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Implementation of 2DOF controller on Single Board Heater system to track reference trajectory

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Abstract - *Accurate reference tracking with minimal steady-state error remains a critical objective in control system design, particularly for complex trajectories such as step and ramp signals. Traditional discrete-time PID controllers often fall short in handling such profiles, especially under dynamic conditions and external disturbances. To overcome these challenges, this study proposes a two-degree-of-freedom (2-DOF) control framework aimed at enhancing tracking accuracy and robustness. . A novel integration of the Auxiliary Aryabhatta's Identity Equation is introduced to support unified tracking of both step and ramp references trajectory within the same control strategy. The proposed methodology is experimentally validated on a single board heater system, where it is tested on reference trajectory both step and ramping temperature profiles. Results demonstrate a significant reduction in steady-state error and improved disturbance rejection compared to standard PID control, confirming the effectiveness of the hybrid reference tracking design.*

Key Words: **2DOF Controller, Single board heater system, reference trajectory tracking, FOPDT model Real time heater control.**

1.INTRODUCTION

The proportional integral derivative(PID) is the most popular technique in both academic and industrial contexts. For many application, PID controllers are easy to implement and work well, particularly when the system dynamics are well understood and reasonably stable. But conventional control system, especially those with a single degree of freedom (1DOF) structure like PID, have serious drawback that impair how well they work in practical situation . in 1DOF system, the same control is used to manage both setpoint changes and disturbances. This makes it difficult to optimize performance for both at the same time, improving one aspect often worsens the other. Traditional controllers may struggle with overshoot, sluggish response, or oscillation when the reference input changes suddenly. If the system model changes due to environment factors, load variations, or aging components, the controller may become unstable or perform poorly . PID and other basic controller reacts to error to errors after they occur , instead of anticipating them. They lack a feedforward path that can improve speed and and precision. The limitation has driven the evolution towards more advanced strategies, one of the most prominent being the Two Degree of Freedom controller. The architecture of 2DOF controller is more adaptable than that of conventional control systems .it offer two distinct control routes to handle tracking and disturbance rejection instead of single control loop. The controller that takes control action before a disturbance disrupts the plant are known as feedforward controller. This control system component is in charge of controlling the controllers response to variation in the setpoint or reference input. In order to identify any discrepancies between the systems actual and intended function ,feedback is used. The objective of the controller is to improve tracking performance, robust disturbance rejection and decoupled tuning.

1.1 Design methodology for 2DOF controller

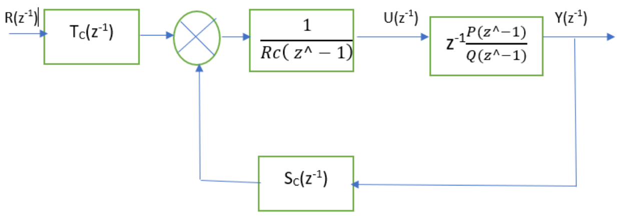

Fig.1. schematic of 2DOF controller

Both continuous-time and discrete-time systems can use the feedback control mechanism described above. The plant, controller output, and reference are $R(z^{-1})$,$U(z^{-1})$,and $Y(z^{-1})$. output signals, in turn. Assuming that a continuous-time plant model is sampled at a given sampling time Ts, we may quickly extract the discrete plant's transfer function as shown ,

$$\frac{Y(z^{-1})}{U(z^{-1})} = G(z^{-1}) = z^{-k}\frac{P(z^{-1})}{Q(z^{-1})}$$

In discrete-time control systems, the plant or system model is typically expressed in terms of polynomials in z^{-1}, where $P(z^{-1})$ and $Q(z^{-1})$ are used to represent the numerator and denominator of the transfer function, respectively. These two polynomials are said to be co-prime when they do not share any common factors other than a constant, ensuring that the system is minimal and controllable. The variable k represents the input delay or time lag present in the system, which is a common feature in many practical processes.

$$Y_m(z^{-1}) = F_m R(z^{-1}) = z^{-k}\frac{Pm(z^{-1})}{\Phi cl(z^{-1})} R(z^{-1})$$

The term $\phi_{cl}(z^{-1})$ represents the desired characteristic polynomial, which is derived by selecting appropriate closed-loop pole locations based on predefined performance specifications such as settling time, damping ratio, and system stability.

The polynomials $R_c(z^{-1})$, $S_c(z^{-1})$, and $T_c(z^{-1})$ are the controller parameters expressed in terms of z−1.

The general control law equation in terms of these polynomials are obtained as :

$$U(z\text{-}1) = \frac{Tc(z^{-1})}{Rc(z^{-1})} R(z^{-1}) - \frac{Sc(z^{-1})}{Rc(z^{-1})} Y(z^{-1})$$

Eliminating the identical terms and settling the resulting expression equal .

The general form given by,

$$degPm < deg\ P$$

To maintain a lower order for the desired closed-loop transfer function compared to the controller polynomial $T_c(z^{-1})$, it is essential to simplify the transfer function by eliminating shared factors between the numerator and denominator. However, this simplification must be carried out with caution. Only those factors associated with stable zeros, meaning roots that lie inside the unit circle in the z-domain, should be canceled.

To manage this, the numerator polynomial $P(z^{-1})$ is typically broken down into two parts based on the location of its zeros. The first part includes desirable (or "good") factors, which have roots within the unit circle and can be safely cancelled. The second part consists of undesirable (or "bad") factors, corresponding to zeros outside the unit circle, which must be retained during controller design.

$$N = N^b N^g$$

To guarantee that the system achieves unity gain in steady state, a constant factor γ is added to ensure that the requirement $F_m(1) = 1$ is met. This condition completes the structure required to provide the intended steady-state response, making the polynomial Tc fully specified .

$$Tc = \gamma Q^g R_1$$

Lets assume that $R_C=P^gR_1$ and $S_C=S_1$ then the equation become easier by doing cancellation of common factor .Furthermore , by matching the numerator polynomial terms, we derive the Aryabhatta's identity as follows

$$Q(z^{-1})R_1(z^{-1}) + z^{-k}P_b(z^{-1})S_1(z^{-1}) = \Phi_{cl}(z^{-1})$$

The equation can be solved to obtain the polynomials $R_1(z^{-1})$and$S_1(z^{-1})$.

1.2 Formulation of the Auxiliary Aryabhatta identity for polynomial reference inputs

The Auxiliary Aryabhatta's Identity Equation is used to determine the polynomial $T_1(z^{-1})$ in order to remove the steady-state inaccuracy caused by the polynomial reference signal. This method will help find the discrete polynomial $T_c(z^{-1})$ for a structure with two degrees of freedom. Let's look at a reference signal, represented by the polynomial

r(t) = tp, where p is the polynomial's degree.

This reference waveform's Z-transform is provided by

$$R(z^{-1}) = \frac{P(z^{-1})}{(1-z^{-1})p+1}$$

Here, a discrete polynomial in terms of z^{-1} is represented as $P_1(z^{-1})$.

$$\frac{E(z^{-1})}{Y(z^{-1})} = 1\text{-}F_m(z^{-1}) = \frac{\Phi_{cl}(z^{-1}) - z^{-k}Q_m(z^{-1})}{\Phi_{cl}(z^{-1})}$$

The Z-transform's final value theorem states that in order to eliminate the steady state error caused by a polynomial reference input, the term $(1-z^{-1})^{p+1}$ must be a factor of the expression $\phi_{cl}(z^{-1}) - z^{-k} P_m(z^{-1})$. This condition allows for the establishment of the following relationship:

$$\phi_{cl}(z^{-1}) - z^{-k}P_m(z^{-1}) = (1-z^{-1})^{p+1}K(z^{-1})$$

In this case, $K(z^{-1})$ represents an unidentified discrete polynomial that requires determination. The equation can be recast as follows by changing the term from Equation .

$$\phi_{cl}(z^{-1}) = z^{-k}P_b(z^{-1})T_1(z^{-1}) + (1 - z^{-1})^{p+1}K(z^{-1})$$

Both $T_1(z^{-1})$ and $K(z^{-1})$ are regarded in this paradigm as unknown discrete-time polynomials that need to be calculated during the controller design phase. The Auxiliary Aryabhatta Identity Equation is the name given to the formulation found in Equation 10 .

2. Configuration with Single Board Heater System

Usually utilized in applications needing exact temperature control, a single board heater system is a small, integrated device made to provide heating through a controlled process. A heating element, control mechanisms, sensors, and occasionally a user interface are all incorporated into a single circuit board or platform in this kind of device. The system's ease of use and effectiveness make it appropriate for a variety of uses, including consumer electronics, medical equipment, and industrial and automobile heating systems. These systems are made to be small, simple to install, and energy-efficient. When precise temperature control is needed and space is at a premium, the heating system is very helpful. All components are integrated into a single board, reducing space requirements.

These systems are designed to minimize energy consumption while maximizing heating output.

The system uses various control algorithms and sensors to maintain the desired temperature range.The system is engineered for long-term use in harsh environments, with protection against thermal overloads and electrical faults.

Fig.2. Single Board Heater System

At the heart of the system is a nichrome coil that acts as the heating element. When an electric current passes through this coil, it generates heat due to its resistive nature. An iron plate is placed near the coil (approximately 3.5 mm away) to absorb and retain this heat. The temperature sensor, typically a thermistor or thermocouple, is positioned close to the plate to accurately measure its surface temperature in real time. This temperature data is sent to the ATmega16 microcontroller, which serves as the brain of the system. The controller compares the measured temperature with the desired reference temperature or setpoint. To regulate the heat output, the system employs Pulse Width Modulation (PWM). By varying the duty cycle of the PWM signal, the controller adjusts the power supplied to the heating coil, thereby controlling the rate of temperature increase. When the system exceeds the desired temperature, a 12V fan located beneath the heater is activated to cool down the iron plate, ensuring that the system remains within safe operating limits. An LCD display mounted on the board shows real-time data such as current temperature, heater and fan states, and serial communication status, providing a user-friendly interface. This continuous process of measurement, comparison, and correction allows the SBHS to track reference trajectories like step, ramp, signals while maintaining stable and accurate temperature control.

A 16x2 display mounted above the microcontroller displays key system parameters, including the plate temperature, heater and fan input levels, and real-time commands transmitted via the serial port. The entire setup functions as a closed-loop feedback control system, capable of maintaining a target temperature or tracking a specified reference signal. Additionally, a user-friendly interface is available for monitoring, parameter adjustment, and real-time control, making the SBHS a versatile platform for control system experimentation and validation

3. Result analysis

The result analysis section presents a detailed overview of the steps taken to design and validate the 2-Degree-of-Freedom (2-DOF) controller for the Single Board Heater System (SBHS).

The first step in our analysis involved identifying the dynamic behavior of the SBHS. This was done using an open-loop test to capture the system's response. In the open-loop test, a step input was applied to the system (in this case, a PWM signal applied to the heater). The system's temperature response was recorded over time. The recorded output was then analyzed to derive the system's transfer function. Based on the observed behavior, it was found that the system could be approximated as a first-order transfer function.

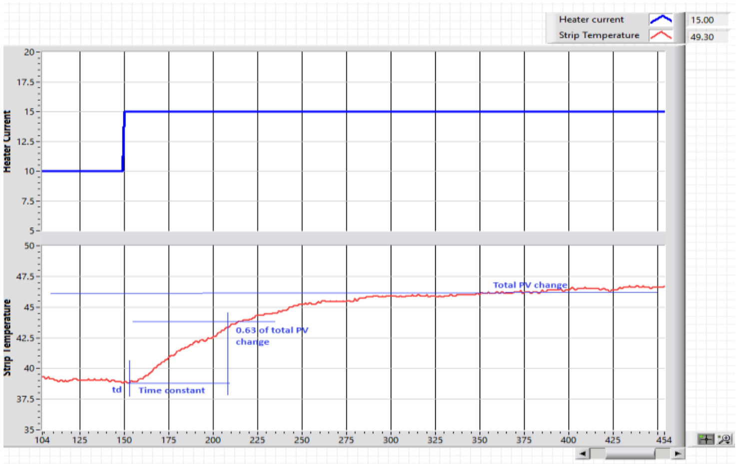

Fig.3. simulation of first order transfer function

This the first order model,

$$G(s) = \frac{1.4}{70s+1}$$

Now discretize this given continuous transfer function

$$G(z) = \frac{0.01988z^{-1}}{1-0.9858z^{-1}}$$

With rise time of 20 sec.

$$\Phi_{cl} = 1\text{-}2z^{-1}\rho\cos\omega + \rho 2z^{-2}$$

$$\Phi_{cl} = 1\text{+}0.5879z^{-1} + 0.6304z^{-2}$$

A step model is given by ,

$$1(z) = \frac{1}{1-z^{-1}}$$

Here , $R_c = B^g R_1$

$\Phi_{cl} = A^b R_1 + z^{-k} B_b S_1$

We got

$R_c = 0.01988\text{-}0.03244z^{-1}\text{+}0.6304z^{-2}$

$S_c = A^g S_1 = 0.0425\text{-}0.04189z^{-1}$

$T_c = \gamma A^g T_1 = (0.0425)(1\text{-}0.9858z^{-1})$

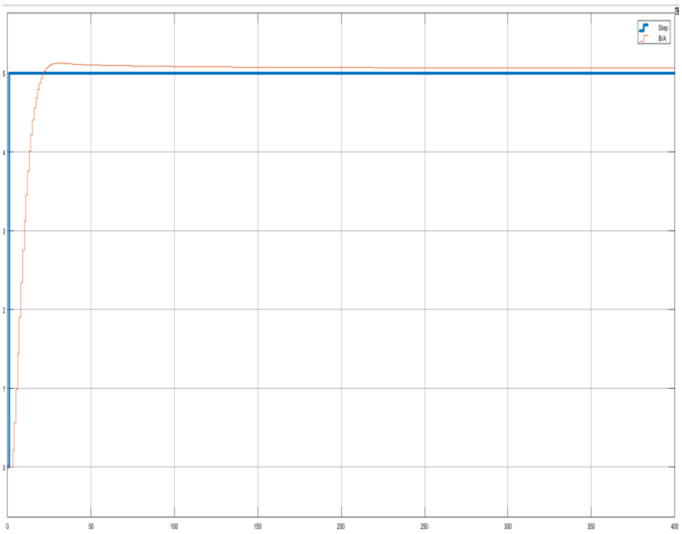

Fig. 4.simulation of 2DOF for step signal

This is the testing with hardware as we can see we have setpoint 25 with fan speed 0 our controller is very nicely following the trajectory that means it is tracking the setpoint. the heater current is our manipulating or we can say controller effort . It will show more effort whenever our temperature will not follow the setpoint.

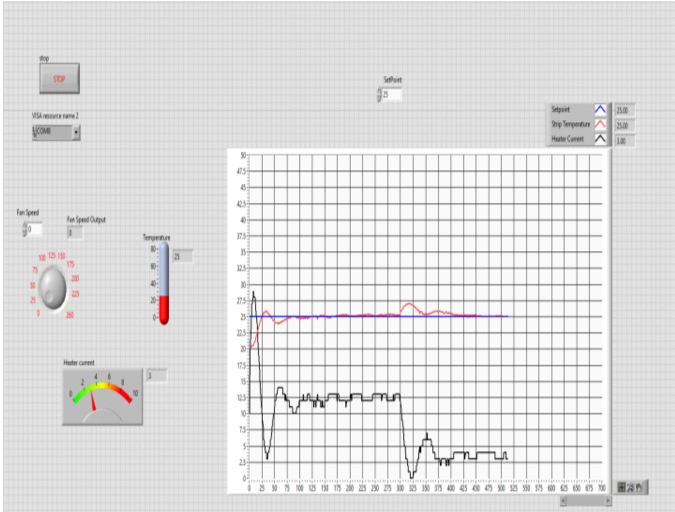

Fig.5.Tracking performance of 2DOF for step signal

This is another real-time experiment conducted on the same plant model, but with a different test condition. In this case, the fan remains ON during setpoint tracking and OFF during disturbance rejection, which is opposite to the previous setup. The intention is to examine how the controller performs under reversed actuator conditions. Interestingly, the designed 2-DOF controller still manages to track the reference signal effectively and shows good disturbance rejection, demonstrating its adaptability. This test further validates the robustness of the controller under varying hardware conditions and control actions. In this fan speed=100 for setpoint tracking as we can see it is settle around 200 sec and fan speed = 0 for disturbance rejection.

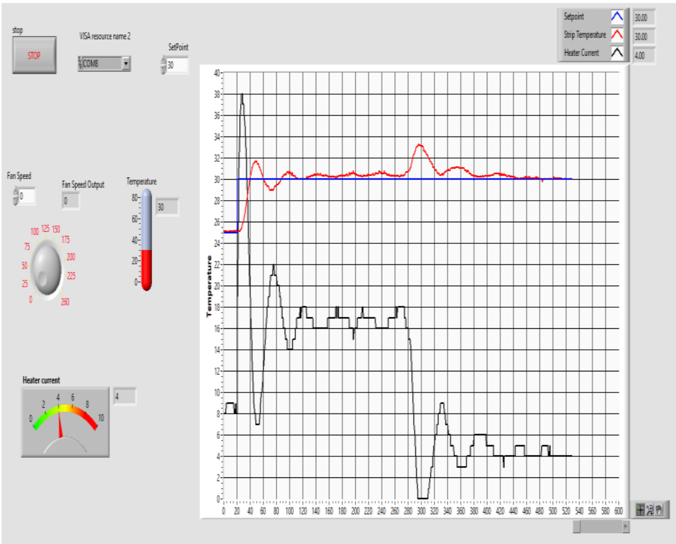

Fig.6. experimental result of both setpoint tracking &disturbance rejection

Result analysis for ramp reference

Data from an open-loop step response was used to identify a second-order transfer function model of the system. Important parameters like natural frequency, damping ratio, and system gain were calculated by examining the system's response to a step input. The discrete-time transfer function was then built using these parameters. The controller design and performance assessment are based on this paradigm.

$$G(s) = \frac{1.4}{(69.2s+1)(0.2s+1)}$$

Lets discretize

$$G(z) = \frac{0.0086z^{-1}+0.0058z^{-2}}{1-1.272z^{-1}+0.2824z^{-2}}$$

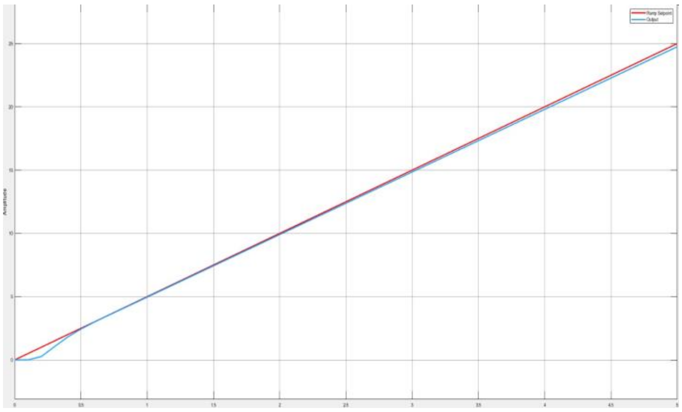

Fig. 7. Simulation of 2DOF for ramp reference

4. Performance evaluation of controller

Parameter	Research paper model	Designed model
Rise time(sec)	127sec	20 sec
Settling time (sec)	325	200
Disturbance rejection (sec)	600	450
Software	Sci lab	Lab view

Fig.7. Comparision of performance

This is the evaluation of controller with the new model and the given model.

5. CONCLUSIONS

Two-Degree-of-Freedom (2DOF) controller for the Single Board Heater System (SBHS) to achieve more accurate reference trajectory tracking. Compared to conventional controllers, the 2DOF controller showed improved performance, especially in handling both step and ramp inputs. The experimental results confirmed that the controller not only follows the desired trajectory more closely but also effectively reduces the impact of external disturbances. These findings suggest that the 2DOF control approach offers a practical and efficient solution for temperature regulation in real-time embedded systems like the SBHS, with clear advantages over traditional control methods.

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