Control Theory 2a

LAB 2 - Implementation of A Digital Controller On An Aerothermal System

Robotics & Automation pathway

Authors	: Alperen ISIK , Hasan Emre AYDIN
Version	: 1 R 1
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B. Introduction

The objective of this laboratory session was to design, implement, and analyze digital controllers to regulate the air flow temperature of an aerothermal system. Through the implementation of Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD), and Proportional-Integral-Derivative (PID) controllers, the goal was to evaluate system performance metrics such as rise time, overshoot, steady-state error, and stability. This practical session provided a detailed exploration of digital control systems, enhancing theoretical knowledge with hands-on experience.

The experimental setup featured a robust aerothermal test bench, including an air flow actuator, a heating resistor, and an LM35 temperature sensor. These components interfaced with an ARM M3 microcontroller that processed the control algorithms and enabled real-time feedback mechanisms through PWM signals.

1. System Overview

The aerothermal system serves as a closed-loop control system structured to regulate air flow temperature effectively. Its primary components and roles include:

- **Reference Input**: The desired air flow temperature setpoint defined by the user.
- **Controller**: The digital controller implemented on a microcontroller (P, PI, PD, PID) to compute corrective actions.
- **Actuator**: A heating element driven by PWM signals, adjusting the heat to meet the reference temperature.
- **Output**: The actual air flow temperature measured in real-time via the LM35 sensor.
- **Disturbances**: Environmental factors such as fluctuations in ambient temperature or variations in air flow.
- **Sensor**: The LM35 temperature sensor, converting the measured temperature to an analog voltage for processing.

The system's closed-loop feedback mechanism was represented as a detailed block diagram to illustrate the interactions between components, disturbances, and corrective actions.

Step 1: Block Diagram Construction The closed-loop control system's block diagram was developed based on the aerothermal system description. Key elements such as reference input, controller, actuator, output, sensor, and disturbances were identified and connected systematically.

Step 2: Digital Controller Implementation The following digital controllers were implemented and analyzed:

1. **Proportional Controller (P)**
   $$u(n) = K_p \cdot \epsilon(n)$$
   - The proportional controller was tested for various K_p values, with a focus on its influence on rise time, overshoot, and steady-state error.
2. **Proportional-Integral Controller (PI)**
   $$u(n) = u(n-1) + (K_p + K_I) \cdot \epsilon(n) - K_p \cdot \epsilon(n-1)$$
   - This controller addressed steady-state errors by integrating past errors, balancing the proportional and integral gains for optimal performance.
3. **Proportional-Derivative Controller (PD) (Optional)**
   $$u(n) = K_p \cdot \epsilon(n) + K_D \cdot [\epsilon(n) - \epsilon(n-1)]$$
   - The derivative action dampened system oscillations, reducing overshoot and improving transient response.
4. **Proportional-Integral-Derivative Controller (PID) (Optional)**
   $$u(n) = u(n-1) + K_p \cdot [\epsilon(n) - \epsilon(n-1)] + K_I \cdot \epsilon(n) + K_D \cdot [\epsilon(n) - 2\epsilon(n-1) + \epsilon(n-2)]$$

A comprehensive approach combining all three actions to achieve precise and stable control.

Step 3: Performance Evaluation Key performance indicators—rise time, overshoot, settling time, steady-state error, and stability—were measured experimentally and compared to theoretical expectations. These metrics were derived from the corrective action table provided in the lab instructions.

2. Results and Observations

- **Proportional Controller (P)**
  - **Strengths**: Reduced rise time.
  - **Weaknesses**: High overshoot and persistent steady-state error.
- **Proportional-Integral Controller (PI)**
  - **Strengths**: Eliminated steady-state error while maintaining reasonable rise time and overshoot.
  - **Weaknesses**: Performance degraded at excessive KI values.
- **Proportional-Derivative Controller (PD)**
  - **Strengths**: Improved transient response by reducing overshoot and oscillations.
  - **Weaknesses**: Limited effect on steady-state error.
- **Proportional-Integral-Derivative Controller (PID)**
  - **Strengths**: Balanced rise time, overshoot, and steady-state error effectively.
  - **Weaknesses**: Required meticulous tuning of Kp, KI, and KD.

Simulink Model Validation

The aerothermal system was represented in Simulink as a first-order system with delay, using the following transfer function:

$H(s) = \frac{5.398}{1+150s} \cdot e^{-14s}$

Digital controllers were simulated with a sampling period of $T_s = 1\,\text{sec}$, and their responses were compared to experimental results. The Simulink designs (Figures 1–4) demonstrated strong alignment with the experimental data, validating the observed performance characteristics.

This lab highlighted the importance of digital controllers in achieving desired system performance. While the P controller offered simplicity, the PID controller emerged as the most effective solution, providing a balance of stability, responsiveness, and precision. Practical experience with the aerothermal system reinforced the theoretical principles of digital control, forming a solid foundation for future applications in automation and robotics.

Recommendations

To further enhance the system's performance:

1. Explore adaptive control strategies for real-time gain tuning.
2. Investigate the impact of sampling period (Ts) variations on system stability.
3. Experiment with robust control techniques to address unmodeled disturbances.

C. State of The Art

Digital controllers and aerothermal systems have become integral to modern technological advancements, finding applications in diverse fields such as industrial automation, HVAC systems, and advanced aerospace mechanisms. Their role is indispensable, offering unparalleled precision and control in processes that are vital to modern human life.

The advent of digital computing technologies, particularly microprocessors and microcontrollers, has revolutionized control system design, enabling the widespread adoption of digital controllers across industries. These systems are favored over their analogue counterparts due to their superior performance, cost-efficiency, scalability, and design flexibility. Digital controllers enable seamless integration with modern data acquisition systems and advanced algorithms, making them suitable for complex control tasks in various sectors.

Digital control systems fundamentally mirror the principles of analogue systems but with significant advancements in implementation. The primary distinction lies in the substitution of the analogue controller with a digital computing unit. This unit processes input signals and generates control commands to actuators with high precision. Since digital computers operate exclusively with binary data, an analogue-to-digital (A/D) converter is crucial to transform analogue signals into a digital format. This conversion is achieved by sampling the analogue signal at regular intervals and holding it constant for the duration of the sampling period.

Similarly, a digital-to-analogue (D/A) converter is required post-controller to translate the digital output back into an analogue signal for the actuator. This ensures compatibility with the physical world, allowing the system to control real-world processes effectively. The seamless operation of digital controllers is further enhanced by features such as noise immunity, programmability, and the ability to implement complex algorithms, such as Proportional-Integral-Derivative (PID) control, which are critical for maintaining system stability and achieving desired performance metrics.

Digital controllers in aerothermal systems, such as the Aerotherm System described in this lab, demonstrate these principles effectively. By utilizing a microcontroller-based digital control scheme, the system controls the airflow temperature with high precision. This includes components such as sensors, actuators, and feedback loops, all of which contribute to a robust closed-loop control framework. The ability to implement Proportional (P), Proportional-Integral (PI), and Proportional-Derivative (PD) control strategies further showcases the adaptability and precision of digital controllers in managing dynamic systems like the Aerotherm.

In summary, the integration of digital controllers in aerothermal systems exemplifies the transformation brought by digital technologies. These systems not only enhance performance and flexibility but also pave the way for future innovations in automation and control engineering.

1. Digital Control Systems

Signal Processing in Digital Control Systems

In analogue control systems, all signals are continuous, directly proportional to the physical quantities they represent. These signals naturally integrate with physical systems without requiring transformation. However, digital control systems, which have become increasingly prominent due to advancements in digital technologies, rely on sequences of binary pulses (on-off signals) for operation. In these systems, the signal value is encoded in binary format, necessitating additional components to bridge the gap between the analogue nature of real-world signals and the digital domain of controllers.

Conversion Process: ADC and DAC

To achieve this integration, two key components are utilized:

1. **Analogue-to-Digital Converter (ADC)**: This device samples the continuous analogue signal at fixed intervals, converting it into discrete binary values that the digital controller can interpret. This conversion process is essential for representing real-world signals, such as temperature or

airflow, in a digital format for further processing. The sampling rate and resolution of the ADC directly impact the fidelity and responsiveness of the digital system.

2. **Digital-to-Analogue Converter (DAC)**: After processing the input data, the controller generates digital outputs. A DAC converts these binary signals back into analogue formats, enabling the system to actuate physical components like motors or heating elements. This reconversion ensures compatibility between the digital controller and the physical processes it governs.

This dual conversion process ensures that digital control systems can effectively manage real-world processes while leveraging the benefits of digital computation, such as noise immunity, precision, and programmability.

Integration with the Aerotherm System

In the Aerotherm system, the digital controller interacts with various components, including the airflow temperature sensor and the heater actuator. The sensor provides an analogue voltage signal proportional to the measured temperature (10 mV/°C), which is converted into digital format by the ADC. The digital controller processes this data to compute control commands based on the desired setpoint and system feedback. Finally, the DAC converts these commands back into analogue signals to drive the heating element and maintain the desired temperature.

The integration of ADC and DAC not only bridges the signal domains but also enables the implementation of advanced control algorithms like Proportional (P), Proportional-Integral (PI), and Proportional-Derivative (PD) controllers. These algorithms are designed to minimize errors, improve stability, and optimize system performance, making the Aerotherm system an exemplary application of digital control principles.

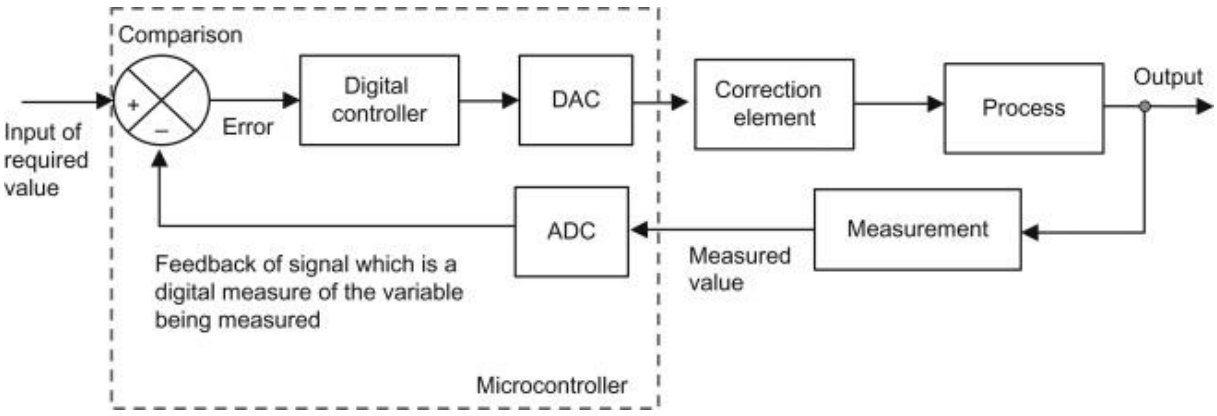


Figure 1 - An Example Control Syst

2. PID Controllers

The proportional-integral-derivative (PID) controller is one of the most widely used feedback-based control loop mechanisms in industrial and engineering applications. This three-term controller—comprising proportional (P), integral (I), and derivative (D) components—continuously calculates the error between a desired setpoint (SP) and the measured process variable (PV). The combined actions of these components adjust the control output to reduce error, stabilize the system, and achieve optimal performance.

Components of PID Control

- **Proportional (P):** This term applies a correction proportional to the current error. While it ensures a quick response, it may result in a steady-state error if used alone.
- **Integral (I):** By accumulating past errors over time, the integral term eliminates the steady-state error but may introduce oscillations or instability if over-applied.

- **Derivative (D):** This term predicts future errors based on the error's rate of change, enhancing system stability and reducing overshoot.

Each component contributes uniquely to system performance, and their combination allows for dynamic and precise control adjustments.

Real-World Applications

The PID controller is highly versatile and is used across various industries. A classic example is **automotive cruise control**: when a car ascends a hill, its speed drops due to gravity. The PID controller compensates for this by increasing engine power, restoring the car's speed to the setpoint smoothly and efficiently without overshooting. This real-time adjustment highlights the controller's ability to maintain stability and minimize error in dynamic conditions.

Historical Development

The origins of PID control trace back to the early 20th century. It was first employed in automatic ship steering systems, where precise control was critical for navigation. The initial implementations were pneumatic, evolving to electronic systems with advancements in technology. Today, PID controllers are implemented digitally, benefiting from the precision and flexibility of modern microprocessors and algorithms.

Relevance in the Aerotherm System

In the context of the Aerotherm system, PID controllers play a critical role in maintaining the desired airflow temperature. By continuously adjusting the heating element's power based on the feedback from the LM35 temperature sensor, the PID controller ensures accurate and stable temperature control. The Aerotherm system enables the evaluation of individual controller components (P, PI, PD, and PID), demonstrating their effects on parameters such as rise time, overshoot, settling time, and steady-state error. This lab allows for hands-on experience in tuning and analyzing digital controllers, providing insights into their practical applications and performance.

Overall, the PID controller's adaptability and robustness have established it as an indispensable tool in modern automation and control engineering.

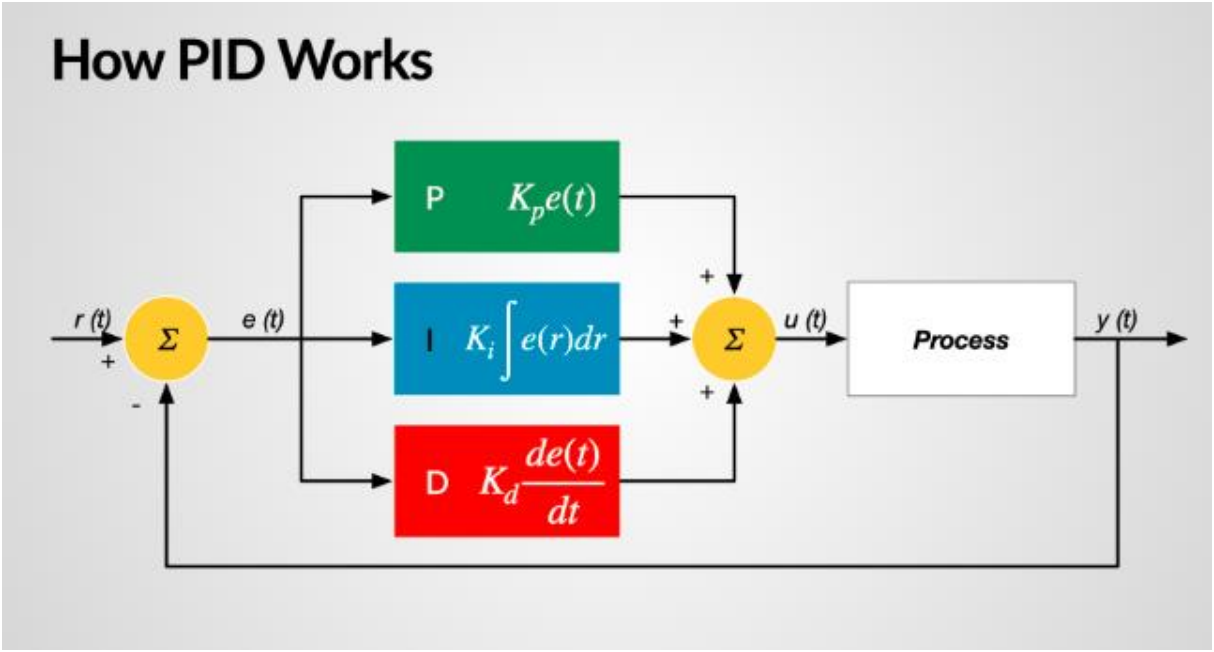


Figure 2 - A block diagram of a PID controller in a feedback loop.

D.The Work

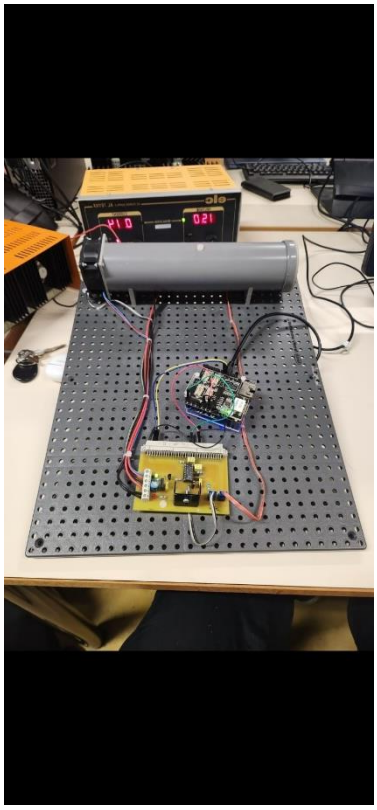


Figure 3 - The Electronics System

1. The Aerothermal System

The Aerothermal System

The aerothermal setup utilizes an ARM M3 microcontroller to regulate the air flow temperature, which is directed from right to left by a fan. The arrangement of the system is illustrated in **Figure 3**, providing a clear visual of the experimental setup.

To understand the system's functionality, a block diagram representation is employed, showcasing the closed-loop control system. This diagram outlines the process from the input, representing the desired

temperature, to the output, which is the actual measured temperature. It also highlights the interconnection of all components used in the experiment, as depicted in **Figure 4**.

Additionally, the microcontroller's code, detailed in the Appendix, includes annotations explaining the controller equations utilized in the system. The specific segments of the code that were modified for the experiment are also highlighted to ensure clarity and reproducibility.

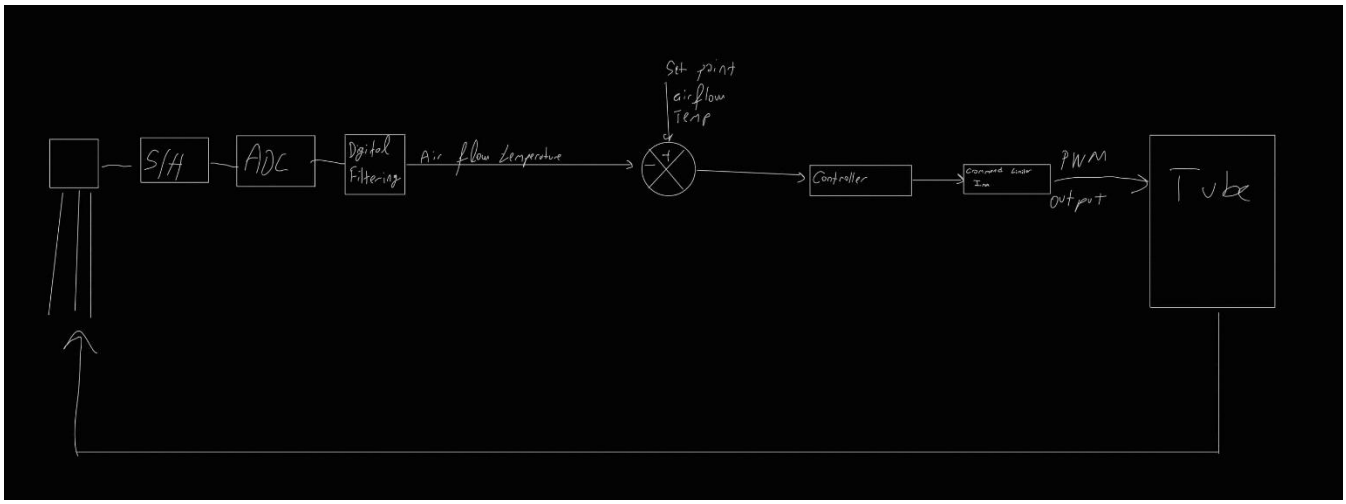


Figure 4 – The Block Diagram for a test bench of an aerothermal system

2. Digital Controller

In control engineering, understanding the dynamic behavior of a system is critical, as it defines both the nature and quality of solutions required to accomplish a control task. One of the key methods for assessing this dynamic behavior is by analyzing the system's step response, which provides insight into how the system reacts to changes in input over time.

At the heart of any control system lies the controller, a pivotal component responsible for evaluating and enhancing system performance. The controller's primary function is to reduce the discrepancy between the actual output of the system, referred to as the process variable, and the desired output, known as the setpoint. By doing so, it ensures that the system operates as closely as possible to the intended parameters. This adjustment mechanism is what makes controllers indispensable in achieving precision and stability in control systems.

Proportional Controller

A proportional controller generates a response directly proportional to the difference between the system's desired value and its current value for the variable being controlled. This approach ensures that the correction applied increases linearly with the magnitude of the error.

In the system's code, this concept is implemented using the formula: $u(t) = Kp \cdot e(t)$

Here, Kp represents the proportional constant, also known as the controller gain, which determines the controller's sensitivity. The term e(t) denotes the steady-state error, reflecting the difference between the target and the actual value at a given time. This straightforward mathematical relationship allows the proportional controller to maintain a dynamic yet stable system response.

P - RESULTS

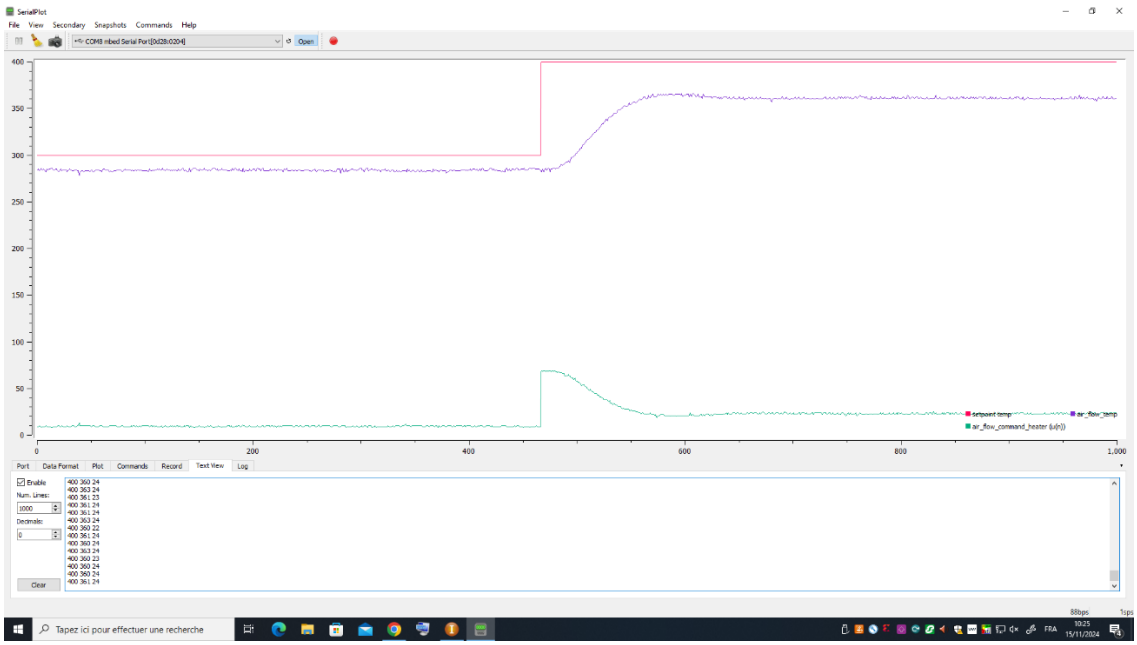


Figure 5 - Result with Kp = 0.6

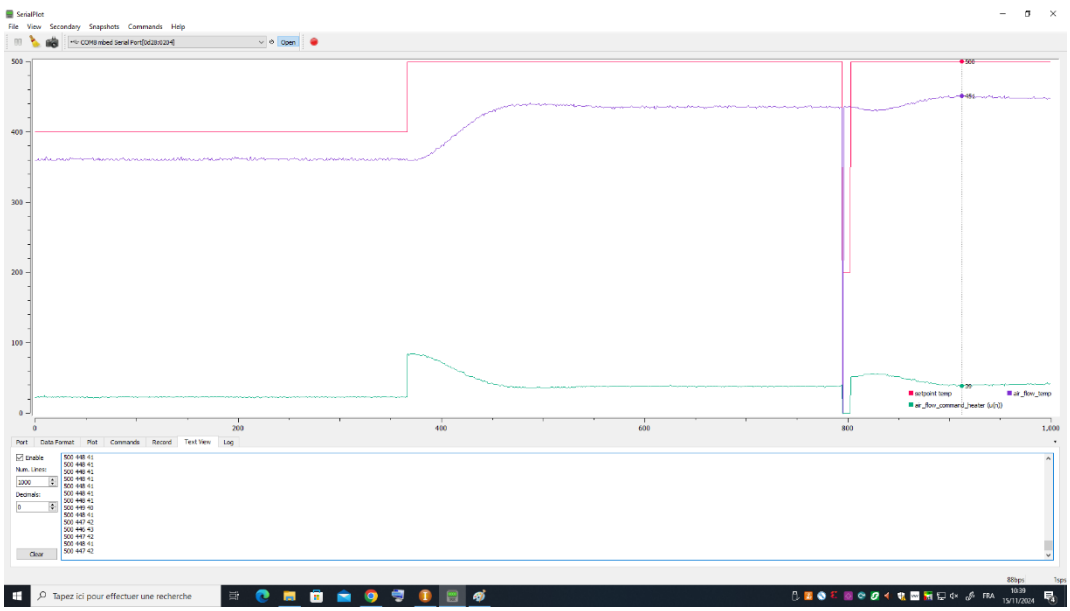


Figure 6 - Result with Kp = 0.8

While the proportional control method is effective in minimizing error, it does not completely eliminate the steady-state error. However, during our experiments, it was observed that increasing the proportional gain (Kp) led to a reduction in this error, contributing to improved system stability.

Despite this improvement, a notable drawback of increasing Kp is the significant overshoot observed in the system's response. As the gain is heightened, the system tends to exceed the desired setpoint before stabilizing, which can introduce instability if not carefully managed.

This trade-off highlights the importance of balancing Kp to optimize performance without compromising system reliability.

2.1. Behavior with a Different Temperature Setpoint

The behavior of the proportional (P) controller should theoretically remain consistent across different scenarios. To test this principle, a new setpoint with a different temperature was chosen, and the system was tasked with approaching this new target. During the experiment, the system's observed behavior closely mirrored the actions taken to reach the previous setpoint.

This consistency confirms that the proportional controller's error correction mechanism operates similarly, regardless of the target's magnitude. However, it is important to note that issues such as overshoot and steady-state error, which depend on the gain value, may have varying impacts based on the specific target setpoint. Thus, tuning the **Kp** value for each scenario remains critical to optimizing system performance.

Result with Kp (Behavior with a Different Temperature Setpoint)

Proportional – Integral Controller

A proportional-integral (PI) controller merges the benefits of proportional and integral control by combining the proportional response to the steady-state error signal with the integral of the error over time. This dual approach ensures that the system not only reacts to the current error but also corrects accumulated errors, enhancing accuracy. The mathematical representation of this method is:
u(t)=Kp·e(t)+Ki·∫e(t) dtu(t) = K_p \cdot e(t) + K_i \cdot \int e(t) \, dt

In the implementation, this formula is coded directly, where KpK_p is the proportional gain, KiK_i represents the integral gain, and e(t)e(t) is the error at time tt. This combination allows the controller to reduce steady-state error while improving the overall stability of the system.

$$u(n) - u(n-1) = K_p\big(\varepsilon(n) - \varepsilon(n-1)\big) + K_I\varepsilon(n) = \big(K_p + K_I\big)\varepsilon(n) - K_p\varepsilon(n-1)$$

Equation 1

PI - RESULT

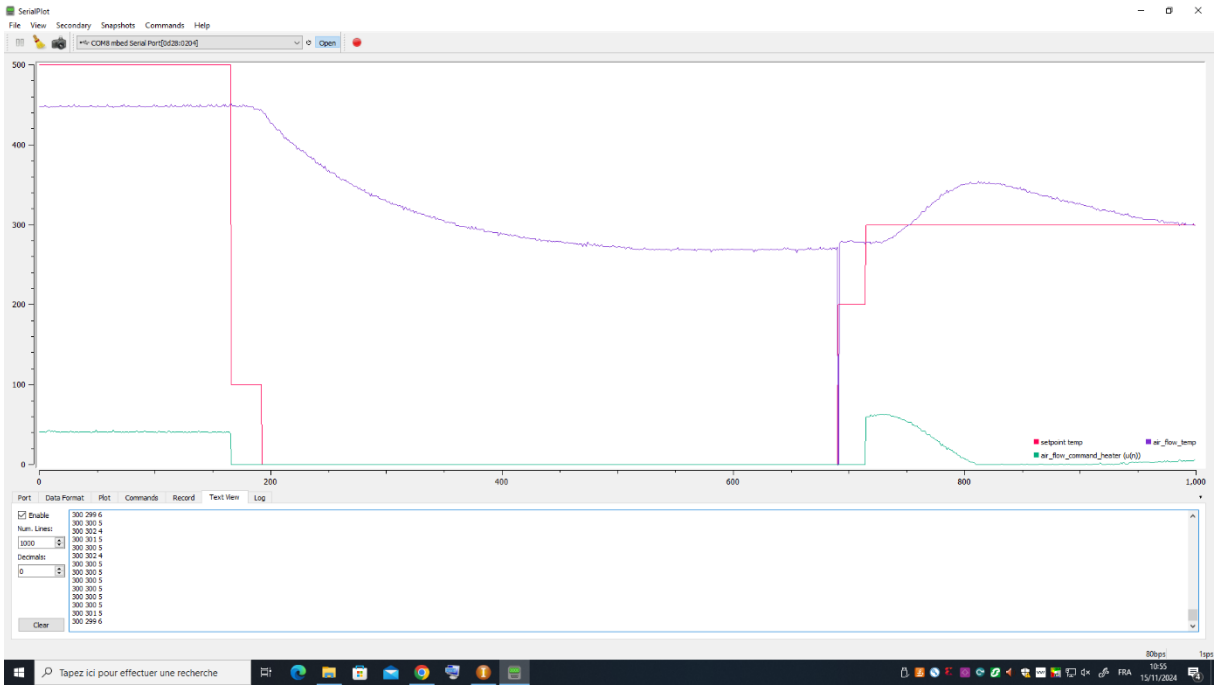


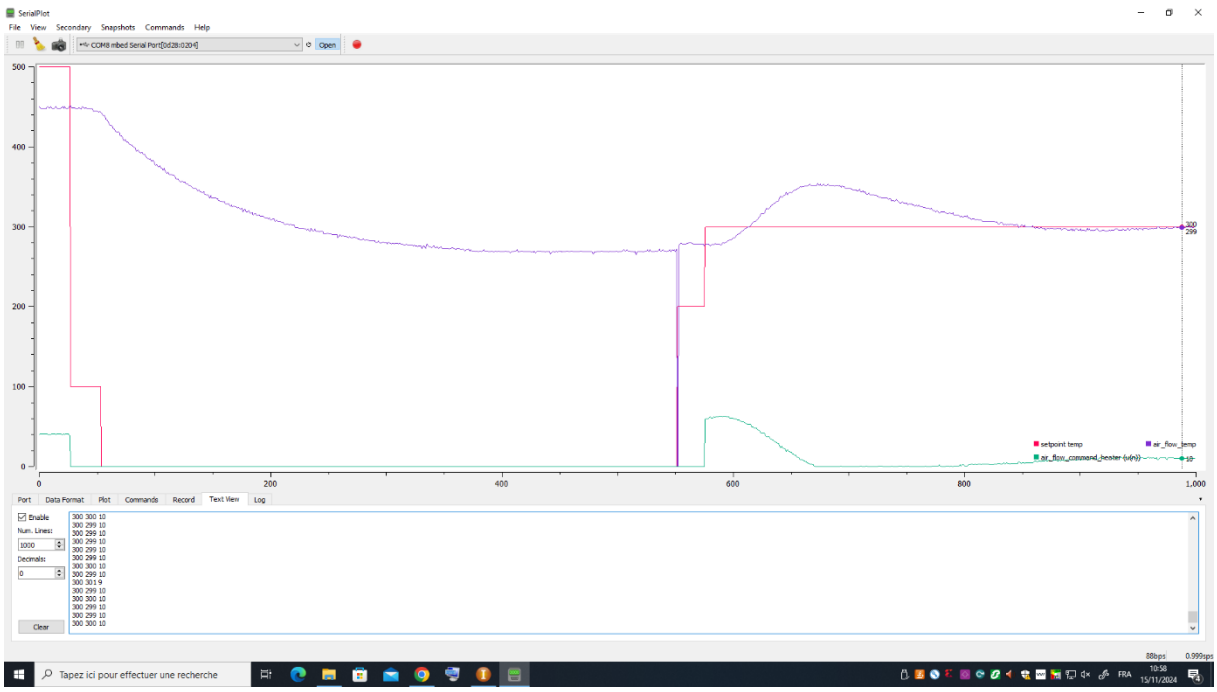
Figure 7 - PI results

Incorporating an integral controller into the system eliminates the steady-state error, effectively reducing it to near zero. This addition enhances the overall stability of the system by minimizing disturbances and ensuring a more consistent response.

However, the inclusion of the integral component does not entirely resolve all issues. The system continues to exhibit overshoot, and the settling time is noticeably extended. In fact, the time required for the system to stabilize is more than twice as long as that observed with the proportional controller alone. This highlights the trade-offs involved in improving accuracy and stability with the integral component.

Additional Section 1: Reducing Overshoot by Lowering Kp

Although the PI controller causes the error to approach zero, **overshoot**, which occurs when the system exceeds the desired setpoint, remains a significant issue. To address this, the **Kp** value was reduced to achieve a more balanced system response. As the gain was decreased, overshoot was significantly mitigated, and the system's tendency to overreact was curtailed. However, this adjustment did not completely resolve the issue and introduced new side effects.



PI results (reducing Overshoot by Lowering Kp)

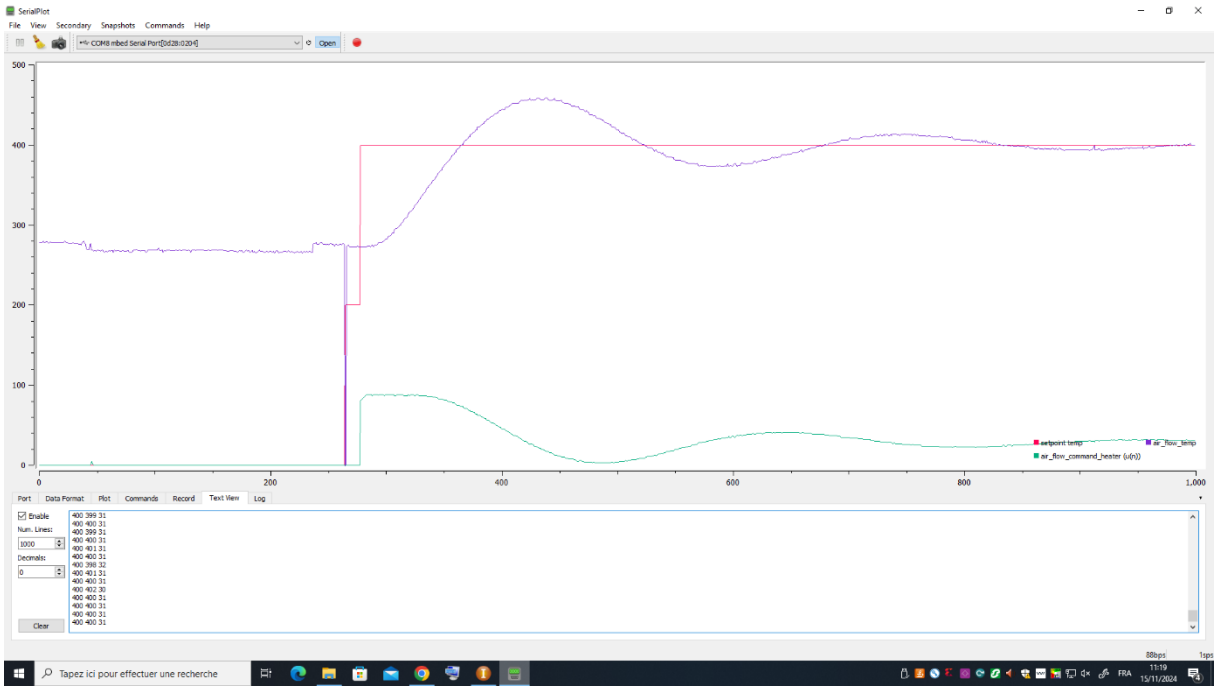
Additional Section 2: Lower Kp and Oscillations

The **Kp** value was further reduced to **0.4**. This lower gain value led to a further reduction in overshoot, but a new challenge emerged: **oscillations**. These oscillations were observed as the system continually moved back and forth around the desired setpoint, rather than stabilizing promptly.

This oscillatory behavior adversely affected system stability, extending the settling time and hindering the controller's ability to achieve the desired level of accuracy. The system's response was analyzed as follows:

- **Lower overshoot:** While the system still exceeded the setpoint, the degree of overshoot was considerably reduced compared to previous configurations.
- **Intense oscillations:** The system oscillated significantly around the target point before settling, resulting in higher energy consumption and reduced controller efficiency.
- **Increased settling time:** The lower **Kp** value slowed the system's transition to a stable state, significantly lengthening the settling time.

These results highlight the need for a more sophisticated tuning process to balance the advantages and limitations of the PI controller. Specifically, optimizing the balance between **Kp** and **Ki** is critical for minimizing both overshoot and oscillations. Furthermore, introducing a derivative component (PID controller) or developing an adaptive control strategy could be valuable next steps to address these challenges effectively.



PI results (Lower Kp and Oscillations)

2.2. Proportional – Integral – Derivative controller

As the name implies, a PID controller integrates three key components: the proportional error signal, the integral of the error signal, and the derivative of the error signal. This combination enables the controller to address current, past, and predicted future errors in the system. Its mathematical representation is:

$$\mathbf{u(t) = K_P\, e(t) + K_I \int e(t)\, dt + K_D \frac{de(t)}{dt}}$$

Equation 2

For the code of the microcontroller, it is written as:

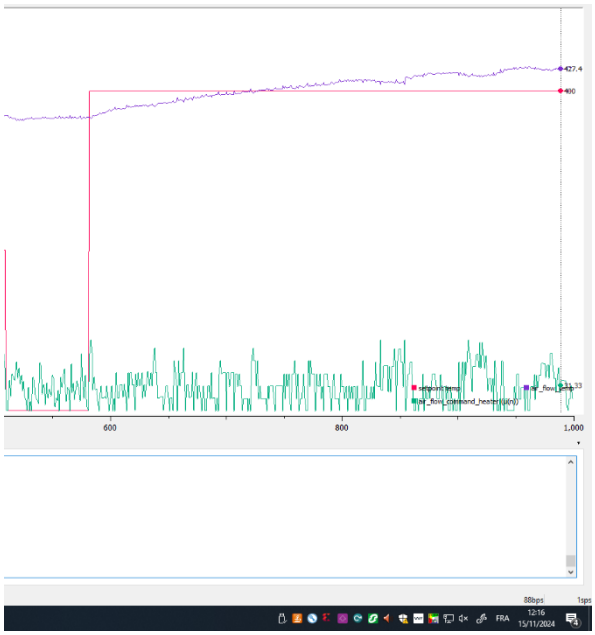
$$u(n) - u(n-1) = K_p\big(\varepsilon(n) - \varepsilon(n-1)\big) + K_I\varepsilon(n) + K_D(\varepsilon(n) - 2\varepsilon(n-1) + \varepsilon(n-2))$$

Equation 3

PID – RESULTS - Assumptions

The system's response with the PID controller is expected to be much smoother and more precise. This improvement stems from the derivative component, which reduces both the rise time and the settling time while retaining the benefits of the proportional and integral controllers. As a result, the system achieves greater stability and minimizes steady-state error.

However, during the experiment, efforts were made to eliminate overshoot using the PID controller, and a noticeable reduction in overshoot was achieved. Nevertheless, the steady-state error unexpectedly increased and did not reach zero, contrary to expectations. This outcome emphasizes the importance of carefully tuning the parameters to fully leverage the advantages of the PID approach.



PID results

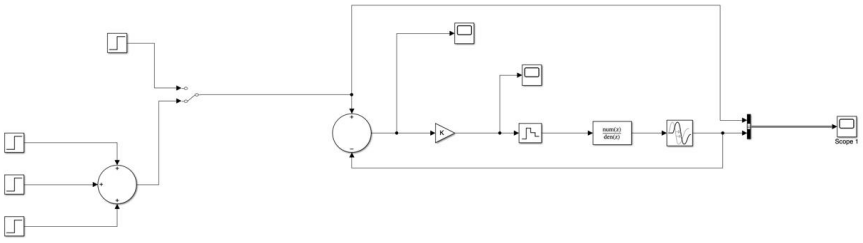
E. Effects of PID, PI, and P Controllers on System Performance: Comparison of Simulink and Real-World Results

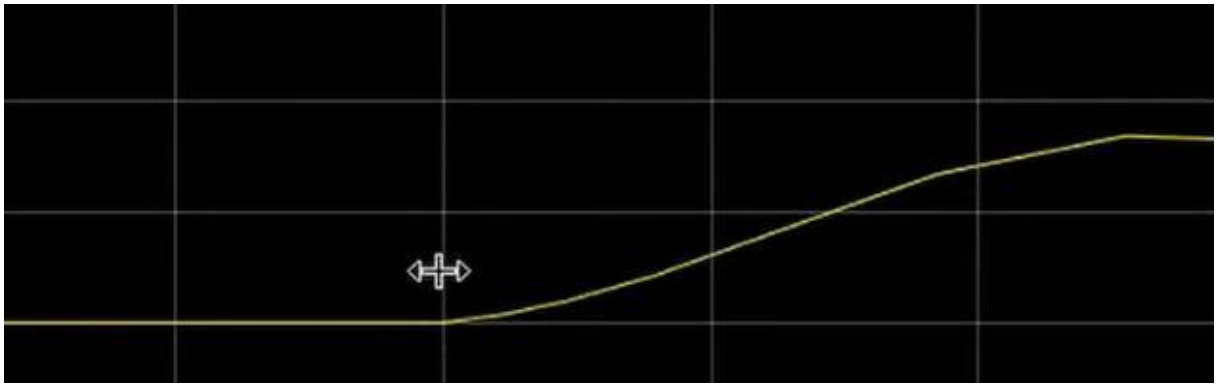
PID (Proportional-Integral-Derivative), PI (Proportional-Integral), and P (Proportional) controllers are widely used feedback control methods in engineering applications. This article evaluates the effects of these controllers on system performance by comparing simulation results obtained in Simulink with experimental results from a real-world system.

P Controller

Simulink Results:

When using a P controller, no overshoot was observed, as expected. However, a steady-state error was present. This outcome indicates that the proportional gain alone is insufficient to eliminate steady-state error, leaving a residual error in the system.





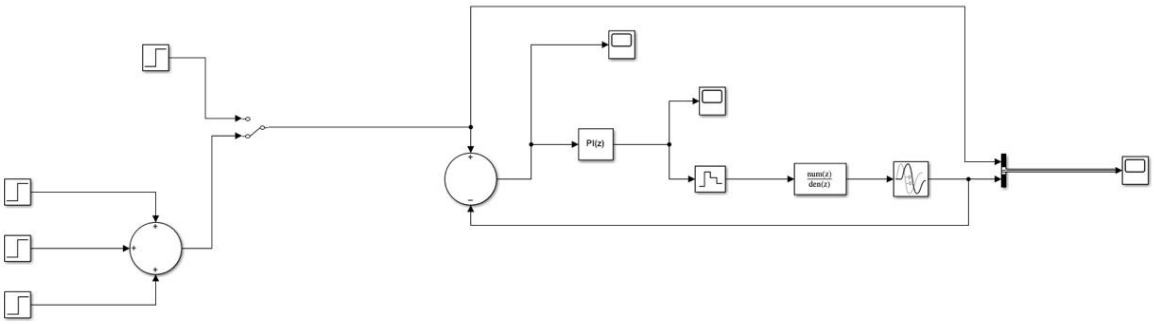
Real-World Comparison:

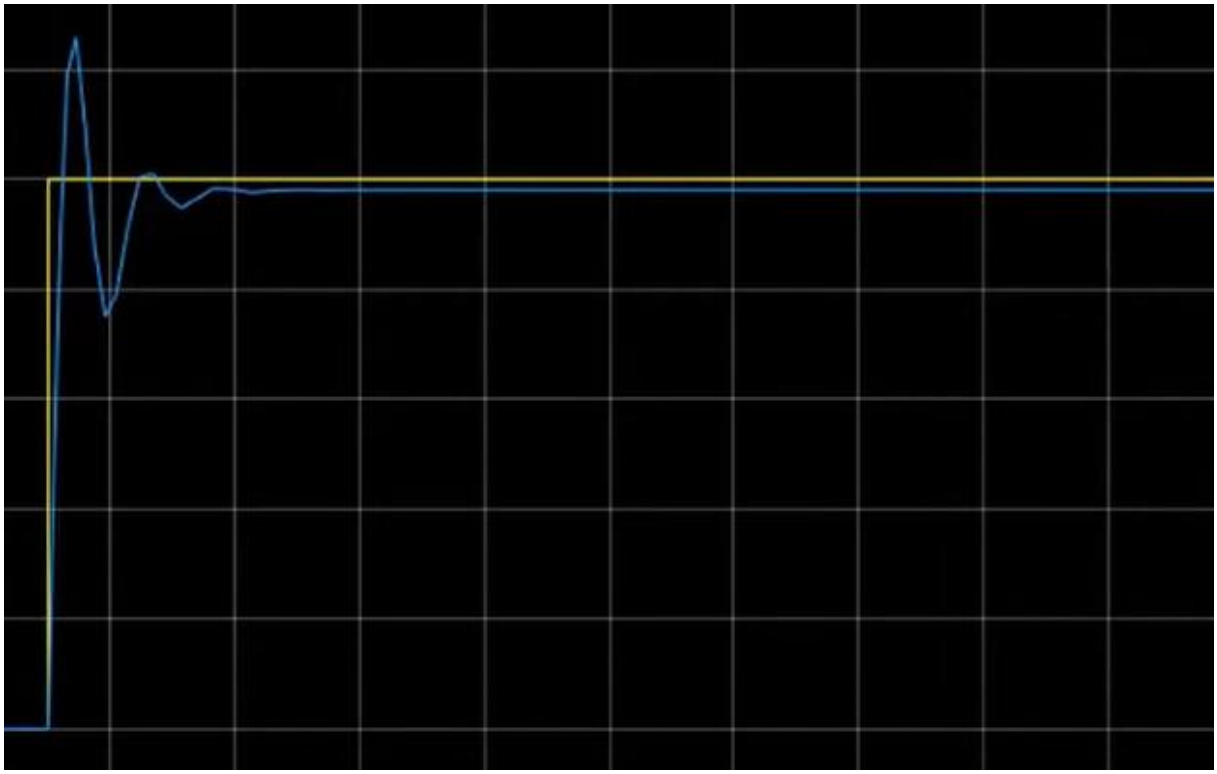
The Simulink simulation and real-world results were quite similar. In both cases, there was no overshoot, but the system retained a steady-state error.

PI Controller

Simulink Results:

With a PI controller, the steady-state error was eliminated due to the integral term of the controller, as expected. However, overshoots were observed, indicating that the system exceeded the desired target before settling into a steady state.





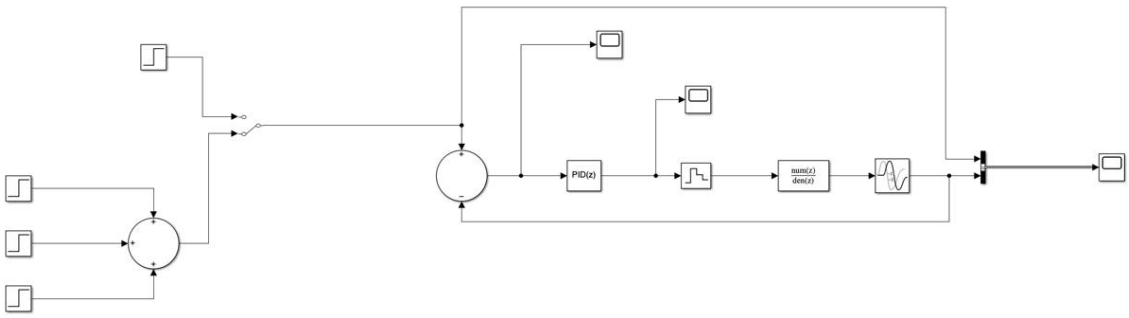
Real-World Comparison:

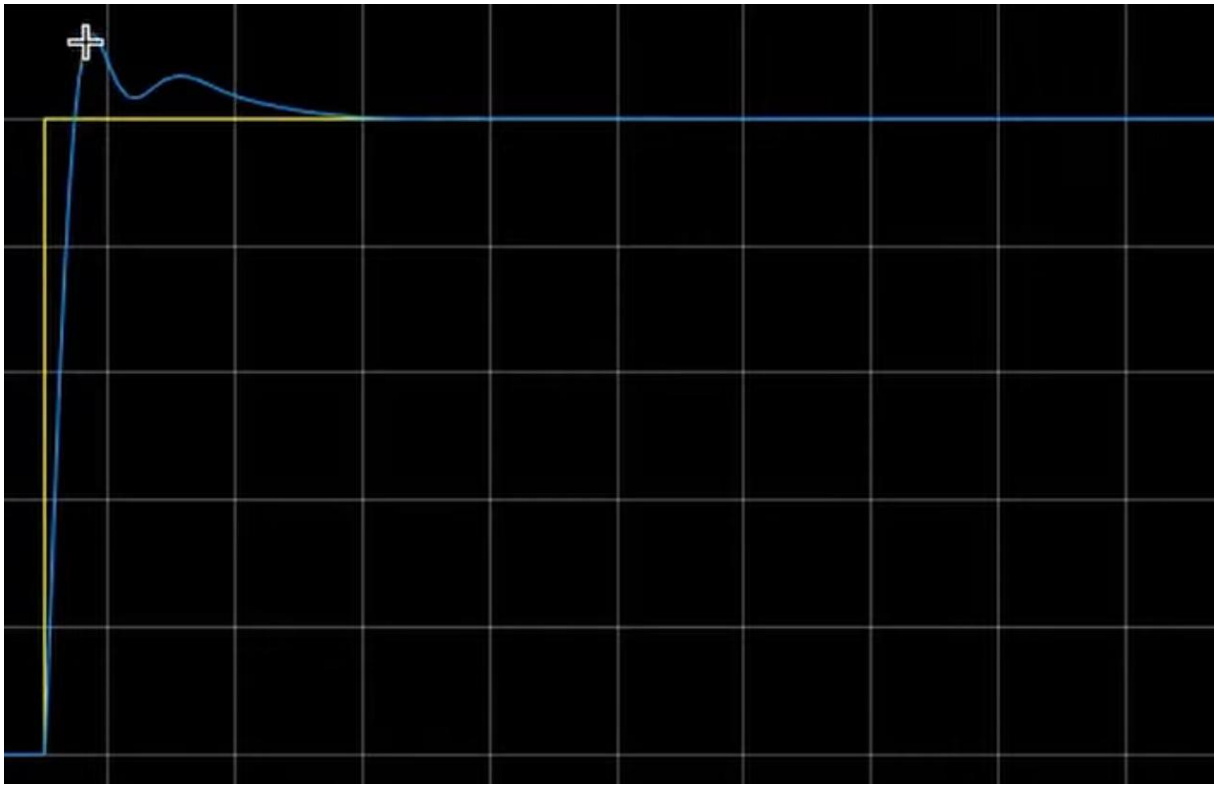
Similar results were obtained in the real-world system. In both Simulink and real-world experiments, the steady-state error was eliminated, but overshoots were present.

PID Controller

Simulink Results:

Using a PID controller, the steady-state error was eliminated as expected. However, contrary to expectations, a small overshoot was still observed. Although this overshoot was lower than with the PI controller, it suggests that fine-tuning may still be required for optimal performance.





Real-World Comparison:

The real-world system provided different results compared to the Simulink simulation. In the real-world system, no overshoot was observed, but a small steady-state error remained. This highlights potential differences between the dynamics of the real system and its Simulink model.

Conclusions and General Evaluation

1. P Controller: Both Simulink and the real-world system behaved similarly, with no overshoot but the presence of steady-state error.

2. PI Controller: The steady-state error was eliminated in both Simulink and the real-world system, but overshoots were observed in both cases.

3. PID Controller: While Simulink showed some overshoot, the real-world system did not exhibit overshoot but retained a small steady-state error. This emphasizes the differences between modeling and real-world dynamics.

These comparisons underline the importance of verifying simulation results against real-world experiments when designing controllers. Accurately modeling system dynamics is crucial to improve control performance and minimize unexpected outcomes.

F. Conclusion

The laboratory experiment provided an in-depth understanding of implementing and analyzing digital controllers on an aerothermal system. Through the application of Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD), and Proportional-Integral-Derivative (PID) controllers, key performance metrics such as rise time, overshoot, settling time, steady-state error, and stability were thoroughly evaluated both in simulation and in real-world scenarios. The results demonstrated the strengths and limitations of each control strategy and highlighted the significance of meticulous parameter tuning to achieve optimal performance.

The **P controller**, while simple and effective in reducing rise time, exhibited significant steady-state error and was unable to eliminate it entirely. The **PI controller** successfully eliminated steady-state error but introduced overshoot and prolonged settling time, showcasing a trade-off between accuracy and stability. The **PD controller**, on the other hand, improved transient response by reducing overshoot but had minimal impact on steady-state error. The **PID controller**, combining the advantages of all three components, achieved a balanced performance, minimizing overshoot and enhancing stability, though its tuning required careful consideration to prevent unexpected steady-state errors.

Comparison of Simulink simulations with real-world results revealed discrepancies that emphasized the importance of validating theoretical models through experimental data. The real-world system dynamics often deviated from the simulated behavior, particularly in the PID controller's case, where real-world performance yielded unexpected steady-state errors despite simulations predicting elimination of all errors.

In conclusion, this laboratory reinforced the critical role of digital controllers in modern control systems, underscoring the need for both simulation and hands-on experimentation to refine controller designs. Moving forward, incorporating advanced techniques such as adaptive control and robust control strategies could further enhance system performance and address limitations encountered during this experiment.

G.Appendix