CONSTRUCTION OF A PROTOTYPE GREENHOUSE AND USE OF DISCRETE PROCESSING TECHNIQUES FOR TEMPERATURE CONTROL

CONSTRUÇÃO DO PROTÓTIPO DE ESTUFA E USO DE TÉCNICAS DE PROCESSAMENTO DISCRETO PARA CONTROLE DE TEMPERATURA

CONSTRUCCIÓN DE UN PROTOTIPO DE INVERNADERO Y UTILIZACIÓN DE TÉCNICAS DE TRATAMIENTO DISCRETO PARA EL CONTROL DE LA TEMPERATURA

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ABSTRACT

This article presents the construction of a prototype greenhouse and the development of an experimental temperature control system as an application of discrete control of a thermal system. The generation and control of temperature is present in the industrial environment, where there are various levels of complexity for the satisfactory use of thermal energy. The structure consists of a wooden box, a 60 W light bulb as a heat source and a cooler for cooling. The temperature was measured using a thermocouple sensor and the data was processed by an Arduino. The Least Squares Method was used to estimate the gray box of the temperature system in the form of a discrete-time transfer function. The conversion of temperature into sensor voltage was determined using mathematical expressions, which allowed the system to be calibrated. The results were promising, since this is a first-order thermal plant with hysteresis and the controller is generic. However, the experimental analysis of the temperature control proved challenging. The main challenge in the project was the existence of intrinsic hysteresis in this type of system. Its clear presence was observed at higher temperatures, as well as the difference between the lamp's heating speed and the cooler's response. Even so, the system maintained the temperature within the specified parameters. One proposal for improvement is to implement a power control for the lamp, to provide more gradual heating.

Keywords: Greenhouse. Discrete control. Thermal system.

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RESUMO

Este artigo apresenta a construção um protótipo de estufa e o desenvolvimento de um sistema de controle de temperatura experimental como aplicação do controle discreto de um sistema térmico. A geração e o controle de temperatura se encontra presente no ambio industrial, onde há vários níveis de complexidade para uso sastisfatório da energia térmica. A estrutura é composta por uma caixa de madeira, uma lâmpada de $60\,W$ como fonte de calor e um *cooler* para resfriamento. Realizou-se a medição da temperatura por meio de um sensor termopar, sendo os dados processados por um *Arduino*. Empregou-se o Método dos Mínimos Quadrados para estimação caixa cinza do sistema de temperatura na forma de função de transferência em tempo discreto. Determinou-se a conversão de temperatura em tensão do sensor por meio de expressões matemáticas, que permitiu a calibração do sistema. Os resultados se mostraram promissores, uma vez que se trata de uma planta térmica de primeira ordem com histerese e o controlador ser de cunho genérico. Contudo, a análise experimental do controle de temperatura se mostrou desafiadora. O principal fator de desafio no projeto foi a existência da histerese intrinseca neste tipo de sistema. Observou-se sua presença clara em temperaturas mais altas, além da diferença entre a velocidade de aquecimento da lâmpada e a resposta do cooler. Mesmo assim, o sistema mantém a temperatura dentro dos parâmetros especificados. Uma proposta de melhoria é a implementação de um controle de potência para a lâmpada, para proporcionar um aquecimento mais gradual.

Palavras-chave: Estufa. Controle discreto. Sistema térmico.

RESUMEN

Este artículo presenta la construcción de un prototipo de invernadero y el desarrollo de un sistema experimental de control de temperatura como aplicación del control discreto de un sistema térmico. La generación y control de temperatura está presente en el entorno industrial, donde existen varios niveles de complejidad para el aprovechamiento satisfactorio de la energía térmica. La estructura consiste en una caja de madera, una bombilla de 60 W como fuente de calor y un refrigerador para enfriar. La temperatura se midió con un sensor termopar y los datos se procesaron con un Arduino. Se utilizó el método de los mínimos cuadrados para estimar la caja gris del sistema de temperatura en forma de función de transferencia en tiempo discreto. La conversión de la temperatura en tensión del sensor se determinó mediante expresiones matemáticas, lo que permitió calibrar el sistema. Los resultados fueron prometedores, dado que se trata de una central térmica de primer orden con histéresis y que el controlador es genérico. Sin embargo, el análisis experimental del control de la temperatura resultó todo un reto. El principal reto del proyecto fue la existencia de histéresis intrínseca en este tipo de sistemas. Se observó su clara presencia a temperaturas más elevadas, así como la diferencia entre la velocidad de calentamiento de la lámpara y la respuesta del refrigerador. Aun así, el sistema mantuvo la temperatura dentro de los parámetros especificados. Una propuesta de mejora es la implantación de un control de potencia de la lámpara, para proporcionar un calentamiento más gradual.

Palabras clave: Invernadero. Control discreto. Sistema térmico.

1 INTRODUCTION

Temperature systems play a key role in the industry and are essential for ensuring the quality, safety, and efficiency of production processes. Temperature control is crucial in several areas, such as in the manufacture of chemicals, food, and medicines, where small variations can compromise the integrity of the fine product (Pawelski, Rossini, Brolin; 2022). In industries such as automotive and electronics, temperature control is necessary to prevent sensitive components from overheating and ensure the proper functioning and safety of products. Therefore, the study and implementation of temperature systems optimize industrial processes, in addition to contributing to sustainability and reduction of operating costs (Cristofoli, Rossini, Monteiro; 2024).

The least squares method was used to estimate the plant parameters (Rossini, 2020). Estimation is of paramount importance due to the difficulty of finding a mathematical model of all the components of a system (Pradela, Maran, Rossini, 2023). A system is divided into three groups, a white box where all the components of the system are known, a gray box where some components of the system are known, and a black box where only the inputs and outputs are accessed (Ljung, 1999). Due to these limitations often present in real terms (gray box and black box) the estimation of the plant allows the approximation of a complete real model of nonlinearities with a theoretical model studied in depth in the graduations (Pawelski, Rossini, Coldebella; 2022), (Takeno, Rossini, Correa; 2022). With the information from the plant estimation, an appropriate controller is implemented for each case (Coldebell, Rossini; 2022a, 2022b, 2023a, 2023b) (Canhan, Brolin, Rossini; 2022a, 2022b 2023a, 2023b).

To perform the control action, an *Arduino Uno R3* was used, so the implementation of the controller took place discreetly (Pradela, Maran, Rossini; 2023). Discretization facilitates the implementation of a robust controller and due to the large number of sensors with integration for microcontrollers, it is possible to implement it with few components compared to analog control (Figueiredo, Souza, Oliveira, Rossini; 2023) (Cristofoli, Rossini, Monteiro; 2024).

Sections II and III describe the principles of operation of the system and the images present, respectively. In Section III, the construction of the system is demonstrated. In Section IV, the modeling of the system and each of its components is presented. In Sections V and VI, the results obtained in the open loop of the model and the plan, respectively, are demonstrated. In Sections VII and VIII, the theoretical and practical results obtained in a closed loop are illustrated. And in Section IX, the conclusion reached is exposed.

2 THEORETICAL FOUNDATION

2.1 THERMAL SYSTEMS

Thermal systems in the control environment are dynamic systems that involve the regulation of thermal variables, such as temperature, heat flow, and pressure, through control techniques. These systems play a crucial role in a variety of industrial and commercial applications, such as HVAC, chemical processes, refrigeration, and power generation. The efficient control of these systems not only ensures the quality of the process, but also contributes to energy efficiency and cost reduction (Ogata, 2010).

A thermal control system is made up of three main elements: the **sensor**, the **controller,** and the **actuator**. The sensor measures the controlled variable, such as temperature, and sends this information to the controller. The controller compares the measured value with the *setpoint* and takes the necessary control action. Finally, the actuator applies this action, which can be the activation of an electric resistance for heating or the opening of a valve for cooling.

The dynamics of a thermal system are governed by principles of heat transfer and thermodynamics. Temperature is the most common variable to be controlled, and its variation over time can be described by differential equations based on energy balances.

A thermal system has some significant difficulties such as time delay, energy efficiency and nonlinearities due to the behavior of materials changing at different temperatures (Ogata, 2010). Throughout this article, some of these difficulties have been addressed, identified in the following sections.

2.2 LEAST SQUARES METHOD AND DISCRETIZATION

For estimation, the Least Squares Method was used (Rossini, 2020). This method is often used for mathematical models and data analysis (Luiz Rossini, Santos Martins, Paulo Silva Gonçalves, Giesbrecht; 2018). The Least Squares Method is based on a dataset, which can be *online* or *offline* (Takeno, Rossini, Correa; 2022). The algorithm looks for the optimal parameters to decrease the sum of squares of the residuals (Montgomery, Peck, Vining; 2021), where such residuals are the difference (error) between the observed value and the value predicted by the model. In this way, the algorithm needs a model to approximate the data with the appropriate parameters (Haykin; 2014). In Section IV, the code used to implement the algorithm was discussed.

Discretization has become essential with the advancement of semiconductor technology, with emphasis on *CPUs*, with the ease and low cost of acquiring a microcontroller, several previously analog techniques, migrated to the discrete world to run embedded systems. In the area of signal control and processing, the discretization and the way it is employed in a signal or system defines how close it is to the analog signal. Some known discretization methods are: Euler discretization, discretization by progressive or regressive differentiation, Tustin discretization (bilinear), among others. This article has addressed the discretization of Tustin in Section IV due to its accuracy and stability (Ogata, 1995).

2.3 CONTROL SYSTEMS

Control systems are fundamental in several areas of engineering and technology, which allows dynamic processes to operate automatically, accurately and stably. They can be classified into two main categories: open-loop control systems **and** closed-loop control systems**.**

In open loop, the system output does not interfere with the control action, that is, there is no *feedback*. These systems are simple, but they can be inaccurate due to a lack of error correction caused by external disturbances. Examples include washing machines or timing systems. Closed-loop systems, on the other hand , use feedback to compare the output with the desired value (*setpoint*) and adjust the control as needed. This ensures greater accuracy, stability and rejection of disturbances.

The most common closed-loop controllers are proportional (P), integral (I), and derivative (D) types**,** or combinations thereof (PI, PD, PID). The PID controller is widely used due to its ability to minimize steady-state errors (integral action) and improve transient response (derivative action).

Mathematically, control systems are modeled by transfer functions or differential equations, and represent the relationship between input and output. Techniques such as root location and frequency analysis are used to design and analyze the stability and performance of the system.

3 PLAN

The plant used in this control system is based on a wooden box with dimensions 20 x 22 cm and a height of 17 cm. The inside of the box was lined with aluminum foil to improve thermal insulation and optimize temperature control. In addition, the plant has a hinged wooden lid, which allows easy access to the interior of the system.

Each part of the plant was chosen based on the functionality and efficiency required for temperature control. The integration between the elements allows the system to perform accurate measurements, promote heating and cooling as demanded, which ensures the balance of the internal temperature. The list of materials used in the construction of the plant and in the operation of the system is presented in Table 1.

Table 1 - Materials used in the construction of the plant.

Materials:	Quantity/Dimensions:
Wooden Box	20 x 22 x 17 cm
Tinfoil	Inner lining
Incandescent bulb (60W) with socket	1
Cooler (12 V)	1
Thermocouple Sensor	1

Source: Authorship.

The incandescent bulb is used as the plant's heat source, so it is responsible for increasing the internal temperature of the system. The lamp was fixed in the center of the inner base of the box, strategically positioned to distribute the heat evenly throughout the space. A power of 60 Watts was chosen, as it provides a sufficient amount of heat to reach and maintain the desired temperature in a controlled manner. It is possible to visualize it through Figure 1.

Figure 1 - Lamp and socket inserted in the plant.

Source: Authorship.

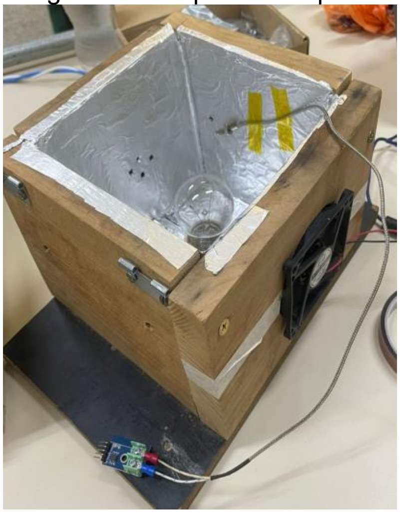
The *cooler*, installed on one side of the box, performs the cooling function. It goes into operation when the internal temperature exceeds the established limits and promotes the exchange of internal air with the external environment. This component is essential to ensure that the temperature of the plant is reduced quickly and prevents overheating, as well as maintaining the thermal balance of the system. The *cooler* already inserted in the plant is shown in **Figure 2**.

Figure 2: *Cooler* inserted into the plant.

Source: Authorship.

With all components integrated, the plant presents a functional and efficient configuration. The lamp, cooler and thermocouple sensor were properly positioned inside the wooden box, while aluminum foil covered the internal surfaces to improve thermal insulation. This structure ensures the correct functioning of the system and can be seen in **Figure 3**.

Figure 3: Complete floor plan.



Source: Authorship.

In addition to the main components, holes were also drilled in the sides of the box with a screwdriver. The holes have the function of allowing air circulation inside the plant when the *cooler* is activated, which facilitates the thermal exchange process and accelerates the reduction of the internal temperature.

This structural modification improves cooling efficiency, which ensures adequate airflow. These details can also be seen in **Figure 3**, which shows the finished plan with all components installed.

4 MODELING OF SYSTEM COMPONENTS

4.1 EQUIPMENT FOR MEASURING AND MONITORING SYSTEM VARIABLES

For the monitoring and control of the system's variables, a set of equipment was used that enable accurate measurement and recording of information in real time. The main element responsible for collecting and processing the data is the *Arduino Uno R3*, which reads the measurements from the thermocouple sensor and controls the other components of the system.

The thermocouple sensor is the device in charge of measuring the internal temperature of the greenhouse. It converts the temperature variation into electrical signals, which are sent to the Arduino for scanning and interpretation. Based on this data, the Arduino makes decisions about the activation of the lamp and cooler, which ensures that the internal temperature remains within preset limits.

The *Arduino Uno R3* was chosen due to its versatility, sensor compatibility and programming simplicity, and allows for the efficient integration of components and the execution of control and monitoring tasks. In **Figure 4**, you can see the Arduino used in the project.

Figure 4 – *Arduino Uno R3*

Source: Authorship

4.2 SENSOR TRANSFER FUNCTION

The sensor used is a k-type thermocouple with an integrated circuit MAX6675, which is responsible for compensating the cold joint and providing bits for communication with a microcontroller due to its 12-bit ADC.

Figure 5: Thermocouple Sensor

Source: Authorship

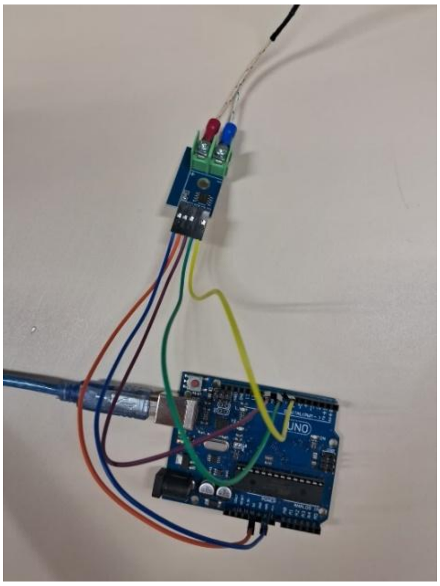
The **Figure 5** demonstrates the sensor with the MAX6675 module with SPI communication. Due to the internal structure of the IC, the transfer function of the sensor can be represented by the **Eq. 1**.

$$FT_{sensor} = \frac{1}{1}\frac{V}{C°} \qquad Eq. 1$$

The Sensor Transfer Function can be considered by the fact that the data processing and nonlinearity compensations are made by the module, so there is no impact of the sensor on the plant.1

The **Figure 6** shows the proper connections of the sensor with the board *Arduino Uno R3* for sampling plant temperature.

Figure 6 – Interface with the microcontroller



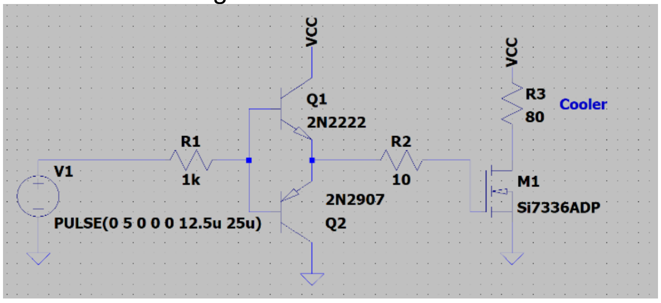
Source: Authorship

4.3 ACTUATOR TRANSFER FUNCTION

For the actuator, a *Cooler* (**Figure 2**) of a computer that acts as an exhaust fan. The actuator has a non-linearity ratio due to the minimum voltage for its actuation. Due to the lack of equipment and structure to be able to collect data from the actuator, it was decided to consider it as part of the plant, so its transfer function will be embedded in the plant's transfer function.

To drive the actuator, a circuit of *driver* to modulate the voltage applied to the *Cooler*. The **Figure 7** demonstrates the *driver.*

Figure 7 – Driver Circuit



Source: Authorship

The drive circuit consists of a configuration of transistors *Push-pull* to supply charge to the capacitor *Gate* intrinsic of the Mosfet M1. The V1 voltage source refers to the signal *PWM (Pulse Width Modulation)* from the digital controller.

Or **Table 1** demonstrates the C++ code used to configure the frequency of the *PWM* at 40kHz.

Table 1 – *PWM Code*

```
void setup()
{
```

```
  Sets PB1 (pin 9 UNO) as output
  DDRB |= (1 << PB1);

  Zeroes registers
  TCCR1A = 0;
  TCCR1B = 0;
  TCNT1=0;

  Configures PWM Registers
  TCCR1B  |=  (1<<WGM13)  |  (1<<WGM12)  |
(1<<S10); Arrow 1 preescaler
  TCCR1A |= (1<<WGM11) | (1<<COM1A1) ; Arrow
mode that resets OCR1A (PB1 / pin 9)

  ICR1 = (399); TOP value, zero account so far
  OCR1A  =  (199);  Comparison  value,  defines  the
duty cycle (0-ICR1)

}
```

Source: Authorship

The transfer (FT) function of the driver is characterized by the ratio of the output voltage to the input voltage, given an applied pulse-width modulation (*PWM*). The driver operates with a PWM modulated input voltage, and its output is also PWM modulated, as it corresponds to a variation proportional to the input.

In the case of the maximum voltage, which corresponds to a cycle of 100% of the *PWM*, the ratio between the output voltage and the input voltage is expressed by the ratio:

$$\frac{Vout}{Vin} = \frac{12V}{5V} = 2,4 \qquad Eq.2$$

This ratio implies that when the *PWM* reaches 100%, the output will be 2.4 times higher than the input voltage. This transfer function is crucial for precise control of the voltage supplied to the oven-resistance, as it allows you to adjust the power supplied to the system efficiently via *PWM*.

4.4 PLANT TRANSFER FUNCTION (GREENHOUSE)

For the collection of data regarding the plant, the 60 W lamp without the actuator was connected in order to achieve the permanent regime of the plant. Then the *cooler was activated* at its nominal voltage and a sampling time of 1 second was defined due to the slow dynamics of the plant, it was verified after some tests that this time is satisfactory. The tests were performed for approximately 15 minutes. Chart **2** explains the code in C++, which uses interrupt to perform data collection on the *Arduino Uno R3*.

Chart 2 – C++ code for data collection

```
#include <avr/io.h>
#include <avr/interrupt.h>
#include <max6675.h>

/* Definitions: Arduino GPIOs used to communicate
with the MAX6675 */
#define GPIO_SO 7
#define GPIO_CS 8
#define GPIO_CLK 10

Arrow baudrate
#define BAUDRATE_SERIAL_MONITOR 38400

Creates MAX6675 object
MAX6675 thermocouple (GPIO_CLK, GPIO_CS,
GPIO_SO);

Stores value
volatile float temperature = 0.0;

Flag
volatile bool leutemp = false;

Accountant
uint8_t counter=0;

void setup()
{
Starts serial communication
Serial.begin(BAUDRATE_SERIAL_MONITOR);

Zeroes registers
TCCR2A= 0;
TCCR2B= 0;

Configures 2 OVF Timer Registers
TCCR2B |= (1<<CS22) | (1<<S21); Arrow moto
OVF with 256 preescaler

Enable interrupt mask for timer 2
TIMSK2 |= (1 << TOIE2); Hablita OVF of timer 2

sei();
}

ISR(TIMER2_OVF_vect)
{
Increments counter until it reaches 24 (1s)
accountant++;

if(counter == 245)
{

counter=0;

Reseta flag
leutemp=true;
}

}

void loop()
{
```

```
if(leutemp)
{

Reads temperature
temperature=thermocouple.readCelsius();
Printa no serial
Serial.println(temperature);

Clear flag
leutemp=false;
}
}
```

Source: Authorship

The information collected is in discrete time and with which, temperature and their respective sampling times, Matlab®'s *toolbox system identification* was used to estimate the parameters and thus plot the response. Chart **3** shows the syntax used to obtain the simulated answer.

Chart 3 – Matlab syntax

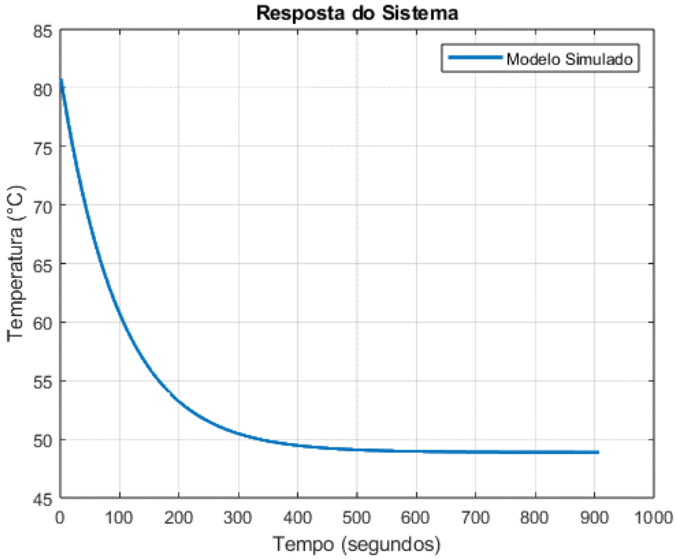
```
close all;
clear all;
CLC;

% Input and output vectors are defined
y_vetor = readtable("MA3_vent.txt"); % output
size = height(y_vetor); % Gets the size of the data
vector
u_vetor=12*ones(size,1); % entry
y_vetor = table2array(y_vetor);

% Regressor Vector: psi = [y(k-1) u(k)]
% Pre-allocating the variables to the values of y1,
u1
y1 = y_vetor(1:size-1);  %y(k-1)
u1 = u_vetor(2:size);  % u(k)

% Matrix Construction X
X = [y1 u1];

% Vector Y with the values of y(k) from k=2
onwards
Y = y_vetor(2:size);
theta = inv(X'*X)*X'*Y % defines the theta matrix,
here is parameter estimation

y(1) = y_vetor(1); % Initial condition
for k=2:size
u(k)=u_vetor(k);
y(k)=theta(1)*y(k-1) + theta(2)*u(k);
End
% Plot the answers
T = 1:1: Size;
plot(t(:),y(:)), grid on % Model obtained
Hold on
plot (t(:),y_vetor(:))   % Actual data
error = sum(abs(y'-y_vetor));
erro_medio = error/size   % Calculation of the mean
error between the curves.
```

Source: Authorship

5 THEORETICAL RESULTS OF THE OPEN LOOP SYSTEM

To validate the theoretical data of the system, the Matlab® software was used to determine the plant transfer function. **Figure 8** shows the graph of the transfer function obtained.

Figure 8 - Simulated graph



Source: Authorship

The estimate used the least squares method, which uses the equation for differences presented in **Eq. 3**.

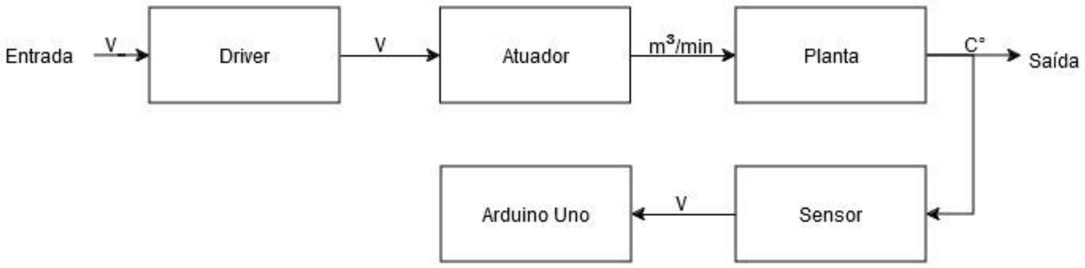
$$y(k) = teta(1)y(k-1) + teta(2)u(k) \qquad Eq.3$$

Subsequently, this same equation was used inversely to find **Eq. 4**, which represents the transfer function in the Z domain.

$$\frac{Y(z)}{U(z)} = \frac{0{,}0406z}{z-0{,}99} \qquad Eq.4$$

For a clearer understanding of the system's behavior, **Figure 9** shows the block diagram of the open-loop system, which illustrates the interactions between the components and the plant.

Figure 9 - Block diagram



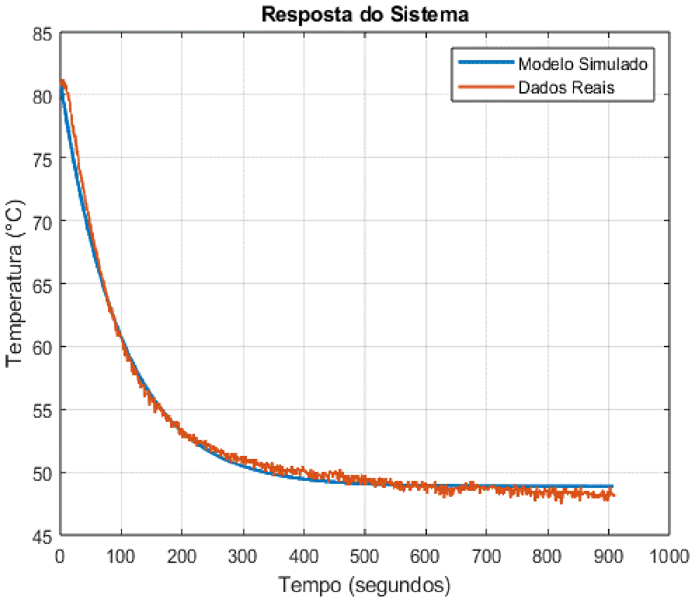
Source: Authorship

From the block diagram presented, it is possible to visualize how the system variables interrelate in an open loop. This configuration allows you to analyze the plant's response without interference from a controller and provides crucial information about the dynamic behavior of the system, such as its stability and response times.

6 PRACTICAL RESULTS OF THE OPEN LOOP SYSTEM

To validate the mathematical model, the experimental transfer function and the transfer function of the mathematical model were plotted. **Figure 10** expresses the two graphs in the *Matlab® software environment.*

Figure 10 – Model validation



Source: Authorship.

In this way, the estimated difference equation results in:

$$y(k) = 0{,}99y(k-1) + 0{,}0406u(k) \qquad Eq. 5$$

It was noted that there is an error between the simulated and the theoretical, in order to validate, in addition to visually, the average error of the values of the estimated vector and the vector of collected data were made. The following were obtained:

$$Erro_{médio} = 0{,}4683 \qquad\qquad Eq.6$$

Due to the small error expressed in **Eq.6**, it was mathematically verified that the estimated model is close enough to use in the tuning of the controller.

7 THEORETICAL RESULTS OF THE CLOSED-LOOP SYSTEM

7.1 CONTROLLER TUNING

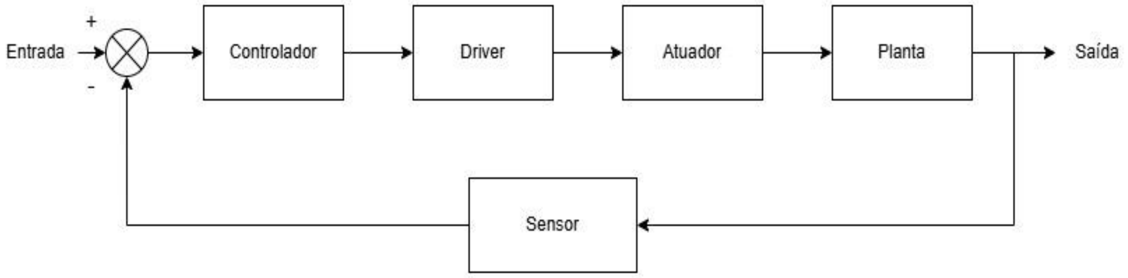
A Proportional-Integral (PI) controller was used in this project, as the objective was to eliminate the error in the system's steady state. The PI controller has as its main characteristics the proportional action, which reacts immediately to variations in the error, and the integral action, which accumulates the error over time and adjusts the system output to minimize changes.

To implement this controller, it was discretized using the Tustin method. This process involved isolated analysis of the system error, without the need for an in-depth study of the plant. Although the plant has an influence on the final answer, only the mathematical model of the error was considered to carry out the design of the controller.

The controller acts in an inversely proportional manner to the error. When the error is positive, i.e. the measured temperature is above the reference value, the actuator (cooler) is activated to reduce the temperature. If the error is negative, indicating that the temperature is below the desired value, the actuator is deactivated to allow heating.

Through Figure 11, it is possible to visualize the block diagram of the closed-loop system, developed in the *Flowchart Maker software*.

Figure 11 – Block diagram



Source: Authorship.

This diagram illustrates the key interactions between the system components and includes the designed controller, driver, actuator, plant, and sensor.

7.2 IMPLEMENTATION OF THE CONTROL LAW IN THE MICROCONTROLLER

To implement the PI controller in the microcontroller, as well as in the other steps, a code in the C++ language was developed that adjusts the control action based on the measured error. The code contains the controller's calculations and the discretization by Tustin's method, It is possible to see this code in **Chart 4** described below.

Chart 4 – Code with the implementation of the controller and the control law.

```
void loop()
{
if(leutemp)
{

Reads temperature
temperature=thermocouple.readCelsius();

Printa no serial
Serial.println(setpoint);
Serial.println(temperature);
Serial.println(Error);

Clear flag
leutemp=false;
}

Error = setpoint-temperature;

Control law
u = -(k+k*a/2)*Error-(((a*k)/2)-k)*Erro_k1+u_k1;

Trunca result
if(u>399) u=399;

if(u<=0){
Writes pwm registrar
OCR1A = (0); Comparison value, defines the duty
cycle (0-ICR1)
if(u<150) u=-150;
}

if(u>0){
if(u>150){
Writes pwm registrar
OCR1A = (u); Comparison value, defines the duty
cycle (0-ICR1)
}
else OCR1A = (150); Comparison value, defines
the duty cycle (0-ICR1)
}

Updates past values
Erro_k1=Error;
```

```
u_k1=u;
}
```

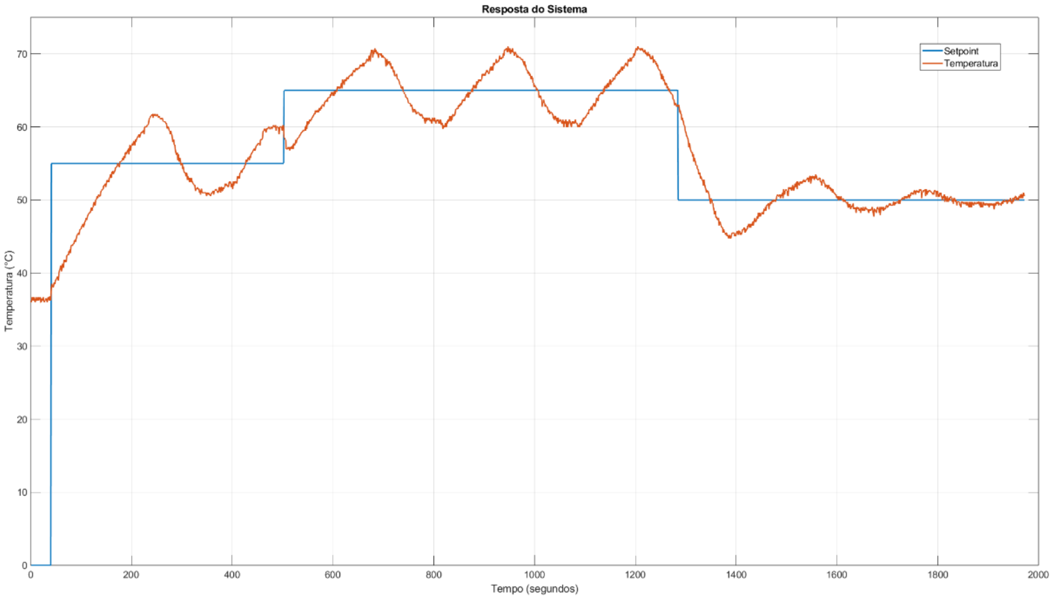
Source: Authorship.

The implemented solution ensures that the control is efficient and stable, which allows for fine adjustments in the behavior of the system. Experimental validation demonstrated that the closed-loop response meets the design requirements, provides relatively precise control of the greenhouse temperature.

8 PRACTICAL RESULTS OF THE CLOSED-LOOP SYSTEM

A test was carried out where the *Setpoint* was changed and the values of the controller and how it followed the reference signal were recorded. For this test, the following *Setpoint values were used*, , and . Figure $55\ ^{\circ}C65\ ^{\circ}C50\ ^{\circ}C$**12** shows the graph referring to the test, the X axis represents the number of samples, as previously mentioned the sampling time is 1 second.

Figure 12 – Results



Source: Authorship.

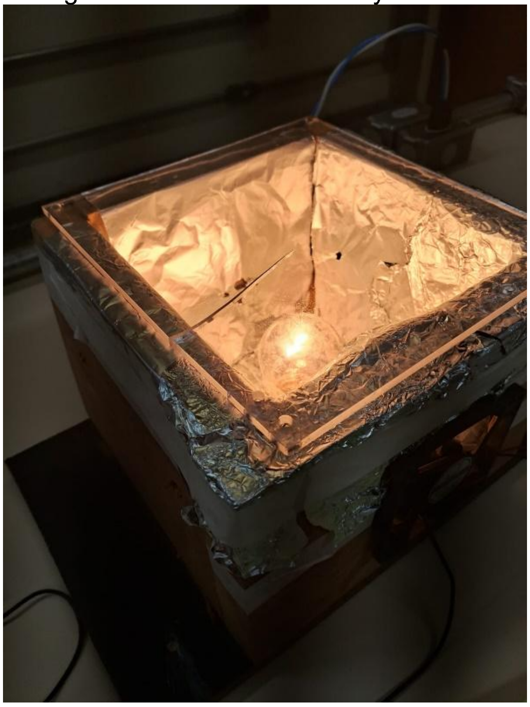
From **Figure 12**, it can be seen that the controller can follow the reference signal. However, it was noted that, at higher temperatures, hysteresis becomes more evident, as in the *Setpoint* of , which showed a variation of approximately . At lower reference temperatures, hysteresis is reduced, where the controller almost approaches a null error, as in the case of the $65\ ^{\circ}C5\ ^{\circ}C$*Setpoint* of $.50\ ^{\circ}C$

This behavior is directly related to the performance of *PWM*. At lower temperatures, the controller is able to work more efficiently, as the variation within the *range* of a allows for more significant adjustments without saturation. In this way, a 0399*Duty-Cycle* of 40% may be enough to reach the *Setpoint* or keep the temperature stable in the event of a null error.

Another factor that influences hysteresis is the difference between the heating speed of the lamp and the response of the actuator. The lamp heats up quickly, while the cooler cannot compensate for the variation at the same speed, which results in thermal oscillations. Despite this, the system maintained satisfactory performance within the established limits. A possible solution to mitigate this hysteresis would be to control the wattage of the lamp, which would allow for more gradual heating. However, this approach would alter the linearity of the system, which was not the initial goal of the project. The solution adopted ensured that, despite the hysteresis observed, the system remained functional and adequate to the requirements of the project.

In addition to the issues related to the thermal response, a structural problem was observed in the greenhouse lid. Initially made of acrylic, the lid suffered cracks due to prolonged exposure to high temperature. Figure **13** illustrates this damage.

Figure 13 – Crack in the Acrylic Cover



Source: Authorship.

While structural damage did not compromise the system's measurements, choosing a more heat-resistant material could minimize this problem in future implementations.

9 CONCLUSION

The development of this project allowed the implementation and validation of a temperature control system for an experimental greenhouse, with a PI controller and an *Arduino Uno R3 microcontroller*. The system proved to be efficient in thermal regulation and ensured the maintenance of the temperature within the established limits.

The modeling of the system occurred by obtaining the plant transfer function, through the method of least squares. The controller was designed and discretized by the Tustin method, which enabled the efficient digital implementation of the control. The closed-loop validation demonstrated that the system responds adequately to temperature variations, even in the face of the difficulties encountered.

In addition to the efficiency of the control, the experimental analysis highlighted challenges and potential improvements. The hysteresis observed, especially at higher temperatures, stands out from the difference between the heating speed of the lamp and the response of the cooler. Despite this, the system was able to keep the temperature within the desired parameters. A possible future improvement would be the implementation of a power control for the lamp, to provide more gradual heating.

Another important point would be the choice of structural materials. The greenhouse lid, made of acrylic, showed cracks due to prolonged exposure to heat. Although this has not compromised the operation of the system, replacing it with a more resistant material can increase the durability of the structure.

It is concluded that the developed system met the proposed objectives, and demonstrated the feasibility of temperature control in a greenhouse through digital control techniques. The design can be expanded with future improvements, such as refining control methods and integrating new sensors and actuators, for even more accurate performance.

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