Intelligent Maneuvering of Underwater Vehicle

by

Ting Nguong Seng

14964

Dissertation submitted in partial fulfillment of
the requirement for the
Bachelor of Engineering (Hons)
(Electrical and Electronic)

JANUARY 2015

Universiti Teknologi PETRONAS
32610 Bandar Seri Iskandar
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

____
(DR SYED SAAD AZHAR ALI)

UNIVERSITI TEKNOLOGI PETRONAS
32610 BANDAR SERI ISKANDAR
PERAK DARUL RIDZUAN
JANUARY 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(TING NGUONG SENG)

ABSTRACT

The main goal of this project is to design a controller in such a way that underwater vehicle (UWV) can maneuver automatically when it is subject to underwater disturbances. Nevertheless, short term target for this project is to ensure that the UWV is able to propagate in a straight line forward direction to designated location. This project focuses more on simulation results because the vehicle fails to operate and requires parts replacement. The first part of simulation utilizes the mathematical model. This part concludes that PID controller works the best with pitch control whereas PD controller works the best when coming to heading control. PID controller for pitch controller does not meet the standard performance; hence, it is re-tuned. After five trials, new set of parameters which display astounding results are obtained. Both controllers designed are able to respond to underwater disturbances effectively. The second part of simulation uses real data to estimate the transfer function for the vehicle behavior. A PID controller is designed based on the transfer function and it is proven to work fine with set point changes and disturbances simulated. Only heading data is available, so the simulation for second part focuses on it. The most crucial factor affecting the robot moving in a straight line is heading control. Therefore, this simulation with heading control should be sufficient.

ACKNOWLEDGEMENT

I was grateful to God as He provided me with life and passion to go on with my final year project. He deserves all the glory and praise from me.

I would like to thank Dr. Syed Saad Azhar Ali for his guidance. He had been extremely helpful while I was doing my final year project. I would also like to extend my gratitude to Mr. Musa for lending a hand in fixing the underwater vehicle. Mr. Zaid who is in charge of wave tank also deserves a thank you as he helps me out a lot while I am searching for a place to test the underwater vehicle.

I would also like to take this opportunity to thank my parents who supported me morally. Their advice were important to me as those were the things that kept me going on despite of ordeal I faced in final year project. Nonetheless, I appreciate all effort my good friends have given while I come to a dead end in this project. I hope that all of my friends can do well in future.

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CHAPTER 1

INTRODUCTION

1. UNDERWATER VEHICLE

1.1 Project Background

Underwater vehicle (UWV) is a device or machine that can travel beneath the deep wavy ocean [1], through the fluvial rivers and in other medium consisted of water. The demand for UWV has increased as people start to realize its reliability and advantages in maritime exploration [2-4].

Malaysia is a blessed country with incredibly long coastline: approximately 4700 km for Peninsular Malaysia and about 2000 km for East Malaysia. It is also well known for its rich reserves in fossil fuels. Geoscientists and geologists have suggested that huge reservoirs might be beneath the water bed waiting for brave adventurers to conquer and rip the fortune out of it.

Deep-water exploration for oil and gas is not very alien to oil and gas (O&G) industry in Malaysia. Sophisticated underwater robotics is essential for the deep-sea installations and operations, especially for pipeline corrosion inspection [5]. Such technology is also crucial for hull inspection of ships and vessels docking in Malaysia [6]. These instances lead to the introduction of this project, “Intelligent Maneuvering of UWV”.

1.2 Problem Statement

The motion control of UWV is extremely vital during operation as it will affect the preplanned trajectory line. Regardless of excellent route line chosen, UWV cannot reach a specified target if it has a defective motion mechanism. Underwater, UWV will be subject to several parameters dependent upon the type of weights [7] as well as type of capabilities mounted [8]. Moreover, the hydrodynamic nature appears to be another mountain to climb in delivering a good control for UWV since underwater current [9] and waves will hinder the planned trajectory of the vehicle. Therefore, a good controller is essential for control of vehicle's pitch and heading movement.

1.3 Objective

The main goal of this project is to design a controller in such a way that UWV can maneuver automatically when it is subject to underwater disturbances. Nevertheless, short term target for this project is to ensure that the UWV is able to propagate in a straight line forward direction to designated location.

1.4 Scope

The controller is designed for underwater vehicle, HydroView Max ^{TM}.

CHAPTER 2
LITERATURE REVIEW

2. LITERATURE REVIEW

The utilization of Remotely Operated Vehicle (ROV) has one apparent downside, which is limitation in the distance it can be away from its interface in a drill ship or surveillance vessel. The distance ROV can travel is dependent on the length of the cable associating itself with its interface [10].

Due to the limited mobility and "unintelligence" of the conventional approach, Autonomous Underwater Vehicle (AUV) is expected to carry on ROV's responsibility regardless of various ordeals it needs to go through before becoming mature technology that offshore O&G industry will set the gaze upon.

Currently, researchers started to explore the possibilities of utilizing AUV in aquatic life farm monitoring [11], interior structure checking[12], hazardous area monitoring [13] and ocean life-form survey. Those researches have shown optimistic remarks.

In fact, both ROV and AUV both fall under the category of UWV. The difference is simply that AUV is more "intelligent" than ROV in the sense that it can make decision by itself without needing constant monitoring of a crew. On the other hand, ROV needs constant control from a team of people working together, checking through the camera attached to the vehicle. Disregarding the fact that it is not user-friendly, it lacks of one important functionality: self-pilot mode in case of disconnection [13]. It has been feared that the expensive equipment like UWV will be lost in the vast ocean; therefore, Bo came up with autonomous self-rescue system which aids the owner in retrieving it when the battery level is low or when water isolation fails [14]. All of these actually show the promising sign that ROV will soon give way to AUV in near future.

Argument about the feasibility of AUV comes around when its dynamics becomes a critical fatal point since it is highly nonlinear and time-varying. It is hard to come out with accurate hydrodynamic coefficients [15] because they are subject to change with regard to new route and unpredictable wave behavior. The only solution to this is probably a more versatile controller design that is capable of mitigating such shortcomings.

There have been lots of controllers proposed: conventional Proportional Integral (PI) controller, Proportional-Integral-Differential (PID), Adaptive Neutral Fuzzy Network (ANFN) controller [16], Fractional Order PI controller [17] and others. From those controllers, the most suitable one for HydroView MAX ™ needs to be identified. Otherwise, new controller which is more versatile and adaptive to dynamic environment needs to be designed. PID controller can only work fine in static environment but not when the surroundings are full of noises and disturbances. Mathematical modeling alone has been proven to be insufficient to cater for ever-changing surrounding; thus, fuzzy modeling has been introduced and the result indicates that it does work better [18].

A lot of algorithms are suggested for modeling but the one supposed to work the best will be evolutionary where it can recalculate the course or path [19] to be taken while operation is conducted. This algorithm might be possible to be blended into dynamic modeling [20] to produce even more efficient controller.
Errors will always be present under constantly-altering external condition. Nevertheless, they can be reduced through compensation in Model Reference Adaptive Control (MRAC) [21] manner. This is yet another useful feature to be incorporated into the new controller design should it be needed.

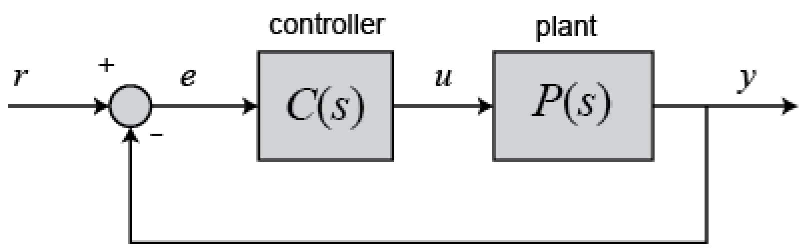
In short, those studies show promising advancement of AUV in becoming conqueror of the ocean. Nonetheless, it will require more improvement and experience before constant enhancement can be made to the technology. More information and innovative ideology are yet to be cultivated and incorporated into the "perfect" controller design for particular task.

From all those previous studies, it can be inferred that a unique controller is needed for each different underwater vehicle depending on the desired control output. In this project, the main character of the day will be HydroView MAX ™. It is an underwater vehicle which is specially designed for salt water environment. The figure below shows how the vehicle looks like.

Figure 1: HydroView Max ™

Among so many controllers, PID seems to be the simplest and perhaps most efficient method to solve most of the real-world control problems. PID control was introduced in 1910 and it started to gain favor of the engineering society after Ziegler-Nicholas tuning methods were brought up [22]. Regardless of variety control schemes, more than 80% of industries are still utilizing controllers which are based on PID theory.

To be brief, PID controller can be treated as three terms, namely proportional, integral and derivative. Hence, it is also known as three-term controller. Considering the unity feedback system below where *r* is reference, *y is output, e* is error, *u* is plant input and at the same time controller output, it actually shows the way PID controller works in a closed-loop system. The error or the difference between the reference value and the output value is sent to the PID controller which will process the integral and derivative of the error. After that, a control signal or corrective output from controller is fed to the plant as input.



Taking $u(t)$ as controller output, the PID algorithm is expressed as:

$$u(t) = K_p\, e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t) \tag{1}$$

where

K_p : Proportional gain

K_i : Integral gain

K_d : Derivative gain

e : Tracking error (Set Point – Process Variable)

t : Time

τ : Variable of integration taking values from time 0 to the present

The transfer function of a PID controller can be obtained by performing Laplace transform of Equation (1), giving

$$C(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d\, s = \frac{K_d\, s^2 + K_p\, s + K_i}{s} \qquad (2)$$

There is term “tuning” when it comes to control system. Tuning refers to the alteration of control parameters such as proportional gain, integral time and derivative time to optimum values so that wanted control response can be achieved.

There are various methods to tune a PID loop. In 1942, Ziegler and Nicholas proposed closed-loop tuning algorithm followed by Cohen and Coon who proposed an open loop tuning method in 1953 [23]. Ziegler-Nicholas method is a proven online method but it involves trial-and-error. It is very aggressive tuning technique. On the other hand, Cohen-Coon method provides good process models. Some mathematical calculations are needed and the technique is offline. Furthermore, it is only good for first-order processes.

Manual tuning is another way too but it requires experienced personnel to do it. The advantage of this method is that it does not require mathematical computation and it is online. One might use the software tools for PID tuning too. Nonetheless, the personnel needs to undergo professional training to be able to use certain software.

Up to date, there are no controllers that match the uncomplicatedness and user-friendliness of PID controller. Due to the great acceptance of PID controllers, academic studies in this area are maturing and this also leads to integration of existing approaches in the software format to further increase the convenience of user in such control [24].

Knowing that there are such good remarks for PID, this project is adopting this control scheme for HydroView MAX ^{TM}. This does not mean that the best controller for HydroView MAX ^{TM} has been determined to be PID. Rather, it is just establishment of a new platform for comparison of controller performance later on when new controller is tested on the vehicle.

CHAPTER 3
METHODOLOGY

3. METHODOLOGY

3.1 Project Plan

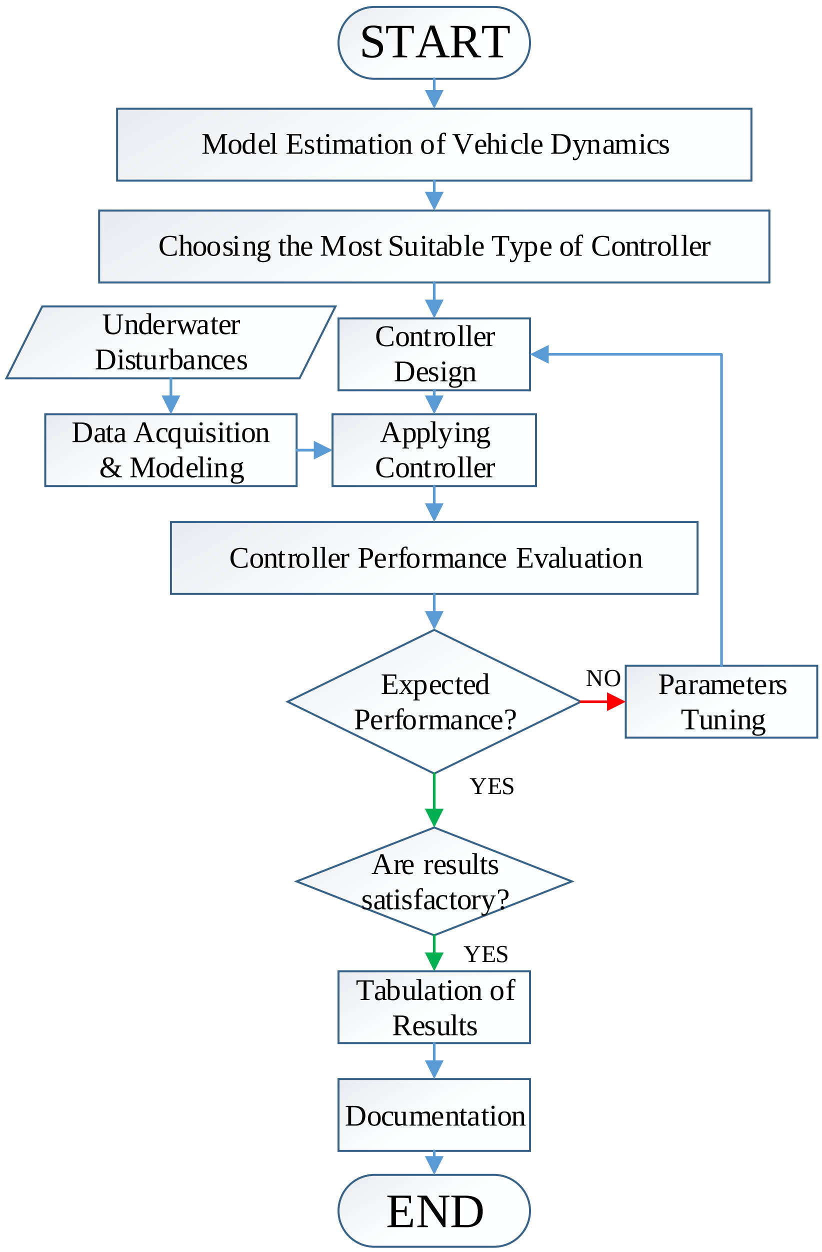


Figure 2: Flowchart of the Project

The flowchart in **Figure 2** shows the detailed plan actions for the final year project. The project kicked off by obtaining estimated mathematical model in the form of transfer function for the vehicle through input-output relationship.

The output was identified to be either pitch angle or heading angle whereas the input was differential thrust applied to the underwater vehicle.

1941 differential thrust inputs and their corresponding heading angle outputs are recorded. Later these data are used to estimate the vehicle's transfer function. After getting the transfer function of the underwater vehicle, it was vital to choose the suitable controller to control both pitch and heading angles. Simulation was carried out to determine the most suitable type of controller for each system. Two systems were there: one is for pitch control while another is for heading control.

After getting the controller design parameters like proportional, integral and derivative gains, underwater disturbances were included to test the controller performance in responding to them. If the performance did not meet the expectation, the controller designed had to be retuned for better performance. The evaluation parameters were the closed-loop stability, rise time, settling time and overshoot of the system.

If the desired performance was met, the results were tabulated. Verification was performed using another set of input to check whether or not the controller was able to perform consistently. Documentation is the final task to keep all the results in record so that the next researcher or the public can refer to the paper should they need insight or information related to the topic.

3.2 Project Key Milestones

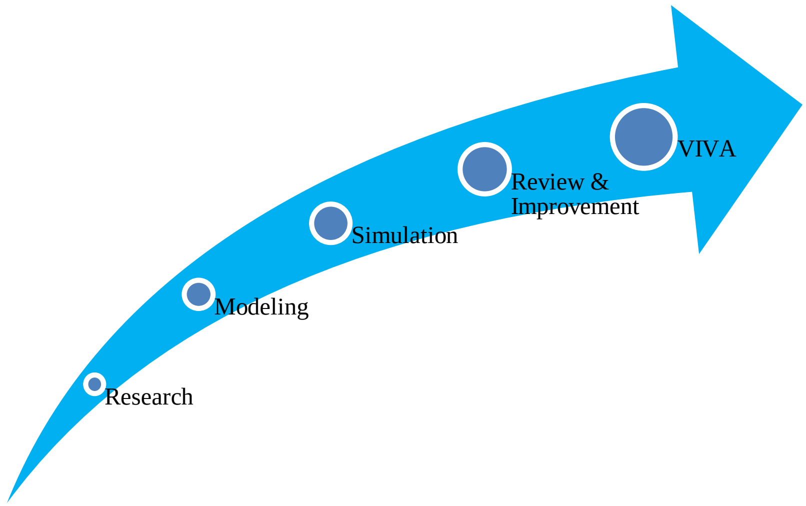


Figure 3: Milestones

There are five key milestones identified in this project. Firstly, literature review needs to be done to understand more about controller design. After that, input and output data need to be obtained to model the vehicle dynamics. Coming up next is actually design of suitable controller. After that simulation is performed with MATLAB software. Improvement (parameters tuning) had been carried out to upgrade the performance of the controller designed. Four milestones have been achieved to date. VIVA presentation will be in Week 15 (during study week).

3.3 Project Timeline (Gantt Chart)

No.	Detail	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Research														
2	Modeling														
3	Controller Design														
4	Simulation														
6	Improvement														
7	ELECTREX														
8	VIVA														

Table 1: Gantt chart

The research needs to be conducted throughout the project so that improvement can be done from time to time. Modeling refers to obtaining transfer function of the plant for the vehicle through input-output relationship which is followed by controller design. Simulation results are obtained and improvement will be carried out to improve the controller performance.

ELECTREX is over and the next stage is VIVA during Week 15. The project does not fall behind the schedule of the plan. Therefore, the targets set in Gantt chart are met.

The nature of this project is more than just merely simulation at first. However, there has been technical problem occurring to the underwater vehicle which requires parts replacement and troubleshooting. This leads to the product of this project to have simulation results only. The controller has yet to be interfaced with the underwater vehicle.

CHAPTER 4

RESULTS & DISCUSSION

4. SIMULATION

4.1 Simulation with Mathematical Model

First of all, it is very important to know about types of system to be controlled. In this project, two systems involved are pitch control system and heading control system.

Pitch Control System

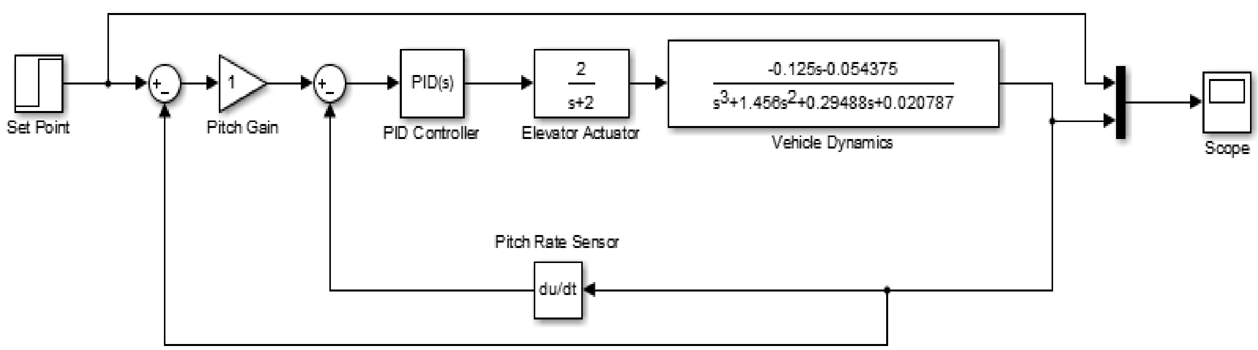


Figure 4: Overview of Control System for Pitch Angle

Before introducing disturbance to the system, the controller is designed and tested on the system.

Different types of controller will be applied to determine which one is giving the best performance. Several types of controller are tested. Among them are proportional (P), proportional - integral (PI), proportional - derivative (PD) and proportional-derivative-integral (PID).

The equation used for the PID controller for MATLAB is

$$P + I\frac{1}{s} + D\frac{N}{1 + N\frac{1}{s}}$$

where

P : proportional gain

I : is integral gain

D : derivative gain

Note: "N" refer filter coefficient for derivative (D) for the rest of the context

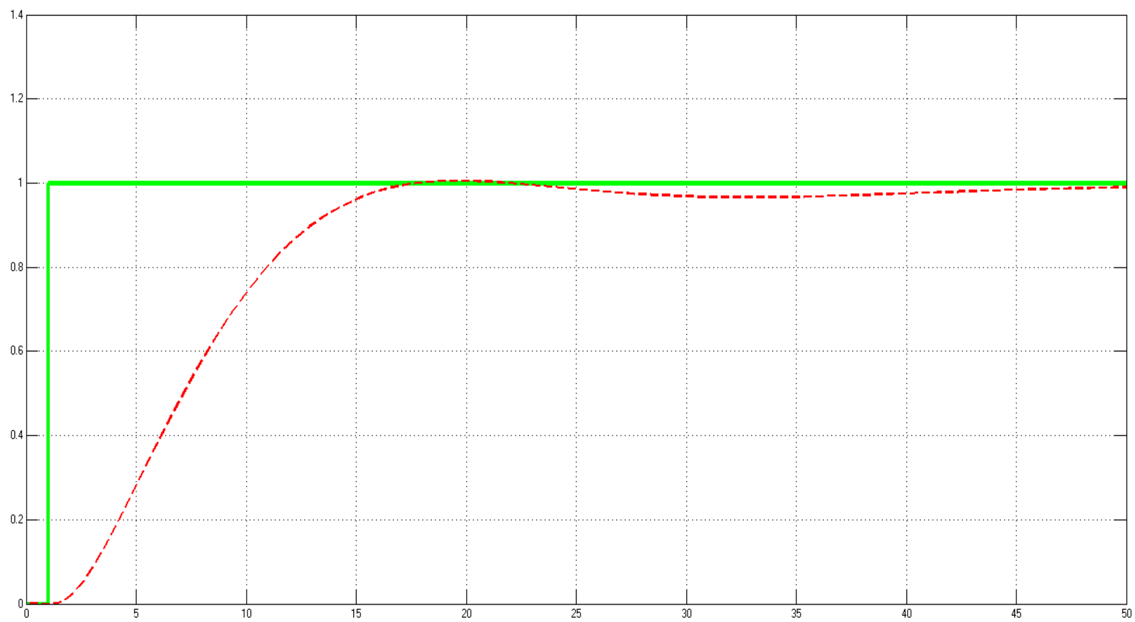


Figure 5: Simulation Result of PID-Controller (Pitch)

The graph in Figure 5 shows the simulation result of PID-controller implemented on the pitch control system. The green line is a step input being fed as a set point or normally known as reference. The red line shows the performance of the controller trying to reach desired value (set point value).

Controller Parameters	Gain
P	-0.7817
I	-0.059785
D	-0.40192
N	0.20456

Table 2: Parameter for PID-Controller (Pitch)

The performance of the controller can be evaluated based on certain criteria such as rise time, settling time, overshoot, peak, and closed-loop stability.

Criteria	Value
Rise time	8.18 seconds
Settling time	40.6 seconds
Overshoot	6.03%
Peak	1.06
Closed-loop stability	Stable

Table 3: Performance of PID-Controller (Pitch)

For this PID controller, the rise time is less than 10 seconds while the settling time is about 40 seconds. It has a small overshoot of 6.03% which within acceptable range. This controller has attained most important element – stability. Hence, this controller can be put into use.

While designing for P-controller, it is found out that it cannot attain closed-loop stability. Therefore, this option is taken out of the list of consideration

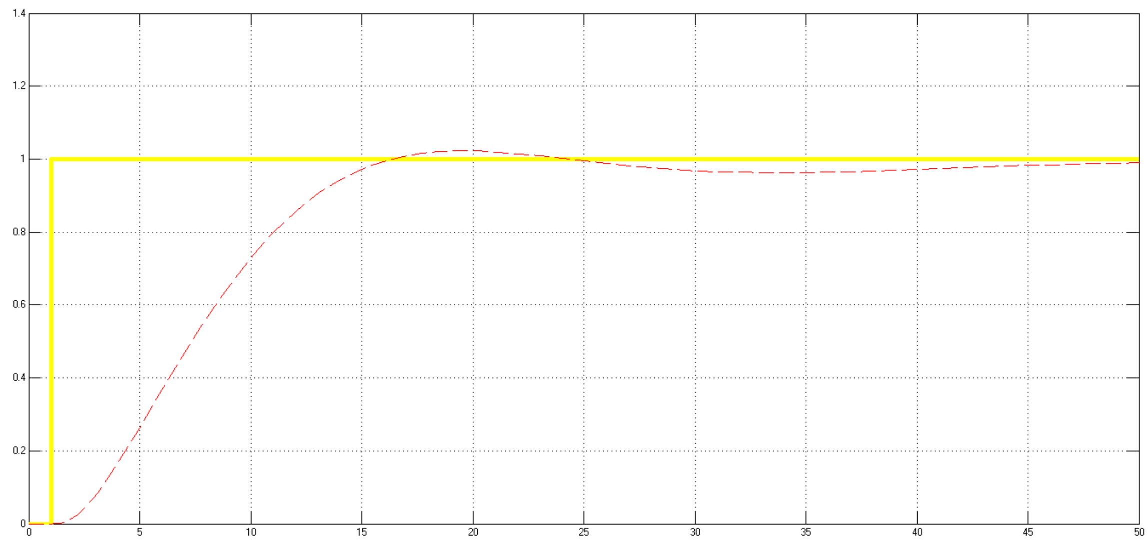


Figure 6: Simulation Result of PI-Controller (Pitch)

The simulation curve above is for PI-controller. The yellow line is a step input being fed as a set point or normally known as reference. The red line shows the performance of the controller trying to reach desired value (set point value). It shows slight and insignificant difference compared to PID-controller.

The PI-controller parameters and its performance criteria are shown in Table 4 and Table 5 respectively.

Controller Parameters	Gain
P	-0.7817
I	-0.059785
D	0

Table 4: Parameters for PI-Controller (Pitch)

Criteria	Value
Rise time	8.19 seconds
Settling time	41.7 seconds
Overshoot	6.03%
Peak	1.08
Closed-loop stability	Stable

Table 5: Performance of PI-Controller (Pitch)

The only difference is a slight increase in rise time and peak. The settling time for PI-controller is 1.1 second more than PID-controller. Other aspects are the same. Here, it can be easily determined that PID-controller works better for this underwater vehicle rather than PI-controller.

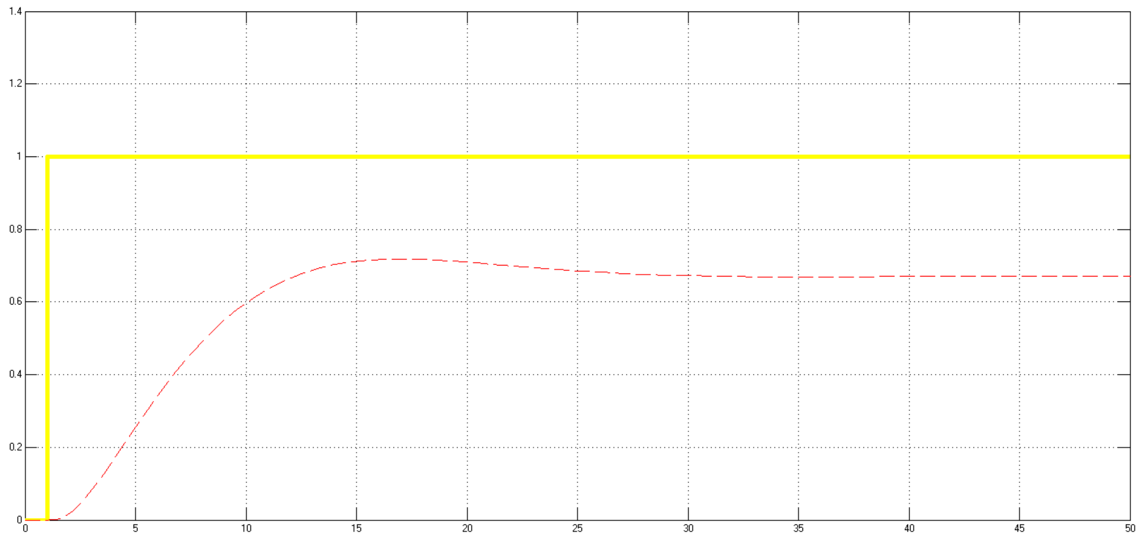


Figure 7: Simulation Result of PD-Controller (Pitch)

The simulation curve above is for PD-controller. The yellow line is a step input being fed as a set point or normally known as reference. The red line shows the performance of the controller trying to reach desired value (set point value). Great difference can be observed from the graph. **PD-controller does not eliminate the steady-state error**.

Controller Parameters	Gain
P	-0.7817
I	0
D	-0.40192
N	0.20456

Table 6: Parameters for PD Controller (Pitch)

Criteria	Value
Rise time	6.42 seconds
Settling time	23.1 seconds
Overshoot	11.6 %
Peak	0.75
Closed-loop stability	Stable

Table 7: Performance of PD-Controller (Pitch)

Although the closed-loop is stable and it has faster response time compared to both PID and PI controllers, it has overshoot of 11.6 % besides not attaining steady-state. This controller is not suitable for pitch control as it does not give desired accuracy (due to the fact that steady-state error is present).

A small conclusion here is that PID-controller has so far appears to be the most well-balanced and promising controller.

Heading Control system

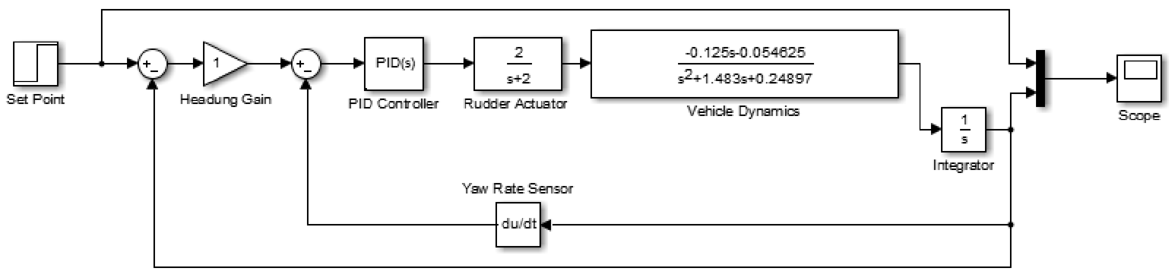


Figure 8: Overview of Control System for Heading Angle

A set point or reference is fed to the system to test the controller performance similar to pitch control. The difference this time is the addition of an integrator following vehicle dynamics block.

The parameters for PID controller are tabulated in the table below.

Controller Parameters	Gain
P	-2.8201
I	-0.07027
D	-6.7709
N	0.75753

Table 8: Parameters for PID-Controller (Heading)

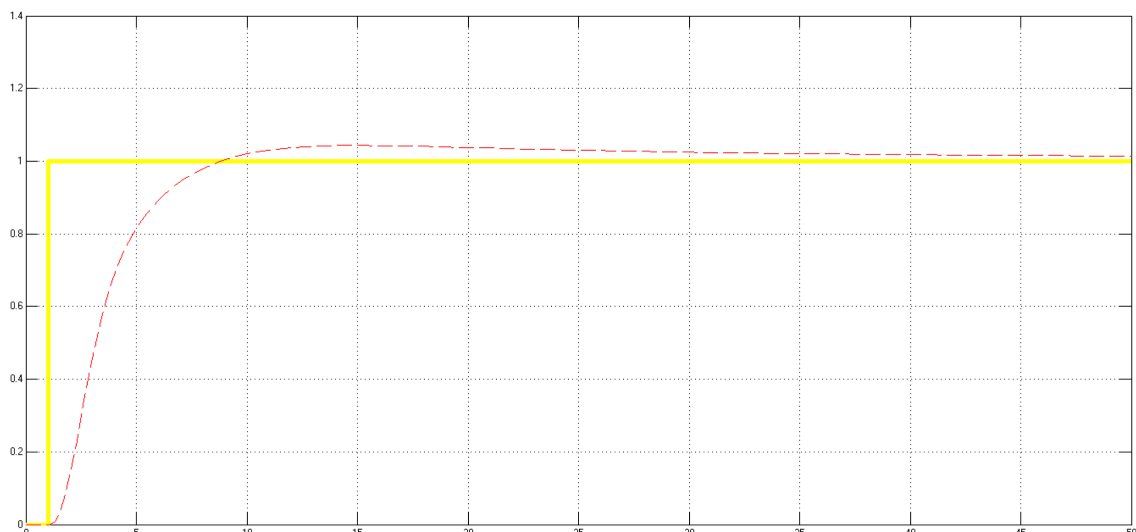


Figure 9: Simulation Result of PID-Controller (Heading)

The graph in Figure 9 shows the simulation result of PID-controller implemented on the heading control system. The yellow line is a step input being fed as a set point or normally known as reference. The red line shows the performance of the controller trying to reach desired value (set point value).

Criteria	Value
Rise time	2.14 seconds
Settling time	33.4 seconds
Overshoot	11 %
Peak	1.11
Closed-loop stability	Stable

Table 9: Performance of PID-Controller (Heading)

The results are good as it gives really short rise time, meaning that the controller is able to respond to the set-point change quickly. This is very important to obtain vehicle heading control of high accuracy. Although the overshoot is more than 11%, the closed-loop is stable. Before jumping straight to conclusion that this is the best controller for heading control, performance of other controllers needs to be observed and considered.

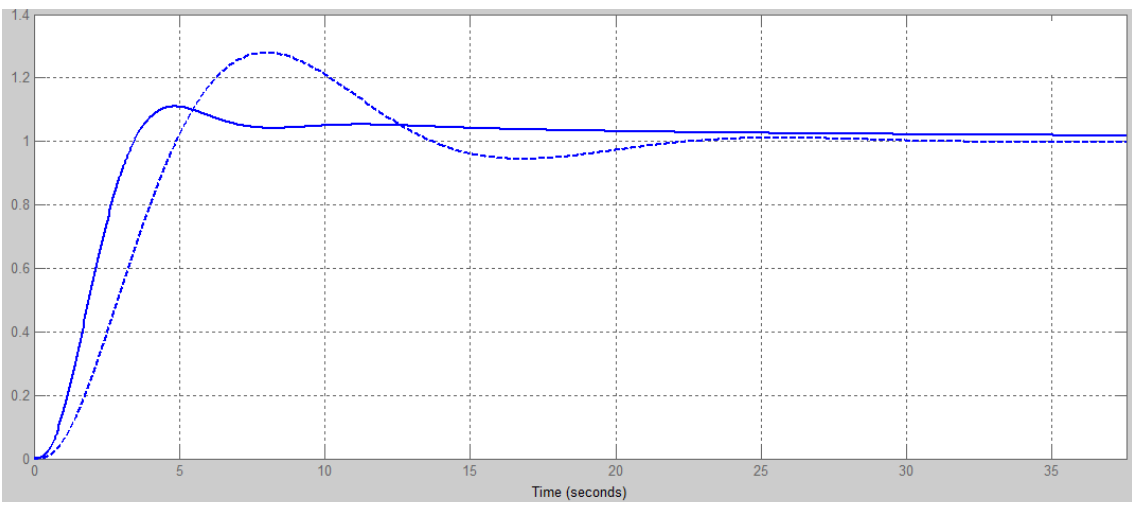


Figure 10: Simulation Result of P-Controller (Heading)

The graph above shows the simulation result of P-controller implemented on the heading control system. The dashed line shows the response of the P-controller whereas the continuous line shows the response of PID-controller. It is easier to compare the performance of both controllers this way.

From the graph, it is obvious that P-controller has greater overshoot and the percentage is 27.9 Compared to PID-controller, P-controller requires slightly more time for it to rise but it settles down faster.

Controller Parameters	Gain
P	-2.8201
I	0
D	0

Table 10: Parameters for P-Controller (Heading)

Criteria	Value
Rise time	3.16 seconds
Settling time	20.6 seconds
Overshoot	27.9 %
Peak	1.28
Closed-loop stability	Stable

Table 11: Performance of P-Controller (Heading)

P-controller has a larger overshoot (more than 20%). The overshoot is a concern here since the deviation from the steady-state value is best not to exceed 10%. Otherwise, it is deemed aggressive but indefinite controller. Both are having stable closed-loop. In overall view, PID is still more preferable since it has less overshoot and fast response to changes in reference input.

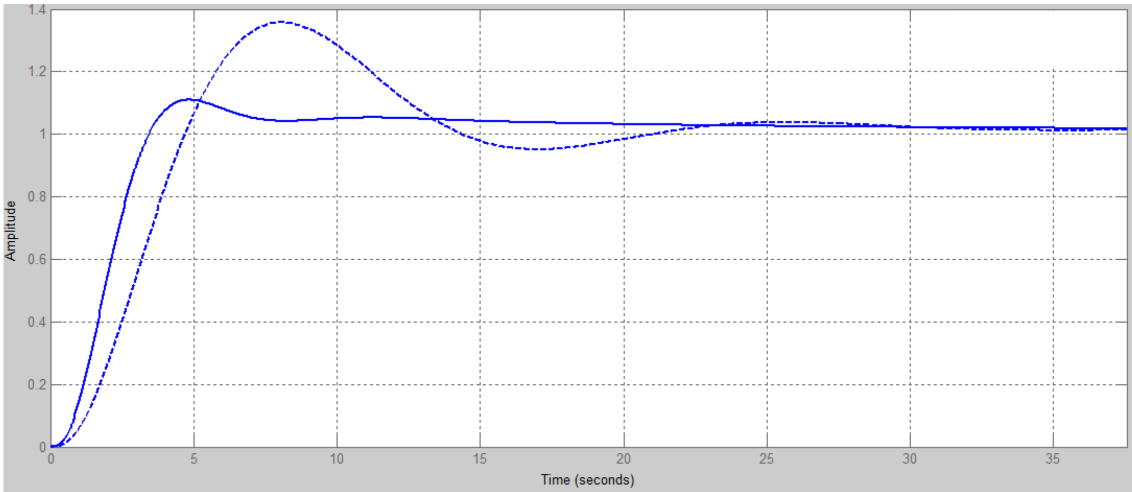


Figure 11: Simulation Result of PI-Controller (Heading)

Figure 8 shows the comparison between PID (smooth line) and PI (dashed line) controllers. PI also has a large overshoot similar to P controller.

Controller Parameters	Gain
P	-2.8201
I	-0.07027
D	0

Table 12: Parameters for PI-Controller (Heading)

Criteria	Value
Rise time	3.02 seconds
Settling time	30.8 seconds
Overshoot	35.8 %
Peak	1.36
Closed-loop stability	Stable

Table 13: Performance of PI-Controller (Heading)

PID still has an edge over its rise time and low overshoot value. PI is also stable in term of closed-loop. It is obvious that PI is no match for PID in term of performance for this case.

Moving on to PD-controller, Figure 12 shows the slight difference for both controllers. The dashed-line refers to PD while another one belongs to PID controller. PD has lower overshoot compared to PID and seems to have shorter settling time.

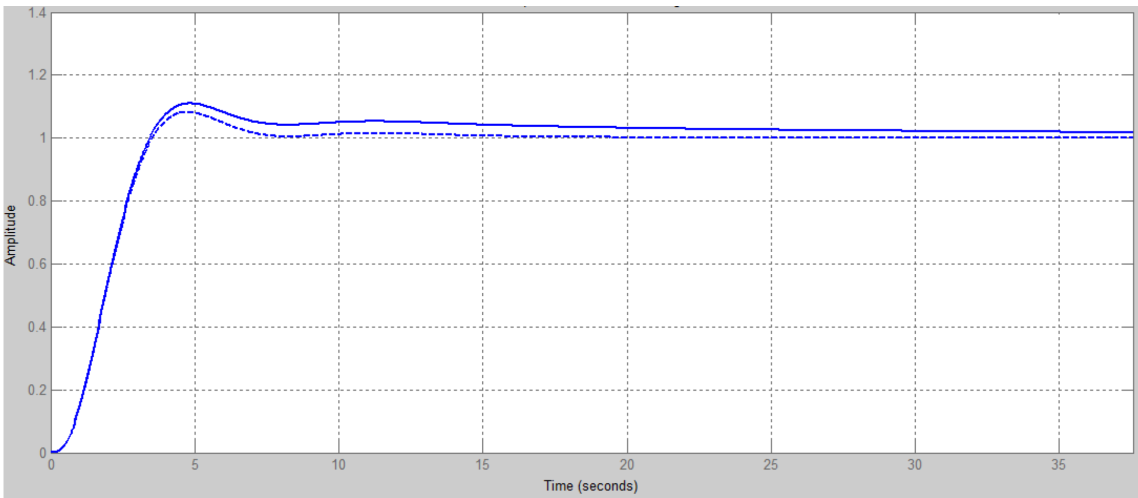


Figure 12: Simulation Result of PD-Controller (Heading)

Controller Parameters	Gain
P	-2.8201
I	0
D	-6.7709
N	0.75753

Table 14: Parameters for PD-Controller (Heading)

Criteria	Value
Rise time	2.18 seconds
Settling time	6.85 seconds
Overshoot	8.24 %
Peak	1.08
Closed-loop stability	Stable

Table 15: Performance of PD-Controller (Heading)

PD-controller display similar time to pick up with the set point value yet it is able to beat PID in term of settling time. PID takes way too long (33.4 seconds) to settle down while PD only takes 6.85 seconds. Moreover, PD has even less overshoot (8.24 %) which is less than the standard of 10 %. One thing left to verify is its stability and it passes the test too.

In a nutshell, PD controller has shown remarkable performance in all those criteria and thus it is the best controller for heading control system.

PID Tuning

After choosing suitable types of controllers for both systems, it is found out that the controller for pitch control is not having satisfactory performance. Therefore, the controller parameters need to be altered to be more efficient.

Firstly, the response time for the pitch control is still too long. Settling time takes more than 40 seconds and that is a good controller. Therefore, to reduce settling time, we need to increase the value of derivative gain, "D". Multiplication of 4 is performed to the previous D value.

After changing the D from -0.40192 to -1.6, the following graph is obtained. Dashed line is for D = -1.6 while the continuous line is for D = -0.40192. One obvious thing that can be observed is that the overshoot has dropped significantly.

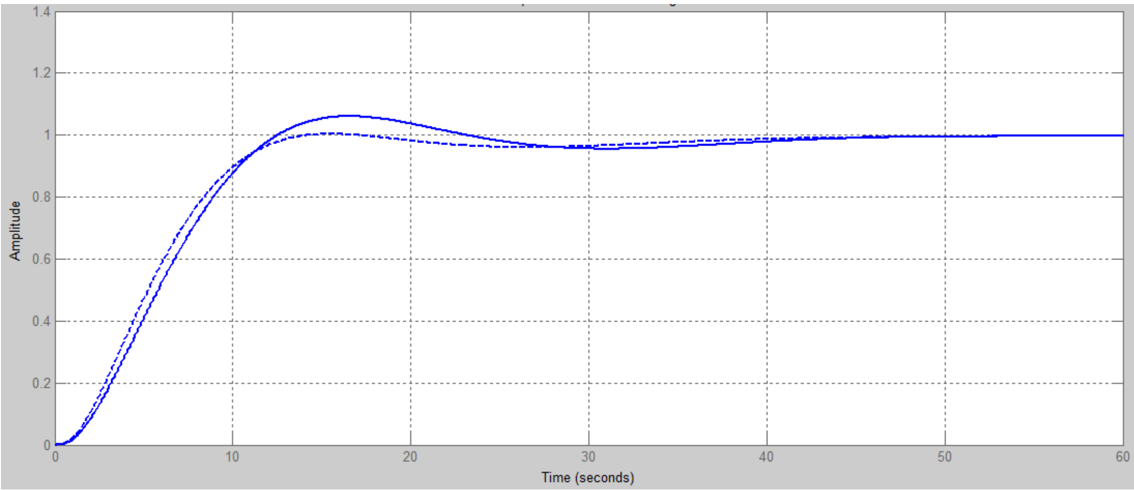


Figure 13: Tuning of PID-Controller (Pitch) – Trial One

Criteria	Value (before)	Value (after)
Rise time	8.18 seconds	8.1 seconds
Settling time	40.6 seconds	36.4 seconds
Overshoot	6.03 %	0.34 %
Peak	1.08	1
Closed-loop stability	Stable	Stable

There is slight decrease in rise time. Settling time, on the other hand, has declined significantly. Closed-stability retains.

It still takes quite long response time. This time, derivative gain is altered to -3.2.

Criteria	Value (before)	Value (after)
Rise time	8.1 seconds	7.9 seconds
Settling time	36.4 seconds	34.7 seconds
Overshoot	0.34 %	0.121 %
Peak	1	1
Closed-loop stability	Stable	Stable

Rise time, settling time and overshoot have decreased. To further reduce the rise time, proportional gain is altered from -0.781697 to a new value of -1.56 (previous gain value multiplied by two).

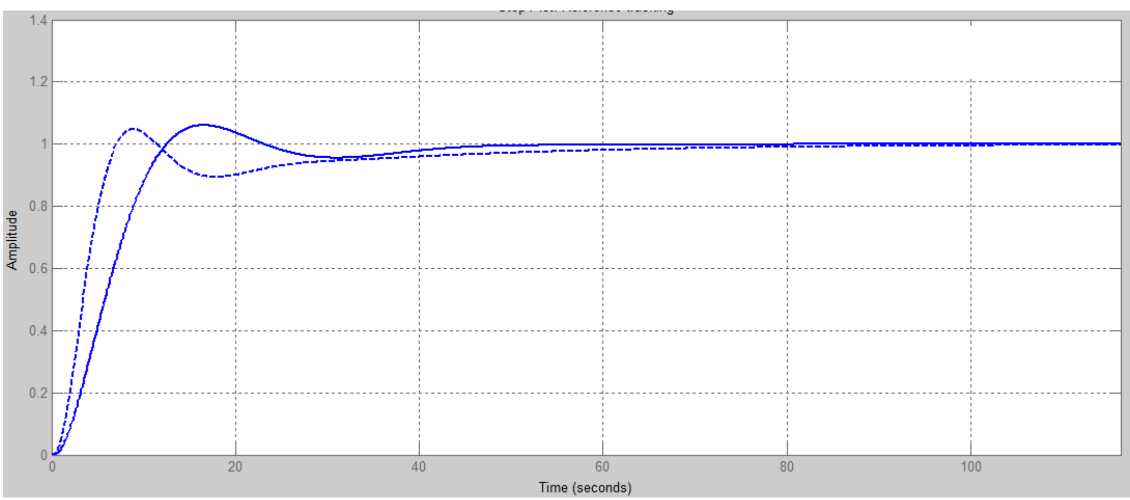


Figure 14: Tuning of PID-Controller (Pitch) – Trial Two

Criteria	Value (before)	Value (after)
Rise time	7.9 seconds	4.44 seconds
Settling time	34.7 seconds	59.7 seconds
Overshoot	0.121 %	4.76 %
Peak	1	1.05
Closed-loop stability	Stable	Stable

The rise time is recued almost by half but the settling time increases. Overshoot is still within the acceptable limit of less than 10% and the system is still stable.

The settling time is back to high value. Since P, I and D are dependent on each other and changing one variable might have effect on the other two, it is speculated that integral gain, "I" needs to be changed too.

The new value of "I" is set to twice of the previous one, which is approximately -0.1. The following graph shows the difference between original PID before tuning (continuous line) and current PID after tuning (dashed line).

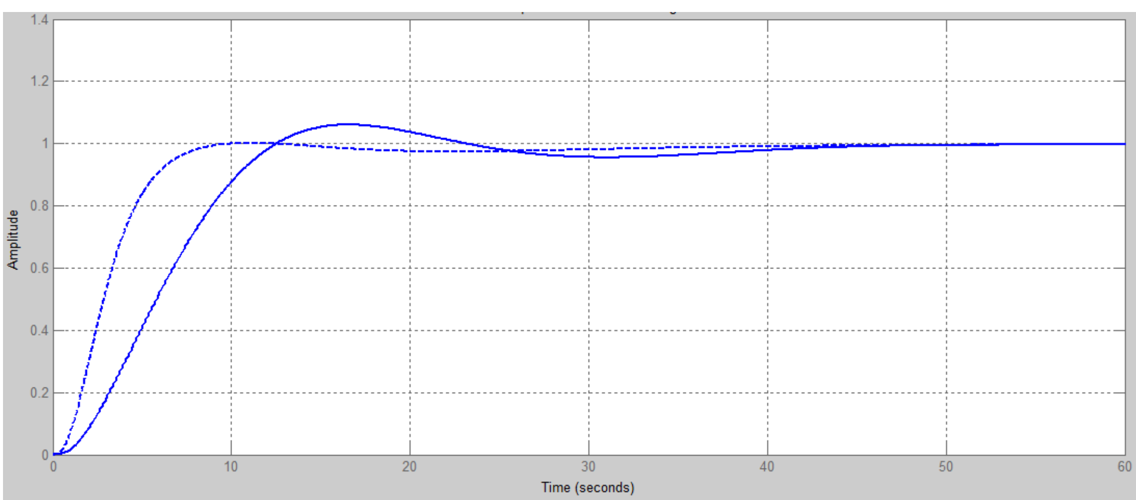


Figure 15: Tuning of PID-Controller (Pitch) – Trial Three

Criteria	Value (before)	Value (after)
Rise time	4.44 seconds	4.64 seconds
Settling time	59.7 seconds	29.5 seconds
Overshoot	4.76 %	0.119 %
Peak	1.05	1
Closed-loop stability	Stable	Stable

This PID is so much better than before. To make the effort of proportional gain less, the magnitude is reduced by 0.2 to see the effect.

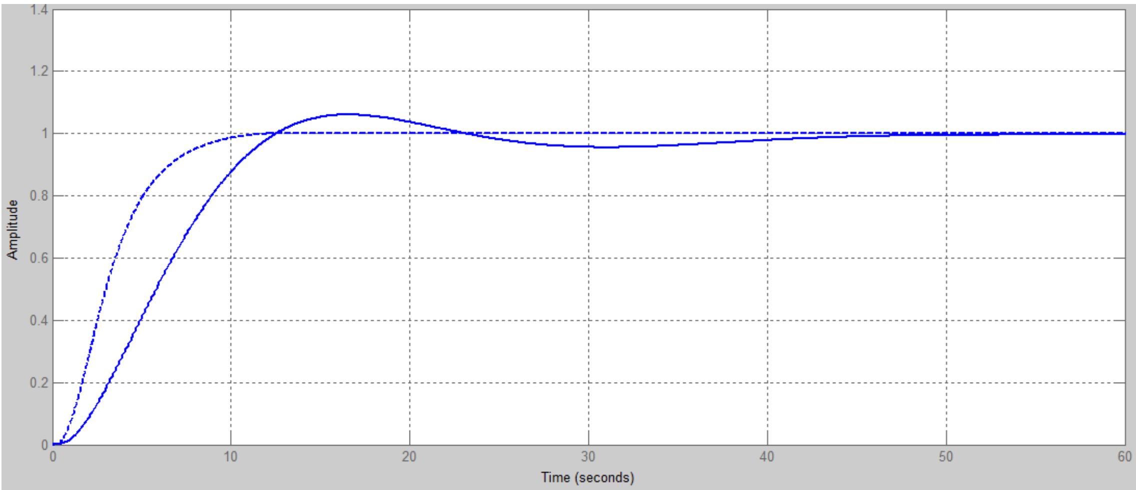


Figure 16: Tuning of PID-Controller (Pitch) – Trial Four

The effect is better than expected. Rise time decrease and overshoot decrease significantly. The system is still stable and the tuning result obtained so far is favorable.

Criteria	Value (before)	Value (after)
Rise time	4.44 seconds	5.4 seconds
Settling time	59.7 seconds	9.54 seconds
Overshoot	4.76 %	0.148 %
Peak	1.05	1
Closed-loop stability	Stable	Stable

Hoping to get even better result, the derivative gain magnitude is reduced by 0.2.

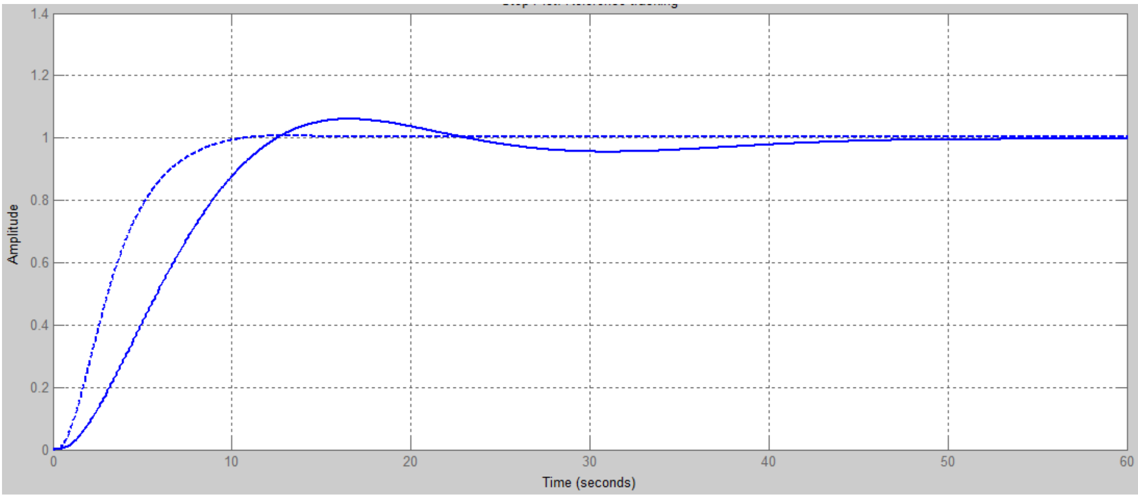


Figure 17: Tuning of PID-Controller (Pitch) – Trial Five (Final)

Criteria	**Value (before)**	**Value (after)**
Rise time	5.4 seconds	5.38 seconds
Settling time	9.54 seconds	9.09 seconds
Overshoot	0.148 %	0.759 %
Peak	1	1.01
Closed-loop stability	Stable	Stable

Now the result obtained is deemed good. After tuning, the new parameters for pitch controller is

Controller Parameters	**Gain**
P	-1.36
I	-0.10
D	-3.00
N	0.75753

Verification

When introducing disturbances, the following response is obtained. The *y*-axis refers to the output angle in radians whereas the *x*-axis refer to time in seconds. The yellow line refers to the reference angle or desired pitch angle input. The red line represents the output angle. The line in teal color is actually the underwater disturbances simulated to test the controller's effectiveness.

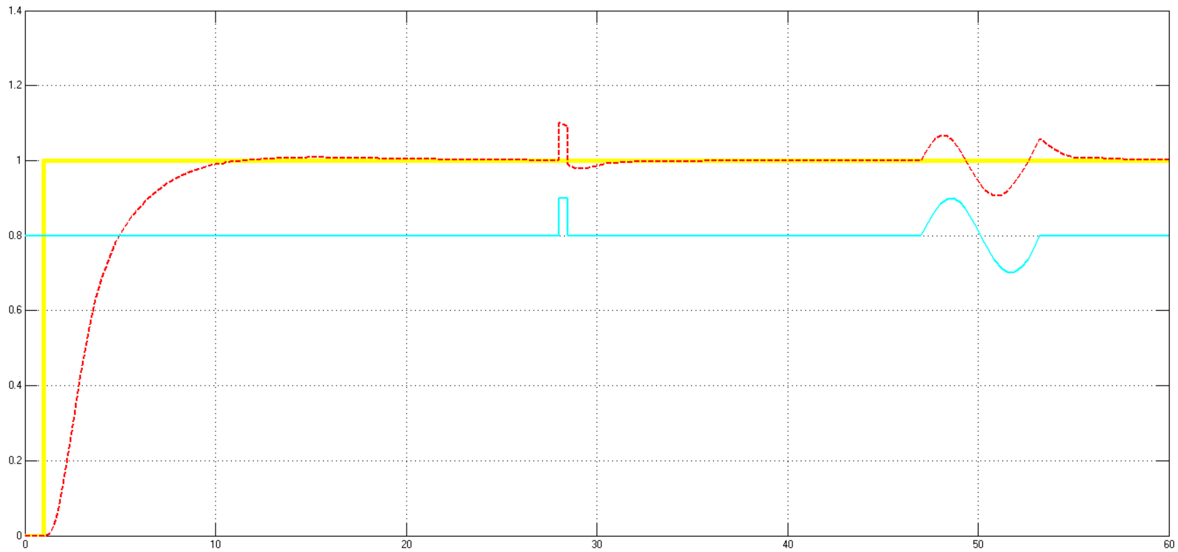


Figure 18: Controller Response with respect to Set-point Change and Underwater Disturbances (Pitch)

From the graph, it can be seen that two types of water disturbances have been added to the system and the controller is able to respond to them effectively. The controller is able to respond to set-point change fast enough too.

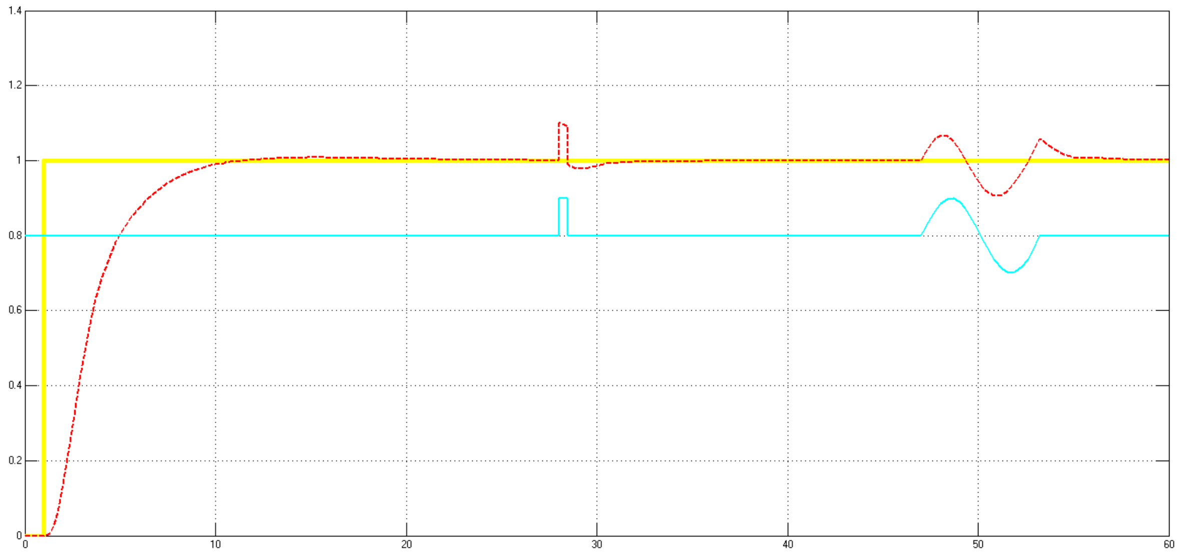


Figure 19: Controller Response with respect to Set-point Change and Underwater Disturbances (Heading)

The response of heading controller is similar to that of pitch. It is able to reject disturbances effectively too not to mention its capability to catch up with change in set-point value.

4.2 Simulation with Real Data

1941 differential thrust inputs and their respective heading angle outputs are recorded. Later, those data are used to estimate the vehicle's transfer function. Those data are not put in appendices because of the vast numerical information. Should any clarification or data inquiry is wanted, one can contact author for it.

Using system identification tool in MATLAB, the transfer function of the underwater vehicle can be estimated. The following shows the transfer function estimated by the software.

```
From input "u1" to output "y1":
  3.826e-05 s - 4.474e-08
----------------------------
s^2 + 0.001667 s + 9.098e-18
```

A new PID controller needs to be designed for new transfer function obtained from the real data.

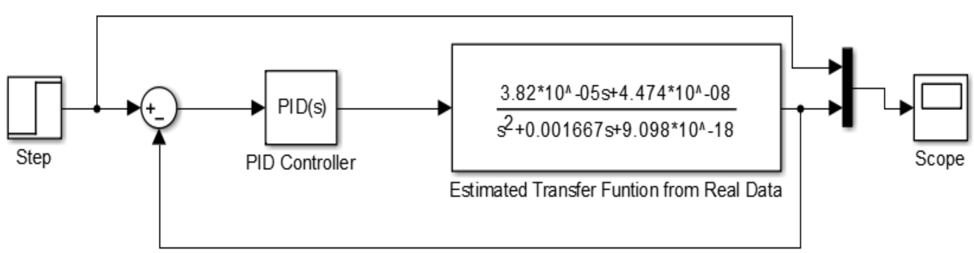


Figure 20: PID Controller for Real Data Vehicle System (Heading)

The controller parameters obtained from the software are:

Controller Parameters	Value
P	28816.77
I	253.1951
D	-13574.0712
N	2.1229

These PID parameters give a good result. Therefore they do not need to be re-tuned.

Criteria	Value (before)	Value (after)
Rise time	174 seconds	1.36 seconds
Settling time	1490 seconds	4.19 seconds
Overshoot	89.7 %	5.67 %
Closed-loop stability	Stable	Stable

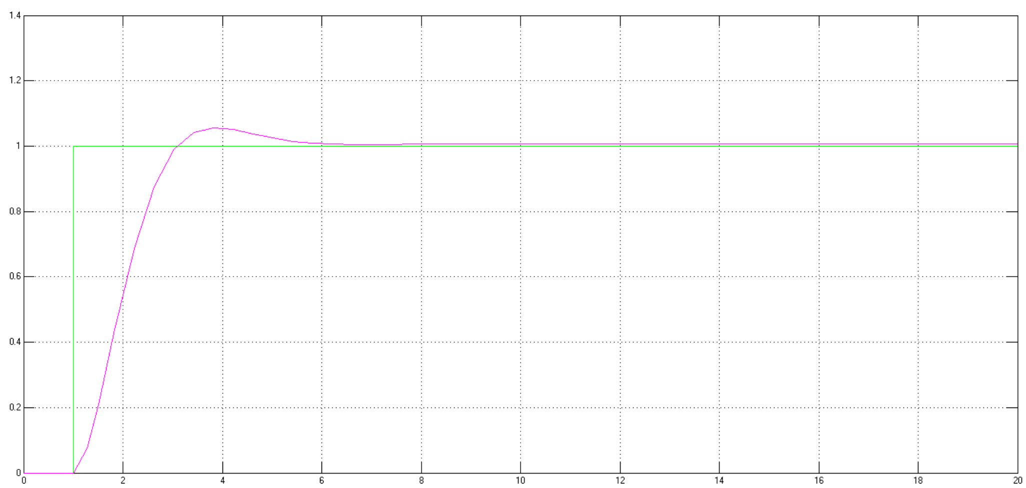


Figure 21: PID Controller Response for Real Data Vehicle System (Heading)

In Figure 21, the green line indicates the reference step signal whereas the purple line shows the actual output of the system after implementing PID control. The overall result is good.

Since only heading data is in hand, the simulation only stops at this aspect. Nevertheless, the most crucial factor affecting the robot moving in a straight line is heading control. Therefore, this simulation should be sufficient. In the future, data should be taken for pitch control with relevant controller implementation for more precise control.

The controller response towards set point change and disturbances needs to be tested and verified too. Therefore, the underwater disturbances block is added to the SIMULINK.

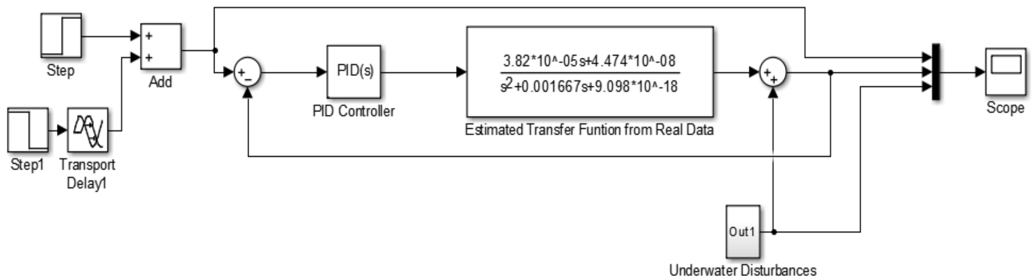


Figure 22: PID Controller Simulation with Added Set Point Changes and Water Disturbances for Real Data Vehicle System (Heading)

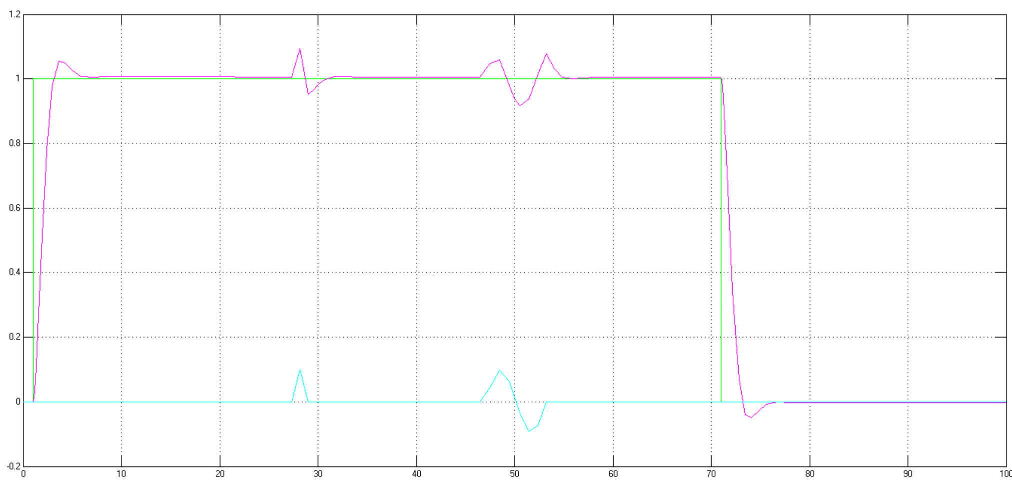


Figure 23: PID Controller Response for Real Data Vehicle System with respect to Set-point Change and Underwater Disturbances (Heading)

From Figure 23, it can be seen that the PID controller can adapt and respond to both set point changes and disturbances simulated quite well. The green line indicates the set point or reference value whereas the teal line shows the disturbances introduced. The purple line is the output response. It can be said that the controller designed for heading control is having laudable performance. The objective of the project is achieved.

CHAPTER 5
CONCLUSION

5. CONCLUSION

For simulation with mathematical model, two controllers have to be designed for both pitch and heading control systems of underwater vehicle. Comparison is done between P, PI, PD, and PID controllers for their performance in responding to the set-point changes. For pitch control, PID is proven to be the most balanced controller to take the task. On the other hand, PD-controller is verified to be the most versatile controller excelling in all assessment criteria when it comes to heading control. The controller chosen for heading control has laudable performance. Nonetheless, PID-controller for pitch controller does not meet the standard performance. Hence, it needs to be tuned. After five trials, new set of parameters which display astounding results are obtained. The controllers now are able to adapt to the new changes of reference value and are capable to settle now in less than 10 seconds. Both controllers have overshoot percentage which is less than 1% (although less than 10% is acceptable). Last but not least, they are stable in closed-loop. For simulation with real data of heading angle with respect to differential thrust input, the transfer function of the vehicle is estimated with the aid of MATLAB system identification toolbox. Auto-tuning gives the PID controller parameters and since those parameters give satisfactory results, there is no need to re-tune the parameters. While set point changes and disturbances are introduced, the PID is still able to handle and give corrective response through the system. This actually proves that the objective of the project is achieved. However, the results obtained are accurate in term of simulation. Experiment is suggested to be carried in the vast ocean for real-time simulation to gather more data in improving the controller for future work. It is also suggested that future researcher can go for U-model, which is a predictive controller model while opting for better controller since it is more adaptive and believed to be able to respond well to both non-dynamic and dynamic models.

REFERENCES

[1] H. Yoshida, T. Hyakudome, S. Ishibashi, T. Sawa, Y. Nakano, H. Ochi*, et al.*, "An autonomous underwater vehicle with a canard rudder for underwater minerals exploration," in *Mechatronics and Automation (ICMA), 2013 IEEE International Conference on*, 2013, pp. 1571-1576.

[2] A. Cadena, "Development of a low cost Autonomous Underwater Vehicle for Antarctic exploration," in *Technologies for Practical Robot Applications (TePRA), 2011 IEEE Conference on*, 2011, pp. 76-81.

[3] P. B. Sujit, J. Sousa, and F. L. Pereira, "UAV and AUVs coordination for ocean exploration," in *OCEANS 2009 - EUROPE*, 2009, pp. 1-7.

[4] R. B. Wynn, V. A. I. Huvenne, T. P. Le Bas, B. J. Murton, D. P. Connelly, B. J. Bett*, et al.*, "Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience," *Marine Geology,* vol. 352, pp. 451-468, 2014.

[5] M. P. Brito, N. Bose, R. Lewis, P. Alexander, G. Griffiths, and J. Ferguson, "The Role of adaptive mission planning and control in persistent autonomous underwater vehicles presence," in *Autonomous Underwater Vehicles (AUV), 2012 IEEE/OES*, 2012, pp. 1-9.

[6] J. C. P. Liou, "AUV hydrodynamics for survivability and controllability," in *OCEANS 2011*, 2011, pp. 1-9.

[7] Y. Liu, P. Fang, D. Bian, H. Zhang, and S. Wang, "Fuzzy comprehensive evaluation for the motion performance of autonomous underwater vehicles," *Ocean Engineering,* vol. 88, pp. 567-577, 2014.

[8] C. C. Wang, Y. R. Lin, and H. H. Chen, "Accurate altitude control of Autonomous Underwater Vehicle," in *Underwater Technology Symposium (UT), 2013 IEEE International*, 2013, pp. 1-3.

[9] S. Fan and C. A. Woolsey, "Dynamics of underwater gliders in currents," *Ocean Engineering,* vol. 84, pp. 249-258, 2014.

[10] A. Hoggarth and J. Carballini, "The evolution of offshore survey technology for pipeline inspections," in *Acoustics in Underwater Geosciences Symposium (RIO Acoustics), 2013 IEEE/OES*, 2013, pp. 1-2.

[11] M. Eichhorn, R. Taubert, C. Ament, M. Jacobi, and T. Pfuetzenreuter, "Modular AUV system for Sea Water Quality Monitoring and Management," in *OCEANS - Bergen, 2013 MTS/IEEE*, 2013, pp. 1-7.

[12] U. V. Painumgal, B. Thornton, T. Uray, and Y. Nose, "Positioning and control of an AUV inside a water pipeline for non-contact in-service inspection," in *Oceans - San Diego, 2013*, 2013, pp. 1-10.

[13] G. Meinecke, V. Ratmeyer, and J. Renken, "HYBRID-ROV - Development of a new underwater vehicle for high-risk areas," in *OCEANS 2011*, 2011, pp. 1-6.

[14] H. Bo, S. Qixin, and L. Jing, "Self-rescue system based on behavior decision-makingand computed torque control for AUV," in *Informatics in Control, Automation and Robotics (CAR), 2010 2nd International Asia Conference on*, 2010, pp. 326-329.

[15] C. Wang, Y. Lin, Z. Hu, and L. Geng, "Hydrodynamic analysis of a waterjet propelled underwater vehicle in vertical plane," in *Proceedings of the International Offshore and Polar Engineering Conference*, 2014, pp. 393-398.

[16] O. Hassanein, S. A. Salman, S. G. Anavatti, and T. Ray, "ANFN controller based on differential evolution for Autonomous Underwater Vehicles," in *Innovative Engineering Systems (ICIES), 2012 First International Conference on*, 2012, pp. 184-189.

[17] D. B. Talange, S. D. Joshi, and S. Gaikwad, "Control of autonomous underwater vehicle using fractional order PI^λ controller," in *Control Applications (CCA), 2013 IEEE International Conference on*, 2013, pp. 1111-1116.

[18] O. Hassanein, S. G. Anavatti, and T. Ray, "Fuzzy modeling and control for Autonomous Underwater Vehicle," in *Automation, Robotics and Applications (ICARA), 2011 5th International Conference on*, 2011, pp. 169-174.

[19] Z. Zeng, K. Sammut, A. Lammas, F. He, and Y. Tang, "Efficient Path Re-planning for AUVs Operating in Spatiotemporal Currents," *Journal of Intelligent and Robotic Systems: Theory and Applications,* 2014.

[20] C. Wang, F. Zhang, and D. Schaefer, "Dynamic modeling of an autonomous underwater vehicle," *Journal of Marine Science and Technology,* 2014.

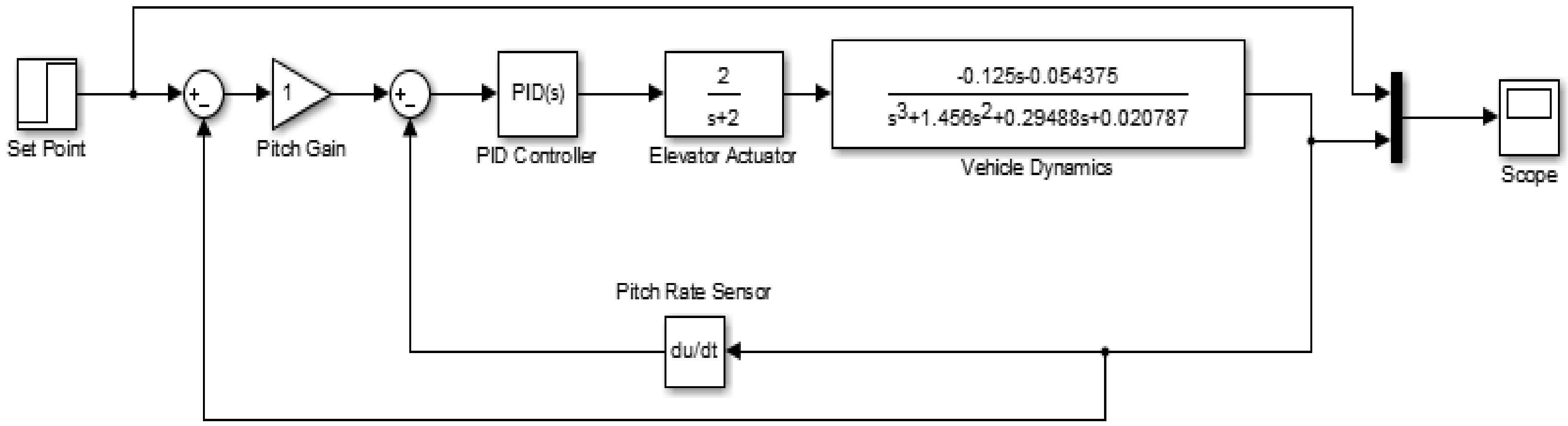
[21] M. Santhakumar and K. Jinwhan, "Modelling, simulation and model reference adaptive control of autonomous underwater vehicle-manipulator systems," in *Control, Automation and Systems (ICCAS), 2011 11th International Conference on*, 2011, pp. 643-648.

[22] A. Kiam Heong, G. Chong, and L. Yun, "PID control system analysis, design, and technology," *Control Systems Technology, IEEE Transactions on,* vol. 13, pp. 559-576, 2005.

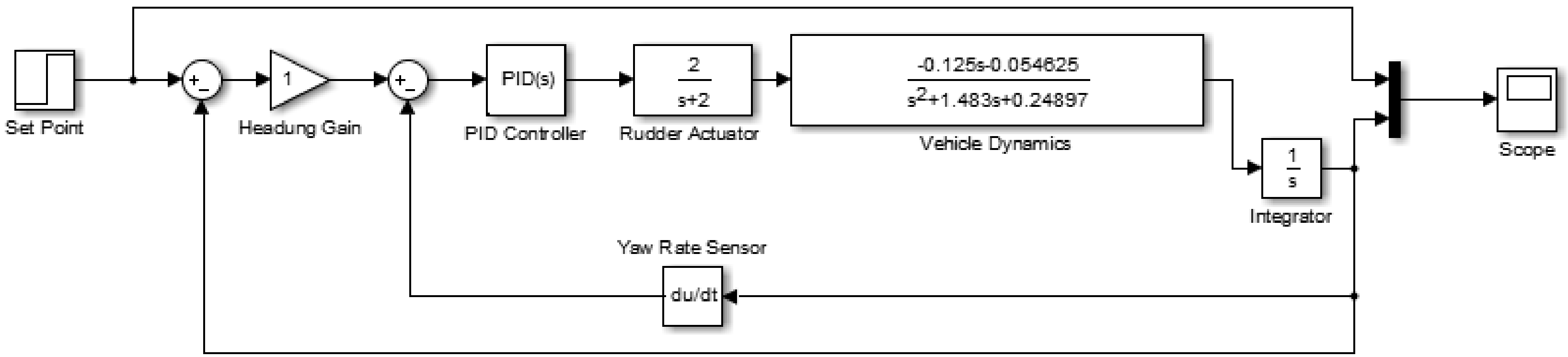
[23] W. Daxiao, X. Mantian, X. Leijun, and Z. Weidong, "A simple but effective MacPID tuning method based on the robust theory," in *Modelling, Identification and Control (ICMIC), Proceedings of 2011 International Conference on*, 2011, pp. 428-431.

[24] A. Gambier, "Digital PID controller design based on parametric optimization," in *Control Applications, 2008. CCA 2008. IEEE International Conference on*, 2008, pp. 792-797.

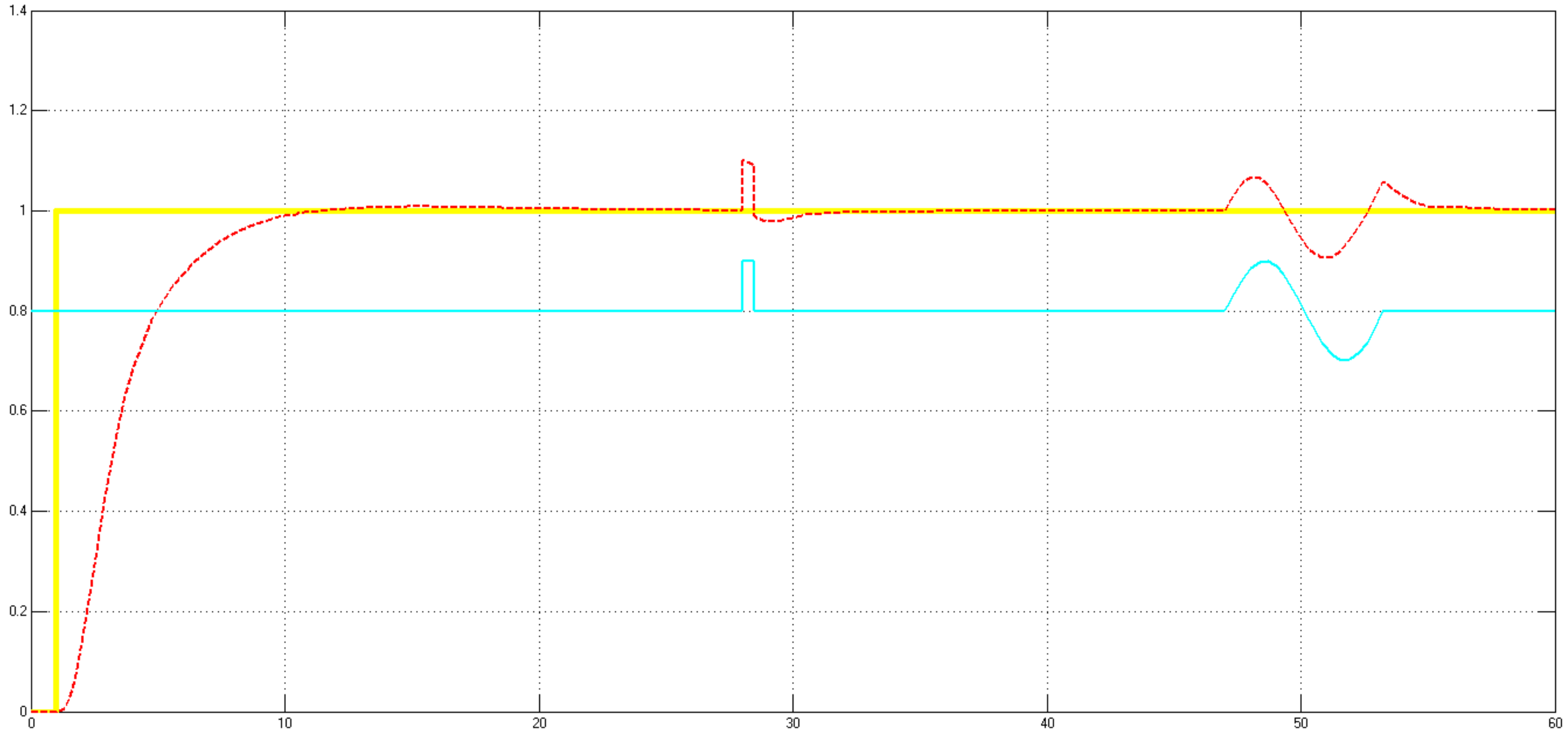
APPENDIX 1: Overview of Control System for Pitch Angle



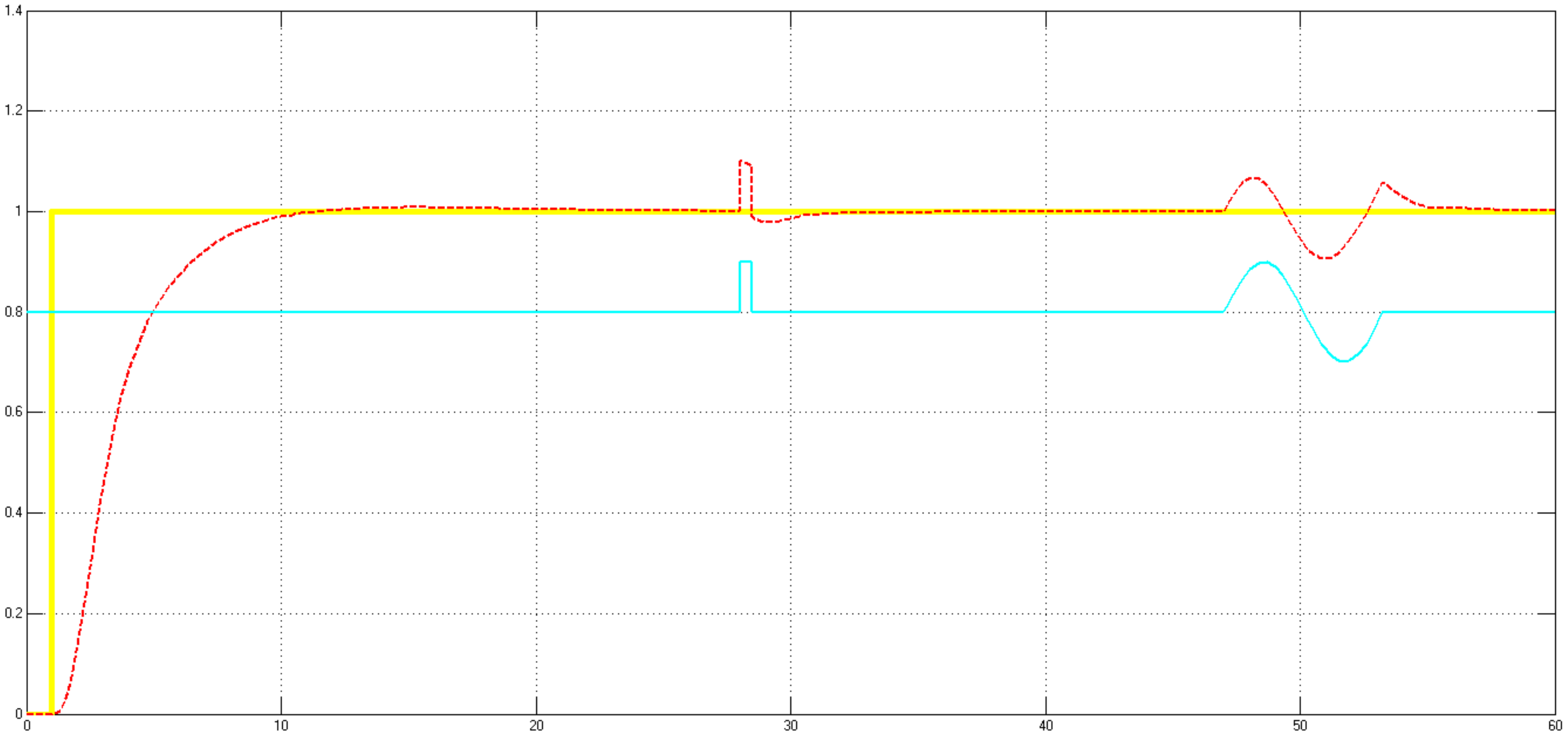
APPENDIX 2: Overview of Control System for Heading Angle



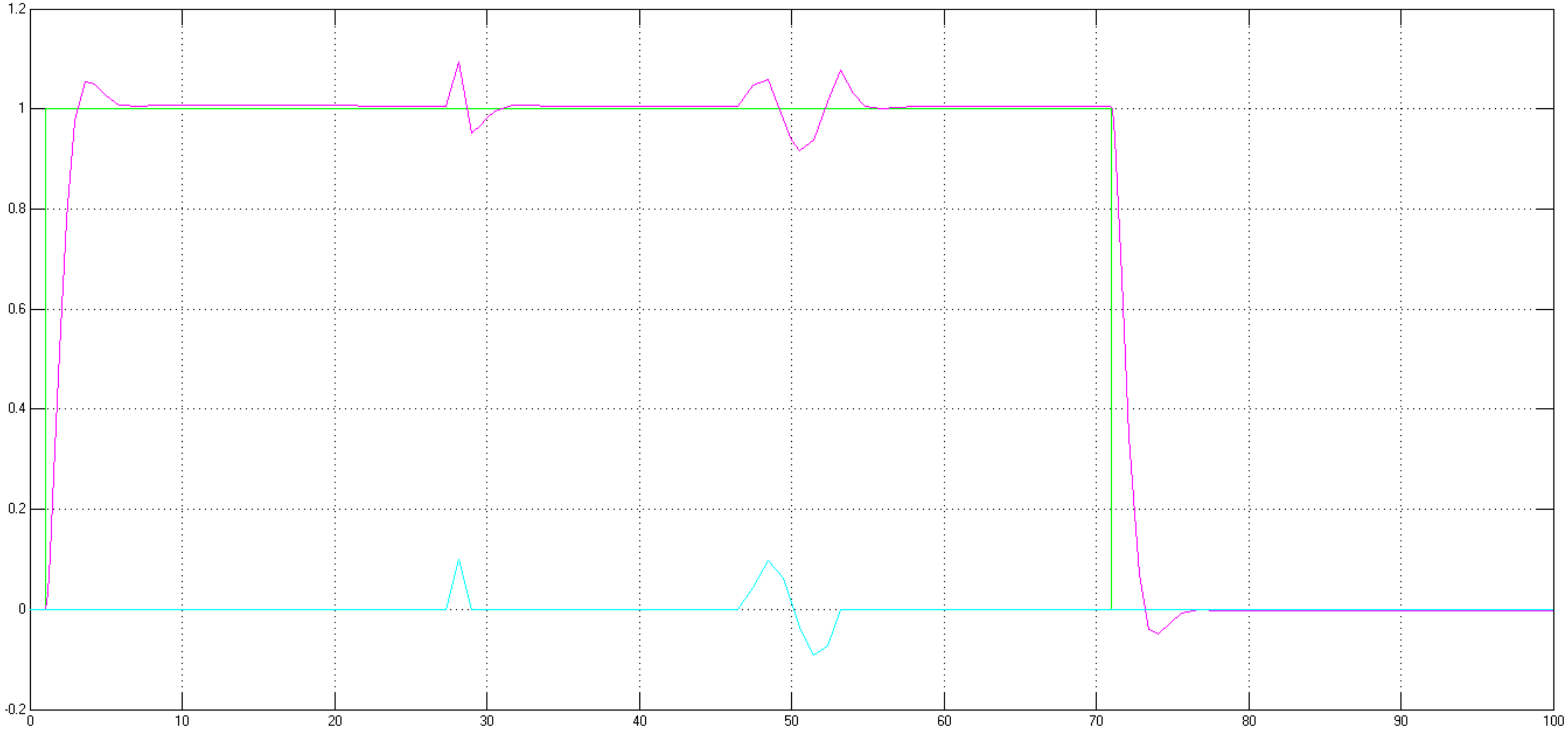
APPENDIX 3: Pitch Controller Response with Respect to Set-Point Change and Underwater Disturbances



APPENDIX 4: Heading Controller Response with Respect to Set-Point Change and Underwater Disturbances



APPENDIX 5: PID Controller Response for Real Data Vehicle System with respect to Set-point Change and Underwater Disturbances (Heading)



APPENDIX 6: Screen Shot of the HydroView MAX for Window Graphic User Interface with Vehicle Connected Online