

Characterization of electromechanical properties of Electroactive Polymer Actuators for Soft Robots in mini-invasive surgery

Imane Ferradj, Eric Monteiro, Damien Thuau, Sebastien Roland, Nazih Mechbal

Abstract. In recent decades, soft robots have attracted considerable attention due to their flexibility and ability to adjust stiffness when interacting with the external environment, making them suitable for mini-invasive procedures. These robotic systems require actuators that are both flexible and lightweight, and electroactive polymers (EAPs) have emerged as some of the most promising solutions. Among EAPs, P(VDF-ter-TrFE-ter-CTFE) terpolymers have been extensively studied due to their unique electrostrictive, piezoelectric, and dielectric properties, making them good candidates for actuation. In this work, we established a methodology to evaluate the electromechanical properties of these EAPs, focusing on matching experimental data with an electromechanical model. This model consists of two main parts: the mechanical model, which computes strains due to electrostriction and piezoelectricity, and the electrical model, which models the hysteresis of the electrical displacement. Terpolymers with different amounts of CTFE are modelled to study the effect of this termonomer on the performance of the terpolymers, including the electrostriction and piezoelectric coefficients, as well as other parameters related to electrical displacement.

Key words: Electroactive Polymers, Multiphysics Modelling, electrostriction, hysteresis

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1 Introduction

Recent advances in soft robotics have highlighted the critical need for compliant actuators that combine large deformations with precise control, particularly for mini-invasive surgical applications. While dielectric elastomers and ionic polymers have been widely explored, ferroelectric relaxor polymers based on poly(vinylidene fluoride) (PVDF) terpolymers offer unique advantages including intrinsic electromechanical coupling, scalability, and compatibility with micro-fabrication processes. Among these, P(VDF-*ter*-TrFE-*ter*-CTFE) terpolymers exhibit tunable electroactivity through CTFE content modulation, enabling transition from ferroelectric to relaxor behavior [1]. However, accurately predicting their complex electromechanical response requires models that simultaneously account for nonlinear hysteresis and coupled piezoelectric-electrostrictive effects that are still a challenge.

This work presents a comprehensive experimental and modeling framework to quantify the composition-dependent electromechanical properties of PVDF-based terpolymers. Building upon previous characterization methods [2], we develop a coupled electromechanical model that integrates three key ingredients: (1) a geometrically exact beam formulation capturing large deformations, (2) Separation of piezoelectric (d_{zx}) and electrostrictive (Q_{xz}) contributions, and (3) a hysteresis-aware electrical model parametrized through simultaneous polarization and deflection measurements.

Our experimental methodology employs a novel multi-physics characterization system combining high-speed videometry with synchronized current-voltage measurements, enabling direct correlation between polarization dynamics and mechanical response. We specifically investigate two material systems - a conventional 65/35 VDF/TrFE copolymer and a 66.5/33.5/8.5 VDF/TrFE/CTFE terpolymer - to quantify how CTFE-induced phase transformation affects key parameters including coercive field (E_c), remnant polarization (P_r), and electromechanical coupling coefficients.

The paper is organized as follows: Section 2 details the actuator fabrication process and characterization setup, including our current decomposition method for polarization extraction and optimized digital image correlation for displacement tracking. Section 3 presents the unified electromechanical model, combining a nonlinear Timoshenko beam formulation with Preisach-type hysteresis modeling. Section 4 validates the model against experimental results, revealing the impact of CTFE incorporation.

2 Experimental setup

2.1 Actuator fabrication

Actuators were prepared by screen-printing process, using P(VDF-*co*-TrFE) and P(VDF-*ter*-TrFE-*ter*) inks on PEKK substrates, with intermediate annealing steps at 100–110 °C and a final anneal at $T_m - 15$ °C to obtain unimorph devices (active area 4 mm × 10 mm). The complete manufacturing process can be found in [3].

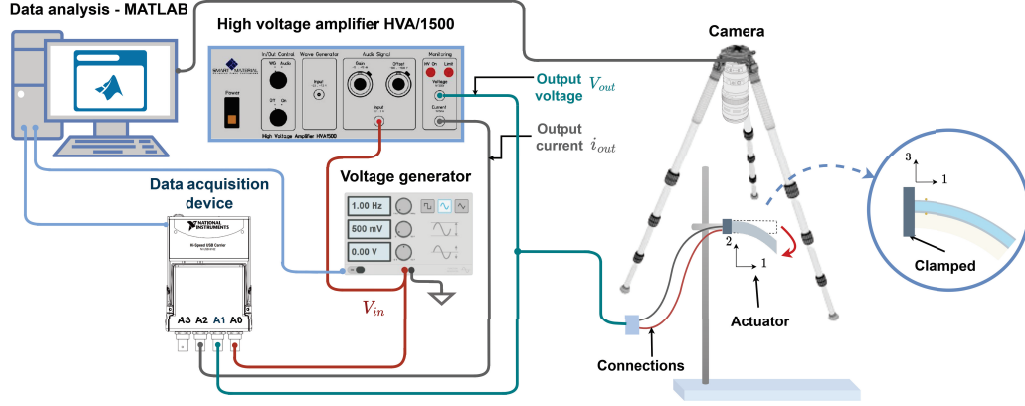


Figure 1: Schematic of the simultaneous electrical and optical characterization setup.

2.2 Experimental characterization system

The ferroelectric polymer actuators were driven by a high-voltage sinusoidal signal generator (Agilent 33220A) and their current response recorded with a Keithley 6517B (100 nA resolution). A Basler usb3 camera (100 fps) captured the macroscale bending (see Fig. 1). All tests were conducted at 25 °C.

2.3 Polarization extraction methodology

The total current can be divided into 3 parts, namely a resistive leakage $I_i(t)$, a capacitive displacement $I_c(t)$ and a ferroelectric contribution $I_{fe}(t)$, such that

$$I_{\text{total}}(t) = I_i(t) + I_c(t) + I_{fe}(t) \quad (1)$$

First, the total current was noise-filtered using Savitzky–Golay filter. The resistive leakage $I_i(t) = V(t)/R_{\text{est}}$ was isolated via linear regression at high voltage and the estimated resistance was about $R_{\text{est}} = 1.7 \text{ M}\Omega$. Then, in a similar way, the capacitive displacement $I_c(t) = C_{\text{est}}dV(t)/dt$ was deduced with an estimated capacitance $C_{\text{est}} = 13.5 \text{ nF}$. Finally, the polarization is obtained by integrating the ferroelectric current $I_{fe}(t)$:

$$P(t) = P(t_{\text{start}}) + \frac{1}{A} \int_{t_{\text{start}}}^t I_{fe}(\tau) d\tau \quad (2)$$

where A is the active area. This workflow is illustrated in Fig. 2 and the obtained polarization depicted in Fig. 3. Note that cycle boundaries were set at $V(t)$ zero-crossings.

2.4 Macroscopic deflection and image processing

A streamlined approach was employed for analyzing actuator deflection. Videos of actuators clamped at one end and driven with sinusoidal voltages were processed using digital image correlation with optimized parameters. The image processing workflow

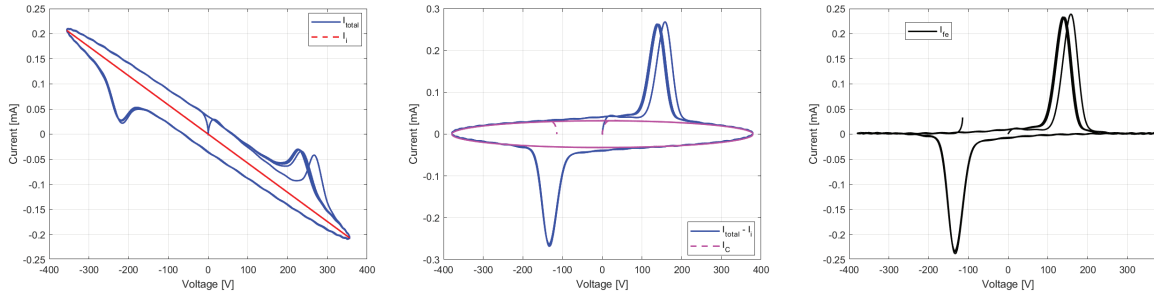


Figure 2: Current-processing workflow: (left) resistive leakage removal; (middle) capacitive displacement removal; (right) final ferroelectric current.

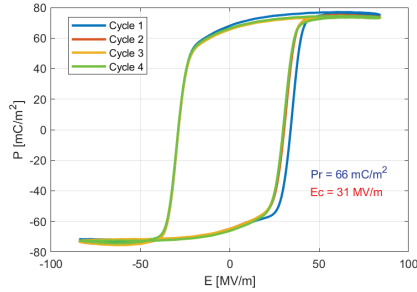


Figure 3: Polarization cycles versus electric field.

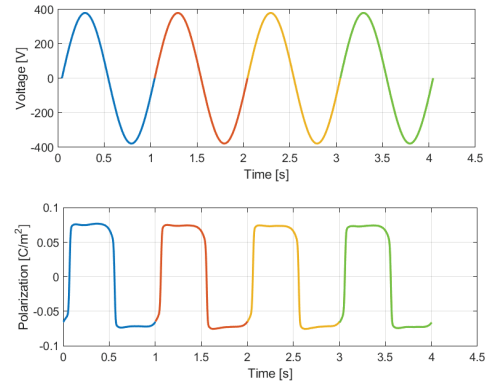


Figure 4: Driving voltage (top) and extracted polarization (bottom) vs. time.

was simplified to focus on essential edge detection and fitting procedures. After spatial calibration, boundary points were efficiently fitted using regularized polynomial optimization. This simplified approach provided accurate deflection measurements while reducing computational complexity.

2.5 Employed actuators – material and geometry

Young's moduli (PEKK substrate $Y_s = 2.9$ GPa; PEDOT:PSS electrodes $Y_e = 0.5$ GPa) were confirmed by DMA and supplier data. Active layer moduli Y_p were extracted from DMA (5 mm strips, 1 Hz, 0.1 % strain), showing transitions at -20°C (glass) and the Curie point, shifting lower with higher CTFE content [4]. Layer thicknesses were measured by SEM cross-sections.

3 Modeling of EAP Actuators for Soft Robots

The modeling of EAP actuators is divided into two main parts: a mechanical model that predicts the deformation of the actuator and an electrical model that describes

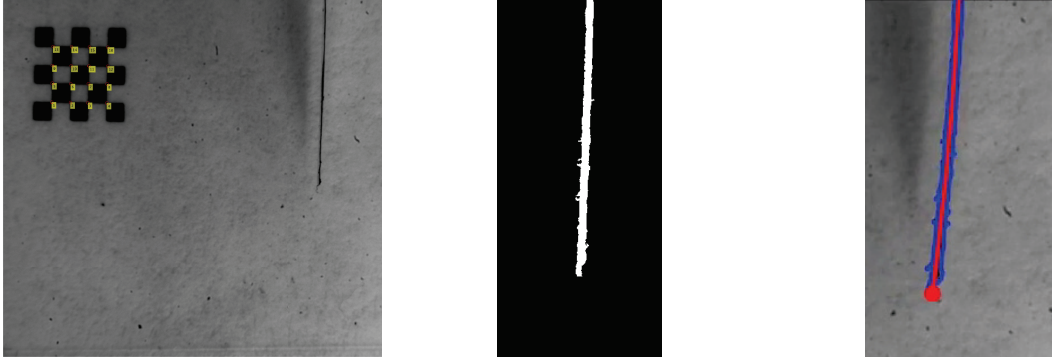


Figure 5: Image-processing workflow for macroscopic deformation: (left) chessboard calibration detection; (middle) texture feature mask; (right) edge tracking and polynomial fit.

Table 1: Active-layer material and geometric properties.

Composition	Class	Y_p [GPa]	t_p [μm]
65/35 VDF/TrFE, 0 % CTFE	Copolymer	1.265	4.5
66.5/33.5 VDF/TrFE, 8.5 % CTFE	Terpolymer	0.171	5.0

the behavior of the electric displacement, which can exhibit hysteresis under an applied voltage. This integrated approach allows us to establish a direct relationship between material composition, electrical response, and mechanical output, essential for designing optimized actuators for soft robotic applications.

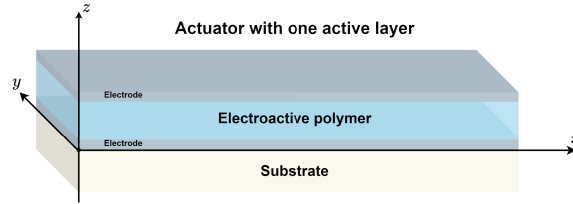


Figure 6: Schematic of the multilayer model.

3.1 Mechanical Model

The employed actuators, depicted in Fig. 6, is modelled as a straight laminated composite cantilever beam of length L with a rectangular cross section. The plies are stacked such that material properties are functions of the z -coordinate. To deal with large deflection and large rotation but small strains, the geometrically exact formulation based on Timoshenko kinematic is used and briefly presented here in 2D. The interested reader

may refer to [5] for more details. Assuming that the cross-section, initially plane, remains plane after deformation and neglecting in-plane deformation of the cross-section, the axial and transverse displacements of any point $M(x, z)$ are defined by:

$$u(x, z, t) = \bar{u}(x, t) - z \sin(\psi(x, t)) \quad \text{and} \quad v(x, z, t) = \bar{v}(x, t) + z (\cos(\psi(x, t)) - 1) \quad (3)$$

where $\bar{u}$ and $\bar{v}$ are the axial and transverse displacements of a centroid while ψ stands for the rotation of the cross section. For the sake of readability, all dependencies are omitted in the following. By means of an ersatz polar decomposition, the non-zero components of the total strain tensor are

$$E_{xx} = (1 + \bar{u}') \cos \psi + \bar{v}' \sin \psi - z\psi' - 1 \quad \text{and} \quad E_{xy} = -(1 + \bar{u}') \sin \psi + \bar{v}' \cos \psi \quad (4)$$

Introducing the axial strain ξ , the shear strain γ and the beam curvature κ , these components reduce to

$$E_{xx} = \xi - z\kappa \quad \text{and} \quad E_{xy} = \gamma \quad (5)$$

Assuming small strains and taking into account electromechanical strains ξ_e like thermal expansion strains, the non-zero components of the stress tensor in the i -th layer are given by

$$T_{xx,i} = Y_i (E_{xx} - \xi_{e,i}) \quad \text{and} \quad T_{xy,i} = G_i E_{xy} \quad (6)$$

where Y_i and G_i represent the Young's modulus and the shear modulus of the i -th layer. The electromechanical strain in x -direction is modelled through a combined effect of electrostriction and piezoelectricity such that:

$$\xi_{e,i} = \begin{cases} d_{zx} E_z + Q_{xz} D_z^2 & \text{in active layers} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

where E_z and D_z represent the electric field and electric displacement in the z -direction, respectively, while ε denotes the permittivity of the active layer. Then, the resultant stresses are computed by integration across the cross-section

$$N = \iint T_{xx} dydz, \quad Q = \iint T_{xy} dydz \quad \text{and} \quad M = \iint z T_{xx} dydz \quad (8)$$

where N , Q and M stand for the axial force, the shear force and the bending moment respectively. Finally, the equation of motion can be derived from the principal of virtual work as follows

$$\iiint (\delta u \rho \ddot{u} + \delta v \rho \ddot{v} + \delta \psi I \ddot{\psi}) dx dy dz + \int (\delta \xi N + \delta \gamma Q + \delta \kappa M) dx + \int (\delta u n + \delta v q) dx = 0 \quad (9)$$

where n and q stand for body forces collinear and normal to the neutral axis of the beam respectively while δu , δv and $\delta \psi$ denote the virtual displacements and rotation. This nonlinear equation can't be solved analytically. Here, this equation is solved using standard finite elements with quadratic shape functions using a total Lagrangian approach in tandem with Newmark time integration scheme and Newton-Raphson algorithm.

3.2 Electrical Model

The behavior of the electric displacement in EAP actuators is nonlinear due to the presence of hysteresis. An empirical model is used to describe this behavior. In this model, the total electric displacement D_z is given by

$$D_z = \varepsilon E_z + P_s, \quad (10)$$

where the first term represents the polarization induced by the electric field, and P_s is the spontaneous polarization that occurs naturally in the material and described by

$$P_s = \begin{cases} P_{sat} \tanh\left(\frac{E_z - E_c}{\delta}\right) - P_{offset} & \text{if } dE_z > 0 \\ P_{sat} \tanh\left(\frac{E_z + E_c}{\delta}\right) + P_{offset} & \text{else} \end{cases} \quad (11)$$

where P_{sat} represents the saturation polarization, E_c is the coercive electric field, δ controls the sharpness of the hysteresis curve and P_{offset} closes the gap between both expressions at high electric field [6].

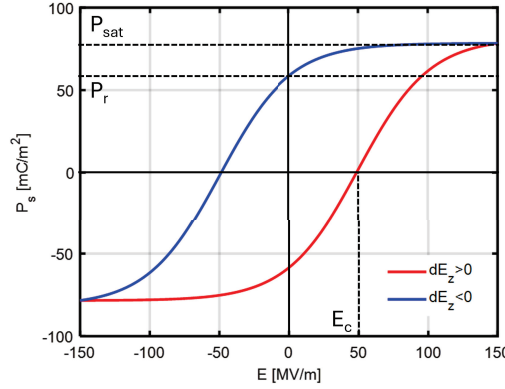


Figure 7: Ferroelectric hysteresis loop.

3.3 Parametric Identification

A concise optimization identifies model parameters by fitting both the D-E hysteresis and tip deflection curves. The single cost function is:

$$J = \frac{1}{2} \left(\frac{\|u_{\text{model}} - u_{\text{exp}}\|}{\|u_{\text{exp}}\|} + \frac{\|D_{\text{model}} - D_{\text{exp}}\|}{\|D_{\text{exp}}\|} \right) \quad (12)$$

where u is the deflection of the tip and D the electric displacement (model vs. experiment). The parameters to identify include the coercive field E_c , the remnant polarization P_r , the saturation polarization P_{sat} , the permittivity ε and the charge-related coefficients d_{zx} and Q_{xz} .

4 Results and discussion

In this section, the developed methodology is applied to the samples presented in Table 1. Based on actuator deflection and electrical displacement measurements as a function of the applied electric field, the numerical model was tuned to achieve the best fit for both signals. After optimization, the model successfully fits the electromechanical response of both samples although they represent two distinct material behaviors, as shown in Fig. 8 for copolymer and terpolymer samples.

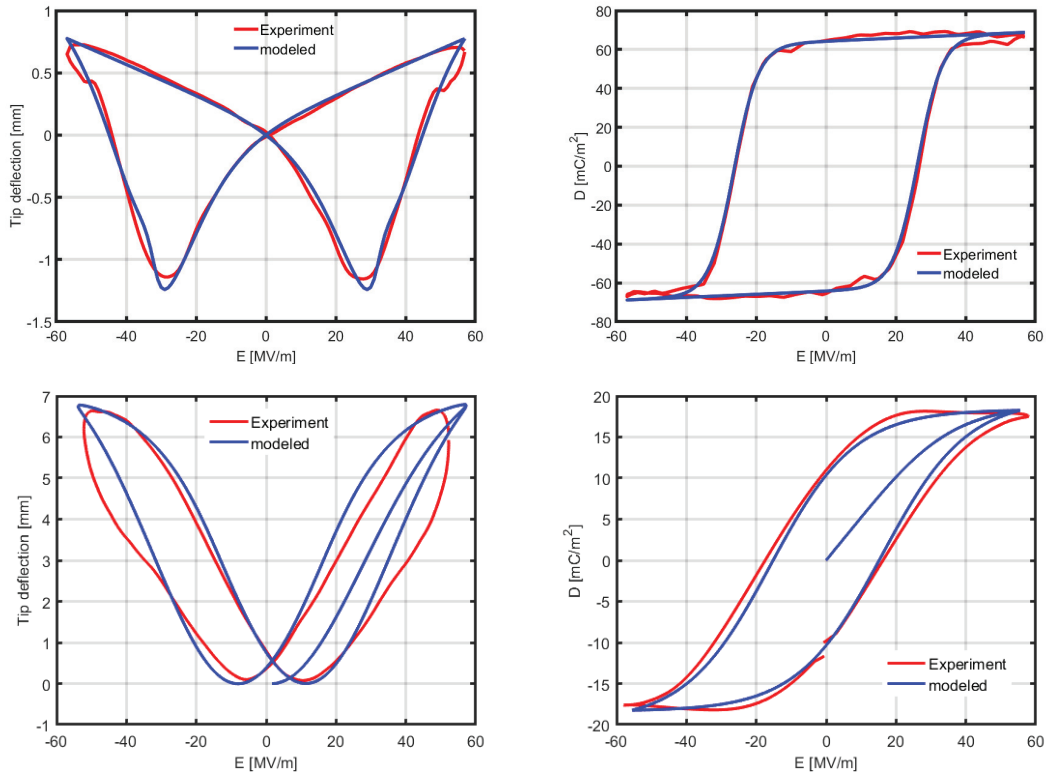


Figure 8: Tip deflection (left) and electric displacement (right) for copolymer sample (top) and terpolymer (bottom).

The presence of CTFE termonomer significantly modifies the electromechanical properties of the material. The addition of 8.5% CTFE in the terpolymer significantly decreases the coercive electric field E_c , remnant polarization P_r and saturation polarization P_{sat} , while simultaneously enhancing the dielectric nature of the material compared to the pure copolymer. These changes directly impact actuator performance, as they determine the operational voltage range and response characteristics of the device. The future soft robot will be composed of multiple EAP strip actuators bonded circumferentially to the

outer surface of endoscope tubes. For electric safety, input voltage must be reduced by increasing the number of active layers and reducing their thickness.

5 Conclusion

This study presents a comprehensive experimental and modeling framework to quantify the composition-dependent electromechanical properties of PVDF-based terpolymers. Our experimental methodology employs a multi-physics characterization system combining high-speed videometry with synchronized current-voltage measurements, enabling direct correlation between polarization dynamics and mechanical response. Through the development of an electromechanical model, we successfully integrated piezoelectric and electrostrictive effects and evaluate their respective contributions independently. This model not only accounts for the non-linear and hysteretic nature of these materials but also provides a deeper insight into the mechanisms driving their actuation under applied electric fields. Finally, the proposed methodology was used to understand how the incorporation of CTFE influences the piezoelectric and electrostrictive properties of P(VDF-*ter*-TrFE) copolymer and P(VDF-*ter*-TrFE-*ter*-CTFE) terpolymer with 8.5% CTFE content.

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