KARADENIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MECHANICAL ENGINEERING DEPARTMENT

FUZZY CONTROL OF CONDUCTING POLYMER ACTUATORS

Mech. Eng. Mohammadreza SABETGHADAM

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Enstitü Müdürü

PREFACE

Biomimetic systems play a vital role in today's industry, as many human-made mechanisms and engineering products are inspired by animals and their motions. Muscles are the natural actuators which generate all movements of the creatures. To develop bio-inspired mechanism, engineers started to look for alternatives for conventional actuators.

One of these alternatives is conducting polymers, which are also called artificial muscles because of their ability to emulate the natural's muscle movements. Controlling the position and force output of these polymers is a matter of concern nowadays because, in every application area of these newly introduced actuators, controlling their output is essential for commanding them.

In this master's thesis, Mamdani fuzzy logic control technique is applied on the conducting polymer actuator to control its force and position output precisely.

I would like to thank my advisor, Assist. Prof. Dr. Mehmet Itik for his guidance and providing experimental setup used throughout this research work. I also would like to thank Prof. Dr. Ismail Hakki Altas, for teaching me the fuzzy control method in his lectures.

My parents, Mitra and Javad, have been a great support during my studies. Without them, it would have been impossible for me to finish this research work. I will always appreciate my sister, Sarvin, who has done more for me than she will ever know. Sepideh was although much help with her realistic, motivating advice. Special thanks to Stephen J. Ganslen, to whom I am indebted for all his assistance during my master's studies. Finally, I would like to thank all my friends who were accompanying me in the ups and downs of my life during the last three years.

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Yüksek Lisans Tezi olarak sunduğum “ Fuzzy Control of Conducting Polymer Actuators ” başlıklı bu çalışmayı baştan sona kadar danışmanım Yrd. Doç. Dr. Mehmet İTİK ‘in sorumluluğunda tamamladığımı, verileri kendim topladığımı, deneyleri/analizleri ilgili laboratuarlarda yaptığımı başka kaynaklardan aldığım bilgileri metinde ve kaynakçada eksiksiz olarak gösterdiğimi, çalışma sürecinde bilimsel araştırma ve etik kurallara uygun olarak davrandığımı ve aksinin ortaya çıkması durumunda her türlü yasal sonucu kabul ettiğimi beyan ederim. 28/11/2014

Mohammadreza SABETGHADAM

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İLETKEN POLİMER EYLEYİCİLERİN BULANIK MANTIK KONTROLÜ

Mohammadreza SABETGHADAM

Karadeniz Teknik Üniversitesi
Fen Bilimleri Enstitüsü
Makine Mühendisliği Anabilim Dalı
Danışman: Yrd. Doç. Dr. Mehmet İTİK
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Elektro-aktif polimer (EAP) eyleyiciler biyolojik kasların hareketlerini taklit edebilmelerinden dolayı yapay kaslar olarak adlandırılmakta ve geleceğin eyleyici teknolojisi olarak görülmektedirler. EAP'lerin bir türü olan iletken (conducting) iyonik EAP'lerin konum ve kuvvet kontrolleri bu tip eyleyicilerin uygulamalarda kullanılabilmeleri için büyük önem taşımaktadır. İletken EAP'ler kuru ortamlarda çalıştıklarında dinamik davranışlarında büyük değişimler gözlemlenmekte ve bu da iletken EAP'lerin hassas konum ve kuvvet kontrolünde model esaslı kontrol yöntemlerin uygulanmasını güçleştirmektedir. Bu çalışmada üç katmanlı bir iletken EAP bir eyleyicinin konum ve kuvvet kontrolü için bulanık mantık kontrolcü tasarlanmıştır. Tasarlanan bulanık mantık kontrolcü deneysel olarak polimer eyleyiciye uygulanmıştır.

Bulanık mantık kontrolcünün cevaplarını daha iyi kıyaslamak için aynı zamanda bir PID kontrolcü tasarlanmış ve sisteme uygulanmıştır. Bulanık mantık kontrolcü, eyleyicinin konumunu ve kuvvetini kontrol etmede iyi bir performans sergilemektedir.

Anahtar Kelimeler: İletken Polimer, Eyleyici, Bulanık Mantık Kontrol, PID Kontrolcü

Master Thesis

SUMMARY

FUZZY CONTROL OF THE CONDUCTING POLYMER ACTUATORS

Mohammadreza SABETGHADAM

Karadeniz Technical University
The Graduate School of Natural and Applied Sciences
Mechanical Engineering Graduate Program
Supervisor: Assist. Prof. Dr. Mehmet ITIK
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Actuators, as the most important part of mechanisms, influence the design process of engineering products. As society's expectation raises to manufacture novel systems which can imitate their natural prototypes, the need for alternatives to conventional actuators becomes more essential. The desired specifications for a new generation of actuators can be described as being light-weight and silent, and they need to consume as little power as possible.

Conducting polymers are a newly discovered alternatives to classic actuators. They are light-weight and silent and they generate a considerable force and displacement upon application of a very low voltage. These characteristics make them worthy of study as actuators. As these actuators need to be applied in industry, controlling their output is very essential. Different control methods are applied on these kinds of actuators to control their output, but in order to achieve a robust optimum control method, more investigation is still required.

In this study a Mamdani fuzzy inference system is used to control the force and displacement output of the conducting polymer actuator. Finally, results are compared with a PID controller to prove the superior performance of the fuzzy logic controller. From the results, it is evident that the fuzzy logic controller outperforms the other technique.

Keywords: Conducting polymer, Actuator, Fuzzy logic control, PID controller

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1. INTRODUCTION

1.1. Literature Review

There is a growing interest in comprehension of biomimetic systems. Thriving characteristics of systems that are widely seen in nature always motivate engineers to build man-made machines that can adapt traits and behaviors of natural systems and mimic their motions. Most inventions of modern engineering world, such as airplanes and submarines, are bio-inspired products which utilize the principles of their natural prototypes like birds and fish to emulate them precisely.

One of the goals of biomimetic studies is to develop muscle-like actuators that can imitate the performance of natural muscles in the same way that they generate motion in natural biological systems.

Mammalian skeletal muscle is capable of generating large work densities (20-70 kJ/kg), and large deflections (20%) at high strain rates (50% per second) for millions of cycles [1]. They are indeed hybrid systems that combine energy storage, control elements and sensing. No other human-made actuator is able to match the performance of the skeletal muscle. Conventional actuators, such as traditional engines and electrical motors, are efficient, but due to some disadvantages such as their large size, inflexibility, and high power consumption, cannot be considered as promising actuators to be integrated in systems which need small and flexible actuators.

In some bio-mechatronic applications such as small robotic flying insects and robotic fish, actuators are required to be tiny, light and flexible. Also these criteria are important factors for employing the actuators to enhance the movement performance of paralyzed people. Therefore, novel actuator technologies must be developed to fulfill the expectations of engineers for designing these kind of bio-inspired devices.

One of the potential candidates as actuators for biomimetic systems are Electro Active Polymers (EAPs). EAPs are smart materials which respond mechanically to electrical stimulation. Mechanical response of EPAs involves a change in their shape and dimension when they are subjected to electrical stimuli. Also, as their mechanical response resembles that of real muscles, they are called artificial muscles [2-4].

EAPs are categorized into two major groups regarding their working principle: Ionic and Field-activated EAPs. Actuation mechanism of ionic EAPs are based on drifting or diffusion of ions which are electrically induced. In contrast to ionic EAPs, field-activated EAPs are driven by the electrostatic force (Columb interaction). Each EAP category exhibits specific electromechanical properties, each convenient for a different application. For further information reader is referred to the books in which EAP technologies are discussed in details.

Conducting polymers are a class of ionic EAPs that can generate considerable displacement when they are exposed to low potentials (less than 10 V). They are lightweight, silent, inexpensive, compact, bio-compatible, easy to mold and shape, and capable of being nanostructured. Also, their low power consumption and simple operation principles make them very attractive as actuators to be used in diverse fields of engineering, robotics, biomedical applications, and biomimetic systems [5-11].

Some recent applications of conducting polymers in technical literature include: A polypyrrole powered robotic fish [12], a micro-pump [13], and a robotic gripper [14]. Although there are many beneficial characteristics of Conducting Polymer Actuators (CPAs), they also have some disadvantages such as drift, hysteresis, and degradation in actuation performance caused by solvent evaporation which affect their positioning ability negatively [15].

In order to enhance commercial capabilities of these actuators and to widen their application areas, modelling and controlling the position/force output of them have attracted researchers' attention. In the case of investigating position output of CPAs, some works on modelling the chemo-electromechanical dynamics of CPAs can be found in [16-22] which do not capture the nonlinear dynamics of the CPAs. Nonlinear models of CPAs are very limited in number as it is very difficult to identify all the effects causing variations in their dynamics [23, 24]. There are also some research studies that are conducted to model the force output of CPAs in the literature. Fang et al. proposed a scalable dynamic model for displacement output and a quasi-static model for force output for a trilayer CPA [15]. Della Santa et al. proposed a lumped parameter model for both displacement and developed force of a muscle-like linear CPA [16]. Alici and Hyunh derived a quasi-static mathematical model to predict the force induced at the tip of a CPA [17, 18]. Minato et al. also quantified the tip displacement and force output of CPAs with varying geometry [19].

Potential applications of CPAs such as micro-manipulation, micro-electromechanical devices require controlling precisely the force and/or displacement output of CPAs. To accomplish controlling the tip displacement of CPAs a number of control methodologies have been applied on them including: a conventional PID controller [25], a robust adaptive controller to overcome time varying actuation behavior of CPAs due to solvent evaporation during the long-time operation in air [26], a repetitive controller to better track the repeating trajectories [27], and an adaptive sliding mode controller to obtain robust performance in the presence of parametric uncertainties and unmodeled disturbances [28].

1.2. Aim and Scope of the Thesis

Most of the control methods which are implemented on CPAs to control their position output in literature are based on linear models. Modelling of CPAs are challenging, and an accurate mathematical model has not yet been achieved which encapsulates explicitly all nonlinearities in their behavior. Also, the characteristics of CPAs are subject to change in the presence of electrolyte evaporation over a long-time period, which demonstrates that the mathematical models cannot predict CPAs behavior when it is exposed to air for a long time. Fuzzy controllers provide a simple and robust framework for specifying nonlinear control laws which accommodate uncertainty and imprecision. The significant characteristics of fuzzy logic (FL) controllers such as, linguistic based structure, quite robust performance for nonlinear systems, and its ability to take into account the uncertainty in the operating conditions, make them a very popular technique in control engineering field [24]. Recently, Druitt and Alici showed that using Takagi-Sugeno fuzzy and neuro-fuzzy methods to control the tip displacement of CPAs may significantly improve their positioning performance [25]. Nevertheless there is still room to enhance and simplify the design procedure of the FL controller by omitting the gain scheduling level and changing the inference system used by Druitt et al. in their proposed methodology.

Controlling the force output of the CPAs has not been studied in technical literature, and the models for force output of CPAs are either quasi-static models which cannot be used in control design [15, 17, 18] or they are not suitable for the trilayer bender type CPAs operating in air [16]. Therefore, fuzzy control techniques have been utilized in this study to control the force generated at the tip of the CPA. The ultimate aim of this study is to precisely control the force/position output of the CPAs by using the Mamdani fuzzy inference system.

2. CONDUCTING POLYMER ACTUATOR AND ITS DYNAMICS

2.1. Conducting Polymers

Conducting or conjugated polymers are normally semiconducting polymers derived from acetylene, pyrrole, aniline, thiophene and ethildioxithiophene, which are doped under the oxidation process during their electrochemical synthesis to become conductors [29]. The first conducting polymer is polyacetylene, which was synthesized by Shirakawa et al. in 1977 and led them to win a Nobel Prize in 2000. The electrical conductivity in the structure of these polymers is determined by alternating carbon-carbon double bonds on the backbone of the polymer. Conducting polymers have been used in numerous applications as electrical components, memory elements, sensors, super capacitors and actuators during the past decades by researchers. Their multifunctional properties make them even more attractive alternatives for conventional actuators. For instance, a conducting polymer actuator can serve as a strain gauge, a resistor, or a capacitor as a part of electrical circuit.

2.2. Actuator synthesis

The conducting polymer which is used as an actuator in this study is Polypyrrole, which was synthesized in the Intelligent Polymer Research Institute of University of Wollongong, Australia. Its dimensions are 14 mm × 5 mm × 0.17 mm, consisting of three main layers as shown in Fig. 1.

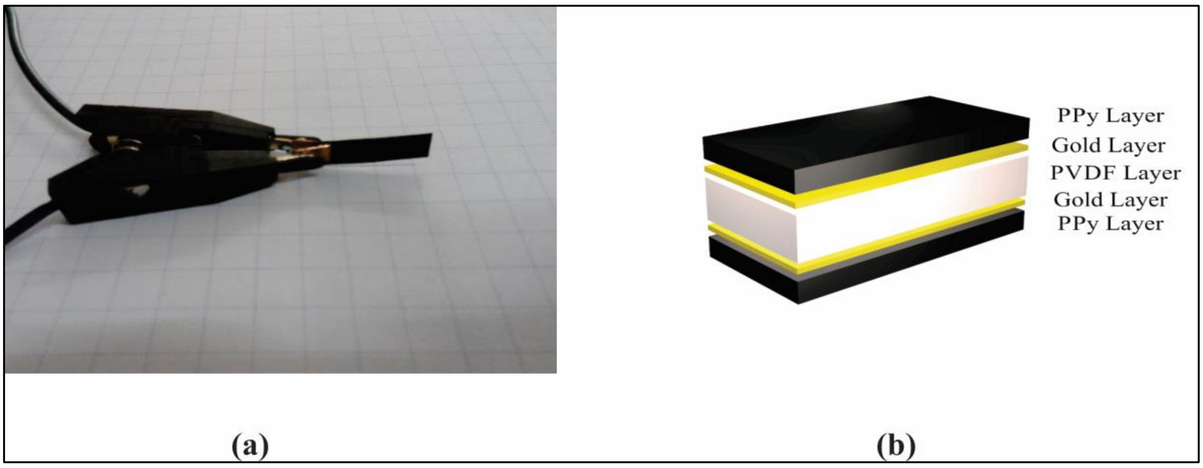

Figure 1. Conducting Polymer actuator: (a) optical image and (b) schematic view of the PPy actuator.

On the outer surfaces, there are two PPy layers, each of which has a thickness of 30 µm, and they perform as electroactive components of the actuator. Between them there is an amorphous, porous nonconductive media layer with a thickness of 110 µm that is made of Polyvinylidene Difluoride (PVDF). Its main duty is to hold electrolyte liquid that supplies ions, which are the main elements of motion in CPAs.

The PVDF layer is coated with 0.2 µm thick gold on both sides to provide a conductive surface on which the PPy electrodes can be electrochemically deposited. The electrolyte is lithium triflouromethanesulfonimide $(Li^{+}TFSI^{-})$. The production steps are given schematically in Fig. 2.

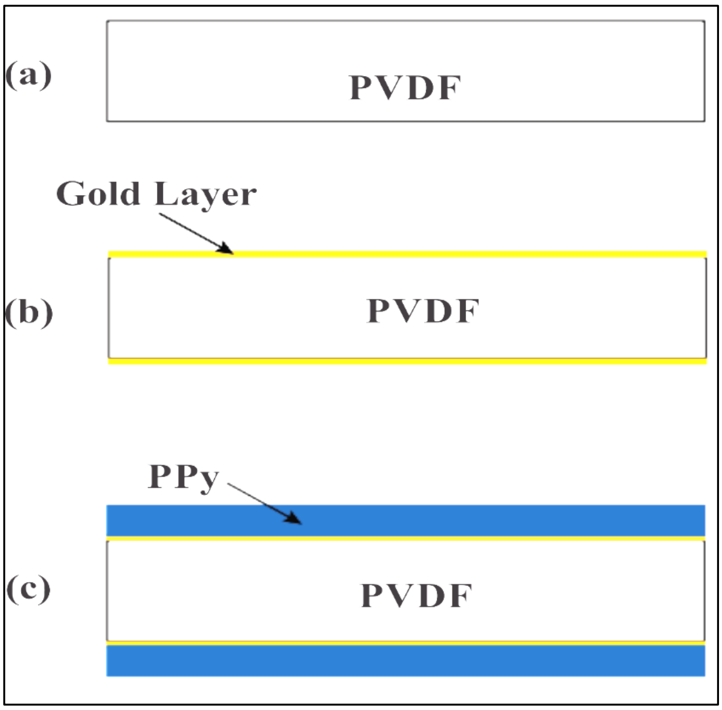

Figure 2. PPy production process: (a) bare PVDF, (b) gold sputtering of PVDF layer, (c) PPy growth on gold-coated PVDF layer

The synthesizing process of the trilayer bending actuator can be briefly described as follows: The polymerization solution was prepared in the room temperature, consisting of monomer (Pyrrole) with concentration of 0.1 M in Poly Carbonate (PC). Afterwards the solution was deoxygenated using N_2 while stirring at least for 20 minutes. Then it was poured into a special glass cell made of engineering silicone which the polymerization takes place in, called the polymerization cell. After preparing the solution, the PVDF layer, which was sputter-coated with thin gold layers on each side, was placed in the cell. Schematic view of the polymerization process is illustrated in Fig. 3. A two electrode setup was also placed in the cell for polymerization which were connected to a galvanostat (Princeton Applied Research, model 363) to provide the constant current density of 0.1 mA/cm^2.

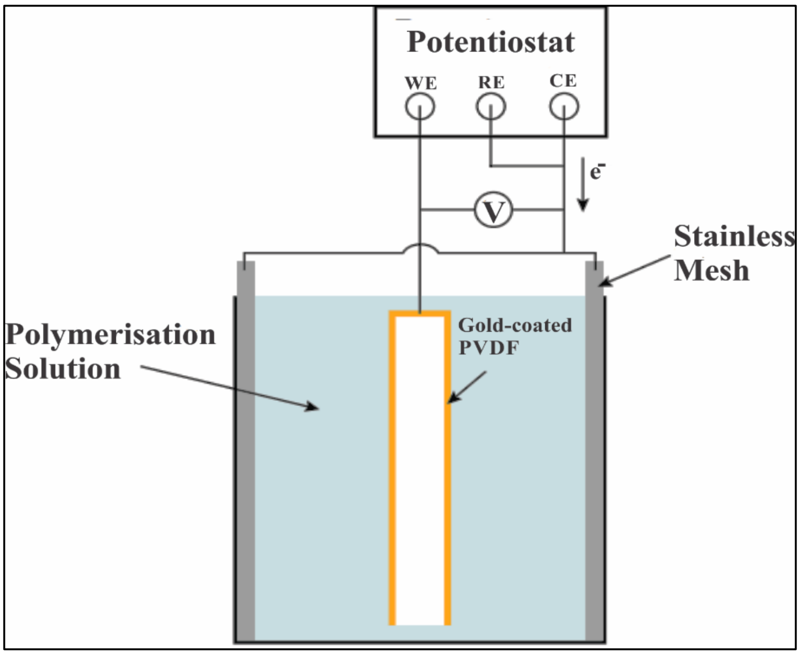

Figure 3. Polymerization cell

During process, the temperature of the cell was kept constant at -35 °C . This process lasted for 12 hours. Once the polymerization process was done, the bulk sheet of the actuator was taken out of the cell and washed with acetone. Then it was submerged and stored in 0.1 M $(Li^{+}TFSI^{-})$ in PC. Then the bender actuator was cut as required from the bulk sheet using a cutter to avoid electrical contact between two PPy layers.

2.3. Actuation Mechanism

The actuation mechanism of CPAs is intimately related to the electronic structure of them, which allows electrons to be removed relatively easy by electrochemical oxidation [30]. When an adequate voltage is passed through the PPy layers on the actuator, the PPy layer on the anode side is oxidized, while that on the cathode side is reduced. The redox equation is as follows.

$$PPy + TFSI^{-} \underset{\text{Reduction}}{\overset{\text{Oxidation}}{\rightleftarrows}} PPy^{+}TFSI^{-} + e^{-}$$

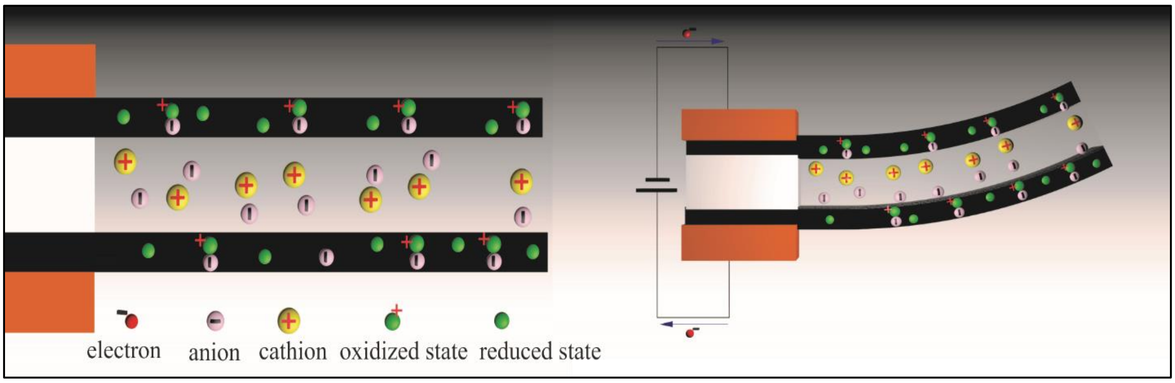

Figure 4. Actuation mechanism of trilayer CPAs

To maintain charge neutrality within the PPy layers, $TFSI^-$ anions will be absorbed by the positively charged PPy electrode. Hence this layer expands. While the anions ($TFSI^-$) are expelled from the negatively charged electrode, reduction of the PPy causes it to become uncharged and a volume contraction occurs [31]. As a result, the expansion-contraction triggered by the redox process causes a newly-created cantilevered structure to bend towards the negative electrode as illustrated in Fig. 4.

2.4. Dynamics of the Actuator

In order to evaluate the fuzzy logic controller's performance, a PID controller is necessary as they are very common types in the control engineering field. To design and fine-tune the PID controller, a mathematical model of the actuator is required. Thus we obtain a transfer function model of the CPA via MATLAB's system identification tool. Modelling procedure is discussed in detail in the following section.

2.4.1. System Identification for Tip Displacement of the Actuator

In order to design and fine tune the PID controller, we needed to obtain a linear model of the position output of the CPA. For this purpose we used the least-squares system identification method to build a transfer function model for each output of the PPy actuator. The system identification method gives us a linear model of the CPA's behavior using a pair of input-output data.

To generate data sets required for system identification, a number of different reference signals were applied on the open loop system, and the response of the actuator was recorded and transferred to MATLAB software. To model the position output of the bender, we applied a sine sweep signal with amplitude of 0.5 V and varying frequency from 0.01 to 2 Hz. To validate the obtained model, the model output was compared with the actuator's response to a step signal with amplitude of 0.2 V. Figures 5 and 6 illustrate the model's output against the actuator's response, which is acquired experimentally. The transfer function model of the position output of the bending actuator is as follows:

$$\frac{15.78\,s^3 + 45.63\,s^2 + 11.70\,s + 0.0022}{s^5 + 12.89\,s^4 + 37.34\,s^3 + 23.51s^2 + 2.74\,s + 0.0005} \qquad (1)$$

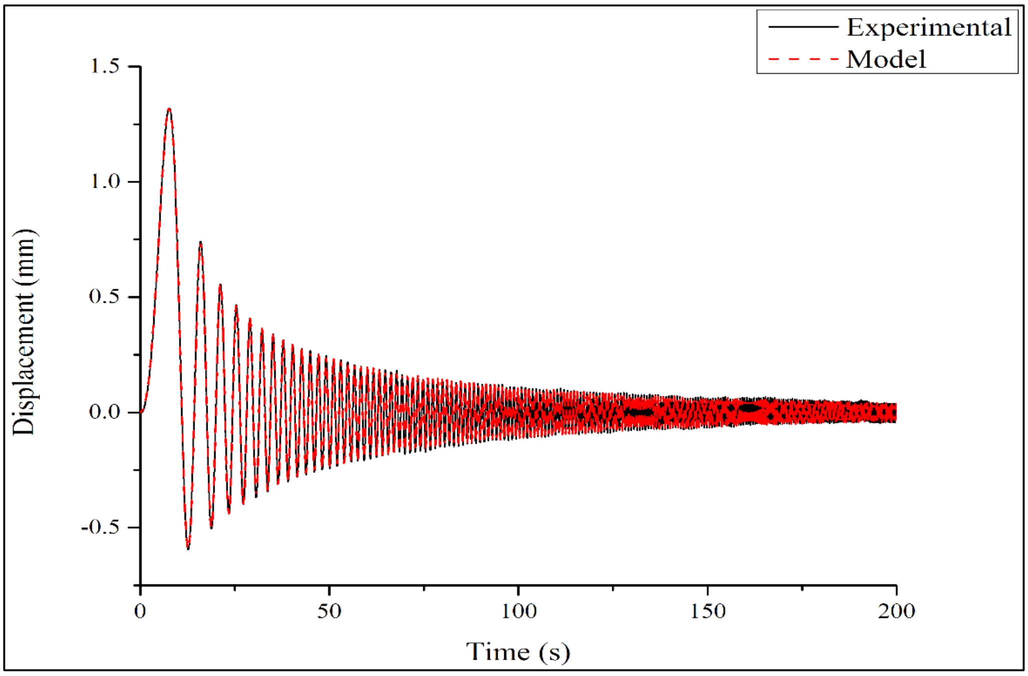

Figure 5. Model and actuator's response to a chirp signal with 0.5 V amplitude and varying frequency between 0.01 and 2 Hz

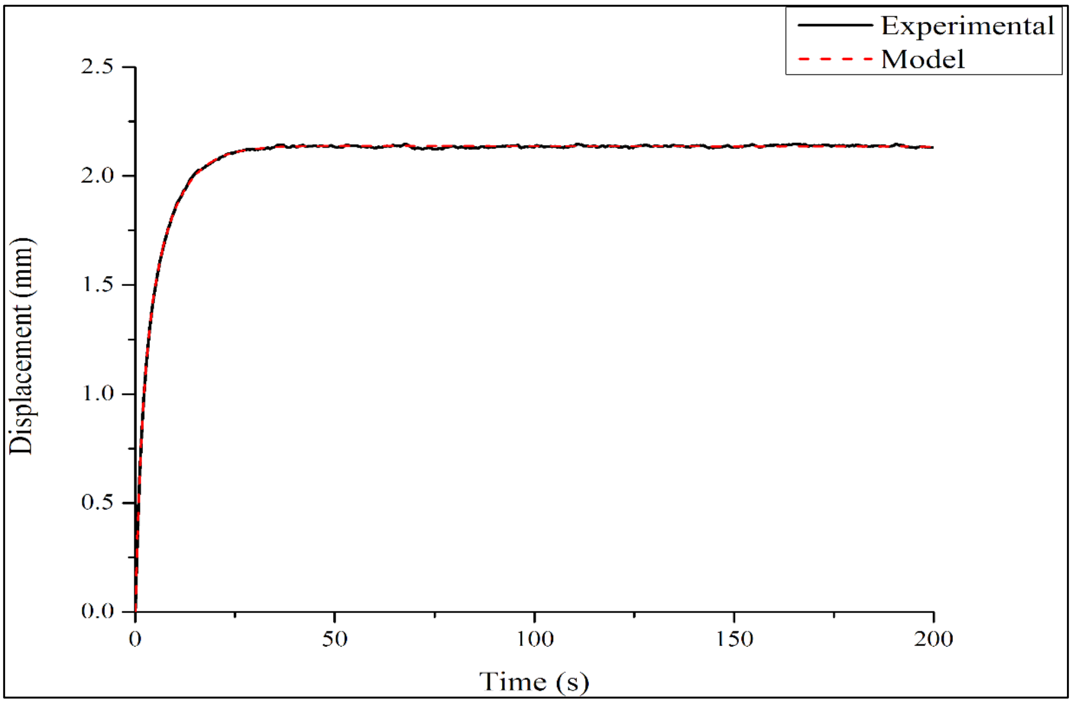

Figure 6. Model and actuator's response to a step reference with magnitude of 0.2 V

2.4.2. System Identification for the Force Output of the Actuator

To design the PID controller for the force output of the CPA, the model of the generated force at the tip of the actuator is required. Therefore a dataset for identifying the force output of the system is generated acquiring the open loop response of the actuator. To obtain the transfer function model of the force output, a PRBS reference signal with amplitude of 0.3 V and frequency of 1 Hz is used to generate input-output datasets required for identification process. The sampling rate of data acquisition is chosen to be 0.01. To validate the obtained model, a step input with 0.5 amplitude is used to compare the output of the model with the experimental response of the actuator. The identified transfer function of the actuator for the force output is:

$$\frac{350.3s^4 + 218.1s^3 + 23.95s^2 + 4.927s + 0.1398}{s^6 + 29.54s^5 + 53.8s^4 + 17.47s^3 + 2.323s^2 + 0.3353s + 0.007283} \tag{2}$$

The transfer function model's output versus experimental output of the CPA is depicted in figures 7 and 8 for PRBS and step reference signals respectively.

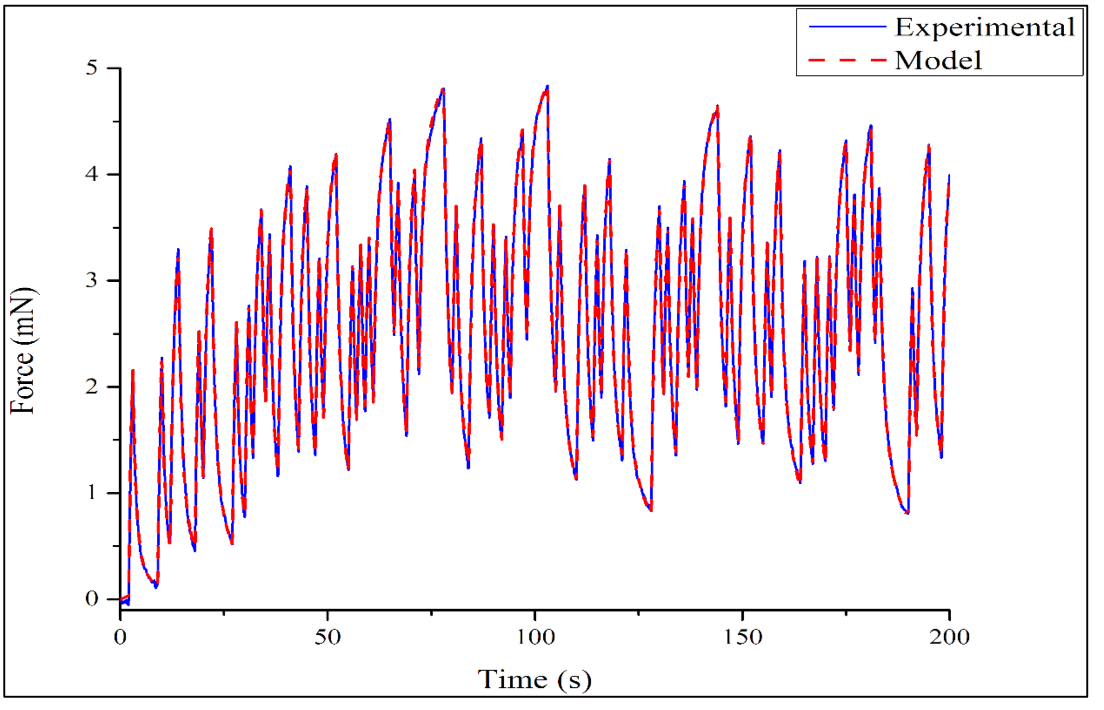

Figure 7. Measured and simulated force output to a PRBS input of 0.3 V amplitude and 1 Hz frequency

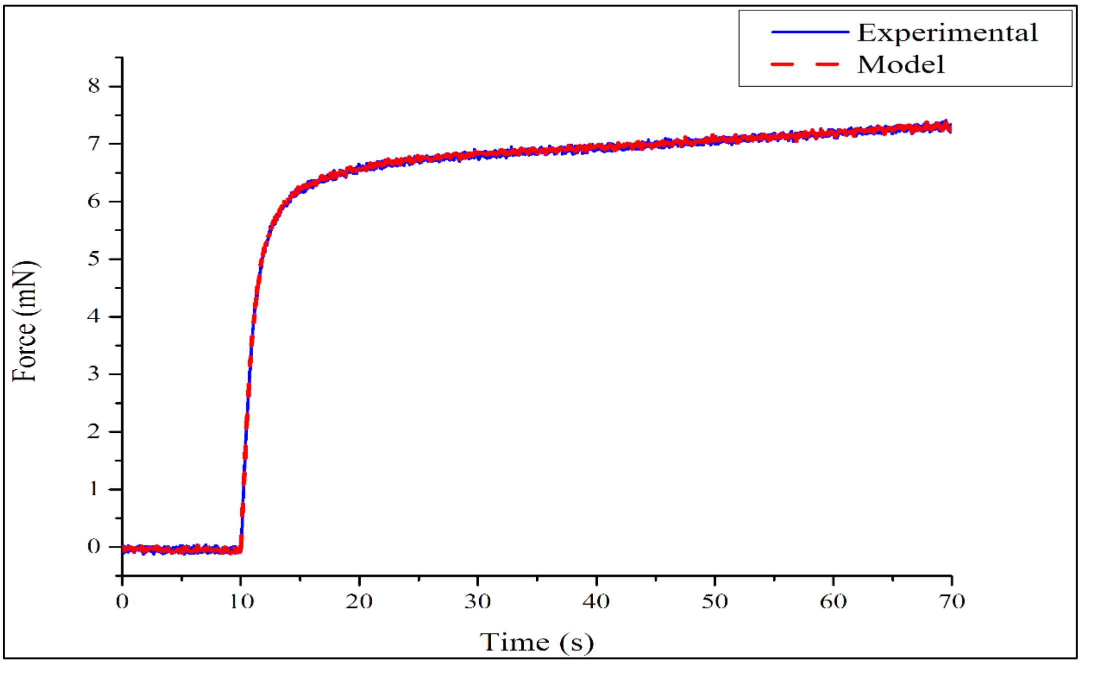

Figure 8. Measured and simulated force output to a step input of 0.5 V amplitude

As is evident from the figures shown, transfer function models represent a successful performance in terms of matching the experimental data acquired.

3. FUZZY LOGIC CONTROL

3.1. Fuzzy Logic Control Background

Fuzzy set theory was first introduced by Zadeh [32], and Mamdani used this theory for the first time in order to control a simple dynamic system [33]. Since then, fuzzy logic controllers are widespread in many engineering applications [34, 35]. FL controllers are one of the most effective control schemes for plants having difficulties deriving mathematical models, or having performance limitations with conventional linear control techniques.

Fuzzy control is based on fuzzy logic rules, which are closer in spirit to human thinking and natural language as compared to traditional logical systems. Fundamentally, it provides an effective method of capturing the approximate, inexact nature of the real world. Viewed in this perspective, the main part of the FL controller is a set of linguistic control rules which define the essential control scheme in terms of “if-then” expressions. In fact, the FL controller provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy.

A FL controller typically includes four major units. These are the fuzzifier, which turns crisp input data into a fuzzy term set; the fuzzy rule base, which contains fuzzy rules describing how the fuzzy system acts; the fuzzy inference engine, which is responsible for approximate reasoning by associating input variables with fuzzy rules; and the defuzzifier, which transforms fuzzy output of the FL controller to a crisp value for the actual system input over the target [36].

When it comes to designing a FL controller, the selection of fuzzy sets of linguistic variables, the shapes of membership functions, the fuzzy rule base, the inference mechanism, and the defuzzification method are considered as design parameters, all of which have influence on control performance. Therefore, it is the designer’s duty to choose these factors with care by observing the system’s behavior in order to achieve the optimum design for the FL controller.

3.2. FL controller Design for Conducting Polymer Actuator

The methodology of the FL controller is very beneficial, particularly when the processes are too complex for analysis by quantitative techniques, or when the available sources of information are interpreted imprecisely, or indeterminately [37]. Modeling of CPAs has not reached the accuracy desired. As a result, proposed models cannot represent all nonlinearities and uncertainties in behavior of these actuators. Therefore, the performance of model based controllers for CPAs are affected by these inaccuracies. FL controllers' non-model-based design feature, their ability to take uncertainties in the operational conditions, and their robust performance for nonlinear systems, make them a promising and superior control method for precise positioning of CPAs compared with model based controllers [25].

In this study, we propose the Mamdani Fuzzy Logic inference system. Design methodology of the fuzzy controller used in this study is based on what Altas and Sharaf proposed in [38, 39] and explained step by step as follows. The development of the FL controller is done in MATLAB/SIMULINK environment.

The design procedure of fuzzy logic controller is based on heuristic information obtained by observation of the dynamical behavior of the CPA. Therefore a successful design requires a knowledgeable domain expert and experimentation. Choosing the inference system determines the format of fuzzy rules. Mamdani reasoning system is selected here, in which fuzzy rules are defined as:

$$R_i \ : \ IF \ e \ is \ A_i \ AND \ de \ is \ B_i \ THEN \ du \ is \ C_i \tag{3}$$

where e and de are the input variables, du is the output variable, A, B and C are linguistic values of e, de and du, respectively.

Step 1: After picking the reasoning system, the initial step to develop a fuzzy controller for CPA is to choose input and output variables. Input variables for the FL controller are determined as error, $e(\mathrm{t})$ and its derivative ($de(t)$). Output of the fuzzy controller is the actuation voltage $u(t)$ .Error, $e(\mathrm{t})$ is defined as the difference between the desired tip displacement of the actuator, y_d and its measured displacement, y_a which can be expressed as:

$$e(t) = y_d - y_a \qquad (4)$$

Derivative of error is defined as:

$$de(t) = \frac{de(t)}{dt} \qquad (5)$$

Step 2: Appropriate membership functions should be chosen to fuzzify the crisp values of each input and output variable. The selection of number and type of the membership functions is based on trial and error. Seven triangular membership functions are considered for each input and output variable. The SIMULINK model of the triangular membership function is given in Figure where xl, xr, xt are crisp values representing the location of the left foot, right foot, and peak point of the triangular membership function. The x is the crisp value of the input variable, where its membership degree is calculated as mu(x) on this fuzzy subset.

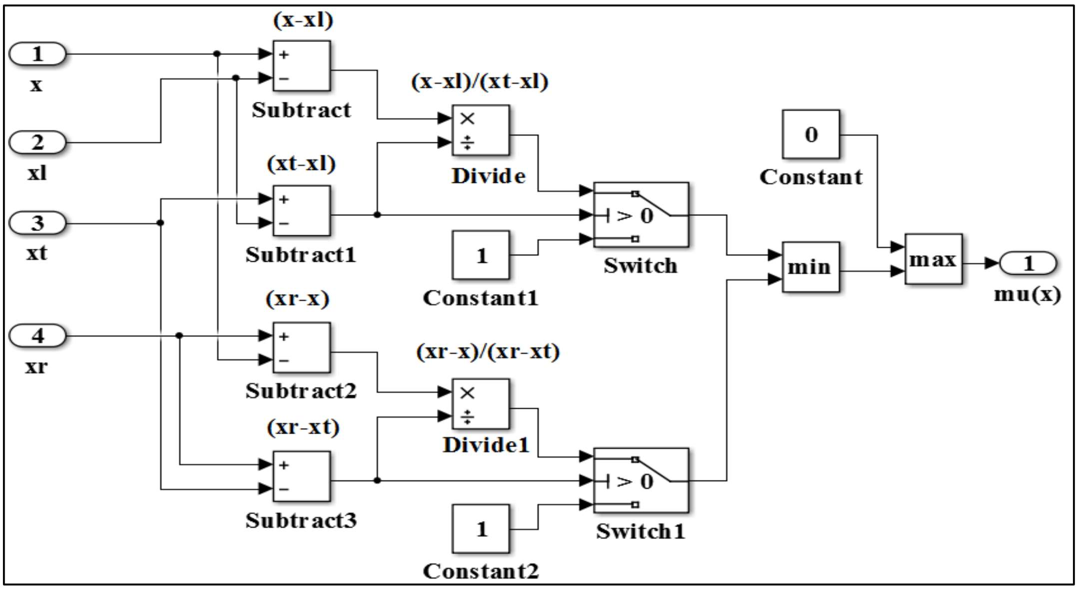

Figure 9. Simulink model of the triangular membership function [38, 39]

The membership functions for input and output variables are illustrated in Figure 10.

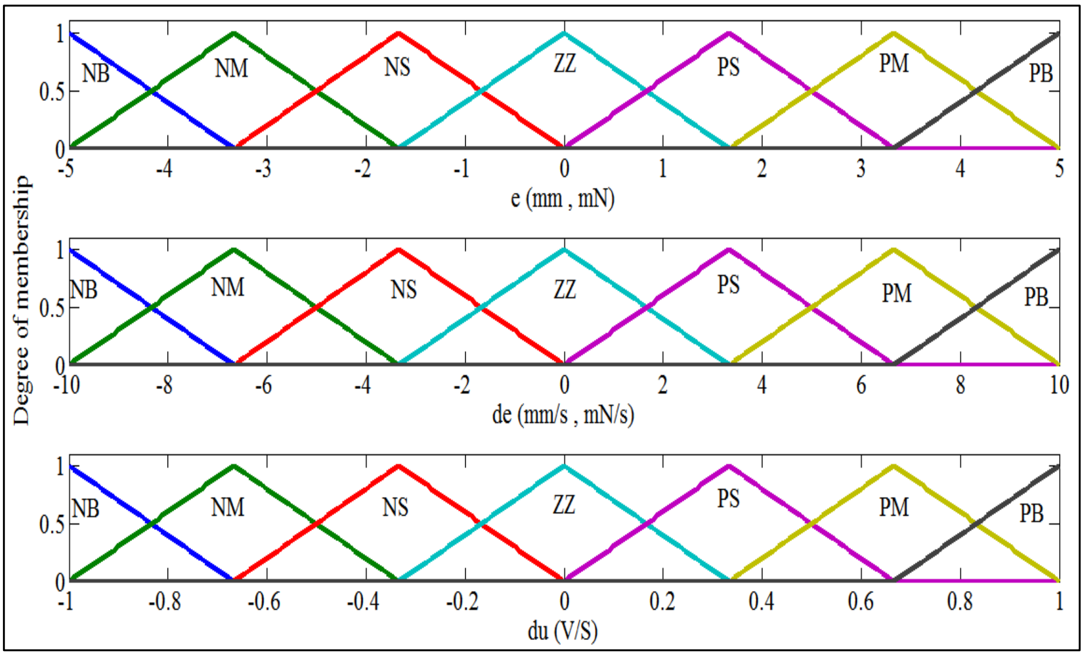

Figure 10. Membership functions of the input and output variables

Utilizing the membership functions shown in figure, the membership degree of each input value is determined and sent to the fuzzification unit which is shown in Figure 11. The part that is represented by $IF\ e\ is\ A_i\ AND\ de$ in (3) forms the input space of fuzzy rules. Thus to model the "and" expression used in the input space, the "min" operator is used in SIMULINK environment. The output of "min" operators shows the strength of each rule in the output space du. The fuzzification procedure for all 49 rules can be seen in Figure 11.

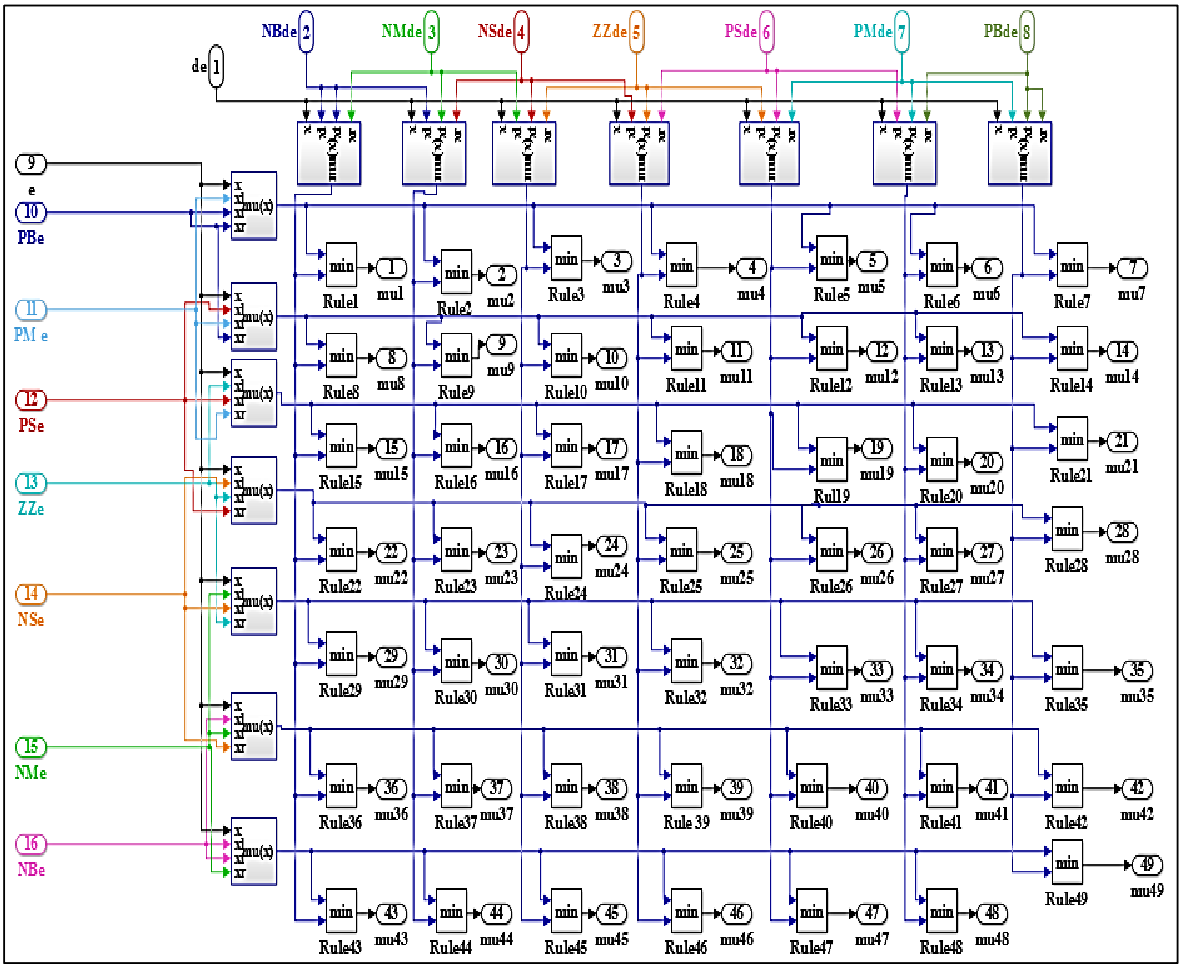

Figure 11. Simulink model of the fuzzification unit [38, 39]

Step 3: In this step we determine the rule base of fuzzy controller, which is obtained based on knowledge of author and experimentation. The rule base used in this study, which consists of 49 rules, is summarized in Table 1.

Table 1. Rule base of the Mamdani fuzzy controller for CPA

U / de / e	**NB**	**NM**	**NS**	**ZZ**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NS	NS	ZZ
NM	NB	NB	NM	NM	NS	ZZ	PS
NS	NM	NM	NS	NS	ZZ	PS	PM
ZZ	NM	NM	NS	ZZ	PS	PM	PM
PS	NM	NS	ZZ	PS	PM	PM	PB
PM	NS	ZZ	PS	PM	PM	PM	PB
PB	ZZ	PS	PM	PM	PM	PB	PB

Based on the fuzzy rule base shown in Table 1, the membership degrees obtained in fuzzification unit are multiplied by crisp values of each corresponding fuzzy subset in the output space du .The model of fuzzy decision table in SIMULINK is given in Figure 12.

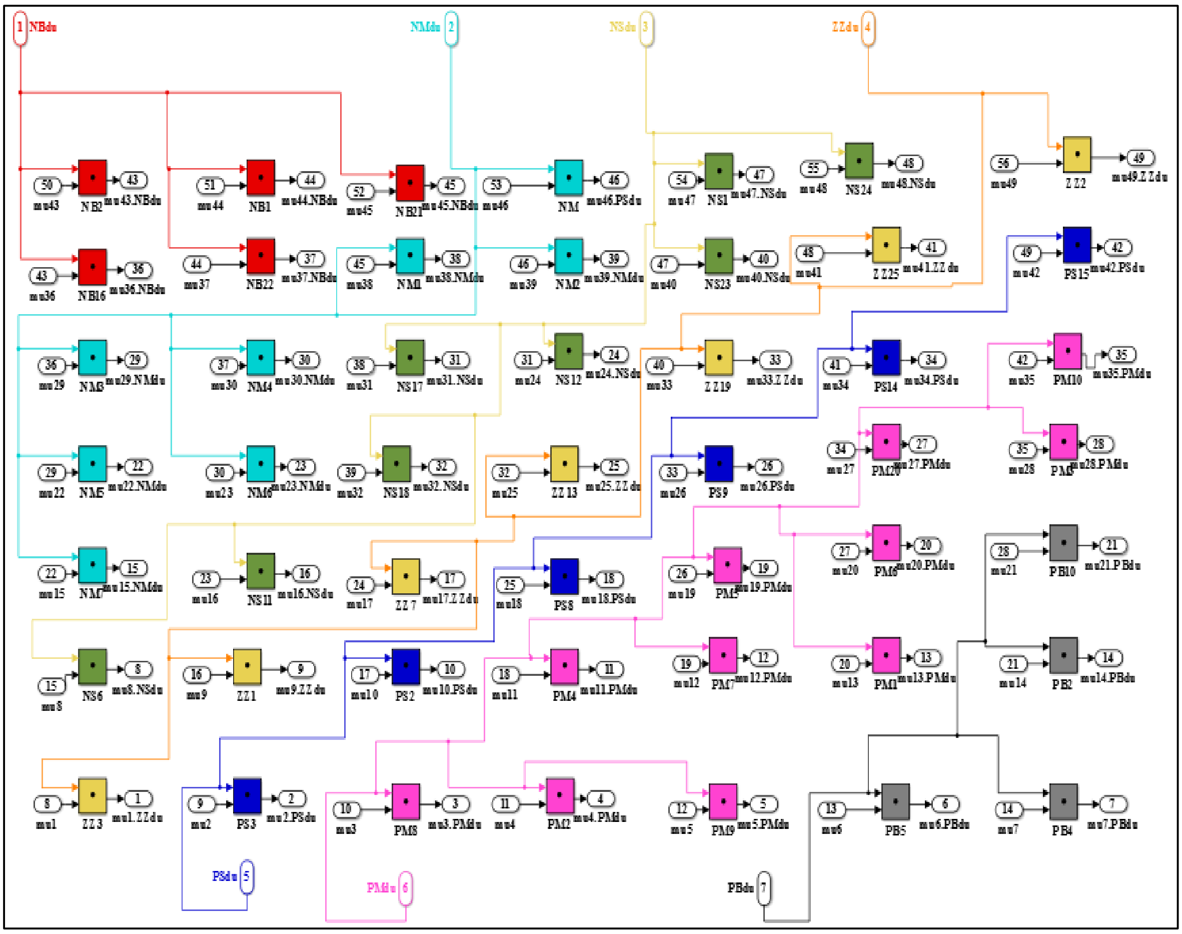

Figure 12. Simulink model of fuzzy decision table [38, 39]

Step 4: The defuzzification of the output value calculated during the fuzzy reasoning is the final step of design process. To obtain crisp values for output, we used centroid defuzzification technique

$$z^* = \frac{\int \mu_i(z)\, z\, dz}{\int \mu_i(z)\, dz} \qquad (6)$$

where z^* is the defuzzified output, μ_i is the aggregated membership degree, and z is the output value. The simulation model of defuzzification procedure in SIMULINK is shown in Figure 13.

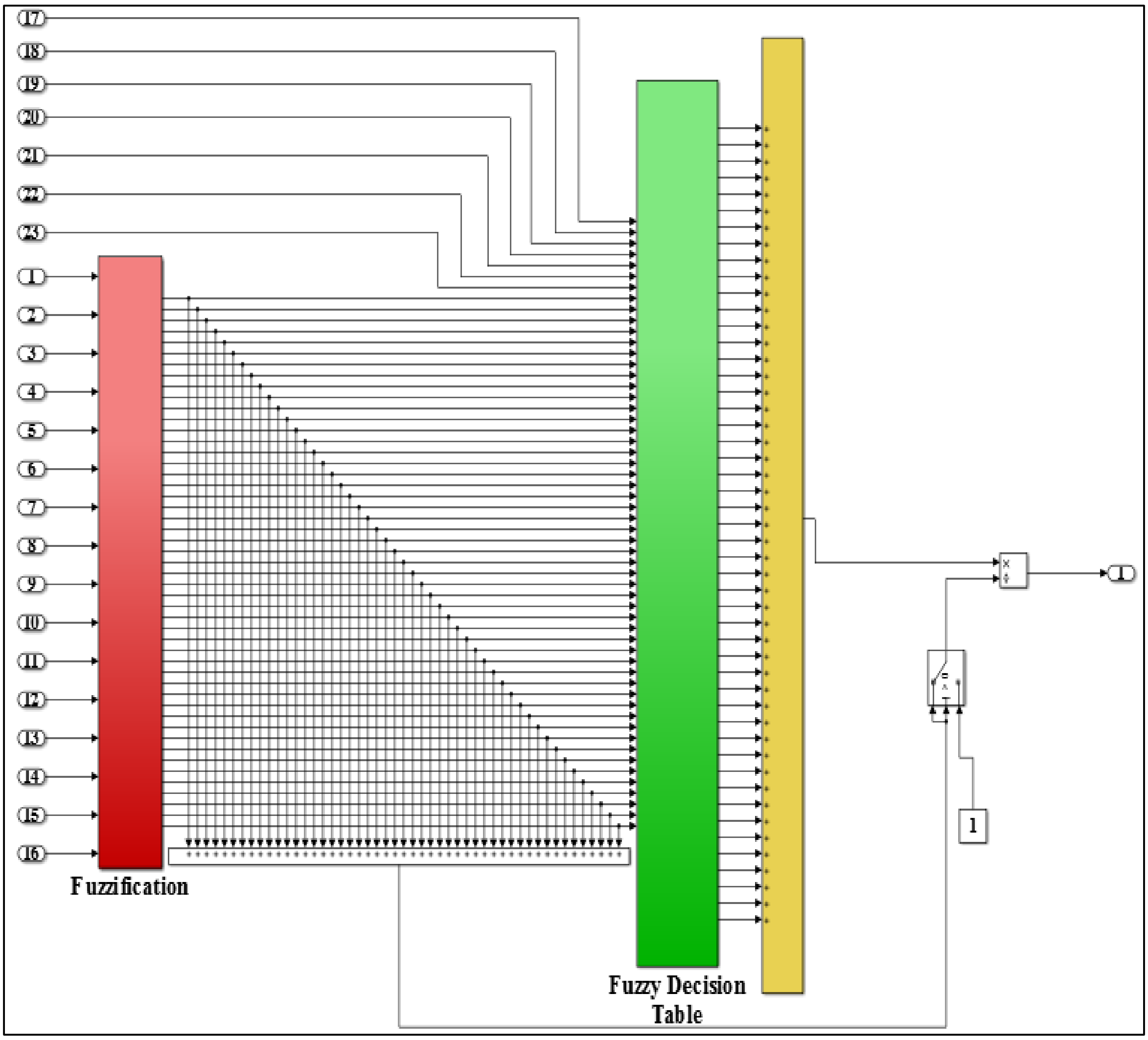

Figure 13. Fuzzy reasoning representing the process from fuzzification to defuzzification [38, 39]

As is observable in Figure 13, to prevent the zero division, which may cause difficulties during simulation such as delayed simulation time and simulation hanging, a signal route has been implemented. Output surface of the Mamdani fuzzy controller and a general overview of the FL controller are illustrated in Figures 14 and 15 respectively.

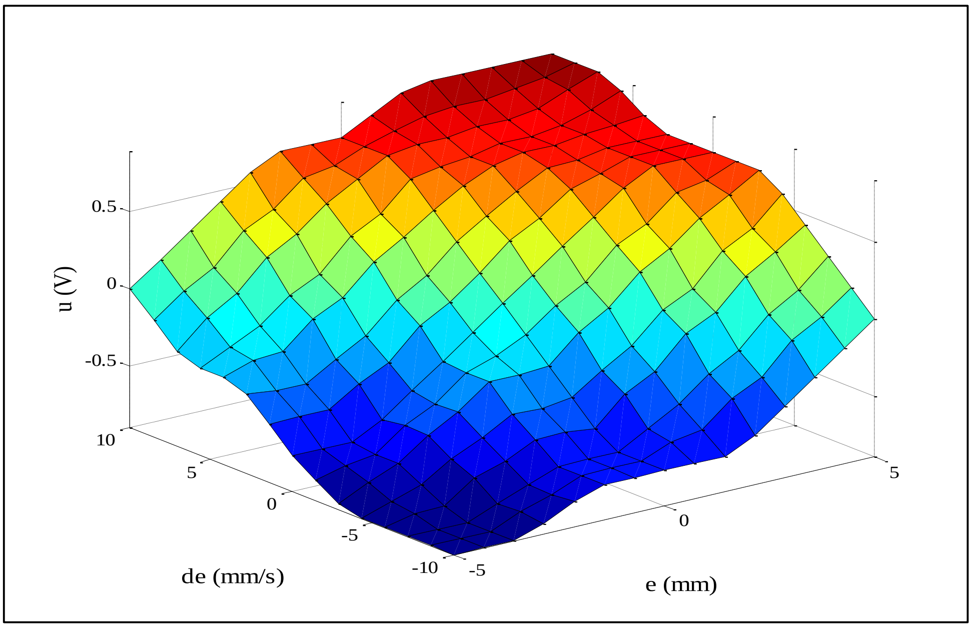

Figure 14. Output surface of the Mamdani fuzzy logic controller

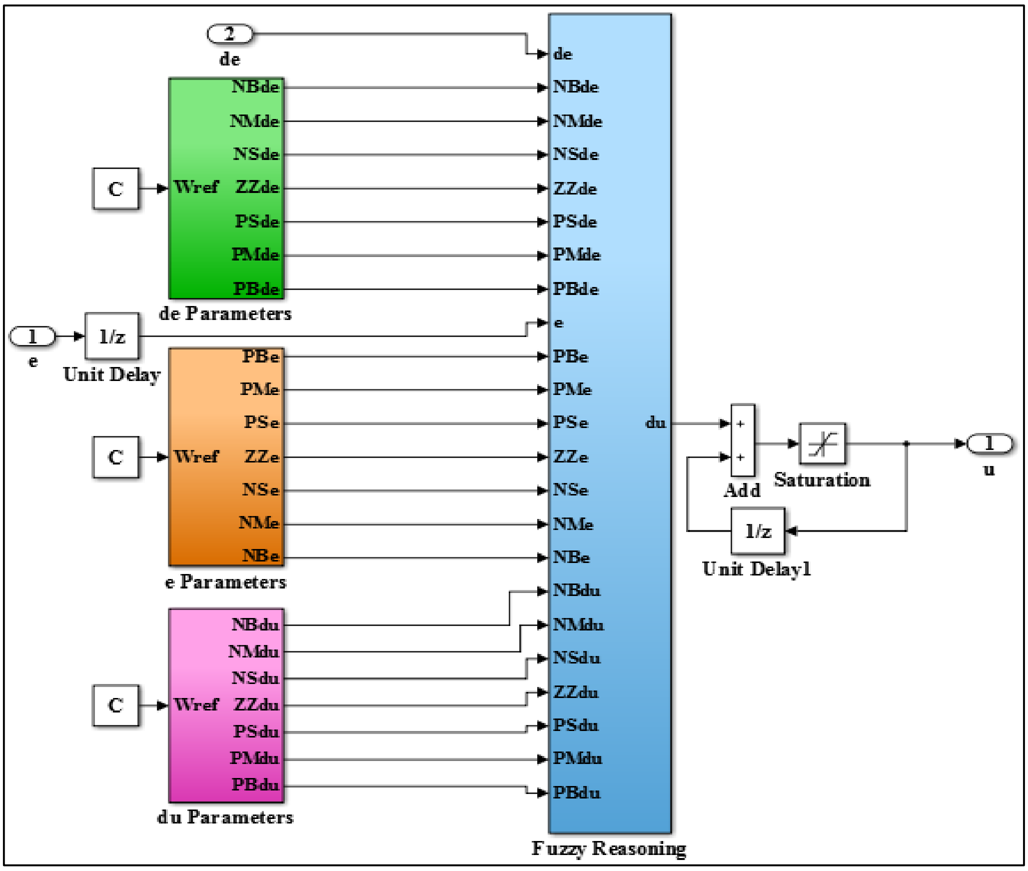

Figure 15. An overview of the FL controller developed in SIMULINK [38, 39]

4. EXPERIMENTAL SETUP AND RESULTS

4.1. Position Control of CPA

The experimental setup to implement the designed Fuzzy Logic controllers for controlling the tip displacement of the CPA is illustrated in Fig. 16. The tip position of the cantilevered PPy actuator is measured using Bauamer OADM 20I6460/S14F laser sensor with a resolution of $5\mu m$. Employing xPC Target platform, an analog signal supplied by the laser sensor has been acquired and transferred to MATLAB/Simulink environment by a National Instruments NI 6251 data acquisition card.

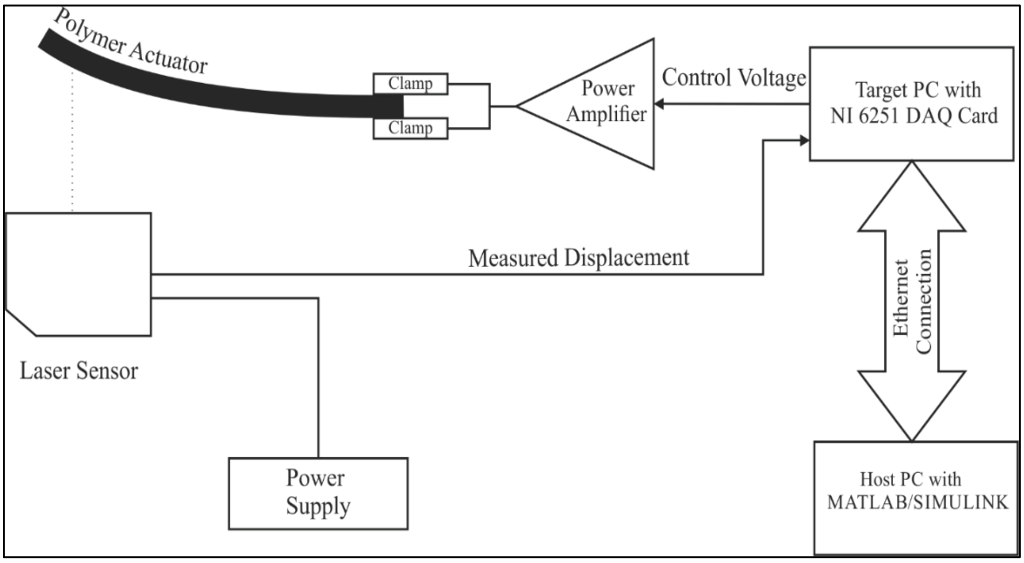

Figure 16. Experimental setup

In order to examine the performance of the proposed FL controller and PID controller, two different signals are used: a square wave with 1 mm amplitude and 0.1 Hz frequency, and a sinusoidal wave with the same specifications. We also design two different PID controllers based on an identified transfer function model for tracking the square wave and sine signals for performance comparison purposes between PID and FL controllers.

Performance of all controllers were first simulated in Simulink using Runge-Kutta solver and sample rate of 0.01 with models obtained in Section 2. After ensuring that controllers are successful in controlling the tip displacement of CPA, they have been implemented experimentally on the actuator. The Simulink block diagram, which is used to implement controllers experimentally, is given in Figure 17.

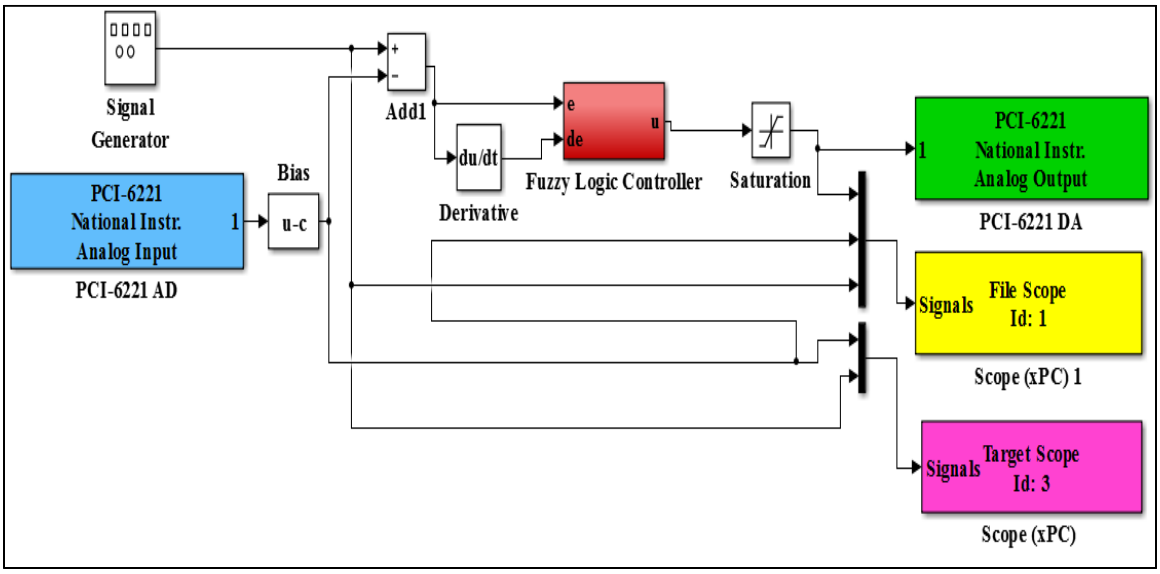

Figure 17. Simulink block diagram of the experiment

4.1.1. Square Wave Signal

Using the square wave as a reference enables us to investigate the step response characteristics of the actuator together with its harmonic response to the signal. We first implemented the FL controller and then a PID controller was also implemented which was tuned based on an identified model of the actuator in MATLAB. The actuator’s tip displacement and the calculated control voltage upon implementation of the Mamdani type fuzzy controller is given in Fig. 18.

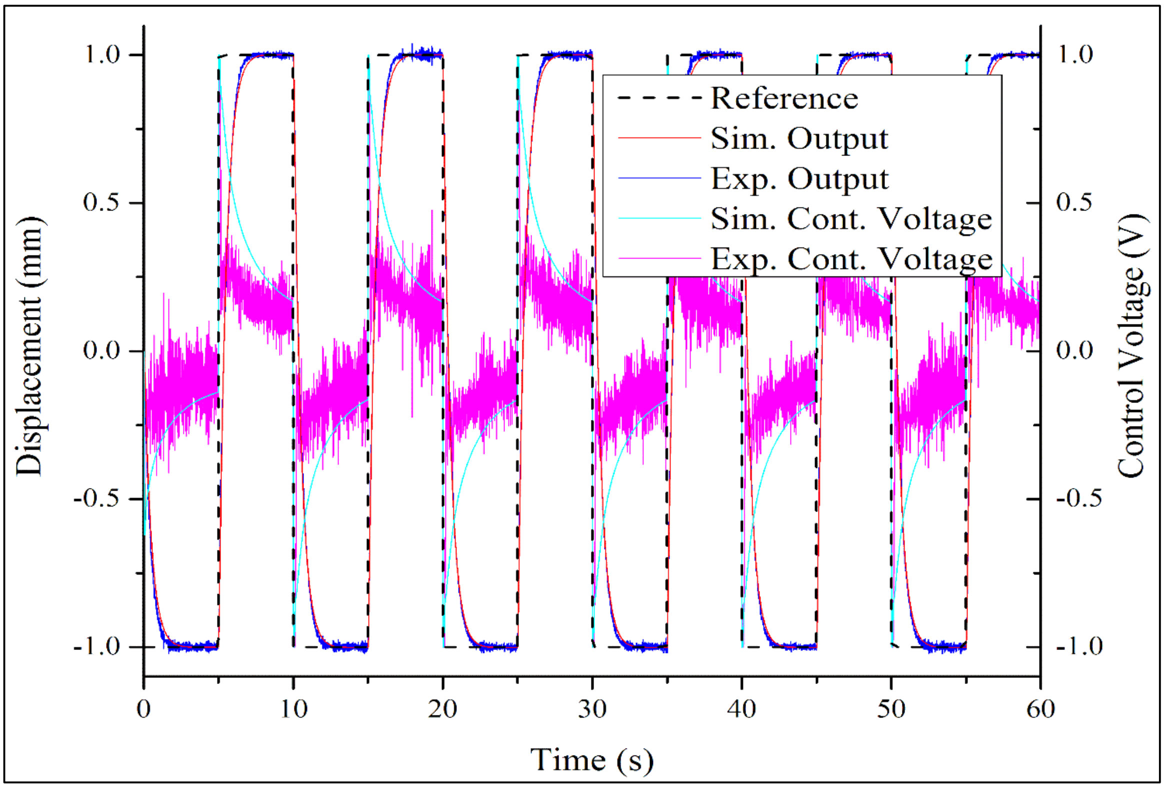

Figure 18. Actuator's tracking response to the square wave signal with the Mamdani fuzzy controller

As can be seen in Fig. 18, the Mamdani fuzzy controller performs quite well in tracking the square wave signal. Moreover, the control voltage inferred by the Mamdani type fuzzy controller stays in the safe operation limit of the CPA.

We also designed a PID controller based on an identified model of the CPA for comparison purposes with the FL controllers. The parameters of the PID controller for tracking the square wave signal were selected as $K_p = 1.7, K_I = 0.7$ and $K_D = 0.008$. The response of the actuator to the PID controller is shown in Fig. 19.

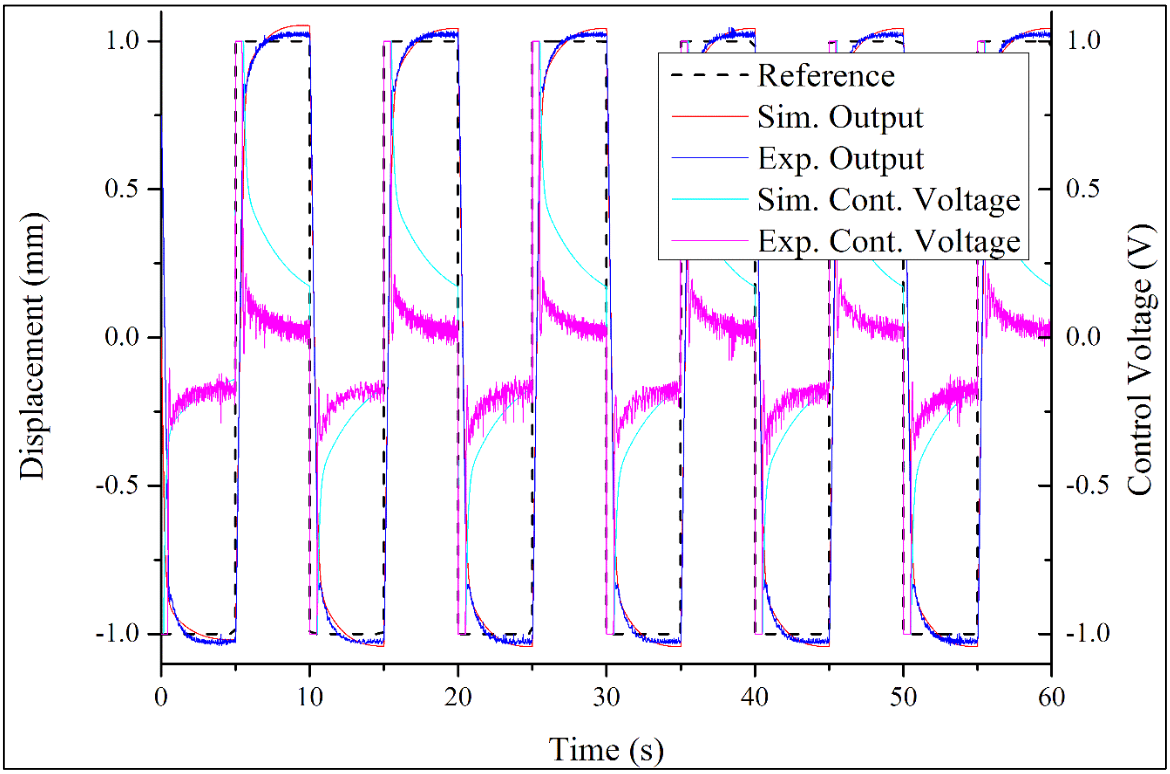

Figure 19. Actuator's response to the square wave signal with PID controller.

In order to compare the performances of controllers, we use the step response characteristics which are given in Table 2.

Table 2**.** Characteristics of the step response of CPA

Control method	Rise time [s]	Settling time [s]	Steady state error [mm]
Mamdani FL controller	0.90	1.50	0.0053
PID	0.97	1.64	0.0299

As expected, the Mamdani FL controller with the 0.90 s has the shortest rise time. As PID fails to get to set point, its steady state error is larger than the FL controller. The ideal controller in terms of the step response characteristics is the Mamdani FL controller because of its fast response and least steady state error.

4.1.2. Sinusoidal Reference

Dynamics of the actuator under the proposed controllers are also investigated for a sinusoidal command with 1mm amplitude and 0.1 Hz frequency. PPy actuator’s tip displacement along with control voltage for the Mamdani fuzzy controller is illustrated in the Figure 20.

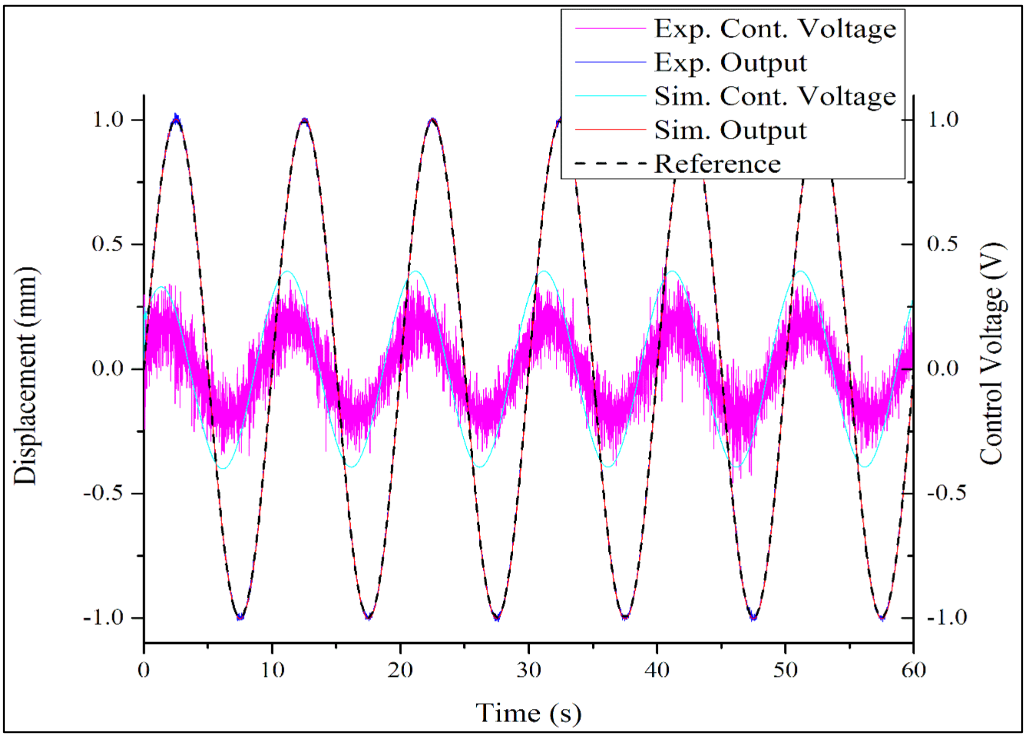

Figure 20. Sinusoidal response of actuator with the Mamdani fuzzy logic controller

We designed and implemented a new PID controller to track the sine input signal because it was impossible to achieve a considerable performance improvement with the PID that was designed for the square wave reference. The new PID parameters were selected as $K_p = 20, K_I = 9.72$ and $K_D = 0.0015$. The response of the PPy actuator upon implementation of PID controller to track the sinusoidal input is depicted in Figure 21. The controller demonstrates adequate results in tracking the input command. Control voltage is within the safe range of applicable voltage to the actuator.

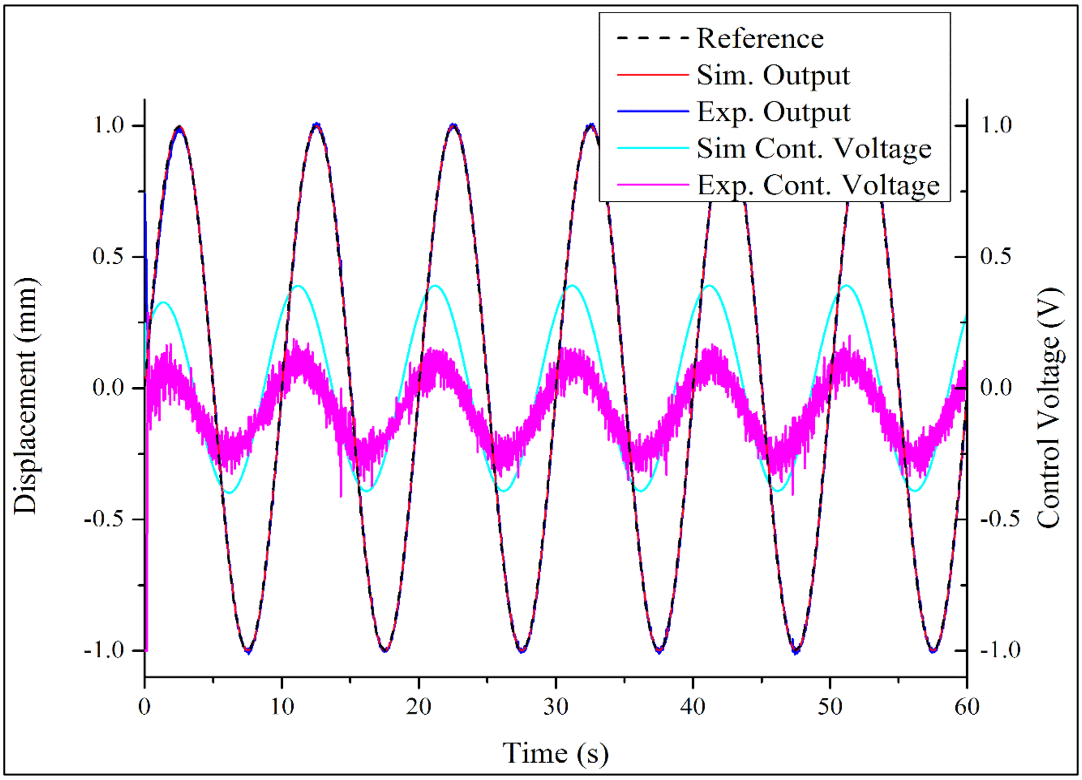

Figure 21. Sinusoidal response of actuator with PID controller

To evaluate the controllers' performances for tracking the sinusoidal signal, we used a metric for the tracking error namely normalized average error (e_a)

$$e_a = \frac{\int_0^{t_f} |y(t) - r(t)|\, dt}{\int_0^{t_f} |r(t)|\, dt}$$

(7)

where t_f is the duration of the experiment. The metric for tracking error of sinusoidal reference for all controllers are given in Table 3.

Table 3. Tracking error evaluation of controllers

Control method	e_a
Mamdani FL controller	0.0061
PID	0.0177

As can be comprehended from Table 3, according to e_a , PID has a larger tracking error compared to the FL controller. The FL controller exhibits 2-3 fold improvements in tracking the sine wave compared to the PID controller.

4.1.3. Repeatability

In order to prove the repeatability of the experiments and robustness of the designed controllers, we applied them on another CPA. The second sample's geometrical specifications are the same as the first one. Again two signals, one square and one sine wave are used as the command inputs. The actuator's step response characteristics are listed in Table 4 for the second sample.

Table 4. Characteristics of the step response of the second sample of CPA

Control method	Rise time [s]	Settling time [s]	Steady state error [mm]
Mamdani FL controller	0.84	1.29	0.0067
PID	1.46	2.90	0.0216

By comparing the results of FL controllers for the new sample to the first sample, it can be seen that the rise time and settling time has been decreased very slightly, which is negligible. However, the rise time of the PID controller has increased and its rise time has been doubled approximately. This can be attributed to the fact that the PID controller was designed by using the identified linear model of the first sample. There is not any significant change in the steady state error of the FL controllers implemented on the second sample, however steady state error of the PID has decreased nearly 50%. With reference to the results in Table 4, it can be claimed that the FL controllers exhibit a repeatable performance both in terms of transient response and steady state response, while the transient response characteristics obtained by the PID are considerably changed.

Tracking errors calculated by using (7) are given in Table 5 for the sinusoidal input. Although, the average error has increased up to nearly three times under the PID controller in tracking the sine wave, there is no significant change in the tracking error of the sinusoidal wave under the FL controllers. The PID controller's sine wave tracking error is increased which shows that PID lacks repeatability and coping with changing dynamics of the actuator.

Table 5. Tracking error evaluation for the second CPA sample

Control method	e_a
Mamdani FL controller	0.0075
PID	0.0371

4.2. Force Control of CPA

The experimental setup to implement the designed Fuzzy Logic controllers for controlling the force output of the CPA is illustrated in Fig. 22. The force generated at the tip of the cantilevered PPy actuator is measured via Millinewton (IPR EPFL, Switzerland) force sensor. Employing an xPC Target platform, an analog signal supplied by the force sensor has been acquired and transferred to MATLAB/Simulink environment by National Instruments NI 6251 data acquisition card.

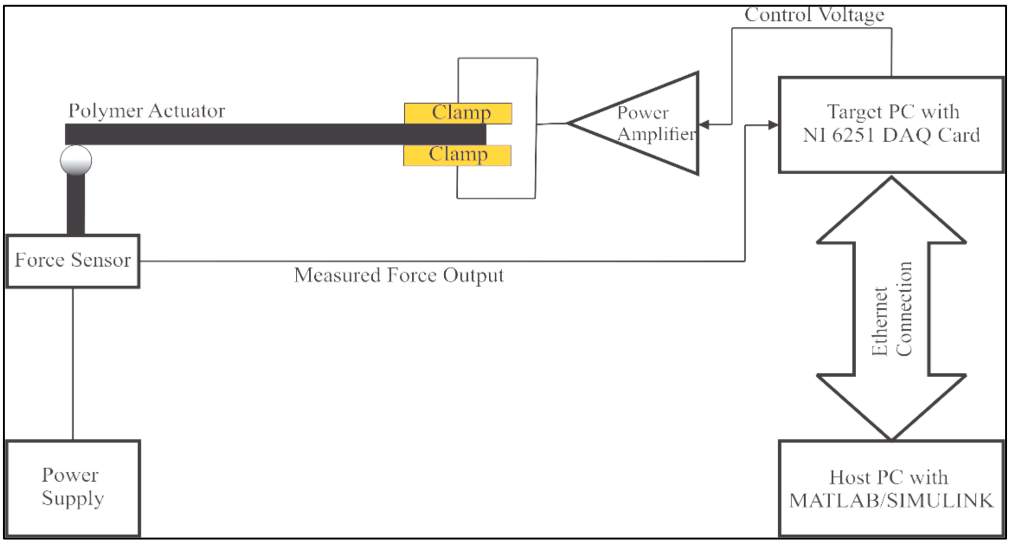

Figure 22. Experimental setup

In micro/nano gripping and cell injection applications where CPAs are very suitable to provide the required motion, it is important to keep the desired force at the tip of the actuator at a constant set point value. In evaluating the designed controller performance for such problems, it is suitable to use a step reference as test inputs to the closed loop control system. Therefore, to examine the performance of the designed FL controller we have used the step reference with three different amplitudes which are 1, 2, and 3 mN. To make a fair comparison a PID controller is designed and fine-tuned using an identified transfer function model. Parameters of the PID controller is as follows $K_P = 0.47, K_I = 0.66, K_D = 0.005$.

We first simulated FL and PID controllers in Simulink, and then all of them were implemented on the experimental setup. The actuator's force output and the calculated control voltage upon implementation of the Mamdani type fuzzy controller is given in Fig. 23. As can be seen in Fig. 23, the Mamdani fuzzy controller performs quite well in reaching the set point. Moreover, the control voltage inferred by the Mamdani type fuzzy controller stays in the safe operation limit of the CPA.

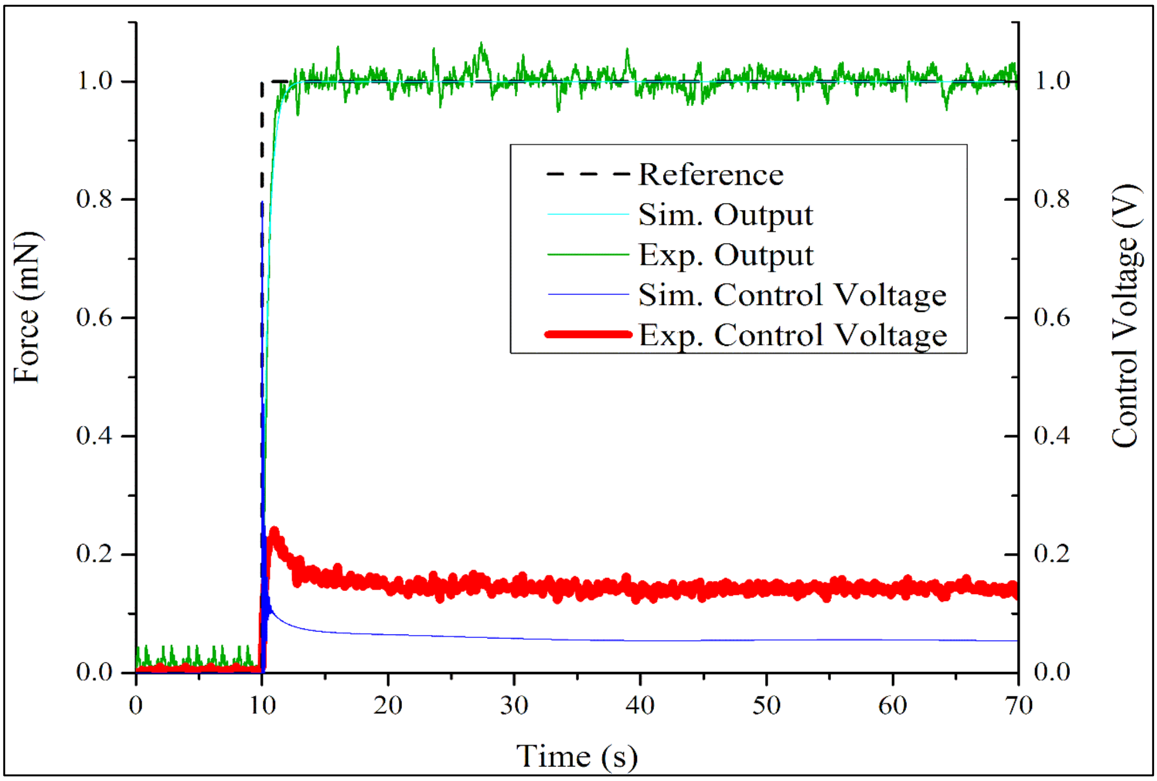

Figure 23. Force response of the actuator to a step of 1 mN under the FL controller

We also designed a PID controller based on an identified model of the CPA for comparison purposes with the FL controller. The response of the actuator to the PID controller is shown in Fig. 24.

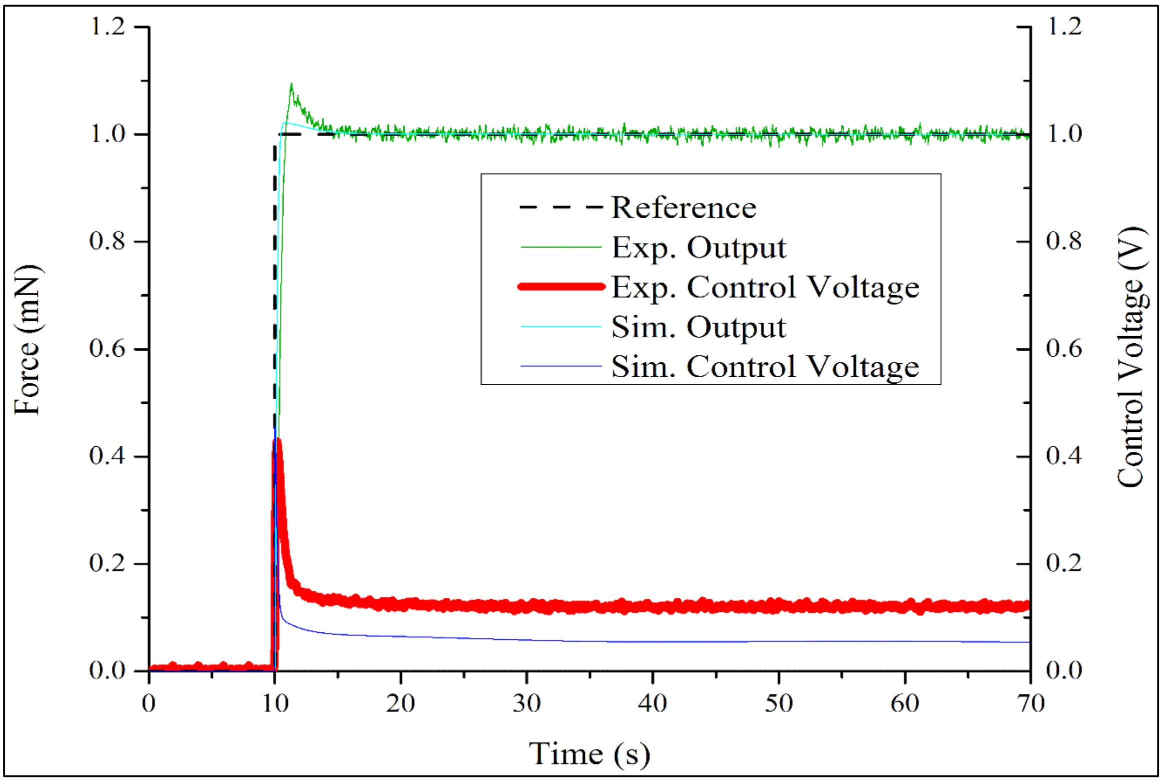

Figure 24. Force response of the actuator to a step of 1 mN under PID controller

As is observable from Figures 23 and 24, controllers are successful in controlling the force output of the actuator and reaching the desired final value, however their performance in terms of step response characteristics are considerably different. Step response characteristics of the actuator to all controllers is summarized in Table 6.

Table 6. 1-mN controlled step response performance

Control Method	Rise Time [s]	Settling Time [s]	Overshoot [%]
Fuzzy Logic	0.79	1.03	0
PID	0.53	4.10	9

Table 6 shows the rise time, settling time, and overshoot of the actuator's response to a 1 mN step reference. The FL controller performs better than the PID controller since there is no overshoot in its response, and it achieves a 4-fold improvement in settling time.

As can be seen in Table 6, the FL controller has no overshoot, and has a faster rise time and settling time comparing to the other controller. When we check the required control voltage to reach and stay at the desired set point, it is seen that the voltage consumption of the FL controller is lower, which shows the superiority of the fuzzy methodology in controlling the force output. However, the controllers' voltage requirements have stayed in the safe operation limits.

For investigating the response of the actuator to the designed controllers with different amplitudes, we used a 2 mN step reference either. Actuator's performance along with calculated control voltage under each control scheme is depicted in Figures 25 and 26.

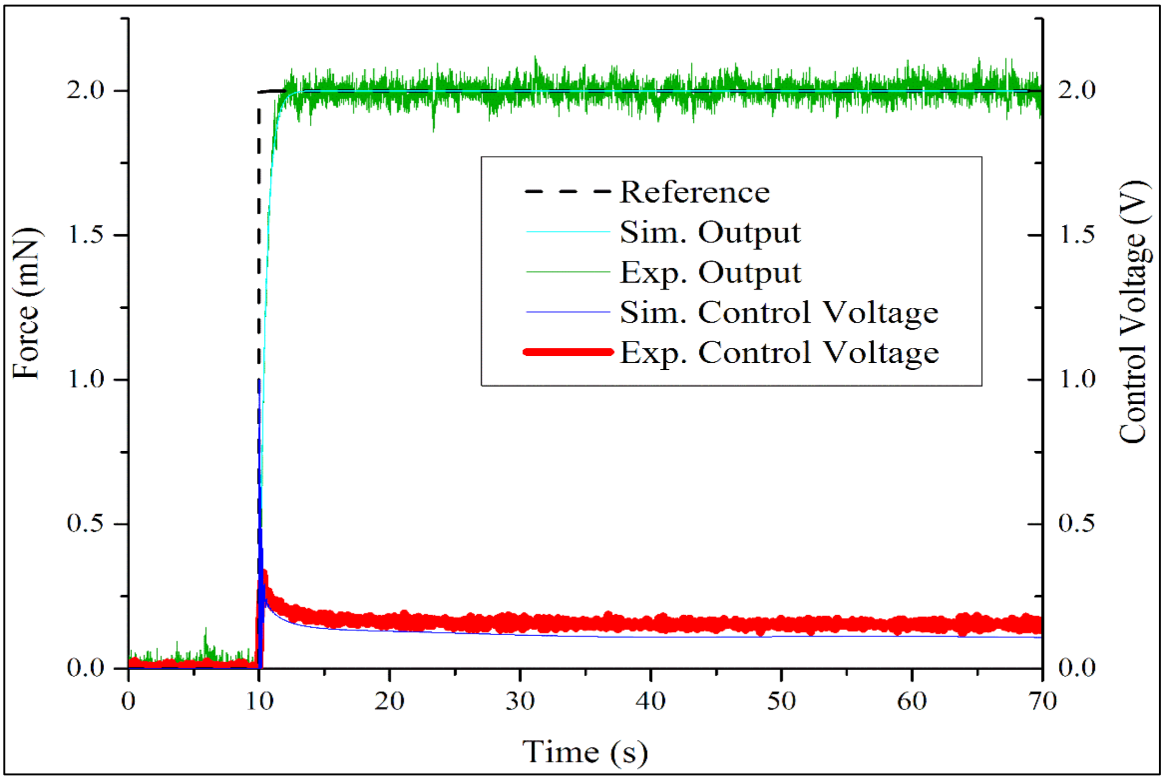

Figure 25. Force response of the actuator to a step of 2 mN under the FL controller

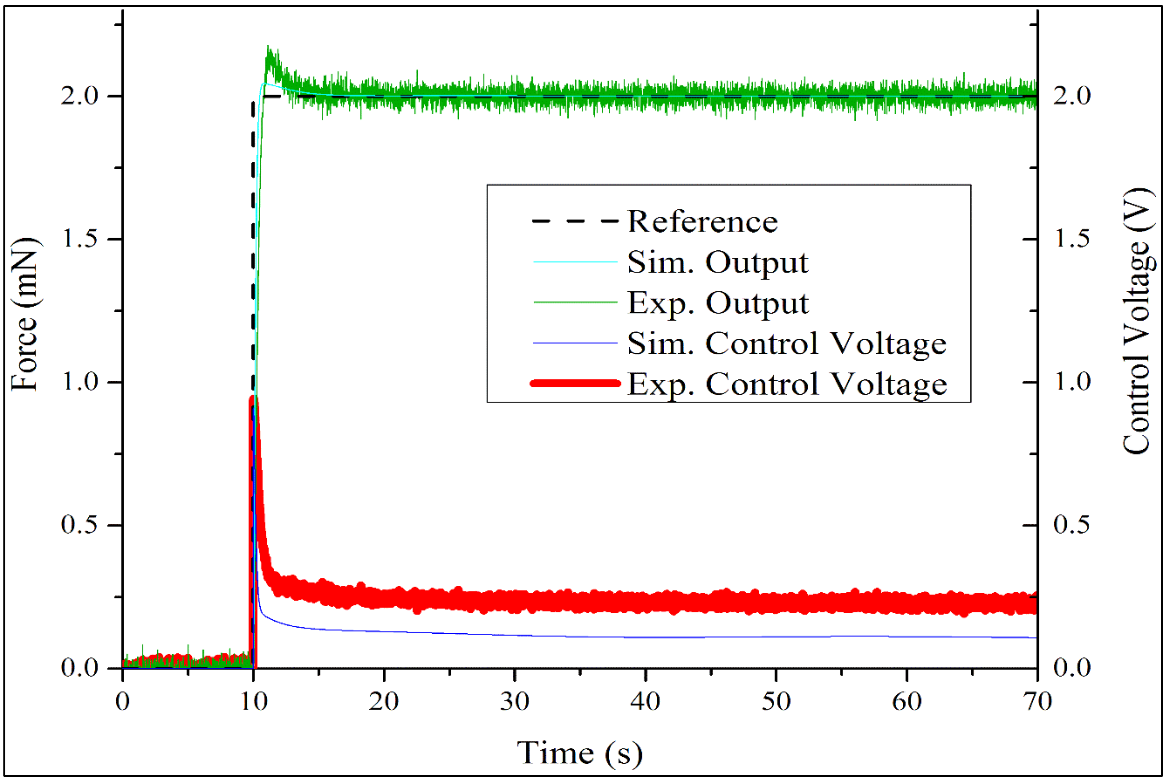

Figure 26. Force response of the actuator to a step of 2 mN under PID controller

Table 7 includes the information about step response characteristics of the actuator upon application of different controllers.

Table 7. 2-mN controlled step response performance

Control Method	Rise Time [s]	Settling Time [s]	Overshoot [%]
Fuzzy Logic	0.95	1.21	0
PID	0.54	4.50	7.5

The FL controller with no overshoot and nearly a 4-fold improvement in settling time beats the PID controller's performance during the 2 mN step response test.

A 3 mN step reference is also applied to the actuator to examine its performance under the more aggressive reference signal. The force generated at the tip of the actuator and the calculated control voltage by fuzzy logic and PID controllers are illustrated in the Figures 27 and 28 respectively.

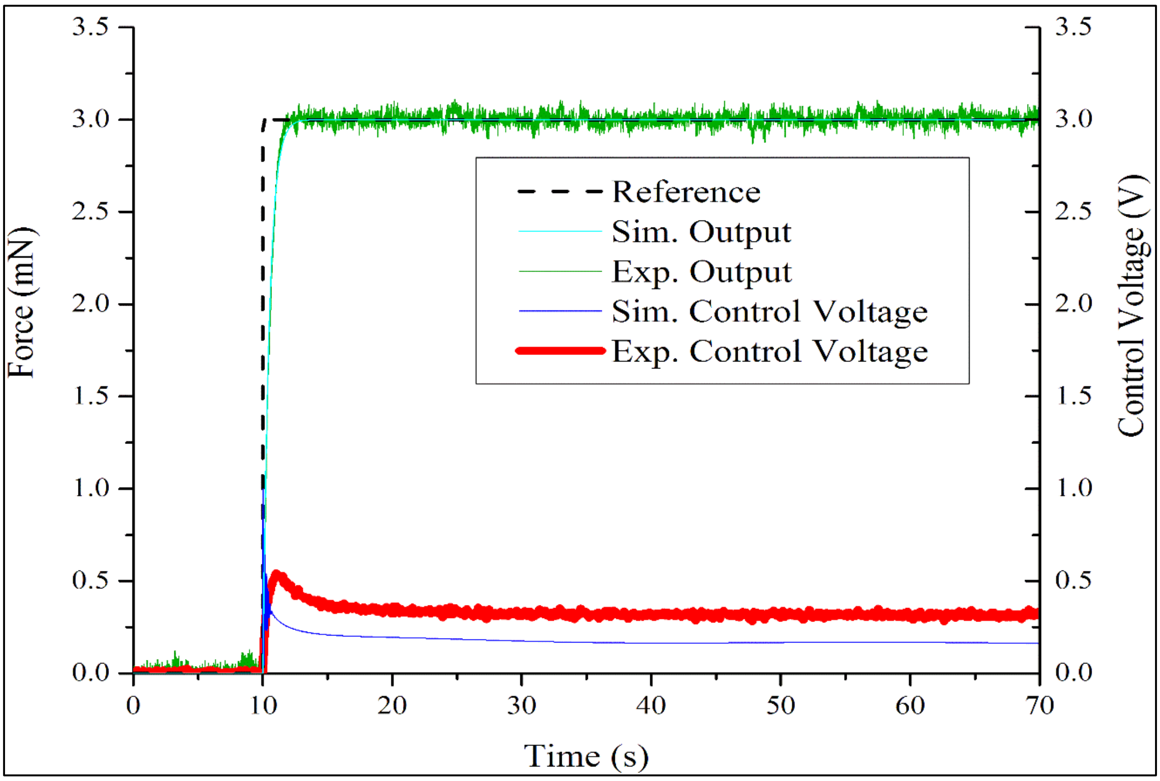

Figure 27. Force response of the actuator to a step of 3 mN under the FL controller

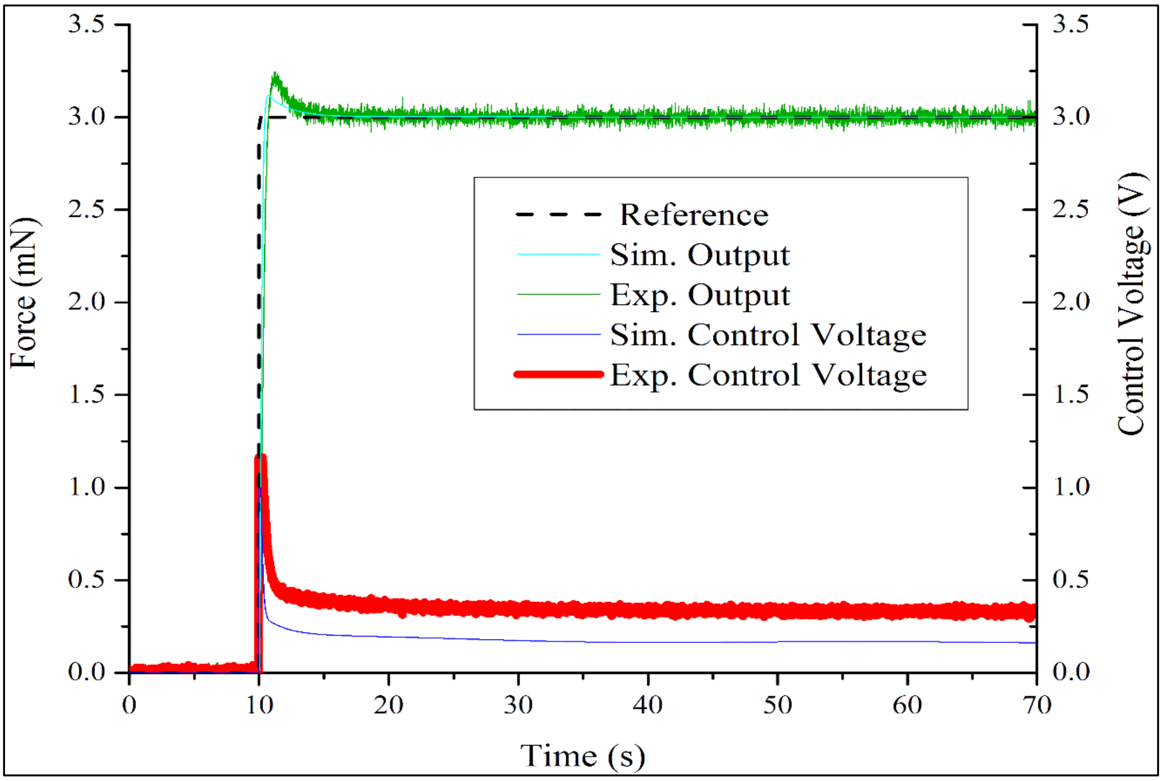

Figure 28. Force response of the actuator to a step of 3 mN under PID controller

It is clear in Figure 28 that the control voltage peak point of the PID controller has increased when 3 mN step input is applied to the actuator. The control voltage becomes nearly 1.25 V which is very close to the maximum safe voltage that can be applied to the actuator. Due to this reason, raising the set point is stopped to avoid harming the structure of the actuator.

As is observable in Figures 27 and 28, the controllers represent an acceptable performance in reaching the desired set point. Control voltages are within the safe range to be applied to the actuator. However, the step response specifications of the actuator for each controller is dissimilar, which makes only one of the control schemes the superior methodology for controlling the force output of the actuator. The step response specification for a 3 mN input is given in Table 8.

Table 8. 3-mN controlled step response performance

Control Method	Rise Time [s]	Settling Time [s]	Overshoot [%]
Fuzzy Logic	1.03	1.57	0
PID	0.57	4.70	7

Considering the information provided in Table 8, it can be seen that the FL controller improved settling time by decreasing it to one-third of the PID controller’s settling time. Moreover, no overshoot is observed in the actuator’s performance with the FL controller while the PID controller’s response exhibits a 7% overshoot, which is not negligible.

As is observable in Figures 27 and 28, the discontinuous sudden jump in the step reference yields an initial high amplitude voltage spike in the control input, which rapidly causes the actuator to produce a force output to reach the desired set point. This high voltage may harm the actuator unless carefully treated. After this initial spike, control voltage reduces to a constant value, which keeps the force output of the actuator at the steady state position.

It can be concluded from Tables 6-8, that controllers are successfully able to compensate for the actuator dynamics under a step input. The best performance among the controllers, for all step references, belongs to the FL controller for demonstrating the fastest rise time and settling time, without any overshoot. It is also evident that the rise time and settling time of the actuator under all control techniques is slightly increased when the set point is raised, as expected.

4.2.1. Repeatability:

In order to prove the repeatability of the experiments and robustness of the designed controllers, we applied them on a second CPA sample. The second sample's geometrical specifications are the same as the first one. Two step signals with varying amplitudes from 1 and 3 mN are used as the command inputs. The actuator's step response characteristics are listed in Tables 9 and 10 for the second sample.

Table 9. Second actuator sample 1-mN controlled step response performance

Control Method	Rise Time [s]	Settling Time [s]	Overshoot [%]
Fuzzy Logic	0.96	1.20	0
PID	0.59	5.05	10

Table 10. Second actuator sample 3-mN controlled step response performance

Control Method	Rise Time [s]	Settling Time [s]	Overshoot [%]
Fuzzy Logic	1.48	2.48	0
PID	0.59	8.70	7.5

A noticeable trend is evident in the results of the second sample's performance with different control methodologies. As in the first sample, the second actuator exhibits no overshoot either while the FL controller is applied to the actuator. By comparing the step response results of this actuator with those of the first CPA sample, it can be understood that the second actuator is constantly slower in rise time and settling time.

With reference to Tables 9 and 10, it can be claimed that all the controllers show a repeatable performance, and as is expected, the FL controller outperforms the PID controller in the step response test for the second sample as well.

4.2.2. Actuator Drift Resilience

To examine if the applied control techniques are capable of eliminating the effects of changing actuator dynamics, a 1 mN step response test is performed for an extended duration of 600 s, which is 10 times longer than previously conducted experiments in this study. The results of the tests are shown in Figure 29.

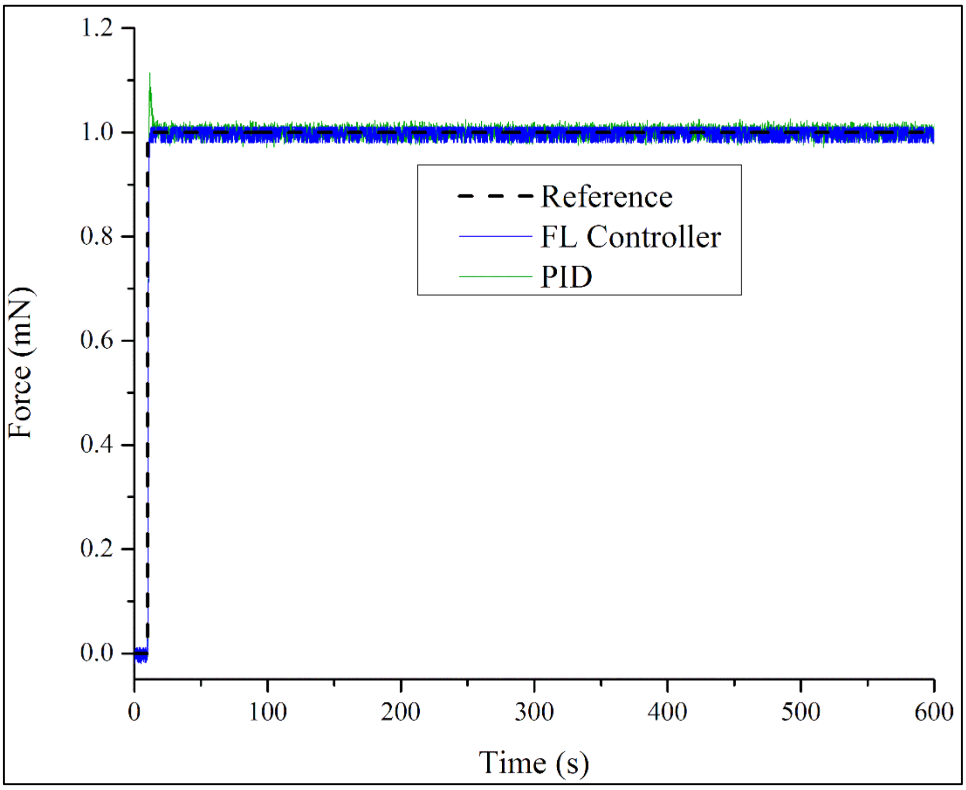

Figure 29. Actuator's long time response to a 1 mN step under different control schemes

It can be understood from Fig. 29 that controllers are successful in compensating the actuator's drift, which is an outcome of the feedback control utilized rather than the control methodologies applied on the actuat

5. CONCLUSION

In this study, the Mamdani fuzzy inference system has been employed to design fuzzy logic controllers for controlling the tip displacement of a trilayer conducting polymer actuator with PPy electrodes. The results show that noticeable enhancements in both step response and sinusoidal reference tracking performances of the actuator have been obtained when the fuzzy logic controller is applied. The rule base used in this study has been formed based on experimentation, and it does not require any gain tuning for the FL controller. The designed controllers have also been implemented on another same-sized CPA to show the repeatability of the results. Because the FL controllers do not require a model of the actuator in the design process, the nonlinearities and variations in the actuator dynamics have been handled effectively in both samples. However, the PID controller which was tuned based on the identified model of the first sample has shown performance degradation when applied to another same-sized CPA sample. Also, two different PID controllers are designed to track the different input commands while no change is applied to the structure of the FL controller upon changing the reference signal, which shows the superiority of the FL controller indeed.

For controlling the force output of a trilayer conducting polymer actuator with PPy electrodes, the same FL controller is applied experimentally and a PID controller is designed and applied for comparison purposes.

The designed controllers have also been implemented on another same-sized CPA to show the repeatability of the results. Because the FL controller specifies nonlinear control laws, which accommodate uncertainty and imprecision, the nonlinearities and variations in the actuator dynamics have been handled effectively in both samples. However, the PID controller which was tuned based on the identified model of the first sample has shown relatively poor performance characteristics comparing to the FL controller for both samples.

The long-term operation test for force output proved that all the controllers proposed in this study are capable of compensating for actuator drift because they utilize feedback control theory.

More effort is still needed to control the force output of the CPAs more precisely. To achieve this, exact mathematical models must be developed. However, currently such a dynamic model does not exist, as the complete mechanism behind the actuation dynamics of the CPAs has not been fully understood yet.

We guess that nonlinear identification and fuzzy modelling of the actuator's behavior with Adaptive Neuro Fuzzy Inference System (ANFIS) could be very helpful in designing and optimizing adequate fuzzy controllers for precise control of the CPA's position and force output. Therefore, as a future study, we propose optimizing the FL controller using the fuzzy model. Also, using adaptive FL methods could be helpful because they can optimize the FL controller online without requiring a model

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BIOGRAPHY

Mohammadreza Sabetghadam received his B.Sc. degree in Mechanical Engineering from Mechanical Engineering Department, Zanjan National University, Zanjan, Iran, in 2011.

He is currently with Mechanical Engineering Department, Karadeniz Technical University, Trabzon, Turkey as a Master Student, studying on smart materials and intelligent control methods.