A method for controlling bimorph piezoelectric actuator using fuzzy logic controller towards robotic assembly

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Abstract

Piezoelectric actuator is one of the most versatile types of smart actuators which is extensively used in different industrial applications like robotics, MEMS, micro assembly, biological cell handling, self-assembly and optical component handling in photonics. By applying potential to a piezoelectric actuator, it can produce micro level deflection with large force generation, very fast response and long term actuation as compared to other actuators. The design and analysis of the bimorph piezoelectric cantilever using novel fuzzy logic controller (FLC) tuned proportional-integral-derivative (PID) system are carried out where the bimorph piezoelectric actuator is used as an active actuator for providing the dexterous behaviour during robotic assembly. Fuzzy is introduced for fast tuning of PID and provides the steady state characteristics. Experimentally, it is verified that the actuator produces steady state behaviour of deflection for handling of the object. A prototype is also developed which shows the potential of handling the small light weight objects for robotic assembly.

Keywords: Piezoelectric actuator, fuzzy tuned PID, gripping system, robotic assembly

1 Introduction

In the past years, robotics and micro system technology have provided good solution to our society in terms of industrial automation, space science, medical facility, biological applications etc [1]. The design of manipulation systems plays important role during handling the objects where the design of the end-effector of the robots is a critical part. In this aspect, several researchers have developed various end-effector of manipulation system for industrial applications [2,3]. These mechanical grippers or end effectors are basically driven by motor or conventional mechanism etc. but these conventional mechanical arrangements suffer from inertia, friction and space problem due to less compact design etc in order to adjust the misalignment error during robotic assembly. When the operation is to be done in small scale then it is preferable to introduce some other kind of actuation mechanism. Regarding this, some of the researchers have intended smart materials based actuation mechanism like piezoelectric actuators, ionic polymer metal composite (IPMC), shape memory alloy (SMA) based micro grippers etc. [4]. These kinds of actuation mechanisms can

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perform the handling operation without any motor/gears which leads to more compact design of the system and the operation is much simple as compared to other conventional mechanisms. They only need precise control system during robotic assembly whereas the major advantages of piezo actuator used in such systems are that it has micro/nano second-range response with micro/nano scale displacement and large force generation whereas it shows nonlinear performance with the applied potential. For improving this behaviour, several attempts by many researchers on different control methods and different models have been given such as P, PD, PID, fuzzy control, self sensing method and visual processing etc [5,6]. While operating the piezoelectric actuator with voltage during micro manipulation, the precise positioning and accurate control system is required. Therefore, a novel method of controlling the bimorph piezoelectric actuator using fuzzy logic controller (FLC) along with PID system for robotic assembly is proposed where precise positioning of the system can be obtained by adjusting/tuning the PID gain through fuzzy controller accordingly. The major advantages of this method are that the desired deflection and force can be achieved very fast and precisely during handling the objects. The major contributions of this paper are on the following points:

(a) Design and analysis of the bimorph piezoelectric cantilever beam using FLC with PID where different gains are tuned for compensation of the error in terms of controlling the voltage for robotic assembly.

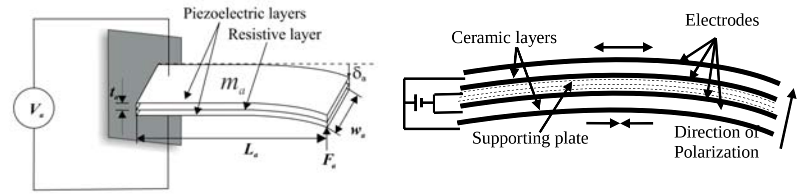
(b) Development of a three piezo fingers based gripping system for handling of the small and light weight objects.

In the last decade, several researchers have carried out research work on various methods of modeling, control and development of piezoelectric actuators for micro manipulation systems using fuzzy logic controller. Luiz et al. [7] have carried out work on an on-line self-organizing FLC whereas Song et al. [8] have established the inverse preisach model for reducing the hysteresis of the piezoceramic actuator. Xu et al. [9] have investigated the periodic motion tracking performance of a positioning system based on an empirical tracking performance index whereas Abdelaziz et al. [10] have given effort on a hybrid fuzzy based robust control method for piezoelectric actuators. Li et al. [11] have focused on fuzzy based PID control system for piezo-ceramic nano-manipulation system whereas Chi et al. [12] have attempted on the fuzzy PID feedback control of piezoelectric actuator with feed forward compensation for micro/nano positioning. Further, we [13] have also focused on stability analysis of piezoelectric actuator using PID controller where PID gains are set for the controller to reduce the hysteresis. Still, it does not provide complete solution for reducing the hysteresis of piezoelectric actuator. Therefore, in this paper, we are proposing a method for optimizing the PID gains using FLC which gives better solution as compared to other methods. This is a novel part of this paper.

The paper is organized as follows: the design and analysis of the bimorph piezoelectric cantilever beam using FLC with PID is discussed in Section 2. In order to validate, the experimental testing setup is described in Section 3 and the results are discussed in Section 4. The conclusion is drawn in Section 5.

2 Design and analysis for controlling the piezo actuator

In order to analyse the piezoelectric actuator for robotic micro assembly, the bimorph piezo actuator is configured in cantilever beam as shown in **Figure 1(a)**. This piezoelectric actuator is actuated through controlled voltage and provides deflection after giving the voltage. The flexible beam is characterized by its free length (L_a), its width (w_a), and its half thickness (t_a). A piezoelectric bimorph actuator consists of two outer active layers of piezoelectric ceramic material and one central resistive layer. When voltages are applied to actuator, a bending moment is induced in the beam as shown in **Figure 1(b)**.



(a) Basic configuration (b) Actuation principle

Figure 1: A bimorph piezoelectric cantilever beam for micro gripper

According to theory of beam, the cantilever configuration of bimorph piezo actuator is considered as a second order spring mass damping system as shown in **Figure 2**.

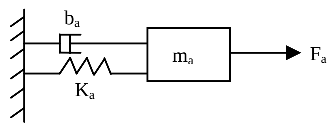


Figure 2: Representation of bimorph piezo actuator as a spring-mass damper system

The basic equation for force (F_a) in term of deflection is given below;

$$F_a = m_a \ddot{\delta}_a + b_a \dot{\delta}_a + K_a \delta_a \tag{1}$$

Where m_a is mass of piezo actuator; b_a is damping coefficient of piezo actuator; K_a stiffness of piezo atuator; δ_a is deflection of piezo actuator.

The generalised second order spring mass-damper, transfer function is

$$G(s) = \frac{K\omega_0}{s^2 + 2\xi\omega_0 s + \omega_0^2} \tag{2}$$

where $K=1/K_a$. The following data are used during simulation as given in **Table 1**.

Table 1: Simulation parameter for controlling the actuator

Parameter	Notation	Numerical value
Voltage	V_m	± 30 V
Mass of piezo actuator	m_a	0.0016 Kg
Lateral stiffness coefficient	K_a	2120 N/m
Damping coefficient	b_a	150 N/ms^{-1}

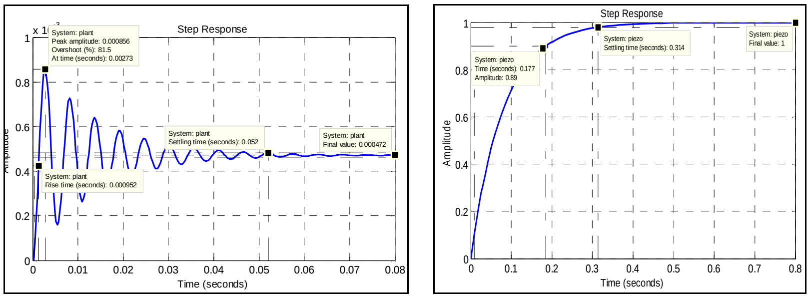
The parameters for piezoelectric actuator are calculated as follows

$\xi = b_a / \sqrt{4K_a / m_a}$ = 0.0652 and $\omega_0 = \sqrt{K_a / m_a}$ =1151.08 (3)

After using the above data, the transfer function is obtained as given below;

$$G(s) = \frac{625}{s^2 + 150s + 1.325 \times 10^6} \tag{4}$$

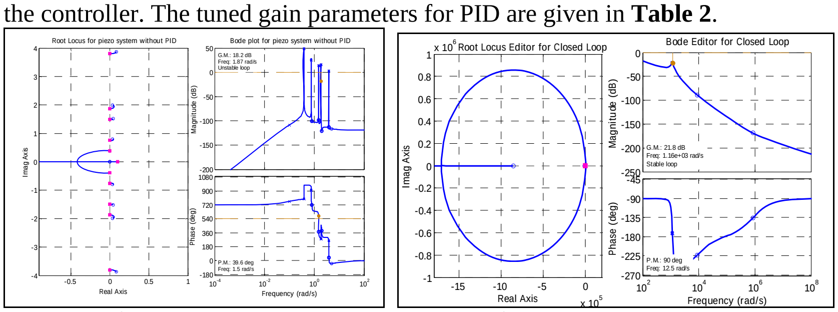
After simulating the behaviour of piezoelectric actuator in MATLAB software, the step response of piezoelectric actuator is shown in **Figure 3(a)**. It shows that the step response is oscillating in nature. The Root locus and Bode plot are plotted as shown in **Figure 4(a)**. From these figures, it is clear that the step response of system is oscillating in nature and there is locus of the system on right half of complex plane Hence this condition shows that the response of piezoelectric system may become unstable according to stability criteria.



(a) Before applying the control system (b) After applying the PID control system

Figure 3: Step response of the piezo actuator after applying PID controller

For achieving the stable system, a close loop system along with PID control law is applied to achieve the faster steady response as compared to other controllers. In this control system, the force is controlled through voltage by adjusting the PID gains of the controller. The tuned gain parameters for PID are given in **Table 2**.



(a) Before applying the control system (b) After applying the PID control system

Figure 4: Root-locus and Bode plot of peizoelctric system

Table 2: Tuned gain parameters for PID controller

Type of gain factor in PID	Numerical value
Proportional gain *(K_P)*	2.9913
Integrator gain *(K_I)*	2.6420×10^{4}
Derivative *(K_D)*	3.4669×10^{-5}

After applying PID controller, the transfer function is also obtained as given in Eq.(5) and the step response is again plotted as shown in **Figure 3(b)**.The Root-locus and Bode plots are shown in **Figure 4(b)**. These shows that the system is stable and gives better performance in terms of the oscillation and zero tracking error.

$$G_{PID}(s) = \frac{0.002167s^2 + 1870s + 1.651\times10^7}{s^3 + 150s^2 + 1.327\times10^6 s + 1.651\times10^7} \quad (5)$$

In order to optimize the PID gains, the FLC is introduced because the major advantage of FLC is that it uses fuzzy set instead of conventional set theory. The block diagram of FLC tuned PID controller is shown in **Figure 5**. The fuzzy sets for input (error signal) are shown in **Figure 6(a-c)**.

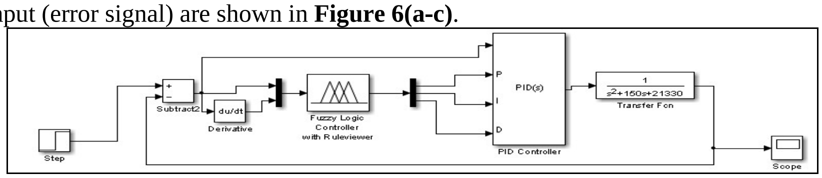
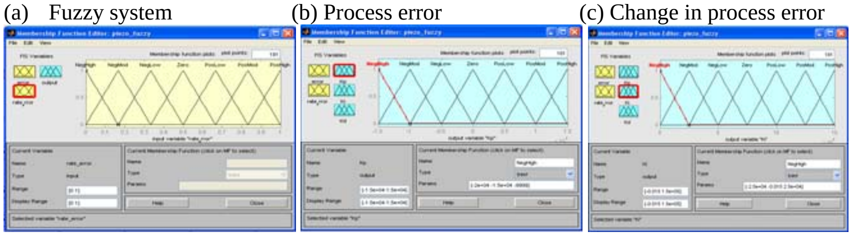


Figure 5: Block diagram of the fuzzy tuned PID control system

(a) Fuzzy system (b) Process error (c) Change in process error



(d) Output of fuzzy for K_P (e) Output of fuzzy for K_I (f) Output of fuzzy for K_D

Figure 6: Membership functions for the error signal

According to fuzzy rules of error *e* and error rate *ec* in the control process, the controller adjustments of ΔK_P , ΔK_I, ΔK_D are acquired by the fuzzy inference. The final parameters of fuzzy PID are calculated and determined by the following formula where K_{P0} , K_{I0}, K_{D0} are the initial value of PID.

$$\begin{cases} K_P = K_{PO} + \Delta K_P \\ K_I = K_{IO} + \Delta K_I \\ K_D = K_{DO} + \Delta K_D \end{cases} \tag{6}$$

The suitable rule base for fuzzy control is established in **Table 3** to **Table 5** to adjust the PID gains accordingly with the error signal. The fuzzy subsets are defined as Negative High (NH), Negative Low (NL), Negative Medium (NM), Positive Low (PL), Zero (ZE), Positive High (PH) and Positive Medium (NM).

Table 3: The fuzzy rule table of ΔK_P

ΔK_P		Rate of change of error (*ec*)				
		NH	NL	ZE	PL	PH
Error (*e*)	NH	PL	NH	NH	NM	PL
	NL	ZE	NM	NM	NL	ZE
	ZE	ZE	NL	NL	NL	ZE
	PL	ZE	ZE	ZE	ZE	ZE
	PH	PH	PM	PM	PL	PH

Table 4: The fuzzy rule table of ΔK_I

ΔK_I		Rate of change of error (*ec*)				
		NH	NL	ZE	PL	PH
Error (*e*)	NH	PH	PM	PM	PL	ZE
	NL	PM	PM	PM	ZE	NL
	ZE	PM	PL	ZE	NL	NM
	PL	PL	ZE	NL	NL	NM
	PH	ZE	NM	NM	NM	NH

Table 5: The fuzzy rule table of ΔK_D

ΔK_D		Rate of change of error (*ec*)				
		NH	NL	ZE	PL	PH
Error (*e*)	NH	NH	NM	NM	NL	ZE
	NL	NH	NL	NL	ZE	PL
	ZE	NM	NL	ZE	PL	PM
	PL	NM	ZE	PL	PL	PH
	PH	ZE	PL	PM	PM	PH

From the **Figure 6(d-f)**, it is clear that after tuning the parameters of PID using FLC enhances the process response in terms of the rise time and the steady state error. Therefore, the signal tracking effect under fuzzy PID control system is better than that of traditional PID. After tuning, these parameters are sent to controller during activation of bimorph piezoelectric actuator.

3 Experimental Testing Setup

In order to acquire the voltage signal for activation of a three piezo bimorph actuator based micro gripper, the schematic diagram of testing layout is shown in **Figure 7**. A piezo actuator based gripper is connected to high voltage (HV) amplifier. A PXI system (NI PXIe-8102) based controller is used for acquiring the real time signal through HV amplifier. The PXI system consists of digital-analog converter (DAC) card (NI PXI-4461) and a controller (NI-6251) where the DAC and controller are connected to computer. For sending the signal ±10 V from DAC card with help of data acquisition (DAQ) assistant, LABVIEW-2012 software is used.

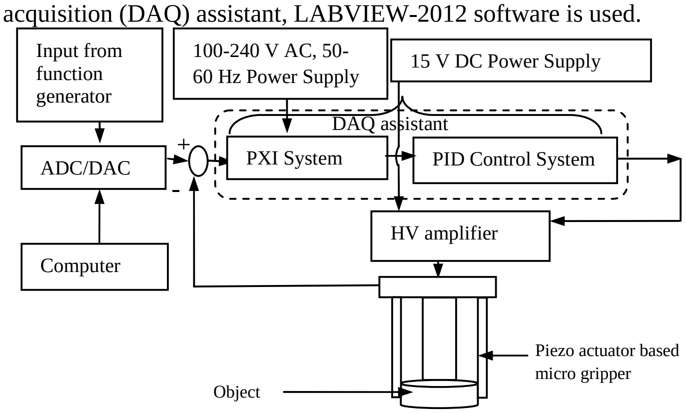


Figure 7: Basic testing layout for activation of piezo fingers based micro gripper

A virtual instrument (VI) platform is designed in LABVIEW software where continuous samples type signal is given for achieving the continuous voltage signal. This is connected to input port of an analog-digital converter (ADC) card. An internal clock is set at a frequency of 1 KHz with reference single ended (RSE) type signal. Noise interference is eliminated by enabling low-pass filtering in the data acquisition (DAQ). The input voltage is given from function generator. The PID control system is used as a negative feedback system and PID controller gains are set for achieving the stability during operation of piezo actuator based gripper. The three bimorph piezo actuator (Model: PL127.10, Make: Physik Instrument GmbH, Germany) are used (size 31.0 mm length×9.6 mm width×0.65 mm thickness). A three piezo finger based gripper is also developed for handling of the small objects.

4 Results and discussions

In order to examine the behaviour of bimorph piezo actuator, an actual testing setup is developed as shown in **Figure 8**. A piezo actuator is fixed with a holder in a cantilever configuration. The piezo actuator is connected to HV amplifier for providing the voltage (±30V). In order to get the controlled voltage, a PXI controller is used and VI is designed and input voltage is acquired from function generator through DAQ assistant and output voltage sent to HV amplifier through another DAQ assistant so that two different voltages are visualized. An amplifier is also used for amplifying the voltage. For controlling the voltage, PID control system is integrated in VI so that we can also adjust gains according to requirement. After adjusting the gains, controlled voltage is sent to piezo actuator.

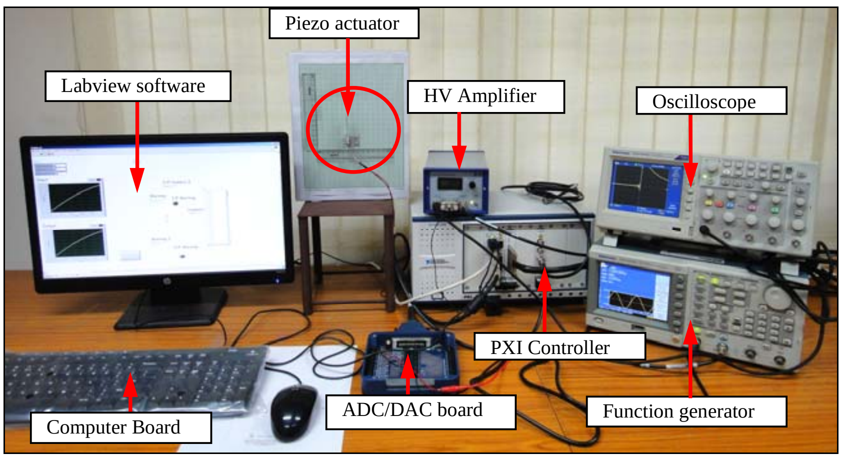
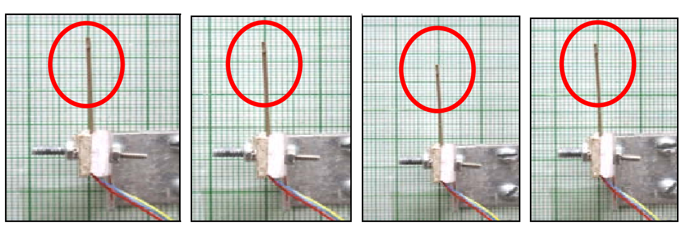


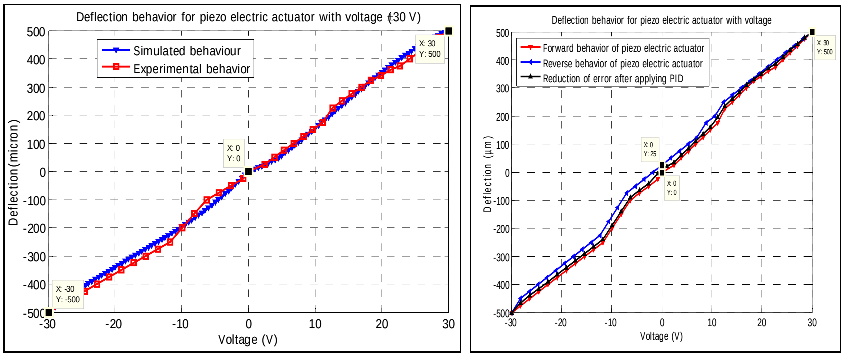
Figure 8: Actual testing setup for activation of piezo actuator

By applying the voltage, bimorph bender bends as shown in **Figure 9** and the experimental data are plotted in **Figure 10**. The maximum deflection of piezo actuator is shown upto 500µm. When voltage is reducing, the actuator does not follow the same path to return its original position. It is envisaged that piezo actuator has a deflection error (hysteresis) of 25 µm. For reducing this hysteresis, the voltage is controlled by adjusting the gains in a PID controller using FLC with reasonable amplification factor in order to get the desired characteristics. The improved characteristic is also shown (**Figure 10**). It shows that the deflection error is now reduced from 25 µm to 5 µm. After that, the controlled voltage signal is sent to gripper during precise handling of small objects.



(A) 0 V (B) 10 V (C) 20 V (D) 30 V

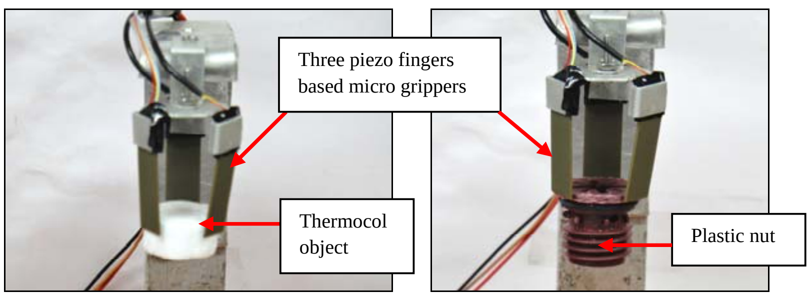
Figure 9: Behaviour of piezoelectric actuator at different voltages



(a) Behavior of piezoelectric actuator (b) Error compensation by controller

Figure 10: Experimental performance of bimorph piezoelectric actuator

A three piezoelectric fingers based gripper is developed as shown in **Figure 11.** All fingers are activated simultaneously which can be used for dexterous handling. This can hold the lightweight object like thermocol, spongy poly plastic nut etc. This handling capability of numerous millimeter-scale components is exhibited through a controlled voltage in robotic assembly.



(a) Lifting of thermocal material (b) Lifting of plastic nut

Figure 11: Prototype of three piezo based fingers

5 Conclusions

In this paper, the design and analysis of the bimorph piezoelectric cantilever beam using fuzzy logic control method with PID is discussed. To provide the stability during applying the voltage to bimorph piezoelectric actuator, a PID control system is used where different gains are tuned and optimised using FLC for compensation of the error in terms of controlling the voltage. Experimentally, it is proved that by adjusting the gains in the control system, the deflection is controlled. By developing a prototype, it is demonstrated that three bimorph piezo actuator based gripper can be used for handling of the small light weight objects. This potential shows that controlled voltage for piezo actuator helps in precise handling in robotic assembly.

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