



# Feedforward neural network position control of a piezoelectric actuator based on a BAT search algorithm



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## ABSTRACT

The precise positional controls of piezoelectric actuators (PEA) are problematic due to highly-nonlinear hysteresis behavior which is inherent in piezoelectric materials. In existing PEA positional control applications that are based only on neural networks, the obtained control response results are insufficient for practical usage. In this paper we apply a combined approach by using a feedforward neural network (FNN) jointly with a BAT search algorithm in order to improve the positional control of an X-PEA mechanism model by also taking into account the hysteresis behavior. The proposed positional controller was successfully implemented and it was capable of significantly improving the overall control response result of an X-PEA mechanism model by minimizing the overshoot value and steady-state error, and decreasing the settling time. In addition, the BAT search algorithm can also be used for training the FNN, optimizing the FNN topology and reducing the computational complexity. The presented simulation results confirmed that the proposed positional controller with combined approach provides better results compared to the classical FNN control approach.

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## 1. Introduction

Over recent years, piezoelectric actuators (PEA) have been increasingly used within many important fields like optics, life science/medical, aerospace/space and instrumentation, whereas they play an important role in various applications like for example in laser tuning, optical switches, fiber filters, micro-positioning, micro-pumps, piezo-valves, medical transducers and so on (Segel, 2011). The field of micro-robotics, in particular, is emerging as one of the more popular technical fields for extensive research where micro-positioning tasks are required. New manipulators are being constantly developed in order to assemble different micro-systems and optic components. Such manipulators have to be very precise and have a submicron resolution. Moreover, they have to be compact, modular, robust and reliable so they can be used not only for micro-positioning tasks but also for specific micro-machining tasks. Due to their strong driving force, high stiffness, nanometer resolution and fast response, PEAs are widely recognized as fundamental elements for the actuation of robots since they can manage extremely small displacements (Bonnail, Tonneau, Jandard, Capolino, & Dallaporta, 2004).

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However, PEAs potentials have been impaired by the adverse effects of highly-nonlinear hysteresis behavior that is inherent to piezoelectric materials. This results in nonlinear and multi-valued mapping between the actuator's input and output and, hence, influences any desired control precision. In the case where a PEA is operated within an open-looped mode the hysteresis problems can lead to further problems of major inaccuracies and restricted control performance, whereas in the case of a closed-looped mode it can additionally lead to severe instability of the overall control system (Adriaens, De Koning, & Banning, 2000). According to such facts, an in-depth understanding of highly-nonlinear hysteresis behavior is necessary in order to design a proper PEA positional controller. The strategy of modern controller designs is based around a system model that takes into account the complicated hysteretic nonlinearities.

In Goldfarb and Celanovic (1997), the authors approximated the hysteresis model by using motion dynamics constructed by an applied force to one set of massless bodies parallel to the springs, and the relationship in terms of applied force, spring constants and break forces, is used to determine the hysteresis dynamics. According to obtained experimental results, it is difficult to determine the critical numbers of springs and massless bodies used to accurately represent the hysteresis dynamics.

As a result, an electromechanical model was proposed (Adriaens et al., 2000), which was constructed by transduction of

the electrical charge and discharge behaviors, in order to generate applied force. In the mentioned study, the functions used for both describing the mechanical model of PEA and shaping the hysteresis loop were derived by using first-order differential and partial differential equations, respectively. However, such a representative model of PEA is more suitable for vibration control than displacement control.

The hysteresis effect that is inherent in each PEA can be further expanded by introducing mechanical friction phenomena with the included Stribeck effect (Canudas de Wit, Olsson, Åström, & Lischinsky, 1995).

In this way the PEAs' overall dynamics can be assembled into mechanical motion dynamics by including characteristics of the Stribeck effect, hysteresis and spring-like behaviors (Lin, Shieh, Huang, & Teng, 2006).

Based on our performed literature review, over the last few years the majority of researchers have used the PEAs' within three main research fields like hysteresis compensation, vibration control and PEA position control, using a variety of approaches (Dong, Hu, & Wang, 2014; Liu, Guo, & Wang, 2013; Peng & Chen, 2014; Rodger, 2014; Xu, 2014; Zhang, Kan, Cheng, Jia, & Wang, 2013; Cha, Agrawal, Kim, & Raich, 2012; Ghafarirad, Rezaei, Zareinejad, Hamdi, & Ansari, 2012; Mehrabian & Yousefi-Koma, 2011; Rodger, 2012; Su, Yang, & Huang, 2011; Tan et al., 2009).

Interestingly, frequency-based hysteresis compensation was investigated closely by Othman, Mahmood, Aibinu, and Rashid (2012) on a piezoelectric tube scanner which could guarantee precise nanoscale positioning. The authors used a neural network scheme in order to generate a proper control signal based on open-loop input/output data. The control signal was calculated within a frequency domain based on an input/output spectrum and the neural network was trained offline using a set of reference signal harmonics for producing the required control signal harmonics. Their experimental results confirmed that the developed control scheme improved the performance of the system by minimizing the effect of hysteresis. Aguirre, Janssens, Van Brussel, and Al-Bender (2012) proposed a new hysteresis compensation strategy for PEA based upon treating hysteresis as being separate from other dynamic effects and by formulating a simplified model to deal with asymmetric hysteresis. The authors confirmed that the accuracy improvement was reached due to the new hysteresis-compensation method. Wang, Pommier-Budinger, Reyssat, and Gourinat (2014) developed an efficient methodology for simultaneous compensation of hysteresis and creep in a PEA within the framework of open-loop control of active optic systems. The hysteresis compensation was achieved by cascading the inverse derivative Preisach model (hysteresis compensator) to the PEA under study. Their experimental results showed that the hysteresis and creep in a PEA can be reduced significantly at the same time for those cases with step-like reference signals that represent the spatial mirror surface deformation generated by thermal gradients.

Vibration control applications with PEAs have also been investigated. For example, Marinaki, Marinakis, and Stavroulakis (2011) designed a vibration control mechanism for a beam with bonded piezoelectric sensors and actuators. A particle swarm optimization (PSO) algorithm was used for the vibration control of the beam. A close comparison of obtained results between the PSO-based controller and a classical linear quadratic regulator (LQR) for different loadings revealed the high performance of the proposed PSO controller provided better results. Wang and Yang (2009) developed a new type of piezoelectric stack actuator with the purpose of exerting the strong actuating power of piezoelectric stack and facilitating the incorporation of piezoelectric stack within the host structure for vibration control application. A vibration control system of a cantilever beam example was applied. A

neural network predictive (NNP) and LQR control strategy were used separately for performing the first bending mode vibration control of the beam. Their simulation results indicated that with this new actuator and NNP control strategy, the first bending mode amplitude of the cantilever beam could be reduced by about 95% compared to those of LQR control strategy where 79% was obtained. Zhang, Li, and Cai (2013) designed an adaptive controller MVSTDR (minimum variance self-tuning direct regulator) for a smart system that consisted of a cantilever beam bonded with a piezoelectric actuator in order to test the vibration suppression. Their experimental results demonstrated that it is feasible to suppress vibration by the MVSTDR for the smart beam with the hysteresis property. The authors showed that the amplitude reduction quantity of the strain within the frequency spectrum analysis is up to about 83.67% with the adaptive controller at the first natural frequency when the smart beam is subjected to free vibration.

Many researchers have contributed significantly to PEA control applications which are one of the more represented areas in the literature. For example, a new hybrid method presented in Bazghaleh, Mohammadzadeh, Grainger, Cazzolato, and Lu (2013) was introduced for sensor-less control of PEAs which increased the estimation accuracies of the black box models of these actuators through reducing the effect of error accumulation. The mentioned black box model mapped the piezoelectric voltage onto displacement together with a complementary algorithm that used the sensing voltage in order to decrease the effect of error accumulation. Modeling and control strategies for a new observably-optimized piezoelectric micro-actuator are presented in Moussa, Grossard, Boukallel, Hubert, and Chaillet (2014). The authors used a topological optimization method which takes into account the optimal full integration of piezoelectric actuating and sensing elements within the device. Their proposed control strategy permits simple reconstruction of the deflection using electric charge measurements and a modal state observer. Finally, the vibrations were also successfully damped.

Clearly, the advanced control techniques can be used in order to ensure efficient positional control of PEA, which is a key element of those applications where high-precision and high-speed positioning and/or tracking is needed. Intelligent control techniques, which are based on genetic algorithms, fuzzy logic, neural networks etc. (Castillo & Melin, 2001), belong to the group of so-called soft computing control techniques. Such control techniques can certainly offer very promising solutions for nonlinear positional control tasks.

In order to address the issue of rate-dependent hysteresis in PEA a feedforward neural network (FNN) has been used in order to identify and predict this nonlinear behavior (Song & Li, 1999). Reportedly, beside neural networks, other control techniques like fuzzy logic and PID have been used for positional control of PEA (de Abreu & Ribeiro, 2002; Lin, Chiang, & Lin, 2011). Furthermore, combinations of neural network use with swarm intelligence have been successfully applied for control tasks and also for identification of the Prandtl–Ishlinskii hysteresis model, which is one of the more important hysteresis models among many others (Yang, Gu, & Zhu, 2013).

In this paper, a FNN control method combined with BAT search algorithm is developed in order to significantly improve the positional control of PEA, and compared with the classical FNN control method in order to clearly show the difference in functionality between them. The BAT search algorithm is used to properly train the FNN, to optimize the FNN topology and to resolve a three-dimensional control problem. According to our literature investigation conducted over the last few years, such as the combined approach for solving the PEA control problems has been absent and it presents a novelty where only the advantages from FNN and BAT search algorithm are used.

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