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A Polyurethane-based Electrospun Nanofiber Bundle Soft Actuator: Fabrication, Modeling, and Control

Riccardo D'Anniballe^{1*}, Giovanni Paoletta^{2*}, and Raffaella Carloni¹

Abstract—This paper focuses on a novel polyurethane-based soft actuator that is fabricated by an electrospinning process. The actuator is a bundle of aligned nanofibers of a polyurethane solution and a salt, which acts as a conductive filler. From the same bundle, three actuators are obtained. Electromechanical tests are performed on one specimen to evaluate the axial displacements and axial forces generated by the actuator, when stimulated by an external electric field. The data generated during the electromechanical tests are used to identify the non-linear dynamics of the specimen by means of a multi-layer perceptron. Subsequently, the identified dynamic model is used to design a position control architecture that controls the applied electric field to regulate the axial displacement of a second specimen. Finally, as a proof of concept for the usability of the nanofiber bundle soft actuator, a third specimen is tested in a robotic prototype, in which a rigid link moves thanks to the actuator's contraction capability.

I. INTRODUCTION

Polyurethane (PU) is a thermoplastic polymer with good mechanical properties, such as high flexibility and low density. Some types of PU are dielectric elastomers that exhibit electrostrictive strain, i.e., the ability to produce large field-induced strain when exposed to an electric field [1], which makes them suitable materials for soft actuation [2], [3], [4].

This paper focuses on a PU-based soft actuator, realized with a bundle of electrospun aligned nanofibers of a PU solution and a salt, which acts as conductive filler [5], [6], [7]. This specific structure has been chosen because nanofibers are characterized by high porosity and high surface-to-volume ratio, i.e., physico-chemical properties that enhance their actuation capability [8]. Moreover, due to the electrospinning process, the fibers have a low elastic modulus and a self-induced dipoles orientation, which increase their dielectric properties [9] and electrostrictive effect [10], [11].

In recent literature, attention has been brought to electroactive polymers organized in fibrous structures, e.g., bundles of fibers, to realize soft actuators whose contraction capability is enhanced by the organized structure [12]. In [13], fibers of polyacrylonitrile gel have been produced and organized in a bundle to realize a soft actuator (mass of 14.5 g, diameter of 8 mm). When preloaded at 0.1 N, the actuator produces a

force of 1.2 N (stress of ~ 24 kPa), when stimulated at 10 V. In [14], a PU-based bundle of electrospun nanofibers, coated in polyaniline, shows a linear contraction of 1.65% when preloaded at 5 mN and stimulated between -0.2 and 0.8 V. In [15], bundles of silk-poly(pyrrole) nanofibers, coated with PEDOT, show a stress of $\sim 260 \pm 20$ kPa and a strain of $1 - 2\%$, when stimulated by a square wave of ± 2 V. In [16], a soft actuator, made of helically aligned fibrous carbon nanotubes, produces a stress of 6 MPa during an isometric test, when a current of 5 mA flows through the actuator. However, the use of electrospun nanofiber bundles as soft actuators for soft robotic systems is still unexplored.

This work shows the potential of using a bundle of PU-based electrospun nanofibers as soft actuator for soft robotics applications, and focuses on its electromechanical characterization, modeling, control, and implementation in a proof of concept robotic prototype. In particular, the actuator is electromechanically characterized to evaluate the axial forces (at fixed displacements) and the axial displacements (at fixed forces) generated when different voltages are applied at its extremities. The actuator shows a high force-to-weight ratio and a high lifting-to-weight ratio. Specifically, when preloaded with a force of 0.2 N, the actuator (mass of ~ 7 mg, diameter of ~ 0.6 mm) produces a maximum force of 35 mN (maximum stress of ~ 124 kPa), when stimulated by a voltage of 300 V, and it can lift a mass of 20.39 g, when stimulated by a voltage of 200 V. Then, its non-linear and multi-domain dynamics (thermal, electrical, mechanical) have been identified by means of a multi-layer perceptron (trained with experimental data), and a position control scheme has been developed on the identified model. Finally, the soft actuator has been tested in a proof of concept robotic prototype.

The remainder of the paper is as follows. Section II describes the fabrication process of the PU-based soft actuator, which is electromechanically characterized in Section III. In Section IV, the dynamic model of the actuator is derived by using a non-linear system identification method that is, then, used to design a position control scheme in Section V. Section VI presents a robotic prototype that exploits the soft actuator. Concluding remarks are drawn in Section VII.

II. FABRICATION OF THE SOFT ACTUATOR

This Section describes the fabrication process of the PU-based soft actuator, i.e., a bundle of aligned nanofibers of PU/PCL polyurethane solution¹ and NBu₄PF₆ salt².

¹Poly[4,4-methylenebis(phenylisocyanate)-alt-1,4-butanediol/di(propyleneglycol)/polycaprolactone].

²Tetrabutylammonium hexafluorophosphate.

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A mat of aligned nanofibers is fabricated by an electrospinning process [17], with a Spinbow™ machine (www.spinbow.it/en/, Italy). Specifically, 61 mg of NBu₄PF₆ salt are solved in a 4 ml mixture of THF:DMF 70 : 30 (v/v). Subsequently, a PU/PCL (7%wt) polyurethane solution is added to obtain the electrospinning solution. The solution is loaded into a 5 ml syringe, connected to a metallic needle (55 mm length, 0.3 mm internal diameter) via a Teflon tubing. A syringe pump controls the flow rate of the polymeric solution, which assumes the form of aligned nanofibers thanks to a high electrostatic field between the needle (connected to a positive DC high-voltage) and a grounded metallic rotating drum, which is positioned at a certain distance from the needle and covered with poly(ethylene)-coated paper. Table I reports the parameters of the electrospinning process.

Flow rate [ml/h]	0.96
Electric potential [kV]	22
Drum rotation speed [rpm]	6000
Distance needles-drum [cm]	22
Relative humidity [%] & Temperature [°C]	22 & 40

III. ELECTROMECHANICAL CHARACTERIZATION

The electromechanical characterization is performed with the InstronTM ElectroPuls E1000 test instrument (www.instron.com).

B. Preparation of the PU-based Soft Actuator

Before starting the electromechanical characterization, the soft actuator is prepared as follows: (i) It is fully immersed in propylene carbonate solvent for 30 s to enhance its conductivity. (ii) It is blotted in filter paper to eliminate the excess of solvent. This operation avoids the swelling of the nanofibers and prevents the salt leakage from the actuator. (iii) It is placed inside the test instrument with two clamps. (iv) It is preloaded at 0.2 N. This value is chosen to allow the complete relaxation of the material after its contraction due to the applied voltage. (v) A period of 10 min is waited to ensure the material stabilization after preloading.

It should be noted that the total mass of the PU based soft actuator (~ 7 mg) is the mass of the dry PU-based soft actuator, i.e., the mass evaluated just after the fabrication and before the preparation procedure described above.

C. Experiments - Axial Displacement

The axial displacement is measured by performing a force control on the test instrument. The instrument is required to maintain a fixed force, i.e., the preload of 0.2 N at the extremities of the actuator, and the axial displacement, produced by the actuator upon stimulation with a voltage, is measured. Three input voltages are applied: (i) Two square voltages, i.e., 100 V and 200 V, for intervals of 30 s; (ii) A trapezoidal voltage with an amplitude of 200 V in an interval of 30 s; (iii) A sinusoidal voltage with an amplitude of 200 V and a period of 30 s.

Figure 4 (left) shows the measurements of the axial displacements for the different input voltages. From Figure 4e, it can be noted that the axial displacement is always positive, independently of the positive or negative applied voltage. This behaviour is due to the electrostrictive effect of the polyurethane, i.e., the ability of dielectric materials to produce a large field-induced strain when exposed to an external electric field [19]. Specifically, there is a quadratic relation between the applied electric field E and the field-induced strain S , i.e., $S = QP^2$, where Q is the electrostrictive coefficient of the material, $P = D - \epsilon_0 E$ is the electric polarization, with D being the electric displacement field and ϵ_0 the vacuum permittivity [20].

Figure 4 (right) shows the currents that flow in the actuator for the same input voltages. From the figures, it can be noted that the applied voltage produces a current in the actuator that is inversely proportional to the length of the soft actuator. This behaviour is due to the piezoresistive effect, i.e., the change in the electrical resistivity of a semiconductor caused by a mechanical strain [21]. Specifically, there is a linear relation between the electrical resistance R of the actuator and its length l , i.e., $R = \rho l/A$, where ρ represents the resistivity of the material and A the area of the cross section of the soft actuator. As a consequence, when the axial displacement increases (i.e., there is a contraction in the soft actuator and its total length l decreases), the current increases. By comparing Figure 4a with 4b, it can be noted that both the axial displacement and the current increases. However, while the current increases immediately when

Fig. 4: Axial displacements (left) and current (right) with different input voltages.

the input voltage is applied as a step function, the axial displacement increases slowly due to the dynamics of the actuator. Nevertheless, by applying a constant voltage for 30 s, it can be noted that the current decreases, mainly due to dehydration of the actuator and, consequently, also the axial displacement decreases. By comparing Figure 4c with 4d or Figure 4e with 4f, it can be noted that, as the input voltage increases slowly from 0 to 200 V, both the axial displacement and the current increases slowly.

D. Experiments - Axial Force

The axial force is measured by performing a displacement control on the test instrument. The instrument is required to maintain a fixed displacement, i.e., the displacement of the actuator is constant, and the axial force, produced by the actuator upon stimulation with a voltage, is measured. Three input voltages are applied: (i) Two square voltages, i.e., 100 V and 200 V, for intervals of 30 s; (ii) A trapezoidal voltage with an amplitude of 300 V in an interval of 30 s; (iii) A sinusoidal voltage with an amplitude of 250 V, a period of 30 s, and a bias of 125 V.

Figure 5 shows the measurements of the axial forces for different input voltages. From the figure, it can be noted that, for increasing applied voltages, the actuator exerts increasing axial forces. Moreover, it should be noted that this actuator

Fig. 5: Axial forces with different input voltages.

has a high force-to-weight ratio, i.e., ~ 510 . Specifically, from Figure 5b, it can be noted that the actuator, which has a mass of 7 mg, is able to produce a maximum force up to 35 mN (starting from a preload of 0.2 N), when stimulated by a voltage of 300 V. The contraction forces slightly decrease in time due to dehydration.

IV. DYNAMIC MODEL

This Section derives the dynamic model of the PU-based soft actuator. Specifically, a non-linear identification method based on an artificial neural network is used to account for the complexity of the actuator, given by the overlaying of different physical effects, some of which of difficult estimation, e.g., electrothermal flows and electrostatic forces.

The non-linear dynamics of the soft actuator is described by a discrete-time non-linear autoregressive model with exogenous input [22], i.e.:

$$\hat{y}(k) = f(u(k-1), \dots, u(k-m), \hat{y}(k-1), \dots, \hat{y}(k-n))$$

where $\hat{y}(k)$ is the predicted output at the time step k , i.e., the axial displacement or axial force; $u(k-1), \dots, u(k-m)$ are the previous applied voltages; $\hat{y}(k-1), \dots, \hat{y}(k-n)$ are the previous predicted outputs, i.e., the previous predicted axial displacements or previous predicted axial forces; $f(\cdot)$ is a non-linear function, namely a multi-layer perceptron; $k \in \mathbb{R}^+$ is the time step, and $m, n \in [0, \dots, k]$.

The training of the multi-layer perceptron, i.e., the training that is needed to define $f(\cdot)$, has been done on the experimental data collected during the electromechanical characterization of one specimen of the soft actuator, and has been performed in the Deep Learning Toolbox of MATLAB (www.mathworks.com, USA), which uses the following open-loop model:

$$\hat{y}(k) = f(u(k-1), \dots, u(k-m), y(k-1), \dots, y(k-n))$$

where both $u(k-1), \dots, u(k-m)$ and $y(k-1), \dots, y(k-n)$ are the experimental data. After training, the designed multi-layer perceptron is defined by the parameters in Table II.

TABLE II: Parameters for the Deep Learning Toolbox in MATLAB.

# Hidden layer(s) & # Output layer(s)	1 & 1
# Input delays (k)	6 for y , 6 for u
# Hidden neurons	10
Minimum gradient	$1e^{-11}$
Training method	Levenberg-Marquardt
Activation function hidden & output layer	sigmoid & linear

A. Validation of the Dynamic Model

Figure 6 (left) compares the experimental data with the non-linear identification of the axial displacements. The error between the experimental data and the non-linear identification has a root mean square error of $4.1 \mu\text{m}$, which corresponds to $\sim 10\%$ of the axial displacement of the actuator when stimulated by a voltage of 200 V. Figure 6 (right) compares the experimental data with the non-linear identification of the axial forces of the actuator, when a sinusoidal voltage is applied. The error between the experimental data and the non-linear identification has a root mean square error of 1.4 mN, which corresponds to $\sim 10\%$ of the axial force of the actuator when stimulated by a voltage of 200 V.

Fig. 6: Experimental data and identification of the axial displacement (left) and of the axial force (right) of the soft actuator.

V. POSITION CONTROL

This Section presents a position control scheme for the PU-based soft actuator, which is designed based on the non-linear model identified in Section IV.

A. Experimental Setup

Figure 7 sketches the experimental setup. The soft actuator (in red) is fixed at the top, while the bottom extremity is attached to a mass of ~ 20.39 g (corresponding to 0.2 N) and is free to move (left figure). When a voltage is applied, the actuator contracts and lifts the mass (right figure).

B. Position Control

The goal of the position control is to regulate the axial displacement of the soft actuator and to achieve a desired position (i.e., $40 \mu\text{m}$) with the mass attached to its bottom extremity. Firstly, the position control has been designed on

Fig. 7: The soft actuator (in red) is fixed at the top, while the bottom is attached to a mass and is free to move (left). When a voltage is applied, the actuator contracts and lifts the mass.

Fig. 8: The position control scheme to modify the axial displacement of the soft actuator. (top) MATLAB/Simulink scheme. (bottom) Implementation on the Raspberry PI 3.

the identified non-linear model in MATLAB/Simulink. Afterwards, the controller has been implemented on a Raspberry PI 3 (Model B) control unit and tested on the actuator.

Figure 8 (top) shows the block diagram developed in the simulation environment MATLAB/Simulink, in which the NNET block represents the identified non-linear model and the PID block is the proportional/integral/derivative controller, whose parameters have been tuned to achieve the desired position. Specifically, the control parameters are $k_p = 7000$, $k_d = 200$, and $k_i = 300$. Figure 8 (bottom) shows the control architecture as it has been implemented on the Raspberry PI 3. The PWM signal of the Raspberry PI 3 is fed into a MOSFET signal conditioning circuit to obtain an analog signal in the mV range. Through a BNC adapter, the circuit is connected to the high-voltage amplifier, which amplifies the signal in the V range by means of a fixed gain of 1000. The axial displacement is recorded with a Logitech™ C930E HD camera (<https://www.logitech.com>, USA) connected to the Raspberry PI 3. Before starting the experiment, an offline calibration of the camera is required, as described in details in Figure 9.

Figure 10 (left) shows the simulated and real control actions, i.e., the voltage that is applied to the soft actuator. Figure 10 (right) shows the reference, the simulated and the real axial displacements. It should be noted that, despite the $\sim 10\%$ error on the identified model, there is a good match between the simulated and real values. The real signals (control action and the axial displacement) are noisy. This is

Fig. 9: Offline calibration of the camera. (a) Acquisition of the image of the actuator's initial position with the camera. (b) Definition of a reference on the image for the pixel-mm conversion. (c) Definition of the reference coordinates. (d) Definition of a region of interest (in pixel) for tracking the actuator's position.

Fig. 10: (left) Simulated and real control action. (right) Reference, simulated and real position.

due to the delay in the power circuit (MOSFET and signal amplification) and to the resolution of the camera (that has to detect displacements in the order of μm), respectively. This is more evident when the system is in steady-state (20-80 s).

Finally, it should be noted that this actuator has a high lifting-to-weight ratio, i.e., ~ 2910 . Specifically, the actuator, which has a mass of 7 mg, is able to lift a mass of 20.39 g, when stimulated by a voltage of ~ 200 V.

VI. ROBOTIC PROTOTYPE

This Section presents the realization of a robotic prototype that makes use of a third specimen of the PU-based soft actuator. This prototype is a proof of concept that aims to demonstrate that the proposed actuator can be used to actuate a link thanks to its contraction capabilities. Figure 11 shows the robotic prototype, i.e., a 3D-printed support on which a rigid conductive link is connected to the support by means of both a free joint and the actuator. When a voltage is applied, the actuator contracts and the rigid link (mass of 196 mg) is pulled and rotates freely around the joint. Figure 12 shows that, when the actuator is stimulated at 300 V, the link rotates of ~ 0.015 rad after ~ 10 s, as recorded by the camera.

VII. CONCLUSION

This paper describes a PU-based soft actuator. The actuator was fabricated by an electrospinning process and consists

Fig. 11: The robotic rigid link actuated by the soft actuator.

Fig. 12: Rotation (in radians) of the rigid link by means of the soft actuator when a constant voltage of 300 V is applied.

of a bundle of aligned nanofibers of a PU/PCL polyurethane solution and NBu_4PF_6 salt, which acts as a conductive filler. The soft actuator was electromechanically characterized to measure the axial displacements and the axial forces, which show electrostrictive and piezoresistive effects. The PU-based soft actuator (mass of 7 mg, diameter of 0.6 mm) has a high force-to-weight ratio (i.e., ~ 510), i.e., it is able to produce a force of 35 mN (stress of 124 kPa) when stimulated by 300 V, and has a lifting-to-weight ratio of ~ 2910 , i.e., it is able to lift a mass of 20.39 g, when stimulated at 200 V. A non-linear dynamic model of the PU-based soft actuator was developed by means of a multi-layer perceptron, which is trained on the experimental data obtained during the electromechanical characterization. A PID-based position control was designed on the identified non-linear model and used on the soft actuator. The experiment shows that the non-linear model is accurate enough to design a PID controller. Finally, a robotic prototype was realized as proof of concept to demonstrate that the electrospun nanofiber bundle soft actuator can be used in soft robotics applications thanks to its contraction capabilities.

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