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Optimization of Small-Scale Coffee Roasting Machine with Servo Temperature and Angle Control for Consistent Roasting Results

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ABSTRACT

The coffee roasting process is essential for creating distinctive aromas and Flavors. Manual roasting often results in uncontrolled temperatures, resulting in uneven and burnt coffee beans. Therefore, an automatic roasting machine was developed to control stable temperatures at setpoints of 180°C (light roast), 220°C (medium roast), and 250°C (dark roast), with a monitoring system to ensure optimal results. Servo angle settings are used to optimize temperature stabilization, while a DC fan serves to remove excess heat from the machine. The system uses an Arduino Uno and ESP32, with a Thermocouple Type K temperature sensor and an I2C LCD display for real-time monitoring. Integration with IoT Blynk allows remote monitoring and control through a mobile application. Research shows that a servo angle of 140° provides the optimal temperature increase, while an angle of 100° is effective for lowering the temperature when it exceeds the setpoint. These angles are used in the system to keep the temperature controlled according to the specified target.

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1. INTRODUCTION

Coffee is a grain that comes from highland plantations and is the main ingredient in making a very famous drink, not only in Indonesia, but also in various parts of the world[1]. Coffee originated in Yemen, which developed coffee into powder and then brewed it to produce a distinctive aroma that no other beverage has. Coffee quickly spread throughout the world and evolved in various processing methods, leading to unique and delicious flavors [2].

The coffee roasting process is an important stage that aims to produce the distinctive aroma and flavor of the coffee beans[3, 4]. The duration of roasting can be measured through changes in the color of the coffee beans, where a darker color indicates a longer roasting process[5]. The longer the roasting time, the darker the color of the coffee beans, this process involves heating green coffee beans to develop certain organoleptic properties through chemical reactions [4, 5].

As coffee evolves, so does the roasting process. Initially, roasting was done manually using a pan and hand stirrer[6, 7]. However, this method resulted in heat wastage due to uncovered pans, and required more time and labor[8, 9]. Research by [1] shows that the manual process causes uncontrolled temperatures, resulting in uneven roasting and burnt coffee beans. In addition, the manual process is less efficient when done on a large scale, which impacts the quality of the coffee.

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Different degrees of roasting (light, medium, dark) are achieved by varying the temperature and time, which can be monitored by changes in the colour of the beans [10]. Optimal roasting temperatures range from 200°C to 300°C, with different profiles affecting the chemical composition and sensory qualities of the final product [11, 12]Roasting duration, including development time after the first crack, affects the flavour profile and chemical markers in coffee [4].

The impact of roasting on coffee quality in Roasting affects the bulk density, hardness, moisture content, ash content, pH level, and caffeine content of coffee beans [13]. Sensory properties, such as aroma, bitterness, acidity, and sweetness, are also affected by the roasting method and degree [14].

To overcome these problems, various studies have developed automatic roasting machines [8], [15]. Some studies such as [16, 17] the importance of temperature control in coffee roasting with flavour quality where the roasting process significantly affects the flavour profile of the coffee. Proper temperature control is essential to achieve the desired degree of roasting (light, medium, dark) and to develop specific Flavors. In addition, in order to achieve high consistency, traditional roasting methods often result in inconsistent roasting due to manual temperature management. An automatic temperature control system can ensure uniform roasting, improving the consistency and quality of the final product [16, 18, 19].

This technological solution by maintaining the temperature but ensuring that the actuator is a servo mechanism for the stirring mechanism ensures even heat distribution and uniform roasting. This reduces the need for manual intervention and minimizes the risk of uneven baking [20]. Therefore, for the development of making machines utilizing small-scale roasting machines which have accessibility are designed to be easy to use and do not require extensive training to operate, making them accessible to small business owners and home roasters [14].

Developing a small-scale coffee roasting machine with precise temperature control and servo mechanism fulfils the need for consistency, quality, and economic viability in coffee roasting for small businesses. The machine is designed to automatically regulate temperature and time using a heating element, but the results are still limited as the temperature achieved is only around 130°C, whereas to achieve optimal light roast results, the required temperature ranges from 160°C to 180°C. Coffee roasting types, such as light roast, medium roast, and dark roast, produce different characteristics and Flavors. Therefore, the developed roasting machine must be able to control the temperature accurately in order to produce roasting quality that complies with the standard.

2. RESEARCH METHOD

This research aims to develop an automatic coffee roasting machine that can control temperature stably and allow remote monitoring. The method used includes designing the system with block diagrams and flowcharts to describe the workflow and relationships between components, such as thermocouple temperature sensors, servo motors, and DC fans. After the system is designed, experiments are conducted to collect temperature data and test the effectiveness of the system in maintaining the temperature at the desired setpoint, using the Blynk application to monitor the temperature in real-time and control the machine remotely. With this approach, it is expected that the developed coffee roasting machine can produce coffee beans with consistent quality according to the specified standards.

2.1. Diagram Block

In this study, two block diagrams were used to describe the workflow of the automatic coffee roasting machine system. In Figure 1, the block diagram explains the *input* part, namely there are temperature sensors, rpm sensors and *switches* or *pushbuttons* which are then processed with a microcontroller and continued with the *output of* actuators such as *DC motors* controlled by motor drivers, 12V DC fans regulated by *relay* modules, and *servo motors* or *control valves* that regulate the *burner* or heater section.

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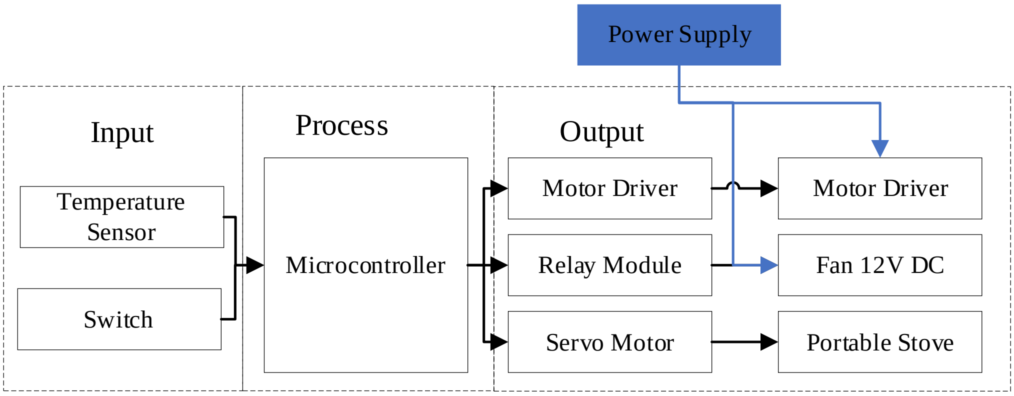

Figure 1. Actuator systems block diagram

The use of two microcontrollers, Arduino Uno and ESP32, in this system is made to take advantage of their respective strengths. Arduino Uno functions to read data from the temperature sensor and display it directly on the LCD with a fast response. Meanwhile, the ESP32 is responsible for sending temperature data to the Blynk platform, enabling remote monitoring and control via a mobile application. By dividing these tasks, each microcontroller can focus on its respective role, namely Arduino Uno for local data processing and ESP32 for wireless communication. This separation also provides redundancy and reliability, so that if one of the microcontrollers has a problem, the system can still run properly. This structure also opens opportunities to develop the system further in the future without changing many parts of the overall system.

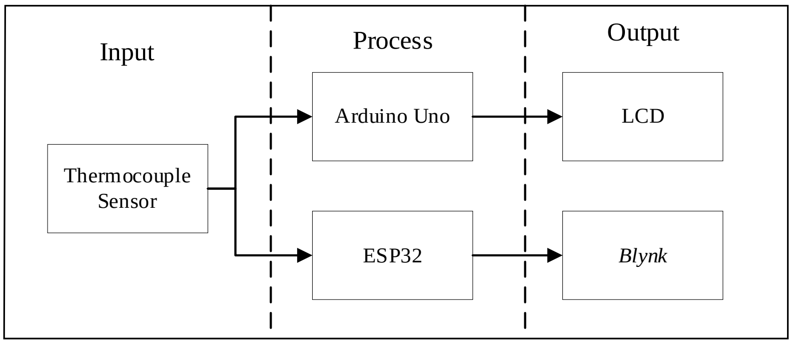

Figure 2. monitoring system

2.2. Research Flowchart

Flowcharts in this study are used to describe the system workflow systematically and facilitate understanding of the processes that occur in automatic coffee roasting machines. Flowcharts are used to describe the overall workflow of the system, which includes the process of designing, testing, and controlling an automatic coffee roasting machine. The system starts with problem identification and literature study, followed by system design, assembly, and testing. The machine is then activated by selecting the roasting option (light, medium, or dark roast), followed by reading the input from the pushbutton and setting the temperature using a servo motor. Once the temperature reaches the desired setpoint, the blower activates to keep the temperature stable, and the roasting process continues until the coffee beans are inserted. In addition, the real-time temperature monitoring system uses a thermocouple sensor, with temperature readings displayed on the LCD and the Blynk app for remote monitoring.

The process starts with turning on the system and selecting a roasting option *(light, medium,* or *dark roast*). Once the option is selected, the system reads the input from the *push button* and the Arduino controls the DC motor and servo to regulate the gas flow and ignite the lighter. The temperature will rise until it reaches the respective set point: 180°C for *light roast*, 220°C for *medium roast*, and 250°C for *dark roast*. Once the temperature is reached, the *blower* activates to maintain the temperature, and the coffee beans are inserted. After that, the system will automatically shut down.

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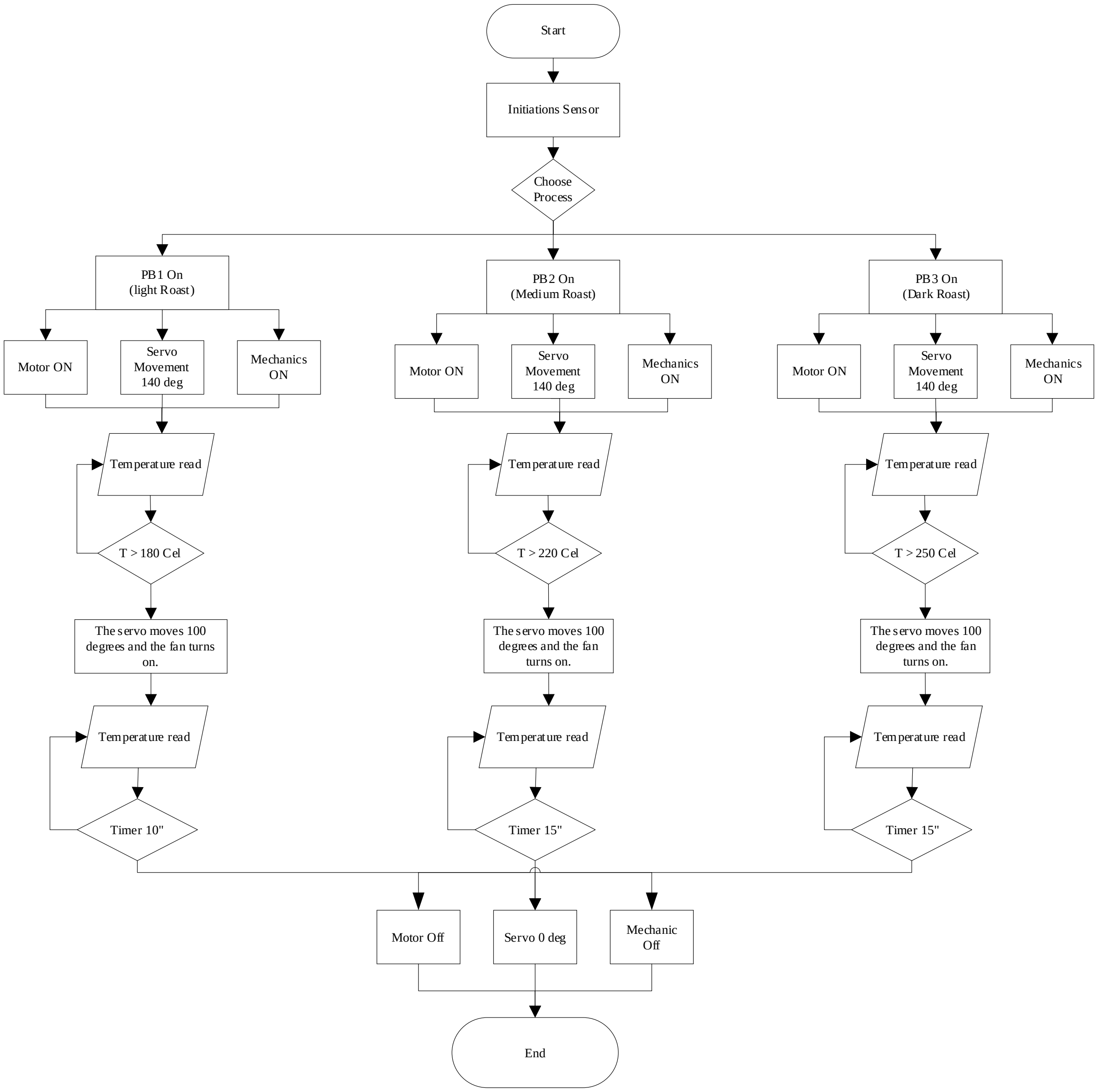

Figure 3. Shows how the coffee *roasting* machine works

2.3. Data Collection Method

Data collection in this study was carried out through a series of tests to analyze the performance of the automatic system in controlling temperature and ensuring consistent coffee roasting results. The first test involved comparing the thermocouple sensor with a manual thermometer to measure the temperature inside the coffee roasting machine. The thermocouple was positioned at the same point as the manual thermometer, with temperature recorded every 10 seconds for 60 seconds. Next, a comparison was made between the temperature readings displayed on the LCD and the Blynk application for real-time temperature monitoring. The temperature was measured and displayed every 10 seconds for 60 seconds. A servo test was also conducted to determine the effect of the motor servo rotation on temperature increase, with tests performed at 5, 10, and 15-minute intervals to observe the temperature changes. Additionally, a test was carried out to assess the temperature decrease by varying the servo motor rotation at different intervals (5, 10, and 15 minutes) to measure the effective decrease in temperature after exceeding the setpoint. Lastly, a temperature stabilization test was conducted where the machine was operated with the gas valve open at a 140° angle, and the servo continuously opened to maintain the temperature below 180°C. Once the temperature reached or exceeded the setpoint, the servo closed by 40°, and the DC fan was activated to dissipate heat.

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2.4. Model Design

The design of the hardware model aims to ensure efficient placement of the system components in order to function optimally. The main components in this system include thermocouple temperature sensors, servo motors, DC fans, and Arduino Uno as the microcontroller, as well as ESP32 for IoT communication. All components are placed with an eye towards ease of access and maintenance, as well as ensuring efficient energy and data flow between each component. The components are connected with appropriate cables and modules to support stable functionality during the coffee roasting process. This design also ensures that each part can be easily installed and accessed for replacement or maintenance, if required.

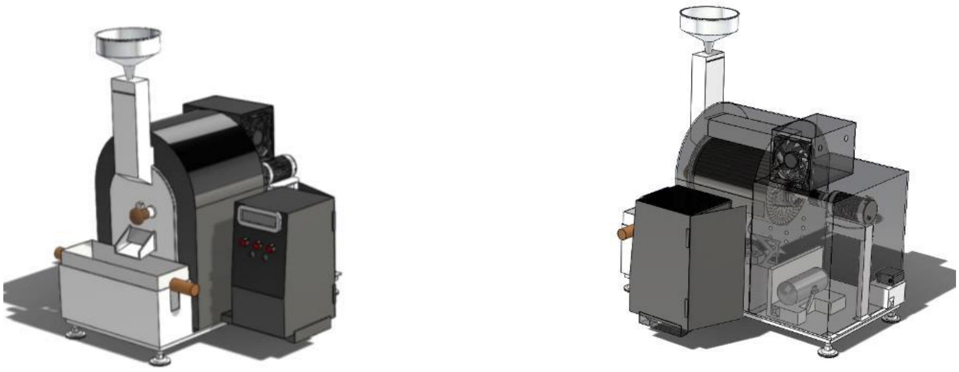

Figure 4. Design of a small-scale roasting machine model

2.5. Blynk App Design

The Blynk app is designed to provide remote control of the coffee roasting machine system. The Blynk app interface allows users to select the roasting type (light, medium, or dark roast) and monitor the temperature of the machine in real-time. The app displays a temperature indicator that shows the current temperature in the machine, as well as the status of active roasting. Users can control the system directly from the app, such as starting or stopping the roasting process, as well as adjusting the temperature settings when necessary. The interface design uses contrasting colors for easy reading, with a simple yet informative look to ensure a comfortable user experience.

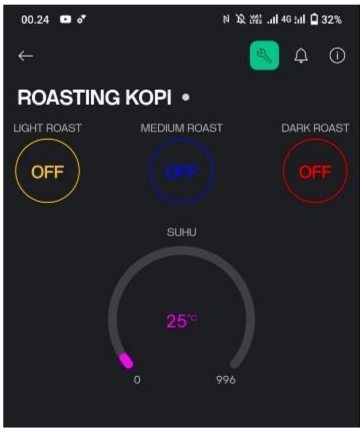

Figure 5. Coffee roasting application

3. RESULTS AND DISCUSSION

The results of designing and making an automatic system and monitoring system that can be controlled through the Blynk application. Furthermore, testing is carried out after the system has been designed. This test aims to determine and analyze the level of success, weaknesses, and the process of making this system. Data management in this system aims to produce good roasting results based on predetermined standards.

3.1 Sensor Analysis

3.1.1 Comparison of Thermocouple and Thermometer Sensors

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Temperature testing using a thermocouple and a manual thermometer was conducted to measure and compare the temperature in the coffee roasting machine. The thermocouple is installed inside the machine in the same position as the manual thermometer. The coffee roasting machine was turned on with a servo rotation of 60°. Every 10 seconds for 60 seconds, the temperature was recorded using both measuring instruments. The data obtained was used to calculate the error between the thermocouple and the manual thermometer, with the aim of ensuring the accuracy and consistency of temperature measurement in the roasting process. The results of this test can be seen in Table 1.

Table 1. Sensor Testing Results

Time (s)	**Thermocouple (°C)**	**Thermometer (°C)**	**Error (°C)**
0	29.25	29.00	0.25
10	29.25	29.00	0.25
20	29.50	29.00	0.50
30	29.50	29.00	0.50
40	29.50	29.00	0.50
50	30.25	30.00	0.25
60	31.00	30.00	1.00
Average error			0.46

Analysed from Table 1, the comparison temperature using the thermocouple shows an average error of 0.46°C compared to the manual measurement using a thermometer. Despite the slight error, with the highest error of 1.00°C at 60 seconds, the thermocouple sensor still shows good accuracy in temperature measurement. Overall, the thermocouple proved to be feasible for use in the coffee roasting machine monitoring system, although it needs periodic calibration to maintain its accuracy.

3.1.2. Comparison of LCD and Display

The display comparison test between LCD and Blynk application was conducted to monitor and display the temperature in the coffee roasting machine. The coffee roasting machine was turned on with a servo rotation of 60°. Every 10 seconds for 60 seconds, the temperature is recorded using both measuring instruments, which is then displayed on the LCD screen and also on the Blynk application connected via a smartphone. The data obtained from these measurements were used to compare the suitability and accuracy of the temperature display between the LCD screen and the Blynk application. This comparison aims to ensure that both display methods are able to show temperature data consistently and accurately, making it easier for users to monitor the coffee roasting process. The results of this test can be seen in Table 2.

Table 2. Comparison of LCD and Blynk Display

Time (s)	**LCD (°C)**	**Blynk (°C)**	**Error (°C)**
0	30.75	30.75	0
10	32.50	32.5	0
20	35.00	35.00	0
30	36.25	36.25	0
40	37.75	37.75	0
50	39.50	39.50	0
60	41.25	41.25	0
Average error			0

After testing and analyzing the temperature measurement using a thermocouple sensor displayed on the I2C LCD and Blynk application which can be seen in Table 2. The temperature displayed on the LCD display has a very fast response time because the data is sent directly from the thermocouple to the LCD. This is the same as the temperature displayed on the Blynk application, which has no delay even though it goes through the process of sending via the internet network.

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3.2 Servo Turn Analysis

3.2.1. Servo Testing Against Rise

This test was conducted to show the relationship between the servo motor rotation and the time required in increasing the effective temperature. Tests were carried out at time intervals of 5 minutes, 10 minutes, 15 minutes to see the temperature increase at each different time interval. The data can be used as a heating controller properly which can be seen in Figure 11.

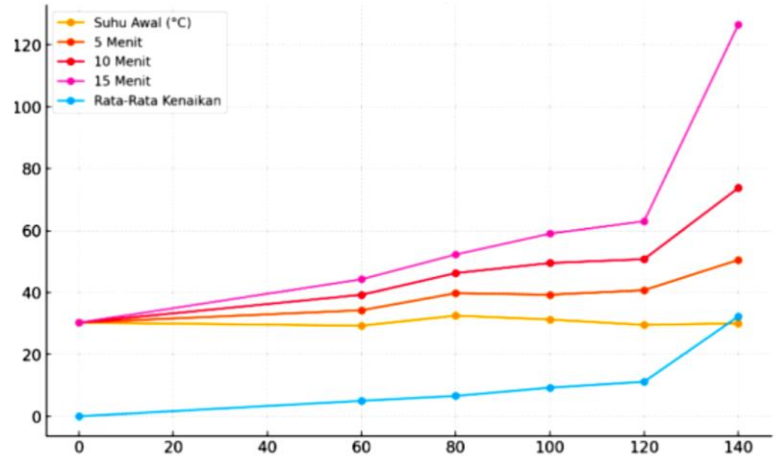

Figure 6. Rise graph The X-axis represents the rotation of the servo and the Y-axis represents the temperature

The test results displayed in Figure 6 show that the larger the servo rotation, the faster the temperature increase in various time intervals. Larger servo turns result in a more significant temperature increase in less time, indicating better heating efficiency. The results of this test were incorporated into the program using a servo angle of 140° for a rapid and optimal temperature increase.

3.2.2. Servo to Drop Testing

This test is carried out to show the relationship between servo motor rotation and the time required for effective temperature reduction. Tests are carried out at time intervals of 5 minutes, 10 minutes, 15 minutes to see the temperature drop at each different time interval.

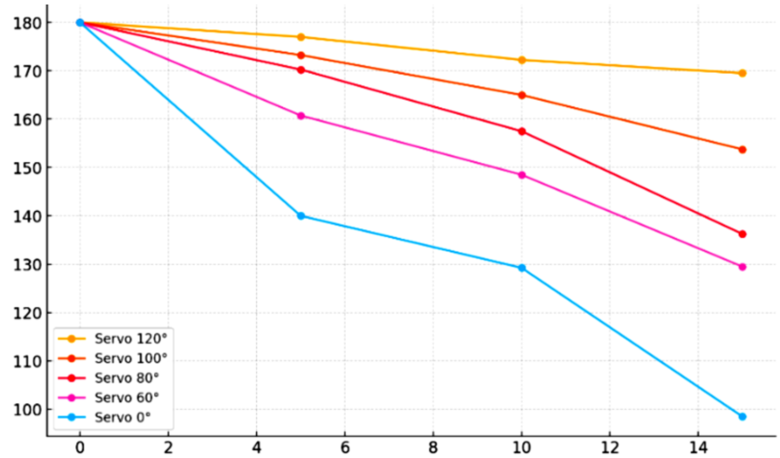

Figure 7. Drop graph The X-axis represents the time (minute) and the Y-axis represents the temperature

The data in Figure 7 shows the temperature drop over a given time for various servo angles, with an initial temperature of 180°C. This test shows that the smaller the servo angle, the greater the average temperature drop, with a more significant temperature drop at longer time intervals. The results of this test were entered into the program using a servo angle of 100° to reduce the temperature if it exceeded the setpoint in the roasting process.

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3.2.3 Stabilization Analysis

The temperature stabilization test of the coffee roasting machine aims to assess the system's ability to maintain a consistent temperature during the roasting process. This test was conducted by monitoring the temperature at various levels of heating intensity to ensure the system could maintain the target temperature of 180°C. The machine is operated with the gas valve opening at an angle of 140°, and the servo will continue to open at that angle as long as the temperature is below 180°C. When the temperature reaches or exceeds the setpoint, the servo will close by 40°, and the DC fan will turn on to dissipate the heat inside the engine. These steps aim to keep the temperature stable around the setpoint. The data from this test is used to assess the efficiency of the temperature control as well as identify and correct potential unwanted temperature fluctuations.

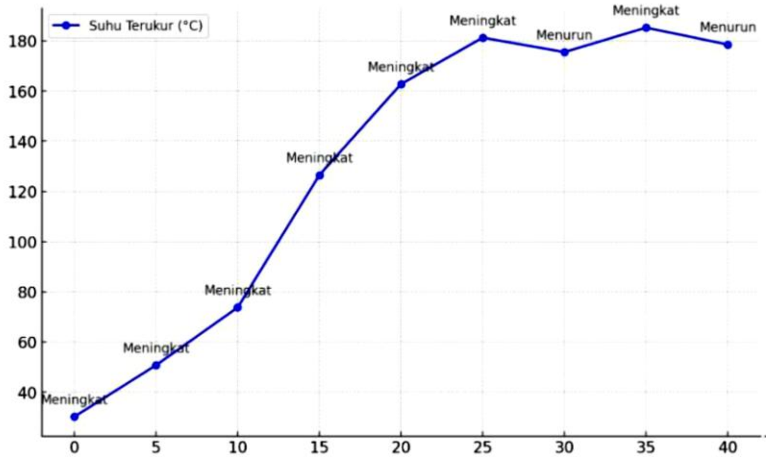

Figure 8. Stabilization Chart The X-axis represents the time (minute) and the Y-axis represents the temperature

Figure 8 shows the change in measured temperature against time during the heating process. From the data provided, the measured temperature continues to increase from the beginning (30.25°C) until it reaches a peak at the 35th minute (185.25°C), before finally decreasing at the 40th minute (178.50°C). So that the temperature can be maintained at approximately 180°C.

3.2.4 Motor Rotation Testing for Roasting

In this test, experiments were carried out with DC motors at two different speeds, namely 68 RPM and 136 RPM, to see the relationship between the motor rotation speed and the time required to achieve optimal roasting results. Table 3 below shows the test data of the motor rotation with speeds of 68 RPM and 136 RPM, as well as the optimal roasting time at 7 minutes, which resulted in the smallest percentage of failure.

Table 3. Motor Rotation Testing Against Time

Motor Speed (RPM)	Set Point (°C)	Time (Minutes)	Present Fail (%)
68	Light Roast	4	10,7%
		5	7,1%
		6	4,3%
		7	3,9%
	Medium Roast	4	6,6%
		5	9,5%
		6	4,5%
		7	3,1%
	Dark Roast	4	6,4%
		5	5,4%
		6	8,8%
		7	4,3%
136	Light Roast	4	53,1%

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		5	6,3%
		6	4,1%
		7	3,3%
	Medium Roast	4	5,8%
		5	8,7%
		6	4,3%
		7	2,4%
	Dark Roast	4	5,5%
		5	4,7%
		6	7,2%
		7	3,3%

Table 3. it shows test results at motor speeds of 68 RPM and 136 RPM for three temperature point sets: Light Roast (180°C), Medium Roast (220°C), and Dark Roast (250°C). The smallest failure percentage is recorded at the 7th minute time, which is the optimal roasting time to produce the best quality coffee beans with minimal losses. To get a good analysis of roasting results, the next sub-chapter uses 4", 5" and 10" times as the best roasting results of the coffee color form.

3.2.5 Analysis of Roasting Results

This research is a coffee bean roasting process that includes the length of the process time, the temperature required, the type of coffee produced and the characteristics of the coffee roasting results using 140° servo rotation opening. The results of the type of coffee roasting obtained will be adjusted to the color according to the SCAA (Specialty Coffee Association of America) standard [9]. In the analysis below, 4 types of coffee are shown consisting of light roast with a temperature of 180 °C, medium roast with a temperature of 220 °C and dark roast 250 **°C** to find out the success of roasting results seen in color and displayed in RGB.

Table 4. Coffee Roasting Color Results

Type	Roasting Temperature (°C)	Time (Minutes)	Color Code (RGB)
Light Roast	180	4"	(248,221,136)
		5"	(251,206,109)
		10"	(120,88,63)
Medium Roast	220	5"	(249,185,91)
		7"	(240,142,62)
		15"	(98,76,66)
Dark Roast	250	5"	(203,126,37)
		7"	(160,83,30)
		15"	(70,67,66)

The results of the coffee process can be seen in Table 4, explained based on the variables of temperature, time, and color of the coffee beans produced. Light Roast process with temperature between 160°C to 180°C, showing changes in coffee beans. The colour code in the light roast process that is closest to the SCAA standard is at minute 10. Medium Roast, with temperatures between 200°C and 220°C, shows changes in coffee beans. The colour code in the medium roast process that is closest to the SCAA standard is at minute 15. While Dark Roast, at a temperature of 230 ° C to 250 ° C, shows changes in coffee. These results reflect the effect of temperature and time on the colour development of coffee beans, which directly affects the flavour profile and characteristics of the coffee produced from each type.

4. CONCLUSION

This research successfully developed a small-scale automatic coffee roasting machine with precise temperature control using a thermocouple and servo mechanism, which allows automatic temperature and roast time setting. Tests showed that the thermocouple had good temperature accuracy with an average error of 0.46°C, and that the LCD and Blynk app were able to display the temperature accurately

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and consistently. Servo motor testing revealed that the larger servo rotation angle accelerates the temperature increase, improving the heating efficiency. This machine shows that the optimal roasting time for Light Roast, Medium Roast, and Dark Roast occurs at 7 minutes with the smallest failure percentage. Although the roasting results show quality consistent with the taste characteristics as standard, the maximum temperature achieved is still around 130°C, which is lower than the optimal temperature for Light Roast. Therefore, while these machines offer a consistent and economical solution for small businesses, improvements are needed to achieve higher temperatures to produce better quality coffee roasts.

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