

Design of a Dynamic HMI–PLC Prototype for Coffee Bean Roasting Profile Control

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Abstract: - The coffee roasting process lacks standardization because key organoleptic attributes depend on manually set time and temperature parameters influenced by bean characteristics and operator experience, introducing variability and human error into the control of the roasting profile. This research aims to design and validate a PLC-HMI-based prototype with a dynamic interface by identifying requirements, developing automation electronics, implementing a PID control algorithm, and creating an HMI to automate and control coffee bean roasting profiles. The methodology involved the design and implementation of an automated temperature control system for coffee roasting through requirements definition, electronic design, hardware-software integration, and experimental validation. The development was structured according to the VDI 2206 standard and focused on the roasting stage under controlled conditions. The results show that the control system achieved stable monitoring of the thermal profile with validated PT100 measurements, maintaining consistent control of the setpoint with an approximate error of 5% in repeated tests. The main conclusion is that the proposed prototype effectively reproduces the controlled roasting profiles, although future improvements, such as the integration of a cooling stage, are required to optimize test efficiency and expand the system's evaluation.

Key-Words: - Industrial automation, Supervisory interfaces, PID, Real-time monitoring, Embedded control, HMI.

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1 Introduction

In the coffee industry, programming a standardized roasting process is challenging due to the influence of organoleptic variables such as flavor, aroma, and color [1]. Automated systems are usually used to control time and temperature to obtain roasting profiles (light, medium, or dark), the parameters of which can vary depending on the characteristics of the coffee bean [2]. Furthermore, achieving ideal roasting depends not only on the machine, but also on the operator's knowledge in assigning the temperature and time variables. The problem of the coffee roasting process is related to the dependence of aroma, flavor, and acidity attributes [3], [4].

Several studies have shown that, even in industrial plants, roasting processes depend on operator intervention, which affects the accuracy and reproducibility of the product [5]. On the other hand, in the coffee sector, there is support software, but the final decision on the roasting point depends on the roaster's experience [1]. Based on the above, the problem relates to the lack of automated and accessible tools that integrate temperature and time

control through dynamic interfaces to adapt to different varieties of coffee.

Therefore, the need arises to improve the control interface of these machines, incorporating pre-configured roasting profiles using temperature and time variables according to the type of bean. Therefore, the following research question is formulated: How is it possible to design a prototype with a dynamic interface using PLC and HMI to control roasting profiles in coffee beans?

The objective of this research is to design a prototype with a dynamic interface, considering the stages of requirements identification, design of the automation system's electronics, design of the PID control algorithm, and development of the HMI interface to automate the roasting profiles. The research concludes with the validation of the prototype's performance through simulations and experimental tests.

The research contributes to the description of a control architecture to overcome the limitations of traditional control, based on the general selection of time and temperature. Furthermore, it also allows for improved roasting quality through a control stage

that combines technology and operational knowledge, increasing the competitiveness of companies. The novelty of this research lies in the design of the roaster, which features an HMI interface with thermal profile control. Furthermore, unlike the PLC-HMI systems mentioned in the documentation, which operate in a fixed manner, this proposed system allows the selection of roasting profiles from an interface without any modification to the controller code. The interface also integrates a graphical display of the temperature and bidirectional synchronization with the PID_Compact block of the S7-1200 PLC.

This paper is organized as follows. Section 2 presents the literature review. Section 3 outlines the research methodology. The results and discussion are presented in Section 4. Finally, Section 5 presents the conclusions and recommendations.

2 Literature Review

In the coffee industry, coffee production consists of several processes, with roasting being the critical stage that determines quality. The statistical importance of coffee is reflected in its position as one of the most consumed and economically relevant beverages worldwide, with global consumption exceeding 173 million bags in the 2022–2023 period [6].

Currently, several researchers are studying the application of automation to the coffee roasting process, where quality depends on precise temperature and time control [7], [8], [9]. Managing specific variables, such as temperature, represents a key advantage of automation, since even small changes can significantly impact the final quality.

Furthermore, variations in temperature, time, and heat profile modify the structure of the bean, [10]. Similarly, detection techniques take advantage of these transformations [11], [12] using mathematical models to predict the internal temperature of roasted batches. Likewise, machine vision systems are applied to evaluate the quality of coffee beans and the degree of roasting [13], [14].

Furthermore, roasting parameters influence the final aromatic profile, making it important to optimize the quality of the final product [15]. Therefore, it is emphasized that the roasting profile should not be defined in a general way, but rather adapted to the specific characteristics of the bean.

Experience in the roasting process is crucial for achieving the desired flavor profile [16], where it is important to employ technological innovations to improve the roasting process through real-time monitoring systems for analyzing variables such as

time and temperature, as well as for decision-making [17], [18]. In these cases, electronic components for prototypes such as Arduino, Raspberry Pi 4, or ESP8266 are used in monitoring systems [19], [20], [21].

Similarly, the integration of automated systems enables automatic measurement using low-cost sensors for freezer automation [22]. Furthermore, automated systems also use microcontrollers for the thermal control of processed coffees by integrating sensors and an adjustable temperature controller [23], [24]. On the other hand, thermal control in industrial processes utilizes IoT-based architectures with low-cost hardware and data transmission managed by cloud applications such as Node-RED for real-time monitoring and parameter adjustment [25].

Other research confirms that visual analysis, predictive modeling, and chemical evaluation technologies have an impact on improving roasting control. Furthermore, pre-drying affects coffee quality during storage, implying that thermal control must consider the entire post-harvest cycle [26]. On the other hand, a systematic literature review describes how the quality of the production chain justifies the need for adaptive roasting systems that guarantee traceability [27].

In summary, the use of low-cost sensors, microcontrollers, control algorithms, and real-time visualization systems has transformed coffee roasting. These technologies enable the automatic monitoring of variables such as temperature and time, which directly impact bean quality. Furthermore, adapting these systems to different processing methods and coffee varieties necessitates customized roasting control.

However, a literature review reveals a gap in research related to the fact that PLC-based systems currently implement static HMI interfaces where roasting profiles are integrated into the controller program. Similarly, previous research has used low-cost microcontrollers such as Arduino or ESP8266, but without profile selection [19], [20], [23]. This research, however, presents a system that allows real-time selection of predefined profiles directly from the HMI without reprogramming the PLC. This feature has not been reported in an integrated manner in the reviewed coffee roasting prototypes, which constitutes its main contribution by proposing a system that combines a Siemens S7-1200 industrial PLC with an HMI interface.

3 Methodology

The system for automatic temperature control in the coffee roasting process consists of a data acquisition module, a programmable logic controller (Siemens S7-1200 PLC), a supervisory interface (HMI), a PT100 temperature sensor with signal transmitter, and a solid-state relay (SSR). The development was structured in stages that included determining the technical requirements, designing the electronic architecture, developing the PID control algorithm, integrating the hardware and software, and experimentally validating the system [17] (Figure 1).

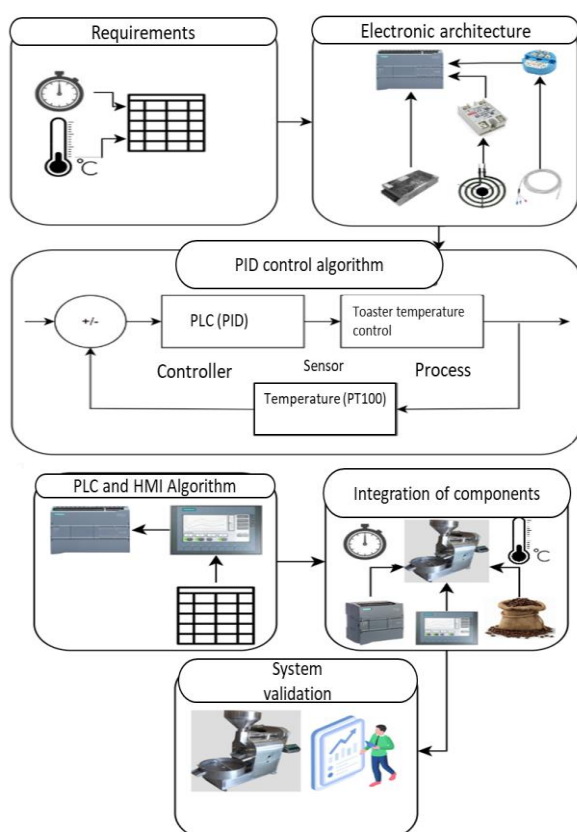


Fig. 1: Stages of development

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The research was limited to the roasting stage and the description of the prototype's operation under controlled conditions, in accordance with previous studies that documented technological solutions applied in thermal processes [17]. Finally, the methodological design was based on the VDI 2206 standard, used in mechatronics engineering projects, to structure the prototype development phases from the identification of technical needs to validation [28].

3.1 System Electronics Design

Time and temperature data were collected from different grain varieties, taking into account density

and sensory properties that affect quality. This data is used for prototype design, considering thermal analysis categories and operating parameters (Table 1).

Table 1. Technical requirements of the coffee roasting system

Category	Description	Parameters	Observations
Thermal analysis	Control the temperature to ensure uniform roasting.	Initial temperature: 25 °C. Optimal range: 180 °C – 220 °C. Total time: 10–15 min.	Maintain a stable heating slope and avoid thermal shock.
Design Parameters	Actuator control and grain roasting.	Drum rotation speed: 40–60 rpm	Adjusts temperature with roasting profile.

Source: created by the authors

It is important to note that the temperature profiles (60 °C, 75 °C, and 91 °C) do not correspond to actual coffee roasting conditions (which range from 180 °C to 220 °C, as shown in Table 1). These lower temperature profiles were selected for the PT100 sensor calibration and PID controller evaluation stages. This selection was based on the methodologies described in research documents for validating the thermal control stage [23], [24]. Validation at actual roasting temperatures (180–220 °C) is planned for future optimization work.

Table 2. Electronic components

Component	Function	Justification	Characteristics
Siemens S7-1200 PLC	Controller	Compatibility with HMI	24 VDC, 14 digital I/O, Ethernet communication
Siemens KTP700 HMI	Human–Machine Interface	Visualize process variables and adjust parameters	7" touchscreen, direct Profinet connection
PT100 Sensor + 4–20 mA Transmitter	Measure temperature in the roaster	High accuracy in the 0–400 °C range	PLC compatible
SSR (Solid State Relay)	Heater control	Avoids electrical noise, fast switching	Control input: 3–32 VDC, output: 24–480 VAC
Heating Element (Oven Heater)	Coffee roasting	Simulates a laboratory-scale electric roaster, controlled by SSR	220 VAC, power 1000–1500 W

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Based on the requirements, the electronic components are defined considering their ease of integration with the functions defined in Table 2. Figure 2 shows the data generation and transmission components, considering the PT100 sensor as part of the analog input. The bidirectional connection of the Siemens S7-1200 PLC with the HMI is used as a controller and interface, and the digital output is provided by the SSR module and the electrical grid.

The interconnection architecture uses a Siemens S7-1200 PLC module for signal processing. The PLC also has a 24 VDC output voltage regulator (SITOP PSU100L), and its connection to the analog input is made via a PT100 sensor and a 4.20 mA current transmitter. The signal received by the PT100 is processed by the PLC, generating pulses that send signals to the SSR, thus enabling the switching of the AC power supply to the heater (Figure 3).

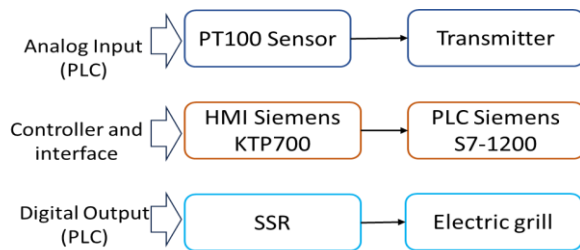


Fig. 2: 2Communication block diagram
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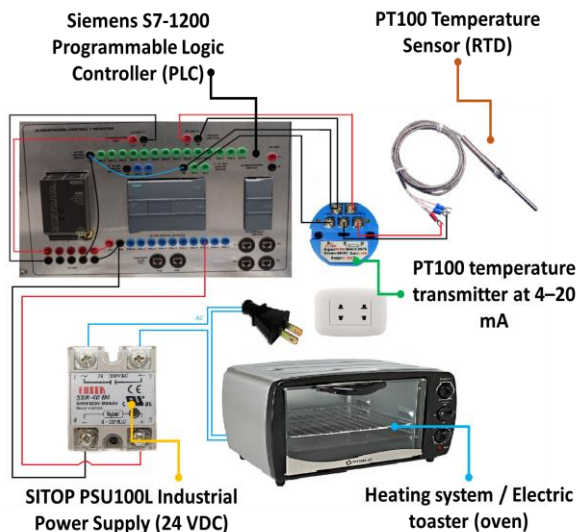


Fig. 3: 3 Prototype connection diagram
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3.2 PID Control Algorithm

A PID control algorithm was implemented due to its accuracy in temperature regulation in industrial systems. Programming was performed in the TIA Portal environment, configuring the process variables, control gains, and internal PLC thermal

optimization functions. The PID controller implemented follows the standard continuous-time formulation expressed by:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int e(\tau) d\tau + K_d \cdot de(t)/dt \quad (1)$$

where $u(t)$ is the control output (PWM to SSR); $e(t) = T_{sp} - T_m(t)$ is the temperature error; T_{sp} is the configured setpoint; $T_m(t)$ is the temperature of the PT100 sensor; K_p is the proportional gain; K_i is the integral gain; and K_d is the derivative gain. For the discrete implementation in the S7-1200 PLC, with a sampling time $T_s = 100$ ms, the equation is:

$$u[k] = K_p \cdot e[k] + K_i \cdot T_s \cdot \sum e[j] + K_d \cdot (e[k] - e[k-1]) / T_s \quad (2)$$

To evaluate performance, indicators with dynamic response were used. The rise time (t_r) is the time it takes for the temperature to increase from 10% to 90%. Additionally, the settling time (t_s) is considered the delay of the response to remain within a band of $\pm 5\%$ of the defined value. The overshoot (M_p) is calculated as:

$$M_p (\%) = (T_{max} - T_{sp}) / T_{sp} \times 100 \quad (3)$$

The steady-state error (ess) is the difference between the measured value and the average temperature obtained in the last section of the tests. The measured values are presented in Section 4.2.

3.2.1 Control Processes

Figure 4 shows the process flow for the control, which begins with the PT100 sensor reading and the reading of a configured setpoint. Both data points are acquired by the PID comparator, and the result is determined considering the desired or limiting parameter (setpoint). Subsequently, the actuator is activated using the PWM protocol to control the thermal process.

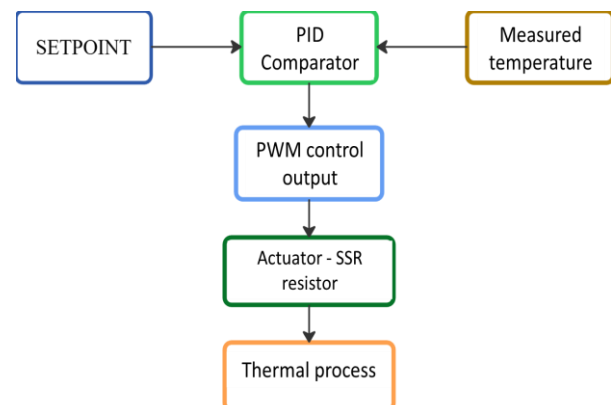


Fig. 4: 4Process diagram for control
Source: created by the authors

3.2.2 Implementation in TIA Portal

To digitize the PT100 signal, a block with an analog input (%IW64) is created that receives the signal from the temperature transmitter. Through the NORM_X block, the variable is transformed into the parameter %MD100 ("Normalized Temperature"). Then, the normalized signal is converted to a real temperature scale to measure the variable %MD104 ("Measured Temperature"). The last SUB block performs a subtraction operation between the measured value and a compensation constant (1.25) for bias correction (Figure 5).

In the PID_Compact controller block, the variable %MD108 ("Measured and Adjusted Temperature") was used to identify the process input, while the parameter Setpoint (28.0) represents the desired temperature value. The PID_Compact block compares the two signals to calculate the desired result (setpoint). The variable %Q0.7 ("Tag_1") receives the output signal, expressed as a pulse-width modulated (PWM) signal, which is received by the solid-state relay (SSR) to control the oven (Figure 6).

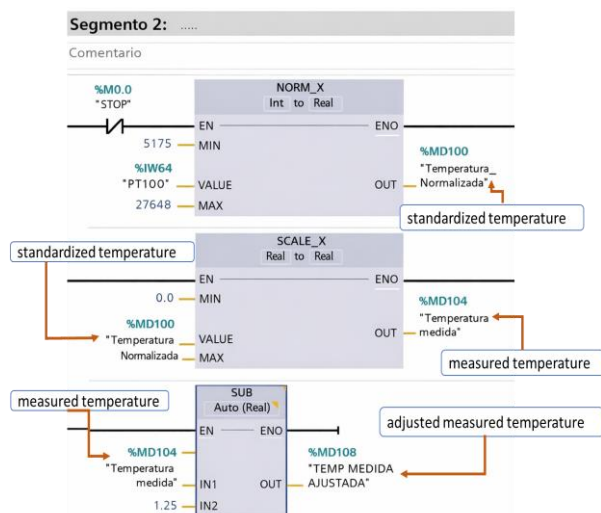


Fig. 5: 5Analog input processing

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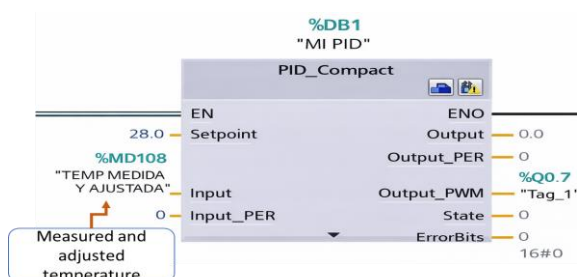


Fig. 6: 6PID_Compact block adjusted to temperature

Source: created by the authors

3.3 PLC-HMI Interaction Algorithm

The PLC control begins by reading the temperature and receiving the HMI command, which is waiting for processing. The PWM output signal is calculated, and the actuator modulates the heater's power considering the measured temperature and the configured time until the selected set point is reached, sending the temperature value to the HMI stage (Figure 7).

On the other hand, the user selects between automatic and manual control. In automatic mode, the interface displays three profiles with setpoints and time parameters. When a profile is activated, the system adjusts the heater to reach the set temperature. In manual mode, the operator enters the temperature and time. Both options display the temperature and elapsed time graphically (Figure 8).

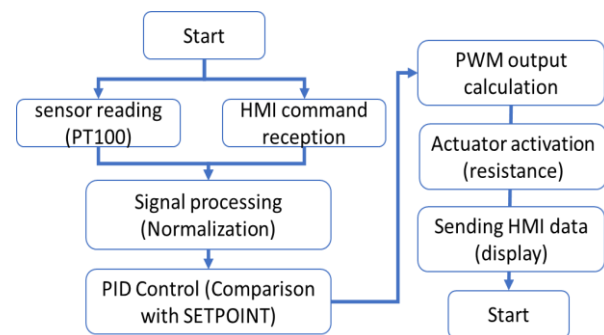


Fig. 7: 7PLC control flowchart

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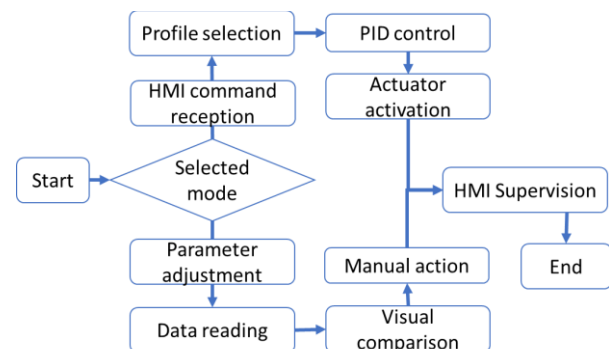


Fig. 8: 8HMI control flowchart

Source: created by the authors

3.3.1 PLC Programming

The Ladder Logic program structure uses %I0.0 (physical control button) to start the oven process. The SR (Set-Reset) block is used, which receives a signal from the physical button or the HMI, keeping the SR block active until it receives a signal from the physical stop button (%I0.1) or the HMI (%M0.0). The output is the Motor (Q0.0), which integrates the process and motor control segment (Figure 9).

3.3.2 HMI Interface Design in Tia Portal

The HMI interface consists of a node called the Root Image (Home) and two main operating modes called Manual and Automatic (Figure 10). Selecting Manual mode enables the user to adjust the roasting temperature and time.

When selecting Automatic mode, the interface displays three preset profiles corresponding to different types of coffee: Arabica, Robusta, and Liberica. Each profile has temperature and time parameters according to the specific characteristics of each variety (Figure 11).

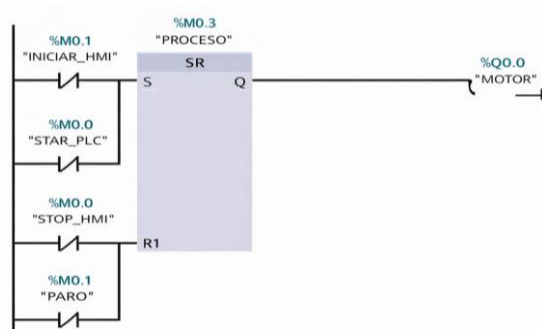


Fig. 9: 9Process shutdown and startup with output to the motor

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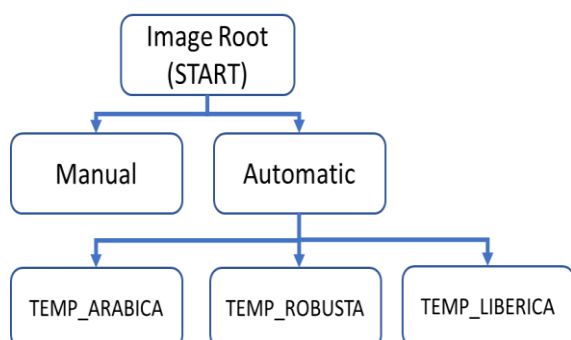


Fig. 10: 10HMI interface structure

Source: created by the authors



Fig. 11: 11Roasting profiles in Tia Portal

Source: created by the authors

The automatic section of one of the 3 selected profiles allows standardization of the temperature,

time, display of the drum temperature in a time graph, and time in the cooking of the grain (Figure 12).

4 Results and Discussion

4.1 Electronic Stage

The connections for temperature control were made using the PLC. Initially, the system was designed with Arduino to perform basic tests and verify the operation of the components, such as the SSR, the temperature transmitter, and the PT100 sensor. Subsequently, the PLC was used as the main platform of the prototype, carrying out more robust tests typical of an industrial environment (Figure 13).

In addition, a shunt resistor was integrated to convert the 4–20 mA current signal into a voltage compatible with the analog inputs. A 500 Ω resistor was used for the PLC because its input accepts up to 10 V, ensuring that the voltage drop does not exceed the electrical specifications of each device. The incorporation of these resistors established proper analog communication between the transmitter and the controllers.



Fig. 12: 12Data visualization in TIA Portal

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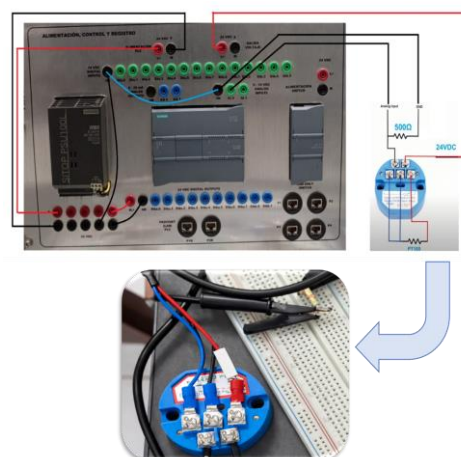


Fig. 13: 13PLC connections with shunt resistor

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4.2 PID Control Algorithm

Three profiles were used, considering temperatures of 60°C, 75°C, and 91°C. Temperature control using the PWM of the PID_compact block has a delay time of approximately 5 seconds. Furthermore, the input control (90.35) stabilizes at the desired value (91), achieving an accuracy of approximately 86% (Figure 14).

The 86% accuracy was determined by comparing the steady-state temperature (90.35 °C) with the set point (91 °C). Additionally, the 5% error was calculated as: $\text{Error (\%)} = |T_{sp} - T_{max}| / T_{sp} \approx 4.9\%$, where T_{max} corresponds to the maximum peak recorded during the stabilization stage.

The thermal control process takes 19 minutes to reach the desired temperature after the profile has been initialized. Because an electric oven and a resistive heater are used, the rise time is slow and without spikes. During model stabilization, the temperature spikes and then decreases over 4 minutes until it stabilizes. The temperature spikes are abrupt, with a margin of error not far from the desired setpoint (5% error) (Figure 15).

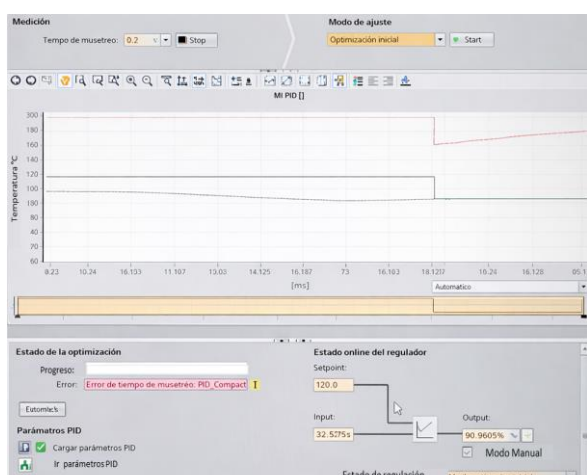


Fig. 14: 14PID block control

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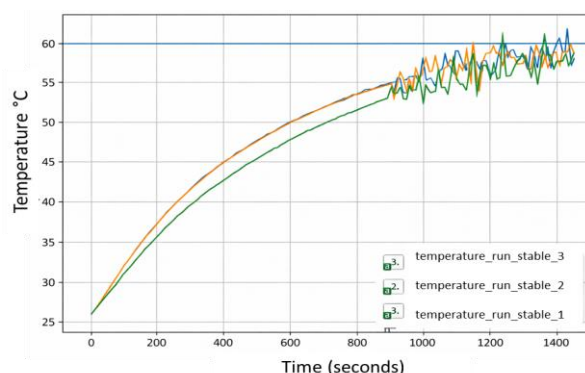


Fig. 15: 15Profile repeatability

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Table 3 shows the performance indicator variables in the experimental tests with the 91 °C profile.

Table 3. PID controller performance indicators (91 °C profile)

Indicator	Symbol	Measured Value	Unit	Reference
Rise time	t_r	~19	min	Fig. 15
Settling time	t_s	~23	min	Fig. 15
Percentage overshoot	M_p	~5	%	Fig. 14 and 15
Steady-state error	e_{ss}	~0.65	°C	Fig. 14
Maximum temperature reached	T_{max}	~95.5	°C	Fig. 14

Source: created by the authors

Three consecutive tests were performed with the 91°C profile, yielding a mean temperature of 90.35°C with a standard deviation of less than 0.1°C, thus validating its repeatability. The coefficient of variation (CV) of less than 3% indicates the repeatability of the PID control system.

4.3 PLC and HMI Interaction Algorithm

The HMI algorithm successfully integrated control functions for the preset setpoint when each profile was selected, activating the signal for data transmission. The automatic reset to 0 was validated when the STOP option was selected or when changing profiles. Furthermore, the PLC's integrated HMI interface provides access to the three programmed profiles: Liberica, Arabica, and Robusta (Figure 16).

The setpoint variation interface functionality was evaluated by verifying the temperature change in the interface and the profile variation with the activation of the SR block (Figure 17).



Fig. 16: 16HMI loaded to PLC module

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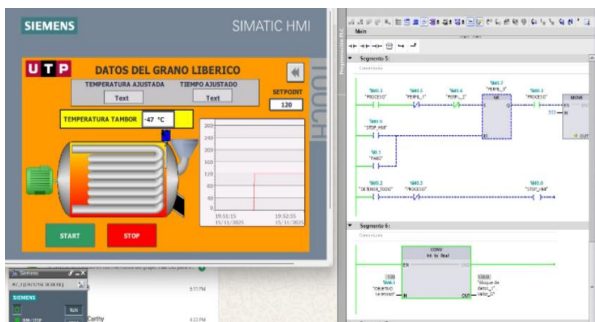


Fig. 17: 17Visualization of the algorithm integrated into the PLC

Source: created by the authors

4.4 Component Integration

The final integration and validation of the system were carried out with the design components (temperature transmitter, PT100 sensor, shunt resistor, PLC, HMI, SSR, and electric toaster oven) integrating the roasting profiles with the control processes (Figure 18).

Figure 19 shows the system's HMI screen, with the 60°C profile configured for the roasting process. This demonstrates the monitoring of temperature control over time via the interface and the PLC module.



Fig. 18: 18Integrated prototype

Source: created by the authors



Fig. 19: 19HMI screen in operation

Source: created by the authors

In one of the evaluations, the 60°C profile was used during validation testing, with tests running for

25 minutes. The prototype underwent thermal control for 25 minutes of testing, validating the integrated operation of the PLC, HMI, and PID controller. Furthermore, it is necessary to expand the number of tests with different profiles and operating conditions, as thermal processes require extended periods to evaluate their stability under demanding scenarios (Figure 20).

5 Conclusion

The results obtained demonstrated adequate performance of the control system during preliminary tests with Arduino and the final implementation with the PLC. The PT100 sensor and temperature transmitter readings were validated through analog-to-analog conversion using shunt resistors, confirming the interpretation of the 4–20 mA signal before integrating the complete system. Furthermore, stable thermal profiles were maintained in tests performed with the 60 °C profile, where three consecutive runs showed an adequate response for setpoint tracking.

On the other hand, the PID algorithm demonstrated consistent behavior after initial adjustments, achieving an approximate error margin of 5% and reducing oscillations during thermal control. These results confirmed the functionality of the prototype and the automation approach used, validating the system's ability to reproduce roasting profiles. During the project's development, limitations were identified that influenced the prototype's evaluation, related to the duration of the thermal tests and the electric furnace's ability to operate continuously. The validation process required extended periods to observe the profiles' stability, which reduced the possibility of evaluating additional configurations.



Fig. 20: 20HMI screen in a 60°C control process

Source: created by the authors

Furthermore, the lack of a cooling system slowed down the testing sequence, as the equipment required long intervals to return to ambient temperature. Integrating a cooling stage is recommended for future work to reduce waiting time and expedite testing cycles.

Compared to microcontroller-based roasting systems [19], [23], [24], the developed system offers superior response accuracy with a steady-state error of 0.65 °C and a variation of less than 3%. Furthermore, regarding profile management, other systems require controller reprogramming to change parameters, while the developed system allows selection from three predefined profiles (Arabica, Robusta, and Liberica) via the HMI. Additionally, the use of the Siemens S7-1200 PLC and the KTP700 HMI validates the prototype's suitability for production environments, in comparison with other studies [19], [20].

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