Fuzzy Logic Based Household Oven Design

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Abstract: This paper presents the real-time household oven design application of the microcontroller-based fuzzy control system of temperature. Because of the complexity, nonlinearity, and dead time, temperature control of the oven is still delegated to many factors. In the computer-aided design process, the mathematical model of the system is derived with an open-loop response. The extracted model is used to obtain the conventional PI control parameters and adjust the PI type fuzzy rule base, which is mainly derived intuitively from the control engineering point of view. Using traditional PI parameters and Fuzzy logic PI rule base, real-time temperature control was realized with the PWM signal generated at the output of the PIC18F4520 microcontroller. The PWM signal produced at the output of the PIC18F4520 microcontroller is used to drive the power circuit designed using IGBT's. Oven responses are obtained for both Fuzzy and PI control systems, in which the developed PI fuzzy control has better performance with less overshoot, less rising and settling time, and smaller steady-state error. A detailed description of designed control systems and experimental works with performance are given.

Keywords: Real-time control, PI type fuzzy control, temperature control, microcontrollers

Bulanık Mantık Tabanlı Ev Fırını Tasarımı

Özet: Bu makale, mikrodenetleyici tabanlı bulanık sıcaklık kontrol sisteminin gerçek zamanlı ev tipi fırın tasarım uygulamasını sunmaktadır. Karmaşıklık, doğrusal olmama ve ölü zaman nedeniyle fırının sıcaklık kontrolü hala birçok faktöre bağlıdır. Bilgisayar destekli tasarım sürecinde, sistemin matematiksel modeli açık döngü yanıtı ile çıkarılmıştır. Çıkarılan model, geleneksel PI kontrol parametrelerinin elde edilmesinde ve esas olarak kontrol mühendisliği bakış açısıyla sezgisel olarak türetilen PI tipi bulanık kural tabanının ayarlanmasında kullanılır. Geleneksel PI parametrelerini ve Bulanık mantık PI kural tabanını kullanarak, PIC18F4520 mikrodenetleyici çıkışında üretilen PWM işareti ile gerçek zamanlı sıcaklık kontrolü gerçekleştirilmiştir. PIC18F4520 mikrodenetleyicisi çıkışında üretilen PWM işareti, IGBT'lerin kullanılarak tasarlanmış olan güç devresini sürmek için kullanılmıştır. Geliştirilen PI bulanık kontrolün daha az aşma, daha az yükselme ve yerleşme süresi ve daha küçük sabit durum hatası ile daha iyi performansa sahip olduğu hem bulanık hem de PI kontrol sistemleri için fırın yanıtı elde edilmiştir. Tasarlanan kontrol sistemlerinin detaylı açıklaması ve performans ile deneysel çalışmalar verilmiştir.

Anahtar Kelimeler: Gerçek zamanlı kontrol, PI tipi bulanık kontrol, sıcaklık kontrolü, mikrodenetleyiciler

1. Introduction

Recently, the effect of energy efficiency on total electricity demand has gained importance rather than electricity demand profiles. By replacing the devices with the highest energy efficiency label on the market, it is predicted that the evening device peak demand can be reduced by 38%. It is estimated that evening electricity peak demand could decrease by 24% in 2035, thanks to the improvement in energy performance. Cooking appliances, which are one of the most unsuitable appliances in terms of energy efficiency, are expected to make the biggest contribution to the peak evening electricity demand towards 2035. [1]

Electric ovens are generally a low-efficiency category among household appliances and determine the overall environmental impact of buildings. The energy class of such devices is determined by a test procedure defined by the European Standard EN 60350, in which the wet clay brick is heated under certain conditions and accurate control of air temperature during testing is required, which indicates the importance

of efficient control strategies [2]. Therefore, it is necessary to focus on efforts to increase the efficiency of ovens.

Fuzzy set theory and fuzzy logic have been some of the common tools in control engineering since the pioneering work of Mamdani [3, 4]. Instead of complex mathematical modeling, in case of uncertainty and unobservable states where modeling task difficult, it provides to mimic to an expert's or control engineer's control action with linguistic rules. These rules also provide the understanding of dynamic systems and control clearer to the user. During the past few decades, fuzzy logic control has been accepted as conventional control and there are many successful industrial fuzzy control applications in the literature [5-7].

Many industrial processes require maintaining the temperature at a predefined reference value. Classical approaches as ON-OFF control and classical proportional integral and derivate (PID) based con-troller have difficulty with fulfilling control tasks because the thermal inertia of temperature control systems is very high and the system also contains non-linearities. Therefore, improvement of the performance of such control systems via novel approaches is of current interest [8-11]. The industrial application also needs real-time control strategies in embedded systems such as Microcontroller, Digital Signal Processor (DSP) and Field Programmable Gate Array (FPGA) based hardware and firmware applications that real-time tasks are executed with minimum latency. The architecture of the digital processor changes according to the complexity of the control system, which directly affects the controller design [12-16]

In this paper, a microcontroller-based embedded PI-type fuzzy control system for temperature control of the oven is proposed. While fuzzy rule base is constructed via control engineering knowledge, the open-loop mathematical model, which is used for obtaining conventional PI control parameters for comparison, is derived with reaction curve methods. Fine-tuning of heuristic rules and membership functions of the proposed fuzzy controller and classical PI controller parameters are performed on simulation via using the derived mathematical model. Firmware codes written in a MicroBasic programming language are developed in both PI type Fuzzy Control and classical PI control for enhanced flash microcontroller-based embedded system. Plant responses are obtained for both Fuzzy and PI control systems, in which the developed PI fuzzy control has better performance with less overshoot, less rising and setting time, and smaller state error. A detailed description of the designed control systems and performance and experimental studies are given.

The paper organization is as follows; conventional PI control and PI type fuzzy control design are given in chapters 2 and 3, respectively. The physical system for the temperature control task is given in chapter 4 and the PI type fuzzy control software is given in chapter 5. Experimental studies are shown in chapters 6 and 7. In the 8th chapter, evaluations of the proposed study are given.

2. Design of PI controller for temperature control system

To control a system more precisely, the dynamic behavior of the plant must be well known. For this purpose, it is necessary to define the controlled objects. Kontrol edilen nesnelerin karmaşıklığı ve çeşitliliği ne olursa olsun, tanımlama için birinci ve ikinci derece olmak üzere iki temel model vardır [17]. Yüksek mertebeden modeller, karmaşıklıkları nedeniyle nadiren kullanılır, ancak bu modellerin daha kesin ve daha başarılı olduğu söylenebilir [18].

When a system with arbitrary complexity is approximated by a first-order model, time delay(L), and time constant (T) values are obtained. Generally, first-order models are used in the step-response approach of temperature control systems. As shown in Figure 1., the response curve includes time delay and breaking point. This curve is a first-order approximation of the time delay model whose step response is formulated as in equation (1).

$$y(t) = \begin{cases} K_p \left[1 - \exp\left(-\dfrac{t-L}{\tau} \right) \right], & t \geq L \\ y_0 & t < L \end{cases} \tag{1}$$

Here y(t) represents the output of the unit step response of the system. y_0 is the value of the output variable for t < L, τ is the time constant, y_{ss} is the saturation value of the output, and L is the delay time.

Using the step response, whose output curve is shown in Figure 1, the step response of the system is obtained to determine the transfer function.
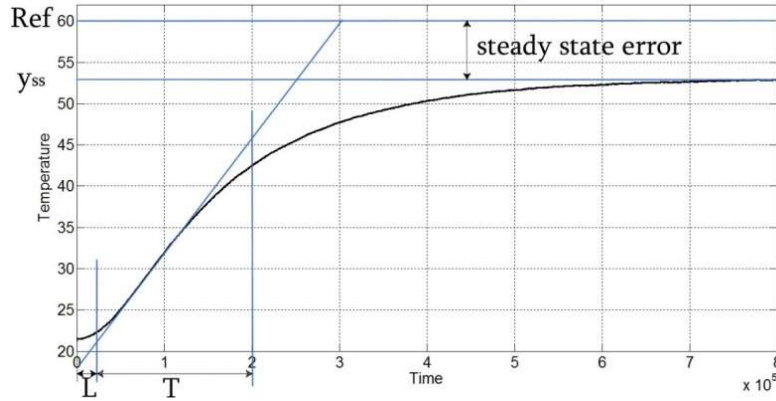

Figure 1. Step response

In the mathematical description of the step response, the initial point of the output signal is y_0, and the output is normalized by dividing y(t) by the maximum value of the input signal, umax (case umax = 60 °C). Hence, the transfer coefficient of the control system is calculated as the equation (2).

$$K_p = \frac{y_{ss} - y_0}{u_{max}} \tag{2}$$

By taking the Laplace transform of the step response function and dividing it by 1/s (Laplace transform of the step input), the time delay transfer function of the controlled plant is obtained as given in equation (3).

$$G(s) = \frac{K_p}{\tau s + 1} e^{-sL} \tag{3}$$

MATLAB's System Definition Toolbox is used for definition and the result in equation (4) is obtained.[19]

$$G(s) = \frac{0.589}{2.42 \, x10^3 s + 1} e^{-120.5s} \tag{4}$$

In the MATLAB / Simulink environment, the system is modeled according to the numerical values in equation (1) and the PI control is designed. The system simulation scheme is shown in Figure 2. The Kp and Ki values were determined by the Signal Constraint block of the MATLAB [20] Optimization Toolbox, and the values found are Kp=3.2703 and Ki=0.002.
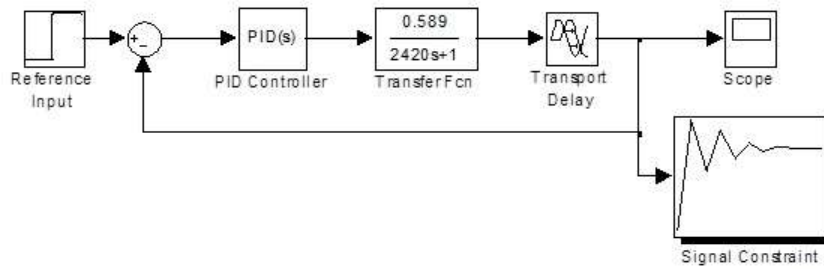
Figure 2. Simulink model for a temperature control system with PI control.

3. Design of fuzzy PI controller for temperature control system

In this section, a fuzzy controller will be designed based on error and change of error signals to improve the response of the temperature control system. A basic FLC scheme consists of the fuzzification interface, the knowledge database, the inference mechanism, and the defuzzification interface shown in Figure 3.
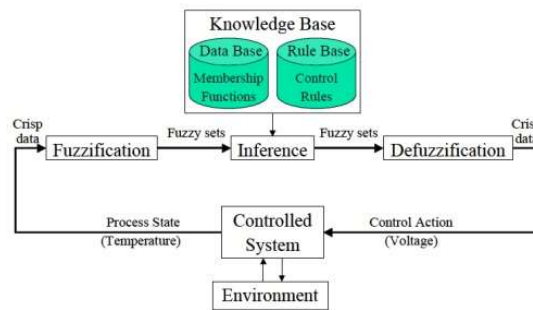

Figure 3. Block diagram of fuzzy logic control system

The fuzzy controller is regarded as an artificial operator that decides which output value is transferred to the system. It takes the plant output, compares it with reference input, and finally calculates the control signal that will guarantee the desired performance. The inputs and outputs are crisp values; the fuzzification unit converts these crisp inputs to fuzzy sets, and the defuzzification block converts back the fuzzy values into crisp outputs.

In this article, the design of a fuzzy PI controller for a home oven will be discussed. The fuzzy PI controller is driven by a set of control rules instead of constant proportional and integral gains. To do this, input variables are selected as error and change of error. The general equation of the linear PI controller is given in equation (5).

$$y(t) = K_D \frac{de(t)}{d(t)} + \frac{1}{T_e} \int_0^t e(t)dt \tag{5}$$

Then, reorganize this equation according to the fuzzy controller's working scheme. Assuming that the output change is the output variable, equation (5) can be rewritten in the form of equation (6).

$$\frac{dy(t)}{dt} = K_D \frac{de(t)}{dt} + \frac{1}{T_e} e(t) \tag{6}$$

Thus, for the input variables e(t) and de(t), the output variable can be synthesized, a fuzzy controller performing the nonlinear law given in equation (7).

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$$\Delta y(t) = F\big(de(t), e(t)\big) \tag{7}$$

The fuzzy rule-based system was characterized by a set of IF-THEN rules determined by the system response. The fuzzy sets of input and output were partitioned into five triangular membership functions corresponding to five linguistic variables (negative large, negative small, zero, positive small, and positive large). The membership functions are chosen as triangular because of the computational cost of real-time control without using floating-point processors. The input and output variables of the fuzzy controller are shown in Table 1 and Table 2 also show the rule base for temperature control.

Table 1. Description of the fuzzy rules

NB	Negative BIG
NS	Negative SMALL
ZE	ZERO
PS	Positive SMALL
PB	Positive BIG

Table 2. Fuzzy rule base for temperature control

$\frac{e}{de}$	NB	NS	ZR	PS	PB
NB	NB	NB	NB	NS	ZR
NS	NB	NB	NS	ZR	PS
ZR	NB	NS	ZR	PS	PB
PS	NS	ZR	PS	PB	PB
PB	ZR	PS	PB	PB	PB

Membership functions of the input and output variables are shown in Figure 4. After that, the PI controller is replaced with a fuzzy logic controller (FLC) to observe the fuzzy controller's performance. The Matlab simulink block diagram of the fuzzy control system is shown in Figure 5. and the output response of the simulation result is shown in Figure 6.
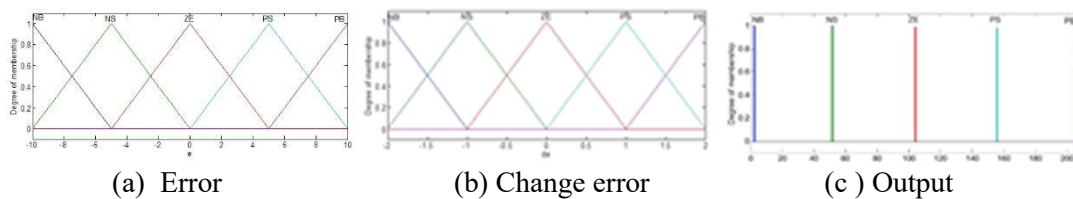
(a) Error   (b) Change error   (c) Output
Figure 4. Membership functions

According to the simulation results in Figure 6., performance parameters such as overflow and settling time of the fuzzy control system are better seen compared to the PI controller.
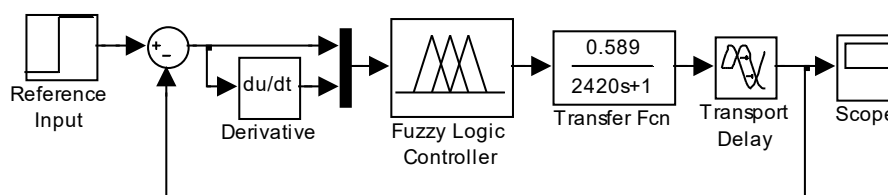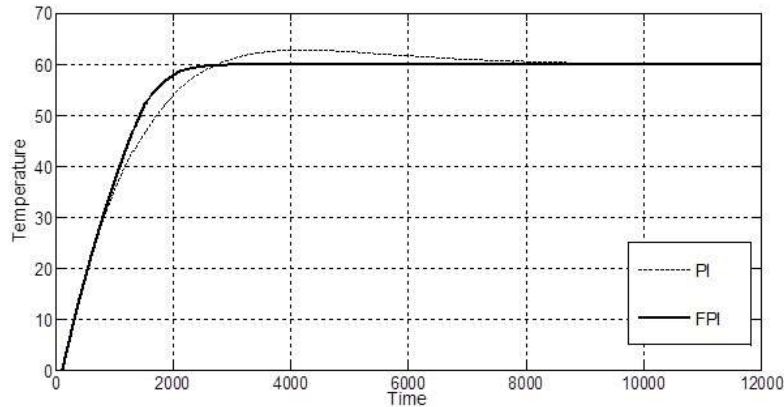

Figure 5. Fuzzy Controller

Figure 6. Comparison of fuzzy and PI controllers' simulation results

4. Temperature control system

There are excessive literature established on modeling industrial temperature control processes [21-25]. These models are based on a transition delay combined with a mode-dependent time constant and are used from both control and economic point of view [26]. Since temperature control systems possess an inherently complex and nonlinear nature, it is difficult to perform optimum control of such plants via classical control schemes including on-off control and proportional-based control [27]. Furthermore, utilization of these classical methods will have negative economical outcomes due to energy loss and fatigue of electrical components. Therefore, it would be appropriate to use advanced control techniques to increase the efficiency of such systems.

In the literature, there are many studies in which phase control resistors and thyristor phase control are used to drive the heating element [29-31]. In this article, DC-DC inverter is used in driving the heating element due to its high efficiency. The temperature control system for a household oven is shown in Figure 7. The household oven consists of a 1100 W and 24 Ω heating element, a power stage with IGBT, a temperature sensor (DS1820), a graphic LCD and a microcontroller (PIC 18F4520) to implement the PI and fuzzy control.
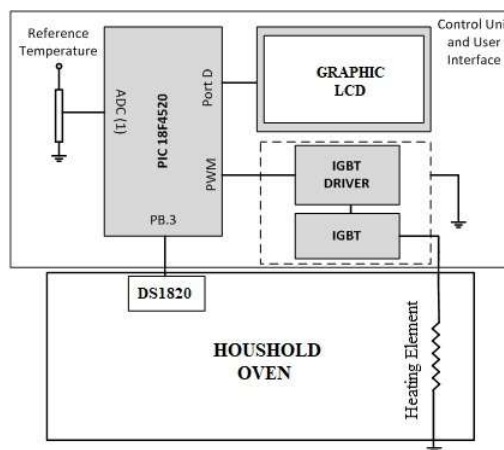

Figure 7. Block diagram of the household oven system

The temperature set value of the oven is applied to the analog input of the microcontroller using a potentiometer. The voltage signal received from the analog input is converted to the temperature value. While the system is measuring temperature, the signal from the sensor is applied to the digital input of the microcontroller. The DS1820 is a digital sensor that provides temperature measurements with an accuracy

of ± 0.5 ºC in the range of- 55 to + 125 ºC. This sensor communicates with the microcontroller only via a wired bus. Temperature data and derivatives are calculated according to equations (8) and (9).

$$e = T_{ref} - T_{read}(k) \tag{8}$$

$$de = T_{read}(k) - T_{read}(k-1) \tag{9}$$

Where error (e), derivative of error (de), reference temperature (Tref) and instantaneous temperature (Tread) are used. After calculating the error and its derivative, the fired fuzzy rules are subtracted from the fuzzy rule base and these fired rules are displayed on the graphical LCD and verified. The fired fuzzy rules are shown in Figure 8. displayed on the graphical LCD.
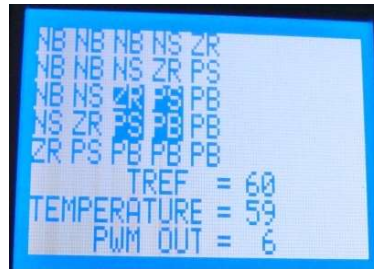

Figure 8. Snapshot of the fuzzy controller rule based on graphic LCD

After calculating the error and its derivative, the fuzzy rules to be applied are obtained from the fuzzy rule base. After defuzzification, crisp signals convert an 8-bit PWM signal, and then this signal is sent to the IGBT driver circuit. An insulated-gate bipolar transistor or IGBT is a three-terminal power semiconductor device used for high efficiency and fast switching. IGBT is controlled via an IGBT driver. The connection diagram of the IGBT + IGBT Driver module to the heating element is shown in Figure 9.

In the circuit shown in Figure 9, transistors Q1 and Q2 are switched simultaneously. When the transistors are on, the heater element DC +310 V is applied, and when the transistors are off, 0V is applied to the heater element. The microcontroller generates a PWM signal based on the temperature information from the sensor and the reference temperature information. This PWM signal has a value that is dependent on the internal temperature of the oven and determined by the controller. The PWM value ensures that the voltage to be applied to the heating element varies between 0 and 310V.
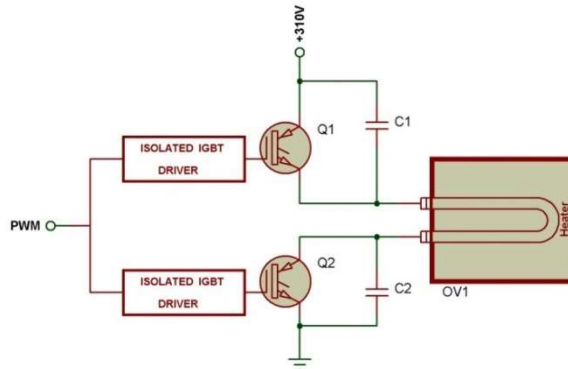

Figure 9. IGBT and IGBT Driver modüle

The experimental setup consists of the oven (1), the Easy-pic5 development board for the microcontroller circuit (2), and the inverter circuit (3). The experimental setup and its components are shown in Figure 10.

Figure 10. Experimental setup for oven

5. Software design of temperature control system

Practically there are many examples of implementations using various software tools for the design of temperature control systems [9]. Without giving a detailed discussion regarding the advantages and disadvantages of these software tools it has to be noted that relatively simple, accessible, and easy to realize tools are more widely preferred. In this study, a fuzzy temperature control system was implemented on the Mikrobasic platform. As shown in Figure 11, the value of the triangular membership function μ(u) is calculated using Equation (10) for any input.

It is necessary to determine the linguistic rules suitable for control purposes. These rules table are used during fuzzyfication and defuzzification. Bu çalışmada kullanılmak üzere belirlenen kural tablosu Tablo 2'de gösterilmiştir.
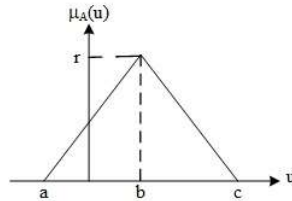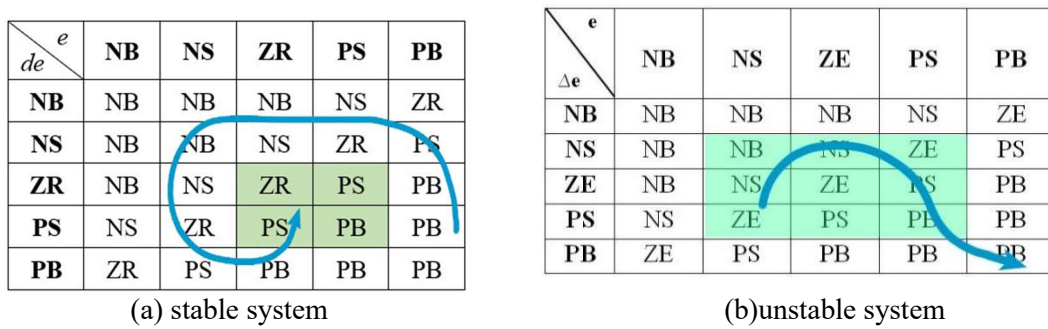

Figure 11. Triangular membership function

Using equation (10), two neighboring membership values are found. After fuzzification, the error and error change values are used to infer from the rule base shown in Table 2, after this inference, the output membership functions and membership degrees are determined. The crisp output value is obtained via the center of gravity (COG) defuzzification method, which is the PWM signal. PWM signal is applied to the input of the IGBT driver circuit via the PWM output of the microcontroller. The program which performs reading temperature data from the sensor, fuzzy inference, and calculation of PWM value is created in Microbasic from Microelectronika software. While temperature information can be seen on the graphic display connected to the microcontroller system, it can be seen in the fuzzy rules in the process. Seeing fuzzy rules on the graphical indicator makes it easy to follow the stable operation of the system. In addition, it is seen in which order the fuzzy rules are warned on the graphic display during the change of the furnace temperature from the initial temperature to the reference voltage.

$$\mu_A(u) = \begin{cases} \dfrac{u-a}{b-a}r, & if\ a \leq u \leq b \\[2mm] \dfrac{c-u}{c-b}r, & if\ b \leq u \leq c \\[2mm] 0, & other\ cases \end{cases} \tag{10}$$

6. Experimental stability analysis approach for temperature control system

Observation of the order in which the fuzzy rules are fired gives an idea of the stability of the system [28]. When this firing order is drawn as a trajectory on the table of rules, a gradual decrease of the error and change of error signals should be observed for a stable system. It means that the trajectory has to move from the outer parts of the table to the center as shown in Figure 12(a). Conversely, for an unstable system, this sort of behavior does not exist (Figure 12(b)). There are two main sources of instability in a fuzzy system: Incorrectly chosen rules and/or membership functions and range of input/output values.

e \ de	NB	NS	ZR	PS	PB
NB	NB	NB	NB	NS	ZR
NS	NB	NB	NS	ZR	PS
ZR	NB	NS	ZR	PS	PB
PS	NS	ZR	PS	PB	PB
PB	ZR	PS	PB	PB	PB

e \ Δe	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

(a) stable system   (b)unstable system

Figure 12 A typical trajectory of rules firing

7. Experimental results

A design has been made using a nichrome alloy heating element to increase the efficiency of the household oven. The temperature set value for the household oven has been determined as 60°C. While real-time temperature control was carried out, temperature data were logged simultaneously. Step responses of FLC and PI controllers designed for real-time temperature control realized with microcontroller are shown in Figure 13. It was observed that the FLC responded faster than the PI in the transient state, and the set value reached a small steady-state error (0.4°C) after a smaller overshoot than the PI controller. As a result, it can be said that it will be more stable and efficient when used in fuzzy logic temperature control ovens. Therefore, it is clear that energy efficiency will also increase in fuzzy logic control ovens.
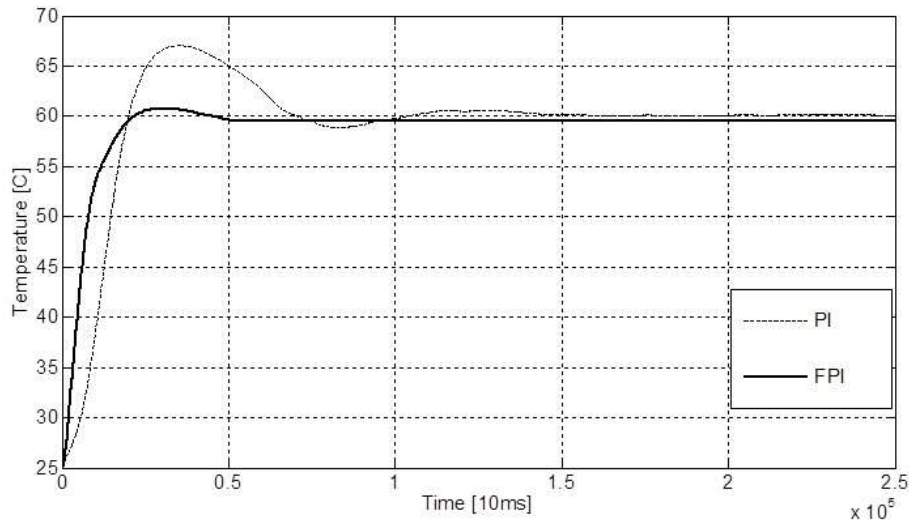
Figure 13. Comparison of fuzzy PI and PI controllers experimental results.

8. Conclusions

In this article, temperature control hardware, programming algorithm and software have been developed for household ovens. Temperature control was applied to microcontroller-based embedded PI type control system and PI type fuzzy control system. As seen in Figure 13, the overshoot value in the PI controller reaches up to 67°C and the settling time reaches 25 minutes. On the other hand, with the fuzzy controller, it is seen that the exceeding value does not exceed 61°C and the sitting time is less than 9 minutes. Since the overshoot time and the settling time are important parameters for the efficiency of the system, it has been experimentally proven that the performance of the fuzzy PI controller is better than the PI controller. The graphic LCD is used to enable the system to monitor its stability. It is ensured that which fuzzy rules are fired during the operation of the system can be seen on the LCD.

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