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Abstract

Polypyrrole actuators may represent time varying and nonlinear dynamics as the solvent evaporation continuously affects their performance. Linear models can be used to design controllers for polypyrrole actuators to some extent but their performance may not be sufficient in order to comply with the requirements for applications where high precision is necessary. This paper proposes a Fuzzy Logic controller to improve the tracking performance of a trilayer polypyyrole conducting polymer actuator. As the fuzzy controller does not require a model for the system, the nonlinearities and uncertainties can be handled effectively. Experimental results show that fuzzy control improves the tracking performance compared to the conventional PID controller which is designed based on a linear model of the polypyrrole actuator.

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Fuzzy Control of a Conjugated Polymer Actuator

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Abstract—
Polypyrrole actuators may represent time varying and nonlinear dynamics as the solvent evaporation continuously affects their performance. Linear models can be used to design controllers for polypyrrole actuators to some extent but their performance may not be sufficient in order to comply with the requirements for applications where high precision is necessary. This paper proposes a Fuzzy Logic controller to improve the tracking performance of a trilayer polypyyrole conducting polymer actuator. As the fuzzy controller does not require a model for the system, the nonlinearities and uncertainties can be handled effectively. Experimental results show that fuzzy control improves the tracking performance compared to the conventional PID controller which is designed based on a linear model of the polypyrrole actuator.

I. INTRODUCTION

Conducting polymers are promising smart materials as actuators and sensors to be used in different fields of robotics and biomedical engineering due to their advantageous characteristics such as low cost, light weight, biocompatibility and low actuation voltage [1-5]. The actuation mechanism of conducting polymer actuators (CPAs) is based on the oxidation and reduction phases caused by the diffusion or migration of the ions to the polymer electrodes, which are polypyrrole (PPy) in this work, upon application of a sufficient potential difference (see Fig. 1).

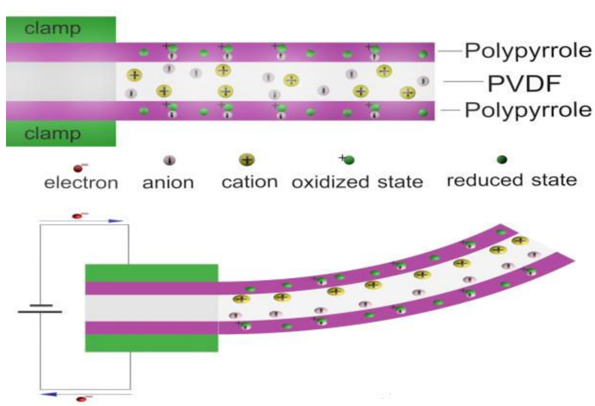

Figure 1. Actuation mechanism of the trilayer conjugated polymer actuator

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CPAs show considerable displacements when small amount of voltage (< 1V) is applied. This unique property of CPAs along with the other advantages mentioned above makes them attractive for diverse applications such as biomedical and robotics. Besides their advantages, CPAs also have some drawbacks such as time-varying dynamics caused by evaporation of the electrolyte, drift, and hysteresis which make their mathematical modeling complicated. As these actuators are in their infancy, the nonlinearities in their dynamics have not fully investigated. Rather, linear models have been proposed for CPAs in order to employ in designing controllers for enhancing their positioning performance [6-11]. Some control applications based on the linear models of CPAs are a PID controller to improve the positioning ability [7], a robust adaptive controller to overcome the drawbacks of the solvent evaporation effect on CPAs' actuation performance during the long time operation in air [12], a repetitive controller to improve the tracking performance for periodic references [9].

As the dynamics of CPAs are complex with time-varying effects and nonlinearities, linear control methods which are designed based on their linear models can improve the positioning performance of CPAs only to some extent. Also, implementing model based nonlinear control theories cannot be applied since an effective nonlinear model for the CPAs have not been obtained yet. In contrast with traditional linear and nonlinear control theory, fuzzy logic control (FLC) is not based on a mathematical model and is widely used to solve problems under uncertain and vague environments, with high nonlinearities [13,14]. Due to this unique characteristic of FLC theory, it may yield promising improvements in position control performance of CPAs.

To our knowledge, the performance of FLC on CPAs has not been tested experimentally yet. Therefore, the aim of this study is to design and implement a fuzzy logic controller to a trilayer CPA in order to minimize the tracking errors and to improve the transient response characteristics in the presence of unmodelled uncertainties and nonlinearities.

The rest of this paper is organized as follows: the trilayer PPy actuator is introduced in section II. In section III, the FLC is designed for the trilayer PPy actuator. Section IV introduces the experimental setup and then the experimentally obtained results are given. Finally, we draw the conclusions.

II. TRILAYER CONDUCTING POLYMER ACTUATOR

The actuator used in this study is in rectangular shape with the dimensions of $10 \times 5 \times 0.17$ mm. It has two PPy layers on the outer surfaces each of which has a thickness of 30 μm. These are the electroactive components of the actuator. A porous, non-conductive media made of Polyvinylidene Difluoride (PVDF), with a thickness of 110 μm separates the two PPy layers in order to preserve the electrolyte and to enable the actuator work in non-aquatic environments [8]. PVDF has its both sides coated with a thin layer of gold with a thickness of approximately 0.2 μm. This is because gold coating increases the conductivity of the actuator. Lithium triflouromethanesulfonimide is used as the electrolyte liquid.

III. FUZZY CONTROL DESIGN FOR CPA

Fuzzy set theory was introduced first by Zadeh [15] and Mamdani used fuzzy set theory to control a simple dynamic plant [16]. Since then FLCs have been applied widely in diverse fields of control engineering [17,18]. Model-independent property of these controllers allows control engineers to design effective controllers without having a proper mathematical model of the system. In fuzzy control the relationships between the outputs and the inputs are described by fuzzy if-then rules.

Fuzzy controllers consist of three major parts:

- **Fuzzification interface** which involves in measuring input values of variables and transferring the range of them into corresponding universes of discourse by scale mapping. Fuzzification interface also converts input data into appropriate linguistic values which may be viewed as labels of fuzzy sets.

- **Knowledge base** which consists of data base and a fuzzy control rule base. The data base supplies required definitions, which are used to define linguistic control rules and fuzzy data manipulation in FLC. The rule base explains the control goals and control policy of the domain experts by means of linguistic control rules.

- **Defuzzification interface** which is responsible to transform the fuzzy outputs that are computed by knowledge base into crisp data.

Selection of the fuzzy sets and universes of discourse play a vital role in the design process of fuzzy logic controllers. There are different kinds of membership functions in fuzzy set theory such as triangular functions, trapezoidal functions, and bell-shaped functions. The point is choosing the one that best describes the input and output of the dynamic system. The design process is divided into three main steps as follows:

1) Selection of Input Variables

As is well known, selection of the input variables is a very critical problem. Owing to the complex behavior of CPAs, the input voltage is determined by a factor of error between the reference and output signal. To enhance the prediction accuracy the derivative of error is taken into account. Hence the fuzzy controller is designed to have two input variables and one output for controlling the displacement of the CPA. The inputs to the FLC are defined as error ($e(t)$) and derivative of the error (de/dt) and the control output of the FLC is the actuation voltage $u(t)$.

The first input is difference between the real location of conducting polymer and its desired location:

$$e(t) = y_d(t) - y_a(t) \qquad (1)$$

Where y_d is the desired location of the actuator and y_a is the actual location of it.

The second input is derivative of the error which is defined as:

$$\mathrm{d}e = \frac{\mathrm{d}e(t)}{\mathrm{d}t} \qquad (2)$$

2) Determination of discourse universes

In order to determine discourse universes we apply a sinusoidal chirp signal as reference to observe the error and its derivative's changing range. Reference signal's amplitude is 0.5 mm and its frequency ranges from 0.01 Hz to 2 Hz. Appropriate range is selected for both error and its derivative as it is shown in Fig. 2.

The range of control signal is chosen to be ± 1V as implementing control inputs out of this range may damage the polymer actuator. A sampling rate of 1 kHz is chosen to generate data sets for the system identification and control design. The Simulink block diagram of the fuzzy controller is given in Fig. 3.

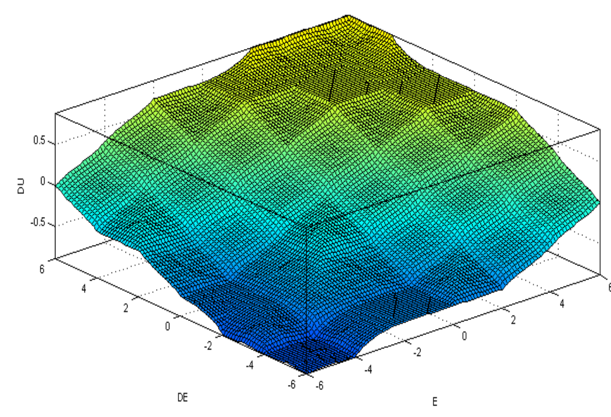

Figure 2. Fuzzy controller output surface

3) Choosing Fuzzy Membership Functions and Constructing Rule base

The most difficult part of designing a fuzzy controller is choosing the right fuzzy sets and membership functions which best represent system's behavior. Therefore, we find the triangular membership functions best suits for our application. Seven fuzzy sets are assumed for each input and output variable. The linguistic values for input and output variables are NB, NM, NS, ZO, PB, PM and PS. In order to build the fuzzy inference system MATLAB fuzzy logic toolbox is used. Mamdani-style system is chosen and centroid defuzzification method is applied. As there are seven fuzzy sets in each universe of discourse, there should be 49 rules which are shown in Table I. In order to compensate the steady state error, we use PD fuzzy +I controller.

TABLE I

RULE BASE OF FLC

u \ de / e	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZO
NM	NB	NB	NM	NM	NS	ZO	PS
NS	NM	NM	NS	NS	ZO	PS	PM
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PM	PM	PB
PM	NS	ZO	PS	PM	PM	PM	PB
PB	ZO	PS	PM	PM	PM	PB	PB

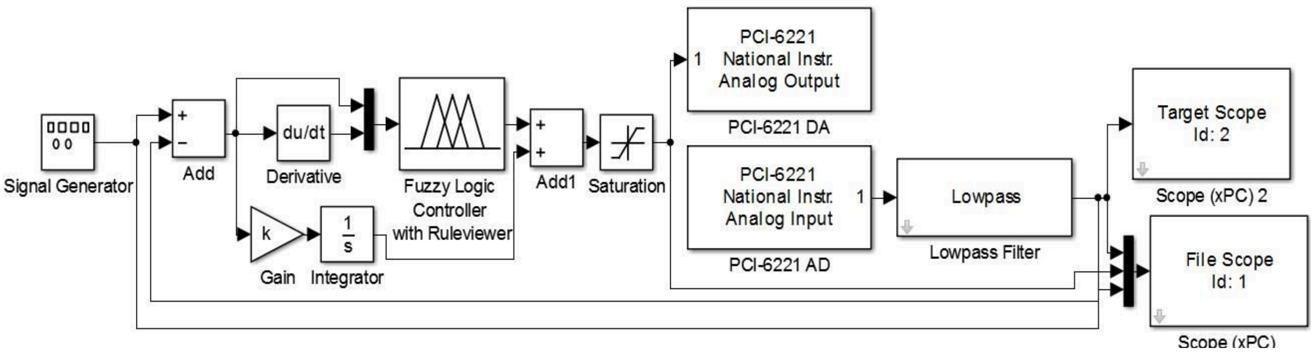

Figure 3. Block diagram of FLC

IV. EXPERIMENTAL SETUP AND RESULTS:

We aim to control the tip point displacement of the PPy actuator with respect to the voltage applied. The experimental setup is illustrated in Fig. 4. The tip position of the PPy actuator is measured by a Baumer OADM 20I6460/S14F laser displacement sensor with a resolution of 5 μm.The analog signal supplied from the laser sensor, which is between 0-10 V, is acquired by a DAQ (NI 6221) to the MATLAB/Simulink environment by using xPC Target platform.

Two different reference signals are tested on the PPy actuator. The first signal is a sinusoidal signal with the amplitude of 1 mm and the frequency of 0.1 Hz. In order to make a comparison, a PID controller is also designed whose parameters are selected as $K_P = 1.5, K_I = 1, K_D = 0.1$. The PID parameters are selected based on the linear system model (3) that is obtained by using a least square system identification method:

$$\frac{Y(s)}{V(s)} = \frac{29.49s^3 + 84.19s^2 + 26.4s + 0.1864}{s^5 + 23.5s^4 + 92.48s^3 + 75.72s^2 + 5.46s + 0.04227} \quad (3)$$

The sensor noise which degrades the performance of the controllers is filtered by using a first order low-pass filter with the cut-off frequency $\omega_c = 30\,\text{Hz}$ in order to avoid noise amplification problem caused by the derivative functions both in PID and FLC.

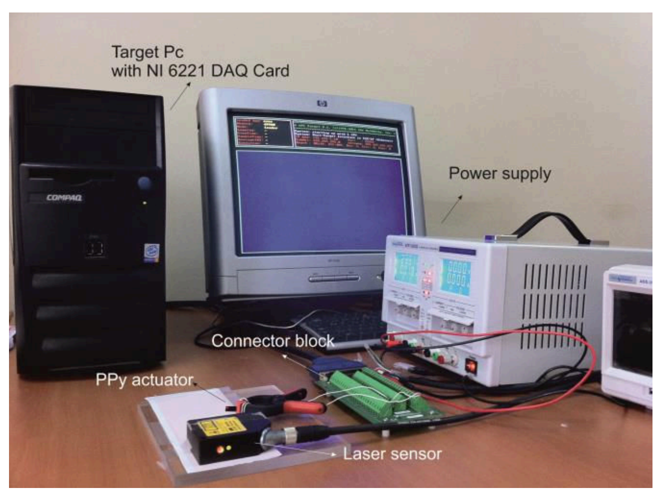

Figure 4. Experimental setup

The responses of the PPy actuator to the PID and fuzzy controllers are shown in Fig. 5. As it can be seen from Fig. 6, FLC reduced the tracking error for the sinusoidal signal approximately to the third of that of the PID control. A comparison for the control inputs of the PID and FLC is given in Fig. 7.

A step signal with 1 mm amplitude is also applied to the PPy actuator. Fig. 8 depicts the responses of the actuator for the FLC and PID control cases. It is clearly observable in Fig. 8 that the step response of the actuator to the PID controller is more oscillatory and its overshoot is larger compared to the step response with the fuzzy logic controller. Comparison of the control voltages of PID and FLC for the step reference is illustrated in Fig. 9.

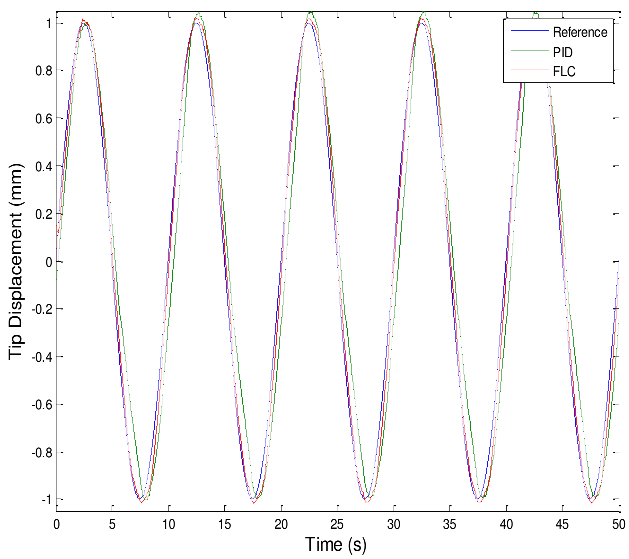

Figure 5. Comparison of displacement of CPA for sinusoidal signal

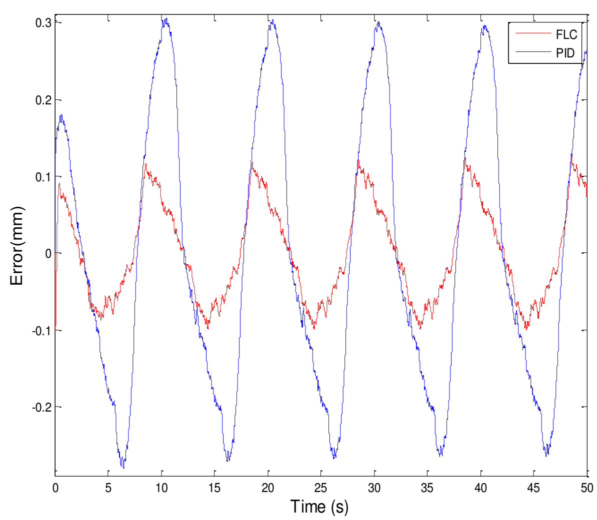

Figure 6. Tracking error of FLC and PID controller

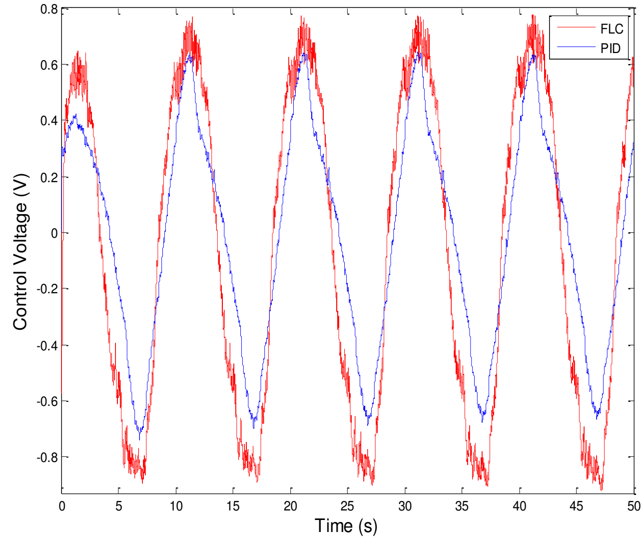

Figure 7. Control voltage of FLC and PID controller

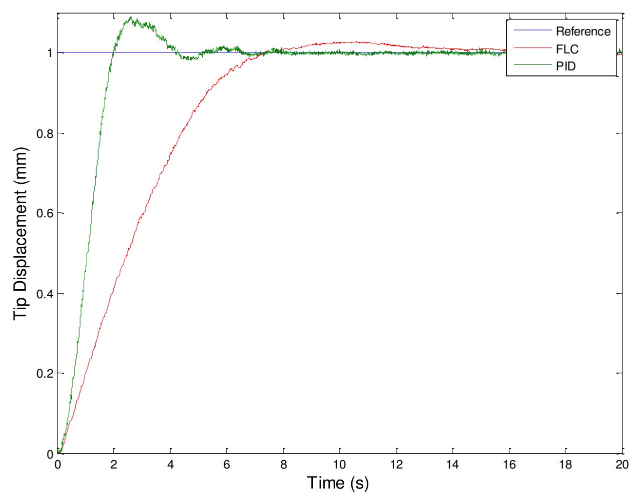

Figure 8. Comparison of the step responses with FLC and PID controller

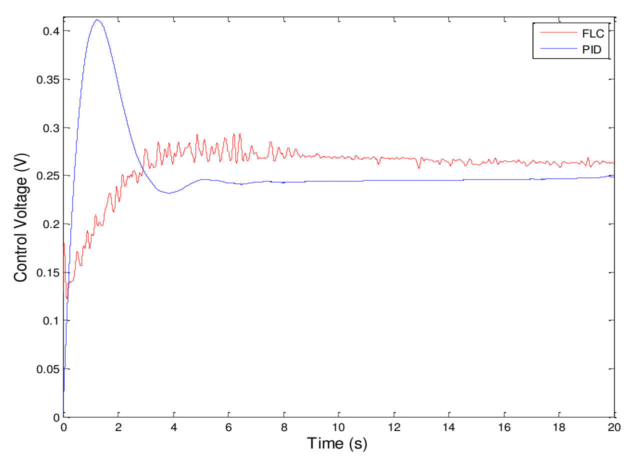

Figure 9. Control voltages for step input

For comparing the controllers more precisely we use a metric, called *Normalized Average Error* [9] over a time span of [0 ,50] seconds. Normalized average error is defined as:

$$e_a \triangleq \frac{\int_0^{t_f} |y(t) - r(t)| dt}{\int_0^{t_f} |r(t)| dt} \quad (4)$$

The normal average error calculated for sinusoidal reference is 8.70% and 25.22% for FLC and PID controller, respectively. It can be easily comprehended that the fuzzy logic +integral controller reduces the tracking error nearly to the third of the error obtained from the PID controller. In order to compare controllers' performance when step signal is applied, we calculate average steady state error. Steady state error of FLC is 0.0027 while PID controller's steady state error is 0.0043. We note that this steady state values are also related to the sensor resolution. One might obtain lower values by using a higher resolution sensor. It is clear that FLC decreased the steady state error for the step input by approximately 35% more than PID. Step response of the CPA is improved by reducing overshoot and it is also less oscillatory comparing to the step response of the system with PID controller.

V. Conclusion

In this study, a proportional derivative fuzzy + Integral controller has been designed and implemented to improve the tracking performance of a trilayer conducting polymer actuator. This is the first implementation of fuzzy logic control to a conjugated type polymer actuator. Experimental results show that the Fuzzy logic controller performed better than the PID as the FLC works based on the learning the behavior of the system, which gives the FLC a better ability to cope with the time-varying dynamics and uncertainties in the PPy actuator.

Future work will focus on improving the performance of PPy actuators in the presence of solvent evaporation which degrades long term performance of CPAs. Also a more advanced fuzzy logic controller such as T-S fuzzy, Type-2 fuzzy controller or control synthesis will be designed and implemented on the CPA and the results will be compared with the controller proposed in this paper.

Acknowledgment

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