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Self-Tuned Fuzzy PID Temperature Controller Implementation in Hot-Air Coffee Roasting Process

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***Abstract*—The temperature progression of a pile of roasted coffee beans has been one of the most critical parameters to monitor and control during the roasting process as it provides a significant impact on the product's flavour formation. The application of heat to the coffee bean requires a precise temperature controller, and traditional PID controllers have been frequently utilized in recent years, which present a challenge due to the process's non-linear nature. The implementation of a Self-Tuned Fuzzy PID controller to control temperature was proposed in this study, and the performance in real-time was compared to a conventional PID controller as a benchmark. Several evaluation criteria were chosen, including the controller's capacity to produce a desired setpoint without steady-state error, its ability to keep up with temperature setpoint changes during the process, and its resilience to disturbance. During the step test, the proposed controller improved percent overshoot and settling time by 88.10% and 61.98%, respectively. Meanwhile, during the setpoint change test, the overshoot was reduced by more than 80%, and the settling time was reduced by more than 20%. Furthermore, the proposed controller was able to stabilize the output during the disturbance test within 70 s, as opposed to the PID controller, which showed continuous temperature fluctuations because of the disturbance.**

***Index Terms*—Arduino, coffee roaster, FOPDT process, real-time control, online monitoring.**

I. INTRODUCTION

COFFEE roasting process has long been believed is the most important step in the coffee production process because it determines practically all the coffee's flavor based on the way the beans are being roasted. Thousands of chemical reactions occur within the bean during roasting, which contributes to the development of the coffee flavor [1]–[4]. During roasting, a certain time-temperature profile set by the roast master is applied to a pile of coffee beans in order to duplicate the intended taste profile.The temperature progression throughout the process can be divided into two stages. The first stage involves temperatures below 160°C and is also known as the dehydration stage. This is followed by the roasting stage, during which the pile bean temperature ranges between 160°C and 260°C and undergoes pyrolytic reaction and other chemical changes that contribute to the coffee's sensory qualities [1].

A rotating drum has long been used across the literature to roast coffee by transferring heat to the coffee bean by conduction through the drum's hot surface. Coffee flavour and final colour consistency may be adversely affected by the use of this technology, which is frequently inefficient at transferring heat [5]. Thus, improvements in heat distribution, colour consistency, and flavour are expected with the development of recent techniques based on forced convection heat transfer using hot airflow. As a result, significant growth of popularity can be seen among researchers and many medium-scale and industrial-scale coffee roasters now employ either fluidized bed roasters or semi-fluidized bed roasters, which, in addition to hot air flow, are also equipped with a heated surface [6]–[12].

Because coffee is roasted in batches, rigorous control is required to ensure that the same quality of roasted coffee is achieved in each batch. The controller's goal would be to maintain a specified time-temperature profile and to stabilize the temperature if there were any heat disturbances during the process. A variety of control strategies can be used to accomplish this. A standard Proportional-Integral-Derivative (PID) controller is used in most commercial coffee roasting machines nowadays to manage the temperature progression of the coffee beans in the roasting chamber [11], [13], [14]. Real-time PID controllers, on the other hand, are rarely tuned to their optimal setting due to operator ineptitude, tuning complexity and time constraints [15]. There may be issues if an operator has an extensive understanding of the dynamics of the process, which makes it extremely dependent on the operator's continued presence. Depending on the intended performance requirement, numerous tuning approaches have been offered in the literature. The Ziegler-Nichols approach, Cohen and Coon method, and approximate M-constrained integral gain optimization (AMIGO) are some of the most commonly used tuning methods.

As an alternate method of dealing with non-linear behaviours, numerous researchers have developed self-tuning Fuzzy-PID (STFPID) controllers by combining PID and Fuzzy schemes. This approach has been demonstrated to be effective in a variety of applications, including aircraft control [16], oil extraction [17], steam temperature control [18], and compact hydro distillation [19]. Several researchers have used the STFPID in recent years to address PID controller shortcomings in temperature-related process control, including setpoint tracking capability and disturbance compensation.

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In this research, a STFPID controller was proposed to improve the limitations of the PID controller in controlling the bean pile temperature during roasting, which includes setpoint tracking capability and disturbance compensation. The performance of the proposed controller was compared to the conventional PID controller, which includes an overshoot percentage, the shortest possible settling time, and a high level of disturbance rejection. The following describes the structure of this paper: Described in section II is the methodology used in this work, including the plant description, the process model, the PID structure and self-tuning methods using Fuzzy. Specifically, section III discusses the results and comparison of outcomes derived from the real-time implementation, which includes step test, setpoint change test as well as disturbance rejection test. Finally, section IV will summarise the findings of the study.

II. Methodology

A. Coffee Roasting Plant Description

The setup consists of three main components, which comprise a SR500 coffee roaster, control circuit, and MATLAB/SIMULINK software. SR500 coffee roaster setup shown in Fig.1 is built with a 1200W heating element, a clear glass roasting chamber where a pile of coffee bean is placed, and a top cover that act as a chaff collector. The machine works by blowing hot air into the roasting chamber, which causes the fluidizing effect to the pile of coffee beans. The clear glass makes it easier to monitor the roast development event, such as the colour change between the roast phase transition, the excesses smoke and bean cracking sound.

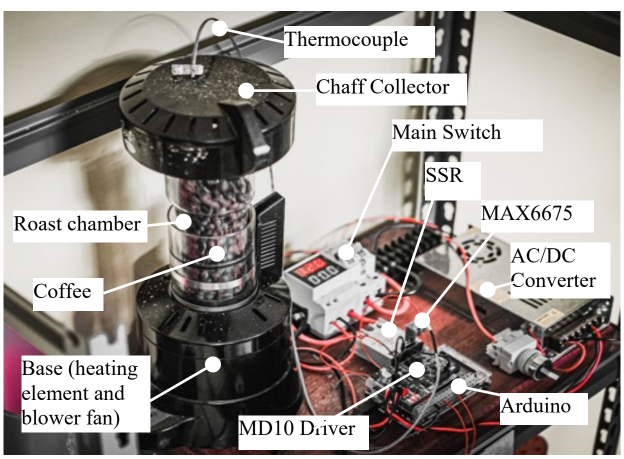

Fig. 1. The SR500 hot-air coffee roaster with 120 g bean capacity

Thus, it has been used for coffee-related research such as roast degree investigation in [20], crack sound characterization in [21] and the study of change in chemical composition by [22]. In this work, a K-Type thermocouple probe was inserted at the roast chamber so that the bean pile temperature progression during roasting can be monitored. The signal from the probe was digitized using the MAX6675 module that can provide up to 12-bit data resolution output as well as performing cold-junction compensation for the thermocouple. It also has up to 0.25℃ temperature reading resolution and can measure up to 1024℃.

In this work, SR500 was upgraded with additional electronic components to enable data logging and better control capability. This includes the use of Arduino Mega microcontroller board to enable computer interface via USB port and programmed to work with industrial standard MODBUS protocol to communicate SR500 with MATLAB/SIMULINK software.

Other than that, an industrial-grade single-phase relay with an input voltage range between 4-32VDC and output current rate at 25A was used to drive the heating element of the SR500. It has zero-crossing features that reduce electrical noise and the back-emf associated with the switching of the heating elements. The switching action was driven by Arduino code that generated 4 Hz PWM signal to drive the heater. A 0% heater level setting on the MATLAB/SIMULINK means that the Arduino will drive the SSR with 0% duty cycle at 4Hz PWM frequency; meanwhile, 100% heater setting simply represents a 100% duty cycle at the same frequency.

SR500 works by means of forced convection where the heat is transferred from the heating element to the bean via airflow generated from the bottom chamber by using a DC motor. In order to be able to control the airflow, a MD10 DC Motor driver board was used to control the DC motor with the aid of the Arduino board. MD10 board uses full solid-state components, which results in faster response time and eliminates the wear and tear of the mechanical relay. It is capable of driving up to 10A continuous current with speed control PWM frequency up to 10 KHz. In this study, the speed control setting is configured using 5KHz PWM frequency with 0% fan speed represented by 0% duty cycle and 100% fan speed represented by 100% duty cycle.

The desired temperature settings for the SR500 were set using MATLAB/SIMULINK software connected via a USB port. The sampling time used to collect temperature data and update the plant's control signal was three seconds, which satisfies the rule of thumb stating that it should be at least ten times faster than the process time constant [23]. In this study, MATLAB version 2017b was used and the Laptop specification as follows: Intel Core i7, 2.4HHz, NVDIA GeForce 940M with 2GB dedicated VRAM and 8 GB DDR3 L Memory capacity.

B. FOPDT Model

One of the most common empirical descriptions of many stable dynamic processes is represented by a first-order linear system with a time delay. As illustrated in (1), a First Order Plus Dead Time (FOPDT) model structure can be expressed as a transfer function comprising the process gain, K, the time constant, τ, and the dead time, θ. The FOPDT parameters were determined in this work utilizing open-loop temperature response data from the roasting process. The coffee bean pile was roasted using a fixed flow rate of hot air entering the roasting chamber. The temperature of the hot air can be adjusted by altering the heater level from 0% to 100%. The identification of the open-loop process transfer function relates the outlet temperature of the pile bean to a step-change in the heater level.

Previous work [24] described the estimation of the process model based on FOPDT over an operating temperature range of 32°C to 230°C, and FOPDT model parameters were defined as K= 1.95, τ= 58.94 s, θ= 4.82 s.

$$G(s) = \frac{K}{\tau s+1} e^{-\theta s} \quad (1)$$

C. PID Controller

The proportional integral derivative controller (PID) is considered to be the fundamental control structure in classical control theory. PID is a commonly utilized feedback control loop mechanism in industrial control systems. By altering the gain values K_p, K_i, and K_d, the system's performance specification can be enhanced. The selection of these values will cause variation in observed responses because each component has its own special purposes. The proportional integral derivative controller (PID) is considered to be the fundamental control structure in classical control theory. PID is a commonly utilized feedback control loop mechanism in industrial control systems. By altering the gain values K_p, K_i, and K_d, the system's performance specification can be enhanced. Because each component serves a unique role, the values chosen will result in diversity in the observed response. The linear relationship between the controller output, $u(t)$, and the error, $e(t)$, can be mathematically described as in (2) and (3), where K_p denotes proportional gain, K_i denotes integral gain, K_d denotes derivative gain, T_i denotes integral time, and T_d denotes derivative time.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (2)$$

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int e(t)dt + T_d \frac{de(t)}{dt} \right) \quad (3)$$

In their attempt to improve the resilience of a PID controller, researchers in [25] developed a set of approximation M-constrained integral gain optimization (AMIGO) tuning rules as a function of K, θ , τ derived from the FOPDT model given by (4)-(6):

$$K_p = \frac{1}{K}\left(0.2 + 0.45 \frac{\tau}{\theta}\right) \quad (4)$$

$$T_i = \frac{0.4\theta + 0.8\tau}{\theta + 0.1\tau} \theta \quad (5)$$

$$T_d = \frac{0.5\theta\tau}{0.3\theta + \tau} \quad (6)$$

Thus, in this work, the controller parameters of the PID controller are set at K_p = 2.9, K_i = 0.1, and K_d = 6.9. This is in accordance with the tuning rules (4)–(6).

D. Self-Tuned Fuzzy PID

Numerous researchers have proposed novel techniques to adjust PID controllers based on intelligent algorithms, notably those including fuzzy logic aspects. It is possible to tune the K_p, K_i, and K_d of PID controller parameters using a self-tuned Fuzzy PID (STFPID) controller that makes use of a Fuzzy Inference System (FIS) in reaction to error ($e(t)$) and error derivative ($de(t)$). Figure 2 illustrates the MATLAB/SIMULINK implementation of the proposed STFPID controller in this study. To ensure that the coffee bean inside the roasting chamber was properly agitated throughout the experiment, the coffee roaster's fan speed was set to 85%, which was the minimum speed required to agitate the coffee bean based on the author's visual observation.

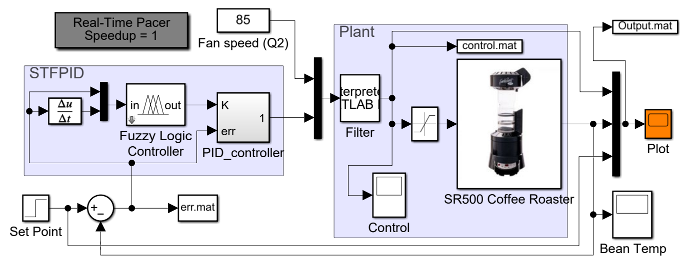

Fig. 2. STFPID controller in MATLAB/SIMULINK for real-time temperature control

The rules for the proposed controller are constructed by taking into account the nature of the operation, which was coffee roasting, as well as the PID controller's features. As depicted in Fig.3, the Fuzzy output K will be used to compute the K_p, K_i, and K_d parameters based on two inputs, which are the error (e) and its derivative (de).

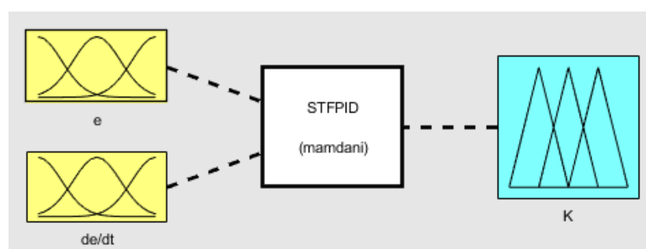

Fig. 3. Fuzzy Inference System (FIS) for the proposed controller

The Fuzzy output K is specified to have a range of 0 to 1. Meanwhile, the minimum and maximum values of K_p, K_i, and K_d have been established based on the results of the PID simulation. Thus, the maximum values of K_p, K_i and K_d were all set to 2.0, 0.05, and 6.0 correspondingly, and the new values of K_p, K_i, and K_d can be calculated using equations stated in (7)-(9). Meanwhile, the minimum values of K_p, K_i and K_d were all set as 0.0.

$$K_{p\,new} = K * (K_{p\,max} - K_{p\,min}) + K_{p\,min} \quad (7)$$

$$K_{i\,new} = K * (K_{i\,max} - K_{i\,min}) + K_{i\,min} \quad (8)$$

$$K_{d\,new} = K * (K_{d\,max} - K_{d\,min}) + K_{d\,min} \quad (9)$$

The membership functions of error and derivative error input fuzzy sets are illustrated in Fig. 4 and 5. Each input variable is represented by a fuzzy set consisting of five membership functions: Negative Big (NB), Negative Small

(NS), Zero (ZE), Positive Small (PS), and Positive Big (PB) (PB). The membership functions for outputs *K* are depicted in Fig.6. Additionally, these outputs comprise five membership functions designated by the abbreviations NB, NS, ZE, PS, and PB.

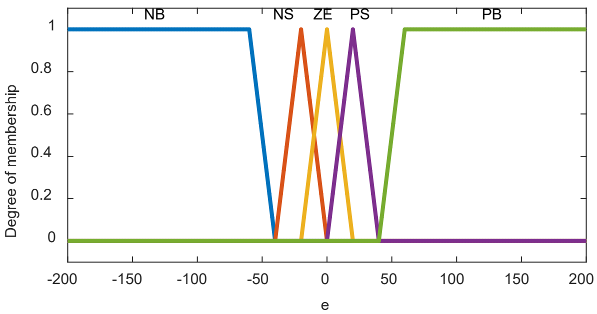

Fig. 4. Fuzzy membership function for error, *e*

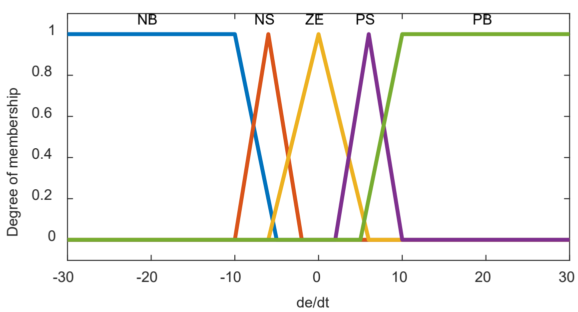

Fig. 5. Fuzzy membership function derivative of error,(*de*)

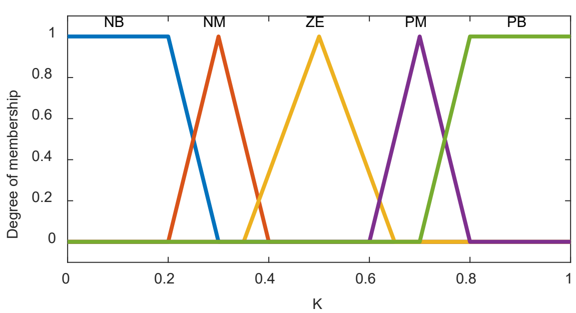

Fig. 6. Fuzzy membership function for output *K*

In general, fuzzy rules are set depending on the regulated plant and the designer's evaluation of the process based on their expertise and experience. Table I lists the fuzzy control rules for K_p, K_i, and K_d in relation to the fuzzy sets of input and output variables.

TABLE I
FUZZY RULES FOR K_P, K_I, AND K_D TUNING

	e(t)				
de(t)	**NB**	**NM**	**ZE**	**PM**	**PB**
NB	NB	NB	NB	NM	ZE
NM	NB	NM	NM	ZE	PM
ZE	NB	NM	ZE	PM	PB
PM	NM	ZE	PM	PM	PB
PB	ZE	PM	PB	PB	PB

III. Results and Discussion

A series of real-time experiments were conducted to compare the proposed controller to a conventional PID controller. A step test, a setpoint change test, and a load disturbance test were carried out and discussed in this section. As described in the preceding section, the pile bean temperature may rise from room temperature to a final temperature between 200°C to260°C at the end of the roasting process, based on the operator's desired time-temperature profile. Accordingly, a temperature range between 50°C and 200°C was chosen for the controller test in this work.

A. Step Test

Figure 7 depicts the real-time temperature output step time response of the roasting process using a typical PID controller. During the test, 80°C was chosen as the desired temperature because it fell within the range of the initial phase of the roasting procedure. Result indicated that there was a significant overshoot percentage of 76% from the PID controller's output. The rising time and settling time of the process output were measured to be 32 seconds and 121 seconds, respectively. There was no indication of a steady-state error since the controller was capable of achieving and maintaining the desired temperature throughout the test duration, despite the presence of a small ripple. Aside from that, the control output depicted in Fig. 7 demonstrates that it struggled to maintain the temperature level until the end of the process by continuously adjusting the heater level between 15% and 35%, which is undesirable because it can lead to long-term damage to the heating element.

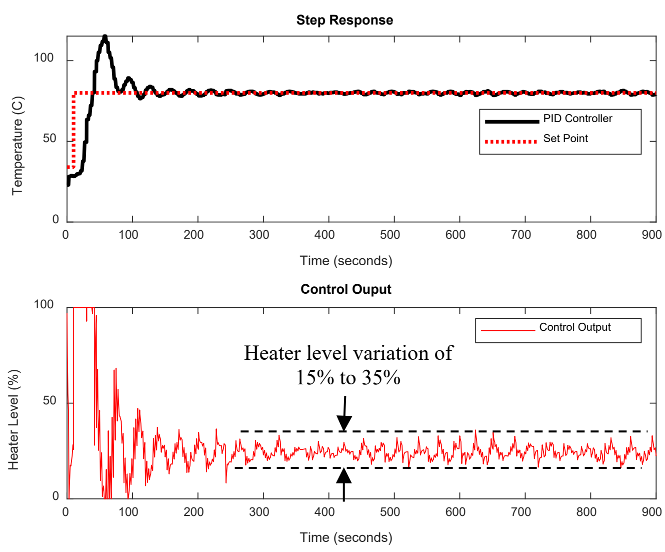

Fig. 7. Step response of the process temperature in PID controller

In comparison to the PID controller, the STFPID controller was able to drive the process output to the desired temperature with significantly less overshoot. It is evident from the response of the process depicted in Fig. 8 that the percent overshoot is 8.7%, the rise time is 38 seconds, and the settling time is 46 seconds. This indicates that the performance of the proposed controller is enhanced by 88.10% in terms of percent overshoot, and by 61.98% in terms of rise time. Furthermore, when compared to the PID controller, the suggested controller exhibits less variance in heater level manipulation, as shown in the control output signal in Fig. 8, which varies between 24% and 25% as opposed to the PID controller's 15% to 35% range in Fig. 7.

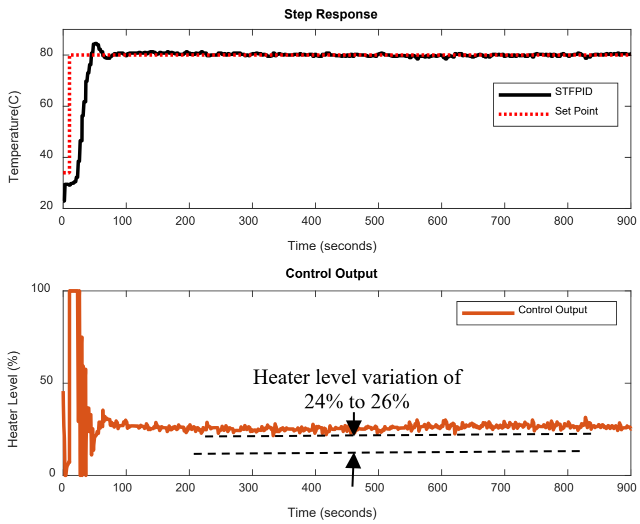

Fig. 8. Step response of the process temperature in STFPID controller

B. Setpoint Change Test

The temperature responses depicted in Fig. 9 and 10 were generated by adding a step setpoint adjustment to both the PID and STFPID controllers. After the response stabilizes at the room temperature about 34°C, the bean pile temperature was altered to a new set point of 104°C after t=200 seconds. Following that, another set point modification was introduced at t=550 seconds to increase the temperature to 174°C. According to Fig. 9, the output temperature changed from steady-state to 104°C with a 51% overshoot and 114 seconds settling time during the first step change and a 41% overshoot and about 180 seconds settling time during the second step change.

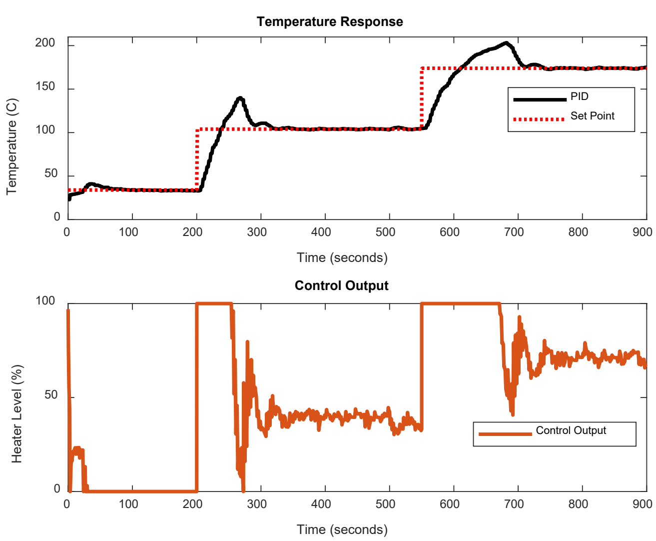

Fig. 9. Temperature response in PID controller during setpoint change test

Meanwhile, as illustrated in Fig.10, the proposed controller successfully reduced the overshoot. The output changed to a new set point at a time of t = 200 seconds with zero steady-state error, 84 seconds settling time and just 2.9% overshoot, as illustrated in Fig.10. At time equal to 550 seconds, when the temperature was changed to a new set point of 174°C, only 8.6% overshoot was recorded.

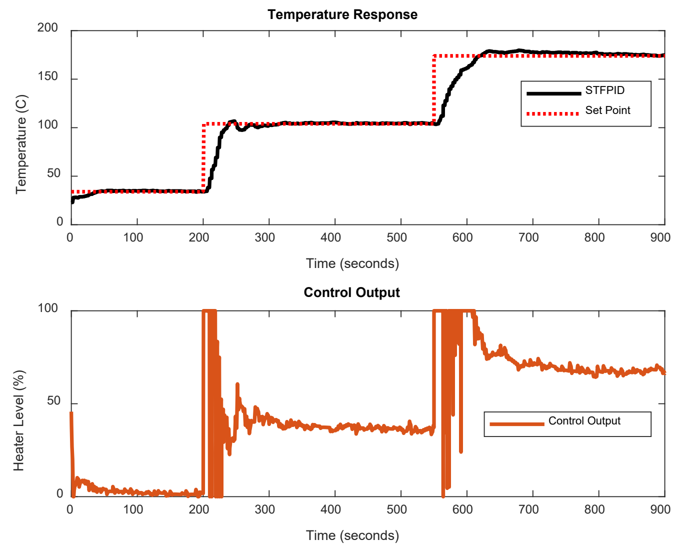

Fig. 10. Temperature response in STFPID controller during setpoint change test

C. Load Disturbance Test

Under both the PID and the STFPID controllers, a disturbance was introduced to the coffee roaster. The disturbance was accomplished by closing the opening at the top cover to interrupt the hot air flow at t = 450 seconds, and the output responded in the manner depicted in Fig. 11 and 12, respectively. The removal of coffee silver skin from the coffee bean surface during the roasting process frequently creates a blockage in the outgoing airflow, causing more heat to accumulate in the glass chamber of a hot-air coffee roaster. It is clear from Fig.11 that the PID controller was struggling to maintain the required temperature between t=450 s to t=900s, and the substantial variation seen at the control output suggested that the controller was attempting to maintain the temperature despite the disturbance. This means that the PID controller's parameters would need to be adjusted after t = 450 seconds when the dynamics of the process have been altered.

Meanwhile, Fig. 12 demonstrates that the proposed controller was more resilient to system dynamic disturbances than the PID controller depicted in Fig. 11. It took approximately 70 seconds for the STFPID controller to restore the temperature to its desired level following the disruption that began at t = 450 s. Additionally, the control output signal demonstrated that the STFPID controller was able to simply handle the disturbance by altering the control signal in response to the process dynamic shifting.

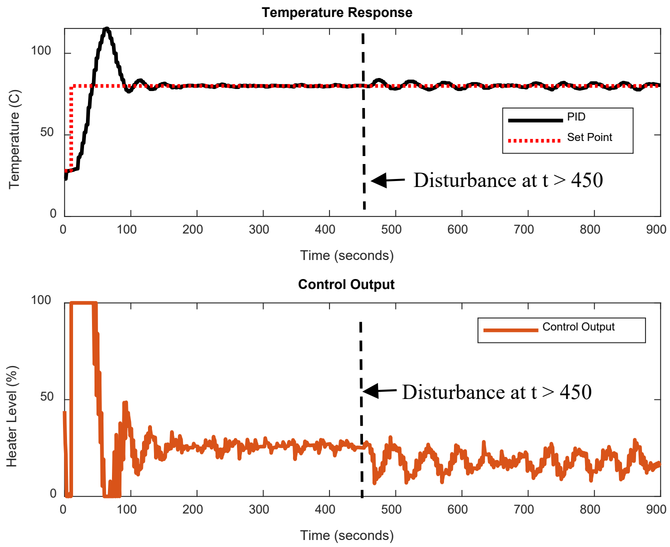

Fig. 11. Temperature response in PID controller during disturbance test

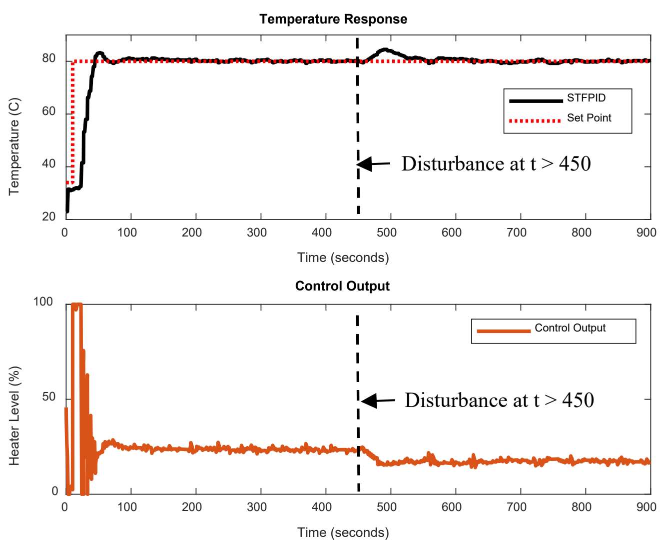

Fig. 12. Temperature response in STFPID controller during disturbance test

IV. CONCLUSION

This study proposed the use of a STFPID controller to enhance the temperature regulation during coffee roasting. The real-time experimental results indicated that the proposed controller was capable of reducing overshoot throughout performance evaluations such as step tests, setpoint changes, and load disturbance testing. Additionally, it considerably enhances robustness, as demonstrated by the quickest recovery time required to restore the temperature to its initial target level without incurring any undesirable output oscillation and steady-state error. This is crucial in the hot air coffee roasting process because temperature fluctuations generated by the bean's endothermic and exothermic processes during roasting can affect the total temperature in the roasting chamber.

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