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Inverse modeling and control of a dielectric electro-active polymer smart actuator

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ABSTRACT

This study focuses on the design of an inverse model for a dielectric electro-active polymer (DEAP) smart actuator using the dynamic nonlinear auto regressive exogenous (NARX) structure and a fuzzy inference system. The unknown parameters of the proposed NARX fuzzy model was identified by the adaptive particle swarm optimization (APSO) algorithm. An augmented proportional-integral-derivative feed-forward inverse (APIDFFI) controller was then developed for position tracking control of the actuator. Finally, an experimental investigation was scrutinized in order to evaluate the effectiveness of the designed inverse model and the proposed controller. The results show that the designed controller based on the inverse model improves the tracking performance of the actuator significantly with the tracking accuracy of about 96% and reduces the tracking errors compared to the conventional proportional-integral-derivative (PID) controller.

1. Introduction

Dielectric electro-active polymer (DEAP) materials have been widely used in various applications, including sensors such as the haptic interface, stroke and surface strain sensors, soft capacitive sensors [1–3], as well as actuators such as portable fusion pumps, transducers, powerful tubular core free push actuators, force feedback gloves, and biomimetic walking robots [4–6]. The advantages of the DEAP materials are low cost, light weight, large deformation capability, no operating noise, high performance, and very low power consumption. The working principle of the DEAP material is shown in Fig. 1. It consists of a polymer film sandwiched between two compliant electrodes. A large actuation voltage of opposite polarity is applied to these two compliant electrodes in order to produce a high electrical field (hundreds to thousands of volts per meter). Because they attract each other, a pressure due to electrostatic forces is created, compressing the polymer film, and reducing its thickness while increasing the area at a constant volume. The polymer film will return to its original size and thickness when the electric charge is removed. However, similar to other smart materials such as ionic polymer metal composite (IPMC), magneto-strictives, piezo-electrics, and shape memory alloys (SMA), the main drawback of the DEAP materials is that they have a nonlinear asymmetric behavior as shown in Fig. 2, which causes positioning inaccuracy or leads to instability, reducing the performance of the closed system.

The inverse model-based control is known as a general structure that uses the inverse model of a nonlinear system to generate the control signal for the system or to estimate the nonlinear characteristics of a system. The inversion of the nonlinear system plays a crucial role in the control problems and requires a sufficiently fast algorithm for the interpolation process. In the literature, several approaches for the inverse modeling and control of a system have been performed. Sun et al. [7] proposed an inverse neuro-fuzzy model to estimate the dynamic characteristics of a robotic manipulator. However, the tracking performance of the designed control approach has only been demonstrated through simulation process. Ahn et al. [8] proposed the internal model control by combining the forward model with the dynamic inverse model to control the SMA actuators. Xiaoliang et al. [9] designed a new iterative learning control algorithm based on an inverse model to decrease the hysteresis causing tracking error of a giant magneto-strictive actuator. The experimental results show that the designed learning control converges about twice as fast as the standard learning control and reduces the hysteresis phenomenon. Hong et al. [10] proposed a physics based dynamic modeling and inverse compensation of cantilevered ionic metal composite sensors. The effectiveness of the scheme as well as the underlying

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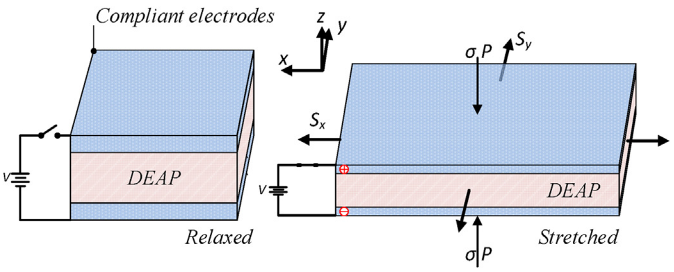

Fig. 1. Operating principle of a DEAP actuator.

model was validated experimentally in the construction of structural vibration signals. Anh et al. [11] successfully developed a nonlinear autoregressive exogenous inverse dynamic model based on a fuzzy algorithm to access the nonlinearities and uncertainties of pneumatic artificial muscle (PAM) manipulators. Nevertheless, the above technique has not been successfully applied to capture the behavior of the DEAP actuator with respect to its working frequency ranges. Truong et al. [12] approximated an inverse hysteresis model for the internal model control strategy to control the position of the actuator under the influence of the hysteresis phenomenon presented in the actuator. This model was established according to the increasing and decreasing of the desired tip displacement of the actuator. However, the designed inverse model has errors due to the inaccuracy in the modeling process of the hysteresis behavior and the computational error in the inverse model. Gorazd et al. [13] dealt with the feed-forward control algorithm based on an inverse of a hybrid fuzzy model for a nonlinear hybrid system. In the optimization process of a complex nonlinear system, the proposed controller requires considerable computational time, which obstructs the real-time implementation. Yuesong et al. [14] developed the inverse compensator to improve the linearity of a giant magneto-strictive transducer. Due to the help of the inverse compensator, the phase lag between the input control signal and the output displacement is decreased, and the growth rate increases with the increase of the excitation frequency.

Several approaches for the control of the dielectric electro-active (DEA) devices have been developed. Gisby et al. [15] proposed a low bandwidth digital control method using pulse width modulation (PWM) to calculate the capacitance of a DEA device. The capacitive self-sensing aspect of this control methodology can only be used to predict the change in area of a DEA actuator. Sarban et al. [16] proposed a physical-based electromechanical model of a DEA actuator for an internal model control (IMC) approach. The inverse model used in the IMC controller needs to be linearized by a linearizing gain scheduling, which was experimentally validated by measuring the DEA actuator elongation using a ramp voltage input. In our previous contributions [17], the forward model of a DEAP actuator was successfully identified via the nonlinear auto regressive exogenous (NARX) fuzzy model. The nonlinear features of the system are presented and the system has been modeled and identified based on sets of input–output training data gathered experimentally. Then, in consideration of the hysteresis behavior of the system [18], the forward hysteresis model was proposed using the classical Preisach model combined with the NARX fuzzy structure for modeling and identification of the nonlinear hysteresis behavior of the actuator. The results show that the designed model is effective and can be used in the control system.

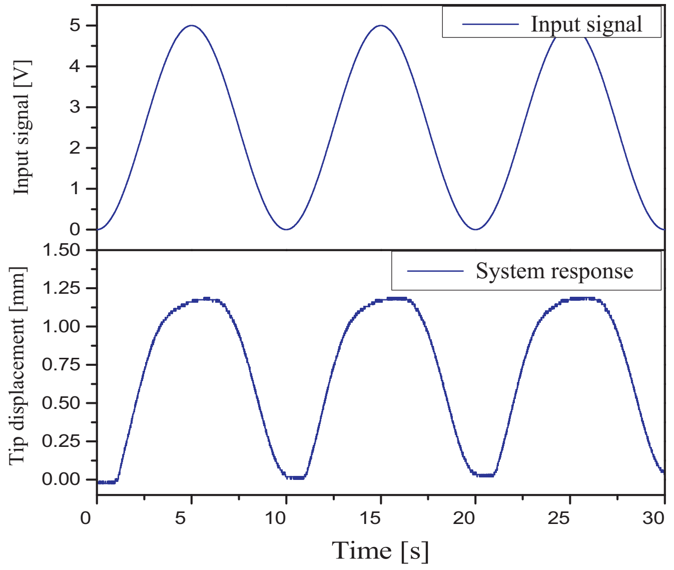

Fig. 2. System response with respect to sinusoidal input signal.

Based on the nonlinear asymmetric behavior of the DEAP smart actuator and the necessity of modeling an inverse model to address the control problems, which use the mathematical models as the controller. This paper proposes an inverse NARX fuzzy model-based adaptive particle swarm optimization (APSO) identification algorithm. In this model, the approximating capability of the fuzzy inference system is combined with the predictive behavior of the dynamic NARX structure. The adaptive element of the APSO identification algorithm is newly proposed by considering the adaptive factors that ensure a steady increase in the maximum fitness cost and prevent the searching process from becoming trapped in the local optima. It is then applied to estimate all unknown parameters of the designed inverse model. In order to investigate the effectiveness of the proposed inverse model on position control, the augmented proportional-integral-derivative feed-forward inverse (APIDFFI) controller was then developed and employed to control the system with several trajectories. The distinctive feature of the developed controller is that it allows the system with unknown dynamic properties to be controlled. Finally, experiments are conducted to validate the performance of the proposed inverse model and the developed controller.

The remainder of this paper is structured as follows. The proposal of the inverse NARX fuzzy model and the identification scheme based on the APSO algorithm to estimate unknown parameters of the proposed model are presented in Section 2. The experimental apparatus and the modeling results are shown in Section 3. In Section 4, the inverse model-based position controller and the experimental results are presented. Finally, concluding remarks are given in Section 5.

2. Proposal of the inverse NARX fuzzy model

2.1. Inverse NARX fuzzy compensation

The proposed inverse NARX fuzzy model for the nonlinear and dynamic behaviors of a DEAP smart actuator presented in this paper is designed by combining the excellent approximating capability of the fuzzy inference system with the predictive features of the dynamic NARX structure. The NARX model structure is non-recursive, so its parameters are easily estimated [11]. In time-series modeling, the delayed input terms in the NARX model structure introduces the dynamics to the model. The resulting model implies that the current control input signal $u_{(t)}$ is predicted as a weighted sum of the past input values, and the current and past output values. The inverse dynamic system can be generally described as follows:

$$u_{(t)} = f\left(u_{(t-1)}, \ldots, u_{(t-n)}, y_{(t-d)}, \ldots, y_{(t-d-m)}\right) \tag{1}$$