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PLC Controlled Fuzzy Logic-Based Egg Hatching Machine

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Abstract: In response to the increasing food demand due to the growing global population, this study has designed a fully automated incubator machine based on a Programmable Logic Controller (PLC) to enhance efficiency in the egg production sector. To align with Industry 4.0 technologies, this machine controls temperature and humidity using fuzzy logic, one of the artificial intelligence methods. The incubator is capable of meeting the specific temperature and humidity needs for the incubation processes of various types of bird eggs. It has been tested under different conditions, and its performance has been examined in detail. The analysis results show that the fuzzy logic-based temperature and humidity control systems on the PLC successfully reached the set reference values and maintained them continuously and stably after initial fluctuations. In conclusion, the design and control of an automated incubation machine with a PLC-based fuzzy logic controller were successfully accomplished.

Key words: Programmable logic controller, fuzzy logic, Industry 4.0, temperature control, humidity control.

PLC Kontrollü Bulanık Mantık Tabanlı Kuluçka Makinesi

Öz: Artan dünya nüfusu ile birlikte artan yiyecek ihtiyacına cevap vermek ve yiyecek endüstrisinde önemli bir yere sahip olan yumurta üretimini daha verimli hale getirmek amacıyla, bu çalışmada PLC (Programlanabilir Mantık Denetleyicisi) tabanlı tam otomasyonlu bir kuluçka makinesi tasarlanmıştır. Endüstri 4.0 teknolojileriyle uyumu sağlamak amacıyla bu makinenin, sıcaklık ve nem kontrolünü, yapay zekâ yöntemlerinden biri olan bulanık mantığı kullanarak gerçekleştirmektedir. Farklı türdeki kuş yumurtalarının kuluçka süreçleri için gereken özel sıcaklık ve nem değerlerini karşılayabilen bu tam otomatik kuluçka makinesi, çeşitli sıcaklık ve nem koşullarında test edilmiş, makinenin performansı detaylı olarak incelenmiştir. Analiz sonuçları, PLC üzerinde bulanık mantık tabanlı sıcaklık ve nem kontrol sistemlerinin belirlenen referans değerlerini başarıyla yakaladığını ve belirli bir süre dalgalanmadan sonra referans değerleri sürekli ve kararlı bir şekilde takip ettiğini göstermektedir. Sonuç alarak, PLC tabanlı bulanık mantık kontrollü otomatik bir kuluçka makinesinin tasarımı ve kontrolü başarıyla gerçekleştirilmiştir.

Anahtar kelimeler: Programlanabilir mantık denetleyicisi, bulanık mantık, sıcaklık, nem, Endüstri 4.0.

1. Introduction

Food production has been one of the fundamental tasks since the presence of humans on Earth. fact, it has been the main reason for the emergence of other sectors such as agriculture, trade, and industry. The food production process is constantly evolving and its development is seen as an indispensable need. Poultry meat and eggs, which are among the most important elements of food and nutrition, are essential food items on the table. Therefore, the production of eggs and poultry meat has become a major food industry worldwide. This production begins with the hatching of chicks. Every year, billions of layer chicks hatch from eggs under industrial conditions worldwide. The incubation process in hatcheries has been highly standardized and does not differ significantly between countries. In short, when they reach the hatchery, the eggs are placed in large-scale incubators (each containing tens of thousands of eggs) and are incubated in the dark, with temperature and humidity controlled in a highly controlled manner [1].

Recently, industrial automation systems have been rapidly advancing and evolving into more intelligent forms, such as Industrial Internet of Things (IIoT), paving the way for the concept of Industry 4.0 [2].

Meanwhile, due to its simple software logic and robust, rugged nature, PLCs remain valuable devices capable of meeting the requirements of IIoT. This is attributed to their modularity (ability to be used in any purpose), ability to support numerous communication protocols, and connectivity with field devices such as sensors and actuators [3]. The literature generally features numerous studies on MCU-based incubator control, primarily using non-industrial controllers and materials [4],[5]. In the other hand, studies on PLC-based temperature control, primarily employing PID based controllers as a control method. In Jakub's study [6], a FOPID was utilized to control temperature under laboratory conditions, employing the S7-1200 PLC as the hardware controller. Meanwhile, Jasmin's study [7] describes simple incubator temperature control using PLC and PID, but it does not

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provide any information about controlling humidity levels. On the other hand, most PLC-controlled humidity systems are predominantly associated with air quality control rather than incubation machines [8]. In conclusion, while there are many studies on applying adaptive controllers to other systems, the literature lacks a study that addresses a PLC-based adaptive controller for an incubation machine controlling both temperature and humidity.

Recent studies, such as the one discussed in [9], explore the integration of IoT for more precise control of incubation environments, highlighting the potential for improved efficiency and adaptability in industrial applications. Therefore, in this article, the aim is to control the temperature and humidity conditions in an incubator machine using PLC, without the need for a computer or computer-based software like Matlab. Differing from studies in the existing literature, a FLC structure has been established in the PLC environment, and the temperature and humidity values of the incubator machine have been controlled. As a result, the design and control of an artificial intelligence-based incubator compatible with Industry 4.0 systems have been successfully achieved.

1.1 Incubation and Hatching

The process of providing the necessary humidity, temperature, and turning conditions for a healthy hatch of a chick from an egg is called incubation [10]. This process naturally occurs as mother hens instinctively sit on the eggs. The incubation process also takes place artificially in incubators and hatcheries, which can provide the necessary humidity and temperature conditions [11]. Despite improvements in incubation conditions and technology, the success rate for hatching young brood from the eggs of modern high-yield poultry breeds has not significantly increased, and about 20% of expensive breeding eggs are still lost as incubation waste. The potential for improving hatchability lies not only in enhancing the biological qualities of the eggs but also in organizing effective incubation [12]. Generally, the incubation and hatching conditions are shown in Table 1 [13],[14].

Table 1. Incubation and hatching conditions.

Chicken	Incubation	Hatching
Days	18	3-5
Temperature °C	37.8	36.8-37.3
Humidity %RH	55-60	65-75
Turning	1 turn per hour	No turning

2. Material and Method

In this study, an S7-1200 PLC was utilized to regulate the temperature and humidity conditions of an egg incubation machine. The use of a PLC as the control hardware aims to enhance the accuracy and modularity of incubation machines [15]. A fuzzy logic controller (FLC) was developed in MATLAB for the control algorithm, and its code was implemented in TIA Portal using SCL and Ladder languages. The FLC is preferred in this study due to its simplicity and effectiveness [16].

The heating system's hardware configuration includes a 300-watt resistance heater integrated with a circulation fan, serving as the heating actuator. This heater is regulated by an AC dimmer, which is controlled by a Pulse Width Modulation (PWM) signal from the PLC. The control aligns with the FLC's duty cycle, ensuring precise temperature regulation. However, since the AC dimmer requires a 5-volt logic signal, it cannot directly use the PLC's PWM signal. To resolve this, a Microcontroller Unit (MCU) is employed to convert the PLC signals into a format compatible with the AC dimmer.

On the other hand, for the humidifier, a manually assembled setup has been utilized due to the unavailability of a suitable analog humidifier for purchase. This setup comprises scold mist nozzles placed within a specific container. The amount of mist produced and introduced into the incubation environment is controlled by a snail fan blower. This manual approach allows for precise regulation of humidity levels, essential for the incubation process.

For sensing purposes, the system employs an HT-2 humidity and temperature transmitter, which have outputs with 0-10 V DC analog signal compatible with the PLC. This sensor is crucial for real-time monitoring of the incubation conditions and giving feedback to the FLC function blocks. Additionally, to facilitate the monitoring and control of the machine's operational conditions, a Human Machine Interface (HMI) was developed using TIA Portal software and implemented in a Siemens KTP 700 HMI unit. This interface allows for efficient interaction and management of the machine's functions. In Figure 1, the block diagram representing the architecture of the system is presented, whereas Figure 2 illustrates the incubator machine, highlighting its design and control mechanisms as developed in this project.

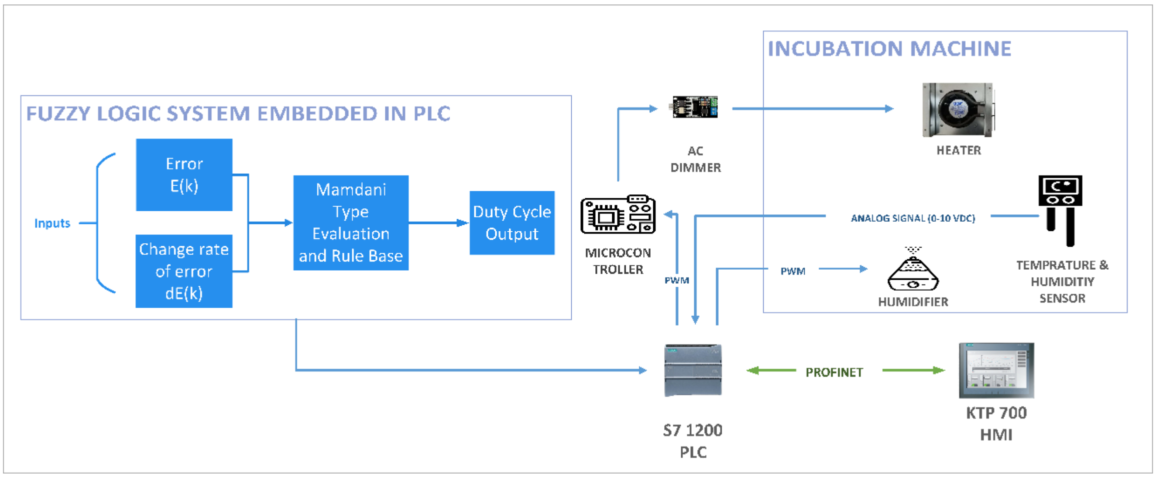

Figure 1. Block diagram of the system.

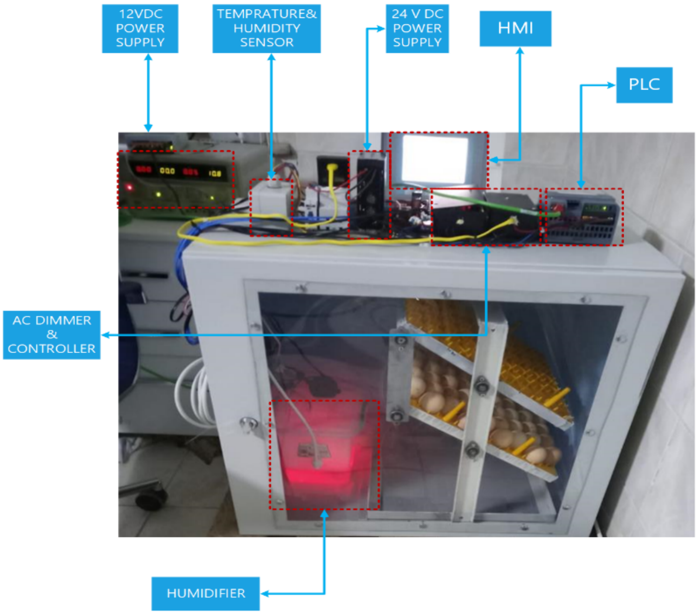

Figure 2. Designed system.

In the conclusion of the study, the control method was tested under both preset temperature and humidity conditions as well as varying conditions.

2.1. Fuzzy Logic Controller Design

Due to the nonlinear nature of humidity and temperature control systems, traditional methods like PID controllers often prove insufficient. The adaptive nature and simple mathematical structure of FLCs present them as a more effective alternative [17]. FLCs offer an advanced method for regulating temperature and humidity in closed boundary systems. Unlike traditional controllers, FLCs utilize fuzzy set theory to handle imprecise and variable environmental conditions typically encountered in temperature and humidity control processes.

In this study, as shown in Figure 3, separate FLC's have been developed for managing humidity and temperature. Each controller is designed with two inputs and one output. This configuration allows for a more nuanced and responsive control mechanism in environmental management systems.

Initially, the membership functions were determined based on previous works in the literature. After conducting a few experiments, the membership functions were adjusted according to the obtained actuators' response.

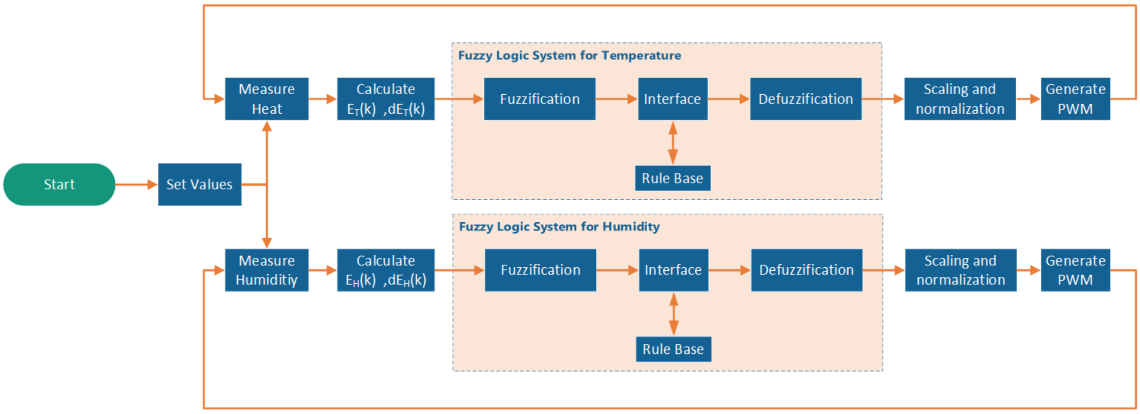

Figure 3. FLC structure.

2.2. Main components of the fuzzy logic system:

Fuzzification: This initial phase involves converting real-time temperature and humidity readings into analog values, which are essential for calculating the error and the rate of change in error, as shown in Equations (1) and (2).

$$E(k) = Referance\ value - Measured\ value \tag{1}$$

$$dE(k) = E(k) - E(k-1) \tag{2}$$

Calculated values serve as the inputs for the FLC. The fuzzification process then maps these inputs onto five distinct membership functions, known as fuzzy sets. These fuzzy sets are organized as NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), and PB (Positive Big), corresponding to the error range from -10 to 10 and the change rate of error range from -1 to 1. This step is crucial for enabling the FLC to handle the nuances of environmental variability with greater accuracy. The membership functions are shown in Figures 4 and 5 for temperature and Figures 6 and 7 for humidity.

Rule Base and Evaluation: The controller's operation is governed by a structured set of if-then rules, typically formulated based on empirical knowledge and experience. These rules are designed to interpret the fuzzified inputs and make appropriate control decisions. For example, a rule might state: "If E(k) is Positive Big (PB) and dE(k) is Negative Small (NS), then increase the duty output rapidly." Such rules are crucial for generating fuzzy output decisions that accurately respond to environmental changes. Given two inputs with five fuzzy sets each, the system requires a comprehensive 5x5 rule matrix, shown in Table 2, to cover all possible scenarios.

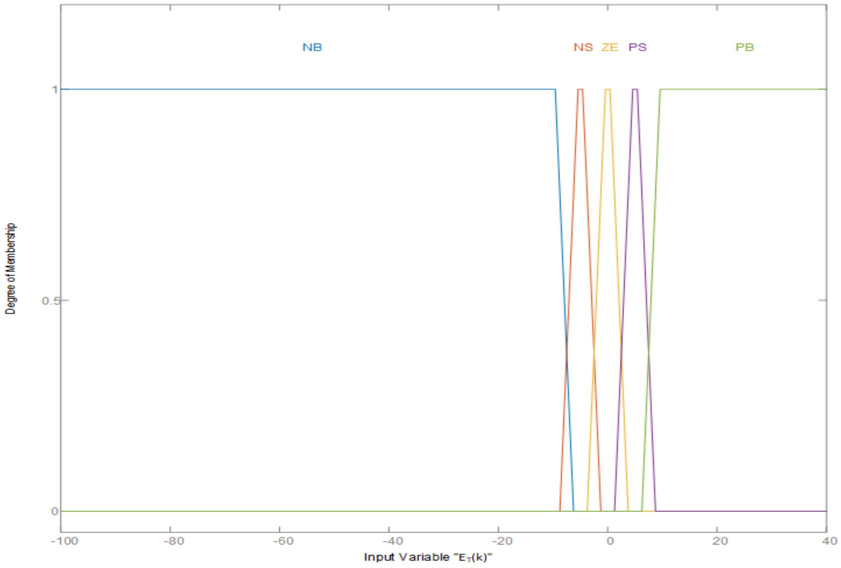

Figure 4. Temperature error membership functions.

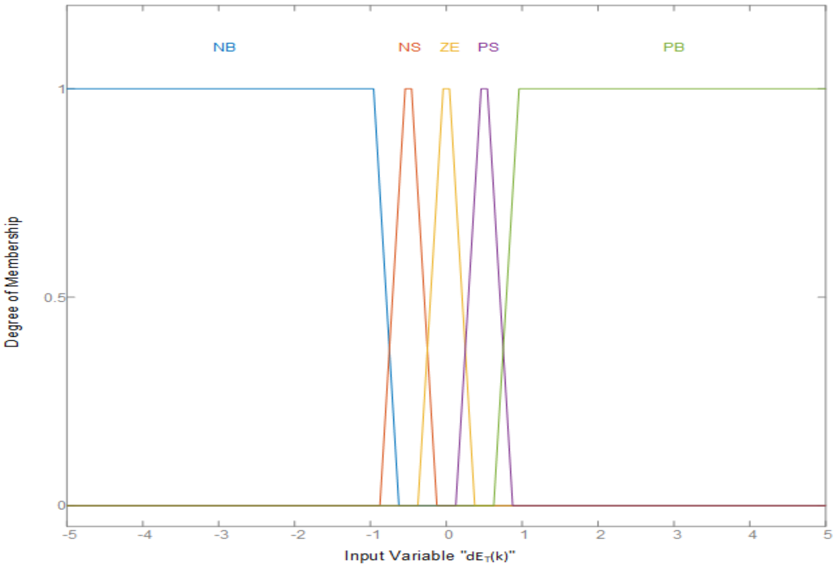

Figure 5. Temperature change rate of error membership functions.

Table 2. Rule Matrix.

E dE	NB	NS	ZE	PS	PB
NB	VS	VS	VS	S	M
NS	VS	VS	S	M	B
ZE	VS	S	M	B	VB
PS	S	M	B	VB	VB
PB	M	B	VB	VB	VB

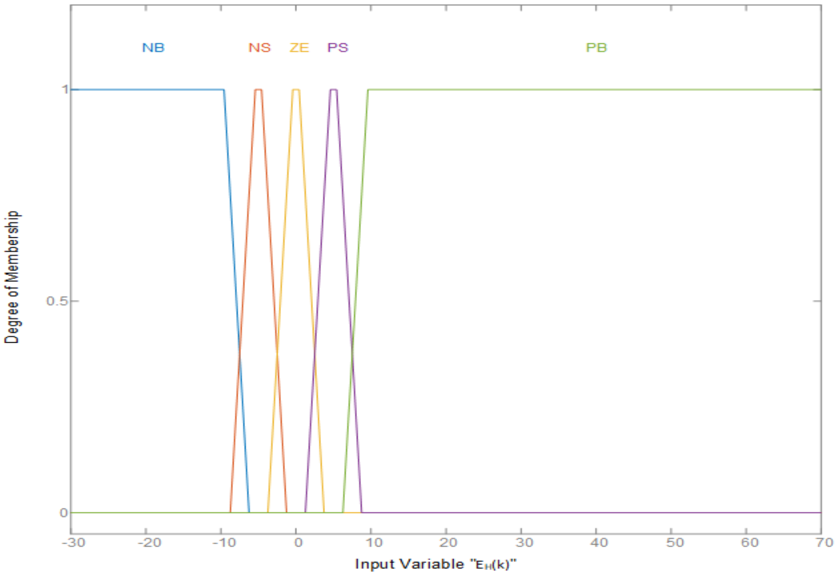

Figure 6. Humidity error membership functions.

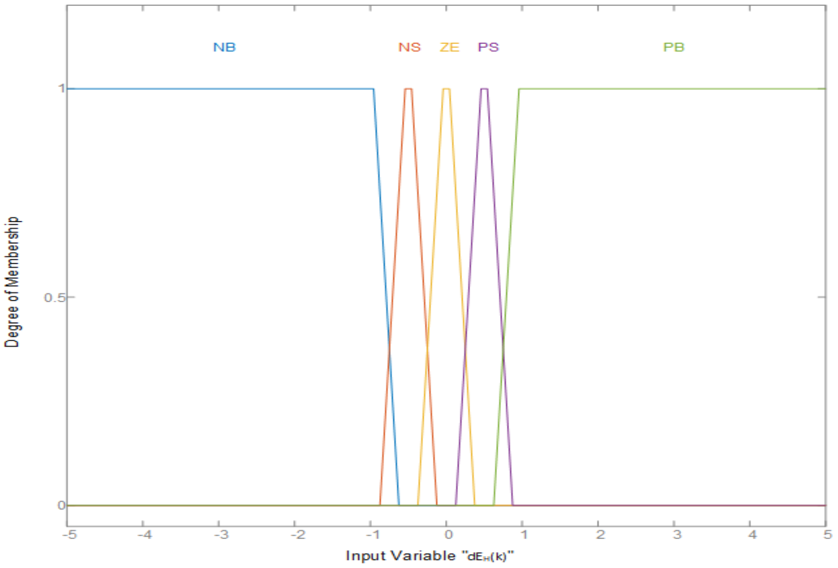

Figure 7. Humidity change rate of error membership functions.

While the rule base determines the controller's response in a verbal (qualitative) manner, it is imperative to convert this verbal data into a quantifiable mathematical form for application in the fuzzification layer. This conversion process is known as evaluation. Various evaluation methods are discussed in the literature, but the preferred approach in this study is the Mamdani method. With this method, the control of systems is successfully carried out based on expert knowledge without relying on a data set [18]. This method relies on the Min-Max principle for evaluation and aggregation. For the defuzzification, the centroid method was applied, as shown in Equation (3).

$$y^* = \frac{\sum_{k=1}^{n} y_k \cdot \mu_c(y_k)}{\sum_{k=1}^{n} \mu_c(y_k)} \tag{3}$$

In this equation, is the crisp output, y^* represents the discrete output values, and $\mu_c(y_k)$ is the membership degree for y_k. The sum over k applies to all discrete points in the output domain. The specifics of the Mamdani method and its reliance on the Min-Max approach are further elucidated in Figure 8 [1]. The control surface of the FLC system is also shown in Figure 9.

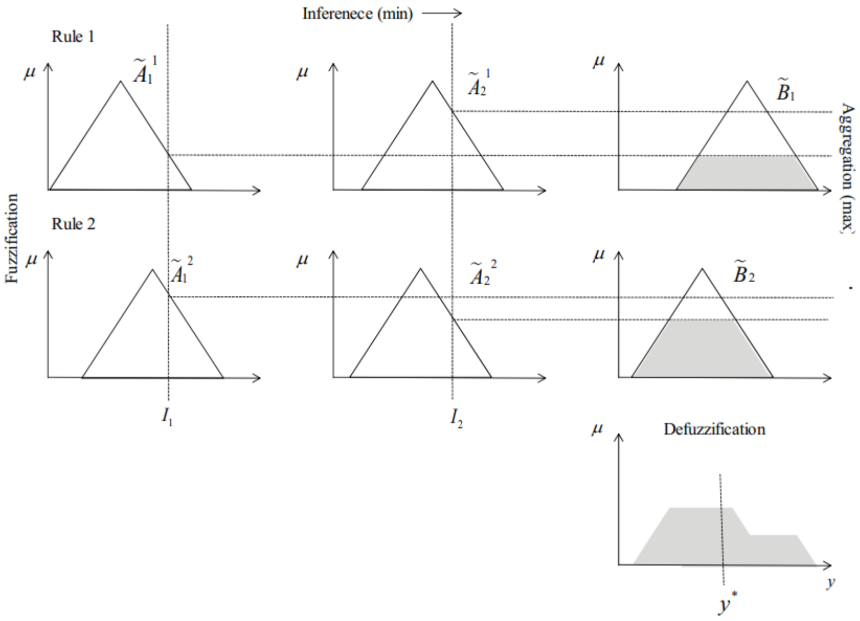

Figure 8. Min-Max Evaluation.

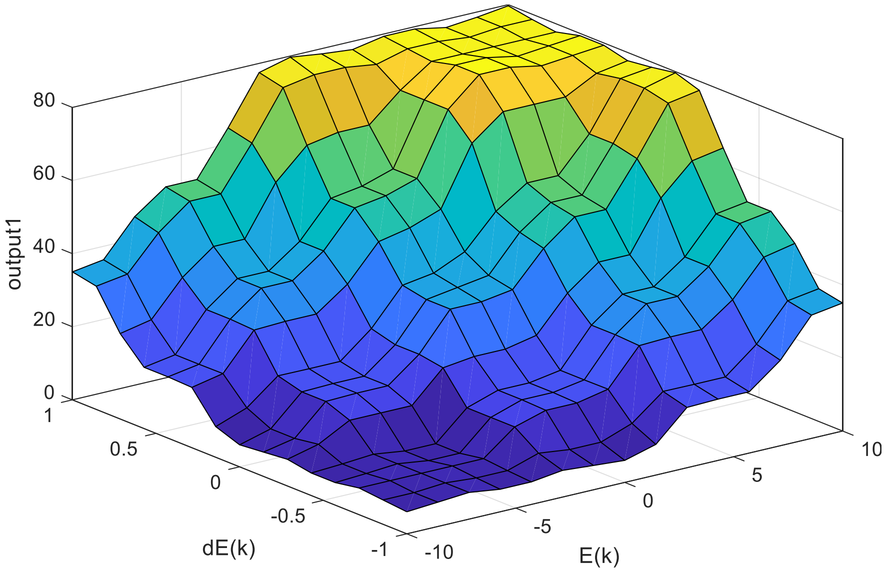

Figure 9. Control surface of the FLC system.

Defuzzification: The evaluation process yields an output that is still a fuzzified value, typically ranging between [0,1]. To make this output applicable to the actuators of the system, it must be converted into a different quantity. In this system, actuators are controlled by a PWM signal, which varies between 0 and 100. Due to the operational differences between the humidifier and the heater, their respective defuzzification member functions are distinct. The specific defuzzification functions for both the heater and the humidifier are depicted in the respective Figures (10-11). These functions are critical for translating the fuzzy evaluation output into a precise and actionable control signal for each actuator.

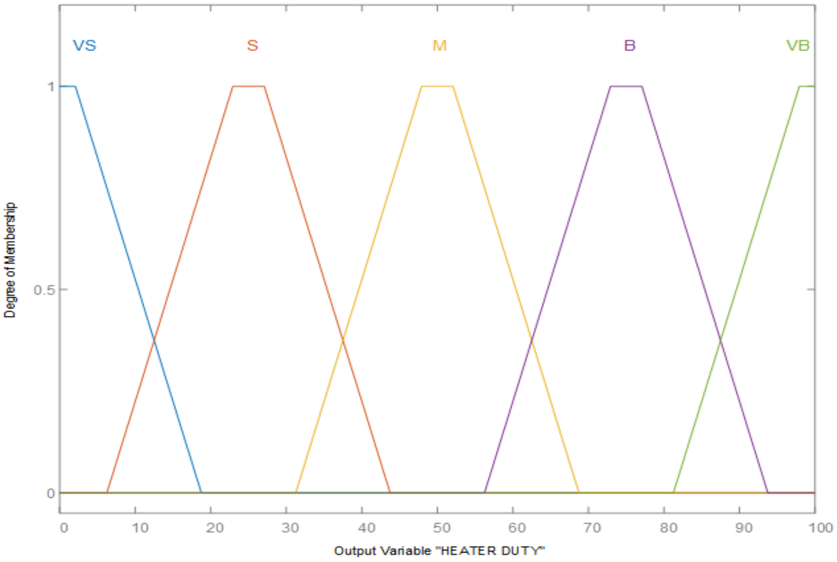

Figure 10. Heater duty cycle membership functions.

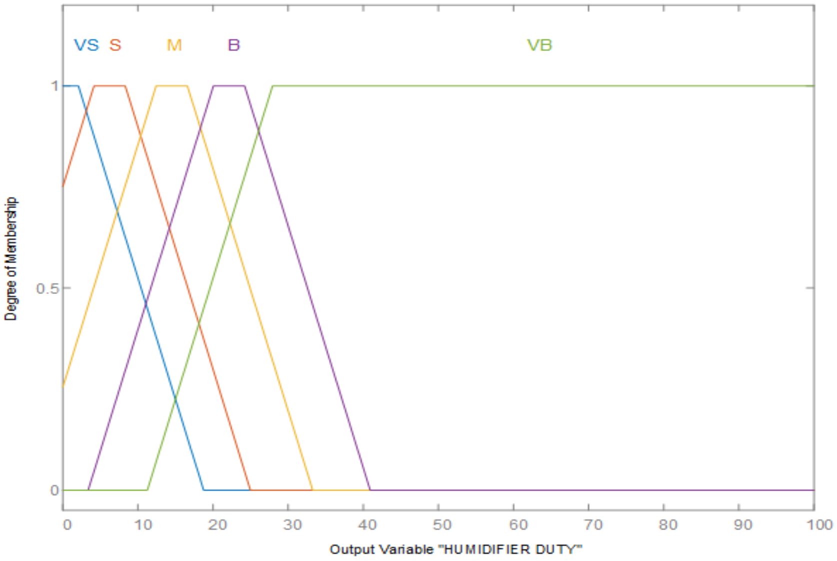

Figure 11. Humidifier duty cycle membership functions**.**

2.3. Implementation of Fuzzy logic controller in S7-1200 PLC

The S7-1200 PLC system offers the flexibility and capability to control a wide variety of devices, supporting diverse automation needs. Its compact design, along with flexible configuration and command sets, has made the S7-1200 widely used in various control applications. The S7-1200 integrates a microprocessor, an integrated PROFINET communication circuit, digital input and output units, and, in some series, an analog input and output unit, all within a compact structure. In this project, both LADDER diagrams and Structured Control Language (SCL) have been employed for programming the control blocks within the TIA Portal project. The program blocks are arranged and presented in a chronological sequence shown in Figure 12, reflecting the block calls in the control part of the project.

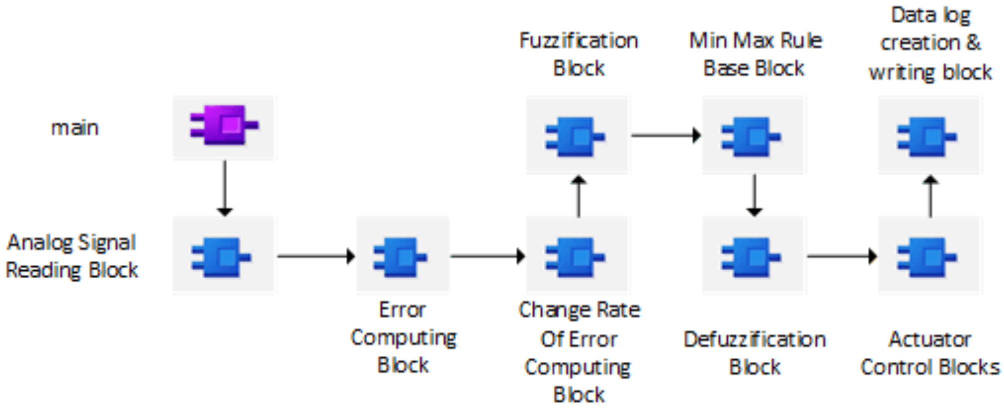

Figure 12. Chronological sequence of the PLC program.

To obtain continuous feedback from the incubation environment and convert the analog signals into digital signals, the S7-1200 PLC's Analog-to-Digital Converter (ADC) module is utilized. This module effectively converts the analog signal on a scale from 0 to 27.648. To make the digital signal meaningful for the control system, normalization and scaling blocks are employed, adjusting the input from 0 to 100, which aligns with the transmitter's actual measuring range. Subsequently, the processed digital signals are fed into error and derivative error blocks, which are configured based on the mathematical equations previously presented. In the next stage, the error and derivative error signals are applied to the fuzzification block, as shown in Figures 12 to 14, which is written in SCL and parameterized according to the design that was executed in the MATLAB environment.

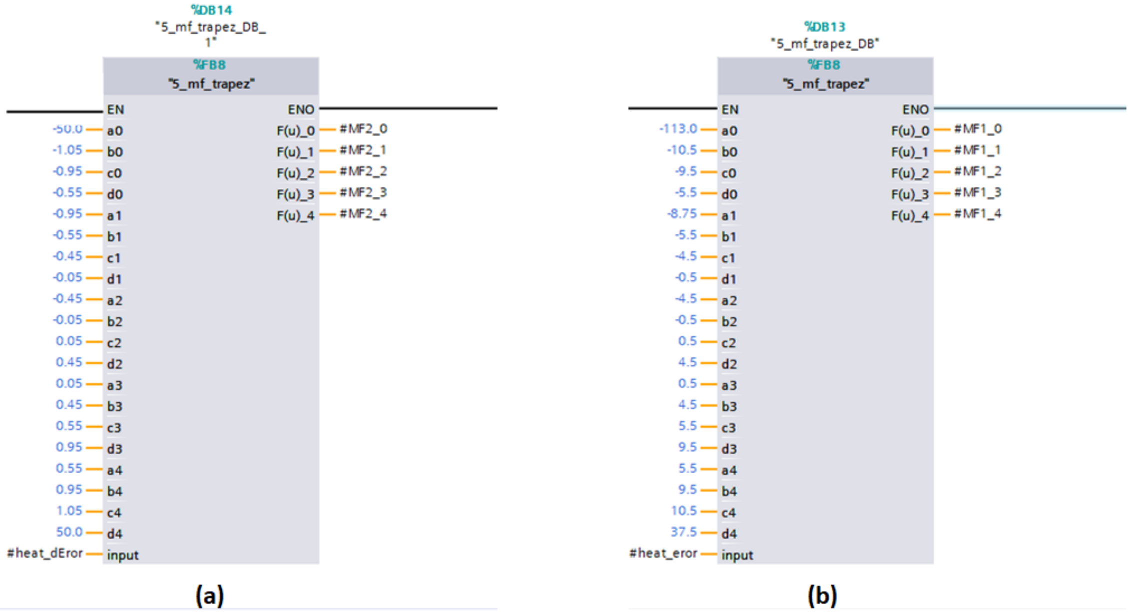

Figure 13. a) Error fuzzification block, b) Change rate of error fuzzification block.

The subsequent block, depicted in Figure 015, represents the rule base and the evaluation stage of the FLC. This stage is developed using both LADDER and SCL.

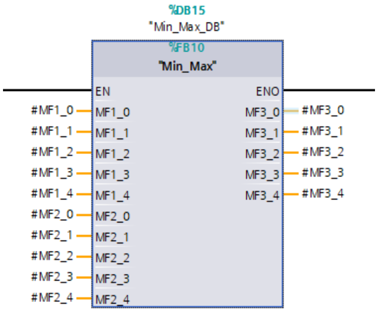

Figure 14. Rule base and the evaluation block.

The fuzzy quantities generated by the min-max block are then fed into the defuzzification blocks, which produce the desired duty cycle needed for the control system. The humidifier and heater actuators are controlled by PWM signals. For this purpose, actuator control blocks containing PWM control blocks are meticulously designed to meet the specific requirements of each actuator.

3. Results and Discussion

The automated incubator machine designed has been operated for poultry incubation, requiring a temperature of 37.8°C and a humidity reference of 60%. The results obtained are presented in Figures 15, 16, 17, and 18. When examining the temperature change shown in Figure 15, it is observed that the temperature of the experimental setup is successfully controlled with the FLC created in the PLC, and the desired temperature value is achieved. Figure 16 presents the variation of the duty cycle value produced by the temperature FLC controller. Upon examining this variation, it is noted that the duty cycle value changes until the desired reference temperature is reached and then remains constant in the steady state.

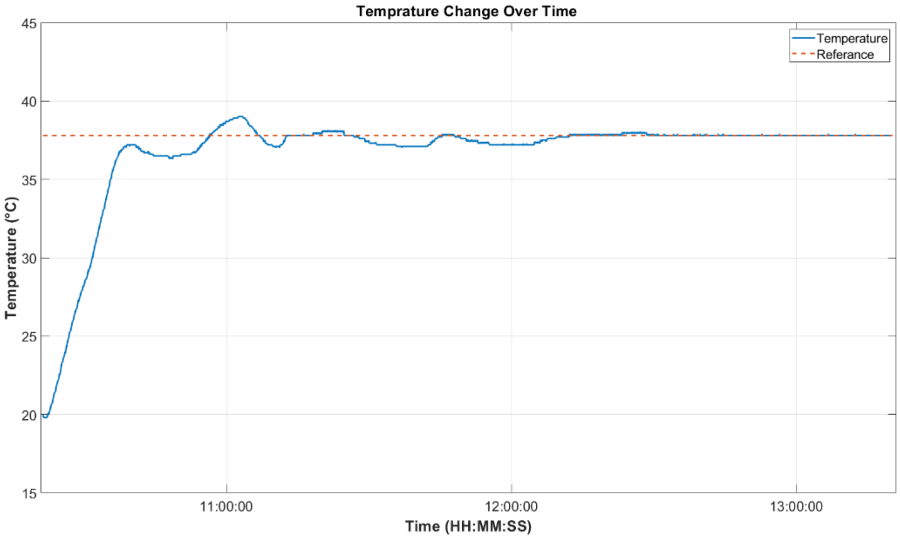

Figure 15. Temperature change over time.

When analyzing the humidity change presented in Figure 17, fluctuations and steady-state errors are observed in the humidity control with the FLC, due to the influence of temperature on the humidity experimental setup. However, when the temperature value reaches the reference value, it is observed that the humidity value approaches the reference value and follows it with an acceptable error. Figure 18 presents the variation of the duty cycle value produced by the humidity FLC controller. Similar to temperature control, this variation shows that the duty cycle value changes until the desired humidity value is achieved and then remains constant in the steady state.

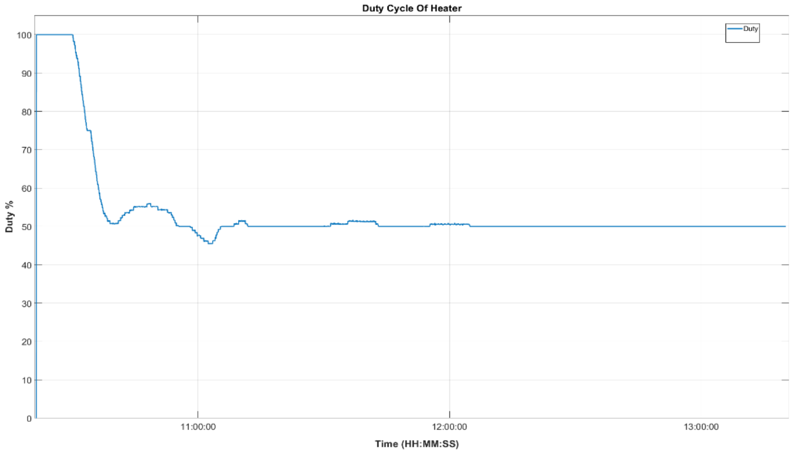

Figure 16. Duty Cycle of Heater.

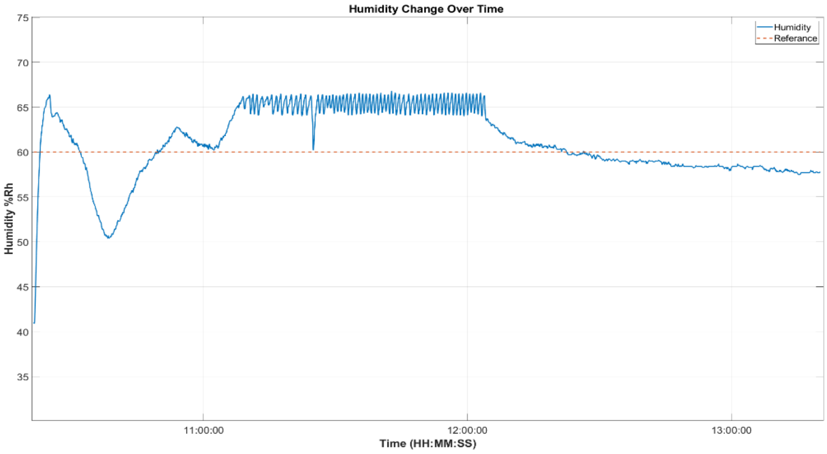

Figure 17. Humidity change over time.

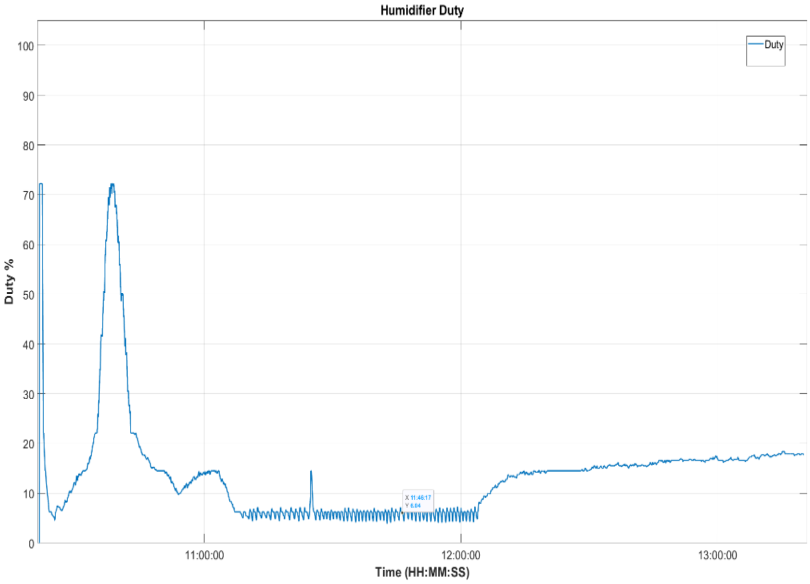

Figure 18. Duty Cycle of Humidifier.

4. Conclusion

As the global population continues to rise, and with it the increasing need for food, this study presents the design of a fully automated incubation machine controlled by PLC-based fuzzy logic to improve efficiency in egg production, a significant sector in the food industry. This study contributes to the literature by demonstrating the successful integration of a FLC within a PLC environment for the precise control of temperature and humidity in an industrial incubation machine, which is compatible with Industry 4.0 standards. This approach not only enhances the efficiency of egg production but also offers a novel solution by utilizing a PLC-based control system instead of traditional microprocessor-based systems. According to the results obtained from the experimental setup created for the temperature and humidity control of the incubation machine, it has been observed that the fuzzy logic-based temperature and humidity controller implemented in the PLC environment successfully controls the temperature and humidity values.

Better performance can be obtained by optimizing the fuzzy logic membership function limits with a suitable optimization method based on the data obtained from the machine. In addition, the actuators used in this project are non-industrial, so to improve the responses, there is a need to purchase a PLC-compatible humidifier.

Inspired by this study, future research could focus on implementing Fractional-Order PID, 2-DOF PID, and other artificial intelligence-based control structures in the PLC environment to enhance the performance of automated incubation machines.

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