

Stan Collins final report

by Stan Collins

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Control System Design

Instrumentation & Control

ACDA5011

Stan Collins

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2. Abstract

In this report, a CIWS turret is modelled as a transfer function where the components are values from a student number. A PID control system is used to better the performance of the system, reducing overshoot to under 5% and settling time to under 2 seconds. The controller is successful in improving the system output, resulting in a stable system. The closed loop system is then simplified to a single transfer function, which is validated using the error between the two systems. The report concludes that a PID controller could be used to modulate the output of any system that could be expressed numerically.

3. Introduction

The angular positioning system attached to an automatic CIWS turret has the transfer function $G(s)$ given by the equation below, where the components of the denominator are the last three digits of a student number.

$$G(s) = \frac{1}{4s^2 + 2s + 9}$$

This transfer function considers the whole response of the turret system, including the motor powering the turret, turret mass, friction and all other factors.

However, when a step input of 1 is put into this system, the system output settles at 0.1 after 10 seconds, nowhere near the required output. As seen in figure 1, the response is also oscillatory overshooting and undershooting the eventual settled value. Due to this behaviour, a controller is required to tune the output to the desired value, referred to as the set point throughout this report.

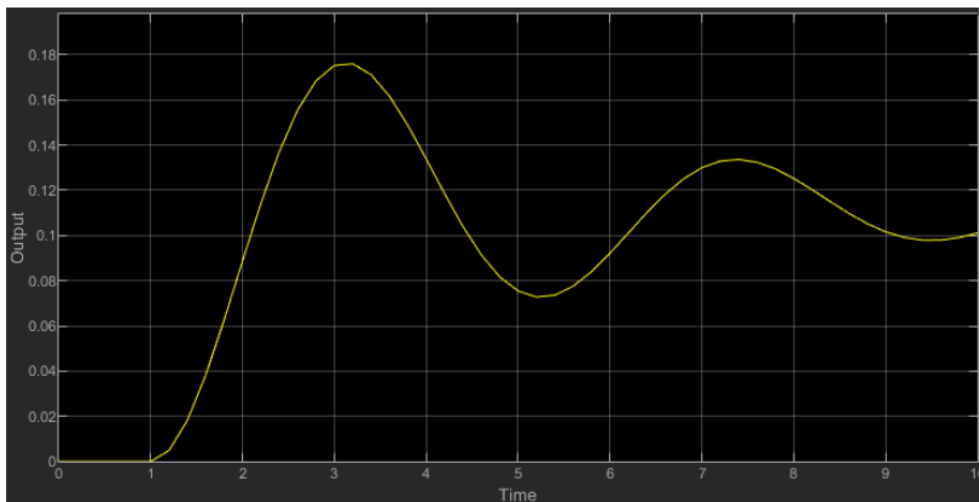


Figure 1: The transfer function response to a step input

Controllers come in many different forms and varieties, but all have the intention to provide a desired system response [1]. This can be in the form of open loop or closed loop systems, and can be applied to any system that can be expressed numerically. Modern applications of control systems are almost limitless, and their presence can be found in everything from spaceship guidance systems [2], temperature controllers for air conditioning units [3], cruise control in modern vehicles [4] or automatic drilling [5].

This report aims to use a PID control system to make the turret output quicker and more accurate. The modified system must have a settling time of under 2 seconds, and have an overshoot of under 5%. The modelling software Simulink will be used to model the system performance and conduct analysis on the system.

4. PID Controllers

PID controllers are closed loop controllers and can be considered in terms of three parameters: P, I and D. Their impacts on the system can broadly be described as follows:

- **Proportional Response (P):** this term is dependent on the error between the desired and actual output. In general, increasing the proportional gain will decrease the response time of the system [6]. Too large a proportional gain can cause the system to overshoot and oscillate. In isolation, a proportional controller will never meet the set point due to the inherent time delays in the system [5].
- **Integral Response (I):** this term adjusts the controller output proportionally to the integral of the error over time. This results in a response from even a small steady state error. The response will increase until the steady state error is zero [3]. A downside to this controller is that if used in isolation the system will not settle and constantly oscillate around the set point [6].
- **Derivative Response (D):** this term acts on the rate of change of the error. It works to reduce the system output if the error is also reducing, as a method of reducing overshoot [6]. Increasing the D parameter will cause the system to react more strongly to changes in the error. Most systems use a small D value as it is highly sensitive to noise in the system, which the controller interprets as changes in the error. Highly noisy systems can cause responses from the derivative controller that make the system unstable [3]. Derivative controllers are never used in isolation, as they produce no corrective effect from a constant error [6].

It is worth noting that none of these controllers effect the system in isolation when combined into a PID controller. Changing the value of the integral parameter can and will affect all elements of the system, irrespective of the effects of the proportional and derivative parameters. The effects of each controller are summed and then sent on to the plant, as seen in figure 2. The output of the PID controller is then fed into the Plant, and then the error is fed back into the PID for further refinement.

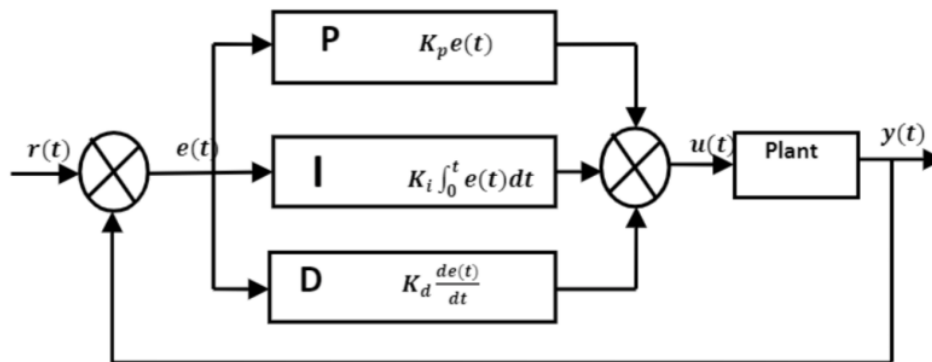


Figure 2: A model of a PID controller configuration [7]

As seen in the circuit diagram, the PID controller only acts on the error between the set point and the output. This makes it an efficient controller as little knowledge of the internal system is required for tuning, meaning it can also be cheaper than other controllers that would require additional sensors [3]. The tuning process itself is relatively simple, and can be done numerically, using code or inbuilt apps, or even micro-controllers.

The PID controller formula as defined in Simulink is given as:

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

where P, I and D and N are constants which can be altered manually or with the assistance of an app.

5. Methodology

The modelling software chosen for this assignment was MATLAB and Simulink, which allowed for the construction and simulation of circuit diagrams.

5.1. Simulink Model

The final circuit used to simulate the problem can be seen in figure 3. The system uses a step input to represent a movement request for the turret. The system here used a PID controller which feeds into the transfer function of the turret, before looping the error back into the system again. A scope is used to plot the initial input, the error between current output and desired value, response from the PID controller and then the output of the transfer function.

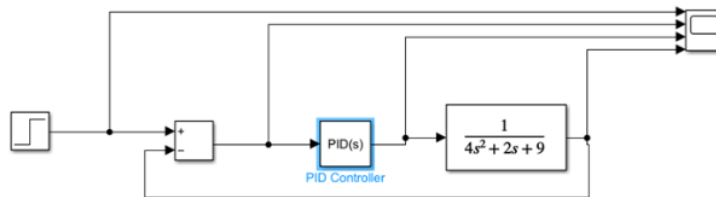


Figure 3: Closed loop control system circuit diagram

The initial response of this system before PID tuning can be seen in Figure 4. The output of the transfer function settles after 10 seconds at around 0.6, an error of 40% from the desired output. As the error never reaches zero, the PID controller always has an output.

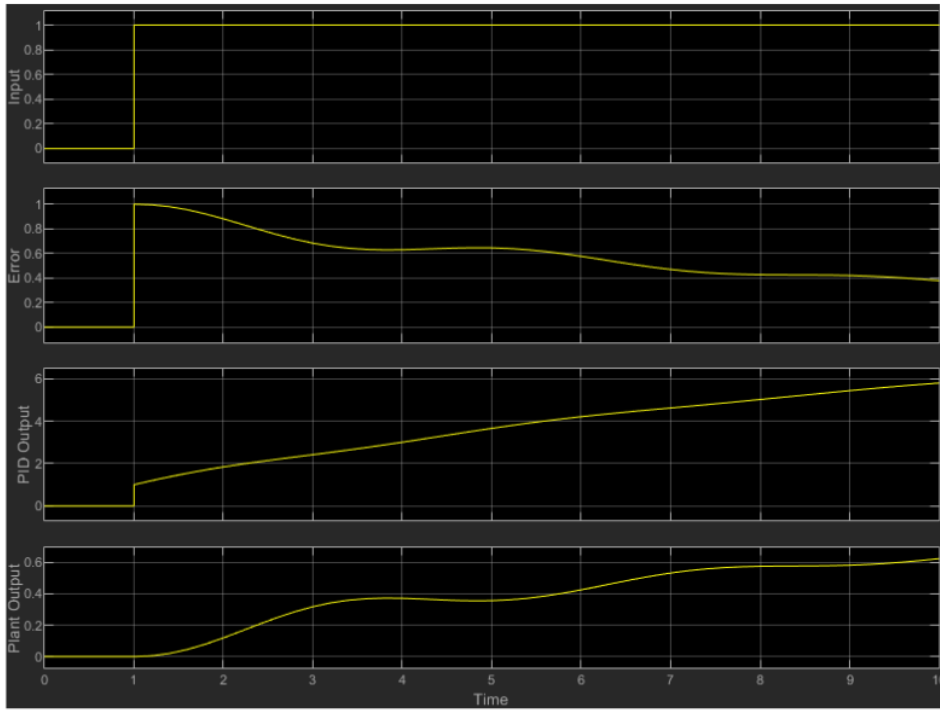


Figure 4: Pre PID tuning system response

5.2. Forward transfer function

In order to complete analysis of the system, the feedback loop must be removed from the system. Each item in the system doesn't happen instantaneously, every action completed introduces delays into the signal, which can be considered as a phase difference on an alternating signal [6]. By representing the system as a single transfer function without a closed loop, the phase difference of the closed loop is removed and its impact on the analysis is negated. The forward transfer function can be considered as the combination of the PID controller and the Plant, represented as:

$$\left(P + I \frac{1}{s} + D \frac{N}{1 + N \frac{1}{s}} \right) \times \frac{1}{4s^2 + 2s + 9}$$

Which, when simplified and the tuned values for P, I, D and N are input (see table 2), becomes:

$$\frac{1.3 \times 10^5 s^2 + 3.24 \times 10^5 s + 1.84 \times 10^5}{4s^4 + 7762s^3 + 3889s^2 + 1.746 \times 10^4 s}$$

5.3. Closed Loop transfer function

To fully simplify the system into a single transfer function, the closed loop must be removed as well. Closed loop systems can be replaced by a single transfer function as seen in figure 5.

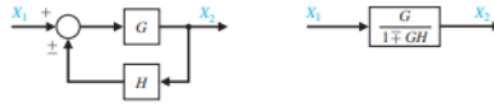


Figure 5: Closed loop system diagram and equivalent diagram [1]

The model in this report has no block in the feedback loop, and so the H term can be considered as 1. When applying this to the Simulink model, the simplified system can be represented as:

$$\frac{5.731 \times 10^5 s^2 + 1.388 \times 10^6 s + 3.755 \times 10^5}{4s^4 + 1.622 \times 10^4 s^3 + 5.812 \times 10^5 s^2 + 1.424 \times 10^6 s + 3.755 \times 10^5}$$

A full breakdown of the simplification can be found in appendix A.

6. Results

The result of the PID tuning on the system can be seen in figure 6. The system now settles at the set point and is deemed settled by the system after only 0.314 seconds. It only overshoots by 3.51%, reaching a maximum output of 1.04. It is also a stable system, settling at a value rather than oscillating to infinity and breaking. A comparison of system robustness can be seen in table 1, and the initial and tuned values for the PID parameter can be seen in table 2.

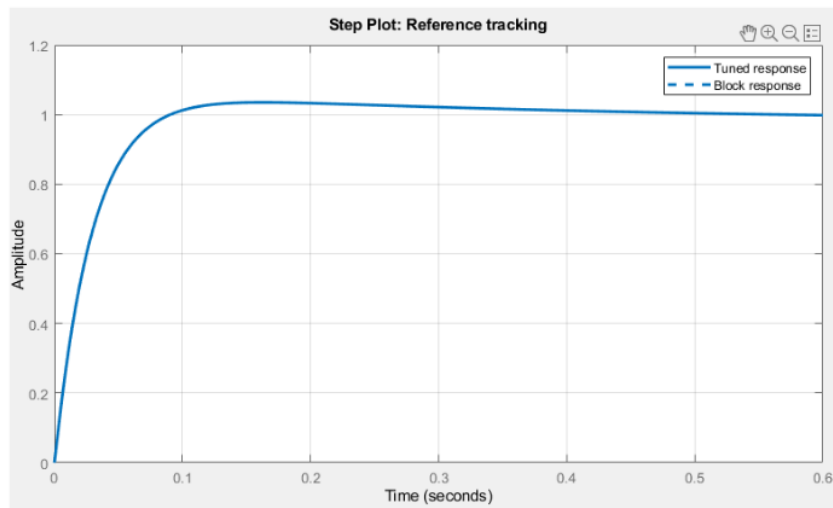


Figure 6: Output of the closed loop system with a tuned PID controller.

Table 1: Pre & post PID tuning system response

	Pre-Tune	Post Tune
Rise time	20.08 seconds	0.0541 seconds
Settling time	37.6 seconds	0.314 seconds
Overshoot	0%	3.51%
Peak	0.999	1.04
Gain margin	19.1 dB at 2.12 rad/s	Infinite
Phase margin	95° at 0.112 rad/s	86.4° at 25.5°
Closed-loop stability	Stable	Stable

Broader system output can be seen in figure 7, which plots input, system error, PID output and plant output. The PID initially has a massive response, due to the requirement to settle quickly, and then reduces to near zero as the error also reduces.

Table 2: Pre and post tuning parameters for the PID controller.

	Initial	Tuned
P	1	342.3476
I	1	92.6388
D	0	141.2997
N	100	4053.4406

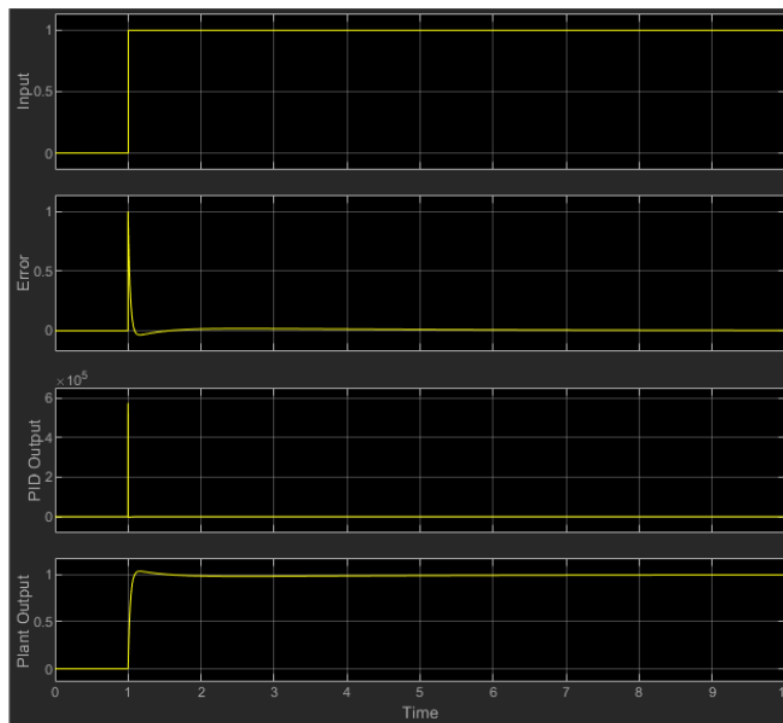


Figure 7: Post PID tuning system response

Before performing analysis on the system, the simplified closed loop system transfer function (as defined in section 5.3) had to be tested to ensure its output matched that of the initial system. Figure 8 shows a new system diagram where the output of the simplified system is taken away from the initial system, leaving the difference between the two systems.

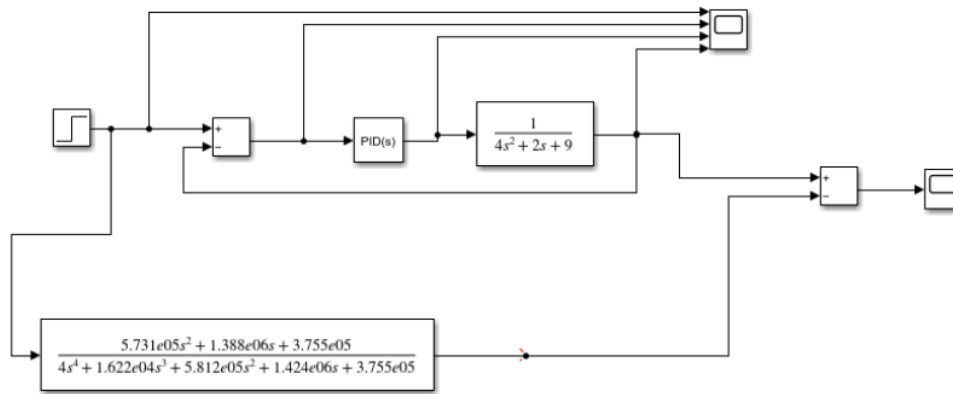


Figure 8: the system diagram measuring the error between the initial system and the simplified transfer function.

The output of the simplified system is shown in figure 10, and the error between the simplified system and the initial system can be visualised in figure 9, where it reaches a peak error of 0.03%, before stabilising towards a reduced error. This peak error occurs at around 2 seconds, during the first undershoot of the system response, before it corrects itself.

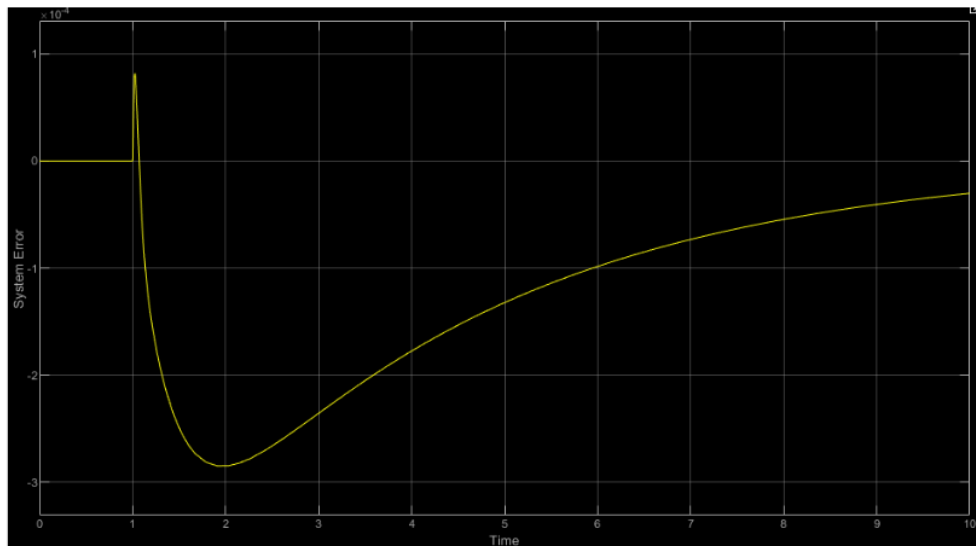


Figure 9: The error between the system transfer function and the initial system

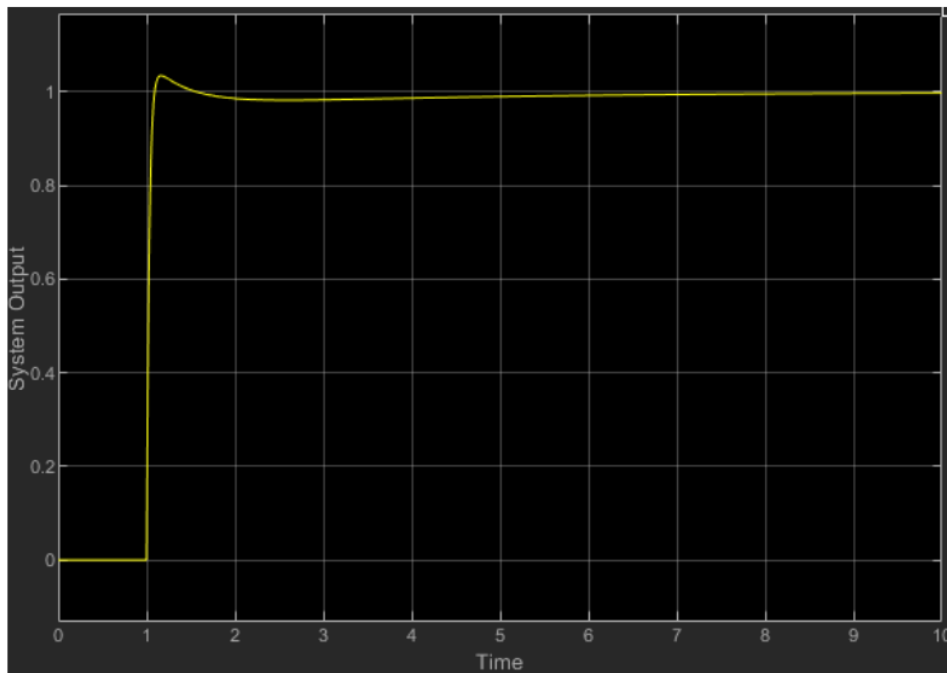


Figure 10: Output of the simplified system transfer function

6.1. Stability analysis

Using the system transfer function, various plots can be created to analyse the performance and stability of the system. Figure 11 shows three pole-zero plots of the various versions of the system.

The far-left plot shows the Plant, with poles at $-\frac{1}{4} \pm \frac{\sqrt{35}i}{4}$, meaning it was a stable process, with two components that would decay in a sinusoidal form.

As the far-right plot shows, the system transfer function has no poles or zeros on the positive of the real axis, meaning the system is in a state of decay towards zero and is therefore a stable system.

The lack of any poles on the imaginary axis of the pole-zero plot means no component will have an oscillatory or sinusoidal decay, rather all components will have an exponential decay response. The far-left pole is the dominate pole and defines the sharp rise of the output [6].

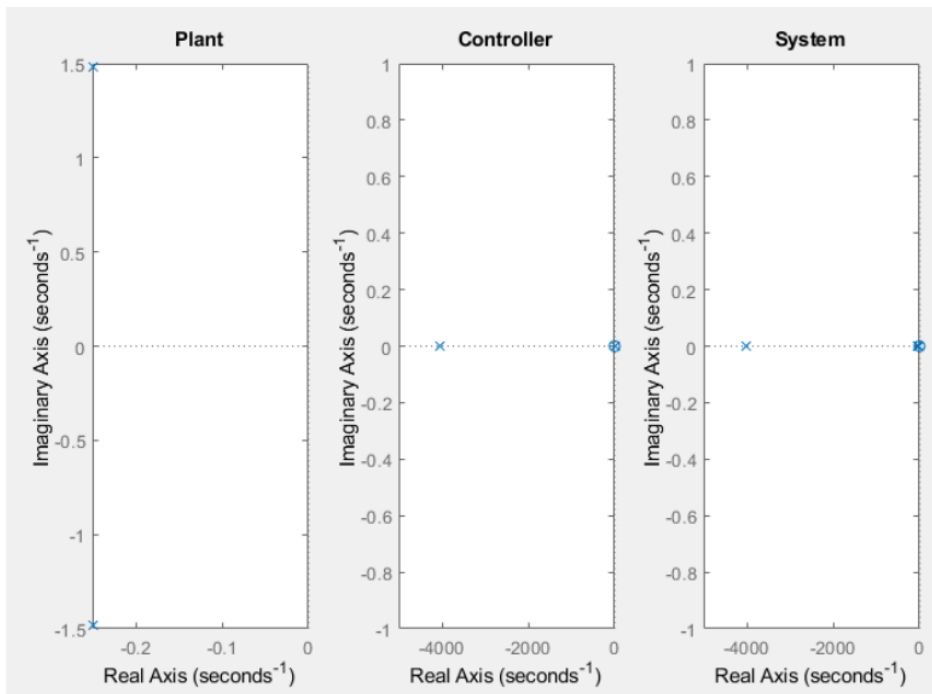


Figure 11: Plot-Zero plots of (from left to right) the Plant, Controller and System. Poles are represented as x, and zeros are seen as an o.

Further analysis on the stability of the system can be seen in the Nyquist and Bode plots of the forward transfer function in Figure 12. The Bode diagram shows the frequency response of the system, with respect to magnitude or gain, and phase. The gain margin for this transfer function is infinite, meaning that no matter the gain is increased, the system will remain stable [6]. The phase margin for this system is positive at 86.4 degrees. Typical systems deem a phase margin of above 30 degrees are deemed stable [1], but the larger the phase margin the more stable the system [6].

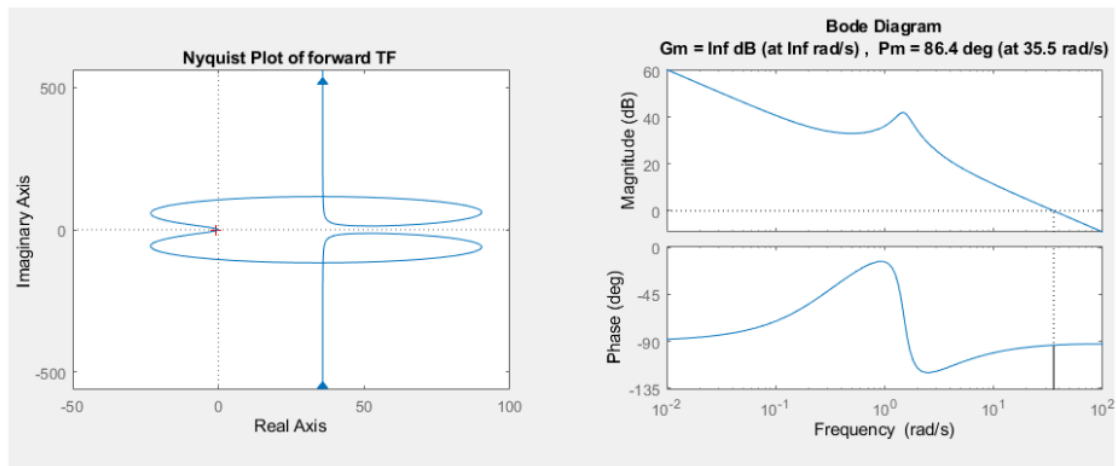


Figure 12: Nyquist Plot (left) and Bode Diagram (right) of the forward transfer function.

The Nyquist plot also demonstrates the performance of the system. Gain and phase margins can be read off the Nyquist plot as a way to double check the Bode plot. The Nyquist plot never reaches -180° (it never crosses the negative real axis) and so has an infinite gain margin [6]. The angle between where the plot crosses a unit circle from the origin and the negative real axis is the phase margin, which matches up to the response from the Bode diagram. [8]

7. Discussion

The PID controller after tuning meets the conditions laid out in the assignment brief, having an overshoot under 5% and a settling time under 2 seconds. It also increases the performance of the system so that its output does reach the desired set point of the system. When comparing the output of the plant alone and the system, you can see that the controller has removed the sinusoidal response, as confirmed by the Pole-Zero plot of the overall system.

The system is deemed highly stable, especially with an infinite gain margin. In mechanical systems, an infinite gain margin isn't realistic, as mechanical wear would be present and material properties would eventually fail.

Assuming this step input is representative of the full range of movement from the turret (300°), the response from the system as simulated in this report would be over $3000^\circ/\text{s}$, around 30 times faster than the real-life performance of an actual Phalanx CIWS, which has a maximum rotational speed of $115^\circ/\text{s}$ [9]. This discrepancy likely comes from real world parameters such as friction, the mass of the turret, and the inertia that must be overcome to move a mass that large [8]. The force required to move a mass that quickly would be astronomical and would require an equally massive force to stop it once it reached its target. It is therefore a safe conclusion that this simulation does not represent the real-life performance of the turret.

Irrespective of real-world comparisons, the PID controller was successful in tuning the output of the transfer function to its desired solution. It demonstrates that for any problem that can be simplified to a transfer function, a PID controller can correct for error in that system, and that the response of the correction can be adjusted to suit the needs and requirements of the user. It is also worth noting that it was not the 'real system' being analysed here, rather a transfer function made from the last digits of a student number. No element of real-world performance was used to develop the transfer function, no parameter estimation or system identification took place, and so the problem in this assignment simply represents any system that could be defined as a quadratic transfer function.

As demonstrated in figure 10, the simplified system transfer function had a similar output to the initial system, validating the transfer function derivations as seen in section 5. However, figure 9 illustrates that the system could use refinement.

As seen in figure 9, the system error is as high as 0.03% for at least the first 5 seconds. While this is acceptable to perform analysis on the system, this error is relatively high. This could potentially be caused by rounding errors in carrying constants between the PID controller and the Matlab interface for calculations, although attempts at reducing this error did not produce better results.

8. Conclusion

In conclusion, this report finds that the PID controller was able to tune the plant output to the desired margins as given in the brief. The plant used in this assignment acts as a stand in for any system that could be modelled numerically, and so demonstrates the PID controller's ability to modulate any system output. The performance of this system is only representative of a stable system, as a system with poles in the positive real axis would demonstrate unstable outputs, either exponentially or sinusoidally. Real life systems would likely be less stable and respond slower or with more error on account of mechanical limitations.

9. References

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10. Appendix A – Forward and system transfer function derivations

Simplification of closed loop system as single transfer function.

(1) Forward transfer function:

$$\left(P + I \frac{1}{s} + D \frac{N}{1 + N \frac{1}{s}} \right) \times \frac{1}{as^2 + bs + c}$$

Where a, b, and c represent the integers of the Plant, and P, I, D and N are the parameters from the controller.

Simplified:

$$\frac{Ps^2 + PNs + Is + IN + DNs^2}{s(s + N)(as^2 + b + c)}$$

Simplified:

$$\frac{(P + DN)s^2 + (PN + I)s + IN}{as^4 + (aN + b)s^3 + (bN + c)s^2 + cNs}$$

(2) Closed loop system:

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

Where G is the forward transfer function and H is any function on the error. As this system has no such operation, H is equal to 1 for this simplification.

Therefore:

$$\frac{\frac{(P + DN)s^2 + (PN + I)s + IN}{as^4 + (aN + b)s^3 + (bN + c)s^2 + cNs}}{1 + \frac{(P + DN)s^2 + (PN + I)s + IN}{as^4 + (aN + b)s^3 + (bN + c)s^2 + cNs}}$$

Simplified:

$$\frac{\frac{Ps^2 + PNs + Is + IN + DNs^2}{s(s + N)(as^2 + b + c)}}{\frac{as^4 + (aN + b)s^3 + (bN + c)s^2 + cNs + (P + DN)s^2 + (PN + I)s + IN}{s(s + N)(as^2 + b + c)}}$$

Simplified:

$$\frac{Ps^2 + PNs + Is + IN + DNs^2}{as^4 + (aN + b)s^3 + (bN + c)s^2 + cNs + (P + DN)s^2 + (PN + I)s + IN}$$

Simplified:

$$\frac{(P + DN)s^2 + (PN + I)s + IN}{as^4 + (aN + b)s^3 + (bN + c + DN + P)s^2 + (cN + I + PN)s + IN}$$

Stan Collins final report

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

Instructor

72/100

PAGE 1

PAGE 2

PAGE 3



Comment 1

Introduction Part should include the background information about control systems. A detailed explanation is needed to relate where exactly the principles of control systems are used, its applications etc.. Also it is necessary to give a brief introduction about the history of turrets and its advantages.

PAGE 4



Comment 2

Good

PAGE 5

PAGE 6

PAGE 7



Comment 3

Good, you have made a stable system.

PAGE 8



Comment 4

settling time and the overshoot values are up to the expectation

PAGE 9

PAGE 10

PAGE 11

PAGE 12



Comment 5

Well Done



Comment 6

Good Findings

PAGE 13

PAGE 14

GRADING FORM: SMU GENERIC_SMOSEY

STAN COLLINS

72

ENGAGEMENT WITH LITERATURE

including reading, referencing, academic conventions and academic honesty



In-text referencing from relevant and diverse academic and industry sources were made extensively.

It is necessary to give a brief introduction about

7

the turrets and its advantages which is relatively lacking.

KNOWLEDGE & UNDERSTANDING

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



Its good that you have explained the concepts of PID controller. You should also use resource statements to show how turrets will make use of PID Controllers to turn its positions.

21

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.



Settling time and the overshoot values are up to the expectation.
The graphs are presented well with proper labelling's.
Needs more points on interpreting the results.

21

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



Proper simulation tool is used.
The graphical outputs are up to the expectations.
Discussions on findings are satisfactory.

16

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.



A good flow is maintained through the report.
Evidences of proper use of the spelling and grammar and a complete and neat presentation of work is seen.

7