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Deflection control for piezoelectric actuator through voltage signal and it's application in micromanipulation

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ABSTRACT

Piezoelectric actuator can be used for handling and grasping of miniature parts in micromanipulation where study of stable displacement and force characteristics with voltage are important for developing a micro gripper. In order to obtain these behaviors of piezoelectric actuator, electromechanical characterization of piezoelectric actuator has been carried out in this paper where a mathematical model for deflection and force response of piezoelectric actuator with voltage is derived with the help of a simple first-order model under a step input voltage. This is controlled through a proportional-derivative (PD) controller. Experimentally, it is verified that the piezoelectric actuator attains the maximum deflection upto 1.5 mm and produces force upto 0.203 N by applying voltage (0–60 V). A prototype of novel piezoelectric actuator based micro gripper along with micro manipulation system is developed. By conducting experiments, it is proved that controlled voltage for piezoelectric actuator helps in compensating the misalignment during micro assembly.

1. Introduction

In the last few years, the piezoelectric actuators are used for many micromanipulation and micro robotics applications such as micro assembly, micro electromechanical system (MEMS), biological cells handling in micro/nanotechnology, self-assembly of silica microspheres and handling of optical components in photonics [1,2]. The major advantages of piezoelectric actuator used in such systems are that it has high micro/nano scale displacement, large force generation, micro/nano second-range response, no backlash, striction or friction, immune to magnetic fields, no wear and tear as compared to other smart actuators for developing the micro gripper like shape memory alloy (SMA), ionic polymer metal composite (IPMC), electro static, ferromagnetic and other electro active polymers (EAP) [3–6]. Only limitation of piezoelectric actuator is that it shows non-linear characteristics with voltage signal. For improving these properties, several researchers have attempted on controlling the voltage signal using different control methods [7,8]. These methods have some limitations such as measurement of long term actuation/force data by applying a voltage signal for developing a micro gripper. The main difficulties for implementing the actuation/force response of piezo bimorph through voltage in real time are controlling the position and sensing the force in micron range to avoid the destruction of object during picking the object. To overcome these problems, the self sensing method and vision based system have also been attempted for electro-mechanical behavior of piezo actuator by supplying the voltage in a micro gripper towards micro assembly by Ivan et al.

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[9,10] and Zhang et al. [11], respectively. These methods have also some limitations such as thermal insulation characteristic and packaging aspect problems of piezo actuators use in real applications when voltage range of 0–60 V was applied. Further in order to analyze the electromechanical behavior of the piezo actuator based micro gripper for handling the micro parts, we are proposing a new method for characterizing the piezo actuator using resistive and capacitive behavior in the strip when voltage signal is applied to piezoelectric actuator.

In this paper, we are establishing a relationship between deflection and voltage of piezoelectric actuator for handling the micro parts by developing a micro gripper towards micro assembly. The major contributions of this paper are on the following points:

(a) A new design of piezo actuator based micro gripper along with micro manipulation system for micro assembly.
(b) Analysis of bi-directional behavior of piezo bimorph actuator using combination of two piezo ceramic layers and one resistive layer between them by applying a voltage signal and controlling the voltage through a proportional-derivative (PD) controller for micro gripper.
(c) Development of a piezo bimorph based micro gripper along with micro manipulation system for handling the miniature parts and evaluation of experimental performance towards pick & place and peg-in-hole assembly.

During handling of micro parts, a micro gripper has to be intended in such manner that can provide the long term stability to hold the object during micro assembly. For this purpose, a three DOF based micro manipulation system along with micro gripper is designed where micro gripper is constructed using bimorph piezo actuators. During development of micro gripper, the bimorph piezoelectric actuator is used in cantilever configuration due to their bi-directional characteristic with flexible behavior. In order to characterize the bimorph behavior of piezo actuator, a mathematical model is derived using resistive and capacitive behavior of the actuator when voltage signal is provided to piezo actuator. For solving this behavior, a Kirchhoff voltage law is applied. By considering the dielectric absorption behavior of bimorph actuator, the bending moment and voltage relationship is obtained. Using this characteristic, deflection and force behaviors are controlled through a PD controller. By conducting experiments, it is found that the piezo actuator produces maximum deflection upto 1.5 mm and generates force upto 0.203 N for handling the object. A micro gripper along with micro manipulation system is also developed for demonstrating the micro manipulation and misalignment adjustment capabilities of miniature parts during micro assembly.

In the past, several researchers have carried out research work on various methods of modeling, control and fabrication of piezo actuators for micro gripper/manipulations. Goldfarb et al. [12] have designed a small scale flexure-based gripper using piezoelectric ceramic actuator for manipulation tasks requiring precision position and force control where optimization have been carried using simple control method. Moskalik et al. [13] have presented the force–deflection behaviour of piezoelectric C-block actuator arrays. A theoretical model has been derived that predicts the force–deflection behavior of a C-block array. Sitti et al. [14] have focused on the design, fabrication and characterization of unimorph actuators for a micro aerial flapping mechanism where PZT-5H and PZN-PT are investigated as piezoelectric layers in the unimorph actuators. Fabricated piezoelectric unimorphs are characterized by an optical measurement system in quasi-static and dynamic mode. Experimental performance of PZT-5H and PZN-PT based unimorphs is compared with desired design specifications. Campolo et al. [15] have proposed an efficient charge recovery method for driving piezoelectric actuators with low frequency square waves in low power applications. The charge recovery method is then applied to piezoelectric actuators with bimorph configuration of piezo actuator. Popa et al. [16] have developed a dynamic model of bimorph MEMS actuators where properties are similar to piezo actuator. The operating principle is based on differential thermal expansion induced by Joule heating process. Pérez et al. [17] have also focused on analysis of bimorph 2-DOF piezo actuator which can be applicable in micromanipulation where the performances of duo-bimorph with end-effector are characterized.

Grossard et al. [18] have developed a method for optimal design of active compliant mechanisms. It is partly based on a flexible building blocks method. Rakotondrabe et al. [19] have given emphasis on the estimation of force in a piezoelectric cantilever for micro gripper. During analysis of the voltage–deflection, the nonlinearities are taken into account. Susanto et al. [20] have also developed a mathematical model for piezoelectric force actuator (PFA) which can be applicable in meso/micro grasping. The model predicts the radial deflection and grasping force–deflection relationship of the PFA which is derived based on composite curved beam theory and Castigliagno's second theorem. Sung et al. [21] have proposed a control method using the proportional–integral-derivative (PID) controller for piezoelectric actuator where the nonlinear characteristic response between input voltage and output displacement is described by second-order linear dynamic system. This PID controller regulates the output displacement of the actuator. Dong et al. [22] have focused on actuating and sensing capability before and after polarization of PZT micro cantilever. In addition, the method for the determination of the piezoelectric constant is developed once the sensing and actuating capability is measured. Al-Wahab et al. [23] have presented a methodology for the appropriate selection and creation of mechatronic handling devices (MHD) using piezo actuators which could be capable to accomplish certain micro and/or nano-operation task.

Zareinejad et al. [24] have used piezoelectric actuators in development of tele-micro manipulation application whereas Tamadazte et al. [25] have attempted on a full automatic micromanipulation and micro assembly where a visual feedback method has been proposed. Liaw et al. [26] have presented a robust adaptive constrained motion tracking control methodology for piezo-actuated flexure based micro/nano manipulation mechanisms whereas Grossard et al. [27] have focused on robust control strategy for a control-optimized piezoelectric micro gripper. An approach used for controlling the actuator tip is based on a mixed high authority control (HAC)/low authority control (LAC) strategy for designing a wideband