ROV

A. Kinematics Model of ROV

Kinematics is part of dynamics, which is a study about motion of the objects without regard to the forces that influence the motion of objects. Description of kinematics from ROV is based on two types of reference, that is, body-fixed coordinate and earth-fixed coordinate. Earth-fixed coordinate is used as the inertial reference with assumption that earth is superficial and its motion is neglected [4]. For object moving in three dimension, variables that must be considered in the kinematics model are:

$$\eta_1 = [x \quad y \quad z]^T \tag{1}$$

$$\eta_2 = [\phi \quad \theta \quad \psi]^T \tag{2}$$

$$v_1 = [u \quad v \quad w]^T \tag{3}$$

$$v_2 = [p \quad q \quad r]^T \tag{4}$$

$$\tau_1 = [X \quad Y \quad Z]^T \tag{5}$$

$$\tau_2 = [K \quad M \quad N]^T \tag{6}$$

vector η is position and orientation coordinate about ROV in the reference of earth-fixed coordinate, whereas vector v is velocity vector, and each τ respectively represents external force vector and external moment vector that acts on ROV body. To obtain the expression kinematics of ROV, the formulation must be transformed from body-fixed coordinate to earth-fixed coordinate. The transformation matrix is usually written like this [4]:

$$\dot{\eta}_1 = J_1(\eta_2)v_1 \tag{7}$$

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix} = J_1(\eta_2)\begin{bmatrix}u\\ v\\ w\end{bmatrix} \tag{8}$$

$$J_1(\eta_2) = \begin{bmatrix} c\psi c\theta & -s\psi\, c\,\theta + c\,\psi\, s\,\theta\, s\,\phi & s\,\psi\, s\,\phi + c\,\psi\, s\,\theta\, c\,\phi \\ s\,\psi\, c\,\theta & c\,\psi\, c\,\theta + s\,\psi\, s\,\theta\, s\,\phi & -c\,\psi\, s\,\phi + s\,\psi\, s\,\theta\, c\,\phi \\ -s\,\theta & c\,\theta\, s\,\phi & c\,\theta\, c\,\phi \end{bmatrix} \tag{9}$$

$$\left(J_1(\eta_2)\right)^{-1} = \left(J_1(\eta_2)\right)^{\mathrm{T}} \tag{10}$$

$$\dot{x} = u\; c\,\psi\, c\,\theta + v(-s\,\psi\, c\,\phi + c\,\psi\, s\,\theta\, s\,\phi) + w(s\,\psi\, s\,\phi + c\,\psi\, s\,\theta\, c\,\phi) \tag{11}$$

$$\dot{y} = u\; s\,\psi\, c\,\theta + v(c\,\psi\, c\,\phi + s\,\psi\, s\,\theta\, s\,\phi) + w(-c\,\psi\, s\,\phi + s\,\psi\, s\,\theta\, c\,\phi) \tag{12}$$

$$\dot{z} = u\,(-s\,\theta) + v(c\,\theta\, s\,\phi) + w(c\,\theta\, c\,\phi) \tag{13}$$

Transformation to earth-fixed coordinate:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = J_2(\eta_2)\begin{bmatrix}p\\ q\\ r\end{bmatrix} \tag{14}$$

$$J_2(\eta_2) = \begin{bmatrix} 1 & s\phi t\theta & c\,\phi\, t\,\theta \\ 0 & c\phi & -s\,\phi \\ 0 & \frac{s\phi}{c\theta} & \frac{c\phi}{c\theta} \end{bmatrix} \tag{15}$$

$$\dot{\phi} = p + q(s\,\phi\, t\,\theta) + r(c\,\phi\, t\,\theta) \tag{16}$$

$$\dot{\theta} = q\,c\,\phi - r\,s\,\phi \tag{17}$$

$$\dot{\psi} = q\,s\,\phi\,/\,c\,\theta + r\,c\,\phi/\,c\,\theta \tag{18}$$

B. Dynamics Model of ROV

Based on Newton's Second Law, derivation of the equations of motion will derive the complete three-dimensional, six degree of freedom (DOF) rigid body governing equations, that will briefly work through the derivation of the dynamic equation of the general form $F = m \cdot a$, where F is external force that is working on the central of mass from the objects (N), whereas $m \cdot a$ is the product of mass (kg) and acceleration (m/s^2). External forces consist of radiation-induced, environmental and propulsive. Radiation-induced forces consist of hydrodynamics damping force and restoring force. Although derivation of dynamics equation is got from various reference resources, in this part, a summary for getting the complete data for the motion dynamics equation of ROV is presented [5][6][7].

- Axial force equation (*surge*):

$$\sum X_{ext} = m\,[\dot{u} + wq - vr - x_G(q^2 + r^2) + z_G(pr + \dot{q})] \tag{19}$$

- Lateral force equation (sway):

$$\sum Y_{ext} = m\,[\dot{v} - wp + ur + x_G(pq + \dot{r}) + z_G(qr - \dot{p})] \quad (20)$$

- Normal Force equation (heave):

$$\sum Z_{ext} = m\,[\dot{w} - uq + vp + x_G(pr - \dot{q}) - z_G(q^2 + p^2)] \quad (21)$$

- Rolling moment equation:

$$\sum K_{ext} = I_{xx}\,\dot{p} - I_{xy} + (I_{zz} - I_{yy})qr - m[z_G(\dot{v} + ur - wp)] \quad (22)$$

- Pitching moment equation:

$$\sum M_{ext} = I_{yy}\,\dot{q} + (I_{xx} - I_{zz})pr + m[z_G(\dot{u} + wq - vr)] - x_G(\dot{w} + vp - uq) \quad (23)$$

- Yawing moment equation:

$$\sum N_{ext} = I_{zz}\,\dot{r} + (I_{yy} - I_{xx})pq + m[z_G(\dot{v} + ur - wp)] \quad (24)$$

C. *Mathematical Modelling Simulation of ROV*

Modelling of the ROV is complete into mathematical equations that will be included in the simulation of MATLAB 2013b/Simulink. External force surge is $\sum X_{ext}$ a summation forces additional mass, hydrodynamic damping force, restoring force and propulsion force **(25)**. External forces on sway and heave directions, and external moments on roll, pitch and yaw directions can be formulated the same way as **(25)**. Equations can be written as follows:

$$\sum X_{ext} = X_A + X_D + X_R + X_P \quad (25)$$

- Surge ($\sum X_{ext}$):

$$\begin{aligned} m\{\dot{u} + wq - vr - x_G(q^2 + r^2) \\ + z_G(pr + \dot{q})\} &= X_{\dot{u}}\dot{u} + X_{\dot{w}}(\dot{w} + uq) + X_{\dot{q}}\dot{q} + Z_{\dot{w}}wq \\ &+ Z_{\dot{q}}q^2 - Y_{\dot{v}}vr - Y_{\dot{p}}rp - Y_{\dot{r}}r^2 \\ &+ X_{u|u|}u|u| - (W - B)\sin\theta + F_{rst} + F_{lst} \end{aligned} \quad (26)$$

- Sway ($\sum Y_{ext}$):

$$\begin{aligned} m\{\dot{v} - wp + ur + x_G(pq + \dot{r}) \\ + z_G(qr - \dot{p})\} &= Y_{\dot{v}}\dot{v} + Y_{\dot{p}} + Y_{\dot{r}}\dot{r} - X_{\dot{w}}(up - wr) + X_{\dot{u}}ur \\ &- Z_{\dot{w}}wp + Z_{\dot{q}}pq + X_{\dot{q}}qr + Y_{v|v|}v|v| \\ &+ (W - B)\cos\theta\sin\phi \end{aligned} \quad (27)$$

- Heave ($\sum Z_{ext}$):

$$\begin{aligned} m\{\dot{w} - uq + vp + x_G(rp - \dot{q}) \\ - z_G(q^2 + p^2)\} &= X_{\dot{w}}(\dot{u} - wq) + Z_{\dot{w}}\dot{w} + Z_{\dot{q}}\dot{q} - X_{\dot{u}}uq \\ &- X_{\dot{q}}q^2 + Y_{\dot{v}}vp + Y_{\dot{r}}rp + Y_{\dot{p}}p^2 \\ &+ Z_{w|w|}w|w| + (W - B)\cos\theta\cos\phi \\ &+ F_{fwdt} + F_{aftt} \end{aligned} \quad (28)$$

- Roll ($\sum K_{ext}$):

$$\begin{aligned} I_{xx}\,\dot{p} + (I_{zz} - I_{yy})qr \\ - m[z_G\,(\dot{v} + ur - wp)] &= Y_{\dot{p}}\dot{v} + K_{\dot{p}}\dot{p} + K_{\dot{r}}\dot{r} + X_{\dot{w}}uv \\ &- (Y_{\dot{v}} - Z_{\dot{w}})vw - (Y_{\dot{r}} + Z_{\dot{q}})wr \\ &- Y_{\dot{p}}wp - X_{\dot{q}}ur + (Y_{\dot{r}} + Z_{\dot{q}})vq \\ &+ K_{\dot{r}}pq - (M_{\dot{q}} - N_{\dot{r}})qr + K_{p|p|}p|p| \\ &- (z_G W - z_B B)\cos\theta\sin\phi \end{aligned} \quad (29)$$

- Pitch ($\sum M_{ext}$):

$$\begin{aligned} I_{yy}\,\dot{q} + (I_{xx} - I_{zz})pr + m[z_G\,(\dot{u} + wq - vr) \\ - x_G\,(\dot{w} + vp - uq)] &= X_{\dot{q}}(\dot{u} + wq) + Z_{\dot{q}}(\dot{w} - uq) \\ &+ M_{\dot{q}}\dot{q} - X_{\dot{w}}(u^2 - w^2) - (Z_{\dot{w}} - X_{\dot{u}})uw \\ &+ Y_{\dot{p}}vr - Y_{\dot{r}}vp - K_{\dot{r}}(p^2 - r^2) \\ &+ (K_{\dot{p}} - N_{\dot{r}})rp + M_{q|q|}q|q| \\ &+ M_{w|w|}w|w| - (x_G W - x_B B)\cos\theta\cos\phi \\ &- (z_G W - z_B B)\sin\theta + (F_{rst} + F_{lst})zp \\ &+ F_{aftt}xp_{aft} - F_{fwdt}xp_{fwd} \end{aligned} \quad (30)$$

- Yaw ($\sum N_{ext}$):

$$\begin{aligned} I_{zz}\,\dot{r} + (I_{yy} - I_{xx})pq \\ + m[x_G\,(\dot{v} + ru - pw)] &= Y_{\dot{r}}\dot{v} + K_{\dot{r}}\dot{p} + N_{\dot{r}}\dot{r} \\ &- (X_{\dot{u}} - Y_{\dot{v}})uv - X_{\dot{w}}uw + (X_{\dot{q}} + Y_{\dot{p}})up \\ &+ Y_{\dot{r}}ur + Z_{\dot{q}}wp - (X_{\dot{q}} + Y_{\dot{p}})vq \\ &- (K_{\dot{p}} - M_{\dot{q}})pq - K_{\dot{r}}qr + N_{r|r|}r|r| \\ &+ N_{v|v|}v|v| + (x_G W - x_B B)\cos\theta\sin\phi \\ &+ (F_{rst} - F_{lst}) \end{aligned} \quad (31)$$

III. PID Controller and Simulation

A. *PID Controller for Pitch Movement*

In the simulation, there is no control system that maintain the hovering state, in surge and heave motion. The influence of pitch angle greatly affects the simulation results. Therefore to maintain the hovering state, the pitch angle should be controlled. The determination of the value of PID control by using MATLAB/SIMULINK is to add PID Controller blocks in the model in order to be close loop system [8][9][10]. Figure 3 shows the additions of the PID block diagram intoROV control loop.

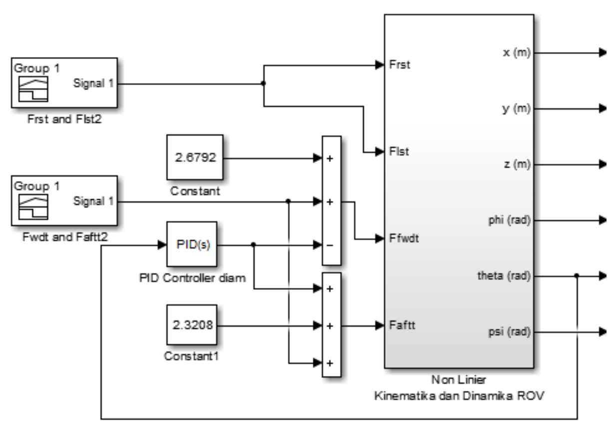

Figure 3 Additions to the PID block diagram hovering condition, surge, and heave motion

Then double click the PID Controller block it will show a Function Block Parameters PID Controller as shown in Figure 4. Then click Tune to linearized modeling to obtain the PID values automatically. The controllers are

- Proportional -60.1528757451922
- Integral -12.3345980314996
- Derivative -26.6314325750794.

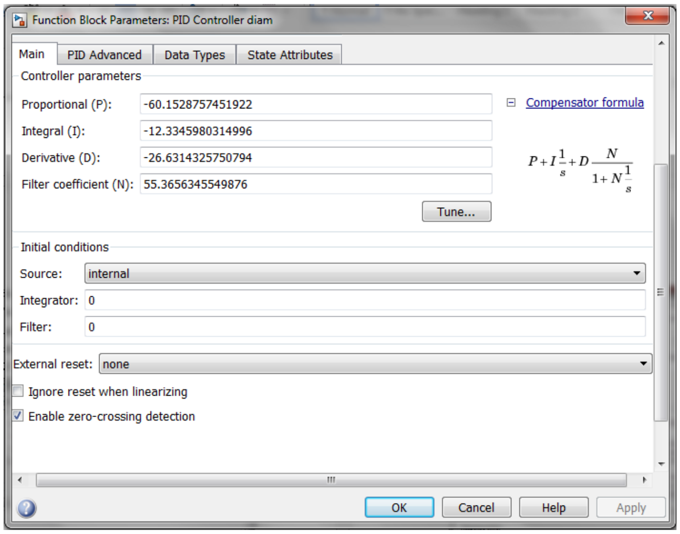

Figure 4 Function Block Parameter PID Controller hovering condition, surge and heave motion

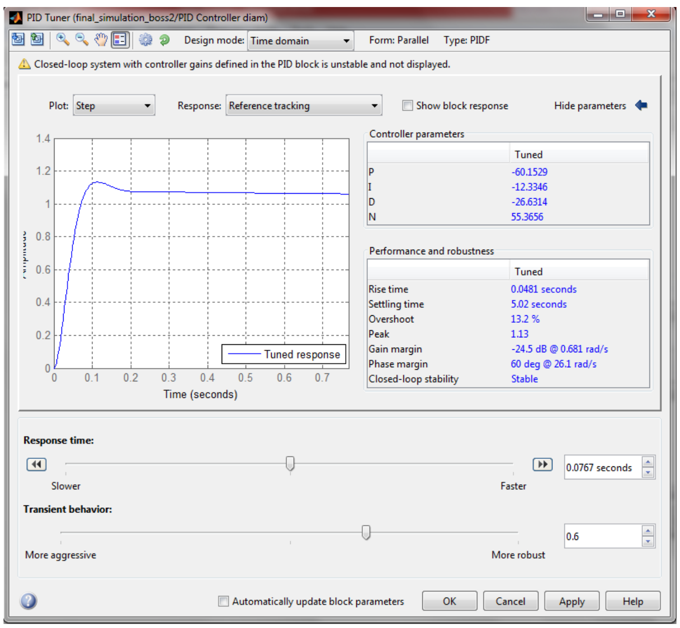

Figure 5 PID Tunner

Figure 5 shows PID Tuner quiescent conditions, which automatically displays the value in 0.0767 s response time, transient behavior damping value of 0.6, the result of PID parameter values such as 0.0481 s Rise time, Settling time 5.02 s, 13.2 % Overshoot, Peak 1.13, gain margin of -24.7 dB, phase margin of 60 deg, Closed-loop Stability Stable.

B. Dynamics System Modeling of ROV Using MATLAB SIMULINK

In this research, dynamics system of ROV is modeled using MATLAB 2013b/SIMULINK with mathematical modeling inside that is connected with toolbox sl3d program that is in MATLAB 2013/SIMULINK, and will be showed on the three dimension inside the virtual reality. All dynamics modeling of ROV is built from block interconnection that represent mathematics analysis of ROV. Figure 6 is showing dynamics model of all about ROV. ROV dynamics is showing physical condition of ROV that is giving the result state about position, velocity and acceleration, linear or angular. Representation of ROV can be seen in the three dimension.

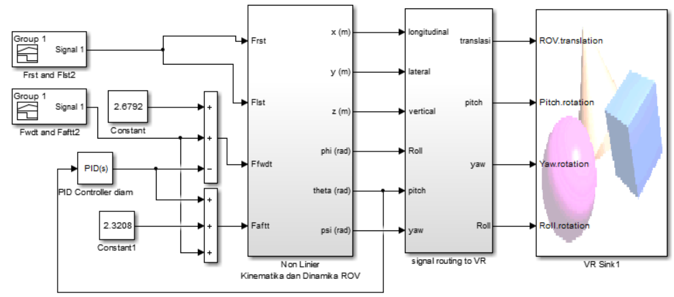

Figure 6 Modeling of MATLAB SIMULINK ROV and Virtual Reality layout

IV. Result and Discussion

Based on purpose of this research, the simulation that will be played are hovering, surge, and heave motion. The result of the simulation will be plots of Pitch, position, velocity, which influence the ROV. Validation in this simulation is using linearization model from model non-linear equation to linear. To analyze the stability of the linear model used eigenvalues of the matrix A. Eigenvalue which is in the left hand (left half plane) indicates the stability of the real axis, while the eigenvalue which is at the right hand (right half plane) indicates the real axis of instability. Figure 7 and

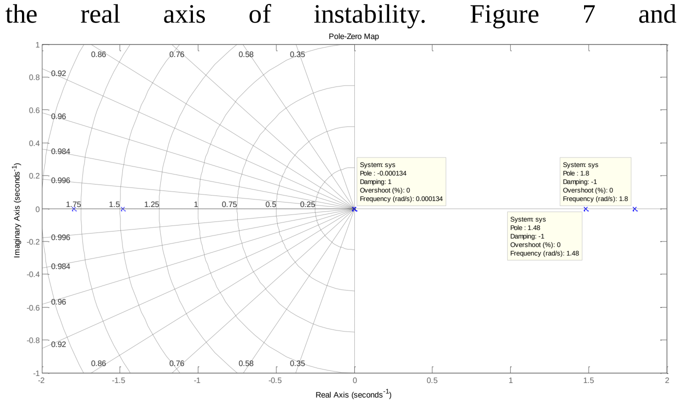

Figure 7 Root location of open loop

Table 2 show six eigenvalues that have real positive value, which indicates the system is unstable.

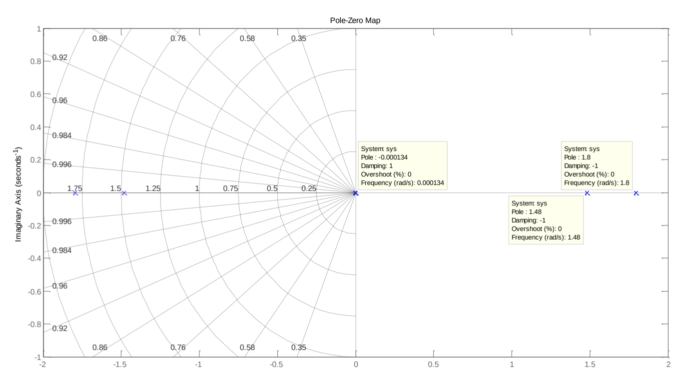

Figure 7 Root location of open loop

Table 2 Eigenvalue, Damping, and Frequency in open loop

Eigenvalue	Damping	Freq (rad/s)
0.00e+00	-1.00E+00	0.00e+00
0.00e+00	-1.00E+00	0.00e+00
0.00e+00	-1.00E+00	0.00e+00
0.00e+00	-1.00E+00	0.00e+00
-1.80e+00	1.00E+00	1.80e+00
1.80e+00	-1.00E+00	1.80e+00
-5.68e-06	1.00E+00	5.68e-06
-1.05e-04	1.00E+00	1.05e-04
1.48e+00	-1.00E+00	1.48e+00
-1.48e+00	1.00E+00	1.48e+00
-4.35e-05	1.00E+00	4.35e-05
-1.34e-04	1.00E+00	1.34e-04

A. Result of the Dynamic Simulation of ROV with Hovering Condition

Effect of orientation on the pitch angle can be seen in the Figure 8 as well as the influence of the orientation angle of pitch, which shows large values with maximum pitch angle being 16 x 10^{-3} deg.

Simulation result of hovering condition ROV are position and linear velocity. Effect of simulation position is on x-axis that can be seen in Figure 9. In ROV simulation during hovering condition, displacement of 0033 m occurs. Effect of linear velocity on the x-axis can be seen in Figure 9, where the maximum speed of the simulation results of is 3.3 × 10^{-4} m/s.

B. Result of the Dynamic Simulation of ROV with Heave Motion

Effect of orientation on the pitch angle can be seen in the Figure 10 as well as the influence of the orientation angle of pitch which shows large values with maximum pitch angle being -1.8 deg, and achieve a constant pitch angle of 0 deg within 25 s.

The simulation results of the heave motion of the ROV are position and linear velocity. Effect of simulated position is on the z-axis, which can be seen in Figure 11. In the ROV simulation, a 12.5 m heave motion displacement occurs. Effect of linear velocity on the z-axis can be seen in Figure 11, where the maximum speed of the simulation is 0.25 m/s.

C. Result of the Dynamic Simulation of ROV with Surge Motion

Effect of orientation on the pitch angle as well as the influence of the orientation angle of pitch can be seen in Figure 12, which shows large value with maximum pitch angle being 14 deg and becomes constant at 0 deg within 27 seconds.

The simulation results of the surge motion ROV are position and linear velocity. Effect of simulated position is on the x-axis, which can be seen in Figure 13. ROV simulation surge motion displacement that occurs on the x-axis is 47 m. Effect of linear velocity on the x-axis can be seen in Figure 13, where it reached the maximum value and became constant at 0.92 m/s.

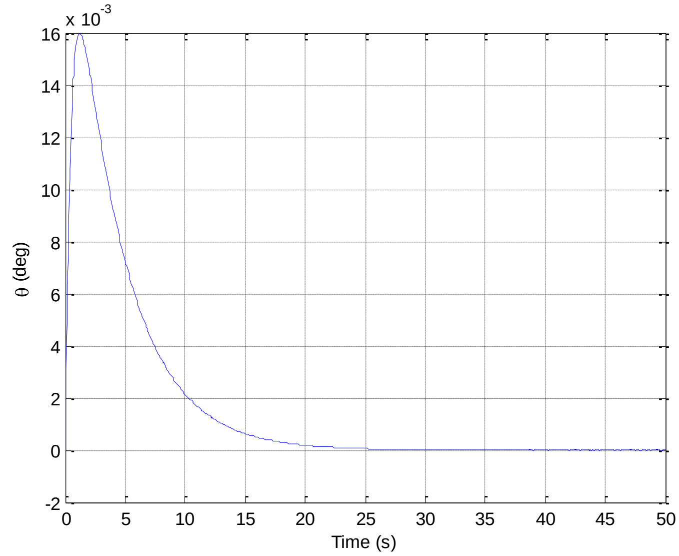

Figure 8 Orientation pitch angle

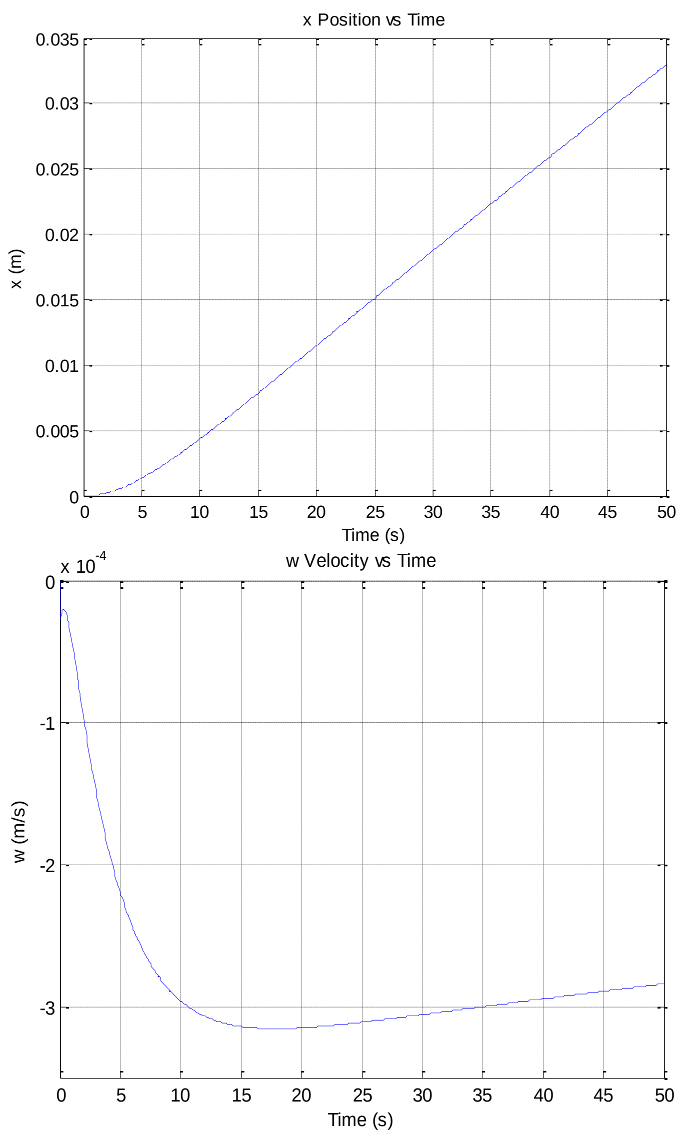

Figure 9 Hovering result plot potition and velocity about the time

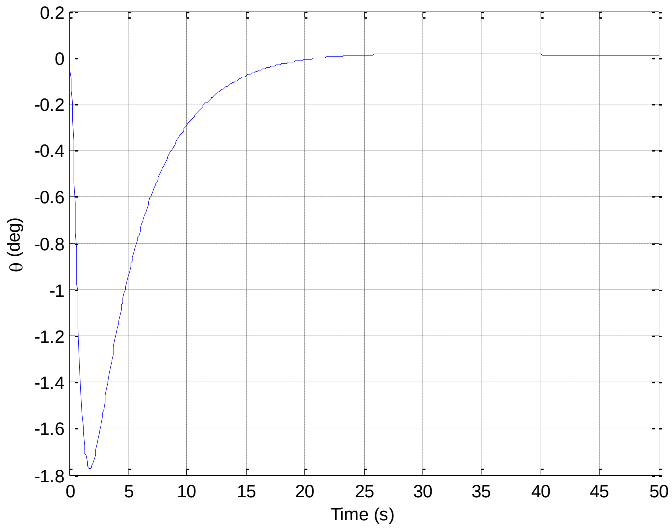

Figure 10 Orientation pitch angle

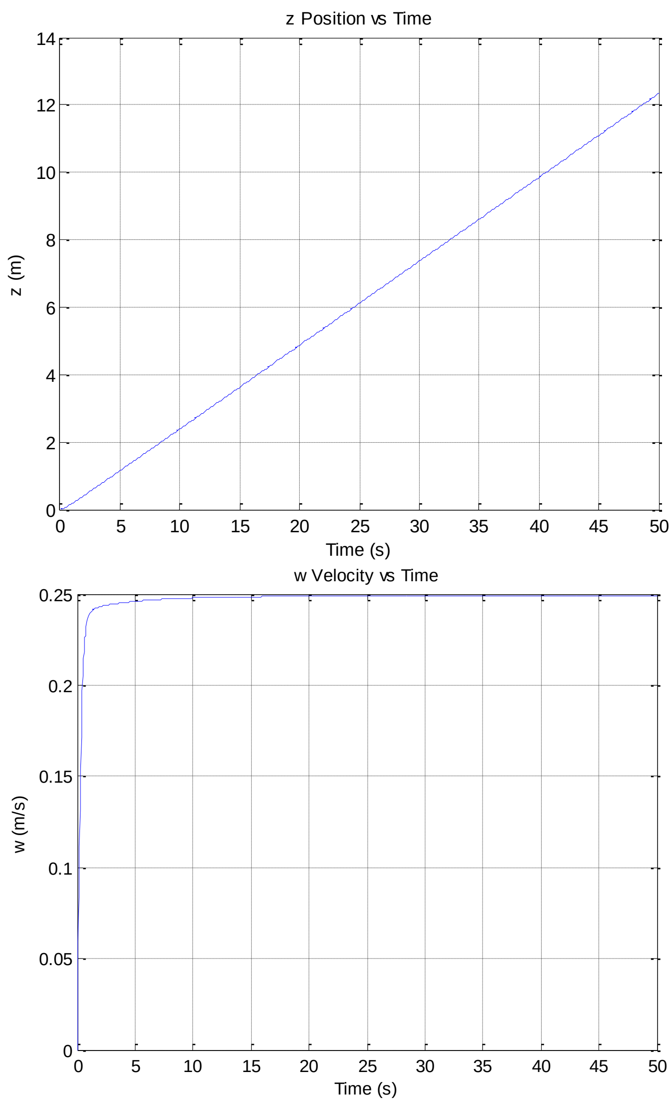

Figure 11 Heave result plot potition and velocity about the time

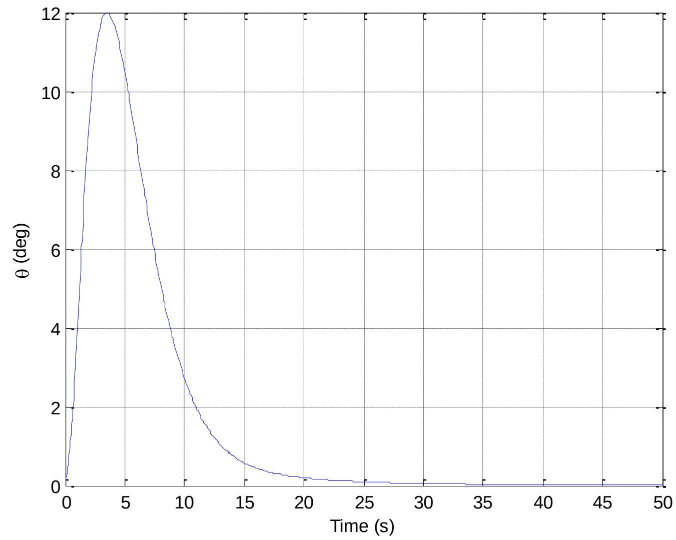

Figure 12 Orientation pitch angle

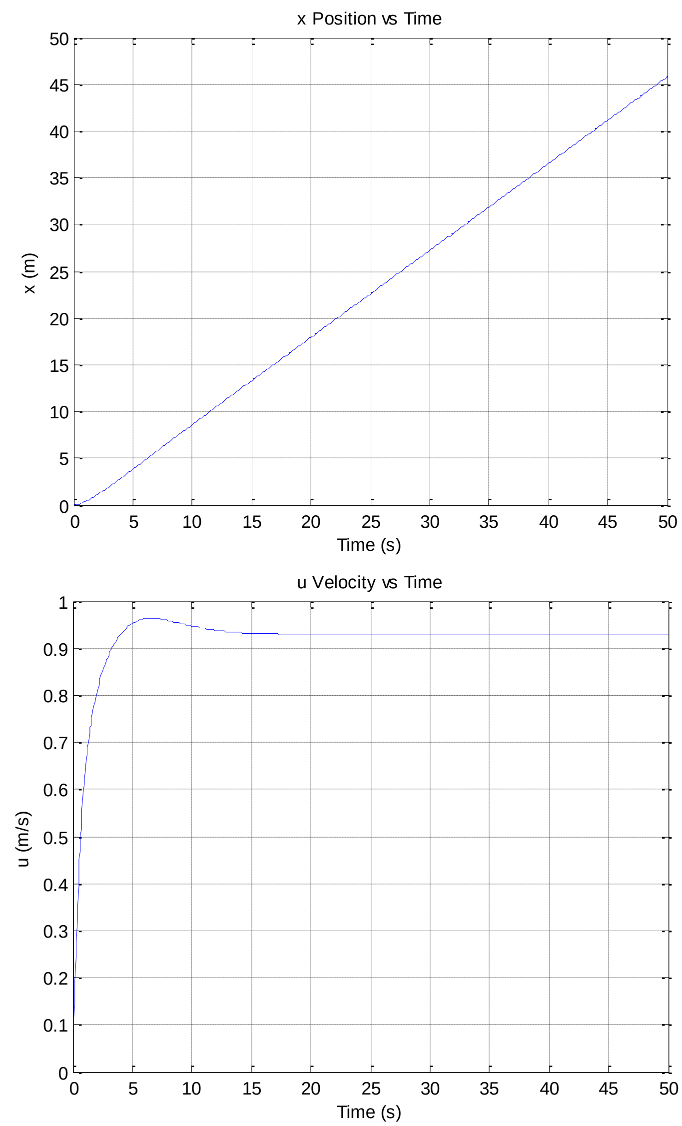

Figure 13 Surge result plot potition and velocity about the time

V. Conclusions

Based on the analysis of the design of the gravity and buoyancy forces (buoyancy) ROV using SolidWorks 2014, the design has been made to float on the water where the gravity is smaller than the upward force (buoyancy). Mathematical Modelling constructed and analyzed with MATLAB 2013b/Simulink to check the block diagram followed by successful simulation run because there is no error occurred. Simulations carried out with quiescent conditions, heave and surge motion by checking the linearized system proves that the model is not stable, then controlled by PID to stabilize the on hovering condition, heave motion, surge motion.

Acknowledgment

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