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DEVELOPMENT OF CONTROL DESIGN FOR TRACKING OF UNDER ACTUATED UNDERWATER VEHICLE USING ROOT LOCUS TECHNIQUE

Azrena Abu Bakar[a], Siti Noormiza Makhtar[a], Siti Nooraya Mohd Tawil[a], Nurul Sheeda Suhaimi[a], Tengku Norliza Tengku Mohamad[a], Ariff Juriah Ariffin[a], Elya Mohd Nor[a,b*]

[a] Department of Electrical & Electronic Engineering, Faculty of Engineering, National Defence University of Malaysia, Sg. Besi Camp, 57000 Kuala Lumpur, Malaysia
[b] Centre for Defence Research and Technology, National Defence University of Malaysia, Sg. Besi Camp, 57000 Kuala Lumpur, Malaysia

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ABSTRACT

This paper presents the development of a position tracking controller for an under actuated underwater vehicle (UUV) using the root locus technique. The development of UUV has seen significant progress in recent years with many prospects of improvement. Its application allows dangerous operations such as search and rescue missions to be performed without human involvement on board. In this paper, the nonlinear dynamic model of UUV is developed, and a second-order step response is obtained. A position tracking control using a PID controller is designed using a root-locus technique to track the position of the UUV nonlinear system. The performance of the closed-loop control system is analysed based on its transient response and steady-state error. The PD controller alone is sufficient to control the steady-state error and transient response based on the analysis. The result of simulation analysis will be used for tuning of a control system in actual underwater remotely operated vehicle UROV developed.

1.0 INTRODUCTION

In recent years, many researchers have shown interest in the study of underwater vehicles. As a result, it has been discussed that the demand for an unmanned underwater vehicle (UUV) is increased [1]. The underwater vehicle has broad applications to assist humans in challenging environments underwater. For example, it can be used to inspect structures such as bridges underwater and assist in the search and rescue team involving the underwater environment. In general, UUV can be classified into two types, autonomous underwater vehicle (AUV) and underwater remotely operated vehicle (UROV) [2]. The main difference is the involvement of human operators in operating the vehicle. UROV needs an operator for its control, while AUV relies on its on-board controllers to dictate its motion autonomously [3]. In addition, the size of UROV is small for underwater applications and may be wired or wireless [4].

In Malaysia, several groups of researchers had been developing underwater robotics, such as in UTEM [5], UTHM [6], and UPNM [7]. In UPNM, a UROV had been successfully developed and can operate underwater equipped with depth control. The overall research performed has shown an excellent working concept of underwater vehicle technology that can be developed in Malaysia. However, the position control of underwater vehicles is a challenging task due to the under actuated nature of the overall system. Trajectory tracking control always plays an essential part in manoeuvring the vehicle in an autonomous control architecture of an unmanned vehicle. Therefore, it is crucial to maintain good positioning for the vehicle and ensure other systems such as obstacle avoidance motion control of the vehicle can perform as intended. However, designing a controller for trajectory tracking poses many challenges due to the under-actuation properties of the underwater vehicle (UV) [5].

*Corresponding Author | Mohd Nor, E. | elya@upnm.edu.my

In general, an under actuated system has less actuators than the variables it needs to control. Under actuated systems exists in airspace vehicles such as multirotor UAV, ground vehicles such as two-wheeled mobile robots, and underwater vehicles. The task of controlling large variables with limited actuators will be much more challenging when external disturbances from the environment are considered in the controlled system's stability. For example, the wave of water acting as an external disturbance will challenge UV to move to the desired position for underwater vehicles. The control design of an under actuated system is challenging due to the lack of actuation capabilities. A good number of control techniques are available, which can be easily applied to the entire class of fully actuated systems, but it is not possible for under actuated systems. Theoretically, the system model of under actuated system does not satisfy Brockett's necessary condition for feedback linearization [8]. Furthermore, it is known that the control technique for an under actuated system is unique in each application, depending on the structure of each system.

Body literature of control systems for the under actuated nonlinear system is continuously growing [8]. Several works have been conducted on the development of control systems for under actuated vehicles. A study described long-duration field experiments in realistic environmental conditions utilized in the degree-of-freedom (DOF) prioritization approach, which improved tracking performance in both cases of humans in the loop and automatic control [9]. The first attempt to use Linear Quadratic Gaussian (LQG) technique to the underwater vehicle control problem can be found in [10]. The linear control strategy is best suited for undefined systems with additive white Gaussian noise and systems with incomplete state information. An example of simulations performed both with and without ocean current disturbances is presented in [11]. One of the best nonlinear control methods is sliding mode control (SMC), especially when parameter constraints are involved. However, the main disadvantage of the SMC is the chattering effect. It may lead to high-frequency modes and negatively affect the system's functionality, even causing the system to destabilize. One research proposes controlling the trajectory of UROV via SMC without any chatter [12]. Another work utilizing SMC control design on AUV is validated by forcing its position to track different cases of desired, time-varying trajectories [13].

Higher-Order Sliding Mode Controller (HOSMC) is the improved version of SMC to minimize the chattering effect and improve overall controller performance. It is a nonlinear control strategy used for the motion control of underwater vehicles [14]. A study on designing Non-Singular Terminal Sliding Mode Controller and an Adaptive Non-Singular Terminal Sliding Mode Control (ANTSMC) in real-time was proposed for trajectory tracking in the X-Y plane, resulting in chattering reduction and faster convergence of the tracking errors [15]. Another powerful tool in position tracking control of an under actuated underwater vehicle is neural networks. Its ability to approximate numerous linear and nonlinear functions and adjust varying input-output relations is proved in many cases [16]. Furthermore, neural networks are simple to implement in hardware and can correctly map multivariable functions. Therefore, a three-layer neural network and a robust adaptive controller were adopted in [17] to overcome unmodeled dynamics and external disturbances imposed on the AUV by the wind, waves, and ocean currents. Simulations results have shown the performance and effectiveness of the proposed controller.

Fuzzy logic controllers (FLC) are effective, robust controllers with numerous applications. For example, FLC is ideal for underwater vehicle control systems because of its successful implementation in nonlinear, complex, and poorly defined systems [18]. For example, one research designed a fuzzy observer-based tracking controller to estimate the actual linear velocity, and the underwater vehicle can track the reference trajectory closely [19]. Despite the growing studies on nonlinear controllers for UV, the PID algorithm is still one of the most practical controllers to manoeuvre the UV. the correction of errors based on PID is still widely used as the baseline for all these controllers. Recently, in [16], a PID controller is used in the hierarchical controller to track the errors and autonomously control the quadrotor system for position tracking. The well-known approach known as the Ziegler-Nichols method is still one of the best for selecting the initial gains before tuning the PID controller gains for the respective system. The Ziegler –Nichols tuning method had been used in finding the gains for a process control system.

This paper aims to present the framework of designing a PID controller for an under actuated underwater system (UUV) using the root-locus technique. The approach is feasible and expected to benefit the control system practitioners involving in the underwater vehicle technology, particularly during upgrading controllers. The paper is divided into four sections. The introduction and background of the study have been presented in the first section. Section 2 is methodology. In this section, the model of

*Corresponding Author | Mohd Nor, E. | elya@upnm.edu.my

the UUV system is presented. Section 3 presents the results and discussions, followed by Section 4 is the conclusion.

2.0 METHODOLOGY

This section discusses the methodology of this study in detail. First, the under actuated underwater vehicle (UUV) nonlinear mathematical model was constructed in Matlab/SIMULINK software. Then, the open-loop performance of the UUV system was characterized using the second-order step response technique. Subsequently, the transfer function is obtained from the UUV nonlinear model. Finally, the controller is designed using the root locus technique, and performance is analysed. Figure 1 shows the methodology.

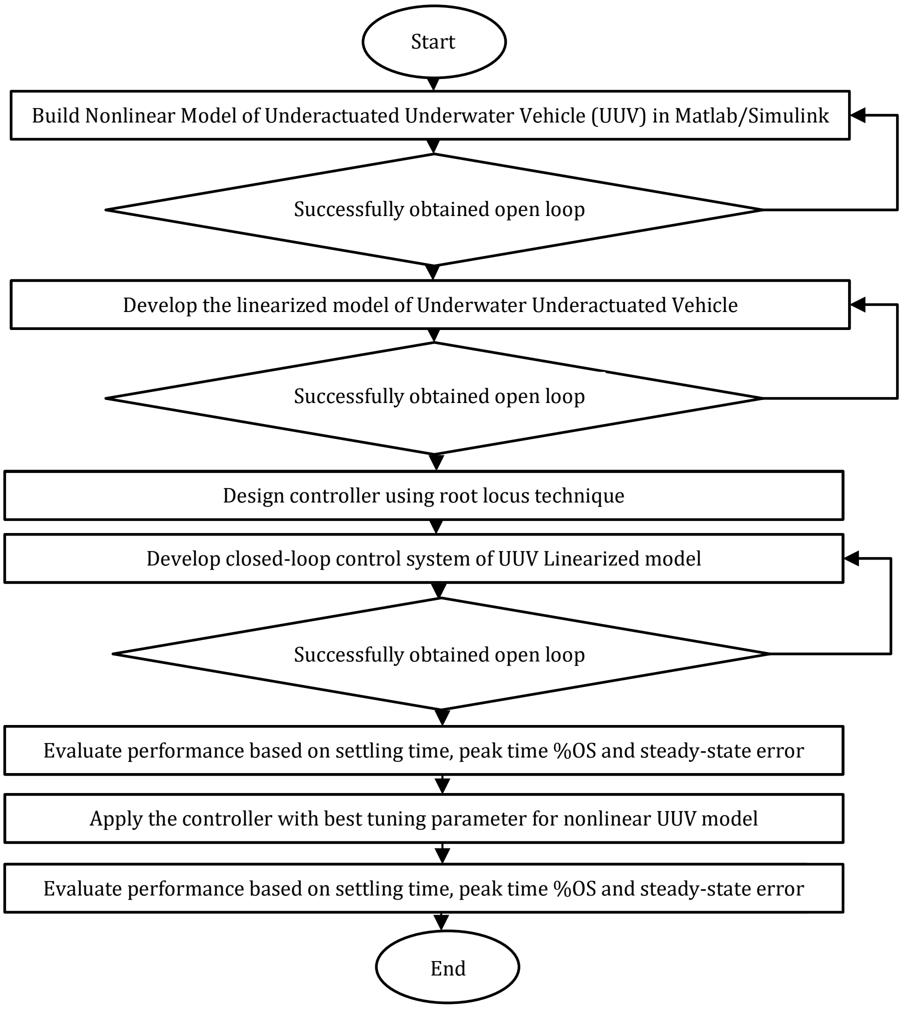

Figure 1. Framework of linear control design for UUV for trajectory tracking

2.1 Nonlinear Model Of Underactuated Underwater Vehicle

The underactuated underwater vehicle (UUV) nonlinear model in the inertial frame is expressed in the x-axis, y-axis, and z-axis. The translational dynamics are [17]:

$$\dot{x} = cos(\varphi)u - \sin(\varphi)\, v \quad (1)$$

$$\dot{y} = \sin(\varphi)u + \cos(\varphi)v \quad (2)$$

$$\dot{\varphi} = r \quad (3)$$

where x, y are positions in earth fixed frame, φ is yaw angle, u, v are linear velocities in body fixed frame, r is yaw angle velocity. The UUV rotational dynamics is expressed as [17] :

*Corresponding Author | Mohd Nor, E. | elya@upnm.edu.my

$$\dot{u} = (m_{22}/m_{11})\text{vr} - (d_{11}/m_{11})\text{u} + (\tau_u + \tau_{d1})/m_{11} \quad (4)$$

$$\dot{v} = - (m_{11}/m_{22})\text{ur} - (d_{22}/m_{22})\text{v} + (\tau_{d2}/m_{22}) \quad (5)$$

$$\dot{r} = (m_{11} - m_{22}/m_{33})\text{uv} - (d_{33}/m_{33})\text{r} + (\tau_r + \tau_{d3})/m_{33} \quad (6)$$

where m11, m22, m33 are inertia vehicles, d11, d22, d11 are damping vehicles while τu is the control input for UUV in x-axis and τr is the control input for yaw angle, φ. The complete structure of the UUV model showing the controls and the forces and control torque acting on these rotors for Equation (1) – Equation (2) are illustrated in Figure 2.

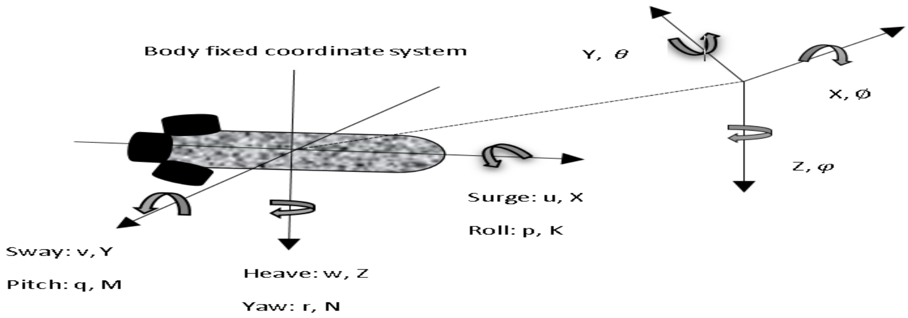

Figure 2. Forces and moment acting on UUV body [12]

2.2 Linearized Model Of Underactuated Underwater Vehicle

The linearized model of underactuated underwater vehicle (UUV) is developed based on second–order system represented as:

$$\mathrm{G_{LUUV}(s)} = \frac{\omega_n^{\,2}}{s^2 + 2\zeta\omega_n s + \omega_n^{\,2}} \quad (7)$$

Equation (3) is a general form of second-order transfer function state the damping ratio $0 < \zeta < 1$ is an underdamped second-order system. The parameters observed from the step response are %OS, Damping ratio, ζ, resonance frequency, ω_n and peak time, T_p [20].

2.3 Controller Design

The controller algorithms are based on the following.

$$G_{PID}(s) = K\frac{(s+a)(s+b)}{s} \quad (8)$$

where a is obtained from the output response of the nonlinear UUV model. The desired poles and angles to obtain a is as follows:

$$\text{Desired poles: } -\zeta\omega n \pm j\omega n\sqrt{1 - \zeta\ 2} \quad (9)$$

$$\sum \theta_z - \sum \theta_p = -180^{o} \quad (10)$$

K is the overall gain of the open-loop system, which is obtained by multiplying the pole lengths [20].

2.4 Closed-Loop Unmanned Underwater Vehicle

Finally, the closed loop of Unmanned Underwater Vehicle model with a proposed linear controller is obtained as a system:

$$\mathrm{G(s) = G_{LUUV}(s).\,G_{PID}(s)} \quad (11)$$

*Corresponding Author | Mohd Nor, E. | elya@upnm.edu.my

3.0 RESULT AND DISCUSSIONS

This section discussed the output response obtained from the open-loop test of the UUV nonlinear model, performance characterization, design of the controller, and validation of the models. The simulations are carried out using nonlinear model Equation (1) – Equation (2) [17]. The parameters are defined as in Table 3 and simulation is done in Matlab/Simulink (2019a) [17].

Table 1. Underactuated Underwater Vehicle parameters [17]

Parameter	Symbol	Value	Unit
Mass	m	185	kg
Added mass	$X_{u\,\|u\|}$	-30	kg
Added mass	$Y_{v\,\|v\|}$	-80	kg
Damping vehicle	d_{11}	70	
	d_{22}	300	
	d_{33}	150	
Control input for $x-axis$	τ_u	4	
	τ_r	1	
External disturbances	$T_{dn,}\ (n = 12{,}3)$	4	

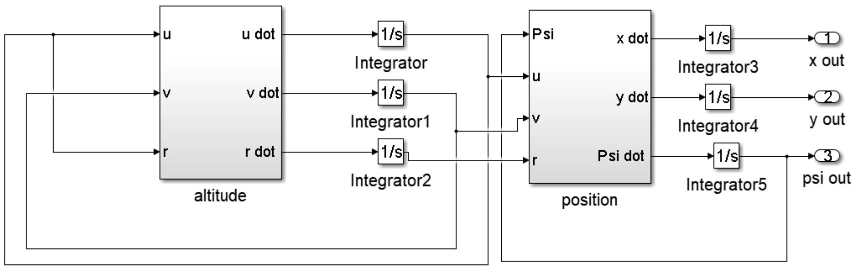

Figure 3. The block diagram of non-linear UUV model developed in Matlab/Simulink

3.1 Open-Loop Performance of Underactuated Underwater Nonlinear Model

The nonlinear UUV mathematical model Equation (1) to Equation (2) is constructed in Simulink. The trajectories obtained from the UUV from the Equation (1) to Equation (2) model are shown in Figure 4. The result shows the horizontal motion of UUV.

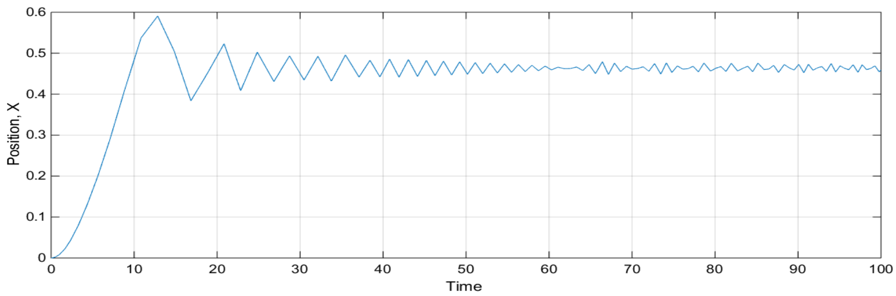

Figure 4. Trajectories of UUV Equation (1) to Equation (2) in the x-axis and y-axis, simulated using MATLAB/SIMULINK

Based on Figure 4, the open-loop response in peak time, settling time, and overshoot percentage is obtained and recorded. The open-loop performance from Figure 5 is displayed in Table 2.

Table 2. Open – Loop Performance of Nonlinear UUV Equation (1) to Equation (2)

Overshoot (%)	Damping ratio	Natural Frequency ω_n	Peak time (s)	Settling time (s)
23	0.4237	0.2757	12.58	34.24

Subsequently, the linearized UUV model is obtained as follows:

$$G_{LUUV}(S) = \frac{0.076}{s^2 + 0.2336s + 0.076} \tag{12}$$

*Corresponding Author | Mohd Nor, E. | elya@upnm.edu.my

The linearized model approximates a second-order system using the general Equation in Equation (3). Figure 5 compares the step response of nonlinear UUV and linearized UUV models.

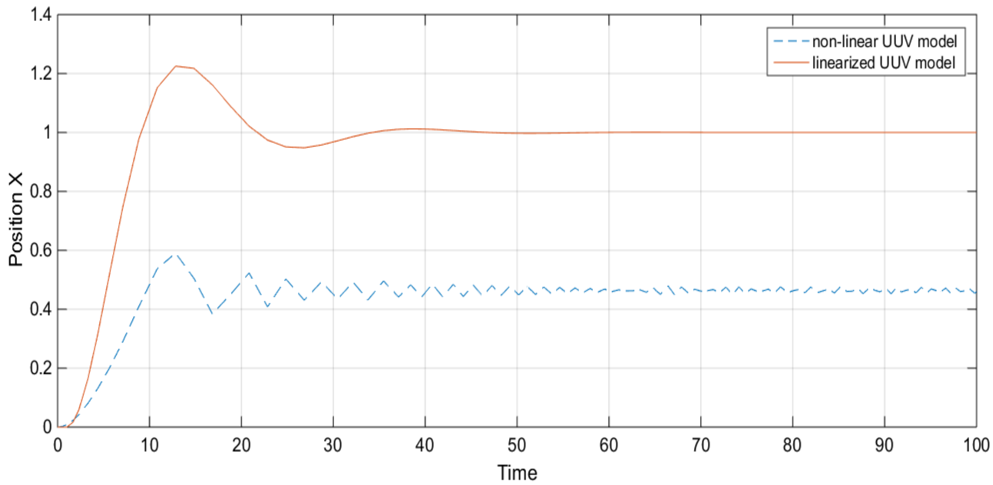

Figure 5. Open-loop step response of Nonlinear UUV Equation (1) to Equation (2) and Linearized UUV model Equation (7)

Based on performance parameters obtained (Table 2), the desired pole of Equation (5) for the UUV is -0.117 ± 0.25i. Meanwhile, the angle formed between the dominant pole and all other poles and zeroes is α=1.674. The transfer function of the PD controller is given by: GPD (s) = K (s + 1.674), where K is the overall gain in the system, which is equal to multiply the pole lengths:

$$K_{overall} = \frac{\pi L_p}{\pi L_z} = \frac{L_{2L_3}}{L_1} \tag{13}$$

.

The calculated gain K is 0.5263. The closed-loop linearized UUV model using the proposed controller based on root locus technique design is graphically shown in Figure 6. The transfer function of the designed PD controller is given by: GPD (s) = K (s + 1.674). The closed-loop block diagram is shown in Figure 3.

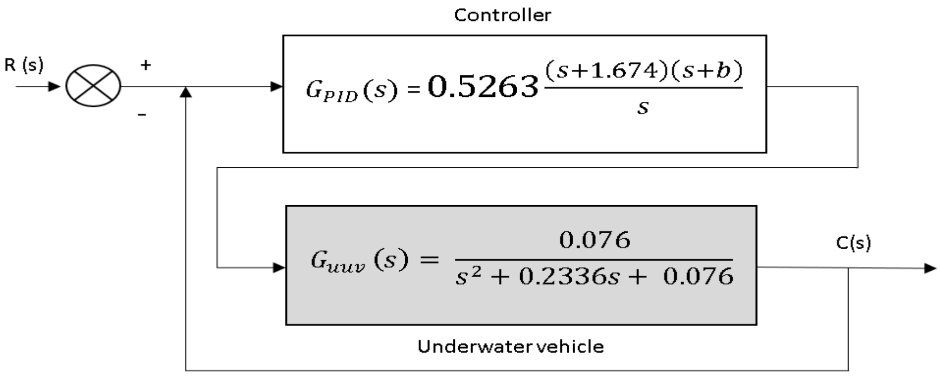

Figure 6: Closed –Loop unmanned underwater vehicle using PID Controller

Table 3. Comparison performance of UUV between a controller and without controller

Performance of Underwater Vehicle	Linearized UUV model without Controller	Linearized UUV model with Controller design using root locus method				
		b = 0.3	b = 0.1	b= 0.02	b = 0.04	b = 0.06
Overshoot (%)	23	82.4	41.9	14.7	22.4	29.5
Settling time (s)	34.24	843	53.3	86	32.6	40.8
Peak time (s)	12.58	10.4	11.8	12.5	12.3	12.2
Gain, K	0.076	0.5263	0.5263	0.5263	0.5263	0.5263
Steady- state error (SSE)	0.53	0	0	0	0	0

*Corresponding Author | Mohd Nor, E. | elya@upnm.edu.my

The best controller design is when a = 1.674 and b = 0.04, which gives the best performance. As a result, the controller is presented as:

$$G_{PID}(s) = \frac{0.5263\ (s^2 + 1.714s + 0.067)}{s} \qquad (13)$$

and

$$G_{PID}(s) = \frac{1}{s}.K_d\left(s^2 + \frac{K_p}{K_i}s + \frac{K_i}{K_d}\right) \qquad (14)$$

The value of proportional gain, *Kp* = 0.9, derivative gain, *Kd* = 0.5263 and integral gain, *Ki* = 0.035 expressed based on Equation (12). Several values are simulated to observe PID's best design value to increase the performance of steady-state response and transient response.

3.2 Closed-Loop Unmanned Underwater Vehicle

The closed-loop block diagram of the UUV model is shown in Figure 7.

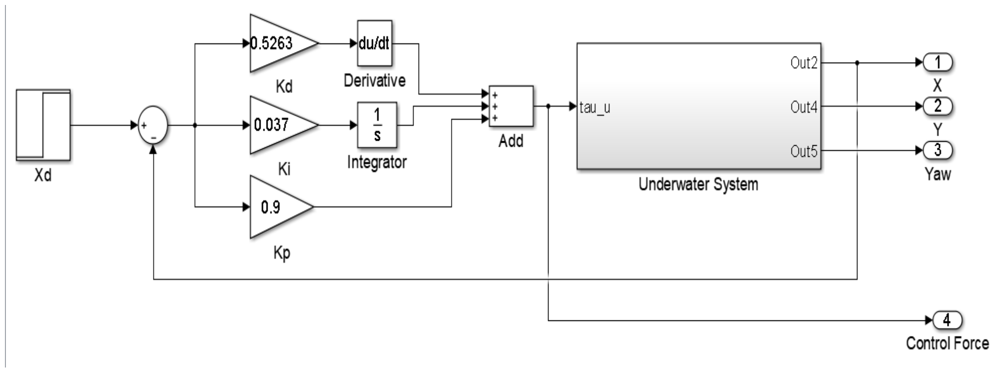

Figure 7: The closed-loop block diagram of nonlinear UUV model Equation (1) to Equation (6)

A response is obtained best with PID 5 is equal to Kp = 185, Ki = 0.7 and Kd = 10. Figure 8 the closed-loop output response using PIC controller Equation (13) and Equation (14) with controller gain Kp = 185, Ki = 0.7 and Kd = 10. The performance of the UUV system in terms of position X and control force for step input 5s is shown in Figure 9. Meanwhile, Figure 10 shows the control torque to obtain the desired response.

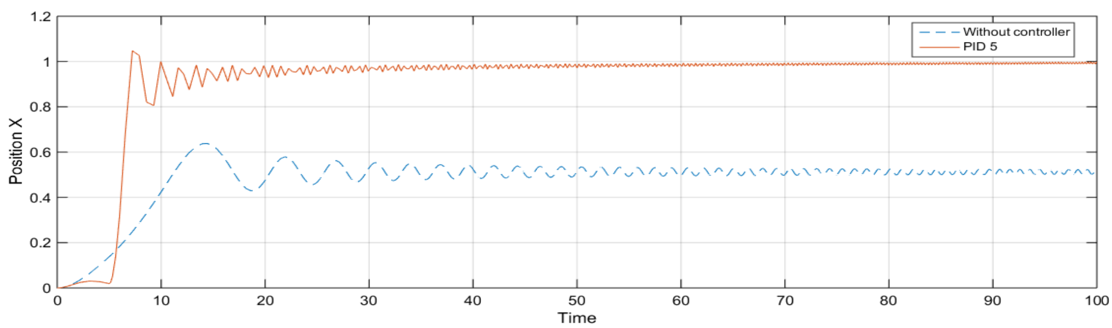

Figure 8. Step response of UUV with controller and without controller

*Corresponding Author | Mohd Nor, E. | elya@upnm.edu.my

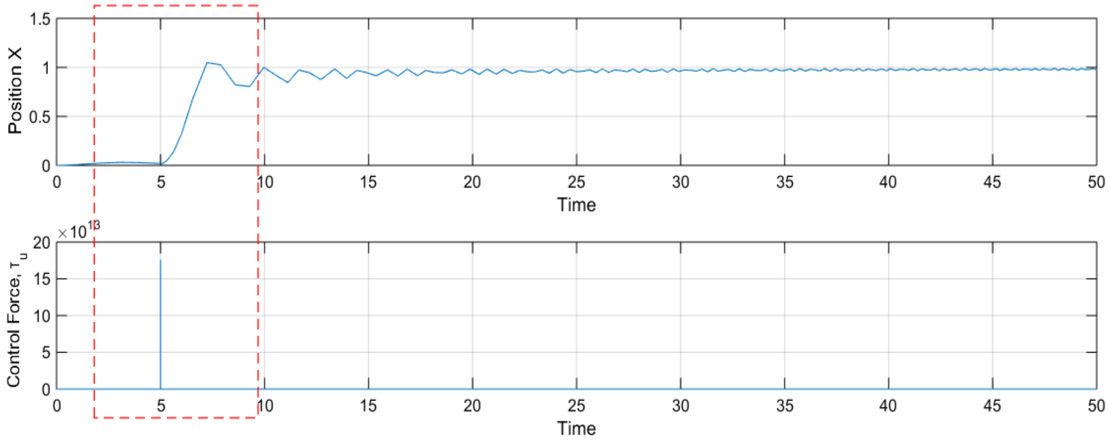

Figure 9. Performance of closed-loop UUV with the proposed controller

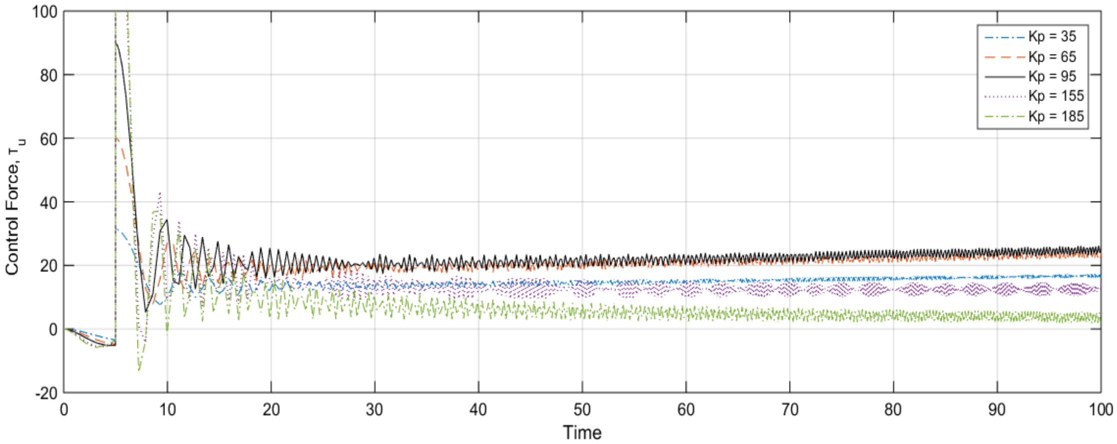

Figure 10. Control force at the transient and steady-state period increase in Kp 35, 65, 95, 155 and 185

4.0 CONCLUSION

The dynamic model of an under-actuated underwater vehicle (UUV) has been successfully developed using SIMULINK. A Second-order step response is obtained. A PID controller is designed using the root-locus technique. The performance of the closed-loop control system is analysed based on transient response and steady-state error. The PD controller alone is sufficient to control the steady-state error and transient response based on the analysis. The result of simulation analysis will be used for tuning the control system in the actual UROV developed. It has been proven that the model was build based on a literature study. A PID controller was proposed that improve the performance of the underwater vehicle in trajectory tracking. The performance of the underwater vehicle with a PID controller was evaluated in terms of overshoot percent, settling time, peak time, and steady-state error. Comparison of performance between underwater vehicle systems with controller and without controller proven the objectives.

5.0 ACKNOWLEDGEMENT

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*Corresponding Author | Mohd Nor, E. | elya@upnm.edu.my