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EL AISSI MOHAMMED-AMINE

Thermally Compensated Precision Voltage Reference

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LOGITECH
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Confidentialité : **€ oui € non**

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I. INTRODUCTION

I.1. Company Introduction: Logitech

Logitech Europe SA is a globally recognized Swiss company specializing in the design and production of peripherals and digital devices that enhance everyday user experiences. Founded in 1981 and headquartered in Lausanne, Switzerland, Logitech has established itself as a leader in consumer electronics, particularly in computer accessories such as mice, keyboards, webcams, headsets, and gaming gear. The company is known for its innovation, focus on user-centered design, and commitment to sustainability and quality. With offices around the world and products used by millions, Logitech continues to influence the way people interact with digital technologies.

The internship was conducted at Logitech Lausanne located at the EPFL Innovation Park, specifically within the Logitech laboratory, a creative and technical environment focused on prototyping, innovation, and advanced system development.

II.2. Internship Project: Thermally Compensated Precision Voltage Reference

This report presents the work carried out during my internship at Logitech Europe SA, within the EPFL Innovation Park, as part of a Master-level engineering program. The project, titled "Thermally Compensated Precision Voltage Reference", focused on analyzing and improving the design of an internal voltage reference used in Logitech's proprietary hardware systems.

The voltage reference is a fundamental component in analog systems, as it directly impacts the accuracy, stability, and long-term performance of measurement and control circuits. In this context, the objective of the internship was to critically evaluate the existing architecture and explore potential optimizations, particularly in relation to temperature drift, noise, stability and aging effects…

The work began with a thorough review of the current implementation, followed by an identification of key areas where performance could be enhanced. Based on this analysis, several circuit designs were proposed, simulated, and refined iteratively in order to address the identified issues. Each solution was evaluated using analog modeling tools, then prototyped and tested in a lab environment to assess its real-world behavior. Throughout this process, the goal was to optimize the design in order to increase the performance of the emulator, and thus the products emulated.

This report details the technical steps taken, the choices made, and the results obtained during this development process, aiming to provide a clear and complete overview of the project's methodology and outcomes.

I would like to express my sincere thanks to my supervisor, Maxim Vlassov, for his guidance, availability, and support throughout this internship.

This project provided an opportunity to apply skills in analog electronics, circuit simulation, and lab instrumentation, while working alongside an experienced engineering team in a highly creative and collaborative setting.

II. REFERENCE VOLTAGE ARCHITECTURE ANALYSIS

II.1. Review of the current architecture

After thoroughly reviewing the current architecture of the reference voltage circuit within the KOSMOS emulator : (tool that helps simulate various external factors), we conducted an in-depth study of the components involved and explored potential alternatives to enhance performance and thermal stability. This analysis included a comprehensive evaluation of advanced precision references such as the **LTZ1000** and **LTC6655**, known for their ultra-low temperature coefficients and high output stability. A detailed comparative table was created to assess key parameters including initial accuracy, long-term drift, temperature coefficient, supply voltage range, and ease of implementation. Furthermore, the study considered component compatibility, power requirements, and circuit complexity, helping to determine the most suitable candidates for future system upgrades. This benchmarking process plays a crucial role in guiding future iterations of the thermostat and reference voltage subsystem toward higher accuracy and reliability.

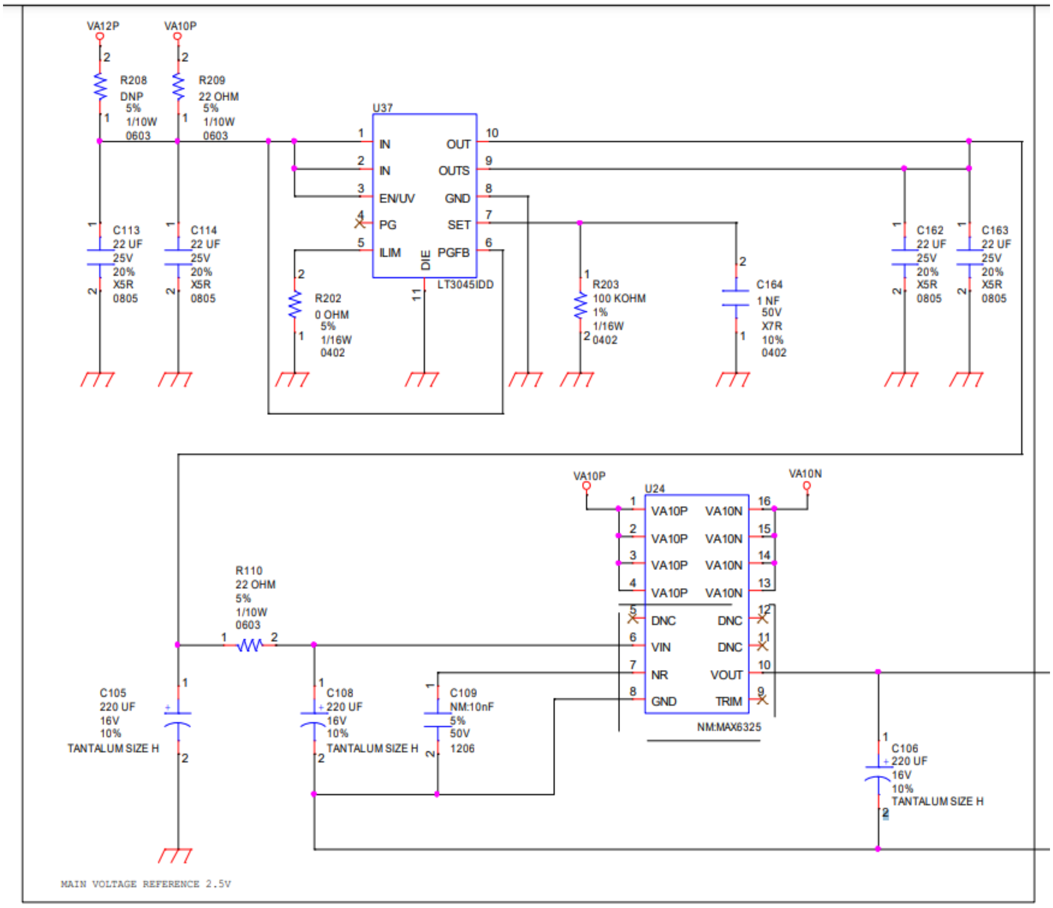


Figure 1: current circuit architecture

The circuit begins with a low-pass filter stage, which attenuates high-frequency noise before the power regulation section. This filtered supply then feeds into a precision low-dropout (LDO) regulator, the LT3045, which is programmed using a 1% tolerance Rset resistor to provide a stable 10 V output. That regulated 10 V line serves as the input to the subsequent reference stage, where it powers a precision voltage reference IC, the MAX6325. The MAX6325 generates a highly accurate and low-drift 2.5 V reference, which is further stabilized by carefully selected resistors and decoupling capacitors to suppress noise and maintain long-term stability. This configuration has been thoroughly tested, is well tuned, and cannot be altered; any future modifications must be made only by adding to the existing architecture rather than changing it.

II.2. Deep research of the interesting characteristics of initial and potential components

Table I: characteristics of initial and potential components

PROPERTIES	MAX6325	LTC6655-…	LTZ1000	LT3045
Noise	1.5µVp-p Noise (0.1Hz to 10Hz)	(0.1Hz to 10Hz) 625nVP-P	1.2µVP-P Noise	0.8µVRMS (10Hz to 100kHz)
Temperature drift	1ppm/°C	: 2ppm/°C Max	0.05ppm/°C Drift with compensation	----------
Accuracy	±0.02% Initial Accuracy	±0.025% Max	----------	100µA SET Pin Current: ±1% Initial Accuracy
Long-Term Stability	30ppm/1000hr	20ppm/√kHr	2 µV/√kHr	
Input Voltage Range	8V ≤ VIN ≤ 36V	VOUT + 0.5V ≤ VIN ≤ 13.2V	>10V	1.8V to 20V(Vin>Vout)
Output Voltage Range	2,5V	1.25V, 2.048V, 2.5V, 3V, 3.3V, 4.096V, 5V	7V-7,5V	0V to 15V(reglable par Rset)
High Bandwidth	--------	----------	-------	1MHz
Dropout Voltage	--------	500mV	-------	260mV
Output Current	±15mA	5mA	50uA	1mA-500mA
Power consumption	18mW	Around mW	>55mW	5.5mW – 50mW
quiescent current	**1.9mA – 2.9mA**	< 1mA	5mA	around 2.2mA
Output current	**up to 15mA**	Up to 5mA	Around mA	Up to 500mA

III. Temperature Regulation System Design

III.1. Introduction

During the architectural analysis of the KOSMOS project: a power emulator simulating various external factors such as USB inputs and keyboard activity, we identified temperature drift as a critical source of precision degradation. As precision is paramount in maintaining the consistency of the emulator's output, particularly in analog signal processing, it became necessary to implement a temperature regulation mechanism.

To address this, we developed a simple yet robust analog thermostat circuit to stabilize the ambient conditions around key analog components. The goal of this system is to maintain a controlled temperature range (Table II), minimizing thermal drift effects, accelerating aging effects, and reducing mechanical stress.

Table II: types of temperature control

Feature	**Steady-State Control**	**Hysteresis Control**
Control Method	Continuous modulation of heating power	On/off switching within a dead band
Temperature Stability	Near-exact setpoint maintenance	Oscillations within a range
Complexity/Cost	Higher (requires advanced control logic)	Lower (simple design)
Use Cases	Precision environments	Residential/consumer appliances

III.2. System Architecture of the hysteresis control

The analog thermostat is composed of the following main components:

- LM35 Temperature Sensor: This precision IC temperature sensor provides an analog output of 10mV/°C, making it directly suitable for easy interpretation and amplification.
- LM324 Quad Op-Amp: Utilized both for signal amplification and comparison. It operates reliably at 5V and offers sufficient performance for the target temperature range.
- IRFZ44N N-Channel MOSFET: Acts as a power switch to control the heating element.
- Trimmer Potentiometer (5kΩ): Used to set the desired temperature threshold by adjusting the reference voltage.
- Heating Resistor: Serves as the heating element, placed near critical analog components.

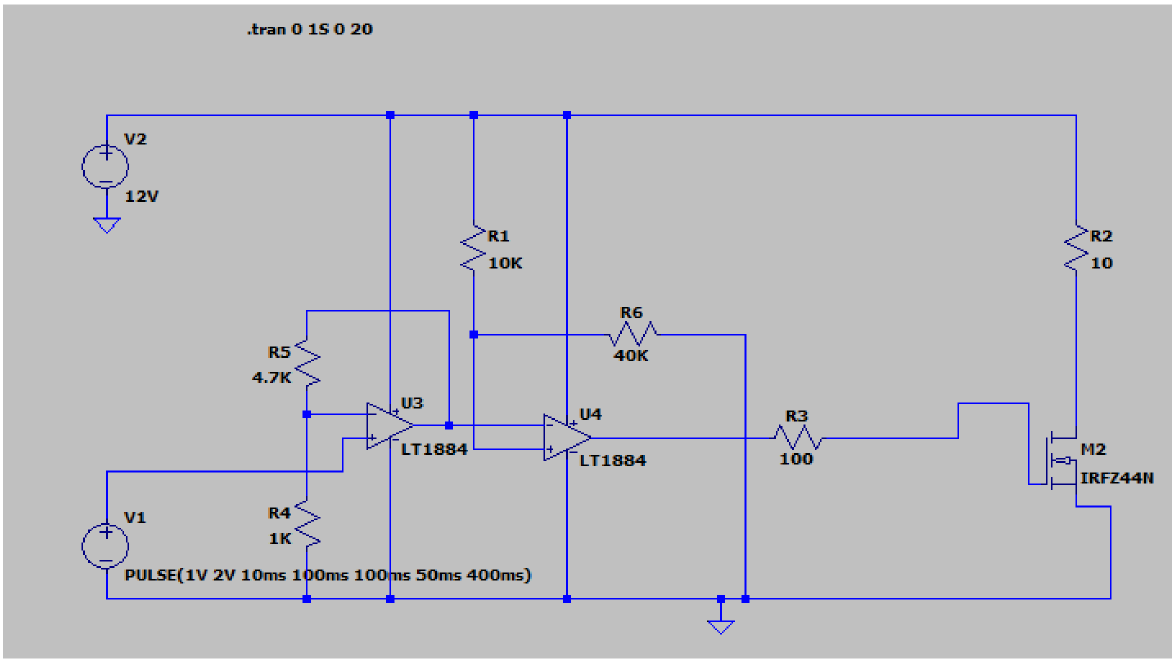


Figure 2: ltspice circuit of the first hysteresis control

III.3. Circuit Operation

This circuit was chosen as a preliminary simple case to understand the systems requirements. The LM35 sensor is positioned to monitor the temperature in the vicinity of the reference voltage circuitry. Its analog output is first amplified using the LM324 in a non-inverting amplifier configuration. The gain is set by using a voltage divider made of two resistors: 1kΩ and 4.7kΩ, achieving an approximate gain of 5.7.

This amplified signal is then fed into the comparator stage, where it is compared against a reference voltage provided by the adjustable 5kΩ trimmer. When the temperature exceeds the desired setpoint, the output of the comparator transitions high (3.8V). Conversely, if the sensed temperature is below the setpoint, the comparator output goes low (0V).

The output of the comparator is connected to the gate of the IRFZ44N MOSFET through a 100Ω resistor, enabling or disabling the heating resistor connected between the 5V supply and the drain of the transistor. The source is grounded, allowing the heating element to be activated when needed, and ensuring the system stabilizes the temperature near the reference circuitry.

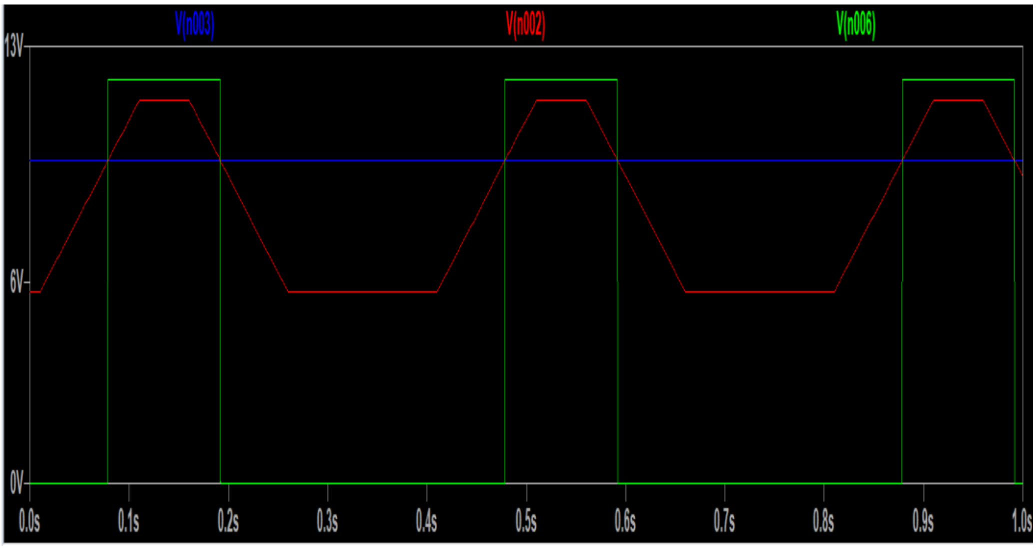


Figure 3: simulation results of the first hysteresis control

Here in this simulation, a supply of 12V was given to observe a wide range of outputs:
V(n002): amplified entry signal of temperature simulated with a variable voltage
V(n003): voltage reference regulating temperature
V(n006): voltage under the heating resitor

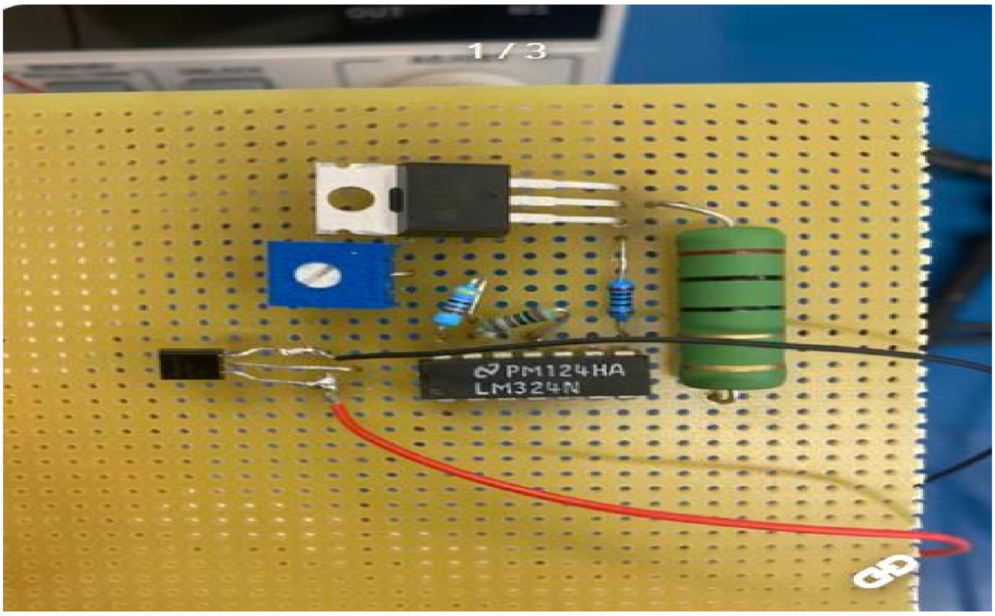


Figure 4: prototype circuit of the first hysteresis control

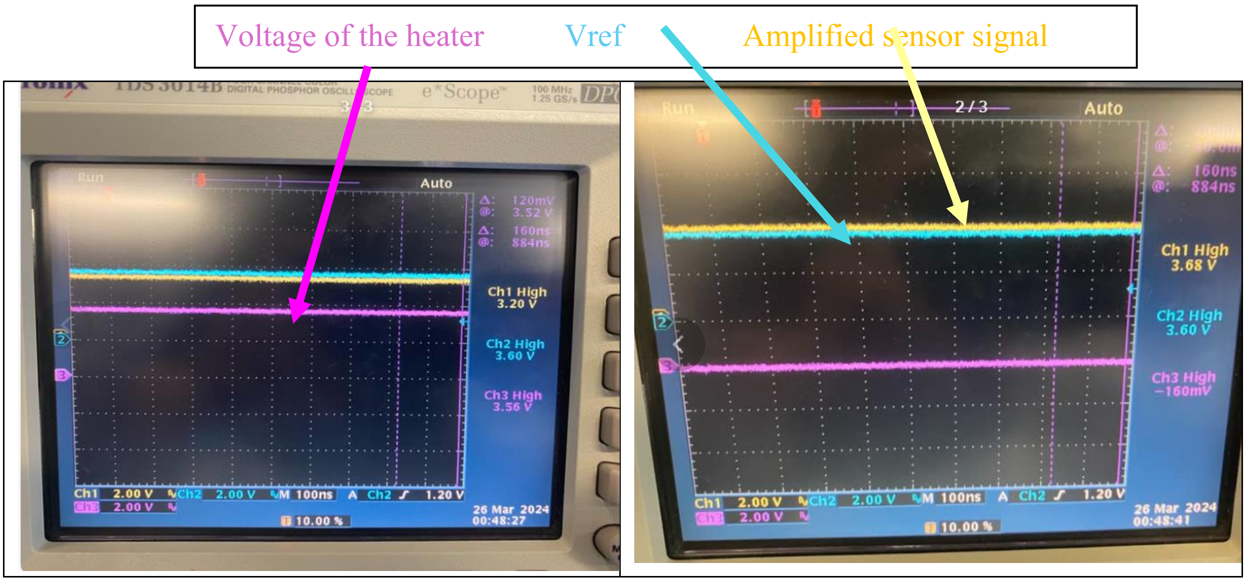


Figure 5: experimental results of the first hysteresis control

III.4. Conclusion

This analog temperature control system offers a low-cost and effective solution for maintaining thermal stability in the KOSMOS project. By actively compensating for temperature variations using a feedback loop driven by LM35 and LM324, and actuated via the IRFZ44N, we significantly reduce the precision errors due to temperature drift. Future enhancements may include digital feedback or PID control for even finer regulation.

However, Initially the thermostat design employed a classic hysteresis-based on/off control using a comparator and a trimmable reference voltage. While this approach provided basic thermal regulation, it quickly revealed its limitations in practical testing. One of the main issues was that the temperature feedback was too weak and slow, leading to long delays in stabilizing the temperature. When the threshold was crossed and heating was activated, the system would often overshoot the target temperature significantly before any cooling could occur. This behavior was due to the high intensity and duration of heating cycles, which caused the reference components to remain overheated for extended periods. As a result, the temperature drifted even further beyond the desired point, compromising the stability and precision of the voltage reference. These limitations prompted a redesign of the control strategy toward a continuous, steady-state regulation loop based on PI (Proportional-Integral) control as well as a solution for good feedback of temperature, which offers smoother, finer control and better compensation for thermal inertia, but first the feedback loop of the temperature should be enhanced.

IV. Optimized hysteresis temperature control feedback system

IV.1. Introduction

This temperature control solution demonstrated a clever and effective approach to thermal feedback by using two TO-220 transistors: one as a temperature sensor (e.g., TIP31C operating in diode mode), and the other (IRFZ44N) as a heating element. By physically coupling them together using a shared heatsink, this setup ensured good thermal tracking between sensing and regulation. However, while this design worked in theory and provided measurable feedback, it created a short circuit since both packages transported current, so we had to approach them as much as possible without them touching, this solution is still viable because of the exellent temperature feedback these transistors packages had, or what we used later on applying a thermal pad for the coupling.

IV.2. Circuit operation

-TIP31C Temperature Sensor
The TIP31C is used in diode mode, with its base and collector shorted and a 10 kΩ pull-up resistor to +5 V. This configuration produces a Voltage that decreases with temperature at about -2 mV/°C, enabling temperature sensing.
-Amplifier Stage (LM324)
An LM324 op-amp amplifies the sensor signal with a gain of 5.7, using a resistor pair (1 kΩ and 4.7 kΩ), making it easier to compare against a reference.
-Comparator with Hysteresis
Another LM324 op-amp acts as a comparator, The reference voltage is set using a 5 kΩ trimmer between 5 V and GND.
-Power Stage – Heating Control
The final stage of the analog thermostat includes a third LM324 op-amp, configured as a linear driver for the IRLZ44N MOSFET. This op-amp ensures smoother and continuous control of the heating element.
The inverting input of the op-amp is connected to the source of the MOSFET.
A 1 Ω resistor is placed between the source and ground, allowing real-time measurement of the drain current (since V = I × R).
The non-inverting input receives the comparator output in the hysteresis version.
The op-amp output goes to the gate of the MOSFET through a 100 Ω resistor.
This creates a closed feedback loop that automatically adjusts the gate voltage to maintain the desired current through the MOSFET. The drain is connected to the +5 V supply, and the load is achieved by running the transistor in linear mode.

-IRLZ44N Heating Without Cooling

To safely use the IRLZ44N as a heating element (Drain = 5 V, Source = GND) without a heatsink or fan:

- The max power dissipation must stay ≤ 2.4 W, based on:
  - T= 175 °C
  - R= 62 °C/W
  - Ambient = 25 °C
- This limits the current to ~0.48 A maximum, which is very important to set in the supply block to safely use the transistor without burning, implying a Vgs of ~2.4 V.
  At this point:
- P = 5 V × 0.48 A = 2.4 W
- T= 173.8 °C, dangerously close to thermal limits.

IV.3. Conclusion

The simulations performed on both analog thermostat architectures showed essentially identical behavior, primarily because LTspice does not allow modeling of thermal feedback between the IRLZ44N (heating element) and the TIP31C (temperature sensor). However, the experimental results revealed a significant improvement in temperature feedback using the second configuration. The system responded faster, with less overshoot and shorter cooling times, compared to the hysteresis-based approach. Heating stabilization was achieved in under a couple of minutes, demonstrating a major step forward in performance. That said, some minor thermal overshoot still remains, indicating that while the heating power is now effective, it still requires tighter regulation. For this reason, the next phase of the project will focus on implementing a PI (Proportional-Integral) controller to achieve more precise and stable thermal regulation by dynamically adjusting the heating effort based on real-time error.

V. Proportional integral temperature control

V.1. Introduction

Compared to the previous circuit, the only change to create a proportional intergral control system is the second AOP that will compare the the error between Vref and the amplified signal to output a linear voltage from 0V to 3,8V depending on the magnitude of the error measured.

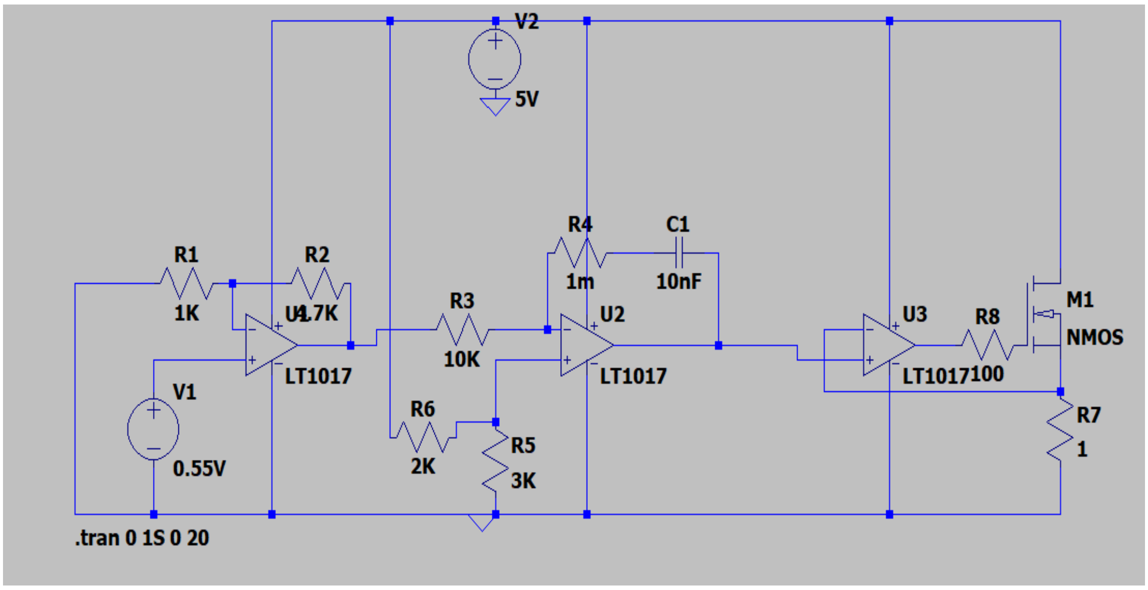


Figure 6: Ltspice circuit of the proportional integral temperature control

V.2. Behavior of the PI-Controlled Heating System

In the PI-regulated version of the thermostat, the output of the PI controller directly controls the gate voltage of the IRLZ44N MOSFET, which operates in linear mode. When the error voltage (difference between the amplified sensor signal and Vref) is high, the PI output rises to 3,8V , increasing the gate voltage. This makes the MOSFET more conductive (reducing Rds(on)), allowing more drain current to flow (uo to 140mA). Although resistance drops, the power dissipated (P = Vds× Id increases significantly, causing the transistor to heat up more. As the sensed temperature approaches the target, the error diminishes, and the PI controller begins to reduce the gate voltage to 3,3V . This gradually lowers the current (about 8mA quinscent current) and power dissipation, creating a smooth, continuous regulation effect. Eventually, when the set temperature is reached, the gate voltage falls below the conduction threshold, effectively switching off the MOSFET, not allowing current and stopping the heating. The inverting input of the op-amp, connected to the source of the MOSFET (via a 1 Ω resistor), ensures that the source voltage and thus the current is tightly regulated according to the PI output.

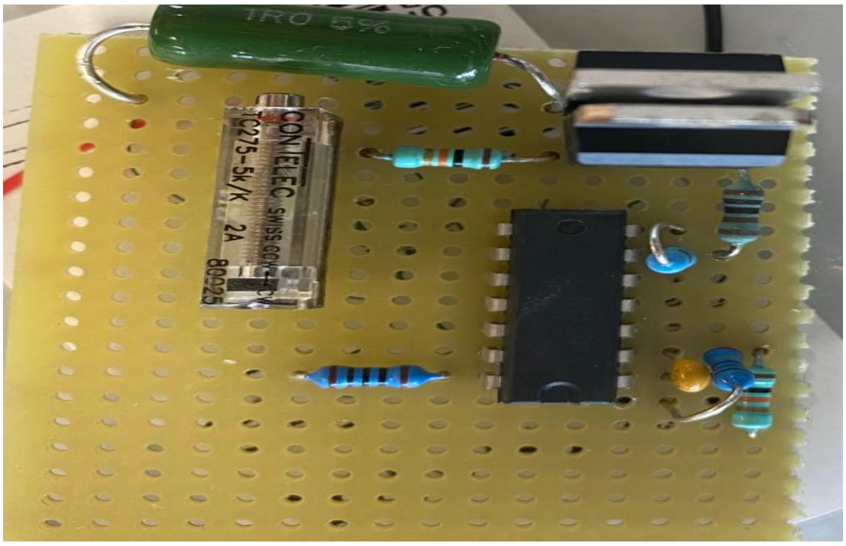


Figure 7: prototype of the proportional integral temperature control

Gate voltage of the heater Vref amplified sensor signal

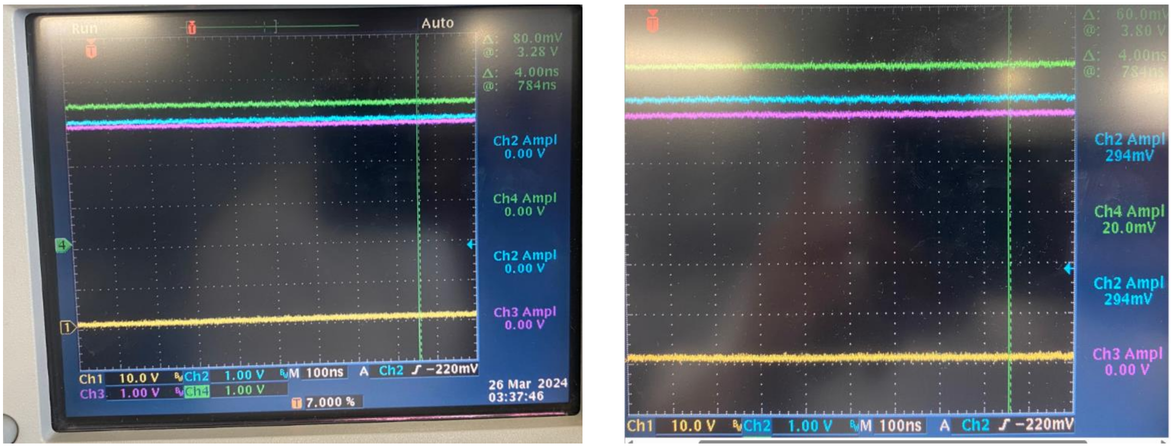


Figure 8: experimental results of the proportional integral temperature control

V.3. Conclusion

Compared to the hysteresis-based version, this solution proved much faster and more accurate, typically reaching the desired temperature range in a few seconds, as opposed to minutes previously, because constantly modulating the current allows better control of the heat dissipated by the power transistor.
Another important point to make is that the change in gate voltage or current passing through the power transistor isn't made exactly when both compared signal are equal, but rather after approaching to a certain limit as we can see in the graphs, that should be due to offsets. As my

PI op-amp needs a small error (e.g. 30 mV) before the gate output changes enough to regulate the current.

V.4. Experimental limits of the analog thermostat

The reference voltage in this system can be expressed as $V_{ref}=5.7\times[0.55\ \text{V}-0.002\ \text{V/°C}\times(T-25\text{°C})]$, which defines a regulation range from 2.46 V to 3.04 V, corresponding to temperatures of 33.3 °C to 89.5 °C. At the lower end of this range ($V_{ref}\leq 2.40$V), the control loop demands currents above 0.48 A to sustain the target temperature, posing a critical risk of transistor burnout due to excessive power dissipation and potential thermal runaway. To prevent this, the supply is limited to 0.48 A, ensuring the transistor remains within safe operating limits. At the upper limit ($V_{ref}=3.04$ V), the regulation point corresponds to ~33.3 °C, where the circuit draws only its quiescent current (~0.008 A). In this condition, the system is stable, with the transistor largely inactive since minimal heating is required, and no additional current is forced into the load. Because there is no active cooling mechanism, the circuit simply halts heating and waits, allowing residual thermal mass to dissipate naturally until equilibrium with ambient temperature is reached.

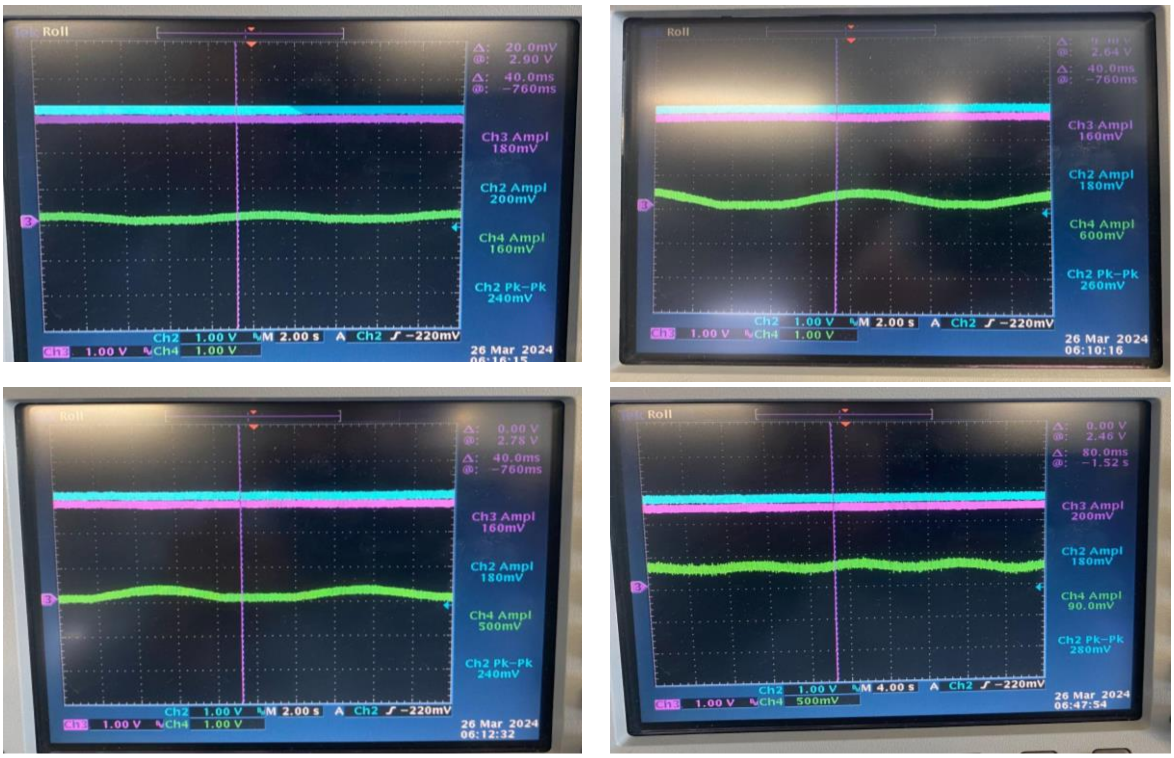


Figure 9: voltage driver response of the proportional integral temperature control system of respectively (Vref=2.46 V Vref=2.85 V Vref=2.95 V Vref=3.04 V)

V.5. Response of the analog thermostat in the climatic chamber

to regulate the thermostat at 50°C, we should set the reference voltage (Vref) to 2.95V.
Here are the measurements of the sensor's temperature across a period of time of 45 min,varying the chamber's temperature from 35 to 20 degrees. We put a thermocouple in the metal side of the sensor, since big gradients of temperature are created across the whole circuit.

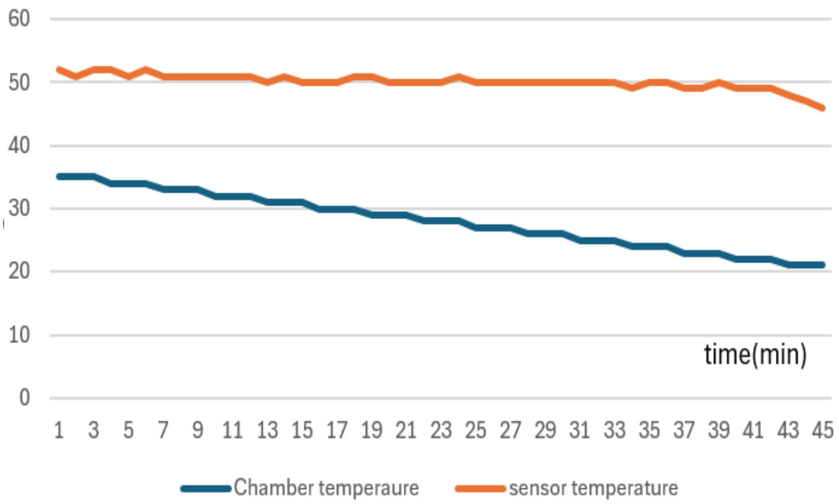


Figure 10: thermal response in the climatic chamber of the proportional integral system

V.6. Result and conclusion:

The analog thermostat demonstrated distinct behavioral patterns across different temperature ranges during the 45-minute observation period. The system's performance can be categorized into three operational zones:

High Temperature Zone (25-35°C): The thermostat exhibited continuous oscillations between 50-52°C, indicating active control engagement but with noticeable temperature swings. The system maintained operation within the acceptable range but demonstrated somewhat of an instability with regular fluctuations between these temperature bounds. This oscillatory behavior suggests the control system is actively responding to temperature deviations but lacks the precision for tight temperature regulation.

Moderate Temperature Zone (22-25°C): The system showed remarkable stability, maintaining a consistent 50°C output with minimal deviation. This represents the thermostat's optimal operating condition where environmental factors provide ideal conditions for stable temperature regulation.

Low Temperature Zone (Below 22°C): A significant performance degradation was observed as ambient temperature decreased below 22°C. The controlled temperature began to decay progressively below the 48°C threshold, with oscillations ceasing entirely. This indicates the system's inability to maintain adequate heating power to overcome increased thermal losses at lower ambient temperatures.

VI. Analog Thermostat Optimization - PID Implementation

To address the oscillatory behavior and limited precision observed in the initial PI-controlled thermostat, a comprehensive redesign was implemented featuring a full PID controller with tunable parameters, enhanced signal conditioning, precision voltage regulation, and improved thermal coupling.

VI.1. PID Controller Implementation

Proportional Control Enhancement

The proportional gain was made adjustable through the implementation of a manual switch (interrupteur) combined with a 1MΩ tunable resistor. This configuration allows for real-time adjustment of the proportional response, enabling optimization of the system's immediate response to temperature deviations without requiring circuit modifications, and by turning off other switches the system started to oscillate for a value of 950k which made me choose 800K as a tuning value (for a 2,825V reference).

- **Integral Control Optimization**

The integral component was enhanced with a dedicated 1MΩ tunable resistor, providing precise control over the accumulation of steady-state error correction. This adjustment capability allows for elimination of persistent temperature offsets while preventing integral windup that could cause system instability, and same as last by turning off the derivative switch, i got to a value of 50K which seems the most stable .

- **Derivative Control Addition**

A new derivative control path was introduced using a 10kΩ tunable resistor. The derivative component provides anticipatory control by responding to the rate of temperature change, significantly reducing overshoot and improving settling time. The lower resistance value (10kΩ vs 1MΩ) reflects the typically smaller contribution of derivative action in temperature control applications, which in the end was fixed at 500ohm for a medium overshoot.

VI.2. Noise Filtering and Enhanced Thermal Coupling

- **Low-Pass Filter Implementation**

A first-order low-pass filter was integrated immediately after the temperature sensor, consisting of a 10kΩ resistor and 1µF capacitor. This filter serves several critical functions:

- **Noise Reduction**: Eliminates high-frequency electrical noise that could cause erratic control behavior with a cutoff frequency of approximately 16 Hz, well above typical temperature dynamics but below most electrical interference frequencies
- **Derivative Stability**: Prevents the derivative controller from amplifying sensor noise,

VI.3. Thermal Pad Implementation

A specialized thermal pad was installed between the temperature sensor transistor and the heating transistor to optimize thermal feedback. This thermal interface material provides:

- **Excellent Thermal Conductivity and Electrical Isolation**: Ensures rapid and accurate temperature sensing and Prevents electrical interference
- **Reduced Thermal Time Constant** and provides **Mechanical Stability**

VI.4. Precision Voltage Regulation

- **LM317 Voltage Regulator Integration**

An LM317 adjustable linear voltage regulator was implemented with a precision trimmer resistor to provide stable reference voltage control.The main purpose was to see the difference between a trimmer and a stable voltage, This enhancement offers:

- **High Precision and thermal stability**: Enables fine-tuned temperature setpoint adjustment with minimal drift
- **Load Independence**: Maintains consistent reference voltage regardless of control circuit loading
- **Trimmer Control**: Allows for precise calibration and adjustment of the desired temperature setpoint

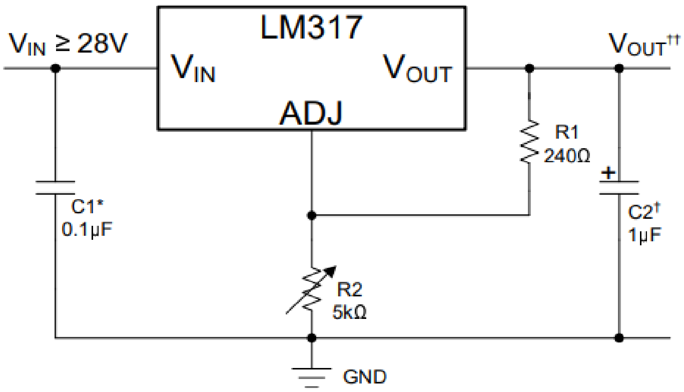


Figure 11: LM317 Voltage Regulator circuit

VI.4. Circuit Simulation and Validation

LTSpice Implementation

The complete PID thermostat circuit was modeled and simulated using LTSpice to validate the design before physical implementation. The simulation included:

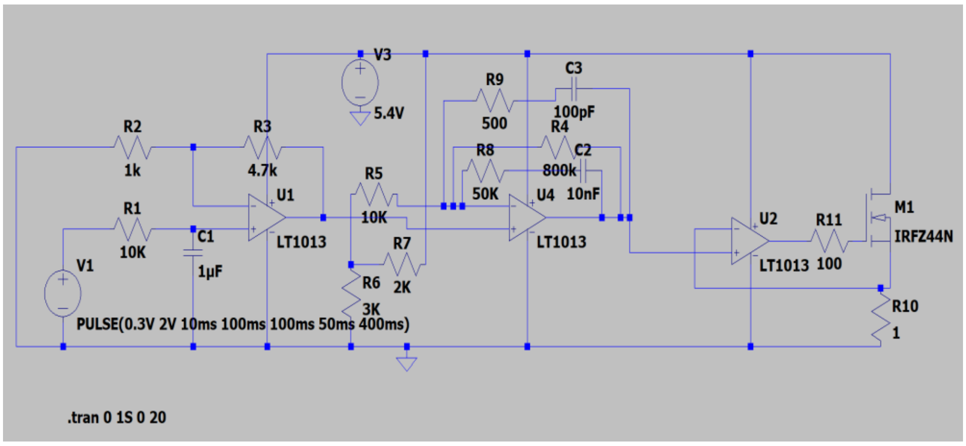


Figure12: ltspice circuit of the PID control circuit

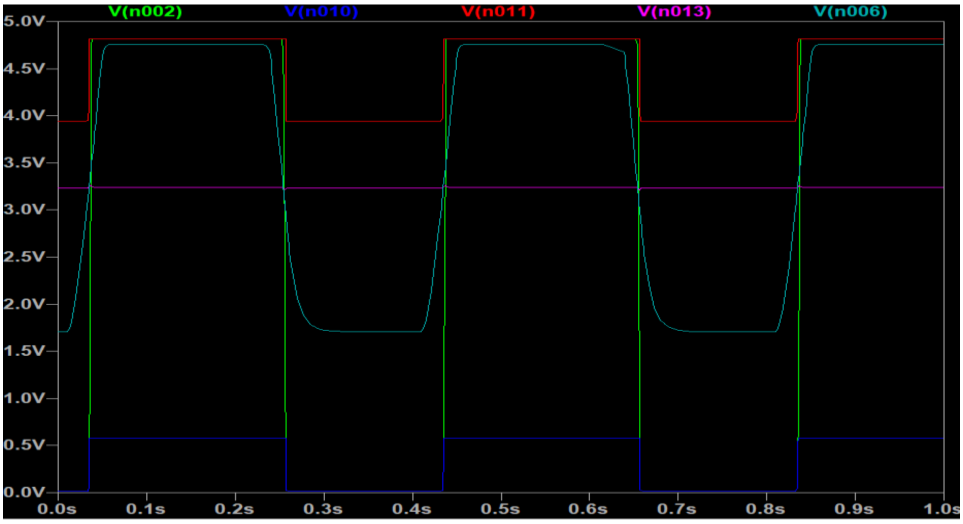


Figure13: ltspice circuit simulation of the PID control circuit

The circuit demonstrates four key signals working in harmony: the light blue trace represents the amplified and filtered temperature sensor signal ranging from 0.3V to 2V after conditioning through the low-pass filter (10kΩ + 1µF), the pink trace shows the reference voltage setpoint (characterized here by two resistors but implemented with the precision LM317 output as previously explained), the green trace displays the PID controller output ranging from 0V to 4.8V which experimentally corresponds to the inverting input of the final operational amplifier in dark blue from 0 to 0.5V maintaining current sensing capability through the sense resistor to control voltage across the heater, and finally the red trace shows the MOSFET gate voltage with moderate precision - operating at approximately 3.9V with only 14mA quiescent current in standby mode blocking any heat, and reaching 4.2V to deliver maximum current of 0.48A when full heating power is required, demonstrating excellent current control resolution..

VI.5. Performance Improvements and conclusion

The optimized PID controller demonstrates exceptional performance with a voltage reference stabilized at 2.825V and an amplified signal maintaining remarkable consistency between 2.794V and 2.795V, representing less than 0.5 degree temperature variation. This system achieves superior temperature control through several key enhancements: derivative control effectively reduces oscillations for smoother operation, precision voltage regulation enables tighter temperature control with improved accuracy, low-pass filtering eliminates noise instabilities for enhanced stability, and improved thermal coupling significantly reduces system response time for faster performance. The tunable PID parameters provide flexibility to optimize performance across different operating conditions, making this controller highly adaptable while maintaining the exceptional stability evidenced by the minimal voltage fluctuation range.

VII. Final Analog Temperature compensation optimization – PID Implementation

VII.1. Circuit Architecture

The thermostat follows a modular control structure:

- A differential amplifier compares the sensor output to a reference voltage set via a trimmer. This voltage represents the target regulation temperature.
- The error signal is fed to an analog PID controller, built using three separate op-amp stages: proportional (scalable), integral (via an RC integrator), and derivative (capacitive differentiator).
- For tuning purposes, manual switches(in the prototype) were added to dynamically adjust the PID gain resistors and evaluate system behavior.
- A summing amplifier merges the three terms into a single control signal via 10K resistors.
- This output then drives a MOSFET (IRFZ44N) used as the heating element, where its source is connected to ground via a 4.7 Ω resistor. The heat generated regulates the nearby sensor's temperature.

The entire op-amp section uses bipolar ±10 V supply rails to ensure full swing and avoid clipping across the control range.

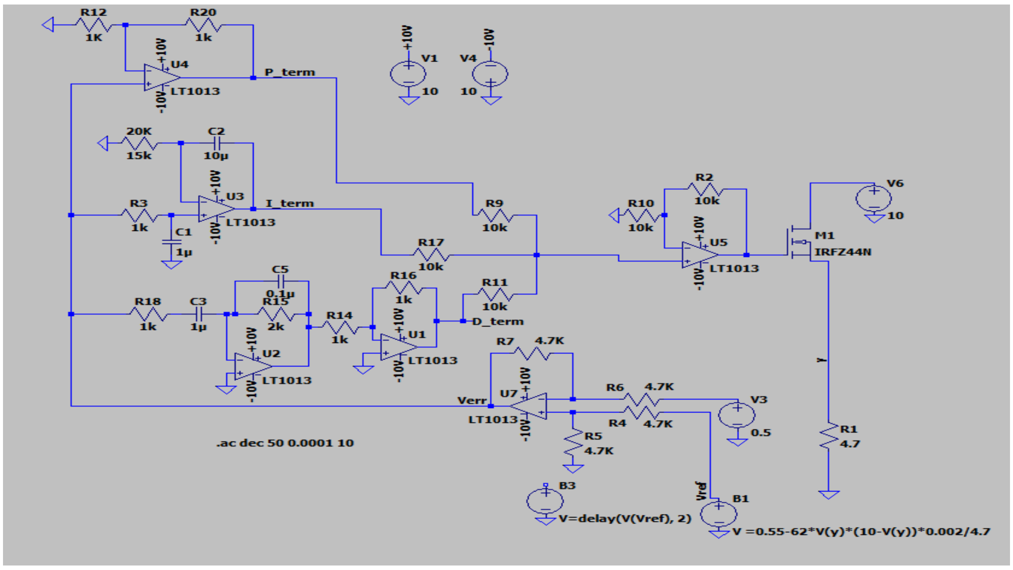


Figure 14: Final PID circuit optimization

VII.2. Thermal Modeling and Signal Propagation

In LTspice, we implemented a thermal feedback delay of 2 seconds in the feedback, representing real-world heat transfer between the heater and the sensor, connected via a thermal pad. An arbitrary behavioral voltage source was used to model the temperature-to-voltage feedback conversion of the sensor under heating: **$V=0.55-62\cdot V(y)\cdot(10-V(y))\cdot 0.002/4.7$**

Here:

- V(y) is the voltage across the sense resistor (i.e., the current through the MOSFET in amps times 4,7).
- 62 °C/W is the assumed **thermal resistance** between junction and ambient 0.002 V/°C represents the **sensor's slope.**

This function models how heat propagates and affects the sensor voltage, simulating thermal lag and feedback.

VII.3. Simulation and Tuning

VII.3.1.Transient response

We used Ziegler-Nichols method as a starting point for PID tuning, refining it through. Step param sweeps in LTspice to test various resistor values for proportional, integral, and derivative paths. This allowed rapid optimization of rise time, overshoot, and steady-state error.

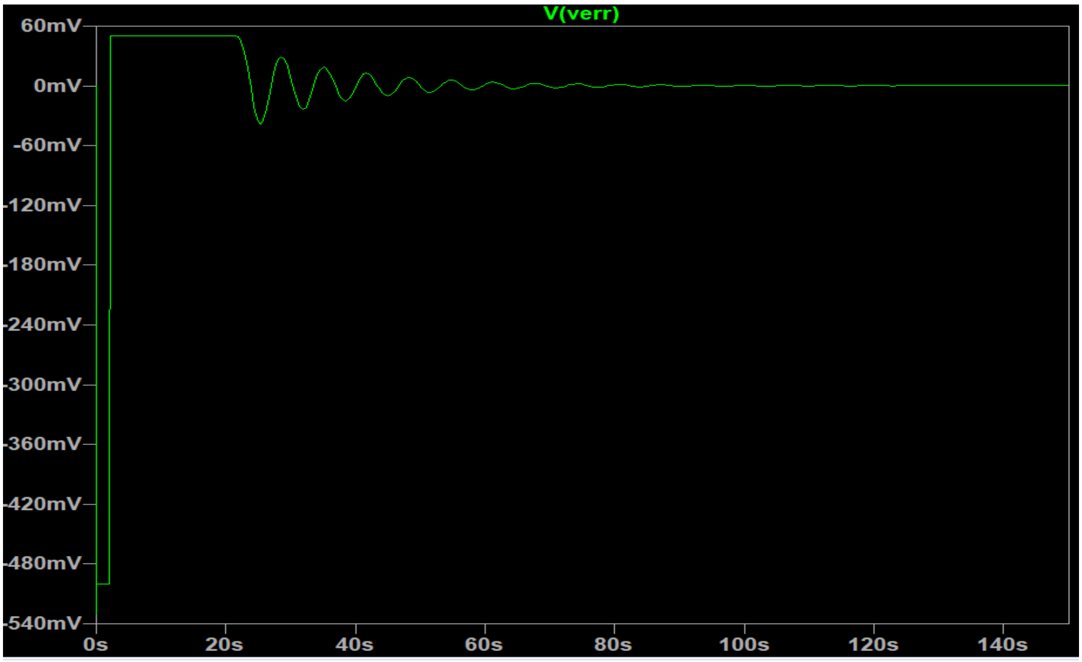


Figure 15: Error response of the PID optimized circuit

Figure 16: Static error response of the PID optimized circuit

VII.3.2.Frequency-Domain Analysis and Stability

In the AC analysis phase, the behavioral voltage source modeling thermal feedback was replaced with an AC voltage stimulus. Due to the inherently slow thermal dynamics, we performed the frequency sweep from 100 µHz to 1 kHz. The system's response was measured at the sense resistor connected to the MOSFET source.

The resulting Bode plot displayed a gain range from –225 dB to –80 dB, and a phase response ranging from 73° to 108°, consistently maintaining a phase margin greater than 45°, which confirms that the PID loop is well-damped and stable. The Nyquist plot further verified the absence of encirclement around the critical point, indicating the system remains convergent and avoids oscillatory instability.

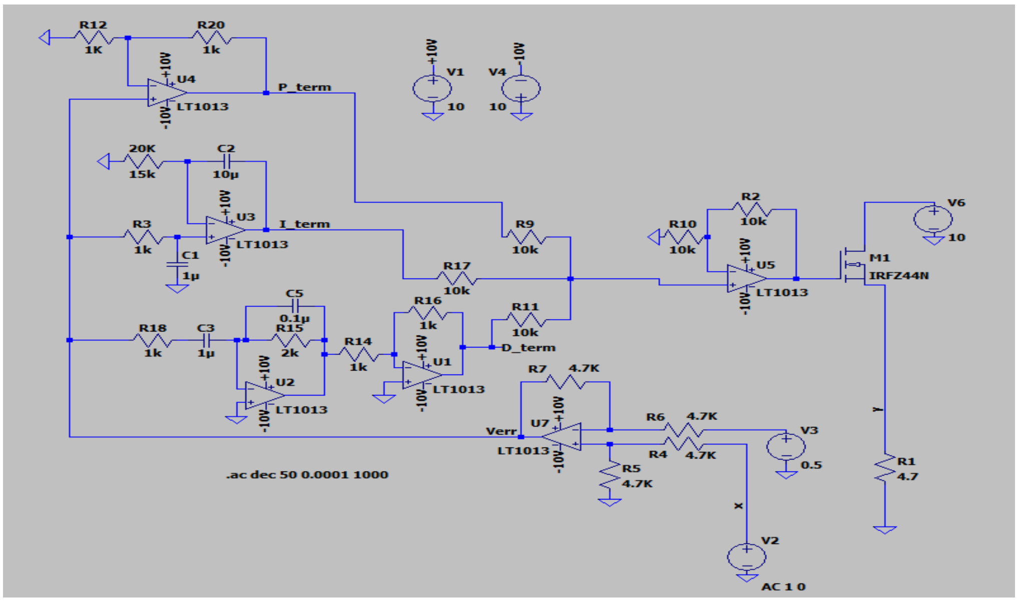


Figure 17: AC analysis of the PID optimized circuit

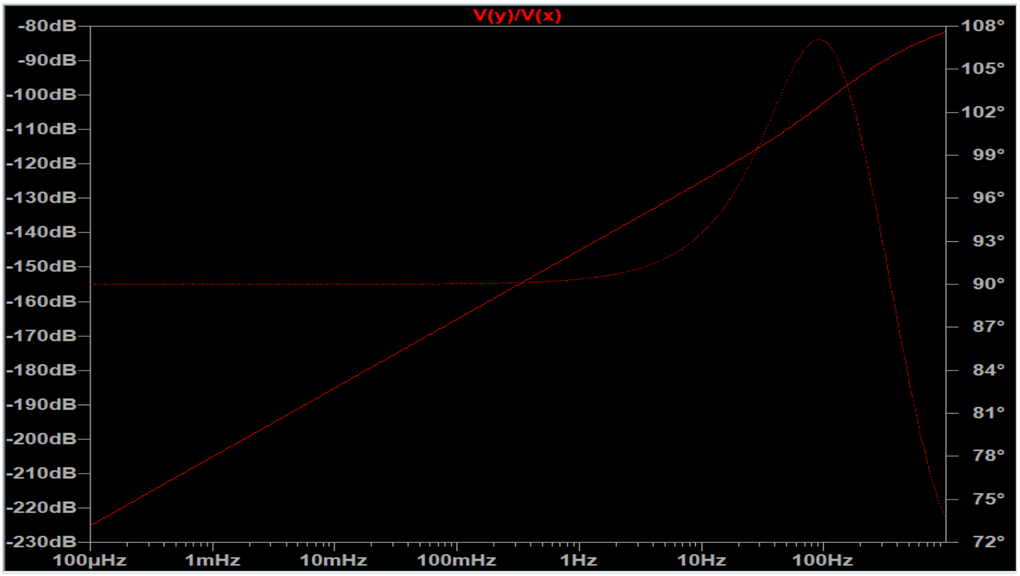


Figure 18: AC analysis response of the PID optimized circuit

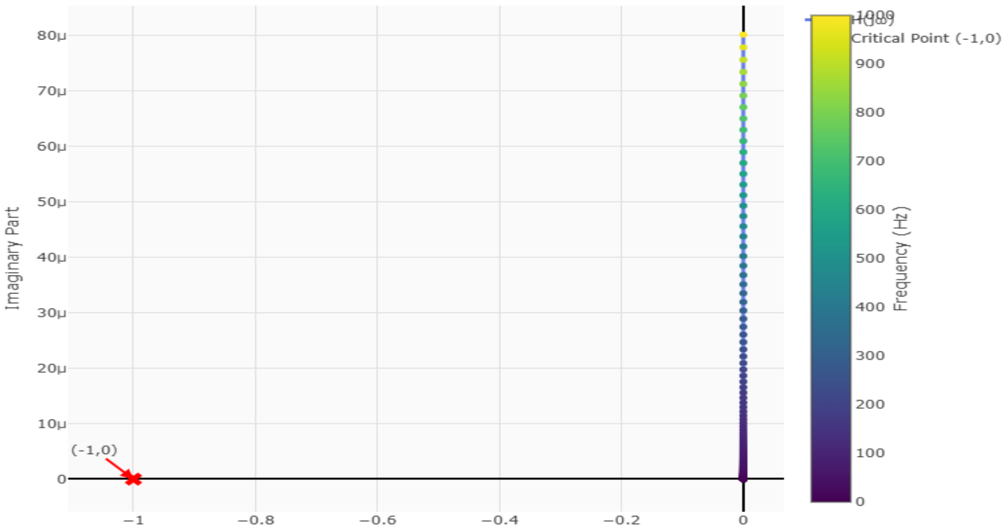


Figure19: Nyquist Diagram – Loop Transfer Function H(jw)

VII.3.3. Experimental Validation and Observations

Following simulation, the circuit was built and tested on a breadboard. It demonstrated excellent thermal regulation: the sensor voltage stayed nearly constant, and the current through the heater oscillated finely between 76 mA and 79 mA, consistent with steady-state PID correction, which is about 1.5 degree oscillation mainly due to non-amplified voltages at the differential amplifier. Although the experimental results closely matched the simulation in terms of oscillation dynamics, a slight discrepancy was observed in the setpoint current:In simulation, the steady-state heater current stabilized at ~180 mA, Whereas in reality, it settled around ~77 mA, likely due to differences in thermal transfer efficiency and component tolerances.

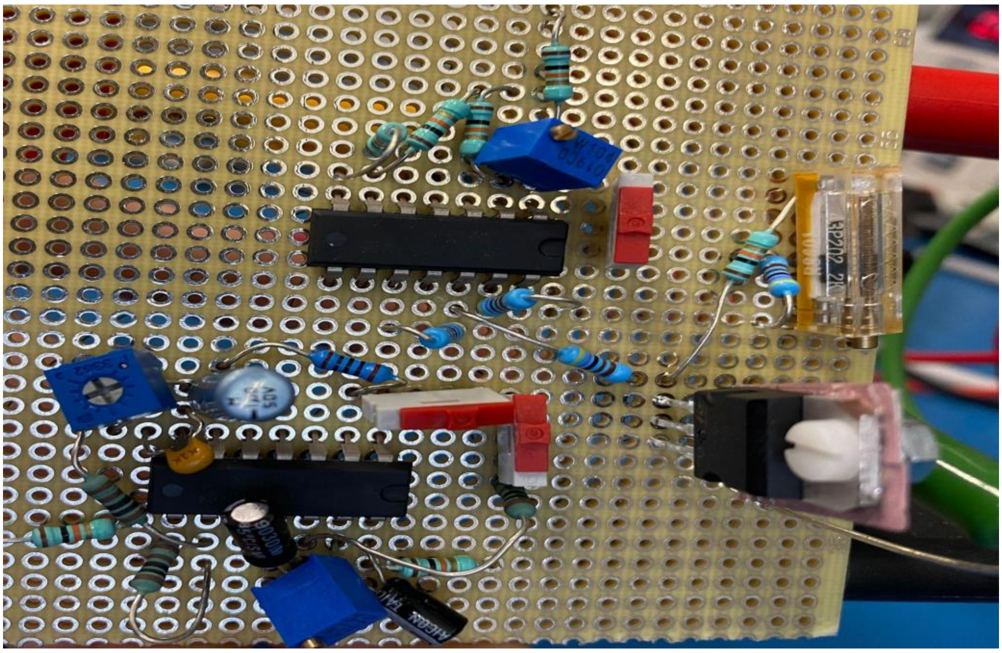


Figure20: Prototype of The PID optimized circuit

A better simulation matching the reality would be to multiply the temperature coefficient with a factor less than 1 that portrays the loss of temperature transfer between the sensor and the heater, we found that 0.88 gives the perfect response of steady state reaching approximately 76mA similar to the reality.

VIII. PID Compensation Circuit PCB Implementation and Results

VIII.1. Introduction to PCB Design and Fabrication

This section introduces the final goal of designing and fabricating a custom Printed Circuit Board (PCB) for the PID compensation circuit. From the outset, the objective was to create a robust, reliable, and scalable solution for integration into multiple boards, ensuring consistent performance and enabling mass implementation, rather than relying on less reliable prototyping methods.

- **Necessity of PCB Implementation:**The design and implementation of a custom Printed Circuit Board (PCB) for the PID compensation circuit was the fundamental objective of this project. This was an inherent requirement, driven by the need for a highly reliable, reproducible, and scalable solution for integration into multiple production boards. The PCB was thus the primary design goal from the project's inception, essential for ensuring consistent performance across numerous units, minimizing noise, and enabling seamless integration into the Kosmos system's architecture for large-scale deployment.
- **Design Considerations:** The PCB design was carried out using specialized EDA software called EASYEDA.. Key design choices focused on optimizing the circuit's analog performance. This included careful component placement to minimize trace lengths for sensitive signals, strategic routing, and the implementation of robust power distribution planed wider that usual for bigger current transfer. A significant consideration was the board's eventual mounting on top of the Kosmos system, requiring precise pin header spacing of 2.54mm and lastly a good thermal coupling using 4 layers of copper and a lot of vias especially in the area where temperature is needed the most . The circuit incorporates several stages:
    - **Low-Pass Filter:** A low-pass filter was added immediately after the temperature sensor to reduce high-frequency noise that could interfere with the precision of the sensed temperature signal. This ensures that the PID controller receives a clean, stable input.
    - **Signal Amplification:** The filtered sensor signal was then amplified by a factor of 5.7 using a differential amplifier. This amplification stage was critical to maximize the resolution of the temperature measurement and optimize the signal-to-noise ratio before feeding it into the PID controller.
    - **PID Controller Core:** This section comprises the Proportional (P), Integral (I), and Derivative (D) components, implemented using one of the best operational amplifiers (OPA4197IPWR 2018 from texas instruments).
    - **Summation Stage:** A summer circuit combines the outputs of the P, I, and D terms to generate the overall control signal.
    - **MOSFET Driver:** The final stage drives a MOSFET, which acts as the heating element controller, regulating the current supplied to maintain the desired temperature. Two distinct PCB versions were designed: one featuring potentiometers and switches for flexible tuning of the PID control parameters during development and testing, and a more compact version with a smaller area, lacking potentiometers or switches, intended for fixed, optimized parameters and easier integration.

VIII.2 PCB Layout and Component Integration

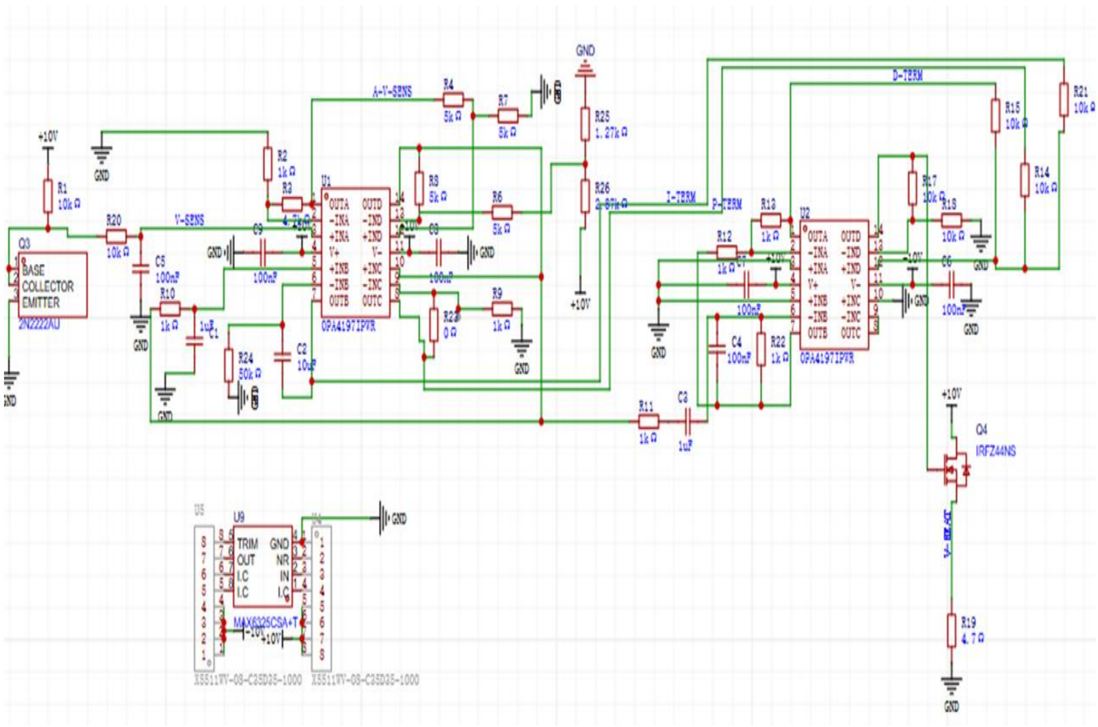


Figure21: easy EDA implemented optimized PID circuit

This section details the physical layout of the two PCB versions and the integration of the PID compensation circuit components.

- **Overall PCB Layout Description:** Both PCB versions were designed as multi-layer boards, specifically utilizing four layers of copper. This allowed for dedicated ground and power planes, crucial for minimizing noise and improving signal integrity in a mixed-signal environment. Numerous vias were strategically placed to facilitate thermal coupling and efficient signal routing between layers. The major functional blocks—power supply, sensor interface, PID controller, and MOSFET drive—were laid out to ensure optimal signal flow and minimize interference.
- **Key Components and Their Placement:** The critical components of the PID circuit include the operational amplifiers for the P, I, and D stages, the precision voltage reference (MAX6325), the temperature sensing BJT (2N2222), and the heating element MOSFET (DPAK TO263). Initial component spacing considerations included placing the heater approximately 1cm from the MAX6325 and 2cm from the temperature sensing BJT as the reference would be between them. This spacing was intended to facilitate thermal coupling and minimal surface spacing of the components, but as discussed in the next section, it presented significant debugging challenges. The 2N2222 BJT was chosen as the temperature sensor due to the unavailability of the TIP31C in an SO-89 package. For the heating element, a DPAK

TO263 package was selected for the MOSFET to allow for better spacing and thermal dissipation.

- **Visual Representation of the PCB:**

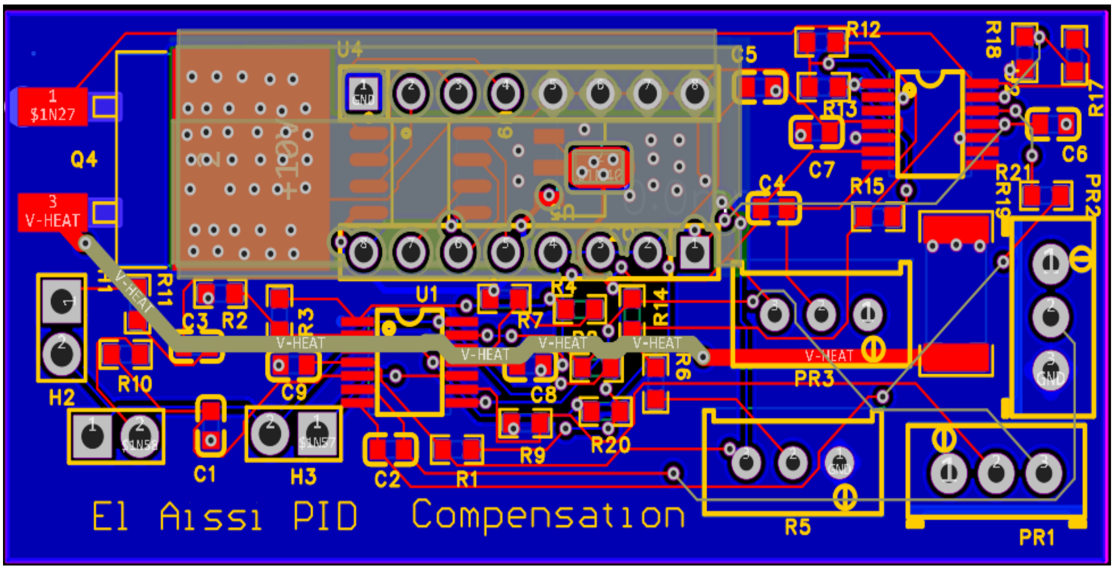


Figure22:layout of thePID tester circuit

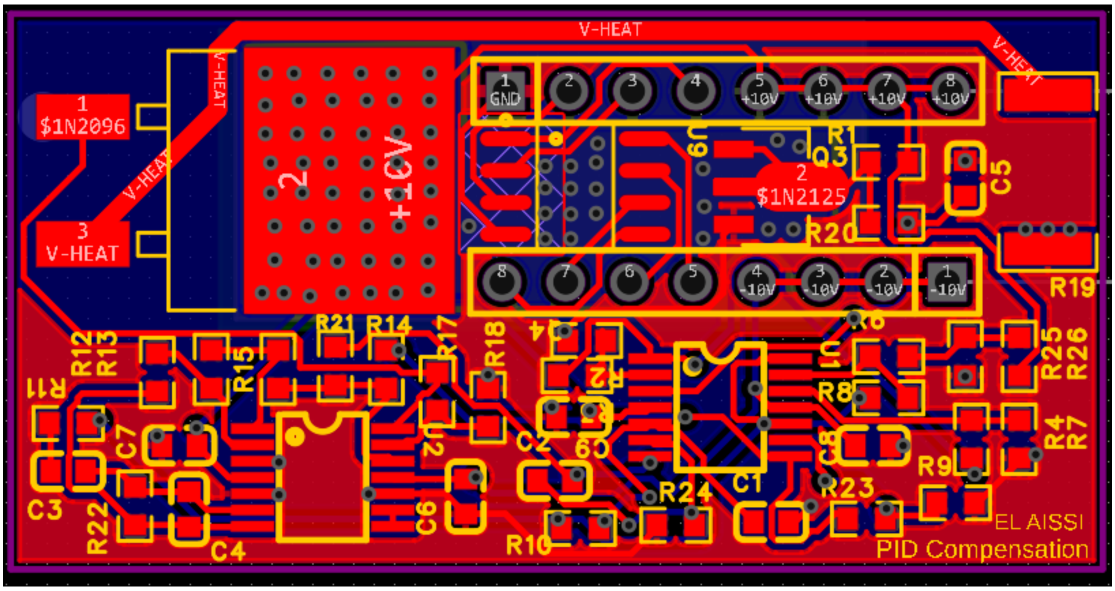


Figure23: layout of the final PID temperature control circuit

VIII.3 Experimental Results and Performance Evaluation

This final section presents the experimental results obtained from testing the PID compensation circuit on the fabricated PCB, along with the significant debugging challenges encountered and their solutions.

1) **Test Setup:** Upon receiving the fabricated PCBs, the debugging process began. The PCBs were integrated into the existing experimental setup, which included a controlled environment for temperature measurement, an oscilloscope for signal analysis, and a precision multimeter

for voltage and current readings. The board was powered, and the heating element was driven to observe its thermal response and the PID system's control.

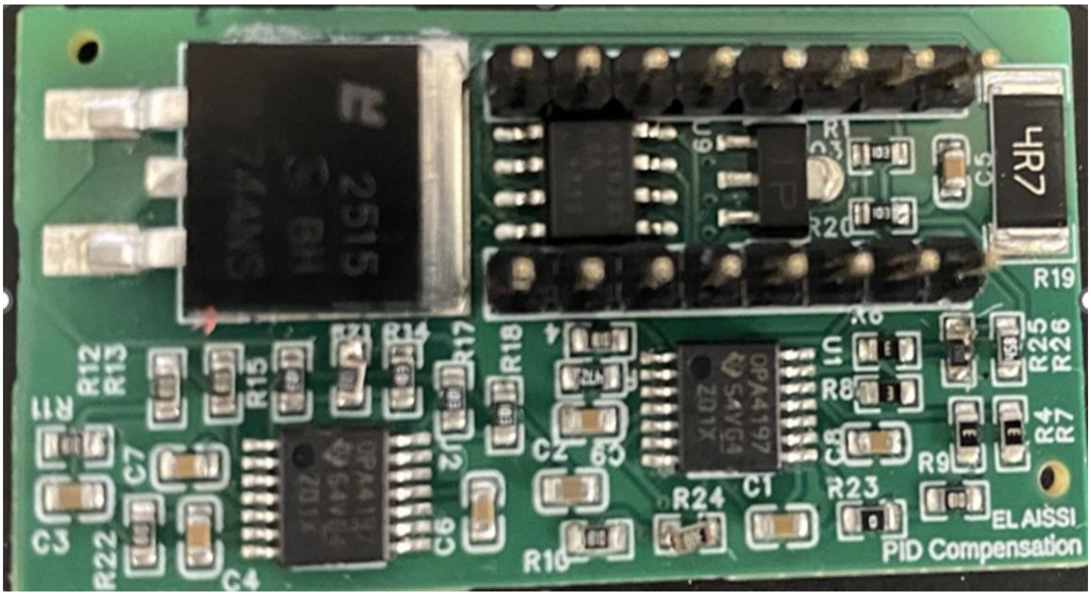


Figure24: PCB of the PID temperature control circuit

2) **Debugging Challenges and Initial Observations:** A major problem quickly emerged: the thermal coupling on the PCB was not as effective as anticipated, leading to significant errors in the temperature control. Despite the four copper layers and numerous vias intended for efficient thermal management, the physical spacing and temperature coupling between the heater, the MAX6325 reference, and the 2N2222 temperature sensing BJT) created problematic temperature gradients and considerable thermal inertia, another problem was the change of set voltage Vref with the resistors that would drift when heated and induce a couple of millivolts of error .The system's behavior was characterized by a large hysteresis loop:

a) When power was applied to the PCB, the system would heat rapidly, especially with current change going to 500mA further increasing the error at the first stage.

b) Upon surpassing the Vref (setpoint), the thermal inertia of the board caused the temperature to continue rising for several seconds.

c) The PID system, unable to react quickly enough to this overshoot, would drastically lower the current to the minimum.

d) This rapid current reduction caused a decrease of voltage sensing further giving wrong signals to the PID control

e) The cycle would then repeat, with the system heating up again, leading to continuous oscillations. Furthermore, these quick changes in current also induced voltage fluctuations that were sensed by the PID system, further compounding the control problems and leading to unstable operation. The integral component of the PID, in particular, was observed to saturate the operational amplifier due to the large error signals, exacerbating the issue.

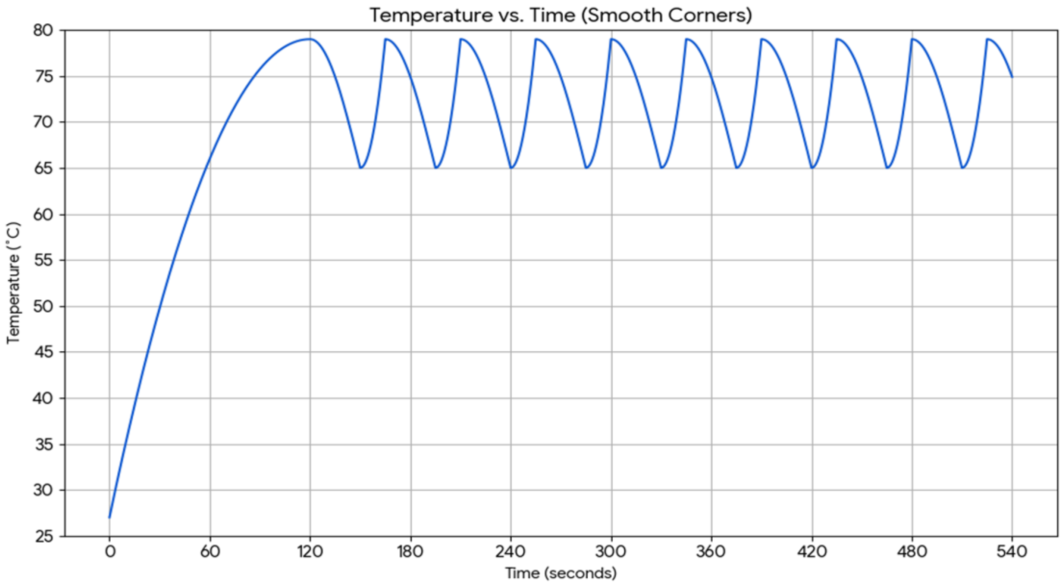


Figure25: temperature response of the delivered PCB

3) **Solutions and Performance Improvements:** To mitigate these issues, two primary adjustments were made to the PID controller:

a) **Reducing Integral Saturation and Initial Heating:** The resistance of the integral summer was increased from 10KΩ to 18KΩ. This change effectively lowered the maximum current supplied to the heating element by preventing the integral term from saturating the op-amp. The new approach involved heating the system with a lower, more controlled current, just enough to reach the setpoint. The trade-off was an increased settling time, requiring the system to wait a couple of minutes to reach the target temperature. However, this significantly decreased the thermal inertia, allowing heat to dissipate more quickly once the setpoint was reached. As a result, the system could react faster to decrease current, which was sensed more rapidly due to the reduced inertia.

b) **Slowing the Integral Term:** The resistance associated with the integral term was further increased from 50KΩ to 200KΩ. This modification significantly slowed down the integral action, making the controller less aggressive in responding to sustained errors. This helped to smooth out the control response, reduce overshoot, and prevent rapid current thus voltage oscillations.

4) **Conclusion of PCB Implementation:** Despite the initial debugging challenges related to thermal management and component placement, the iterative adjustments to the PID parameters on the PCB ultimately led to a more stable and controlled temperature compensation system (1 degree variation if encapsulated). The fabricated PCB provides a compact and robust solution for the precision voltage reference, demonstrating the successful transition from prototype to a more integrated design. The lessons learned regarding thermal coupling and PID tuning on a physical board are invaluable for future analog circuit designs.

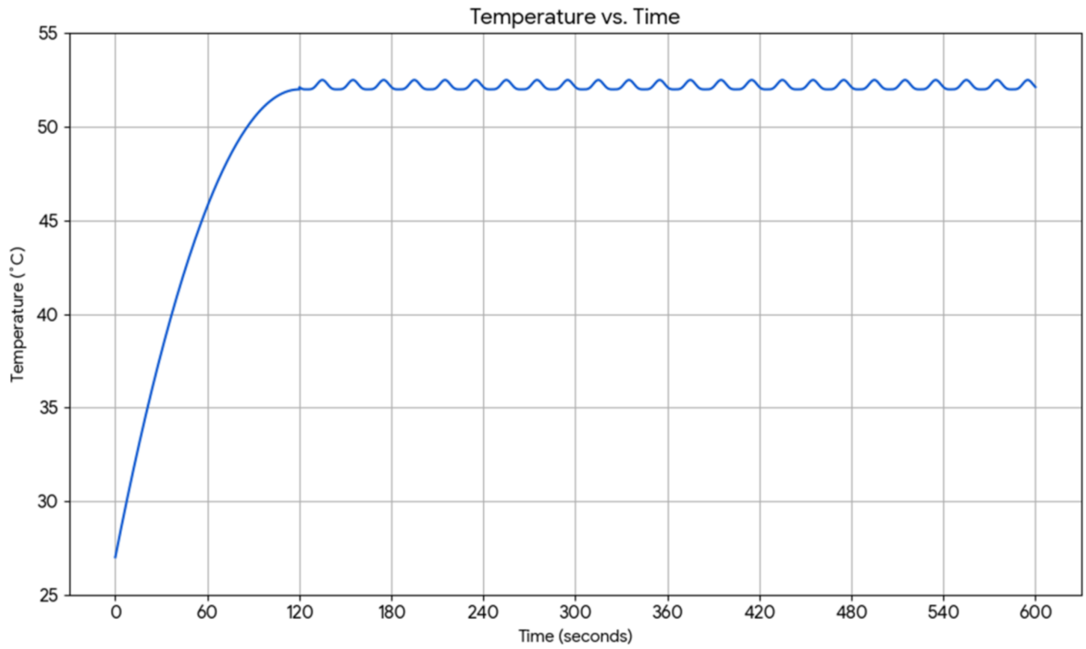


Figure26: temperature response of the circuit after debugging

5) Another viable solution was not to reach the setpoint which would give the best precision possible (way less than 0.1 degree variation primarily controlled by air flow of the room) using a resistor of 20k limiting the current to around 100mA setting the temperature to around 48 degrees with 5 percent accuracy, creating a Tradeoff between accuracy, control and precision.

6) further improvements would involve:

- setting a current source right at the collector of the sensor eliminating current change errors.
- eliminating the derivative term as its primary reason was to eliminate overshoot which is close to non-existent in our case.
- setting the gain of the P term to tunable gain from 0 to infinity rather than starting with 1. that would mean changing to inverting amplification and would involve setting the polarity to positive one more time with another stage exactly like the one used after the derivative term.
- switching the heating element to a BJT like the LTZ1000 configuration, as with this configuration we could benefit from the dual package bjt transistors, as one package holds both the sensor and the heater, that would give excellent thermal coupling.
- one last critical point would be to linearize even more the last summer stage with an inverting summer, fixing the other input to a floating theoretical mass, and that would be feasible with the previous improvement with a PNP transistor this time.

Environmental and Societal Impact Assessment

1. Carbon Footprint of the Internship

My internship lasted from **February 10 to August 10, 2025** (approximately **26 weeks**, 5 days/week, 8.4 hours/day). I commuted daily by metro, a low-carbon transport mode, for a distance of **3 km each way (6 km/day)**. Over the whole period (~130 days), this represents **~780 km travelled**, corresponding to about **31 kg CO_2eq** (using 0.04 kg CO_2eq/km for metro). On site, I worked mainly on a computer (≈60 W for 8.4 h/day), representing ~66 kWh over the internship, or **~20 kg CO_2eq** (assuming 0.30 kg CO_2eq/kWh). A monitor (~25 W) added ~28 kWh, i.e., **~8 kg CO_2eq**. Laboratory prototyping equipment (soldering iron, oscilloscope, electronic boards, etc.) was used intermittently; I estimate ~30 kWh total over the whole internship, i.e., **~9 kg CO_2eq**.

Finally, I ordered **10 PCB prototypes (5×3 cm, ~4-layer boards)** from JLCPCB, shipped internationally. Small shipments of this scale (~0.3–0.5 kg total by air) can add ~**25–30 kg CO_2eq**.

Overall footprint ≈ 90–100 kg CO_2eq, well below the European annual per-capita objective of 2 tons CO_2eq.

2. Initiatives to Reduce the Footprint

Several actions were taken to minimize emissions:

- **Low-carbon commute** via metro instead of private car.
- Use of **eco-PCBs** offered by JLCPCB, following Logitech's procurement policy.
- **Energy-conscious practices**, such as turning off lab equipment and computer peripherals outside of active use.
- Reduced printing, preferring digital documentation.
- Minimizing PCB order size and area and prototype waste.

The project itself also contributes to sustainability: improving thermal regulation extends circuit board lifetime, thereby reducing e-waste. However, rebound effects should be considered: more reliable electronics can encourage increased consumption, which needs to be balanced by circular-economy approaches.

3. Ethical and Social Aspects at Logitech

Logitech demonstrates a clear commitment to environmental and social responsibility. On the ecological side, dedicated waste sorting is available with streams for PET, aluminum, paper, and general waste. The adoption of eco-PCBs in prototyping reflects the company's broader sustainability policies.

Socially, Logitech has mandatory diversity and inclusion programs, promoting equal opportunities regardless of gender, ethnicity, or disability. Well-being initiatives are integrated, including ergonomic workspaces, employee health programs, and mental health awareness. These measures contribute to preventing burnout and improving employee satisfaction.

One area of possible improvement could be increased transparency in laboratory energy use and systematic recycling programs for electronic components and failed prototypes.

4. Utility of the Project

For the company strategy:
The project aligns with Logitech's focus on product reliability, sustainability, and reduced environmental impact. By integrating thermostats to regulate board temperature, failure risks are reduced, extending product life and decreasing warranty returns.
For the users:
Users benefit from products that are more reliable, durable, and energy-efficient. Fewer failures mean less frustration, lower replacement costs, and reduced e-waste.
For myself:
This internship was an opportunity to develop not only technical skills in electronics optimization but also awareness of sustainability in engineering. I learned how choices in materials (eco-PCBs), design (thermal regulation), and company policies (waste management, inclusion) directly influence the environmental and societal footprint of a project. I also understood the importance of life-cycle thinking: improving efficiency is valuable, but long-term product sustainability must include considerations for reuse, recycling, and energy sobriety. This experience reinforced the role of engineers as both technical experts and responsible societal actors.

5. Positive and Negative Impacts of the Project

Positive impacts:
- Improved circuit-board reliability and thermal performance.
- Extended product lifetime → reduced electronic waste.
- Adoption of eco-PCBs, lowering production environmental impact.
- Alignment with corporate sustainability and user needs.

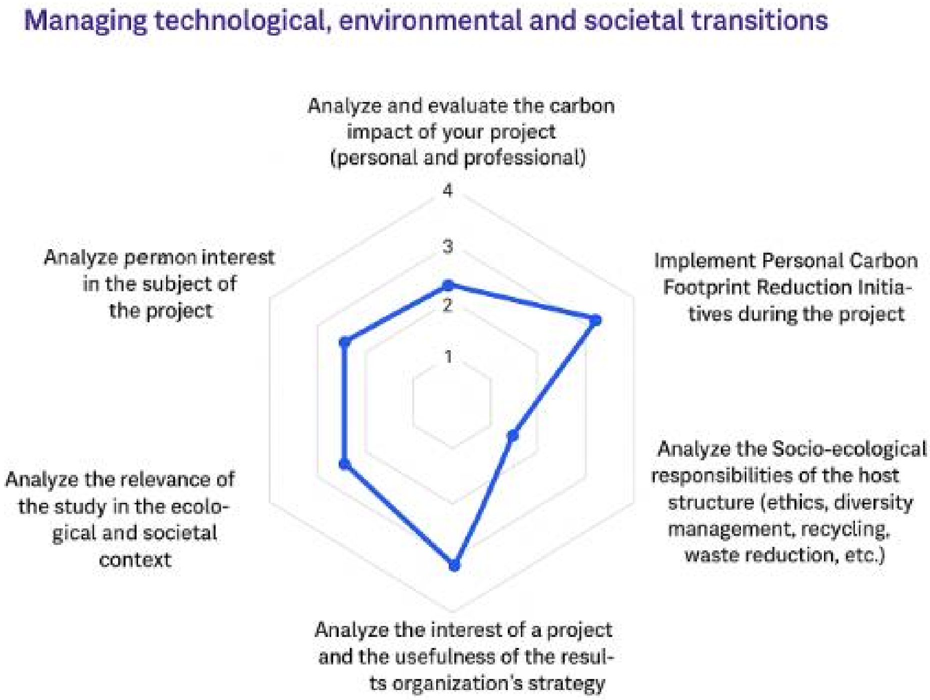
Negative impacts:
- Additional components (thermostats) slightly increase material use.
- Prototype shipments by air freight contributed to CO_2 emissions.
- Potential rebound effect if higher efficiency encourages greater product turnover.

From a life-cycle perspective, the project reduces impacts during the use phase (extended lifetime, fewer replacements). To maximize positive impact, strategies such as design for disassembly, recycling of failed prototypes, and energy monitoring could further strengthen environmental benefits.

6. Sustainable Engineering Solutions

The main challenge addressed by this project is reducing electronic waste. Optimizing thermal management already contributes to longer product lifespans, but more can be done:

- **Circular design**: ensuring boards are modular and recyclable, with components easy to separate.
- **Thermal simulations early in design**: reducing unnecessary iterations and material waste.
- **Eco-material expansion**: extending eco-sourcing beyond PCBs to other components (plastics, connectors, packaging).
- **Recycling strategy**: collaborating with partners to recover metals and components from failed boards.
- **Awareness of rebound effects**: integrating user education and lifecycle responsibility into product communication.



GENERAL CONCLUSION

The implementation of an analog PID-based temperature compensation system successfully demonstrated the feasibility of achieving precise thermal regulation through modular op-amp control stages. Starting with LTspice simulations, the thermal model incorporating a realistic heat transfer delay and sensor feedback enabled accurate prediction of system dynamics, which closely matched experimental results. Optimized PID tuning minimized overshoot, ensured stability across the frequency domain, and validated the loop's robustness through both Nyquist and Bode analyses.

The transition from breadboard prototype to PCB implementation highlighted the challenges of real-world integration, particularly regarding thermal coupling, component placement, and setpoint drift. Although the initial design exhibited significant oscillations due to thermal inertia and sensor-heater spacing, systematic adjustments to the integral path and current-limiting strategies restored stable operation, reducing temperature variation to within 1 °C under encapsulation. Further refinements achieved even finer accuracy (<0.1 °C), albeit at the cost of setpoint range, underscoring the tradeoff between precision, control speed, and absolute temperature regulation.

The final PCB demonstrated that analog PID compensation can be effectively miniaturized and deployed for scalable integration into larger systems, providing a compact and reliable solution for temperature control in precision applications. Key lessons learned such as the importance of thermal coupling, careful component placement, and integral action tuning offer a strong foundation for future iterations. Proposed improvements, including current-source biasing, optimized proportional scaling, and the adoption of dual-package BJT heaters/sensors, provide clear pathways toward enhanced performance and long-term stability.

In summary, the project achieved its primary objective: the design, optimization, and realization of a robust analog PID compensation circuit capable of stable and precise thermal control, while also delivering valuable insights into both the limitations and opportunities of analog control in thermally sensitive systems.

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ENGLISH RESUME

This internship at Logitech Europe SA, carried out within the EPFL Innovation Park in Lausanne, focused on the design, simulation, and implementation of a thermally compensated precision voltage reference intended for the KOSMOS emulator platform. The work began with an in-depth review of the existing voltage reference architecture, followed by a comparative study of high-stability components such as the LTZ1000, LTC6655, and MAX6325. After identifying thermal drift as the main source of precision degradation, several analog thermostat solutions were explored, ranging from simple hysteresis-based on/off control to proportional–integral (PI) and full proportional–integral–derivative (PID) control loops. Using LTspice simulations, thermal feedback models, and frequency-domain stability analysis, optimized architectures were developed and validated experimentally. The transition from breadboard prototypes to a custom multi-layer PCB revealed real-world challenges of thermal coupling, overshoot, and integral saturation, which were mitigated through iterative tuning and design refinements. Ultimately, the project resulted in a compact and robust PCB-integrated PID compensation circuit capable of achieving sub-degree stability, with potential improvements identified for future iterations. This work combined theoretical analysis, circuit simulation, and hands-on experimentation, while providing practical insights into precision analog design and control in a collaborative engineering environment.

RESUME EN FRANÇAIS

Ce stage réalisé chez Logitech Europe SA, au sein du parc d'innovation de l'EPFL à Lausanne, s'est consacré à la conception, la simulation et l'implémentation d'une référence de tension de précision thermo compensée destinée au système émulateur KOSMOS. Le travail a commencé par une étude détaillée de l'architecture existante de la référence, suivie d'un comparatif approfondi de composants de haute stabilité tels que le LTZ1000, le LTC6655 et le MAX6325. Après avoir identifié la dérive thermique comme principale source de perte de précision, plusieurs solutions de régulation analogique ont été étudiées : d'un simple contrôle à hystérésis basé sur un comparateur, vers des boucles de régulation proportionnelle-intégrale (PI) puis proportionnelle-intégrale-dérivée (PID). Grâce à des simulations LTspice, à un modèle de rétroaction thermique et à des analyses fréquentielles de stabilité, des architectures optimisées ont été développées et validées expérimentalement. Le passage du prototype sur breadboard à un circuit imprimé multicouche a révélé des défis concrets de couplage thermique, d'overshoot et de saturation intégrale, qui ont été résolus par un ajustement itératif et des optimisations ciblées. Le projet a finalement abouti à un circuit de compensation PID intégré sur PCB, compact, robuste et stable à moins d'un degré, tout en ouvrant la voie à des améliorations futures. Ce travail a permis de combiner analyse théorique, simulation électronique et expérimentation pratique, tout en offrant une expérience enrichissante au sein d'une équipe d'ingénierie collaborative.