

University of Wales Trinity Saint David

Instrumentation & Controls



Control System Design

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Abstract

This report showcases simulations designed on Simulink tuned to specific thresholds. The last three digits of the student identification number is used to get different/unique results. The graphs show the difference between the untuned and tuned PID. Using the data from the simulation, the transfer function of the closed loop control system is solved in the simulation steps.

The report also highlights the advantages of closed-loop systems, such as better accuracy, resilience to disturbances, and resource efficiency. It also presents the Phalanx CIWS, a radar-controlled naval defence system, as an example of a complex closed-loop system with multiple components and sensors.

Introduction

The purpose of this report is to find the transfer function of a closed loop system. The transfer function represents the relationship between the output and all inputs of the control system [1]. A closed loop control system is designed using technical computer software, MATLAB, and Simulink. Simulations will be run to compare systems with different tuning. Systems that are capable of controlling a system such as the angular positioning system attached to an automatic Control In Weapon System (CIWS) turret will also be included in this report.

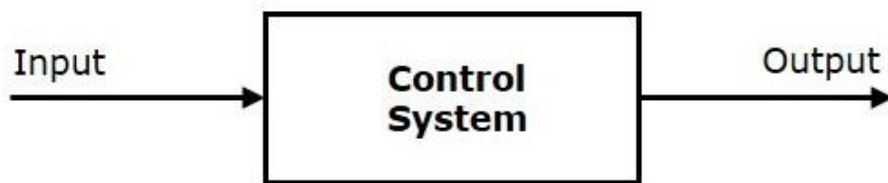


Figure 1: Open Loop Model: Adapted from [2]

A control system is a set of mechanical or electronic devices, usually computerized, that regulates the behaviour of other systems using control loops.

There are two types of control systems that are used by many industries worldwide in the likes of production and distribution [2]. The two types are open loop control systems and closed loop control systems. An open loop control system has no feedback meaning that the input will be applied for a constant time regardless of what the output is whereas a closed loop system is dependent on the process output.

Open Loop Control System

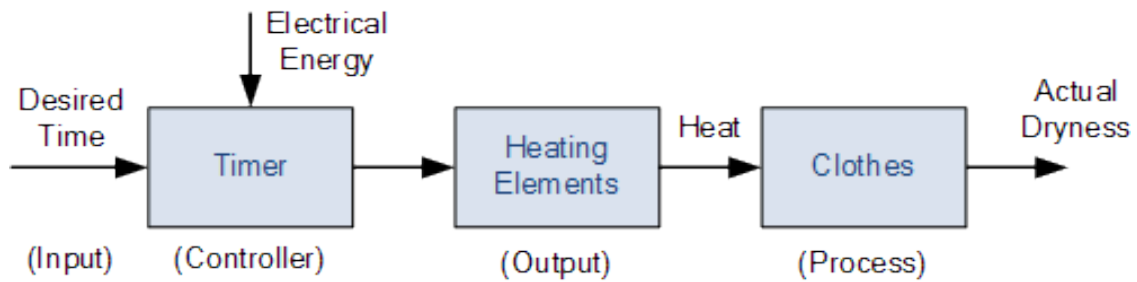


Figure 2: Dryer Open Loop Model: Adapted from [3]

Figure 2 shows an open control system for an electric clothes dryer. The user will select a setting on the appliance, and it will do exactly that. The system will not know whether the clothes in the dryer are still wet and will not submit feedback to the input making this an open loop system [3].

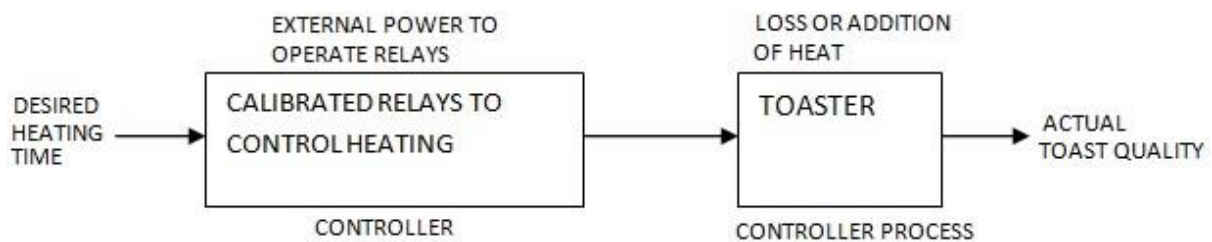


Figure 3: Toaster Open Loop Model [4]

Figure 3 shows the open system for a toaster. Once again, there is no feedback in this system. A system like this can quite easily be engineered to being a closed loop system by adding a device that would measure the quality of the toast.

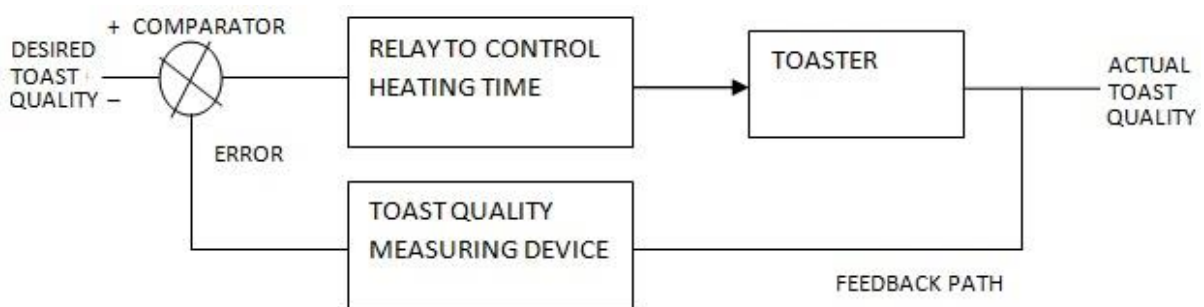


Figure 4: Toaster Closed Loop Model: Adapted from [4]

Figure 4 shows a closed loop system of a toaster which has a toast quality measuring device implemented [4].



Figure 5: Traffic Light Open Loop Model. Source: Adapted from [5]

Figure 5 is an open loop control system for an original traffic light. The first ever traffic light in Britain was in Piccadilly, London (1926) and was manually operated. A year later (1926/1927), an automatic traffic light, working off a timer, was introduced with a similar model to the control system in Figure 5 [6].

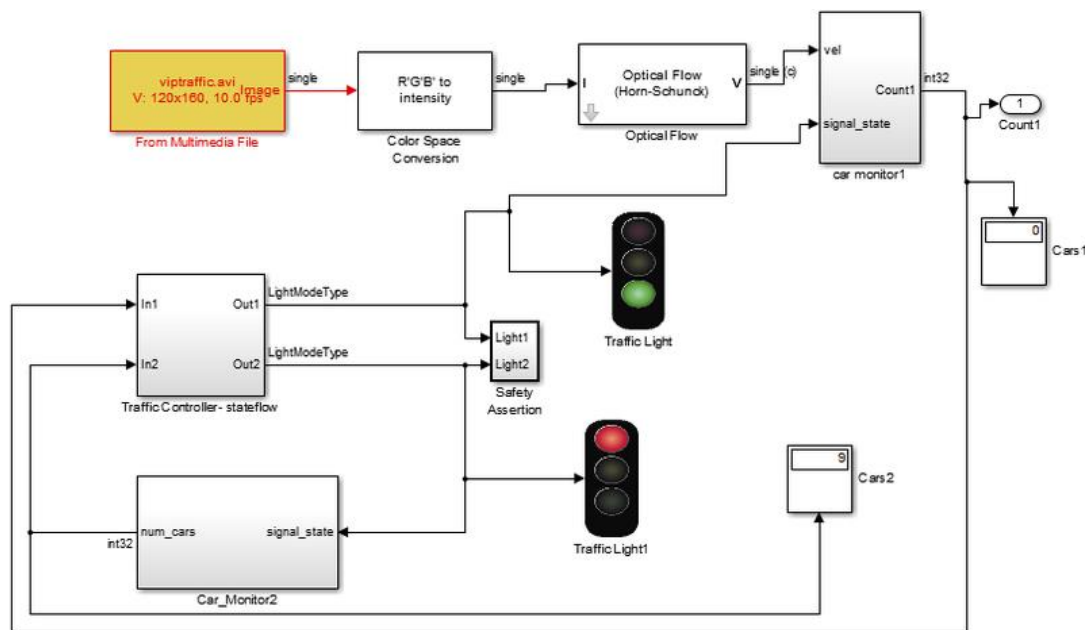


Figure 6: Traffic Light Closed Loop Model: Adapted from [7]

A way that traffic lights can be made more efficient is to add a monitoring system. Figure 6 shows a closed control system for an actuated traffic light system. It can be seen in Figure 6 how the system used a “car monitor”, like a radar device, to detect cars and control the lights/traffic.

Open loop systems are simplistic as they require no measurement. They are also inexpensive to design and maintain in comparison to closed-loop systems. However, open-loop systems come with limitations such as poor reliability and flexibility. Open loop systems find it difficult to adapt to uncertainties and self-correct themselves from accidental stoppage. It also has poor accuracy due to there being no unwanted system performance.

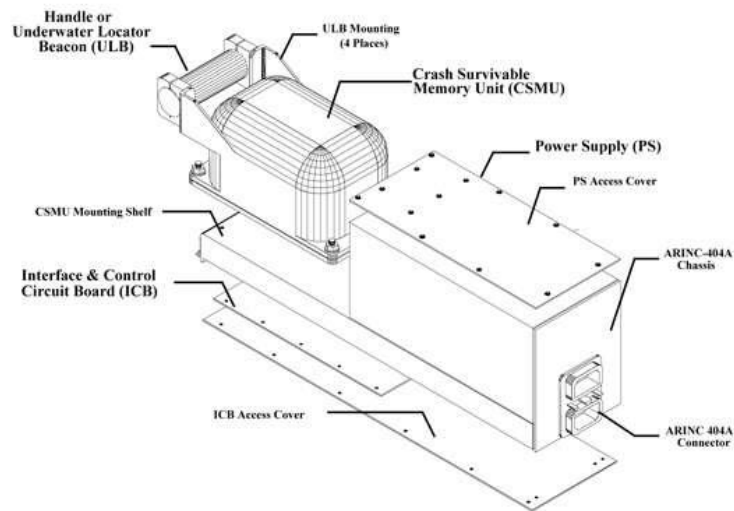


Figure 7: Flight Radar Recorder: Adapted from [8]

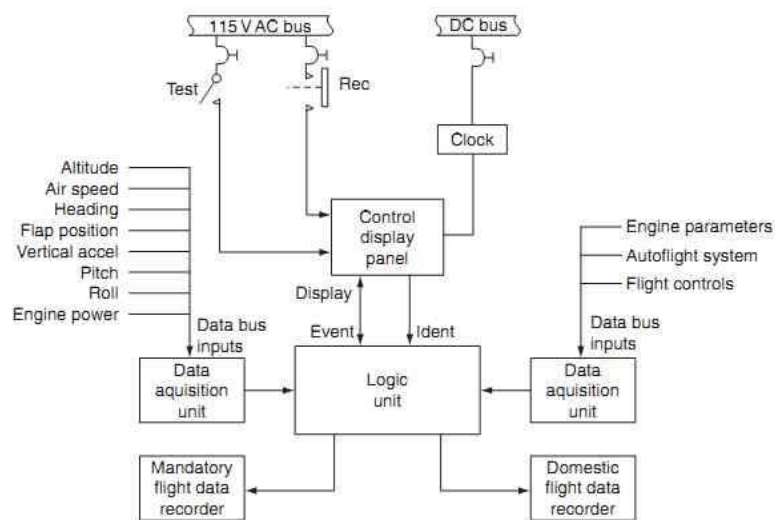


Figure 8: Flight Data Recorder System Model: Adapted from [9]

Figure 8 is an open-loop flight data recorder system. It autonomously collects and records essential flight parameters without using feedback or intervention. It operates passively, observing the flight without influencing the aircraft's control systems. The recorded data is analysed post-flight for safety and performance insights [9].

Closed Loop Control System

An example of the difference between a closed loop system and an open loop system is the cruise control system found in most modern-day vehicles. When the driver enables cruise control, the system will control the vehicles throttle and vary the engine power (system output) so that the wheels of the vehicle will maintain the speed they desire (desired system output).

Cruise control is a closed loop system because feedback is required for it to work. The reason feedback is required in cruise control is because of the many factors it needs to consider such as cargo weight, inclination, and resistance from wind. When driving, it is very unlikely for the road to be perfectly flat so the system must consider when the vehicle is changing terrain to maintain a constant speed. When the vehicle is travelling up an inclined surface, more throttle is required/applied to maintain a constant speed whereas when the vehicle is on a decline less throttle will be required/applied [10].

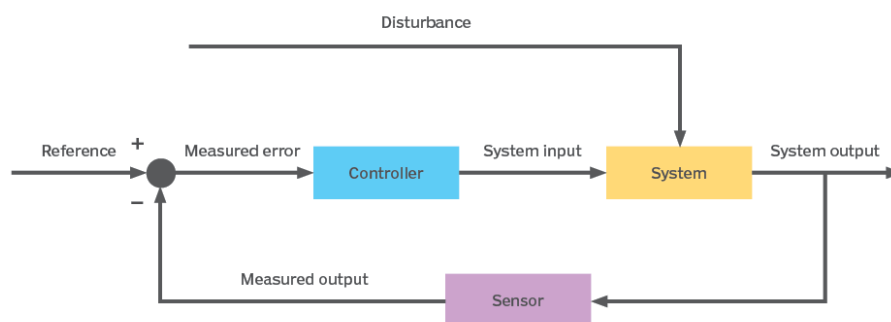


Figure 9: Closed Loop Model: Adapted from [10]

Closed loop systems can get complex and tend to be more frightening than an open loop system. Lots of different devices/systems are added to accurately send feedback to the input. Many modern-day inventions are open-loop systems that have been re-engineered to be closed-loop.

Other examples of closed-loop systems:

- Air-Conditioning
- Missile launch system
- Radar
- Smoke detector system
- Light Bulb
- Hand Dryer
- Television Remote
- Inkjet printer

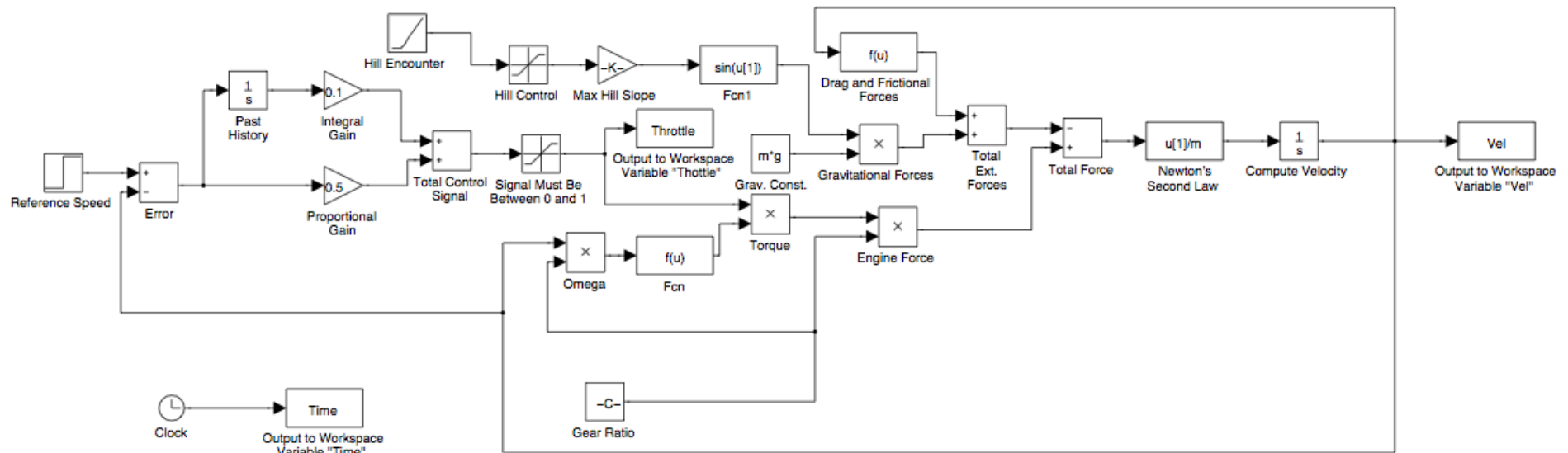


Figure 10: Cruise Control Closed Loop Mode: Adapted from [10]

Figure 3 is a complex system diagram, designed on Simulink, of a closed loop system for the cruise control function in a vehicle. There are many advantages of using a closed loop system, one being accuracy. Mathematical operations are used in this system to produce a suitable output for the scenario that the vehicle is experiencing [11].

Advantages

- Capable of controlling external factors
- Reliability and stability in outputs
- Resilience upon disturbances and changes
- Resource-efficient

Disadvantages

- Greater complexity
- Requires tuning or integration
- Susceptible to oscillation or runaway conditions
- Failure in sensors will cause unwanted system performance

Closed-In Weapon System

The Phalanx CIWS (Close-In Weapon System) is an advanced, radar-controlled, autonomous naval defence system designed to provide rapid, accurate, and highly effective protection against incoming threats such as anti-ship missiles, aircraft, and small boats, utilizing a high rate of fire and advanced tracking sensors. The Phalanx is equipped with a M61 Vulcan Gatling-style rotary cannon. The M61 Vulcan is a 20mm calibre, six-barrelled gun that is capable of firing at an extremely high rate, typically around 4,500 to 6,000 rounds per minute [12].

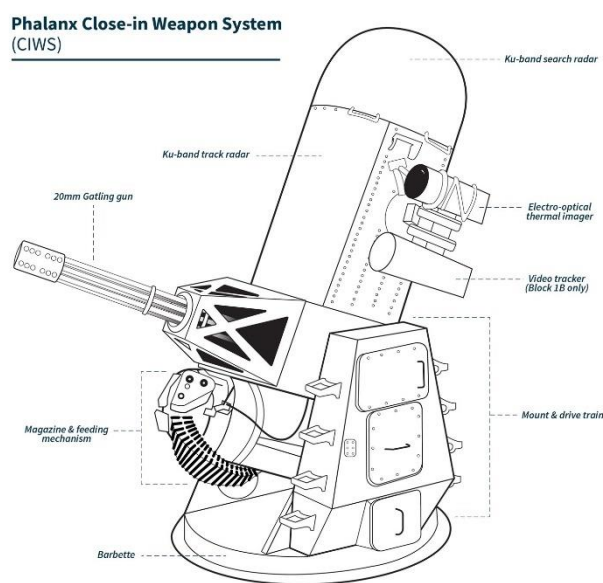


Figure 11: CIWS Technical Image: Adapted from [13]

The Phalanx CIWS comprises a radar system for threat detection and tracking, a computerized fire control system for evaluating and calculating firing solutions, electro-optical sensors for enhanced tracking capabilities, a versatile control interface for manual or autonomous operation, an ammunition storage magazine for the M61 Vulcan, power and cooling systems to sustain operational readiness, a stabilized mounting platform for precise tracking, safety mechanisms to prevent accidental engagements, and integration with the ship's combat management system for coordinated defence with other onboard weapons and sensors [13].

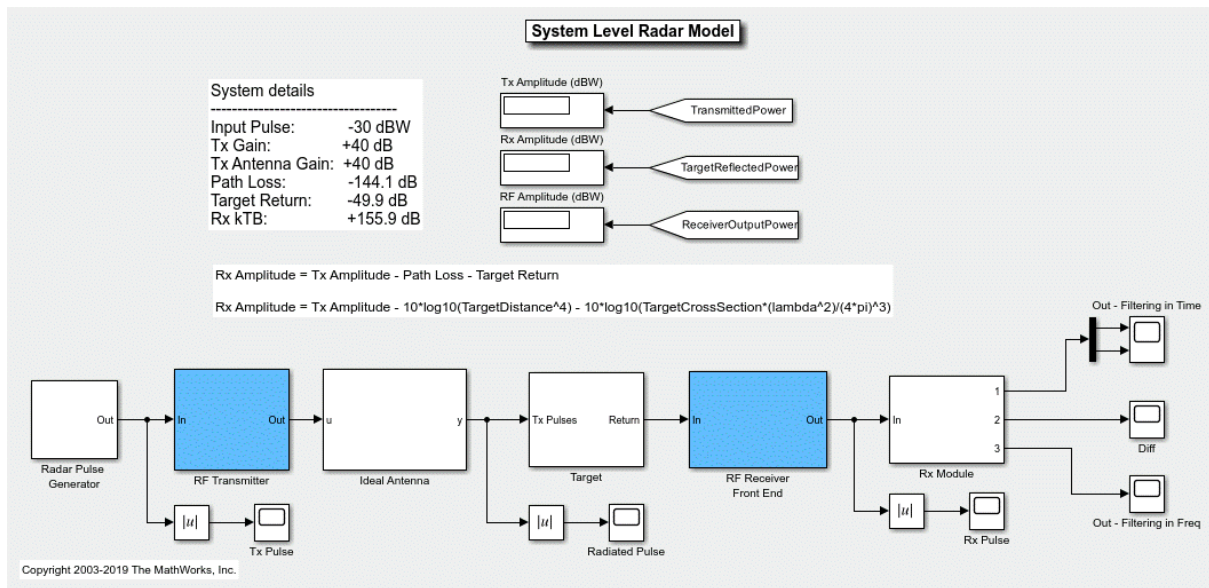


Figure 12: Radar System Model: Adapted from [14]

Figure 5 shows the radar system simulation, like what would be used in a CIWS. This system consists of a transmitter, a channel (with a target) and a receiver.

A basic radar system diffuses and emits high-energy wave signals that are transmitted until they reach the target/object. The signal (reverberated signal) will then bounce back and be received by the detection system [15].

The Radio Frequency (RF) Transmitter consists of a filter and an amplifier. The radar uses a high-performance filtering device to easily isolate the required information from external interference noise.

The amplifier is a non-linear device which amplifies the reverberated signal [16]. For the signal to be exported into visual data, the amplifier must amplify the reverberated signal as it is weak in comparison to the signal transmitted [17].

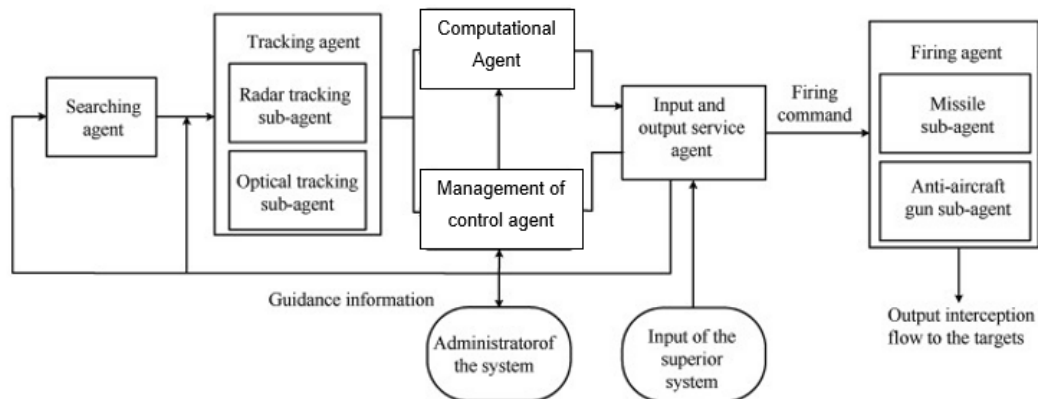


Figure 13: CIWS Model: Adapted from [18]

An ideal antenna element with specified boresight gain operating at 2.1 GHz. This number is the gain which is the ability that the antenna must radiate or direct electromagnetic energy in a specific direction. Various factors will contribute to the antenna having a gain of 2.1 GHz in this simulation, such as the antenna's design, size and shape, simulation parameters, operating frequency, and environmental factors.

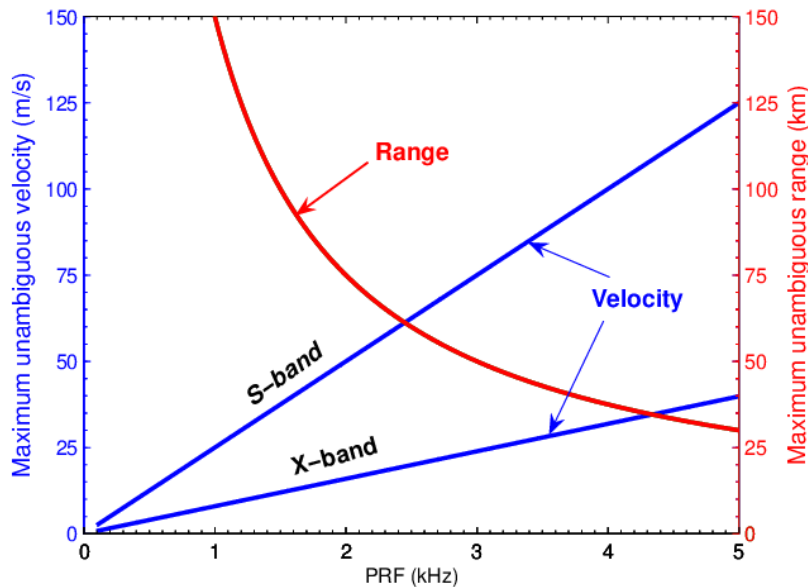


Figure 14: Radar Bands Graph: Adapted from [14]

X-band: The frequency range spans approximately 8 to 12 GHz, making it extensively utilized in diverse military applications, particularly in CIWS systems, owing to its exceptional capability to deliver high resolution and accuracy.

S-band: The S-band radar functions within the frequency range of around 2 to 4 GHz, providing improved penetration capabilities through challenging weather conditions, albeit generally exhibiting slightly lower resolution when compared to the X-band.

C-band: Operating within the frequency range of approximately 4 to 8 GHz, the C-band radar finds application in CIWS systems for specific purposes, although it is not as prevalent as the X-band and S-band radars.

Many CIWS systems use X-band or S-band radars, but some advanced systems may incorporate other frequency bands as they offer greater performance and countermeasure resistance.

The CIWS also has an RF Receiver which has In a CIWS radar system, a Low-Noise Amplifier (LNA) is used to make the radar more sensitive and accurate. It amplifies weak incoming signals from targets, improves the system's ability to detect small or distant targets, and reduces the noise in the receiver. This helps the radar to work effectively in identifying and tracking potential threats like missiles and aircraft.

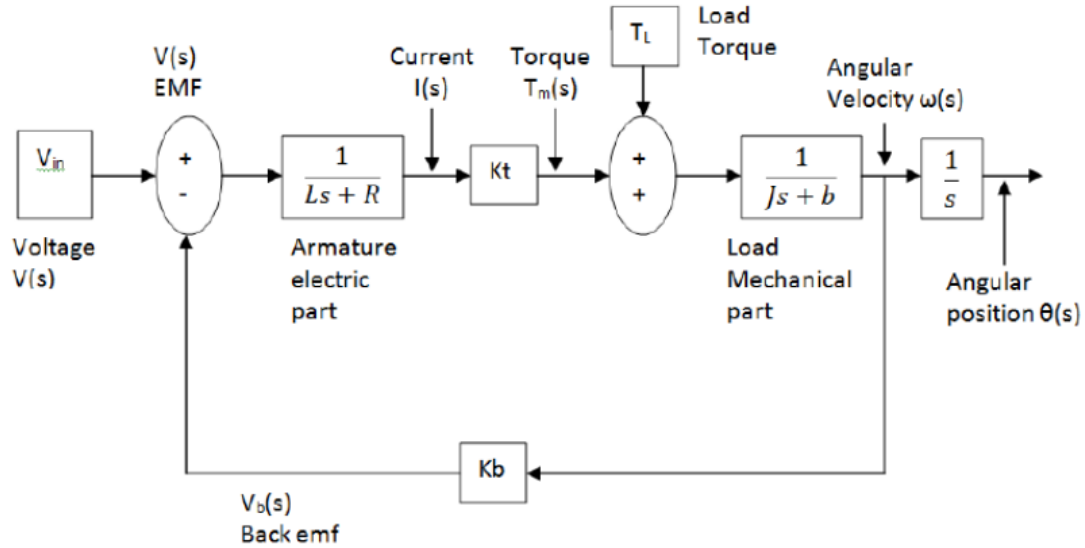


Figure 15: Angular Positioning System Model: Adapted from [19]

Figure 11 is an angular positioning system model that relates the input voltage to the angular position. This is a similar setup to what is used in the CIWS. This is used in conjunction with the radar system in Figure 10. The radar system locates and tracks the target then the angular positioning system positions align the CIWS with the target. The CIWS firing system will then activate and eliminate its target.

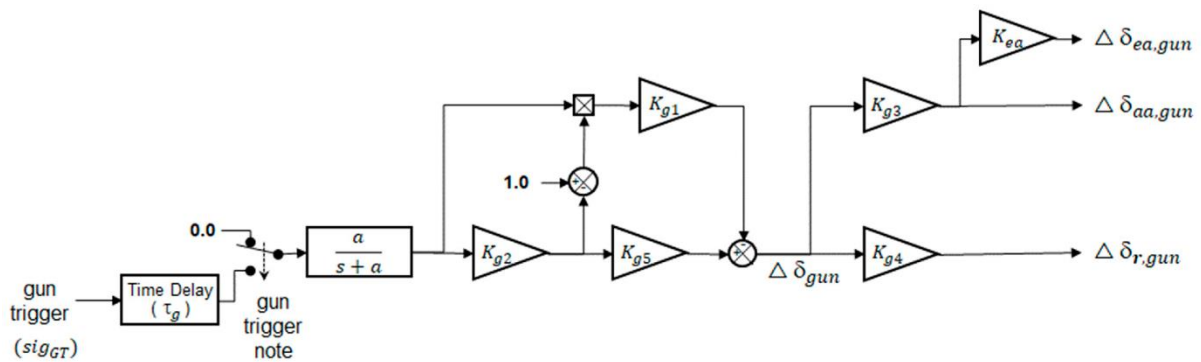


Figure 16: open-loop gun compensation control: Adapted from [19]

Figure 12 is a firing system which would be like the one used in a CIWS [19].

Simulation Setups

Step

Step time: 1

Initial value: 0

Final value: 1

Sample time: 10e-6

List of signs: + - (Enables thorough assessment of system behaviour and design for handling both positive and negative inputs effectively.)

PID Controller

Proportional (P): 1

Integral (I): 1

Derivative (D): 0

Filter coefficient (N): 1

Tuner

Settling time to be within 2 seconds

Want Overshoot to be below 5%

Response Time: 0.1290s

Transient Behaviour: 0.846

Transfer Function

Number of coefficients: [1]

Denominator coefficients: Change from [1 0 1] to [2 1 2]

Student ID: 2114212

Scope

Number of input ports: 4

Sample time: -1

View

View then select "Legend" (organizes and documents complex models)

View then select Style to change appearance such as colour and line type.

Method

Student ID: 2114[212]

$$a = 2$$

$$b = 1$$

$$c = 2$$

$$P = 56.3217s$$

$$I = 16.0867$$

$$D = 30.7169s^2$$

$$\frac{D(ds^2) + P(kps) + I(ki)}{s}$$

$$\frac{1}{as^2 + bs + c}$$

$$\frac{1}{2s^2 + s + 2}$$

$$\frac{kds^2 + kps + ki}{s} \times \frac{1}{2s^2 + s + 2}$$

$$\frac{30.7169s^2 + 56.3217s + 16.0867}{s} \times \frac{1}{2s^2 + s + 2}$$

$$\frac{30.7169s^2 + 56.3217s + 16.0867}{2s^3 + s + 2}$$

$$\frac{30.7169s^2 + 56.3217s + 16.0867}{2s^3 + s + 2}$$

$$1 + \left(\frac{3s^3 + 30.7169s^2 + 56.3217s + 16.0867}{2s^3 + s + 2} \right) \times 1$$

$$\frac{30.7169s^2 + 56.3217s + 16.0867}{2s^2 + s + 2}$$

$$\frac{2s^3 + 31.7169s^2 + 56.3217s + 16.0867}{2s^3 + s + 2}$$

$$\frac{30.7169s^2 + 56.3217s + 16.0867}{2s^3 + 31.7169s^2 + 56.3217s + 16.0867}$$

Results

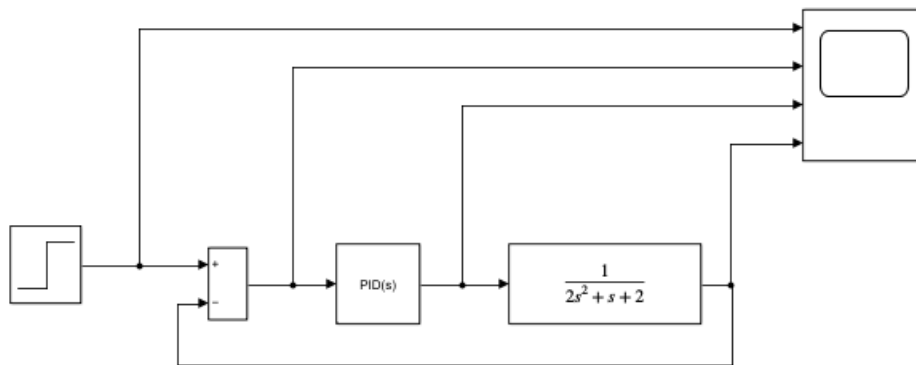


Figure 17: Closed Loop System Designed on Simulink Using Student ID

Figure 17 is the closed loop circuit built on Simulink where the transfer function can be seen using numbers [2 1 2]. These numbers were difficult to tune and required a lot of time to get a decent overshoot and settling time. Below are some of the failed attempts:

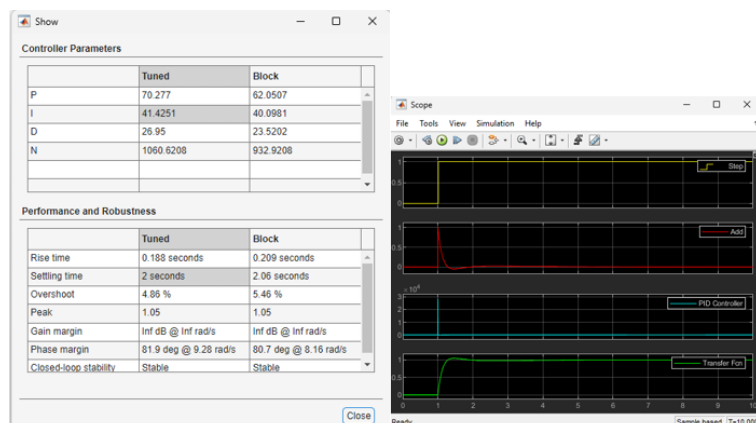


Figure 18: Failed Tuning Attempt

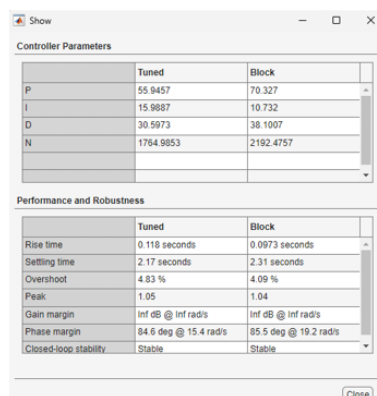


Figure 19: Failed Tuning Attempt

After lots of trial and error, a settling time under two second and a overshoot of under 5% was achieved.

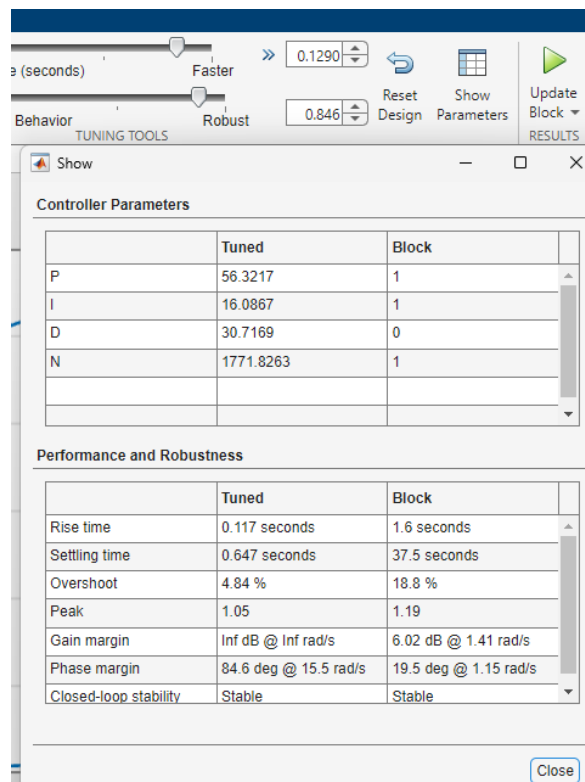


Figure 20: Successful Tuning Attempt

Figure 20 has an overshoot of just less than 5% and a time quite under two seconds but this was the best possible outcome. The PID figures used to calculate the transfer function can also be seen here.

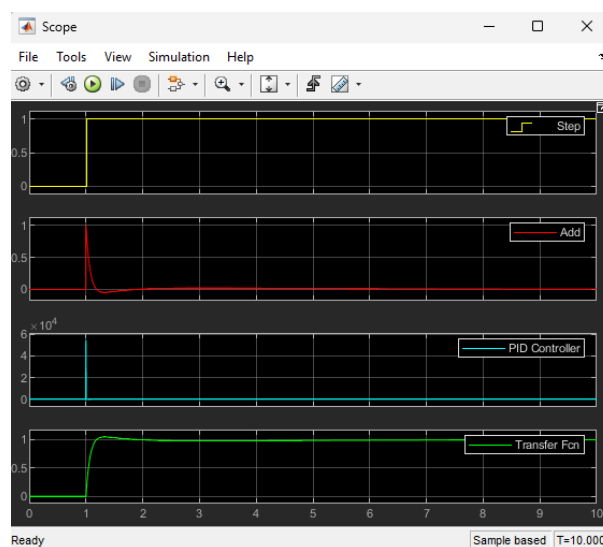


Figure 21: Figure 20 Graph

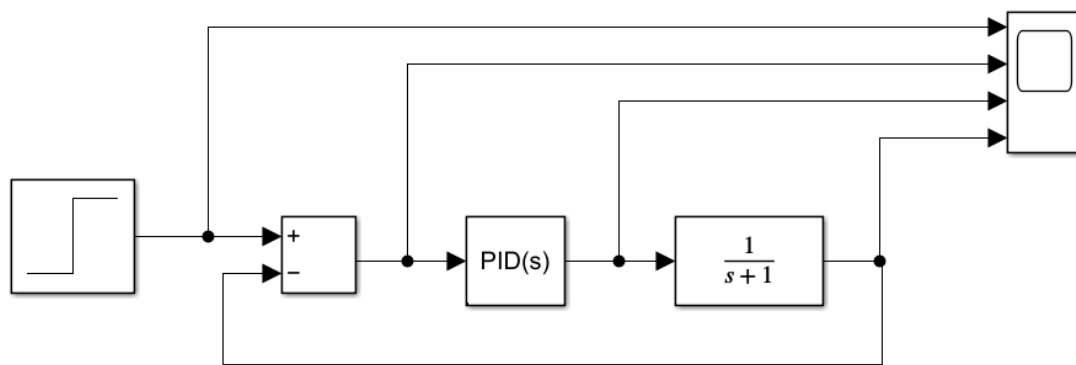


Figure 22: Closed Loop System Designed on Simulink Not Using Student ID

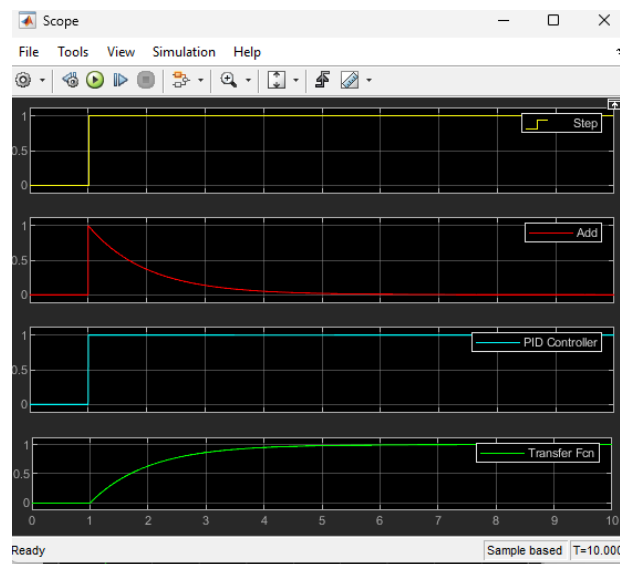


Figure 23: Graph of Figure 22

Figure 22 and Figure 23 are the untuned simulations.

Discussion

Comparison of Figure 21 (tuned) and Figure 23 (non-tuned):

- The transfer function when tuned increases at a quicker rate than the non-tuned version.
- The step stays the same for both results.
- The PID controller peaks then almost instantly decreases quicker than non-tuned.
- The Add peaks and decrease like the PID but it can be seen in the line that Add decreases more than the non-tuned version.

Systems are designed specific to its function. E.g., a heating system will not require rapid response whereas a weapon system like the CIWS will require rapid response components and lots of systems.

When raw data is used, the results will not be accurate, or the ones anticipated.

Want to tune it so stuff that is affecting it is taken out.

Conclusions

In conclusion, the tuned version of the system is a lot more accurate and relative to the designer's needs. Closed-loop control systems offer significant advantages, including better accuracy, resilience to disturbances, and resource efficiency. The Phalanx CIWS exemplifies a complex closed-loop system, showcasing its radar-controlled capabilities and multiple sensors. As a crucial component in naval defence, closed-loop systems play an essential role in achieving optimal performance and adapting to dynamic environments. Their continued development ensures enhanced protection and mission success in various applications, particularly in defence and military systems.

References

- [Electrical4U, "Transfer Function of Control System," 22 October 2020. [Online].
1 Available: <https://www.electrical4u.com/transfer-function/>. [Accessed July 2023].
]
- [P. Kirvan, "Control System," TechTarget, March 2023. [Online]. Available:
2 <https://www.techtarget.com/whatis/definition/control-system>. [Accessed July
] 2023].
- [Electronics Tutorials, "Open-loop System," Electronics Tutorials, [Online].
3 Available: <https://www.electronics-tutorials.ws/systems/open-loop-system.html>.
] [Accessed July 2023].
- [S. Hrishikesan, "Examples of Open Loop and Closed Loop Control System,"
4 January 2019. [Online]. Available:
] <https://www.electronicsandcommunications.com/2019/01/examples-of-open-loop-and-closed-loop.html>. [Accessed July 2023].
- [LearnLearn, "Traffic Light Control Systems," [Online]. Available:
5 <https://learnlearn.uk/ibcs/traffic-light-control-systems/>. [Accessed July 2023].
]
- [M. Maxwell, "The History of Traffic Lights," Stoneacre, March 2020. [Online].
6 Available: <https://www.stoneacre.co.uk/blog/the-history-of-traffic-lights>. [Accessed
] July 2023].
- [V. I. George, "Research Gate: SIMULINK model for vehicle detection and traffic
7 density [24]," [Online]. Available: [https://www.researchgate.net/figure/SIMULINK-](https://www.researchgate.net/figure/SIMULINK-model-for-vehicle-detection-and-traffic-density-24_fig2_284887606)
] [model-for-vehicle-detection-and-traffic-density-24_fig2_284887606](https://www.researchgate.net/figure/SIMULINK-model-for-vehicle-detection-and-traffic-density-24_fig2_284887606). [Accessed
July 2023].
- [N. FAUBERT, "Secrets inside an airplane's black box," EDN, March 2014.
8 [Online]. Available: <https://www.edn.com/secrets-inside-an-airplanes-black-box/>.
] [Accessed July 2023].
- [Industrial Electronics, "Aircraft Electronics + Electrical Systems: Flight data and
9 cockpit voice recorders (part 2)," Industrial Electronics, [Online]. Available:
] https://industrial-electronics.com/aircraft_18b.html. [Accessed July 2023].

- [G. Wright, "closed loop control system," [Online]. Available:
1 [https://www.techtarget.com/whatis/definition/closed-loop-control-](https://www.techtarget.com/whatis/definition/closed-loop-control-0)
0 [system#:~:text=A%20more%20complicated%20example%20of,engine%20power](https://www.techtarget.com/whatis/definition/closed-loop-control-0)
] [%20\(system%20input\)](https://www.techtarget.com/whatis/definition/closed-loop-control-0). [Accessed July 2023].
- [K. J. Å. a. R. M. Murray, "Feedback Systems: An Introduction for Scientists and
1 Engineers," 2014.
1
]
- [J. Pike, "MK 15 Phalanx Close-In Weapons System (CIWS)," Military Analysis
1 Network, January 2003. [Online]. Available: [https://man.fas.org/dod-](https://man.fas.org/dod-2)
2 [101/sys/ship/weaps/mk-15.htm](https://man.fas.org/dod-2). [Accessed July 2023].
]
- [America's Navy, "MK 15 - Phalanx Close-In Weapon System (CIWS)," America's
1 Navy, September 2021. [Online]. Available: [https://www.navy.mil/resources/fact-](https://www.navy.mil/resources/fact-3)
3 [files/display-factfiles/article/2167831/mk-15-phalanx-close-in-weapon-system-](https://www.navy.mil/resources/fact-3)
] [ciws/#:~:text=MK%2015%20Phalanx%20CIWS%20provides,have%20penetrated](https://www.navy.mil/resources/fact-3)
%20other%20fleet%20defenses.. [Accessed July 2023].
- [Mathworks, "Radar System Modeling Mathworks," [Online]. Available:
1 <https://uk.mathworks.com/help/simrf/ug/radar-system-modeling.html>. [Accessed
4 July 2023].
]
- [TEMWELL Group, "Radar System," TEMWELL Group, 09 04 2021. [Online].
1 Available: <https://www.temwell.com/msg/msg138.html>. [Accessed July 2023].
5
]
- [FURUNO Technology, "Radar Basics," FURONO, [Online]. Available:
1 <https://www.furuno.com/en/technology/radar/basic/#:~:text=Directivity%20of%20t>
6 [he%20Antenna%20Unit&text=However%2C%20since%20the%20reverberated%](https://www.furuno.com/en/technology/radar/basic/#:~:text=Directivity%20of%20t)
] [20signals,be%20exported%20into%20visual%20data..](https://www.furuno.com/en/technology/radar/basic/#:~:text=Directivity%20of%20t) [Accessed July 2023].
- [Mathworks, "Amplifier," Mathworks, [Online]. Available:
1 <https://uk.mathworks.com/help/simrf/ref/amplifier.html>. [Accessed July 2023].

7

]

[Y. W. L.-j. J. J. H. C. M. Tang Tang, "Close-in weapon system planning based on
1 multi-living agent theory," in *Defence Technology: Volume 18, Issue 7*, Beijing,
8 School of Information and Electronic, Beijing Institute of Technology, Beijing,
] 100081, China, 2022, pp. 1219-1231.

[C.-H. J. a. C. Kim, "Flight Control Law for Stabilizing Transient Response of the
1 Aircraft during Gun Firing," Flight Control Test Team, Korea Aerospace Industries,
9 Ltd., Sacheon 52529, Republic of Korea & Flight Control Law Team, Korea
] Aerospace Industries, Ltd., Sacheon 52529, Republic of Korea & School of
Aerospace and Software Engineering, Gyeongsang National, 2023.

[Electronics Coach, "Examples of Closed-Loop Control System," Electronics
2 Coach, [Online]. Available: [https://electronicscoach.com/examples-of-closed-loop-](https://electronicscoach.com/examples-of-closed-loop-control-system.html)
0 control-system.html. [Accessed July 2023].

]