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On the implementation of linear position control using fuzzy logic approach

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Abstract

This paper investigated a significant application of fuzzy set theory and fuzzy logic. The proposed work aimed to simulate Fuzzy Logic Controller (FLC) for linear position control. With this objective, an initiative is taken to design and simulate a Fuzzy Inference System (FIS) to control linear position in a computer-assisted environment. In this paper, the implementation of a Mamdani Fuzzy Inference System has been demonstrated with the application of controlling linear displacement. The design and simulation of conventional fuzzy logic controller (FLC) for a single input single output (SISO) system, is carried out. The system consists of a fuzzy logic controller that analyzes probable control situation based on the error distance and its error derivative. The controller determines the sufficient linear motion required to obtain the desired set-position while providing a smooth motion for the slider. The robustness of the proposed control scheme is verified by numerical simulation. The proposed scheme has better performance than the conventional method due to parameter variation and extraneous disturbance. To demonstrate its performance, the proposed control algorithm is applied to a real time position control system.

Keywords: Centroid; Defuzzification; Fuzzification; Mamdani Inference System

1. Introduction

Linear acceleration control is the main obligation of applications including machine tools and industrial machinery, in computer peripherals such as disk drives and printers, in space robotics, and in many other places where linear motion is required. It also used in the appliance requiring precise linear sliding movement and the wide range of linear motion products. The linear sliders provide advanced linear motion functionality in versatile linear motion solution. They are the component that ranges from ON/OFF devices with the simple linear controller to complex, user programmable modules that act as controllers within integrated multi-axis motion control systems. One of the major intricacies in realizing proposed Linear Position Control System (LPCS) is the controller design. Simple linear movement with simple velocity profile is relatively easy to design. The conventional position controller controls the position, not force while Fuzzy force controllers, regulate force without precise control of the movement trajectory. The hybrid position/force controllers, controlling position in one direction, have the advantage of simultaneously maintaining the desired movement path and force for the smooth movements. Several approaches were applied to model nonlinear system of LPCS. In present work, Fuzzy system modeling (model-based approach) has been used for our research purpose. Thus, the system had position control in one direction and speed-dependent force control in the opposite direction. One additional problem in designing the controller is the uncertainty about the subject and the nonlinear dynamics of the machine such as the Coulomb friction in the mechanism. In a classical design process, the control parameters are determined according to the system model. For a position control, the output load is also part of the dynamic system and the dynamic model of the subject is not as clear and invariable as the mechanical system. To solve this problem, fuzzy logic control is incorporated in the proposed LPCS. Fuzzy control is best known for tracking with nonlinear systems and systems that have uncertainty in its parameters. The uniqueness of a fuzzy modeling approach is its ability

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to utilize both qualitative and quantitative information. Qualitative information is human modeling expertise and knowledge, which are utilized in the form of fuzzy sets, fuzzy logic and fuzzy rules [1]. Many researchers have tried to maintain the stability by fine-tuning by enhancing the fuzzy rule set, through a stable linear proportional, integral, and derivative (PID) controller. Designing a controller for position control is more difficult because the external disturbance itself is subjected to another unresolved controller (the human control).Here we have designed a fuzzy logic controller using fuzzy logic toolbox in MATLAB (Version 7.0.0.499 R2010a 32 bit) software and simulate the designed model using the Simulink.

A major portion of research work on designing the hardware mechanism for automatic control system invariably revolves around the study of DC position control system. The present study has been designed with the objective in mind despite the constrained like friction, dead zone, nonlinearities due to driver saturation , motor current limitation and low speed of response associated with any mechanical system. The main purpose of the current study is to construct a linear position control system specialized for regulating a vehicle brake. The system, incorporating hybrid position/force control and fuzzy logic, shall be able to assist the subject in performing movements along the straight path inside the cylinder with specified loads. The specific goals of current work include design and simulation with control algorithm implementation and performance analysis of the proposed system. The schematic diagram in figure.1 shows various built-in subsystems which are now discussed in subsequent sections of this paper.

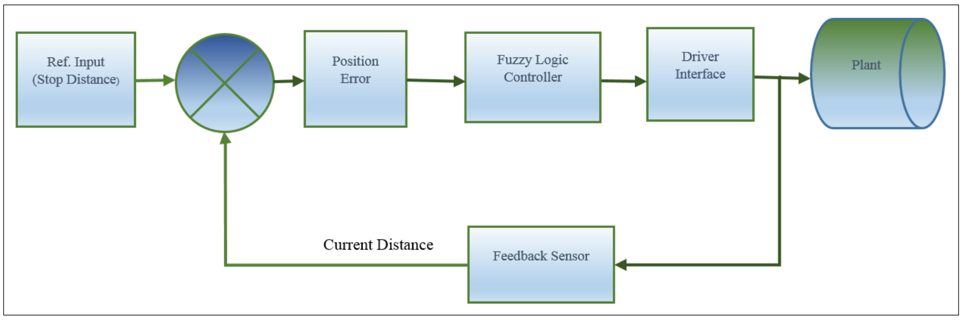


Figure 1 Position control system

In [2] position control of a Brushless direct drive (BLDD) motor was proposed using a fuzzy logic controller(FLC), because of its simple structure and robust performance in a wide range of operating conditions. Although vehicle brake system is intrinsically nonlinear and its dynamics will be described by second order differential equations, it is often possible to obtain a linearized model of the system. If the system operates around target point and the error signals involved are small signals, a linear model that approximates the nonlinear system in the region of operation can be obtained. In [3] dynamics was derived using an integrated Fuzzy PID approach and the control was design by the equations linearized around steady-state value. Even though the controller is tested, but experimental results need to obtain to validate the simulation results and still not yet done. Thus, this paper presents investigations of performance comparison between conventional PID control and intelligent fuzzy logic control schemes for a position control experimentally. In this work, the LPCS was modeled to mimic the human mind to effectively employ modes of reasoning that are approximate rather than exact, to test controllers designed. Performances of both control strategy with respect to *Error distance* and *Error derivative* i.e. Error rate were examined if the error is being decreased with incremental error rate then motor speed should be exponentially decreased. Comparative assessment of both control schemes to the LPCS system performance was analyzed and discussed.

2. Review of literature

The control objective is to achieve the desired position and direction while maintaining the MTWIP (Mean Time to Work in Process) in a balanced state. The utilization of a Takagi-Sugeno model is employed to accomplish this. The results clearly indicate that the IT2 FLS performs better in the presence of modeling uncertainty and external disturbances.

Umesh Kumar Bansal [2] uses BLDD motor that has a PID controller to regulate its speed. The KP, KI, and KD gains of the PID controller are tuned based on fuzzy logic. The author noted that the specific characteristics of PID controllers and the adaptable characteristics of fuzzy controllers are both found in the fuzzy self-tuning PID controller. The simulation outcomes of the proposed work showed that the designed self-tuned PID controller achieved excellent dynamic characteristics of the BLDD motor. It revealed perfect speed tracking with minimal rise and settling time, minimal overshoot, minimal steady state error, and superior performance compared to a traditional PID controller.

Ivana Todic and her colleagues [3] conducted a study that specifically examined the regulation of Electro Mechanical Actuators (EMA) for aerospace purposes. The EMA is controlled utilizing a position regulator and a control mechanism that combines position and speed regulation. The author's research indicates that the operational limits of varying-speed motor drives are determined by the operational limits of single speed motors. This results in the system being underutilized and increases the risk of high power losses for the motor. The primary aim of his suggested research is to mitigate power losses, minimize heating, and reduce current consumption in the entire system.

Yongming Li and Shaocheng Tong [4] released a paper titled "Adaptive Fuzzy Control with Prescribed Performance for Block-Triangular-Structured Nonlinear Systems." This research utilizes fuzzy logic systems to ascertain the unidentified functions of nonlinear systems. A novel observer-based output-feedback control scheme is formulated using the adaptive fuzzy control theory and the back stepping design technique. The suggested control method effectively addresses the issue of excessive complexity in the back stepping design and eliminates the limiting assumption that unknown nonlinear functions must adhere to a global Lipschitz condition. The suggested strategy ensures that the tracking errors gradually approach a minimal residual set, while adhering to the specified performance limit. The simulation results of the chemical process control system are shown to further illustrate the efficacy of the proposed control technique.

In 2018, Bing Chen and his colleagues [5] conducted a study on the development of an observer and adaptive fuzzy control for nonlinear strict-feedback systems. The work proposed a robust fuzzy observer to estimate undetectable state variables of a system using the convex combination method. The proposed adaptive fuzzy output feedback controller ensures the convergence of the tracking error to a small region near the origin, while ensuring that all signals in the adaptive closed-loop system stay within specific constraints. We present the simulation's results to illustrate the efficacy of the proposed methodology.

The publication "Fuzzy Logic Controllers for specialty vehicles" was authored by Lishu Qin et.al [6] in 2017. Employing a fusion of phase plane analysis and the variable universe approach. Despite the small amount of fuzzy rules in the rule base, it is possible to improve the accuracy of the fuzzy logic controller's performance. The application of Lyapunov stability theory ensures the stability of the closed-loop system. Implementing this design method can significantly alleviate the workload for fuzzy logic controller developers and reduce the time required for developing the fuzzy logic controller.

The paper titled "Task Space Control of an Autonomous Underwater Vehicle Manipulator System by Robust Single-Input Fuzzy Logic Control Scheme" was published by Pandurang S. Londhe et.al [7] in 2017. The numerical demonstration of the suggested control scheme's effectiveness is conducted on a planar undersea vehicle gripper system. The main goal of the proposed control strategy is to accurately follow the specified trajectory of the end-effector in the task space, even in the presence of external disturbances, ambiguities in the system, and internal sounds related to the AUVMS. Simulation outcomes have shown that the suggested control method enables the AUVMS to accurately follow the specified spatial trajectory and provide superior and reliable control performance.

The paper titled "Feedback Error Learning Control of Magnetic Satellites Using Type-2 Fuzzy Neural Networks with Elliptic Membership Functions" was published by Khanesar et.al [8] in 2014. The learning process is grounded on the feedback error learning approach, which enhances both the stability of the learning itself and the stability of the entire system. Additionally, this method allows for the inclusion of additional components in the control scheme to provide robustness. The simulation findings demonstrate that the suggested control algorithm outperforms traditional control techniques in terms of reduced steady state error and faster response to transients.

Haibo Du et.al [9] published a study on the development of a positioning-tracking device for a linear motion controller using vectorization technique. The primary aim of this work is to address the issue of position tracking control for a permanent magnet linear motor. This will be achieved by employing the discrete-time fast sliding mode control (SMC) method. An exhaustive analysis is presented to establish that the fast terminal sliding mode control law can provide superior precision compared to the conventional linear sliding mode control law. The suggested strategy is validated using computational simulations and empirical findings, which confirm its effectiveness and highlight the advantages of the discrete-time fast terminal sliding mode control (SMC) approach over previous methods.

The publication "A Modular Implementation Scheme for Non-singleton Type-2 Fuzzy Logic Systems with Input Uncertainties" was authored by Zaheer et.al [10] in 2015. The recommended implementation method encompasses a comprehensive approach that includes both the fuzzyfiers and the membership functions. In order to assess the efficacy of the suggested approach, kind-2 fuzzy logic controllers are implemented for three distinct applications: controlling the altitude of an airplane, enabling obstacle avoiding for an autonomous vehicle, and facilitating wall following for a robot. The proposed system effectively handles all three uses. Furthermore, the performance outcomes in all three application configurations demonstrate that NS Fuzzification can enhance the resilience of kind-2 fuzzy logic systems against significant uncertainties.

The paper titled "Adaptive Inverse Control of Cable-Driven Parallel System Based on Type-2 Fuzzy Logic Systems" was published by Tiechao Wang et.al [11] in 2015. The antecedents of the interval type-2 fuzzy nonlinear autoregressive model exogenous (NARX) forward models are constructed by establishing the monotonic property of the fuzzy NARX model. The antecedent parameters may then be derived based on this property. In addition, the subsequent parameters of the advanced models are calculated offline using a constrained least squares approach. The experiment findings demonstrate that the suggested type-2 fuzzy control method successfully achieves the control objectives and exhibits excellent control performance.

Shaocheng Tong et.al [12] released an article on the design of adaptive fuzzy tracking control for single-input single-output uncertain non-strict feedback nonlinear systems. This work examines the topic of designing an adaptive fuzzy tracking control for the same system. The unified framework of adaptive back-stepping control design encompasses both adaptive fuzzy state feedback techniques and observer-based outcome feedback control design approaches. The robustness of the closed-loop systems is demonstrated by the utilization of Lyapunov value theory. The simulation examples are presented to validate the efficacy of the provided control strategies.

The publication "Observed-Based Adaptive Fuzzy Decentralized Tracking Control for Switched Uncertain Nonlinear Large-Scale Systems with Dead Zones" was authored by Shaocheng Tong et.al [13] in 2016. An adaptive fuzzy decentralized output-feedback tracking control strategy is created for the switched subsystem using the adaptive randomized back stepping implementation technique. The stability of the entire closed-loop system is demonstrated by the utilization of the Lyapunov function and the mean dwell-time approaches. The simulated example is presented to demonstrate the efficacy of the proposed control methodology.

Li Qiu and colleagues [14] have released a publication titled "Robust Cooperative Positioning Control of Composite Nested Linear Switched Reluctance Machines (LSRM)".The composite layered LSRMs across communication networks are represented as a Markov time-delay system to facilitate long distance movement and parallel close movement for industrial needs. The suggested robust collaborative positioning control system is tested through multiple experimental trials to confirm its effectiveness and practicality.

The publication "Position Control for Magnetic Rod less Cylinders with Strong Static Friction" by Hongjiu Yang et al. [15] was released in 2018. This work proposes a resilient controller based on an adaptive extended state observer (AESO). The suggested controller combines the benefits of a sliding-mode controller and a linear active disturbance rejection controller to achieve accurate and reliable control. The experimental results demonstrate a substantial enhancement in both reaction rate and position accuracy through the utilization of the strategy presented in this research.

Liang Sun and Zewei Zheng [16] published a paper titled "Disturbance Observer-Based Robust Layered Control for Spacecraft Proximity Makeovers." The papers present the design of a 6-DOF robust condition feedback saturated controller. This controller is capable of continuously monitoring relative position and synchronizing attitude. The stability of the closed-loop system that is used with this control method is rigorously established under mild presumptions. Furthermore, it is proven that both the relative position and with regard attitude converge to a small neighborhood around zero. The numerical simulation result provides evidence of the efficacy of the proposed strategy for designing controllers.

Li Qiuet.al [17] released a study on the design of a Networked $H\infty$ Controller for a Direct-Drive Linear Motion Control System. The network-induced random delay, which cannot be avoided, is represented by a Markov chain that has uncertain transition probabilities. This work presents a linear motion control system that utilizes a double-sided linear switched reluctance machine (DLSRM) in the experiments. The experimental tests on the networked DLSRM system are conducted to validate the efficacy and feasibility of the proposed $H\infty$ control approach for industrial applications of networked control systems.

The 2015 paper by J. F. Pan et.al.[18] on high-precision dual-loop position control of an asymmetric bilateral linear hybrid switched reluctance motor, and the 2015 paper by Benoit Huard et.al.[19] on sensor-less force/position control of a single-acting actuator, both show better performance and faster rise time compared to single-loop control strategies.

Benoit Huard et.al [19] released a study titled "Linear Control of Switching Valve in Vehicle Hydraulic Control Unit (HCU) Based on Sensor less Solenoid Position Estimation." This study presents a novel approach to establish a real-time linear controller for the switching valve in the HCU. The approach involves integrating a new sliding-mode controller (SMC) with a nonlinear sliding-mode observer (SMO). The sensor less linear pressure controller's tracking capabilities was validated using simulations and experiments, which yielded findings that supported its performance across various conditions. This study offers a valuable approach to achieve real-time linear control of a high-frequency switching valve that is comparable to a high-performance proportional valve.

3. Fuzzy Logic Controller

The cornerstone of fuzzy logic is rooted in the simulation of human views and perceptions to regulate any system. One approach to simplifying complicated systems is to accept a certain degree of imprecision, ambiguity, and uncertainty [10]. An experienced operator creates a versatile control mechanism utilizing often used phrases such as "suitable," "not very suitable," "high," "little high," "much high," "far," and "too much high" that are regularly seen in people's daily lives. Fuzzy logic control is built upon these logical linkages. Fuzzy sets are utilized to represent linguistic variables. Zadeh created Fuzzy Sets Theory in 1965 as a means to represent and manipulate imprecise knowledge [11, 12]. The relationship between fuzzy logic and fuzzy set theory is analogous to the relationship between Boolean logic and classical set theory. Fig.2 depicts a fundamental construction of a Fuzzy Logic Controller (FLC).

To enhance the performance of FLC, adjustments are made to the regulations and membership functions. The membership functions are modified by reducing the width of the membership functions in the vicinity of the ZE region, resulting in a higher level of control precision. Conversely, increasing the width of the area that is distance from the ZE zone results in a quicker response in terms of control. Furthermore, the performance can be enhanced by modifying the stringency of rules [4].

4. Experimental model development

The following assumptions are prepared while developing the model

- Difference between Initial distance and stopping distance should not be zero.
- The drive gears of the position control system do not slip.
- The center of gravity of the position control system is at the center of the base.
- All damping is viscous in nature, no Coulomb friction is included.
- No backlash in the gears (DC motor) of the model.

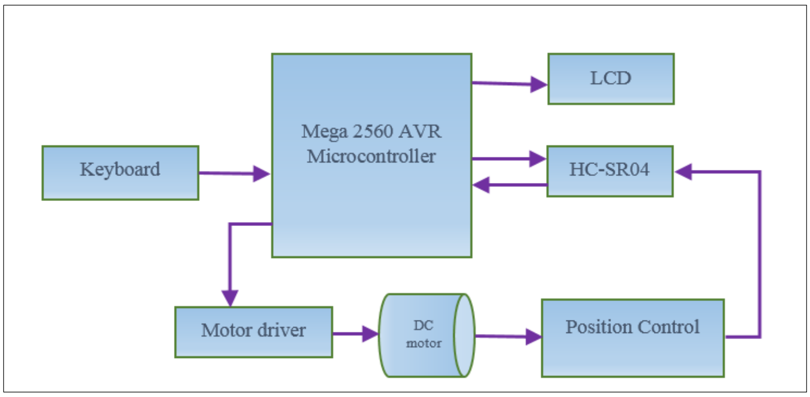


Figure 2 The proposed system architecture

5. Design of fuzzy controller

5.1. Design of Fuzzy Logic Controller

The structure of the control system with the proposed real time implementation of fuzzy controller is shown in Fig.2. The proposed fuzzy controller based on Mamdani's fuzzy technique is implemented as a position controller**.**

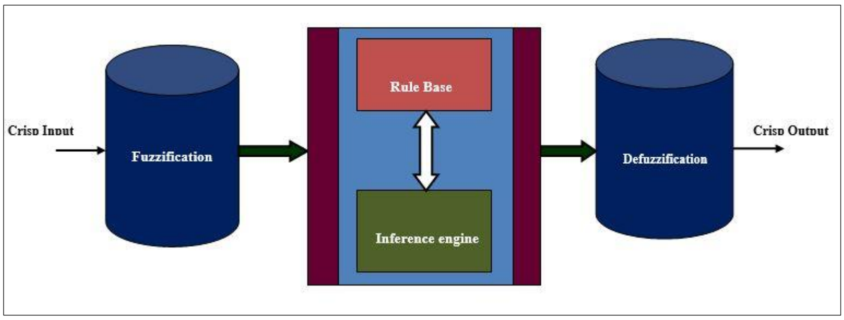


Figure 3 Structure of fuzzy logic controller

The traditional Fuzzy Logic Controller usually works with input signals of the system error e and the derivative error ce in the error. The system error is defined as the difference between the reference point and the current output at the moment t:

$$e(t)=r(t)-y(t) \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Hence the error derivative ce at the moment t will be:

$$ce(t)=e(t)-e(t-1) \ldots\ldots\ldots\ldots (2)$$

Proportional integral control technique is commonly using traditional control technique but the performance of the PID controller is mainly based on a suitable choice of the gains (Kp, Kd, Ki). Tuning of gains becomes the most difficult task. To overcome this problem a robust controller is needed. Fuzzy is one of these control technique which is robust about too many nonlinear procedures. The fuzzy controller uses a systematic method to control a nonlinear procedure based on human experience. This is defined as a heuristic method this can enhance the operation of closed loop system. The operation of the fuzzy controller is based on its capability to simulate several role implications at the same time, it results in the significantly comprehensive output. A well designed fuzzy controller can provide enhanced operation in presence of variations in parameters, external perturbations, and load existence than conventional PID controllers. The design of fuzzy controller mainly consists of four building blocks: Fuzzification block, fuzzy knowledge-based (Membership Function and Fuzzy Rule Base) block, fuzzy Inference engine and Defuzzification block.

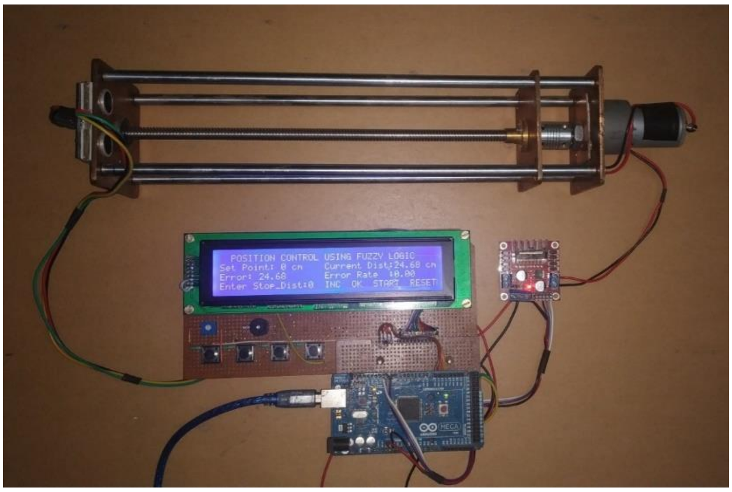


Figure 4 Experimental setup of model

Figure 5 LCD 40 x 4 Character Display

5.2. Fuzzification

The conversion of the crisp (classical) set to the fuzzy set is called the Fuzzification. Triangular fuzzifier is used among different fuzzifier such as Triangular, Trapezoidal, Singleton and Gaussian. By assigning some membership function to each and every input with the help of the fuzzifier is convert the input crisp value into the fuzzy set, [8, 9].

5.3. Membership Function

A graph of input crisp value and membership value which varies from 0 to 1 is called the membership function. It provides impreciseness to the fuzzy logic. The triangular membership function is used among the different membership functions such as trapezoidal, Gaussian, sigmoid, piecewise linear.

5.4. Fuzzy Rule Base

Fuzzy rule bases have garnered considerable interest in diverse disciplines because of their capacity to manage ambiguity and imprecise data. By integrating fuzzy logic into decision support block, proposed system will more accurately simulate how technical operator might tackle intricate situations with significant levels of ambiguity. The fuzzy model offers a more predictable approach to input, membership functions, and inference rules, resulting in enhanced accuracy rates in mapping task between input crisp values to output crisp value. The rules established and applied in the fuzzy model take into account the most important factors and aid in defining the membership functions. Hence, the utilization of fuzzy rule bases enables the development of a complex framework that can be employed for our predefined events, such as the mapping the error and change in error to output duty cycle.

Table 1 The Fuzzy Rule Base

ce / e	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NM	NM	NS	Z
NM	NL	NM	NM	NS	NS	Z	PS
NS	NL	NM	NS	NS	Z	PS	PS
Z	NM	NS	NS	Z	PS	PS	PM
PS	NS	NS	Z	PS	PS	PM	PL
PM	NS	Z	PS	PM	PM	PL	PL
PL	Z	PM	PM	PM	PL	PL	PL

5.5. Inference Engine

Fuzzy inference engine consists of the knowledge base, in which the rules are framed. It can be broadly categorized into two types

- Mamdani method
- Sugeno method

Sugeno method is generally based on mathematical analysis and calculations. But in Mamdani method linguistic logic used to make the rules which are very simple compared to the Sugeno method. Mamdani method is computationally efficient when compared to the Sugeno method. The fuzzy sets have been determined as NL(negative large), NM(negative medium), NS(negative small) and Z(zero), PS(Positive small), PM(positive medium), PL(positive large).

5.6. Defuzzification

Defuzzification is the last step of a fuzzy logic system, in which the fuzzy output of the inference engine gets converted into a precise value that can be received for further processing. This is achieved by identifying the most significant value or central point of the fuzzy output, which matches the level of membership in each fuzzy set. The interpretation of the outcomes of a fuzzy logic system and their use in implementation is a critical procedure. Converting the fuzzy output into a crisp value is an important step in the fuzzy logic system. This conversion allows for easy interpretation and utilization of the value in subsequent decision-making processes.

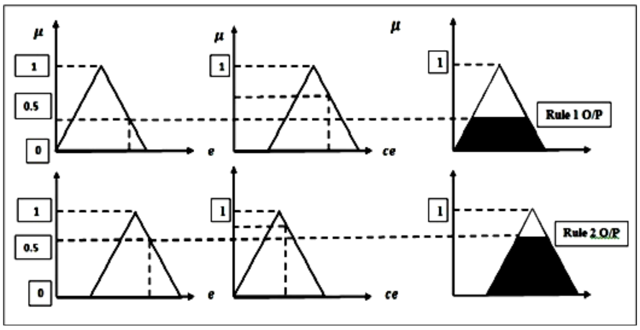


Figure 6 Understanding Defuzzification process

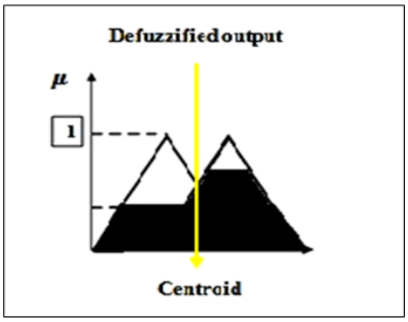


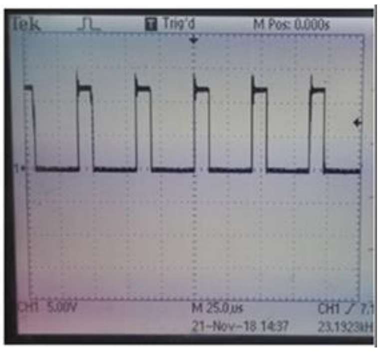
Figure 7 Defuzzyfied Output

5.7. Simulation results

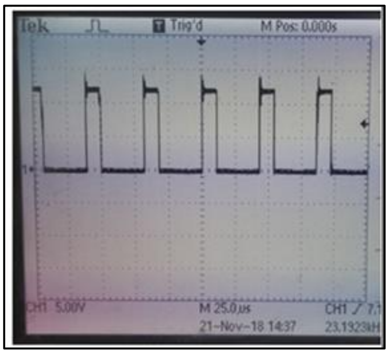
The Mamdani control strategy using PI and Fuzzy logic is implemented for linear position control using real time custom hardware and results are presented in this section. The performance of the Fuzzy logic controller is analyzed by using Steady State Error and error derivative analysis. The main objective of the Mamdani controller is to achieve target distance with minimum steady state error. The reference distance to the linear position controller is taken as 10 mm. The performance analysis using Fuzzy logic controller are shown in figure 21 to fig 24 .The resulting PWM with Total Period of 43 µsec and frequency of 23.29 KHz of rectangular wave form is examined using dual channel storage type oscilloscope

Table 2 LCD Display Showing the Experimental results

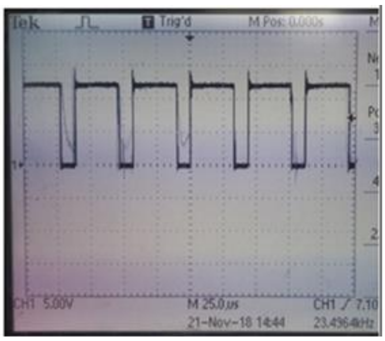
T_{ON}(µsec)	T_{OFF}(µsec)	Duty Cycle	Error	Change in Error
10.75	32.25	25%	4.62	-1.14
20.64	22.36	48%	8.35	0.315
33.11	9.89	**77%**	14.7	0.929
41.71	1.29	**97%**	25	2.00



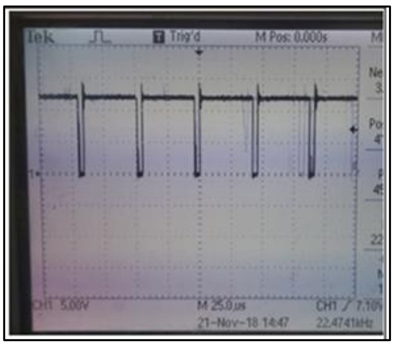
Resulting PWM for 25%



Resulting PWM for 48%



Resulting PWM for 77%



Resulting PWM for 97%

Figure 8 Duty Cycle for controlling DC motor

6. Conclusion

This paper demonstrates the implementation and design of a fuzzy controller for linear position control of a mechanical plant. The structure of real-time implementation of the fuzzy controller has been introduced in this work. The Mamdani fuzzy technique is used to obtain the fuzzy controller. The fuzzy controller is developed **as** a two-term fuzzy controller using the system error and the derivatives of the error. This is evident from the obtained results, where the transient responses of the system output have shown an improvement after several rules with the implemented fuzzy controller. The experimental results realize a good transient behavior of the proposed system, it maintains a constant difference of target speed and output speed with a small system error and minimum error derivative. The system performance is satisfactorily verified with the validity and robustness of the proposed structure of the fuzzy controller.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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