

SH Instrumentation and Control Assignment

by Sam Hawkins

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ACDB5011 – Instrumentation and Control

Samuel Hawkins¹

¹ UWTSD IQ Campus, Waterfront, IQ Campus University of Wales Trinity, Swansea SA1 8EW, UK;
2216506@student.uwtsd.ac.uk

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Abstract

This paper has demonstrated how to create a closed loop control system in MATLAB. It has shown the effects of tuning and has found the values required to achieve a rise time of less than two seconds with no overshoot. Hand calculations have been conducted to validate the simulation and plots verify the system is stable.

1. Introduction

- 1.1. The aim of this paper is to demonstrate an understanding of the theory behind control systems and to be able to design one with typical software available. Using MATLAB and Simulink, design a closed loop control system for a close-in weapon system (CIWS). This system must be able to follow a unit step input and be able to bring the process under control within two seconds and with less than 5% overshoot. Once this is completed, the closed loop transfer function must be determined and validated against using both hand calculation and Simulink simulations.
- 1.2. PID control systems are essential for modern process control. They are simple to design and implement making them suitable for uses in various sectors and applications examples seen are industrial, chemical, mechanical and electro-mechanical process control. I.e. Thermostats, cruise control, altitude control in aircraft.
- 1.3. There are four types of controllers, however the focus is on the PID controller. PID stands for proportional (P) plus Integral (I) plus Derivative (D) and the output is the sum of these three terms. [1]
- 1.4. A closed loop system is named this as it uses feedback giving it an understanding of the state of the system. The system state values are compared to the input state and subtracted to find the error signal; this value is the remaining control action required to meet the desired target input value. [2]
- 1.5. PID controllers are useful here as they use absolute error value, the integral and derivative to control process value as integral adds up the previous errors and derivative speculates future errors due to overshoot. The proportional captures the current error. With these values specified correctly, they will create a functioning PID controller. ¹
- 1.6. The transfer function is a mathematical model that describes how a system's output relates to its input. This can be seen by the formula below:

$$\text{Transfer Function} = \frac{\text{Output Value}}{\text{Input Value}}$$

Caption required

- 1.7. The following terms will be discussed many times throughout this paper:

- Gain – Is the measure of how the system amplifies the input signal to produce the desired output signal. Low gain is a slow response and stable. High gain has a fast response and typically unstable.
- Set Point – Is the value that the output of the system is trying to achieve.
- Tolerance – is the maximum error acceptable for the defined system.
- Precision – Is a systems degree of freedom from random errors.
- Reproducibility - Is the closeness of output readings when the same input is applied when there changes in measurement conditions. In this case method for determining results.

¹ An alternative to a PID controller would be to use predictive functional control. This is a model based approached effective for single input/output applications. This is suitable for processes that have dead time, and it can constrain both the manipulated and the controlled signal. However, this may be better suited to more low level, basic controller only. As the intent is to not have dead time in this closed loop system and multiple inputs. predictive functional control would not be suitable. [7]

- 1.8. A famous example of a CIWS is the phalanx. This is an American made automated weapons system capable of firing 4500 rounds/minute designed to defend against aircraft, missiles and small boats. As such this system must be fast, responsive and allow no margin for error otherwise disastrous events may occur. Examples of use by the UK is on HMS Albion and Type 45 Destroyers employed by the Royal Navy. [3]



Figure 1 - Phalanx in Operation GIF [4]

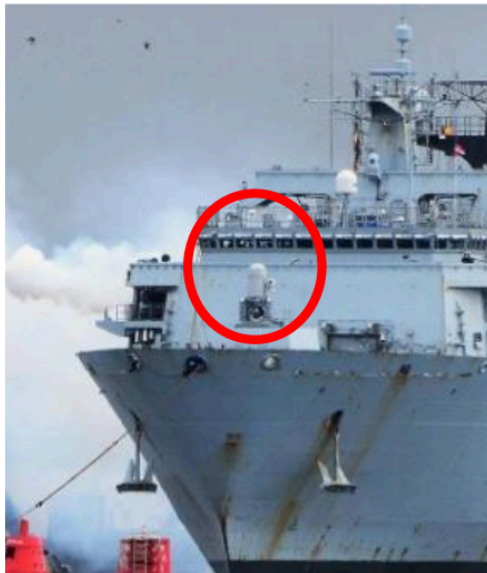


Figure 2 - Phalanx on HMS Albion [5]



Figure 3 - Phalanx on Type 45 Destroyers [6]

2. Simulation Setup & Results

2.1. Before designing the closed loop system. The transfer function (G) for the angular positioning system if the CIWS must be calculated. This required the last three digits of the student number then adding one.

2.1.1. Student Number = 2216506

2.1.2. Last three digits adding one = 617

a = 6

b = 1

c = 7

2.1.3. This is the formula for transfer function (G):

$$G(s) = \frac{1}{as^2 + bs + c}$$

2.1.4. Then substitute the letters with the numbers:

$$G(s) = \frac{1}{6s^2 + s + 7}$$

3. Creating Closed Loop System in Simulink

3.1. To create the system, a step, subtract, PID controller and transfer function block was added and connected as seen in figure 4. This was then attached to a scope with 4 inputs to record data at each point.

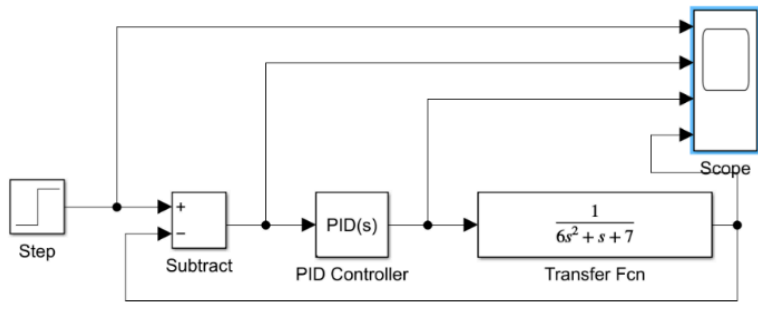


Figure 4 - Closed Loop Block Diagram

3.2. It can be seen in figure 5 that the outputs recorded by the scope show that the transfer function does not meet the set point value of the system. As such it would not even achieve the desired movement required by the CIWS.

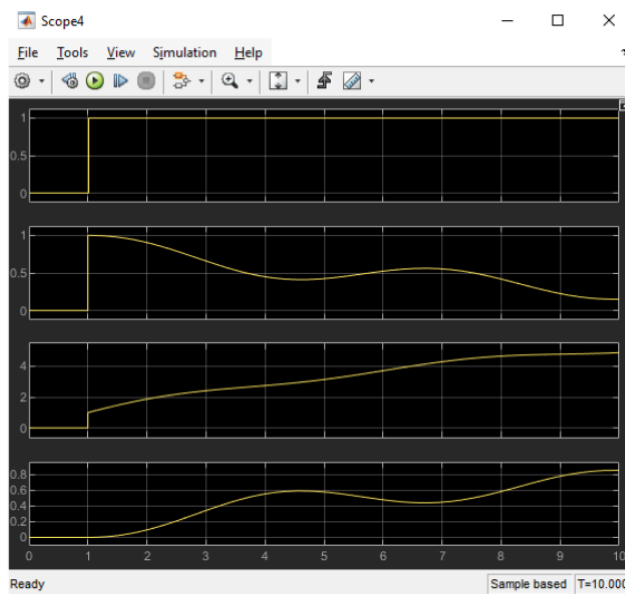


Figure 5 - Untuned System Scope

3.3. To ensure that the system meets the set point, the system was tuned using Simulink auto tune function which aids the user in altering the response time and transient

behaviour that modifies the PID values leading to a desired output. Results can be seen in block column of figure 6.²

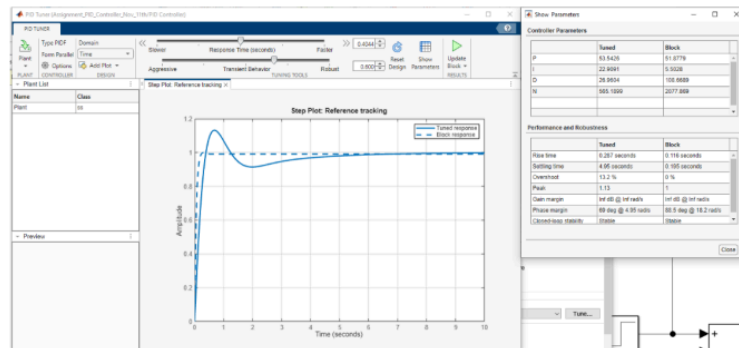


Figure 6 - Tuned System

3.3.1. The response and setting time as a result of tuning are:

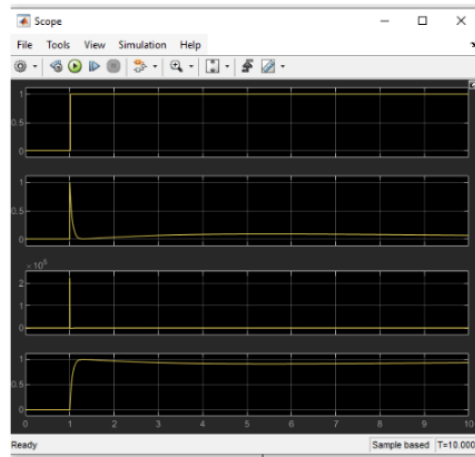
Response/Rise time = 0.116 Seconds
 Setting time = 0.195 Seconds
 Overshoot = 0%
 Peak = 1

3.3.2. The PID parameters as a result of the tuning are:

Proportional (P) = 51.8779
 Integral (I) = 5.2028
 Derivative (D) = 108.6689
 Filter Coefficient (N) = 2077.869

3.4. It can be seen in figure 7 scope, which input one is the step block having a value of 1. Input 2 is the output from the subtract block which receives values from the step and transfer function "looping" providing the required feedback to make the closed loop system to function as intended. Input 3 is the output of the PID controller and output 4 is the value of the transfer function.

² Even before the rise of AI as we know it, neural networks were being developed to create artificial systems that could perform tasks similar to how humans do. As such an alternative to manually tuning would be to train a neural network based on desired input and outputs and training the network to achieve the minimum criterium function. [3]. More recent studies use AI to replace the PID controller or tune an existing one. [4] Using AI should reduce the time and number of tuning attempts.

*Figure 7 - Tuned System Scope*

4. Hand Calculations

- 4.1. To confirm the values used in the PID controller, hand calculations were conducted to derive values that would be used in the transfer function block, replacing the PID controller block.
- 4.2. Using the PID tuner in MATLAB, the following values were obtained:

Kp: 51.8779
Ki: 5.5028
Kd: 108.6689
N: 2077.869

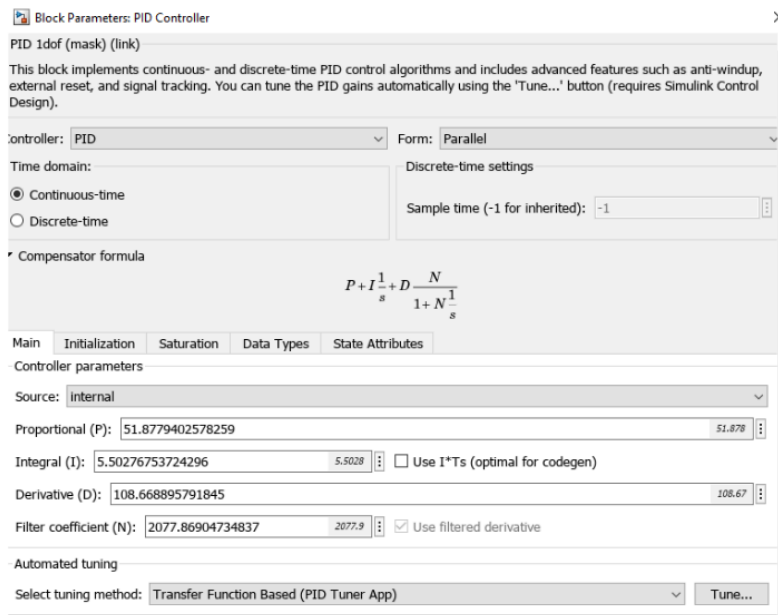


Figure 8 - Tuned PID Controller

4.2.1. So, the formulas used to derive values to be used transfer function block replacing the use of the PID controller will be:

$$\text{Controller} = K_p + K_i \frac{1}{s} + K_d \frac{s}{N^s + 1}$$

$$\text{Controller} = 51.8779 + \frac{5.5028}{s} + 108.6689 \frac{s}{2077.869s + 1}$$

$$\text{Plant} = \left(\frac{1}{6s^2 + s + 7} \right)$$

Using the formula:

$$G = \text{Controller} * \text{Plant}$$

4.3. To calculate the forward path transfer function of the system, the controller's transfer function must be multiplied by the transfer function of the process.

$$= \left(51.8779 + \frac{5.5028}{s} + 108.6689 \frac{s}{2077.869s + 1} \right) \times \left(\frac{1}{6s^2 + s + 7} \right)$$

$$= \left(51.8779 + \frac{5.5028}{s} + 108.6689 \frac{s}{2077.869s + 1} \right) \times \left(\frac{1}{6s^2 + s + 7} \right)$$

$$\begin{aligned}
&= \left(51.8779 + \frac{5.5028}{s} + 108.6689 \left(s \frac{s+2077.869}{2077.869} \right) \right) \times \left(\frac{1}{6s^2+s+7} \right) \\
&= \left(51.8779 + \frac{5.5028}{s} + 108.6689 \left(s \left(\frac{2077.869}{s+2077.869} \right) \right) \right) \times \left(\frac{1}{6s^2+s+7} \right) \\
&= \left(51.8779 + \frac{5.5028}{s} + 108.6689 \left(\frac{2077.869s}{s+2077.869} \right) \right) \times \left(\frac{1}{6s^2+s+7} \right) \\
&= \left(51.8779 + \frac{5.5028}{s} + \left(\frac{225799.7386s}{s+2077.869} \right) \right) \times \left(\frac{1}{6s^2+s+7} \right) \\
&= \left(\frac{((s(s+2077.869)) \times 51.8779) + (s+2077.869)5.5028 + s(225799.7386s)}{s(s+2077.869)} \right) \times \left(\frac{1}{6s^2+s+7} \right) \\
&= \left(\frac{51.8779s^2 + 107795.4802s + 5.5028s + 11434.09753 + 225799.7386s^2}{s^2 + 2077.869s} \right) \times \left(\frac{1}{6s^2+s+7} \right) \\
&= \left(\frac{225851.6165s^2 + 107800.983s + 11434.09753}{s^2 + 2077.869s} \right) \times \left(\frac{1}{6s^2+s+7} \right) \\
&= \frac{225851.6165s^2 + 107800.983s + 11434.09753}{(s^2 + 2077.869s)(6s^2 + s + 7)} \\
&= \frac{225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + s^3 + 7s^2 + 12467.214s^3 + 2077.869s^2 + 14545.083s} \\
&= \frac{225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}
\end{aligned}$$

4.4. The values can be substituted into the transfer function block and the block diagram can now be redrawn as shown in figure 9 below.

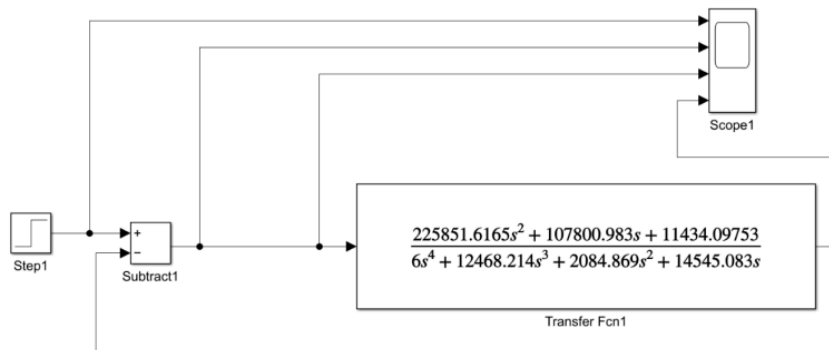


Figure 9 - Closed Loop Transfer Function

4.5. The results of this can be seen in figure 10. Input 1 represents the step, input 2 and 3 (would have represented the PID controller) represents the subtract value and input 4 represents the output from the transfer function which then feeds back into the subtract block, forming the closed loop system.

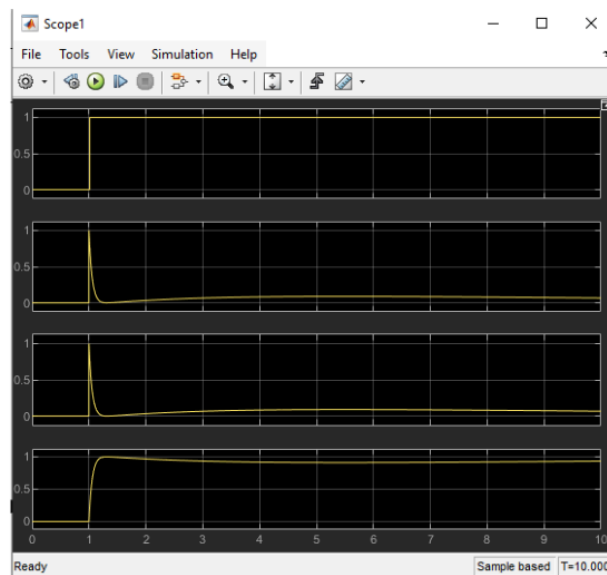


Figure 10 - Closed Loop Transfer Function Scope

4.6. Input 4 represents the same curve as seen in figure 6 with the block response meeting the requirements of achieving the desired set point within the allotted time and with no overshoot and so it can be seen there is no oscillation. However, it can be seen after achieving set point it then begins to dip below 1.

5. Validating Hand Calculations

5.1. To validate the values calculated above, an additional transfer function is calculated and subtracted from each other to find zero.

$$TF = \frac{G}{1 + GH}$$

5.2. Where TF is the transfer function of the whole system, G is the forward path transfer function, and H is the transfer function of the feedback loop, $H = 1$

$$TF = \frac{\frac{225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}}{1 + \left(\frac{225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s} \right) \times 1}$$

$$TF = \frac{\frac{225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}}{\frac{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s + 225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}}$$

$$TF = \frac{\frac{225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}}{\frac{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s + 225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}}$$

$$TF = \frac{\frac{225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}}{\frac{6s^4 + 12468.214s^3 + 227936.4855s^2 + 122346.066s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}}$$

$$TF = \frac{225851.6165s^2 + 107800.983s + 11434.09753}{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s} \times \frac{6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s}{6s^4 + 12468.214s^3 + 227936.4855s^2 + 122346.066s + 11434.09753}$$

$$TF = \frac{(225851.6165s^2 + 107800.983s + 11434.09753)(6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s)}{(6s^4 + 12468.214s^3 + 2084.869s^2 + 14545.083s)(6s^4 + 12468.214s^3 + 227936.4855s^2 + 122346.066s + 11434.09753)}$$

$$TF = \frac{1355109.699s^6 + 646805.898s^5 + 68604.58518s^4 + 2815966287s^3 + 1344085725s^2 + 142562774.9s + 470871032.8s^4}{36s^8 + 74809.284s^7 + 12509.214s^6 + 87270.498s^5 + 74809.284s^4 + 155456360.3s^3 + 25994592.85s^2 + 181351207.5s + 1367618.913s^6 + 2841960880s^5 + \dots + 224750927.6s^3 + 23838595.48s^2 + 3285030508s^3 + 1567974245s^2 + 166309897.6s + 475217712.6s^4 + 3315355100s^3 + 734076.396s^5 + 1525436933s^4 + 255075520.3s^3 + 1779533685s^2 + 68604.58518s^4 + 142562774.9s^3 + 23838595.48s^2 + 166309897.6s}$$

5.3. Then add the terms together:

$$TF = \frac{1355109.699s^6 + 2816613093s^5 + 1815025362s^4 + 3652344211s^3 + 1591812840s^2 + 166309897.6s}{36s^8 + 149618.568s^7 + 156836488.4s^6 + 2868776820s^5 + 2182074458s^4 + 3712993395s^3 + 1803372280s^2 + 166309897.6s}$$

- 5.4. Once this is done, the block diagram can be redrawn as shown in figure 11. Adding the final calculation into a secondary transfer function block that will connect to a subtract block. This subtract block is connected to the output of the very first closed loop system design in figure 4. The aim is that the output values from the closed loop system will be subtracted from the validation hand calculations to show that they are the same. If this is the case, then the output from the subtract block will be zero.

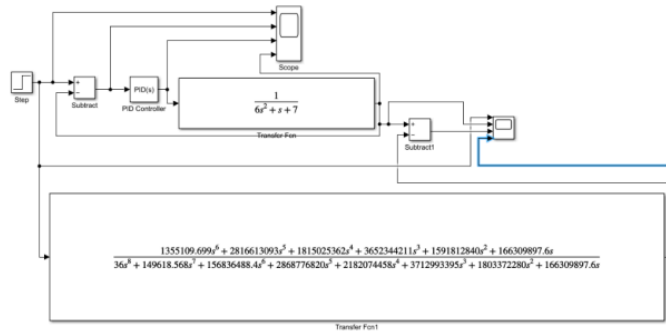


Figure 11 - Validation Block Diagram

- 5.5. The results of this can be seen in figure 12 below. Input port 1 represents the step input. Input 2 represents the output value from the closed loop system used before the subtract block. Input 3 represents the output value from the subtract block. Input port 4 shows the output value from the validation transfer function block. It can be seen that both input port 2 and 4 are from a glance identical to each other.
- 5.6. Input port 3 shows the value to be a ridiculously small number. The reason this is not absolutely zero is due to rounding error when conducting hand calculations. If there were a mathematical error, the value would be much larger.

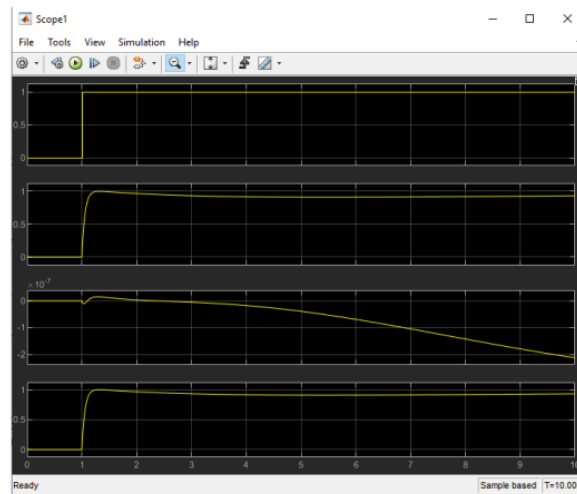


Figure 12 - Validation Scope

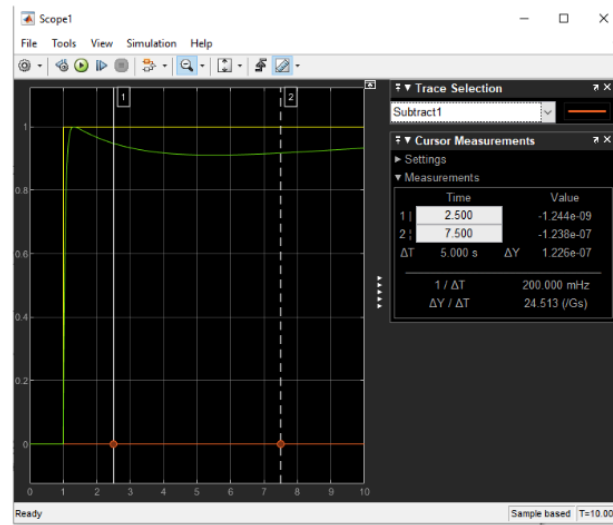


Figure 13 - Validation Scope Overlay

5.7. Another way to represent the results is seen in figure 13 which is the same scope readout as figure 12 but the different trace is overlaid on top of each other.

```

P =
      1
-----
 6 s^2 + s + 7
Continuous-time transfer function.

>> G = C*P

G =
      2.259e05 s^2 + 1.078e05 s + 1.143e04
-----
 6 s^4 + 1.247e04 s^3 + 2085 s^2 + 1.455e04 s
Continuous-time transfer function.

>> CLTF = (G/(1+G))

CLTF =
      1.355e06 s^6 + 2.817e09 s^5 + 1.815e09 s^4 + 3.652e09 s^3 + 1.592e09 s^2 + 1.663e08 s
-----
 36 s^8 + 1.496e05 s^7 + 1.568e08 s^6 + 2.869e09 s^5 + 2.182e09 s^4 + 3.713e09 s^3 + 1.803e09 s^2
+ 1.663e08 s
Continuous-time transfer function.

>> figure
subplot (2,2,1)
pzplot (P)
subplot (2,2,2)
pzplot (C)
subplot (2,2,3)
pzplot (G)
subplot (2,2,4)
pzplot (CLTF)
>>

```

Figure 14 - MATLAB Pzplot Instructions

5.8. Figure 14 shows the commands used to create a Pzplot for P, C, G, the closed loop transfer function (CLTF) and root locus (see figure 15 and 16). Their values are from the tuned PID controller in figure 6. The process (P) was found by using the same formula used in the transfer function in figure 4. The gain (G) was found using Control (C) multiplied by the Process. The CLTF was found by:

$$CLTF = \left(\frac{G}{1 + G} \right)$$

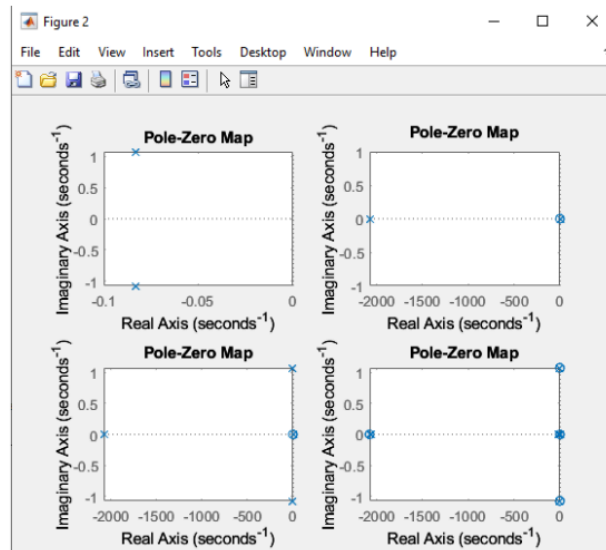


Figure 15 - PZ Subplots

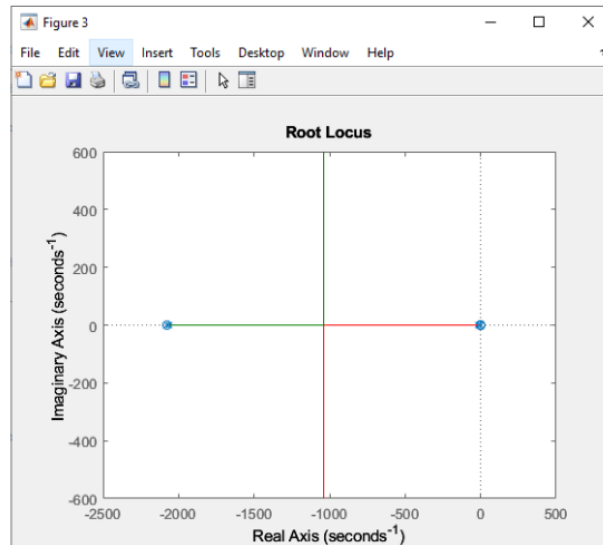


Figure 16 - Root Locus

6. Discussion

- 6.1. The results show a tuned PID controller being used in a functional closed loop system. This can be seen in figure 7 after creation and figure 12 after validating.
- 6.2. A crucial aspect of control systems is stability within the system. It is important as it reduces the error between the measured process and its desired set point. When the CIWS is in operation it must maintain its set point to be able to deliver effect. On the seas waves hit the ship and the turret must compensate for this. The system measures where it is and where it needs to be (set point) to maintain correct position by rotating (process). Delay can occur by any number of reasons such as hydraulic leaks, worn gears, or faulty motor.³ This delay creates lag and so it fails to meet the set point, this lag then changes the phase relative to the controller and process. This then leads to the system over correcting and worsening the situation leading to phenomena like oscillation where the turret will jitter and fail to acquire its target as the steady state error will not close. This is an unstable system.
- 6.3. Results from figures 15 & 16 show that the system is stable as all poles are on the negative axis of the real plane. As if any pole crosses into the positive axis of the real plane, the system will become unstable.

7. Conclusion

- 7.1. In this paper, the simulation setup and results show that a closed loop feedback system was created through a tuned PID controller. These values were obtained:

Kp: 51.8779
Ki: 5.5028
Kd: 108.6689
N: 2077.869

- 7.2. The subsequent iteration of the system shows the output to have the appropriate gain and that there is no oscillation, overshoot of less than 5% and achieved set point in the time required of less than two seconds and so has demonstrated that the system is stable.
- 7.3. If this were to be done again, a Nyquist diagram can be plotted to better understand the stability of the system.

³ Error can be introduced through any manner of ways. There are new approaches to predict closed loop stability to create a more efficient feedback gain that will lead that will respond to real time errors as they are introduced. These methods are significant as it provides an alternative to using manual trial and error tuning. [10]

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SH Instrumentation and Control Assignment

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

67 /100

PAGE 1

QM

Abstract - results

Good abstract, although you should include a statement of your results.

PAGE 2

QM

Caption required

You should always include a caption on figures, equations and tables to allow you to refer to them in your text.

e.g. An illustration of this can be seen in figure 2. The relationship of the variables is shown in equation 2. Table 1 shows the results of the first experiment where the control variable, temperature in degrees celsius is shown in the first column....

PAGE 3

PAGE 4

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Caption required

You should always include a caption on figures, equations and tables to allow you to refer to them in your text.

e.g. An illustration of this can be seen in figure 2. The relationship of the variables is shown in equation 2. Table 1 shows the results of the first experiment where the control variable, temperature in degrees celsius is shown in the first column....

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Comment 1

What are the implications of this in the context of the CIWS?

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QM

Ref Qual

You should try to use more high quality reference sources, such as textbooks from reputable academic publishers and articles from peer reviewed journals.

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GRADING FORM: SMU GENERIC_SMOSEY

SAM HAWKINS

66.90

ENGAGEMENT WITH LITERATURE

including reading, referencing, academic conventions and academic honesty



"Inclusion of a wide range of research-informed literature, including sources retrieved independently.

Selection of relevant and credible sources. Very good use of referencing conventions, consistently applied."

6.5

A few more high quality references would have improved your mark here

KNOWLEDGE & UNDERSTANDING

Knowledge of the basic underlying concepts and principles of a subject.



Knowledge is extensive. Exhibits understanding of the breadth and depth of established views.

A little more detail in your descriptions of the concepts you are using would have given you more marks here.

20.4

COGNITIVE & INTELLECTUAL

Evaluate underlying concepts and principles of a subject and interpret qualitative and quantitative data in order to develop lines of argument and make sound judgements.



"Sound, logical, analytical thinking; synthesis and evaluation. Ability to devise and sustain persuasive arguments, and to review the reliability, validity and significance of evidence. Ability to communicate ideas and evidence

19.5

accurately and convincingly.
Sound, convincing conclusions /
recommendations

A bit more detail in your analysis of the results
and the implications of them for the CIWS would
have given you more marks here.

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



An advanced application of a range of methods,
materials, tools and/or techniques.
The context of the application is well considered,
with extensive use of relevant examples.
Application and deployment extend beyond
established conventions. Innovation and creativity
evident throughout.

14

TRANSFERABLE SKILLS

*Communicate the results of their study/work accurately and reliably,
and with structured and coherent arguments; the qualities needed for
employment requiring the exercise of some personal responsibility
within a structured and managed environment.*



Can communicate well, confidently and
consistently in a suitable format.
Work is coherent and fluent and is well structured
and organised.

6.5

Refer to things by their numbers.
Caption equations as well as images.
Your writing style needs a little work, you
occasionally refer to things using the wrong
terminology,

