

Instrumentation and Control
Implementation of a PID based control system in the CIWS

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Instrumentation & Control

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Table of Acronyms

Acronym	Full wording
CIWS	Close In Weapons System
P	Proportional
PD	Proportional Derivative
PI	Proportional Integral
PID	Proportional Integral Derivative
TF	Transfer Function

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1. Abstract

A report considering the implementation and tuning of a control system for the angular positioning of a CIWS turret system and an exploration of control systems. Exploring the mathematics behind the simulation of control systems including developing a full system transfer function.

2. Introduction

2.1 CIWS System

A close in weapons system (CIWS) is a weapon system designed to function autonomously or with a person-in-loop system, as a final line of defence against fast moving missile & aircraft attacks [1]. A number of these systems exist in current service; however, this report shall focus on the Phalanx system developed by General Dynamics & Raytheon. The Phalanx is available in both naval and ground-based forms, and is based upon a 20mm gatling cannon, mounted upon a two-axis positioning system, which allows for a full range of motion [2]. The system is designed to be autonomous, automatically detecting, evaluating and tracking potential targets [2].



Figure 1 – The Phalanx CIWS [2].

An electrically driven actuation system [2] is used to aim the weapon system. This system shall require a control system to determine the current position of the system in relation to the required, consider this, and then engage actuation to reach the required point. Specifically, this must be achieved within two seconds of request and with a maximum overshoot of 5%. This ensures that the weapon system is effectively aimed in a minimal timeframe.

2.2 Requirements

The formal system requirements are defined in figure 2 below, this control system shall be responsible for the angular (horizontal) target system only. These requirements must be met or exceeded during the control system simulation.

Req. No.	Requirement
1	The targeting position shall be obtained within 2 seconds of command.
2	During movement, the system shall not overshoot its setpoint position by more than 5%.

Figure 2 – Control System requirements

3. Control Systems – Background

3.1 Introduction

A Control system is a device which can regulate energy, to obtain a desired result [3]. Broadly speaking, there are two types of control system: open-loop & closed-loop. This section shall consider the elements of a control system and the principles behind them.

3.2 Open / Closed Loop Systems

An open-loop control system is one which does not contain any method of feedback, and is based solely upon a variable input- for example, a water tank requires it's level to be maintained, so a flow control valve is fitted to the inlet, which is manually adjusted by a person, to keep the level within its limits [3].

A closed-loop control system is one which features both a control and a transducer – which can be defined as a device which measures a metric, such as temperature – and are based upon a theory of feedback [4]. An example of a closed-loop control system is a household thermostat, where when the temperature falls below a setpoint, the heating is enabled until it reaches an upper limit.

3.3 Sensors & Actuators

Sensors (Transducers) are devices which measure a metric. The use of sensors allows the actuator to be implemented in a more effective / efficient manner, as it shall be operating based on physical feedback, rather than blindly [4].

Actuators are the part of the system which affect the process, which could be to heat or cool in a heating system; they are the effector, which results in the change of condition [4].

In terms of this study, the actuator is a motor which moves the CIWS in a rotary movement, and the transducer could be implemented through several methods, but it shall be considered as a rotary inductive position sensor- which measures its position with a hall effect sensor, which moves around a disc which contains a number of magnets which encode individual positions.

3.4 Types of Close Loop Control

3.4.1 Proportional Controller

A proportional controller (PI) is a controller which computes the feedback signal in proportion to the feedback error as described in equation one, where $u(t)$ is feedback, $e(t)$ is error and K_c is the proportional gain [5]. Essentially, this controller can multiply or divide (positive or negative gain) a control signal based upon the feedback which it receives. This is the simplest closed loop controller and is often used when steady-state operation is not demanding [5]. Due to the nature of proportional controllers, they may never truly reach the steady state – instead sitting just below the requested level – which limits the use of this type of controller.

$$u(t) = K_c e(t)$$

Equation 1 – Proportional Control Equation [5].

3.4.2 Proportional plus Derivative Controller

Building upon the proportional control, a proportional derivative (PD) controller adds a damping element, the derivative, which is used to smooth oscillation when a steady state cannot be achieved using a PI controller [5]. The output of a typical PD controller may be calculated as described in equation two, where $K_c \tau_D$ is the derivative term [5]. The steady-state error present in proportional controllers may still be present in PD controllers.

$$u(t) = K_c (r(t) - y(t)) - K_c \tau_D \frac{dy_f(t)}{dt}$$

Equation 2 – Proportional Derivative Controller [5].

3.4.3 Proportional plus Integral Controller

The most commonly used closed loop controller, proportional integral (PI) controllers remove the steady state error – they may be expressed as shown in equation three, where the output is the sum of the proportional function and the integral action [5].

$$u(t) = K_c e(t) + \frac{K_c}{\tau_I} \int_0^t e(\tau) d\tau$$

Equation 3 – Proportional Integral Controller [5].

3.4.4 PID Controllers

Effectively combining all of the previous methods, the PID controller allows the most effective control, it is described in its most simple form in equation four [5].

$$u(t) = K_c e(t) + \frac{K_c}{\tau_I} \int_0^t e(\tau) d\tau + K_c \tau_D \frac{de(t)}{dt}$$

Equation 4 – PID Controller [5].

3.5 Mathematical Modelling

Control systems may be modelled mathematically, to allow effective tuning based upon output. Processes may be modelled as transfer functions, which are differential equations that describe the ratio of transformation between the input and the output of a system [3].

To determine the transfer function of a system, the Laplace transform must first be determined, which is rearranged into the transfer function by placing one side over the other [3].

In terms of this study, the system transfer function is given, but total system transfer function, once a controller is implemented, must be derived. The transfer function totally characterizes the performance of a system and as such, is critical to modelling [3].

4. System Design

The plant transfer function (TF) is described in equation five below, this is the TF that describes the angular positioning system in the CIWS which requires control.

$$G(s) = \frac{1}{7s^2 + 5s + 5}$$

Equation 5 – CIWS Plant Transfer Function (Angular Positioning).

A PID controller is used in this system due to the precision required, which is implemented before the plant, with a subtractor placed before the plant, feeding back into the input signal. A stepped input (0 to 1) is used to model a change in the commanded position to model the full system response. Finally, an oscilloscope is added to measure at various points within the system: the input signal, post subtractor, post PID controller and full system output. The full system is shown in the block diagram, figure 3 below.

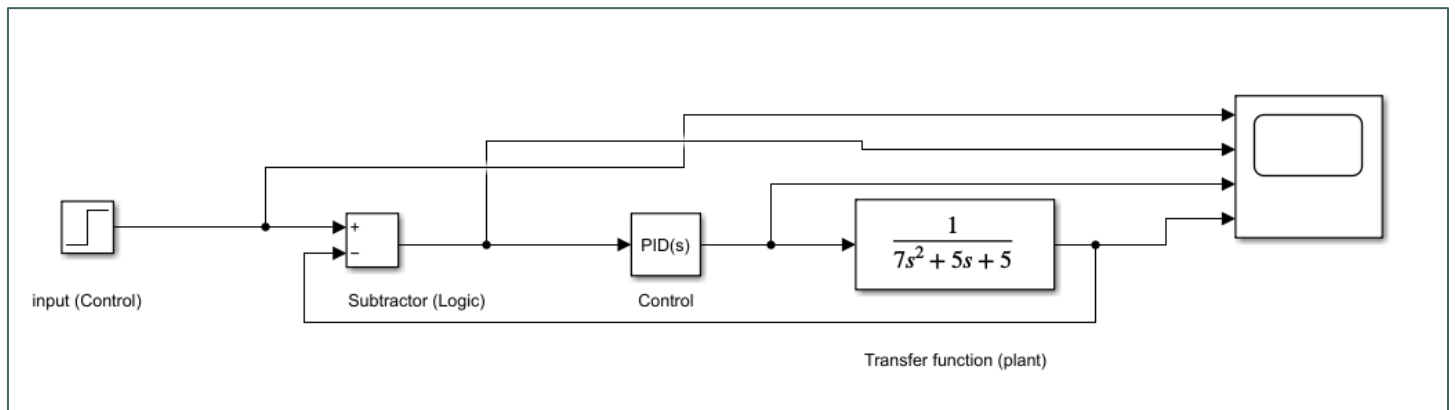


Figure 3 – CIWS Full Control System, block diagram.

5. System Simulation

Once constructed within Simulink, as shown in section four, the simulation is first run without any tuning to anticipate response. Figure four shows the response seen on the oscilloscope, which depicts an oscillation in the response, and a long settling time (beyond what can be seen on the 10 second scale). The first graph shows the changing input, with the second showing post subtractor, third shows post PID controller and fourth the full system output. The system must now be tuned to find the most efficient response.

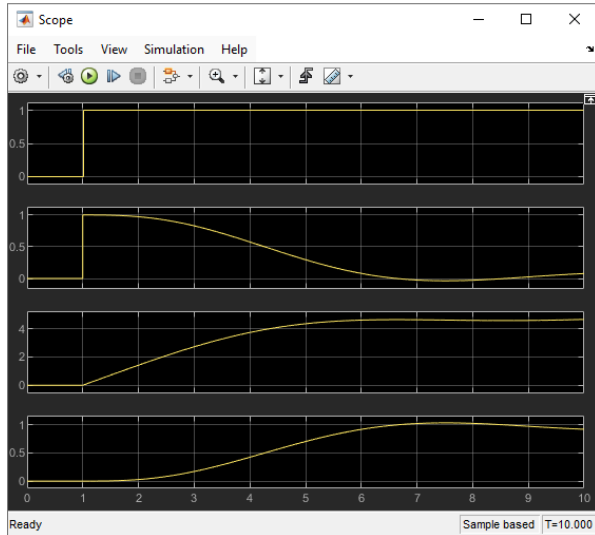


Figure 4 – Untuned system response.

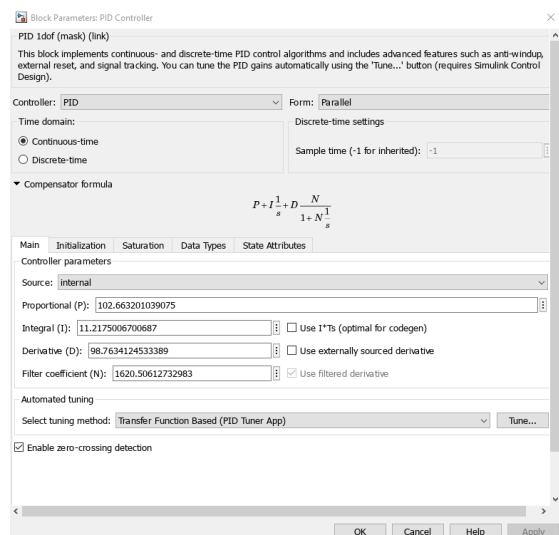


Figure 5 – PID Controller window, Simulink

The PID controller is selected within Simulink, and the window in figure five (above) opens, from which the tuning function may be accessed. In this window, the response time and transient behaviour may be adjusted to tune the block. Please note, that in figure six, the “block response” is the one which has been tuned, and the “Tuned response” is the one which Simulink is suggesting. Once tuned, the response time is within the required two seconds, and there is little to no overshoot – meaning that the system requirements have been met. The system is now tuned.

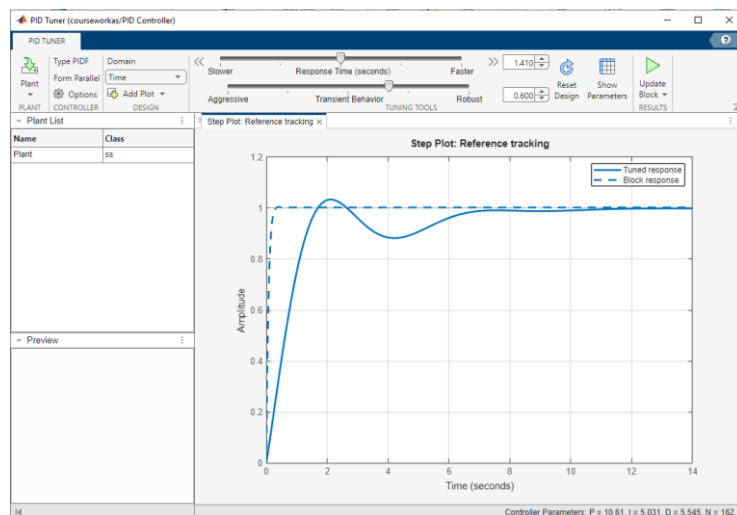


Figure 6 – Tuning the PID Controller.

The simulation may now be run in the main Simulink software, providing the full data output from the oscilloscope. Once confirmed, the system can be simplified into a singular transfer function.

Firstly, the PID controller is made into a transfer function, as shown below in equation six.

$$C = 103 + 11.2 \times \frac{1}{s} + 98.8 \times \frac{s}{0.000617 \times s + 1}$$

Equation 6 – Transfer function for PID Controller.

This is then multiplied by the plant transfer function, to find the new system transfer function, which is shown in equation seven.

$$B_{sys} = G(s) \times C = \frac{1.601e05s^2 + 1.664e05s + 1.818e04}{7s^4 + 1.135e04s^3 + 8108s^2 + 8103s}$$

Equation 7 – Combined PID & Plant Transfer function.

Now, the feedback loop is added into the transfer function, resulting in the full system equation, shown in equation eight. Full details of the methodology for the mathematics are available in appendix A.

$$SystemTF = \frac{B_{sys}}{(1 + B_{sys})} = \frac{1.121e06s^6 + 1.819e09s^5 + 3.187e09s^4 + 2.853e09s^3 + 1.495e09s^2 + 1.473e08}{49s^8 + 1.589s^7 + 1.3e08s^6 + 2.003e09s^5 + 3.436e09s^4 + 2.984e09s^3 + 1.561e09s^2 + 1.473e08s}$$

Equation 8 – Full system transfer function.

This can now be implemented as a single transfer function, and the results compared against that of the original system, a block diagram shows the two separate systems (original and combined) below in figure seven.

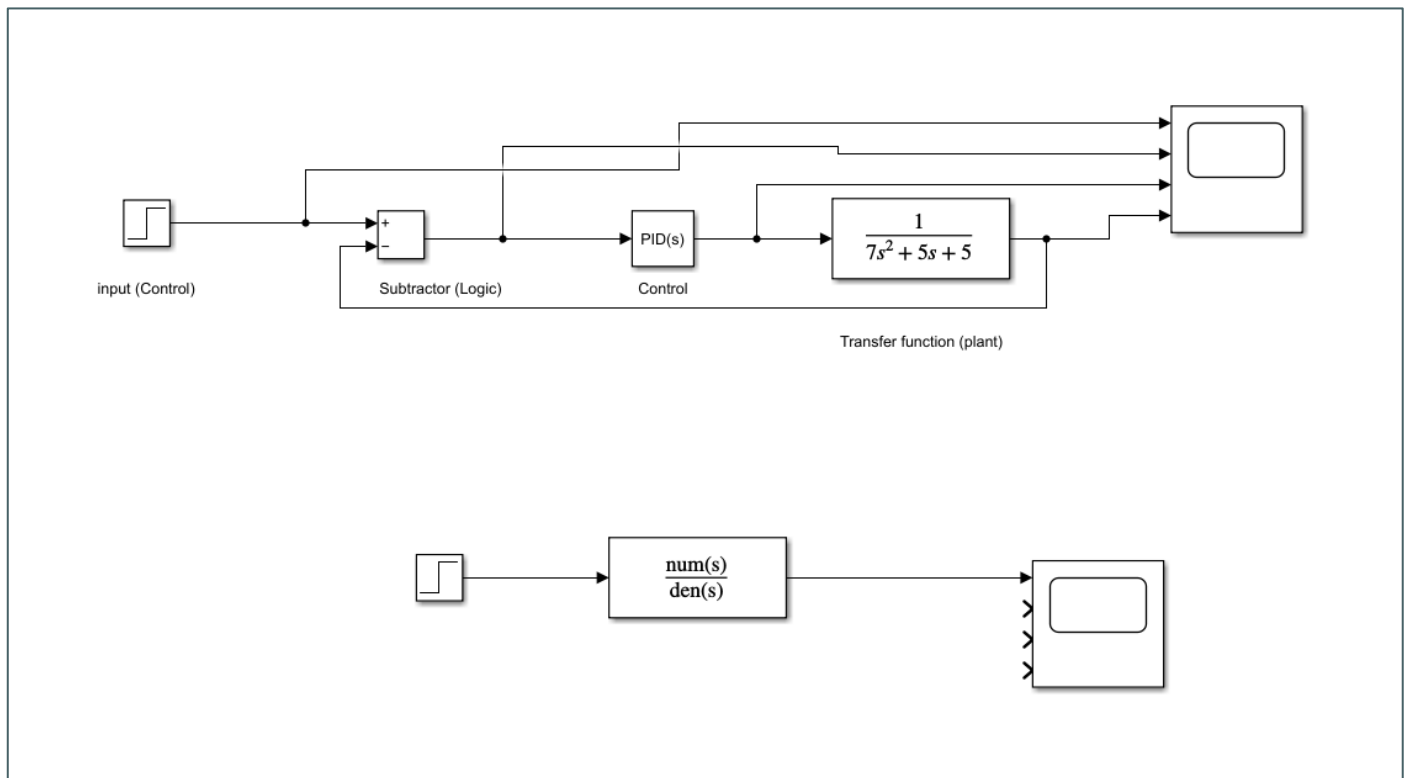


Figure 7 – The original and combined system block diagrams.

6. Results

6.1 Tuned System Results

The final output data is shown in figure eight below, where the graphs are in the same format as figure four. The setpoint is increased from zero to one, which is followed by the full system in around a quarter of a second, well within the limits specified in the requirements. The overshoot, as shown in figure nine, is well within the required tolerance (5%, or 1.05 in terms of the simulation). The result is a fast reaction, with little to no under, or overshoot, and a steady state achieved almost immediately, with a minor undershoot after the setpoint is reached. This is to be expected with the large damping derivative used in the PID.

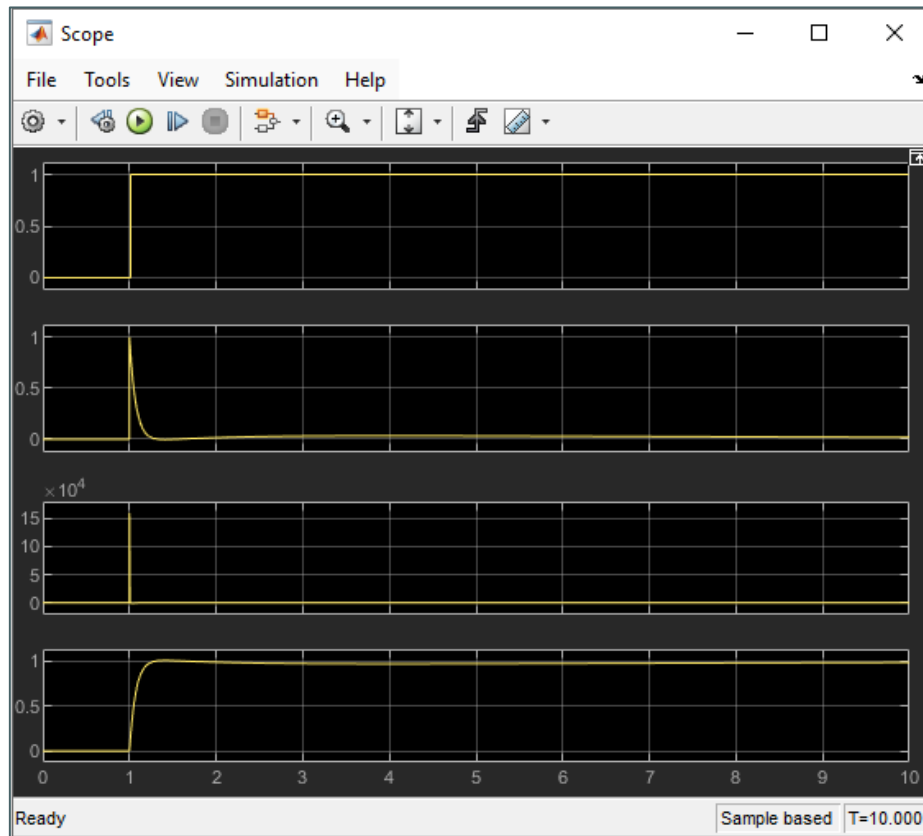


Figure 8 – Oscilloscope reading of tuned PID controlled CIWS system.

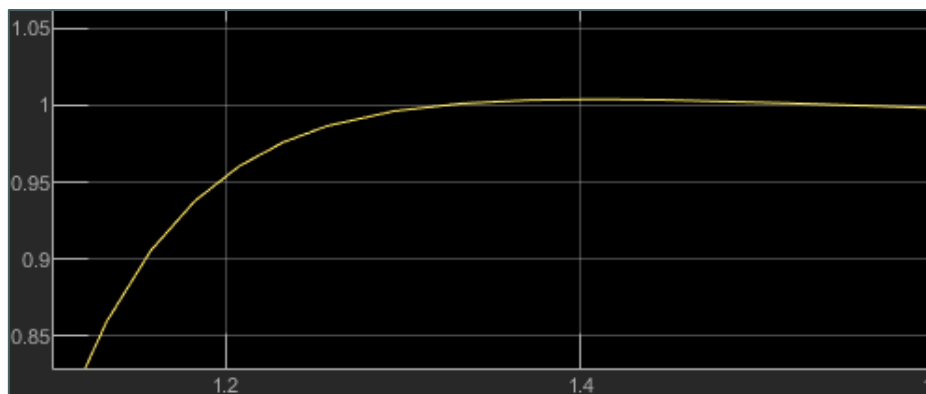


Figure 9 – Oscilloscope reading of full system output at input change, increased scale.

6.2 Full System Transfer Function

The full system transfer function, as discussed in section five, is a duplicate of the original system, but combined into a singular transfer function. This may be done to reduce the number of elements in especially complex systems. To confirm that the full system function is correct, a side-by-side comparison of the final output is used. As can be seen below, in figure 10 (original) and 11 (combined), the response is identical, meaning that the full system transfer function does mirror the original system.

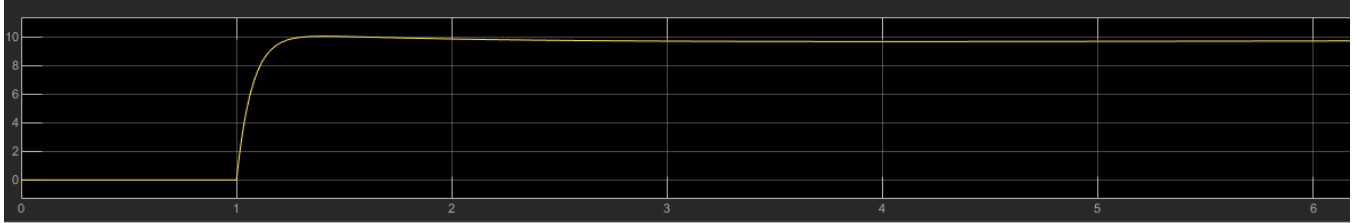


Figure 10 – Original System Response.

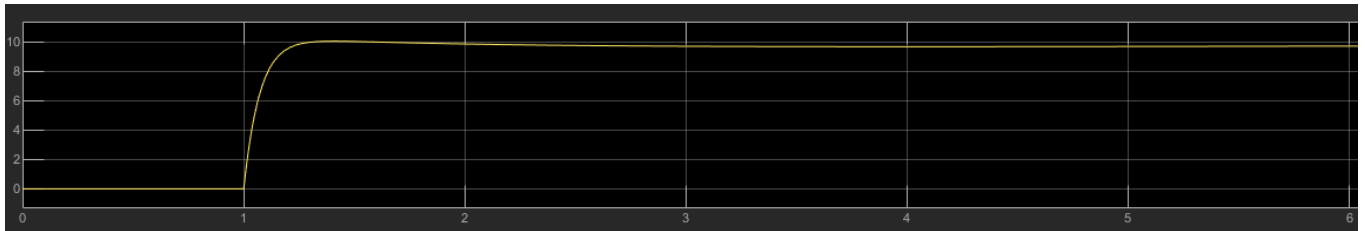


Figure 11 – Full Transfer Function Response.

6.3 System Stability

Pole-zero plots describe the relationship of the system, whereby the poles describe the positive response & the zeros the negatives [6]. The ideal system shows a response where poles and zeros are matched, describing a matched response, with little to no over or under shoot. The plots for the plant, controller and forward transfer function describe the components of the system, with the plant describing the response of the plant itself, which has a positive response in either direction. The controller describes a positive response, with suitable damping. The forward transfer describes the combination of these. The plot for the system transfer function describes the entire system, and shows a good response, where all poles and zeros are reasonably matched- showing a system with little to no oscillation. All plots are in the negative real axis, which describes a decaying (opposed to a growing) oscillation.

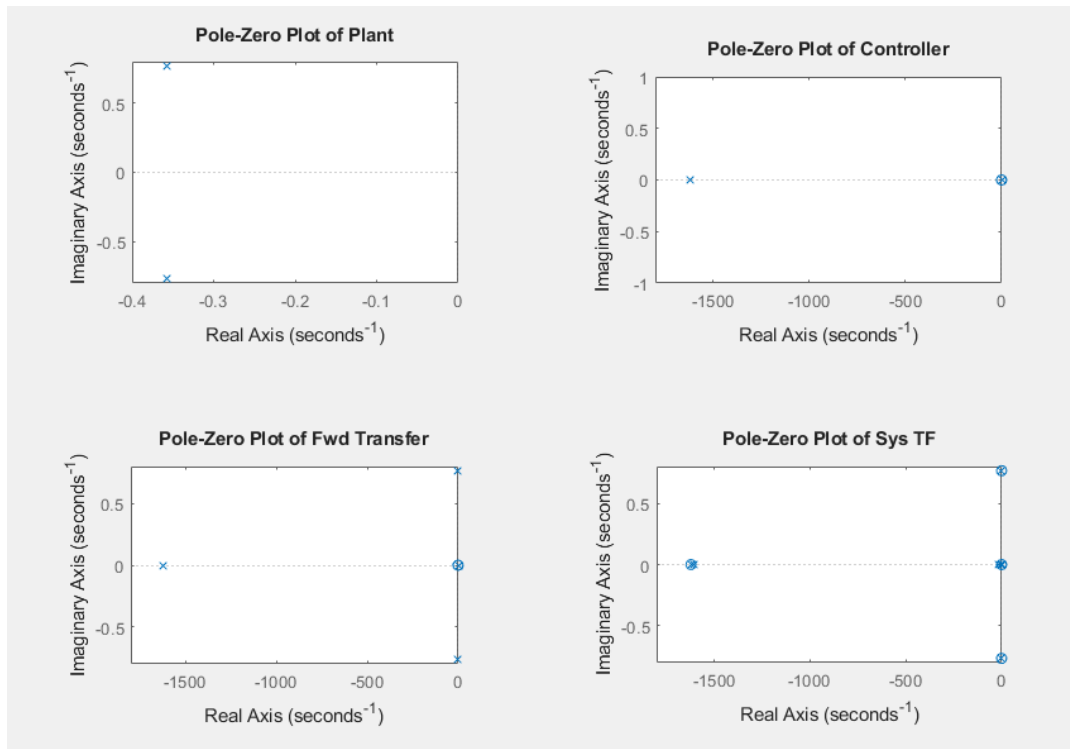


Figure 12 – Pole Zero plots of various elements & full system.

Root locus plots describe the behaviour of a system when the proportional gain is changed. The green axis describes an overdamped system, the red underdamped and the midpoint the critical damping point. In this system, the marks are on either end, showing that it is not critically damped on the real axis, however critical damping may not produce the ideal response, and in this case it is not required.

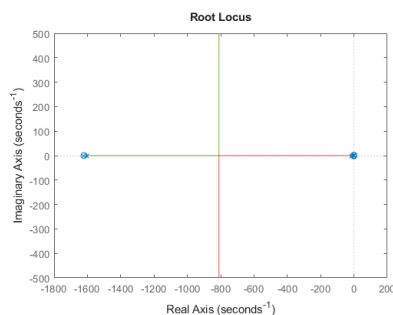


Figure 13 – Root Locus Plot.

Nyquist plots describe the phase and gain margins of the system, where the phase margin is the angle of the blue line passing through. The phase angle is less than π , showing a stable system response.

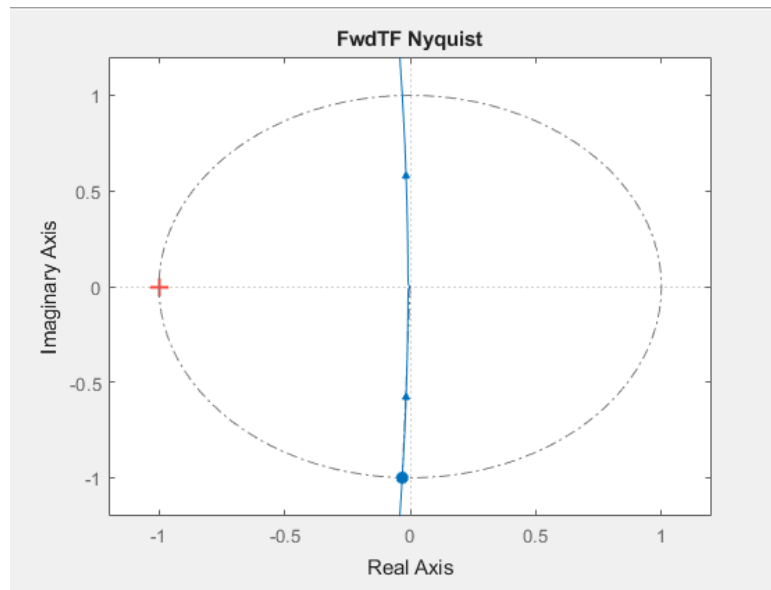


Figure 14 – Nyquist Plot.

7. Discussion

The results produced provide the desired characteristics for the control system specified and provide a strong starting point for real world implementation. However, other limitations exist in the real world, such as available power & mechanical limitations.

In this simulation, control signals show an initial peak of 16×10^4 units, which may be impossible to supply in a real-world application. This mass application of energy could result in overpowering of plant, damage to power supplies or mechanical damage.

Mechanical limitations are the failure points of the plant used. Where in simulation, a system may be able to apply a large force, in reality this could result in mechanical failure. This is not considered in the scope of this simulation but could be considered by relating mechanical limitations to inputted power through an equation.

8. Conclusions

In conclusion, this study provides an insight into the methodologies of designing and tuning PID based control systems. Using methods such as Nyquist plots, Pole-Zero diagrams & root locus plots to determine the response of the system based upon it's tuning.

The solution provided meets the requirements specified, however this likely doesn't provide a solution which is tangible to use in real-world applications, as discussed in section seven

The combination of the sub-systems (plant, controller, subtractor) allows this system to be combined with other systems which it may integrate into- allowing wider system simulation and testing, which is critical for real world integration.

9. References

- [1] Raytheon, “Phalanx Weapon System,” RTX, 01 10 2025. [Online]. Available: <https://www.rtx.com/raytheon/what-we-do/sea/phalanx-close-in-weapon-system>. [Accessed 22 11 2025].
- [2] General Dynamics, “Phalanx CIWS,” GDOTS, 01 03 2024. [Online]. Available: <https://www.gdots.com/armaments/naval-platforms-system/phalanx/#>. [Accessed 22 11 2025].
- [3] S. M. Shinnars, Modern Control System Theory and Design, Volume 1, New York: John Wiley & Sons, Inc., 1998.
- [4] G. C. Goodwin, S. F. Graebe and M. E. Salgado, Control System Design, Newcastle: Centre for Integrated Dynamics and Control, 2000.
- [5] L. Wang, PID Control System Design and Automatic Turning using MATLAB / SIMULINK, Chichester: John Wiley and Sons, 2020.
- [6] T. Walstra, J. Lagerberg and R. V. D. Boomgaard, “Poles and Zeros,” in *Digital Signal Processing*, Oxford, Oxford University Press, 2016, p. 4.2.8.

10. Appendices

Appendix A – Transfer Function Combination

```

MATLAB ▶
Command Window
>> CTf = 1 / 1620.50612732983

CTf =

    6.1709e-04

>> C

C =

      1      s
Kp + Ki * --- + Kd * -----
      s      Tf*s+1

with Kp = 10.6, Ki = 5.03, Kd = 5.54, Tf = 0.00617

Continuous-time PIDF controller in parallel form.
Model Properties
>> C.Kp

ans =

    10.6086

>> C.Kp=102.663201039075

C =

      1      s
Kp + Ki * --- + Kd * -----
      s      Tf*s+1

with Kp = 103, Ki = 5.03, Kd = 5.54, Tf = 0.00617

Continuous-time PIDF controller in parallel form.
Model Properties
>> C.Tf=1/1620.50612732983

C =

      1      s
Kp + Ki * --- + Kd * -----
      s      Tf*s+1

with Kp = 103, Ki = 5.03, Kd = 5.54, Tf = 0.000617

```



```
>> C.Tf=1/1620.50612732983
```

```
C =
```

$$K_p + K_i * \frac{1}{s} + K_d * \frac{s}{T_f s + 1}$$

```
with Kp = 103, Ki = 5.03, Kd = 5.54, Tf = 0.000617
```

Continuous-time PIDF controller in parallel form.

[Model Properties](#)

```
>> C.Ki=11.2175006700687
```

```
C =
```

$$K_p + K_i * \frac{1}{s} + K_d * \frac{s}{T_f s + 1}$$

```
with Kp = 103, Ki = 11.2, Kd = 5.54, Tf = 0.000617
```

Continuous-time PIDF controller in parallel form.

[Model Properties](#)

```
>> C.Kd=98.7634124533389
```

```
C =
```

$$K_p + K_i * \frac{1}{s} + K_d * \frac{s}{T_f s + 1}$$

```
with Kp = 103, Ki = 11.2, Kd = 98.8, Tf = 0.000617
```

Continuous-time PIDF controller in parallel form.

[Model Properties](#)

```
>> G = C * Proc
```

```
G =
```

$$\frac{1.601e05 s^2 + 1.664e05 s + 1.818e04}{7 s^4 + 1.135e04 s^3 + 8108 s^2 + 8103 s}$$

Continuous-time transfer function.

 [Model Properties](#)

```

      1      s
Kp + Ki * ---- + Kd * -----
      s      Tf*s+1

with Kp = 103, Ki = 11.2, Kd = 98.8, Tf = 0.000617

Continuous-time PIDF controller in parallel form.
Model Properties
>> G = C * Proc

G =

      1.601e05 s^2 + 1.664e05 s + 1.818e04
      -----
      7 s^4 + 1.135e04 s^3 + 8108 s^2 + 8103 s

Continuous-time transfer function.
Model Properties
>> SystemTF = G/(1+G)

SystemTF =

      1.121e06 s^6 + 1.819e09 s^5 + 3.187e09 s^4 + 2.853e09 s^3 + 1.495e09 s^2 + 1.473e08 s
      -----
      49 s^8 + 1.589e05 s^7 + 1.3e08 s^6 + 2.003e09 s^5 + 3.436e09 s^4 + 2.984e09 s^3 + 1.561e09 s^2 + 1.473e08 s

Continuous-time transfer function.
Model Properties
>> N1 = cell2mat (SystemTF.Numerator)

N1 =

      1.0e+09 *

           0           0      0.0011      1.8186      3.1867      2.8528      1.4955      0.1473           0

>> D = cell2mat (SystemTF.denominator)

D =

      1.0e+09 *

      0.0000      0.0002      0.1300      2.0028      3.4363      2.9842      1.5611      0.1473           0
fx >>

```