PI vs PID Temperature Control of an Uncalibrated Portable Heater for Sensors

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***Abstract*—Wearable heating pads are widely used as therapeutic warmers for tending to multiple health conditions. Precise temperature control is the key to ensuring the safety and effectiveness of the device due to its near-skin application. The paper presents a comparative analysis of temperature control using Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers based on time domain response parameters. The system utilizes an Arduino microcontroller to perform the error calculation between the set point and real-time temperature and accordingly generate PWM pulses to control the actuator driving the heating pad. The device features three different modes of operation based on the analog output voltage from an external driving circuit. Alongside, characterization data, system design and implementation of controllers, a comparative time domain response parameter analysis based on experimental data is also presented.**

***Index Terms*—PI vs PID controller, temperature control, heating pad, Arduino Uno**

I. Introduction

Wearable healthcare systems are showing significant advancements in the fields of therapeutic treatment and medical monitoring. This is due to the advancement in material science, integrated circuit design and fabrication and manufacturing innovation [1]. Among these, wearable heating pads are an attraction for providing therapeutic warmth to soft tissue pains, muscle spasms, strains/sprains, osteoarthritis, and menstrual cramps [2]. The recent advancements in fabrication of flexible electronics have led to development in conductive textile fibrous material. These materials have excellent properties like soft texture, comfort, light weight, excellent absorption, and moisture handling characteristics. Hence, a flexible heating pad made up of polyester filament mesh and metal conductive fiber covered with a polyimide film is a great choice for near skin application [3]. Lab-on-chip technology is also gaining a lot of attention in thin film heater applications due to its compact platform and utilizes thin film heaters on glass substrates to achieve uniform temperature distribution [15]. However, the effectiveness and safety of the heating pad depends on the accurate and precise temperature control. Due to the near skin application excessive heat might lead to discomfort and burns whereas insufficient heat might lead to insufficient therapeutic outcomes [2].

To address these issues, a proportional-integral (PI) controller is used in previous works [4], which gets temperature feedback from the heating pad with the help of a temperature sensor. It calculates the error between set point and feedback temperature to proportionally vary current flowing through the heating pad to regulate the temperature [4]. Another method, an On/Off controller, is used as it is simple and cost-effective, but here, the temperature fluctuates slightly in a cold environment [5].

The objective of this work is to develop a control system for the heating pad and incorporate different modes of operation based on the output of the driving circuit. The temperature control for three different modes of operation, off, low, and medium, is realized by PI and PID controllers to regulate the different set point temperatures triggered by the mode of operation. This study also includes a comparative analysis of the system's performance for the time response parameters such as steady-state error, settling time, rise time, and peak overshoot for both the designs from the experimental testing. The PID controller offers precise and reliable control with very little overshoot and steady-state error compared to the PI controller. This makes it appropriate for systems demanding precision and accuracy of control. The system's objective is to deliver accurate temperature control while ensuring the safety and comfort of the users.

II. Control System Design and Associated Components

An N-channel MOSFET, an Arduino Uno microcontroller, and a semiconductor temperature sensor are used to devise a control system for the heating pad in the present work. The electric heating pad from Sparkfun Electronics, which has resistance 9 Ω, is used [6]. To regulate the temperature of a heating pad, an ultra-low resistance N-channel MOSFET (IRF540N) is used as an actuator to control the current flow through it. PWM signal generated by Arduino UNO microcontroller is utilized to adjust the voltage across the gate terminal of the MOSFET, with the value determined by the PI and the PID controllers [4] [7]. The LM35 (Texas Instruments) temperature sensor gives temperature feedback from the heating pad. The analog read pin of the microcontroller senses the analog voltage output from the driving circuit. Three different modes of operation are designed based on the analog output voltage from the external driving circuit: off, low, and medium.

The first aspect of temperature control design for an uncalibrated heating pad requires characterization of the system, which involves analyzing the step-response characteristics of the heating pad to determine its transfer function. The second aspect is to determine gains for PI and PID controller and hence the root locus technique is used to determine gains that satisfy the required time domain specifications [4]. The third aspect is to trigger different modes of operation, such as off, low, and medium, based on the output of the driving circuit. This will lead to the automatic control of temperature based on the output of the driving circuit to eliminate human intervention. After the selection of mode of operation, the triggered temperature should be controlled using a microcontroller

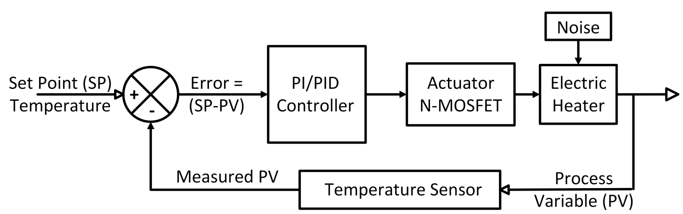

Fig. 1. Block diagram of closed-loop temperature control system, shows the feedback generation from the heating pad and compares it with the set point value to generate an error signal that drives the actuator

The block diagram given in Fig. 1 illustrates the closed-loop control system, which utilizes an Arduino Uno microcontroller to implement the PI/PID controller. For the system, the target temperature is set and determined by the user, defined as Set Point (SP), which the controller wants to achieve. The LM35 temperature sensor gives the real-time recorded temperature, defined as Process Variable (PV). This process variable is fed back to the controller to analyze the error between SP and PV. Based on the error calculated, the controller generates a controlled voltage output at the PWM pin, which drives the N-MOSFET actuator. The actuator drives the current flowing through the heating pad, which changes the temperature of the pad [4].

III. Characterization of Heating Pad

Characterization of the system using a mathematical model involves a detailed analysis by the physical mathematical method [8] [9]. Hence, this work utilizes a simpler characterization of the systems based on the step response. The response from the heating pad is obtained by making a flow of 0.5 A current through it to record temperature for 15 minutes. The delay caused by supply to reach steady state value of current is ignored for characterization of system [4]. The step response characterization method is used for first-order system [10]. For second-order systems, the algebraic method of characterization is used to get the transfer function of the system [11]. The unit-step response characterization is plotted by normalizing the output temperature by dividing it by a factor of 0.5.

The general form of the transfer functions for first-order (1) [4, eq. (1)] and second-order (2) [4, eq. (6)] systems are presented below.

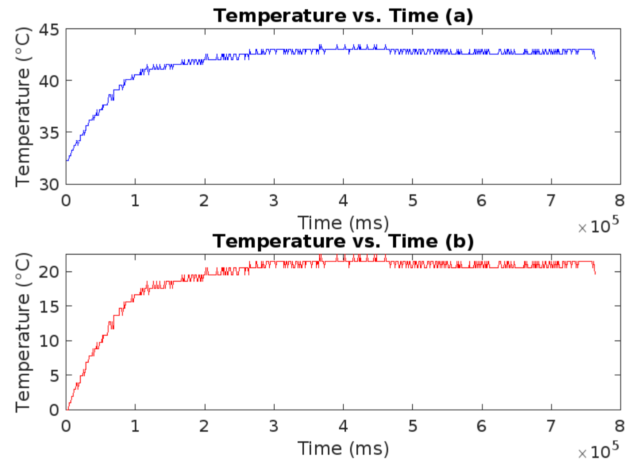

Fig. 2. (a) Response of Heating pad with 0.5 A current and (b) Normalized unit step response of heating pad derived from the fig. 2 (a)

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K}{Ts+1} \tag{1}$$

$$G(s) = \frac{K(T_1 s+1)}{(T_2 s+1)(T_3 s+1)} \tag{2}$$

where $G(s)$ represents the transfer function, K is the open-loop gain, T is the time constant and $Y(s)$ and $U(s)$ are defined as the output and input of the systems, respectively.

To get the unit step response of the heating pad, the step response (Fig. 2 (a)) is shifted by a value of 32.26, and the unit step response characteristic is plotted by normalizing the output temperature by dividing it by a factor of 0.5 as shown in Fig.2 (b).

According to the Final value theorem, the gain value is calculated to be 21.5. The time constant of the system is calculated by utilizing equations presented in [4, eq. (2-4)].

Averaging five points on either side of the inflection point helps smooth out noise and optimize the estimation of the time constant, T.

$$T = \frac{T_1 + T_2 + \ldots + T_5}{5} = 96 \tag{3}$$

Therefore, the first-order transfer function of the targeted system $G(s)$ is obtained as

$$G(s) = \frac{21.5}{96s+1} \tag{4}$$

The time constant of second-order system is calculated by utilizing equations presented in [11, eq. (18-24)]. By taking five sets of coordinates on normalized shifted waveform of temperature vs time and averaging the time constants, we get the time constants as

$$T_1 = 273.454, T_2 = 647.21, T_3 = 1136.0$$

Substituting the value of time constants and open-loop gain in (2), we get the second-order transfer function of the electric heating pad as:

$$G(s) = \frac{0.138(s + 0.00088)}{(s + 0.003657)(s + 0.0015451)} \tag{5}$$

IV. Determination of Gain of the PI and PID Controllers

The gain estimation of PI and PID controllers can be done by using the root locus technique. Using the root locus technique, the pole of the closed loop system is made to pass through the complex conjugate poles, determined from the time domain specifications. The detailed method is found in the literature [12] [13]. The time domain specification is taken as 4 seconds of settling time and 0.8 damping ratio as described in literature [4]. The dominant complex conjugate pole is given as

$$s = -1 \pm j0.75$$

The general representation of PI controller transfer function is [4, eq. (20)]:

$$G_{PI}(s) = K_p + \frac{K_I}{s} = \frac{K(s + z_c)}{s} \tag{6}$$

where K_p and K_I are proportional and integral gains and z_c is the zero location of transfer function.

The general representation of a compensated open-loop transfer function is [4]

$$G_c(s) = G_{PI}(s) \cdot G(s)$$
$$= K' \frac{(s + z_c)}{s} \cdot \frac{(s + 0.00088)}{(s + 0.003657)(s + 0.0015451)} \tag{7}$$

To determine values of gain and zero location, the closed loop root locus of the compensated system should pass through the complex conjugate pole. By using root locus angle criteria, the gain of the system at s is found to be $K' = 2$, and the value of zero is found to be $z_c = 0.6$ [12] [13] [4].

Hence the value of $K_I = z_c * K_p = 8.6952$ and $K_p = \frac{K'}{0.138}$=14.492

The derived transfer function representation of the PI controller is:

$$G_{PI}(s) = \frac{14.492(s + 0.6)}{s} \tag{8}$$

Similarly, the previous method and time domain specification is used to get proportional, integral and derivative gain of the PID controller. The general representation of the transfer function of a second-order system with one zero is:

$$G(s) = \frac{b_0 + b_1 s}{s^2 + a_1 s + a_0} \tag{9}$$

$$G(s) = \frac{0.138s + 0.0001247}{s^2 + 0.0052021s + 0.00000565} \tag{10}$$

The general representation of the transfer function of the PID Controller is [14, eq. (1)]:

$$G_{PID}(s) = K_P + \frac{K_I}{s} + K_D s \tag{11}$$

By solving the root locus, we get: The best gain $K_P = 19.1, K_I = 9.61, K_D = 2.31$.

The derived transfer function representation of PID controller is:

$$G_{PID}(s) = 19.1 + \frac{9.61}{s} + 2.31s \tag{12}$$

V. PI and PID Control System

The block diagram provided in Fig. 3 shows the current modulation technique of the electric heating pad. The actuator is implemented using an N-MOSFET operating in common source mode. The gate-to-source voltage is varied to get modulated the drain current. A change in drain current results in a variation in the temperature of the resistive heating pad. The microcontroller is programmed with the desired gain values to realize the PI and PID controllers. The PWM pin of the controller generates analog voltage in the range of 0–5 V, which helps set up the desired current through the heater [4]. One analog pin is used to sense the heating pad's temperature, while the other is used to sense voltage input from the driver circuit. Based on the input from the driver circuit different modes of operation of the heating pad will be triggered.

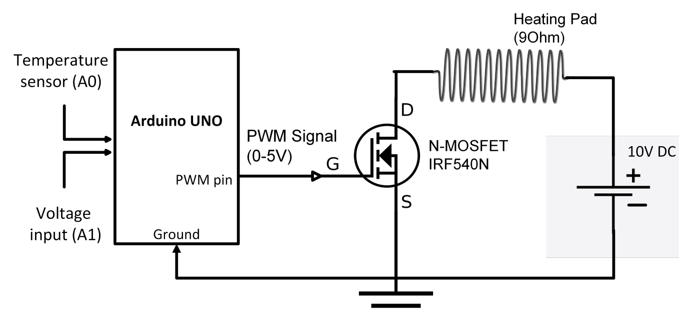

Fig. 3. Schematic of current modulation technique in temperature control system. Here, the voltage input (A1) triggers the set point temperature and the Arduino microcontroller generates a PWM signal based on the difference between the set point and real-time temperature, which drives the actuator

A. Experiment Setup

The temperature control of the heating pad was tested by varying the input voltage to trigger different set point temperatures. The input voltage from the driving circuit is given to analog read pin A1 of the microcontroller. Depending on the voltage input, three modes of operation are decided, which are listed in Table 1. The temperature sensor is connected to the A0 pin of the microcontroller, which gives the real-time temperature feedback. The experimental setup is configured at room temperature, and then, depending on the input voltage, different modes, such as low, medium, and off, are configured to verify the operation of the controller.

B. Result and Discussion

Based on the collected data for both the PI and PID controllers for different set point operations, the system performance is compared based on rise time, peak overshoot,

TABLE I
THREE MODES OF OPERATION, WHERE A CHANGE IN INPUT VOLTAGE TRIGGERS DIFFERENT SET POINT TEMPERATURE

Mode of operation	Input voltage range (in Volts)	Set point temperature (in °C)
Low	1.7-2.3	40
Medium	2.7-3.3	35
Off	Greater than 5	0

settling time, and steady-state error parameters. The table 2 indicates the exact value of the parameters in each case. The

TABLE II
COMPARATIVE PERFORMANCE ANALYSIS OF DIFFERENT TIME DOMAIN PARAMETERS FOR PI AND PID CONTROLLERS

Parameter	PI Controller	PID Controller)
Rise time (in sec)	28.06	31.068
Peak overshoot (in %)	11.2	8.75
Settling time (in sec)	158.343	135
Steady-state error (in %)	1.54	0.39

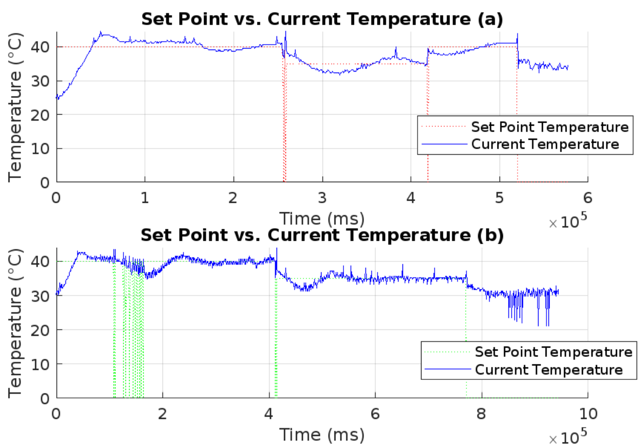

Fig. 4. Set point vs current temperature variation plot for PI Controller (a) and PID Controller (b). Here, temperature is triggered based on the input voltage from the driving circuit, and the response is recorded for three modes of operation, which are low, medium, and off

rise time of the system is considered to be the time taken for the response to rise from 10% to 90% of the set point value. The rise time for the PID controller exceeds that of the PI controller by 10.7%, which indicates aggressive derivative action in trying to prevent overshoot and oscillations strongly. This leads to a slower response of the PID controller. The settling time is the time required for the response to reach and stay within a specified tolerance band of the final value (±5% band is used for calculation). The settling time and peak overshoot are reduced by 14.7% and 21.9%, respectively, for the PID controller with respect to the PI controller due to the presence of derivative control action. The initial system oscillation amplitude and the number of oscillations before settling are also lower in the case of the PID controller. Steady-state error is defined as the difference between the set point and the final steady-state value (considering the average of the last 10 temperature readings). The steady-state error value is reduced by 74.7% in the case of the PID controller as compared to the PI controller.

VI. CONCLUSION

In this paper, the comparative analysis of time-domain characteristics is done, as presented in Table 2, demonstrating that the performance of the PID controller excels that of the PI controller in terms of peak overshoot, rise time and settling time. These attributes make the PID controller an ideal choice for ensuring safe and precise temperature control. Furthermore, the design showcases three different operational modes based on the input voltage. The temperature set point can be readily adjusted, thus enhancing its ease of use.

VII. ACKNOWLEDGEMENT

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REFERENCES

[1] V. Bhaltadak, B. Ghewade, and S. Yelne, "A Comprehensive Review on Advancements in Wearable Technologies: Revolutionizing Cardiovascular Medicine," Cureus, May 2024, doi: 10.7759/cureus.61312.
[2] C.Lercara, L.Y.Chan, E.Ho, S.Baskaran, A.Elzayat,"Therapeutic Modalities – Thermal" PM&R Knowledge NOW.[Online]. Available: https://now.aapmr.org/therapeutic-modalities-thermal.
[3] Md. R. Repon and D. Mikučionienė, "Progress in Flexible Electronic Textile for Heating Application: A Critical Review," Materials, vol. 14, no. 21, pp. 6540–6540, Oct. 2021, doi:10.3390/ma14216540.
[4] P. F. Khan, S. Sengottuvel, R. Patel, K. Gireesan, R. Baskaran, and A. Mani, "Design and Implementation of a Discrete-Time Proportional Integral (PI) Controller for the Temperature Control of a Heating Pad," vol. 23, no. 6, pp. 614–623, Dec. 2018, doi: 10.1177/2472630318773697.
[5] J.-X. Wu and Y.-C. Liao, "Self-regulated thermal comfort control for wearable heating device," Journal of the Taiwan Institute of Chemical Engineers, vol. 121, pp. 74–80, Apr. 2021, doi: 10.1016/j.jtice.2021.04.001.
[6] https://www.sparkfun.com/products/11289
[7] Arduino Uno. https://store.arduino.cc/products/arduino-Uno-rev3
[8] G. Stephanopoulos, "Chemical Process Control", Vol. 2, NJ:Prentice Hall, Englewood Cliffs, 1984.
[9] William L. Luyben "Process Modelling, Simulation and Control for Chemical Engineers"; Singapore: McGraw Hill, 1990.
[10] J.Mikleš, M.Fikar. "Process modelling, identification, and control.", Heidelberg: Springer Berlin, 2007.
[11] L.Chen, J.Li, R.Ding,"Identification for the second-order systems based on the step response","Mathematical and Computer Modelling",Volume 53, Issues 5–6,2011, Pages 1074-1083, ISSN 0895-7177, https://doi.org/10.1016/j.mcm.2010.11.070.
[12] Nagrath, I. J.; Gopal, M. Control Systems Engineering; New Delhi: New Age International Publishers, 2017.
[13] K. Ogata; Modern Control Engineering; PHI Learning: Delhi: Pearson College Div, 2010.
[14] A.Patel, V.Savani, et al., "Performance Analysis of PID Controller and Its significance for Closed Loop System", "INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH TECHNOLOGY (IJERT)" Volume 03, Issue 03, March 2014
[15] G. Petrucci et al., "Thermal characterization of thin film heater for lab-on-chip application," 2015 XVIII AISEM Annual Conference, Trento, Italy, 2015, pp. 1-4, doi: 10.1109/AISEM.2015.7066835.