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Hardware Implementation of Fuzzy Controller Using the Lookup Table in 8-bit Microcontroller for the Stability of Inverted Pendulum System

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Abstract

The inverted pendulum is a typical multi-variable, nonlinear, and unstable system. This paper aims to obtain the **stability of a real pendulum around the equilibrium point using the fuzzy logic controller**. This fuzzy logic controller is designed in MATLAB toolbox environment. In this paper, the mathematical model of the inverted pendulum is unknown. The **simple tuning algorithm** is used to set the parameters of the fuzzy control system, which will allow the user to set the parameters of the control system without getting involved in the system dynamics and the basic concepts of fuzzy logic. The control scheme was implemented in the form of a **lookup table** in an **8-bit microcontroller**, and a good performance was obtained in real-time fuzzy control of the inverted pendulum. The actual test results indicate that the fuzzy controller implemented in the microcontroller can **stabilize an inverted pendulum** and has advantages over classical controllers in this field.

Keywords: Fuzzy Logic Controller, Inverted Pendulum, Simple Tuning Algorithm, Microcontroller

1 Introduction

Fuzzy logic has a wide range of applications in control systems. The term “fuzzy” refers to the fact that the logic governing the system can deal with concepts that cannot be expressed as “true” or “false”. The fuzzy controller tries to determine the ambiguity and uncertainties inherent in the control problem in the model. Fuzzy logic has the advantage of presenting and implementing the solution of the problem, which is comprehensible to human operators [1] [2].In this way, they use their experience to design the controller, without having a precise mathematical model for the system. In contrast, the price that a

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designer has to pay is the complexity of calculations in three stages, "fuzzification", "basic rules", and "defuzzification". however, it is worth considering that, under inappropriate conditions, when the system is unknown or only qualitatively expressed, the designer is forced to perform various analyses and many calculations in the design [3].

According to the above paragraph, the computational load that a fuzzy controller puts on the hardware is huge, and this challenge becomes more critical when the control system must operate in real-time [4]. Today, with the development of technology, many powerful processors are available that can implement such algorithms in real time, but they are expensive hardware, which limits the possibility of using them for many projects. On the other hand, since the tuning of a fuzzy controller is a heuristic task, it is sometimes difficult to find the optimal parameters required for the controller to perform well [5]. Thus, the use of this control method is not very popular among researchers.
In this paper, we face the challenge of implementing a fuzzy controller for the stability of an inverted pendulum system on a simple and cheap 8-bit microcontroller. The inverted pendulum is one of the classic, non-linear, hard, yet attractive control cases that visually reveals the capabilities of a control system. To implement the fuzzy controller, the offline calculation method of all possible states is used for the inputs of the fuzzy controller. the results are stored in a lookup table, and the microcontroller uses this table to apply the output corresponding to the inputs. Furthermore, to set the optimal parameters of the fuzzy control system (the range of membership functions, shapes, percentage of overlap, etc.), the method described as the Simple Tuning Algorithm (STA) is used [6] [7]. STA uses the usual characteristic of the error behavior around the equilibrium point of the control system. In this method, the algorithm can reduce the overall sensitivity of the control system with only one variable whose tuning causes compression or expansion of the membership functions around the equilibrium point of the system. It is possible to reduce or increase the overall sensitivity of the control system and thus get rid of getting involved in fine-tuning each membership function.
In the rest of the paper, we will review the inverted pendulum hardware, describe the design of the fuzzy controller, and explain how to build the lookup table in MATLAB software. We will examine the STA method and the results of applying this method on the shape of the membership functions and also on the response of the control system. Finally, we will review the practical results of this project.

2 Methodology

In this section, we will explain how to build the inverted pendulum hardware and discuss how to design a suitable fuzzy controller for the stability of the inverted pendulum. Therefore, the simple tuning method is explained. Finally, we will describe how to implement the fuzzy controller as a lookup table in the hardware.

2.1 Inverted Pendulum Hardware

The inverted pendulum hardware includes a rail and a carriage and the inverted pendulum can freely move to the left and right on the carriage. The belt and pulley mechanism is used to move the wagon, and its driving force is supplied by two DC motors installed at the end of the rail (Figur 1-a). The position of the pendulum is calculated by a potentiometer mounted on the carriage. The output of this potentiometer is a variable voltage proportional to the angle, which is converted into a digital value by the microcontroller.

The angle calculation mechanism by the potentiometer can be seen in Figure 1-b.

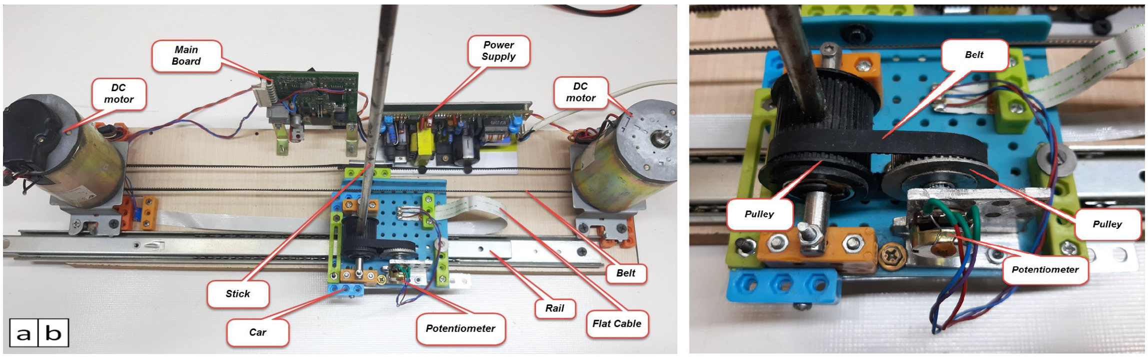

Figure 1: a): Inverted pendulum hardware b): angle calculation mechanism.

Since the carriage is moving and the potentiometer is fixed on the carriage, a flat cable installed under the carriage is used to connect the potentiometer to the control board. As you can see in Figure 1-a,the device includes a power supply board and a main board. The 12V 5A power supply board is responsible for supplying the required voltage for the motor driver and microcontroller. The main board includes an 8-bit AVR microcontroller and a high-amp DC motor driver IC. This board also includes inputs and outputs for connecting to a computer and programming the microcontroller IC. You can see the general block diagram of the electrical part of the device in Figure 2. The used microcontroller is an 8-bit microcontroller made by Atmel company called ATmega32. This micro includes 32 KB of internal flash memory, 2 KB of RAM, and an internal 10-bit analog-to-digital converter [8]. The working frequency of this micro is 11.0592 MHz. A complete H-bridge motor driver IC called VNH2SP30 is used to control the speed and direction of the motors, which can drive a 30A 16V motor and support the maximum PWM frequency of 20 kHz [9]. According to Figure 2, two inputs INA and INB are used to control the direction of rotation, and PWM input is used to control the rotation speed of the motors [10].

2.2 Fuzzy Controller Design

The fuzzy controller consists of 25 rules based on 5 fuzzy regions. In this design, the position error and the derivative of the position error are considered as inputs, and the output is duty cycle of the PWM signal, which is sent to the DC motor driver section. Table 1 shows the controller fuzzy variables employed.

Table 1: The names of the fuzzy variables used in the fuzzy controller.

Input Variables		Output Variables
Angle	Angle Change	Duty Cycle
NB: Negative Big	NB: Negative Big	BD: Big Decrease
N: Negative	N: Negative	D: Decrease
Z: Zero	Z: Zero	H: Hold
P: Positive	P: Positive	I: Increase
PB: Positive Big	PB: Positive Big	BI: Big Increase

Figure 3 shows the membership functions of the error input, the error derivative, and the duty cycle of the PWM signal output variables, respectively, and you can see the control surface of the fuzzy controller in Figure 4. The fuzzy associative memory, integrated by

25 rules is shown in Table 2.

Table 2: fuzzy associative memory for the control system

	NB	N	Z	P	PB
NB	BI	BI	I	D	BD
N	BI	I	H	H	BD
Z	BI	I	H	D	BD
P	BI	H	H	D	BD
PB	BI	I	D	BD	BD

2.3 Simple Tuning Algorithm

When implementing a fuzzy controller it's necessary to consider many parameters to compute, like, number and ranges of membership functions, rules, shapes, percentages of overlap, etc. To tune the above parameters in this control system, an algorithm called simple tuning is used. The algorithm implemented in this system is based on the properties of the control surface, allowing the modification of the controller's behavior by means of manipulating the ranges of the membership function of the input variables. In this method, we can modify the behavior of the controller only by changing and setting one parameter. This parameter only changes the input membership functions and compresses or expands them around the equilibrium point of the system and has no effect on the output membership functionsl [5]. In this way, the sensitivity of the system can be reduced or increased. The simple tuning algorithm for the fuzzy controller consists of four steps:

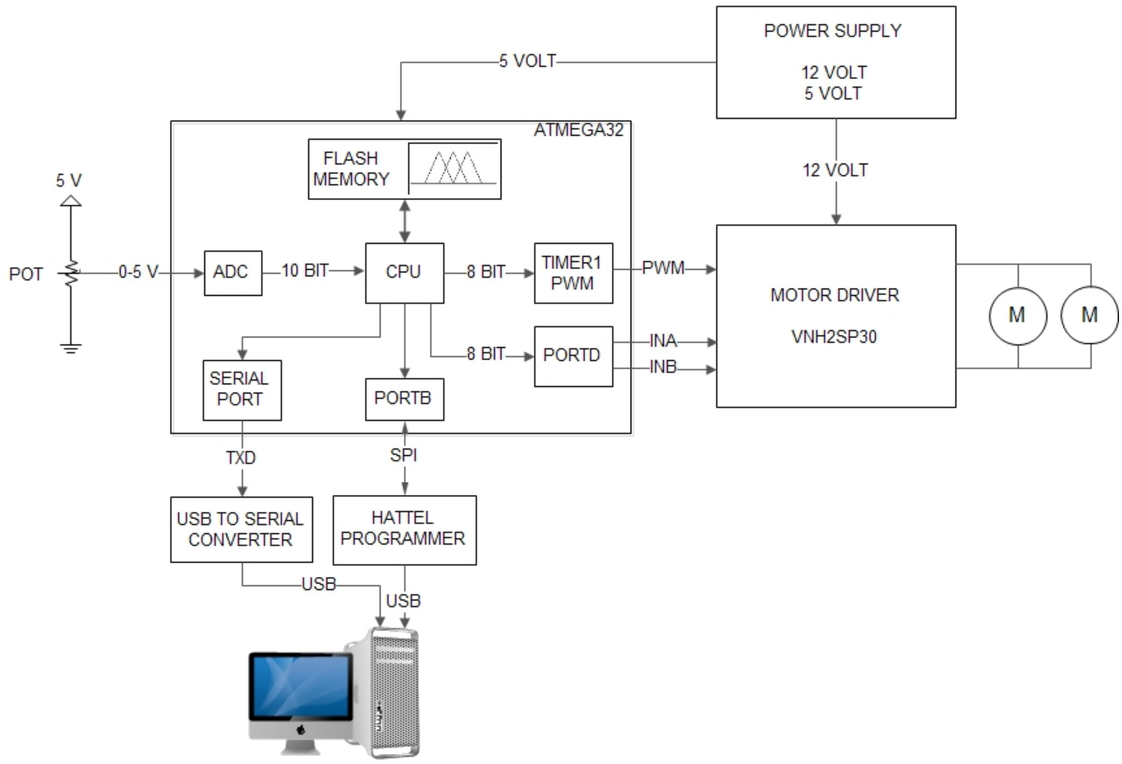

Figure 2: Block diagram of electronic hardware.

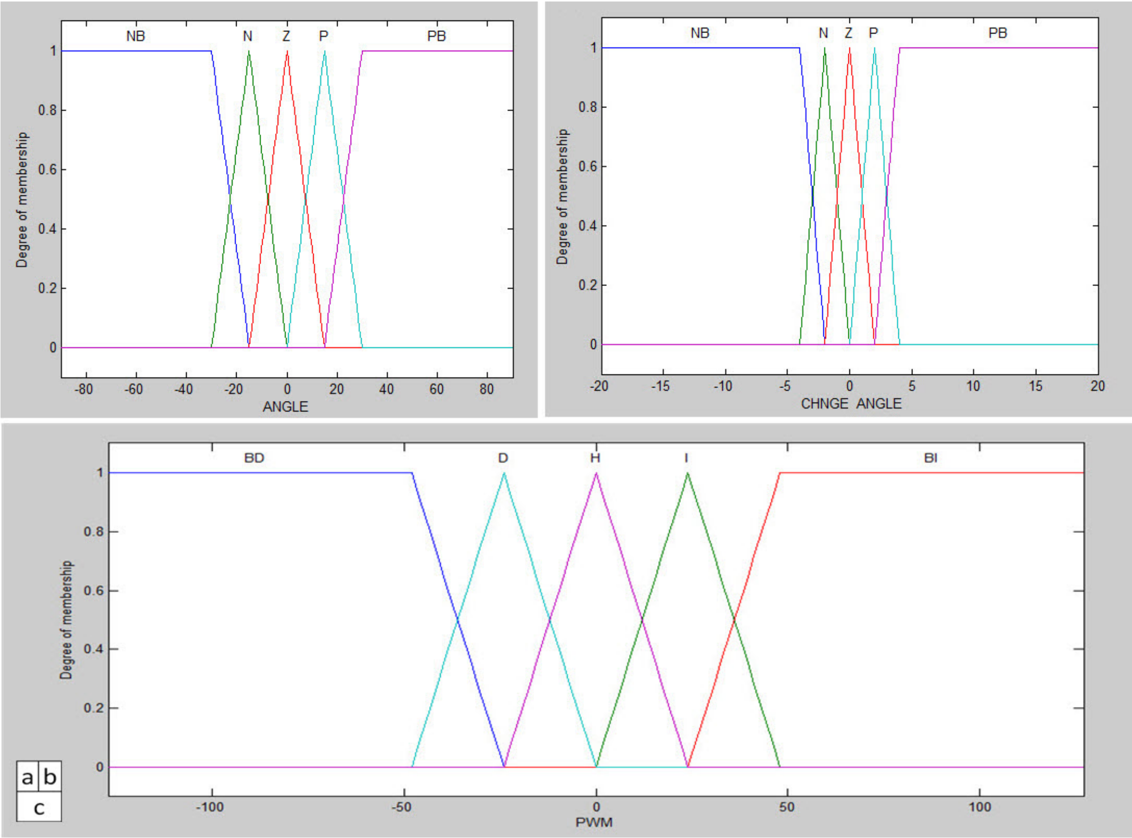

Figure 3: a) Membership functions of the angle error input variable; b) membership functions of the angle error derivative input variable; c) membership functions of the duty cycle of the PWM signal output variable.

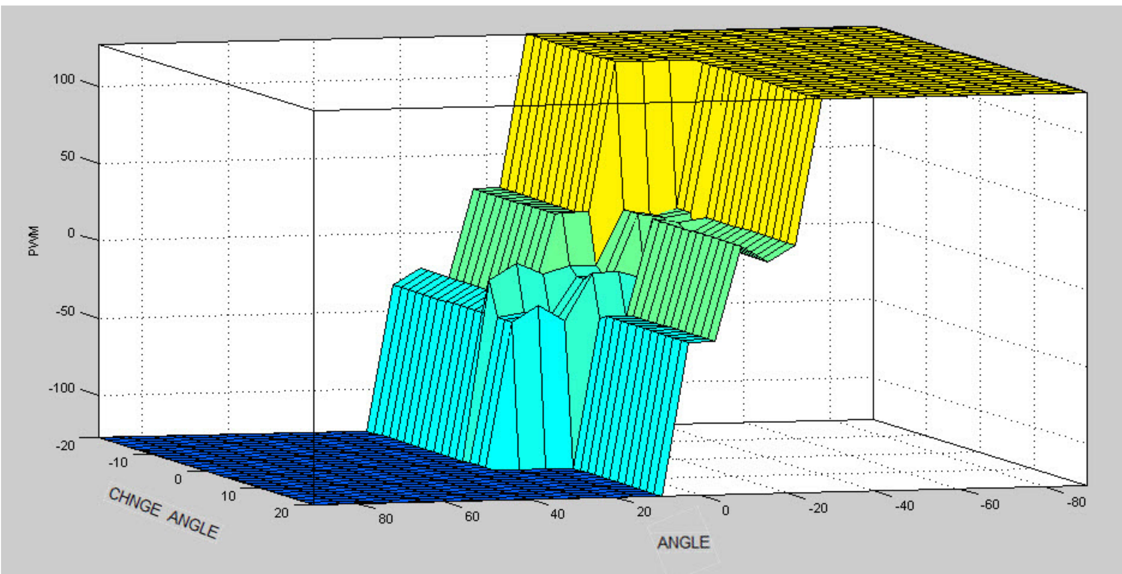

Figure 4: Control surface of the fuzzy controller.

1. Select the tuning factor: A number $k \in [0, 1]$ is used to define the tuning adjustment level. k=0 is the biggest settling time and k=1 the smallest.

2. Normalization of the ranges of the Fuzzy Controller's variables. The range of each input fuzzy variable is modified in order to have the lower and upper limits equal to -1 and +1, respectively (angle input and angle derivative).

3. Calculate r(k) using the following formula.

$$r(k) = \frac{30k^3 + 37k^2 + 52k + 1}{40}$$

   Then, raise the key points of each normalized input membership function of the fuzzy system to the power of r(k).

$$VOP_{final} = (VOP_{initial})^{r(k)}$$

4. Now, return the new normal membership functions to the original range.
   The Matlab® code of the functions to calculate and save the vector which contains the operation points are given in reference [11].

Two coding languages, MATLAB and Basic, have been used to implement the fuzzy control system using the lookup table method in the 8-bit microcontroller. The offline part of the program, which includes coding the fuzzy controller and implementing the simple tuning algorithm, as well as creating a lookup table based on the control surface of the fuzzy controller, is implemented in MATLAB software.

The lookup table is saved in a text file called Table.txt. The real-time part of the control system implemented in the microcontroller is written in Basic language. In this section, the control loop that includes reading the analog input (potentiometer voltage), converting it to an angle corresponding to the read voltage, and calculating the derivative of the angle is performed. Next, according to the lookup table, which is stored in the flash memory simultaneously with the microcontroller program, the output value of the fuzzy control system is extracted. This output is duty cycle of the PWM signal, which is written directly in the PWM register of the microcontroller. This control loop is executed at a high speed several hundred times per second to keep the inverted pendulum system stable. In Figure 5 , you can see the process of designing and tuning the fuzzy controller and its implementation in the microcontroller.

3 Results

Several tests were performed for different values of k, and each time the lookup table was calculated, the corresponding values were stored in the microcontroller flash memory, and the control algorithm was applied in the inverted pendulum hardware. In this section, we analyze the results obtained from real tests. We applied the tests considering the lowest sensitivity to input k = 0 to the highest sensitivity to input k = 1 and the best results were obtained for k = 0.9 and k = 1. By comparing the best results, the k = 0.9 was chosen because the overshoot of the system in the k = 0.9 is less than k = 1 and we have a smoother curve. Perhaps the response of the pendulum with k = 1 is faster and more agile than k = 0.9, but we have small fluctuations at the equilibrium point, which is not attractive. For other values of k, the system will be either strongly oscillating or

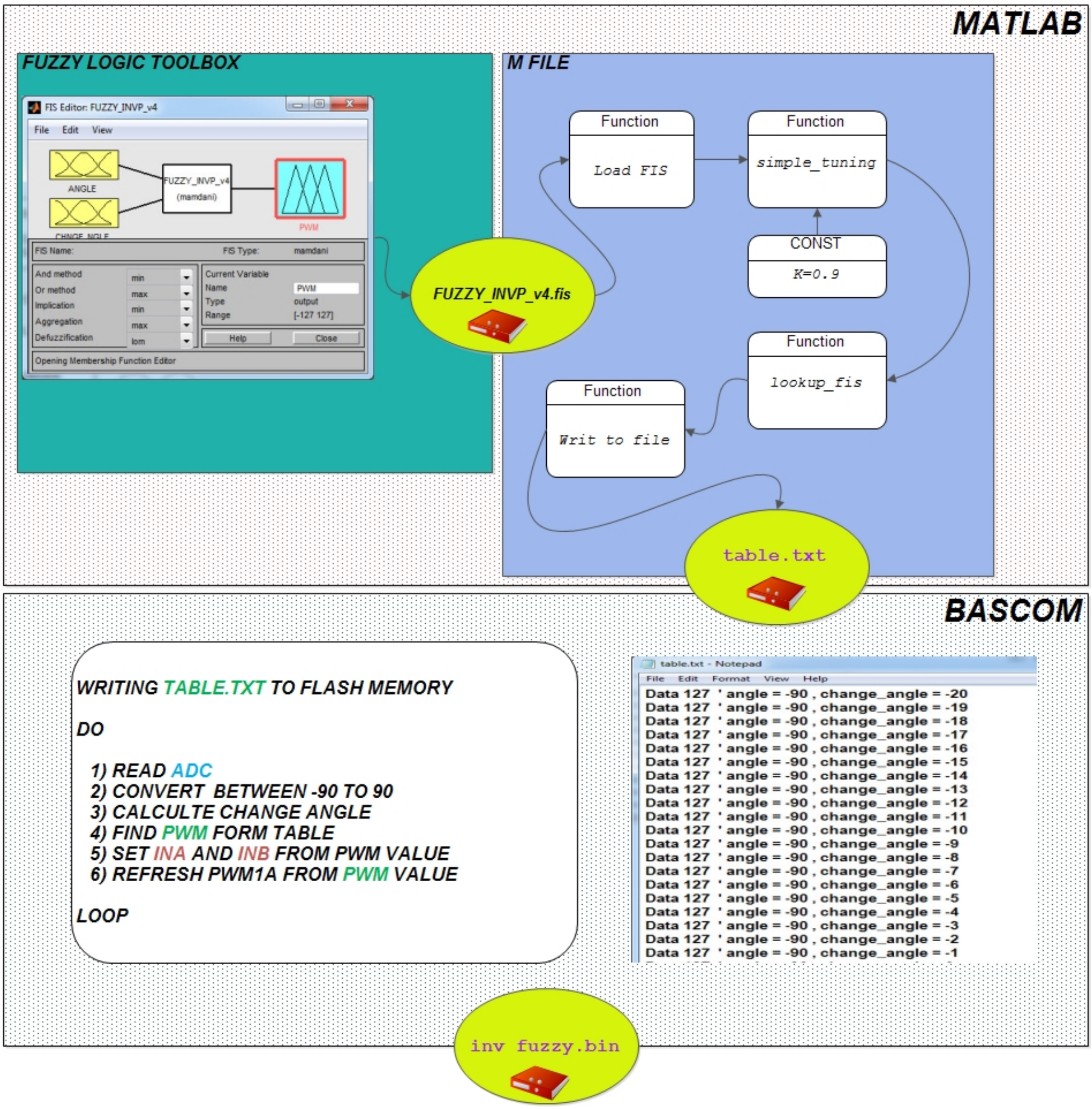

Figure 5: Designing and tuning the fuzzy control and its implementation in the microcontroller.

completely unstable. You can see the video of how the pendulum is stable considering k = 0.9 on YouTube and Aparat. The Matlab and bascom codes are given in Github site.

If you are reading the printed version of this article, you can access the video link by scanning the barcode of Figure 6.

In Figure 7, you can see the effect of different values of k on the input membership functions. In fact, by changing the values of k and approaching the number 1, it is possible to see how the system's sensitivity to input changes increases and decreases and how it affects the shape of the control surface of the fuzzy controller.

4 Discussion

the inverted pendulum on a cart is an under actuated, unstable non-linear system that is used as a benchmarking problems in control theory. The non-linear nature of the system

YouTube Aparat GitHub

Figure 6: Scan the QR code with your mobile phone.

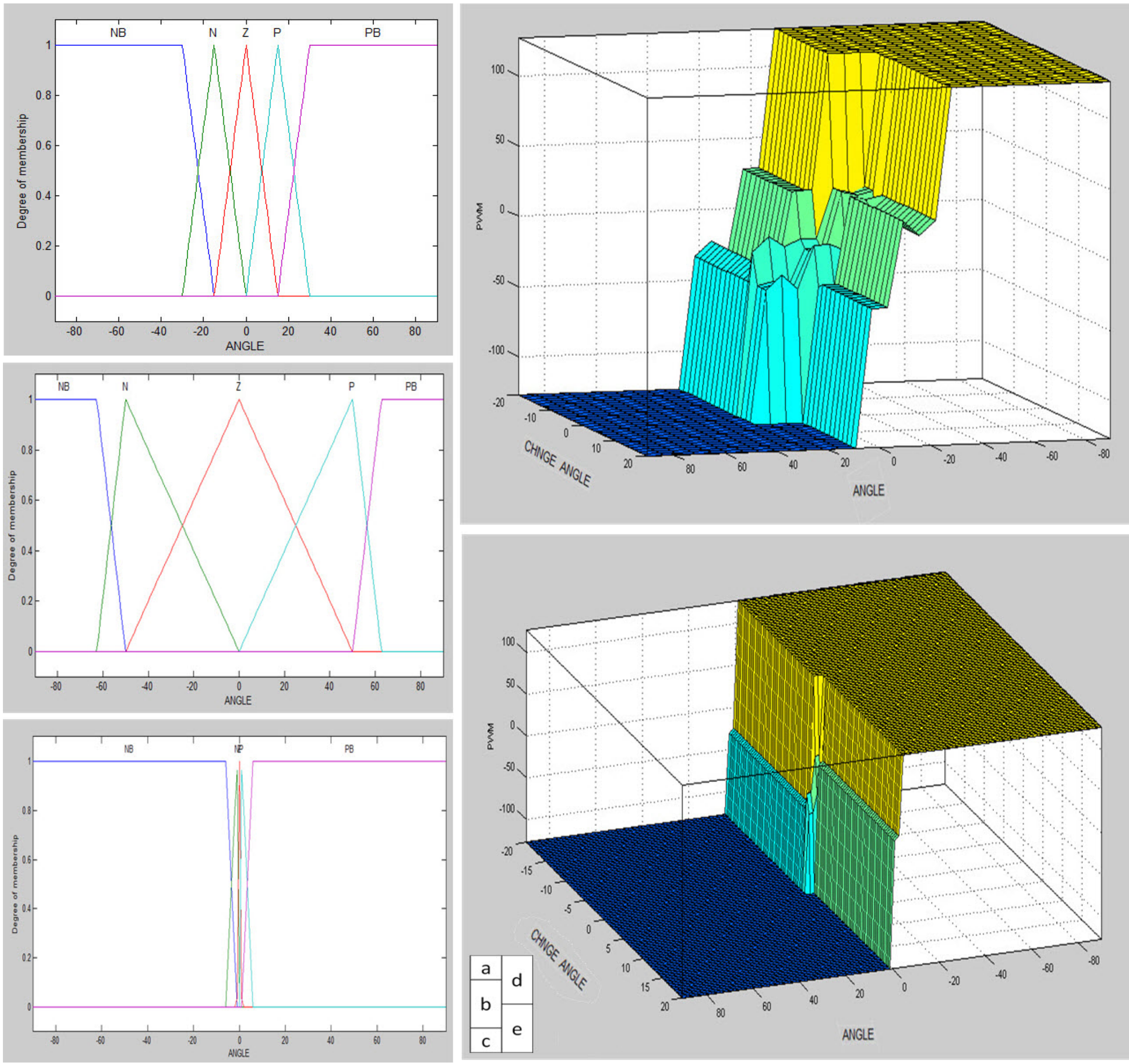

Figure 7: a) Membership functions for error input with k = 0.5; b) membership functions for error input with k = 0.2; c) membership functions for error input with k = 0.9; d) the shape of the control surface of the fuzzy controller for values of k = 0.5; e) the shape of the control surface of fuzzy controller for values of k = 0.9.

makes linear controllers, such as the proportional integral derivative (PID) controllers, possibly unfeasible as they only guarantee stability of a linear system. A fuzzy-logic controller provides many different stable controllers applicable to inverted pendulum on a cart .The use of fuzzy controllers can be considered a viable and efficient tool to deal with real systems, since we can achieve a well tuned fuzzy controller by a simple algorithm with the capacity to modify the necessary parameters by itself to find the desired response, manipulating the settling time of the system. In agreement to the experimental results obtained in this work, it's remarkable the fact that the nearest to 1 is the value of the tuning factor k, the fastest systems response is acquired.

5 Conclusion

This project aimed to design an inexpensive hardware controller for the stability of the inverted pendulum, which was successfully achieved. It was proved that the fuzzy controller implemented in the microcontroller was effective and feasible in the angular control of the pendulum in the vertical position. Further, the use of the simple tuning algorithm is very efficient in adjusting the sensitivity of the control system and adjusting the response speed of the system. The method used in this paper is suitable for control systems whose equations are unknown and the control system designer does not have enough knowledge to tune the parameters of a fuzzy system.

References

[1] L. Zadeh, "Fuzzy sets". Information and Control, Vol. 8, 1965

[2] Eftekhari, M., Mehrpooya, A., Saberi-Movahed, F., Torra, V. (2022). How fuzzy concepts contribute to machine learning. Cham, Switzerland: Springer

[3] R.E.Precup and H.Hellendoorn,A survey on industrial applications of fuzzy control,Computers in Industry,Volume 62, Issue 3,2011.

[4] L. Reznik, "Fuzzy Controllers," Victoria University of Technology, Melbourne, 1997.

[5] G.Ramirez E,Simple Tuning of Fuzzy Controllers, International Conference on Fuzzy Systems, Neural Networks and Genetic Algorithms, FNG 2005, Tijuana, Mexico.

[6] J. Kackprzyk, "Multistage fuzzy control: a model-based approach to fuzzy control and decision making," Journal of Multi-Criteria Decision Analysis, vol. 7, no. 4, pp. 239–240, 1998.

[7] T. J. Ross, Fuzzy Logic With Engineering Applications, John Wiley and Sons, Singapore, 3rd edition, 2010.

[8] Microchip Technology, The high-performance, low-power Microchip 8-bit AVR® RISC-based microcontroller, available at:
https://ww1.microchip.com/downloads/en/DeviceDoc/doc2503.pdf.

[9] ST Microelectronics, Automotive fully integrated H-bridge motor driver, available at:
https://www.st.com/resource/en/datasheet/vnh2sp30-e.pdf.

[10] M.N. CIrstea , A. Dinu, J.G. Khor, and M. McCormick, Neural and Fuzzy Logic Control of Drives and Power Systems, Oxford: Newnes, 2002.

[11] M. A. P. García, I. M. M. Sánchez, O. Montiel, R. Sepulveda, O. Castillo, O. (2006). Simple tuning of a fuzzy pulse width modulation controller for a DC motor application. In Proceedings of the 2006 International Conference on Artificial Intelligence, ICAI'06 (pp. 598-604). (Proceedings of the 2006 International Conference on Artificial Intelligence, ICAI'06; Vol. 2).