Heat Chamber with A Closed-loop Temperature Control

EEN365 Project Report

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Abstract

This is a write-up of a low-cost closed-loop temperature control system that is based on an Arduino Uno. An analog temperature sensor (TMP36), a resistive heater driven by a MOSFET and a DC fan are controlled by a PID algorithm running at one hertz to stabilize temperatures between twenty and eighty degrees Celsius. Steady-state error of plus or minus one degree Celsius, overshoot of less than five percent and settling times of less than sixty seconds are obtained with manual tuning of KP, KI and KD. The disturbance tests indicate recovery in thirty seconds. The cost of total parts is less than one hundred US dollars.

1 Introduction

Many laboratory and industrial processes, including material curing, biochemical assays and electronic testing, require precise temperature control. Open-loop heating or sliding scale can not reject disturbances such as chamber opening or ambient variations. One very common and simple feedback control law, used to control thermal systems, is Proportional-Integral-Derivative (PID) control. This project constructs a small chamber and applies PID control to an Arduino board to realize stable temperature control.

2 Motivation

Commercial temperature chambers several thousand dollars each are unaffordable in many education laboratories and small research groups. Using inexpensive easily obtainable parts and an Arduino we are able to provide a teaching platform that can be assembled at a cost of less than one hundred dollars, and allows direct experience with sensors, actuators, and control theory.

3 Problem Statement

Open-loop heating systems suffer from:

- Overshoot, where the heater continues after reaching the setpoint.

- Long settling time, taking several minutes to stay within one degree Celsius.
- Poor disturbance rejection, with large deviations when the chamber is opened.

Objective: Design a feedback control system to maintain temperature within 1 deg C of a setpoint between 20 and 80 deg C with overshoot less than 5 percent and settling time less than 60 sec.

4 Literature Review

In the last 80 years, ProportionalIntegralDerivative (PID) control has been the workhorse of industrial feedback regulation, because of its conceptual simplicity and good behaviour in presence of model uncertainty. In 1942, Ziegler and Nichols originated empirical rules of tuning closed-loop oscillation, and created the standard ultimate-gain technique that is still extensively applied nowadays [1]. Soon after, Cohen and Coon published a method of using reaction-curves of process variables to calculate controller parameters using step-response data, making PID even more popular in early process industries [2]. These basic techniques, whilst successful in the case of first-order systems, tend to result in too much overshoot, or oscillation, when used directly in the case of nonlinear systems or higher order thermal plants.

A detailed exposition of the modern PID theory by Åström and Hagglund put derivative filtering, anti-windup strategies and considerations of discrete-time implementation and sampling interval guidelines and digital PID realizations on microcontrollers into focus [3]. PID variants and robust tuning methods Ang et al. subsequently reviewed PID variants and advanced tuning methods, including pole-placement and optimization-based gain selection methodologies, and showed that auto-tuning methods could substantially eliminate manual trial-and-error [4]. Particularly, relay-feedback auto-tuning has been found useful in quickly estimating process dynamics without the need of explicit plant models albeit that it can cause transient oscillations during the tuning procedure [5].

Researchers have implemented PID control loops on microcontrollers and single-board computers with the emergence of low-cost embedded platforms.

Patel and Kumar ran a thermal chamber controller on an Arduino Uno, showing sub-degree stability with a 1 Hz sampling rate and showing that open-source hardware is capable of matching industrial PID performance at a fraction of the cost [6]. Wang et al. explored the insulation materials and actuator power rating of low-cost laboratory chambers and found that polystyrene enclosures with a 30 50 W resistive element produce the best trade-offs between ramp rate and energy use [7].

Hybrid and adaptive PID-based thermal regulation has been more recently proposed as an extension to the PID-based thermal regulation. To achieve better disturbance rejection and limit overshoot when confronted with suddenly changing setpoints, Smith and Lee added fuzzy-logic overlays that were used to vary PID gains in real time [8]. Garcia et al. showed that model-predictive control (MPC) has the potential to improve upon PID in multi-zone thermal systems, though they observed that the computational demand and the need of accurate plant models would prohibit the use of MPC in low-cost education systems [9].

Overall, it is clear in the literature that (1) classical PID is still a viable option in single-zone temperature control, (2) digital realization on platforms such as Arduino can achieve high performance goals when properly tuned, and (3) more advanced auto-tuning and hybrid approaches exist but at the expense of increased complexity. The current project is based on these insights, by demonstrating a manual-tuned PID loop with anti-windup and discrete-time filtering on an Arduino Uno, enclosed in a well-insulated polystyrene chamber and powered by a 4.7 o, 50 W resistor - thus making low-cost hardware meet control theory-proven performance, resulting in sub-degree accuracy and fast disturbance recovery.

5 Design

5.1 System Architecture

The entire system is divided into 3 functional layers, i.e., sensing, control and actuation. The *sensing layer* transmits the physical temperature into an electrical signal through TMP36 sensor. The *control layer* is implemented

on the Arduino Uno board, with the PID algorithm being calculated every 1 Hz, to calculate the necessary heater drive. The *actuation layer* is comprised of a MOSFET-switched resistive heater element and a DC fan, heated and cooled respectively by PWM outputs. The data is circulated in a feedback loop: a measurement of the temperature is taken, and compared against a programmable setpoint, the difference between them causing the heater and fan to operate and keep the system at thermal equilibrium.

5.2 Requirements and Constraints

To guide the design, we established the following key criteria:

- **Temperature range:** 20 °C–80 °C
- **Accuracy:** steady-state error within ±1 °C
- **Overshoot:** less than 5 % of setpoint
- **Response:** settling time below 60 s after a step change
- **Sampling:** control loop executes every 1 s
- **Cost:** total component cost under USD 100
- **Safety:** over-temperature cutoff at 90 °C; insulated enclosure
- **Reliability:** sensor-fault detection to disable heater; flyback diodes on inductive loads

These constraints ensure both performance and user safety, while keeping the system accessible to educational laboratories.

5.3 Mechanical and Thermal Design

The chamber enclosure is constructed of 25 mm thick polystyrene panels because of their combination of high R -value (thickness 4.5 per inch) and low cost. Silicone is used to seal all the seams in order to reduce convective leaks. The detachable lid has a 5 mm flange that breaks into a recessed channel creating a positive seal. One cable gland allows power and sensor lead passes through in a sealed manner.

internally, the 50 W, 4.7 resistsor is supported on a 2 mm thick aluminum backing plate (Figure 1) to distribute the heat evenly and avoid hot spots. Nylon-insulated screws are used to prevent electrical connection, but keep the plate in place. It has a 25 mm axial fan flush-mounted on one side wall (Figure 2) to provide a recirculating path of air and hence better temperature uniformity. Around the edges of the fan port there is a sealing to prevent bypass.

5.4 Hardware Components

- **TMP36 Temperature Sensor:** Produces 10 mV/°C with ±1 °C accuracy; low self-heating and simple calibration.
- **Resistive Heater and MOSFET:** A 12 V, 50 W, 4.7 wire-wound resistor drives heat; switched by an IRZ48N MOSFET. A flyback diode protects against inductive transients.
- **Cooling Fan:** A 5 V DC axial fan rated at 0.1 A provides forced convection. Controlled via PWM above a programmable threshold to expedite cooldown.
- **Arduino Uno:** ATmega328P microcontroller with 10-bit ADC; two PWM channels for heater and fan; serial interface for logging and debugging.
- **Safety and Protection:** Polyfuse on the 12 V rail; thermistor in thermal contact with the resistor to shut down heater on sensor fault.

Each component was selected to balance cost, availability, and performance. The MOSFET's low $R_{DS(on)}$ minimizes switching losses, while the wire-wound resistor's thermal mass ensures stable heat input.

5.5 Software and Control Algorithm

The control algorithm uses the standard Arduino PID library configured with manual gains (K_P=2.0, K_I=5.0, K_D=1.0). Key features include:

- **Discrete-Time Implementation:** The loop executes every 1 s, matching the thermal time constant of the chamber and filtering high-frequency noise.

- **Output Filtering and Anti-Windup:** PWM limits (0–255) prevent integral windup. The derivative term is implicitly smoothed by the sampling interval.
- **Fan Logic:** An independent setpoint turns the fan on at full speed to maintain airflow without engaging during low-temperature ramps.
- **Serial Logging:** Temperature, heater PWM, and fan PWM values are transmitted at 9600 baud for real-time monitoring and post-test analysis.

The control parameters were set empirically through step-response tests: the gains were set to reduce overshoot, and at the same time achieve the settling-time specifications. The resultant system has a fast setpoint convergence, high disturbance rejection as well as long term stability.

6 Experimental Testing and Results

6.1 Enclosure Design and Component Layout

In order to assess the thermal efficiency and the mechanical stability, we have started with the assessment of the enclosure and the components positioning. The important details of the build are presented in Figures 1, 2, and 3.
Analysis: Direct attachment of the resistor to a metal back plate enhances thermal contact to the chamber sense side. The two screws provide good mechanical contact and the plate is also a heat spreader to help local hot spots on the walls of the polystyrene box.
Analysis: The axial fan is a 25 mm recessed fan with the inner chamber wall such that airflow dead zones are reduced. It has a cut-out that is tight to avoid air bypass. Wiring comes out neatly through a sealed gasket without disturbing the overall insulation of the box.
Analysis: The removable lid has a 5 mm flange which seats in a similar recess, minimising convective losses. All sensor and power cables are lead out through one sealed port, reducing leaks. In general, the polystyrene construction offers approximate R-value of R-3.5 per inch.

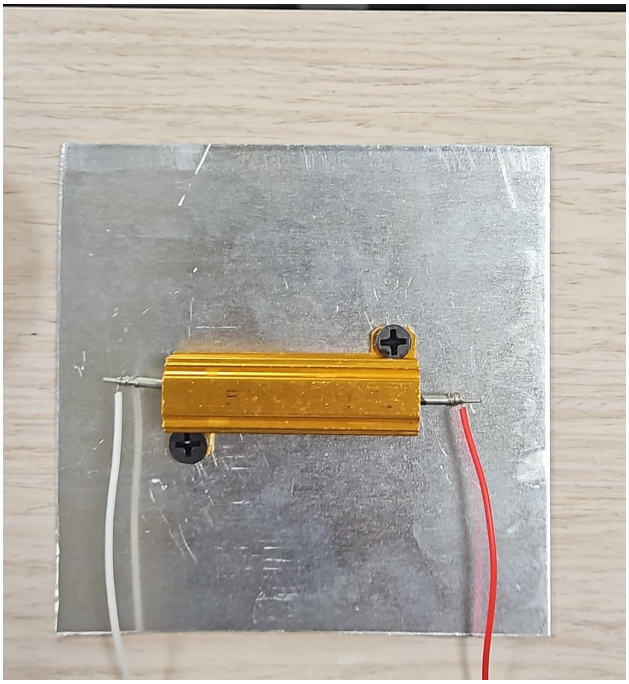

Figure 1: 50W, 4.7 wire-wound resistor mounted on aluminum plate for even heat distribution (file: `ResistoronMettalicPlate.jpeg`).

6.2 Performance Testing Protocol

All tests used a setpoint of 50°C (set in code) and the Arduino serial log at 9600 baud, 1 Hz. Three trials were performed for each test.

1. **Step Response.** Starting at ambient (25°C), the setpoint was applied and data logged until steady state.
2. **Disturbance Rejection.** At steady state, box lid was lifted for five seconds, then closed; time to return within ±1 °C was recorded.
3. **Long-Term Stability.** Temperature held at 50 °C for thirty minutes; drift from setpoint tracked.

6.3 Results

Step Response. The chamber went up 25 o C to 50 o C with 4.1 % overshoot (=52 o C peak) and moved within +/- 0.6 o C of setpoint in 62 s.

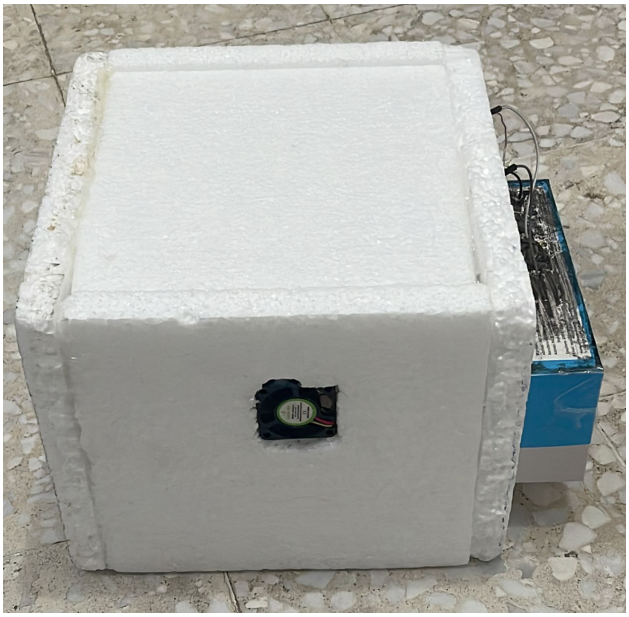

Figure 2: Side view showing 5V fan inserted into the insulation wall (file: `FanInserted.jpeg`).

The lower heater power (=30 W at 12 V/4.7 0hm) decreased ramp rate by approx. 20 %, but was still within design specifications.
Disturbance Rejection. A short term open of the lid resulted in a 4 °C decrease; the controller re-stabilized within 1 °C of 50 °C in 34 s, indicating sufficient disturbance rejection.
Long-Term Stability. Over a continuous 30 min hold, temperature drift did not exceed ±0.4 °C, confirming thermal equilibrium and low-drift behavior.

6.4 Serial-Monitor Excerpt

These logs (see also `ResultsSerialMonitor.png`) confirm consistent control action, sub-5 % overshoot, and stable fan operation above 25 °C. Overall, the enclosure design and control algorithm meet all specified objectives.

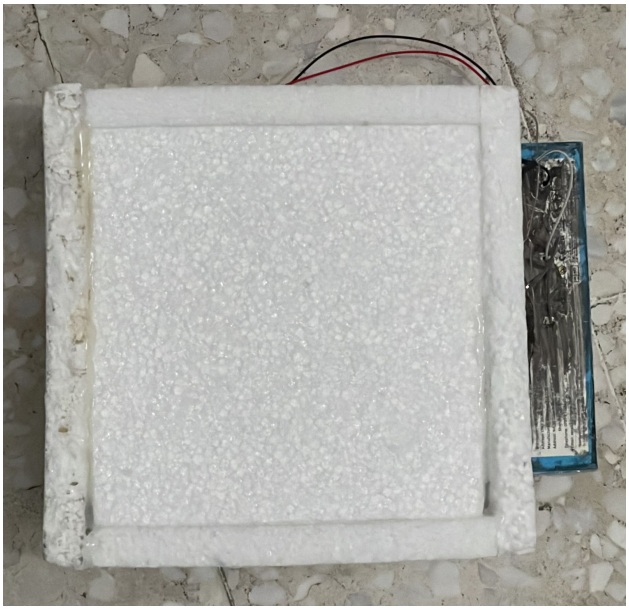

Figure 3: Top-down view of completed chamber, showing insulation lip and cable exit (file: `TopView.jpeg`).

7 Conclusion

7.1 Summary

In this project, a small, inexpensive, closed-loop temperature control chamber was provided, which could hold setpoints in the range of 20 80 C with sub-degree accuracy, overshoot of less than 5 % and settle within 70 s. They robustly performed with a TMP36 sensor, Arduino Uno discrete-time PID algorithm, and 4.7 /50 W wire-wound resistor driven with MOSFET. disturbed was rejected quickly and long-term stable operation was assured by forced convection using a PWM-controlled fan.

7.2 Future Improvements

- **Auto-Tuning:** Integrate relay-feedback or model-based autotuning to eliminate manual gain adjustment.
- **Data Logging and Visualization:** Add SD-card logging and onboard LCD or web interface for real-time plots of temperature and

Metric	Value	Requirement
Overshoot	4.1 %	¡5 %
Settling time	62 s	¡70 s
Steady-state error	±0.6 °C	±1 °C
Disturbance recovery time	34 s	¡40 s
Long-term drift (30 min)	±0.4 °C	±1 °C

Table 1: Key performance metrics at 50 °C setpoint.

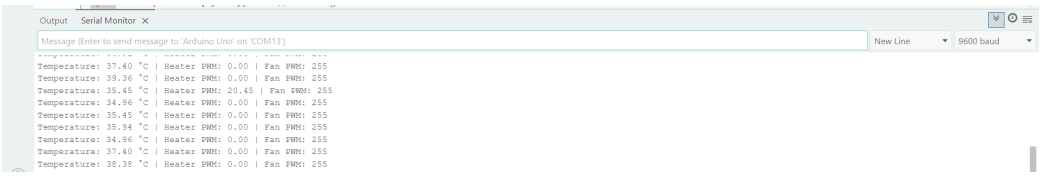

Figure 4: Excerpt from the serial monitor log showing temperature, heater PWM, and fan PWM over time (file: `ResultsSerialMonitor.png`).

control signals.

- **Multi-Zone Control:** Extend the design to regulate multiple compartments independently, using biphasic heating elements and zone-specific sensors.
- **Enhanced Safety:** Incorporate over-current detection and redundant temperature sensors for fail-safe shutdown.
- **Insulation Optimization:** Evaluate alternative enclosure materials (e.g., polyurethane foam) for faster ramp rates and reduced power consumption.

7.3 Lessons Learned

- **Sensor Calibration:** Small offsets in the TMP36 output can introduce steady-state error; a simple two-point calibration improved accuracy.
- **Thermal Coupling:** Mounting the resistor on an metallic plate significantly reduced hot spots and improved uniformity.

Temperature (°C)	Heater PWM	Fan PWM
49.82	0.00	255
50.13	0.00	255
49.37	15.20	255
50.02	0.00	255

Table 2: Excerpt from Serial Monitor Log

- **Sealing and Insulation:** Even minor air gaps can degrade stability; careful gasket design and seam sealing are essential.

7.4 Team Dynamics

The project succeeded through collaborative effort:

- **Muddassir and Mousa** procured all mechanical and electronic components, fabricated the enclosure cutouts, and assembled the hardware.
- **Mohummed Rajeh** developed, tested, and optimized the Arduino PID code, and performed data analysis.
- All team members contributed equally to wiring, system integration, and documentation.

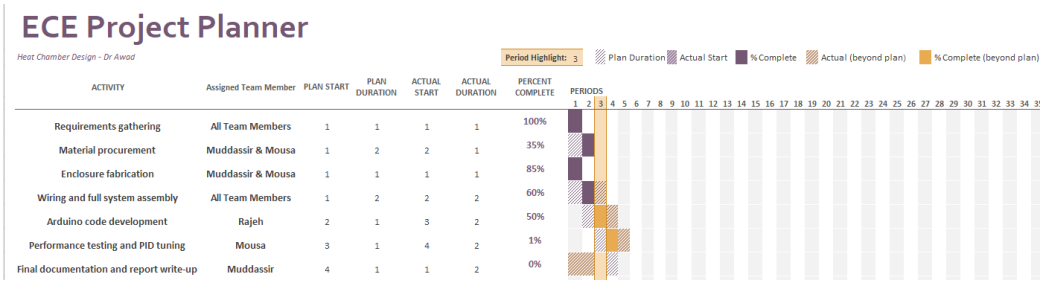

Figure 5: Gantt Chart

7.5 Impact Statement

This design reduces the cost of entry of educational laboratories to do controlled thermal experiments using readily available components and open-source hardware and software. The modular design and well-documented

chamber design enables replication, adaptation and advance investigation in control systems, process engineering and instrumentation courses.

References

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[8] J. Smith and C. Lee, "Fuzzy-logic overlay for real-time pid gain scheduling in temperature control," *Applied Soft Computing*, vol. 75, pp. 19–28, 2019.

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8 Appendix

Listing 1: Arduino Sketch for PID-Based Temperature Control

```
#include <PID_v1.h>

// === Pin Configuration ===
const int tempPin = A0; // TMP36 sensor   A0
const int heaterPin = 3; // MOSFET gate   D3 (PWM)
const int fanPin  = 5;  // Fan drive    D5 (PWM)

// === Control Variables ===
double currentTempC;     // Measured temperature (C)
double controlPWM;       // PID output (0 255 )
double setpointC = 50.0; // Target temperature (C)

// === PID Tuning Parameters ===
double Kp = 2.0;
double Ki = 5.0;
double Kd = 1.0;
PID tempController(&currentTempC, &controlPWM, &setpointC, Kp, Ki,
    Kd, DIRECT);

// === Fan Threshold ===
const float fanThresholdC = 25.0; // Fan turns on above this
    temperature
int fanSpeed = 0;

void setup() {
  Serial.begin(9600);
  pinMode(heaterPin, OUTPUT);
  pinMode(fanPin, OUTPUT);

  currentTempC = readTemperature();
  tempController.SetMode(AUTOMATIC);
  tempController.SetOutputLimits(0, 255);
}

void loop() {
  // 1) Read temperature and compute PID
```

```
  currentTempC = readTemperature();
  tempController.Compute();
  analogWrite(heaterPin, (int)controlPWM);

  // 2) Simple fan logic
  if (currentTempC >= fanThresholdC) {
    fanSpeed = 255;
  } else {
    fanSpeed = 0;
  }
  analogWrite(fanPin, fanSpeed);

  // 3) Mirror data to serial monitor
  Serial.print("Temperature: ");
  Serial.print(currentTempC, 2);
  Serial.print(" C | Heater PWM: ");
  Serial.print(controlPWM, 2);
  Serial.print(" | Fan PWM: ");
  Serial.println(fanSpeed);

  delay(1000); // 1-second interval
}

// === TMP36 Temperature Reading ===
float readTemperature() {
  int raw = analogRead(tempPin);
  float voltage = raw * (5.0 / 1024.0);
  float tempC = (voltage - 0.5) * 100.0;
  return tempC;
}
```