Three-Dimensional Hysteresis Modeling of Robotic Artificial Muscles with Application to Shape Memory Alloy Actuators

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***Abstract*—Robotic artificial muscles are increasingly popular in novel robotic applications. Their full utilization is challenged by the three-dimensional and coupled hysteresis nonlinearities among input, strain, and tension force. No prior studies on three-dimensional hysteresis models with coupled variables have been reported for robotic artificial muscles. This paper presents an approach to capturing and estimating the three-dimensional hysteresis in shape memory alloy (SMA) actuators. Experimental results confirm that the proposed scheme is effective. This study can be applied towards other robotic artificial muscles.**

I. Introduction

Robotic artificial muscles are actuators that have similar working mechanisms as biological muscles – they can contract in their cross-sectional directions. Compared to electric motors and hydraulic actuators, robotic artificial muscles have demonstrated high power-to-weight and force-to-weight ratios, inherent compliance, and good dynamic range in a muscle-like form factor [5, 15, 17]. They are increasingly popular in novel applications such as safe human-robot interaction, prostheses and orthoses, and soft robotics [10, 11, 12]. However, it is often a challenging task to utilize these actuators due to the three-dimensional and coupled hysteresis nonlinearities – any of the two variables among input, strain, and tension force are often correlated (Fig. 1(a)). No prior studies on three-dimensional hysteresis models with coupled variables have been reported for robotic artificial muscles. Shape memory alloys (SMAs) are a group of metallic materials with the capability of returning to the previous shape under temperature or stress stimulus [7]. While SMA actuators have been adopted in various applications, the modeling is challenging due to the hysteresis among steady-state voltage V, contraction length L, and force F, as shown in Fig. 1(b).

This paper presents the *first* study to successfully capturing and estimating the three-dimensional and coupled hysteresis in SMA actuators by recursively embedding two Preisach hysteresis models.

II. Background

Modeling of two-dimensional hysteresis has been an active research area. Compared to physics-based models, phenomenological models that are data-driven are more widely used [1, 13]. Among them, Preisach model has proven to be effective for various hysteresis behaviors [9, 14, 18]. However, three-dimensional hysteresis model needs to be developed for robotic artificial muscles. Compared to two-dimensional hysteresis, fewer strategies on multi-dimensional hysteresis exist, and the current methods have some noticeable limitations for robotic artificial muscles. For example, a model was proposed for the hysteresis in a piezoelectric actuator [4]; however, the modeling capability was limited due to a low number of parameters. A model was proposed for the hysteresis of the magnetization process [3], the inputs were independent but not coupled.

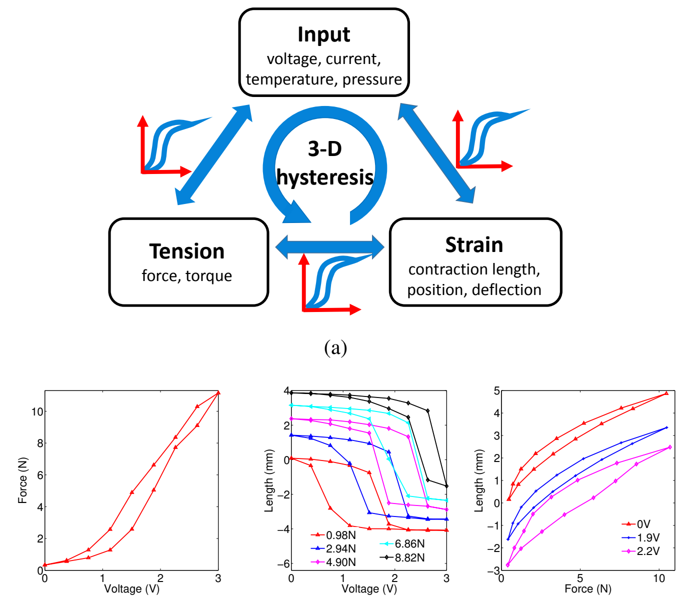


Fig. 1. (a). Three-dimensional and coupled hysteresis in robotic artificial muscles. (b). The experimental $F-V$ hysteresis (left), $L-V$ hysteresis (middle), and $L-F$ hysteresis (right) of an SMA actuator.

Physics-based models for the SMA actuators are proposed, but the analysis is often constrained to particular types of SMAs [2]. The existing phenomenological models can only capture two-dimensional hysteresis. For example, only the voltage – strain hysteresis was captured with the proposed model [8]. In practice, such as SMA-actuated robot hand for grasping object with different temperatures and weights, the strain and tension force of the actuators would vary together, resulting in complicated relationships.

III. Three-dimensional Hysteresis Model

The proposed model is derived by modeling the $F-V$ hysteresis and embedding the modeled $F-V$ relationship. More details on Preisach model can be found in [9, 14, 18].

A. $F-V$ Model

A Preisach model is adopted to capture the $F-V$ hysteresis:

$$F(n) = H_1[V(n)] = \sum_{i=1}^{N_1} \sum_{j=1}^{N_1+1-i} w_{ij} s_{ij}(n) + c_0, \qquad (1)$$

where H_1 is a Preisach model, N_1 is the discretization level of H_1, $\{w_{ij}\}$ are the model parameters, $s_{ij}(n)$ is determined by the voltages up to time n, and c_0 is a constant bias. The length of the actuator is maintained close its resting length, so $L \approx 0$ and L was assumed not present in the model. The model can be identified with a linear least-squares algorithem and solved efficiently.

B. Proposed $L-F-V$ Model

The following three-dimensional model is proposed:

$$L(n) = H_2[F - H_1[V]](n) = \sum_{i=1}^{N_2} \sum_{j=1}^{N_2+1-i} \mu_{ij} p_{ij}(n) + c_1, \qquad (2)$$

where H_2 is a Preisach model, N_2 is the discretization level of H_2, $\{\mu_{ij}\}$ are model parameters, $\mu_{ij}(n)$ is determined by the force and voltage up to time n, and c_1 is a constant bias. Note that $F(n) = H_1[V(n)]$ held only when $L = 0$. The negative term of $H_1[v]$ is used since the $L-V$ hysteresis is monotonically decreasing. The proposed model can be identified based on $L-V$ and $L-F$ hysteresis measurements.

C. Comparison Methods

Two additional approaches are considered for comparison. The Summed Preisach model considers that the contraction length can be expressed as a weighted summation of two Preisach models. This approach cannot capture the shape difference of each hysteresis curves. The Linear Preisach model simplifies the $F-V$ hysteresis to be linear. Due to this simplification, significant modeling errors are expected.

IV. Experimental Results

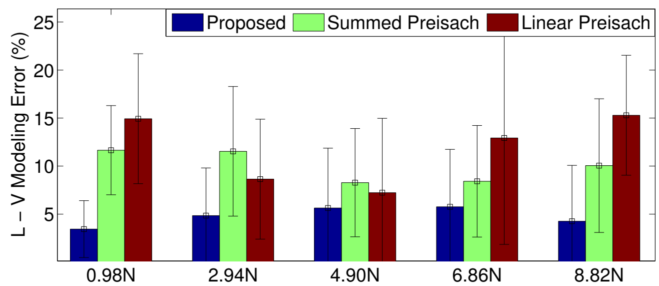
Model identification and verification are conducted. The performance is measured by the average and root-mean-square (RMS) of the absolute errors divided by the output range.

A. Model Identification

The proposed model is identified. The average and RMS errors for the $F-V$ hysteresis are 1.2% and 1.9%, respectively. The average and RMS errors for the $L-V$ hysteresis are 4.8% and 7.2%, respectively, and the average and RMS errors for the $L-F$ hysteresis are 4.3% and 4.9%, respectively. The Summed Preisach model and Linear Preisach model are also identified. The three approaches are compared for modeling the $L-V$ hysteresis, and the results are shown in Fig. 2(a). The proposed model produces the best overall results.

B. Model Verification

The verification for the $L-V$ hysteresis is provided. A randomly-chosen voltage input is applied to the SMA actuator under different loading forces. The experimental measurements of the steady-state contraction lengths are measured and compared with the model estimation values. The model estimation errors are provided in Fig. 2(b). The effectiveness of the proposed approach is further validated.



(a)

Methods	Proposed	Summed	Linear
Average error	4.7%	9.3%	10.4%
RMS error	6.9%	11.3%	13.5%

(b)

Fig. 2. (a). The $L-V$ hysteresis modeling error comparisons. (b). The model verification error comparisons of the three models for the $L-V$ hysteresis.

V. Conclusion and Future Work

This study proposes an approach to capturing the three-dimensional and coupled hysteresis of robotic artificial muscles by embedding a two-stage Preisach model. Experimental results confirm that the proposed approach can effectively describe and estimate the hysteresis in SMA actuators.

This study is general in two aspects: First, the proposed model can be constructed using any existing two-dimensional hysteresis models; Second, the proposed scheme is based on a phenomenological model that does not carry physical implications, so it can be applied towards SMA actuators with other diameters and materials, as well as other types of robotic artificial muscles.

Based on this study, future directions are envisioned in the following three areas: First, the validation of the proposed model for other robotic artificial muscles, such as McKibben actuators and Super-coiled Polymer actuators [16, 19], is desirable. The successful modeling and verification of the proposed model for these robotic artificial muscles and actual robotic systems can further strengthen this work. Second, open-loop control of robotic artificial muscles can be realized. By inverting the proposed model, the inverted model can be adopted to compensate for the three-dimensional hysteresis in robotic artificial muscles. Last but not least, by incorporating the dynamics of the actuators, closed-loop control [6, 12] of robotic artificial muscle-powered robots can be investigated for real-time tracking control.

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