Development of a Didactic Kit for Temperature Control: A Comparative Analysis of Passive and Active Cooling Strategies

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Abstract: This paper presents the development and implementation of a didactic kit designed to control the temperature of a resistor using two different approaches. The first one involves passive cooling by varying the duty cycle to the resistor, while the second approach employs active cooling through a DC fan. The kit utilizes an ESP32 Dev Module, coupled with PID controllers and MOSFETs, to enable power modulation and fan RPM control, respectively. The experimental results demonstrate that the active cooling strategy outperforms the passive one in terms of response time and stability. The didactic kit serves as an educational tool, offering hands-on experience with control techniques and facilitating a better understanding of engineering applications.

Keywords: didactic kit; ESP32; temperature control; duty cycle.

Desenvolvimento de um Kit Didático para Controle de Temperatura: Uma Análise Comparativa das Estratégias de Resfriamento Passivo e Ativo

Resumo: Este artigo apresenta o desenvolvimento e a implementação de um kit didático projetado para controlar a temperatura de um resistor usando duas abordagens diferentes. A primeira abordagem envolve resfriamento passivo, variando o ciclo de trabalho para o resistor, enquanto a segunda abordagem utiliza resfriamento ativo por meio de um ventilador DC.O kit utiliza um microcontrolador ESP32, juntamente com controladores PID e MOSFETs, para permitir a modulação de potência e o controle da RPM do ventilador, respectivamente. Os resultados experimentais demonstram que a estratégia de resfriamento ativo supera a passiva em termos de tempo de resposta e estabilidade. O kit didático serve como ferramenta educacional, oferecendo experiência prática com técnicas de controle e facilitando uma melhor compreensão das aplicações de engenharia.

Palavras-chave: kit didático; ESP32; controle de temperatura; ciclo de trabalho.

1. INTRODUCTION

Didactic plants are platforms that enable the simulation of industrial problems, creating controlled environments and situations, as stated by [1]. The use of such plants can promote the development of real engineering solutions in the academic environment by providing a practical application of control techniques in physical systems which may include common variables in industrial plants such as temperature, level and flow.

Temperature control is necessary, as in many cases the substance used in the industrial process can change its physical and chemical properties depending on the working temperature [2]. This highlights the importance of this type of control, as this variable is present in several industrial processes and equipment, such as boilers, ovens and greenhouses as evidenced by [3].

Therefore, a didactic kit was developed to enable the control of the temperature of a resistor using two different approaches. The first approach involves controlling the power supplied by changing the duty cycle sent by a microcontroller. This duty cycle will control the power provided by a MOSFET, acting as a switch, which will vary the power delivered to the resistor. In the second approach, the temperature of the resistor will be controlled by changing the duty cycle provided to a DC fan, using the same triggering strategy as in the first approach. This will change the fan's RPM while a DC current will supply maximum power to the resistor.

This versatile kit finds application in a wide range of disciplines within electrical engineering, computer engineering, control and automation engineering, and chemical engineering at the Centro Universitário SENAI CIMATEC. It can be utilized for both validating phenomenological modeling and conducting empirical modeling through dynamic system identification techniques. Beyond its extensive use in studying classical and advanced control strategies, the kit also serves as a valuable resource for courses in microcontrollers, electronics, and digital signal processing. Its diverse applications make it an indispensable tool for hands-on learning and experimentation in engineering education.

2. METHODOLOGY

The designed circuit will utilize an ESP32 Dev Module to control the temperature of the resistor. As mentioned before, the control will be carried out using two different approaches. Both will use an IRLZ44N MOSFET as a switch to provide power to their respective loads (DC Fan or 5W Resistor) as shown in Figure 1 and 2, respectively. Both circuits draw power from an external 12 volts source.

Figure 1. Circuit for resistance

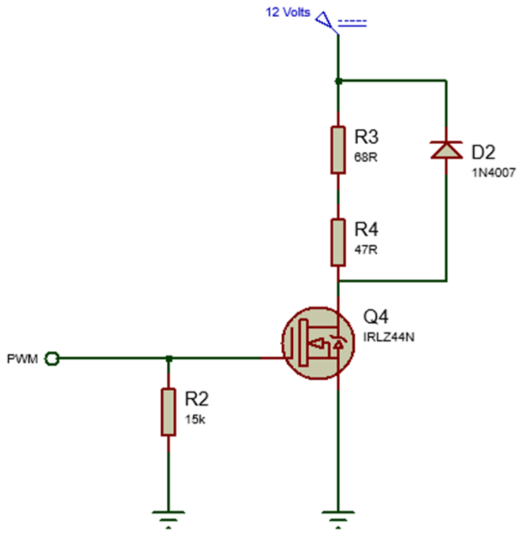
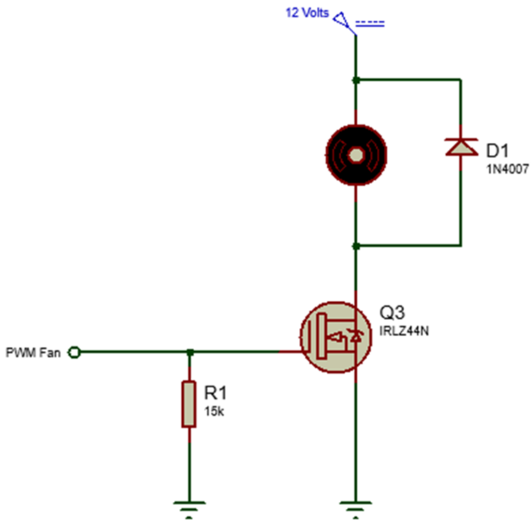


Figure 2. Circuit for DC Fan



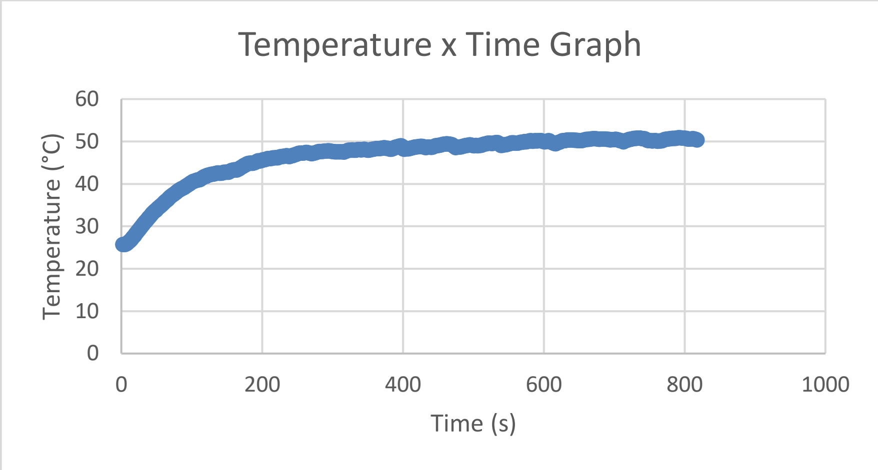
The PWM signal in Figure 1 represents the duty cycle provided by the ESP32. The circuit also requires a 15k resistor and a 1N4007 diode. For the first control approach, the load will be a 5W 68R resistor (R3). This resistor is placed in series with another 5W 47R resistor to prevent overheating. These values were tested and selected empirically to keep the maximum temperature close to 50 degrees. The temperature of the 68R resistor will be measured using a DS18B20 digital sensor. This sensor communicates over one-wire, which means it only requires one data line (GPIO) to communicate with the microcontroller. With this measurement, the control was implemented using a PID (proportional-integral-derivative) controller, and the PWM shall decrease while the temperature is rising.

For the second control approach, the load will be the DC fan as shown in Figure 2. The 68R resistor in Figure 1 will always operate at the highest duty cycle possible, meaning it will receive the maximum DC current the control circuit can provide and will be constantly heated while the DC fan in Figure 2 will be responsible for cooling this resistor. Therefore, the PWM must have the opposite behavior compared to the first approach, increasing the duty cycle when the temperature is rising. The control was also implemented using the PID controller. This technique was chosen for both cases because its usefulness lies in their general applicability to most control systems as mentioned by [4].

3. RESULTS AND DISCUSSION

Firstly, tests were conducted to validate the hardware to ensure that the components could handle the maximum current value provided. The circuit was kept under these conditions for hours and did not overheat or cause any damage. Afterwards, using the serial data provided by the ESP32, another test was performed to measure the maximum temperature the monitored resistor could reach. This temperature is approximately 50 degrees, as shown in Figure 3, and for this project's purpose, it was considered suitable and safe.

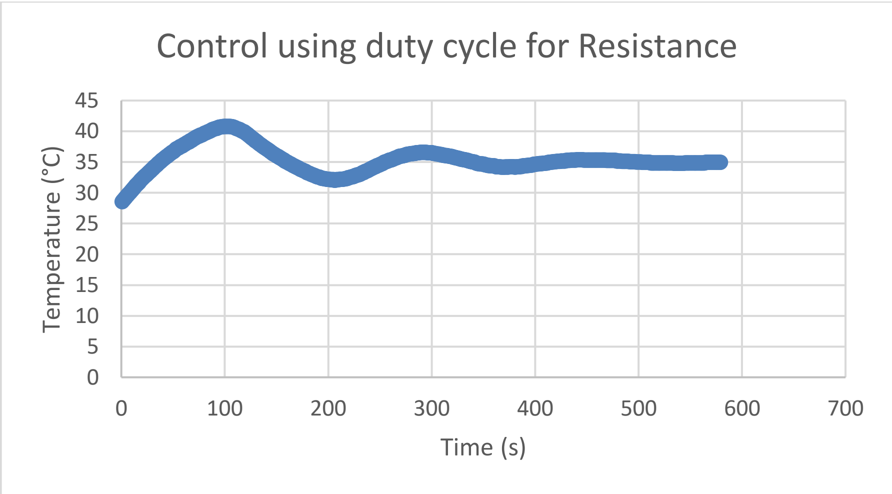
Figure 3. Temperature curve for the resistor



The test in Figure 3 represents the step response to 12 volts. We can determine the system has first-order characteristics such as no overshoot and nonzero initial slope [5].

The next test was to control the temperature of the load resistor by changing the power provided, altering the duty cycle that triggers the MOSFET. The setpoint was 35 degrees, and the results are displayed in Figure 4.

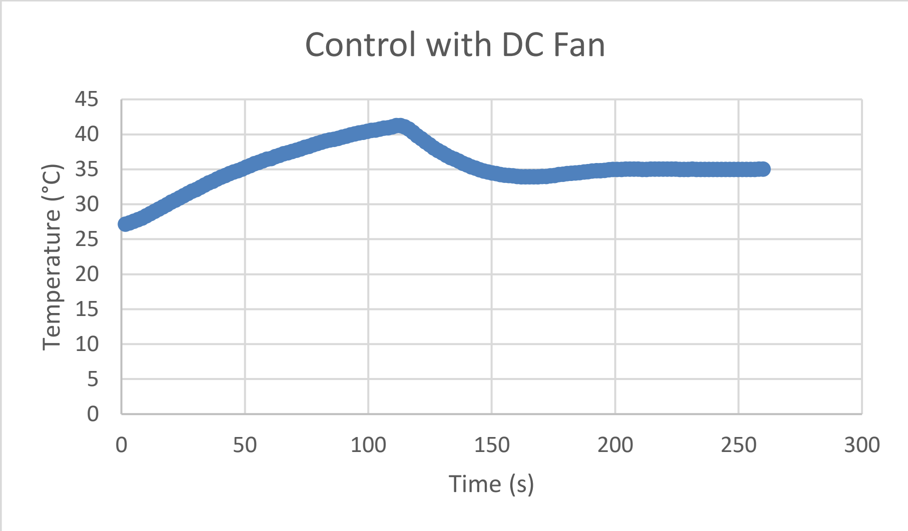
Figure 4. Results for first control approach



By analyzing Figure 4, we can see that the temperature stabilizes at about 580 seconds (approximately nine minutes), indicating a slow system response. This behavior was expected, as there is no actuator to actively cool the resistor. Even though the power provided may decrease proportionally with the change in the duty cycle, the system still needs to cool by exchanging heat with the surroundings.

The final test was to use the DC fan to cool the resistor. The setpoint was also 35 degrees, and the results are shown in Figure 5.

Figure 5. Results for second control approach



It is notable that this system reaches the desired setpoint in about 250 seconds (close to four minutes), less than half the time of the other control approach. This system also exhibits much less oscillation to reach the desired temperature measurement, but has the same overshoot. For both control strategies, the KP, KI, and KD parameters of the PID controllers were set to 10, 1, and 4, respectively. Those parameters were obtained by trial and error.

The primary objective of this study was to validate the physical system through practical experiments. However, it is worth mentioning that the transfer function can be obtained using the step response in Figure 3 and tuning techniques such as the Ziegler-Nichols method can be employed to further optimize the PID controller's performance. The manual tuning process employed in this project, through trial and error, allowed for a satisfactory control response. Nevertheless, the Ziegler-Nichols method offers a systematic approach to tuning PID parameters based on experimental step responses [4], which can potentially enhance the system's transient and steady-state characteristics. Future investigations may explore the application of these tuning techniques to fine-tune the control system and achieve even more precise temperature regulation in the didactic kit.

4. CONCLUSION

In conclusion, the development of the didactic kit for controlling the temperature of a resistor using two different approaches has proven to be a valuable tool for understanding control techniques in engineering applications. The utilization of an ESP32 Dev Module, coupled with PID controllers and MOSFETs, allowed for effective manipulation of power delivery and fan RPM, resulting in distinct control strategies. The tests conducted demonstrated that while the first approach showed a slower response due to passive cooling, the second approach, utilizing active cooling with a DC fan, achieved faster and more stable temperature control. This project serves as an educational platform, fostering a deeper understanding of control system design and its practical implications. By promoting hands-on learning experiences, this didactic kit enables students and researchers to explore real-world engineering challenges in a controlled and safe environment, paving the way for the development of innovative solutions in the field of process control and automation.

Moreover, the versatility of the kit was showcased by its applicability in various disciplines within the engineering curriculum at Centro Universitário SENAI CIMATEC. As a cost-effective solution, the entire project, including the materials, did not exceed R$ 150,00, making it an affordable option for fabrication.

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