Closed loop control of a rotational joint driven by two antagonistic dielectric elastomer actuators

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ABSTRACT

Dielectric elastomers are a subclass of electronic EAPs able to produce large deformations (and thus mechanical work) when an external electric field is applied. While the intrinsic compliance of this kind of polymeric actuators have been always addressed as major benefit with respect to traditional electromagnetic motors, unable to fully capture the capabilities and mechanical properties of biological muscles, their polymeric nature poses peculiar challenges in controlling a system which is subject to nonlinearities, hysteresis and viscous creep behavior. In this paper we explore the controllability properties of a simple rotational joint driven by two dielectric elastomer actuators arranged in an antagonistic configuration. A number of sensors are used to obtain information about the state of controlled system: the angular position of the joint is measured by an angular encoder, custom-designed tension sensors are used to monitor the tension of the two driving tendons and linear encoders provide accurate measurements of the displacements generated by the two actuators. Using this feedback information, a control algorithm has been implemented on a microcontroller unit in order to independently activate the two actuators, allowing a closed loop control of both the angular position of the joint (position control) and the tensions of its tendons (force control). A description of the developed control strategy and its performances under different load conditions are discussed in this paper.

Keywords: dielectric elastomer actuators, closed loop control, antagonistic configuration, force sensors

1. INTRODUCTION

Electroactive Polymers (EAPs) are polymers able to respond to electrical stimulations, modifying their shape when an external voltage is applied to them [1]. For this reason, EAPs are also often called “artificial muscles” because, even if they don’t share the same operative principle of biological muscles, their functional response is similar. EAPs are in fact able to generate a large variety of motion types (e.g. contraction, elongation, bending) and can develop forces similar to those of mammalian muscles. These peculiar characteristics of EAPs make them extremely attractive for the study of novel actuation mechanisms, and it is expected that, in the near future, their continuous improvement in terms of performance and reliability will open new perspectives to fields like prosthetics, robotics, telepresence, rehabilitation etc.

Dielectric Elastomer Actuators (DEAs) represent one class of electroactive polymers that have already demonstrated good performances and offer great potentials for mechatronic and robotic applications, especially in the field of biomimetic mechanisms and humanoid robotics. DEAs are in fact superior in terms of lightness and energy efficiency compared to traditional electromagnetic actuators. Their intrinsic softness is advantageous when a safe, compliant interaction with the surrounding environment is required. Compared to many other EAPs, moreover, dielectric elastomers actuators are also able to produce high strains and forces, and respond to externally applied electrical stimuli with fast operation cycles [2][3].

In its basic configuration, a dielectric elastomer actuator is a “rubber capacitor”, consisting of an elastomeric film (the dielectric), with the two faces coated with compliant electrodes. When a high voltage difference is applied to the two electrodes, positive charges appear on electrode and negative charges on the other, generating an electrostatic attractive pressure known as Maxwell stress (Figure 1). This stress is equal to the permittivity of the elastomeric dielectric multiplied by the square of the applied electric field. All dielectric materials experience the effect of Maxwell stress, but if an elastomer with low Young modulus and high breakdown strength is used as dielectric, the electrostatic pressure will produce a macroscopic effect, forcing the electrodes to come closer and squeezing the elastomer layer.

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Moreover, since the dielectric medium is an elastic but nearly incompressible material, the actuation of the elastomer will result not only in a reduction of its thickness but also in an increase of its area (constant volume deformation). According to this property, a dielectric elastomer actuator can be thus used as a contractile or an expanding device, depending whether axial contraction or planar expansion is exploited to produce mechanical work.

Figure 1: Operation principle for a single-layered dielectric elastomer actuator and theoretical evaluation of Maxwell pressure in function of the applied electric field.

In literature, dielectric elastomers are typically employed in two major actuating configurations: the rolled configuration and the multilayer stack. In the first configuration, a film of material is rolled in a cylindrical shape, similarly to rolled capacitors\cite{4}\cite{5}. Actuators exploiting this configuration are remarkably simple to fabricate: since the electrode layer do not present any mechanical discontinuity between turns, the device can be obtained by manually rolling a single electroded film of elastomer. According to the specific arrangement of the electrodes in this configuration, the actuator elongates in its axial direction when electrically activated (Figure 2a).

The second common actuating configuration is the multilayer stack\cite{6}\cite{7}. In this configuration, the device is obtained by stacking together many layers of elastomer film, electrically connected in parallel, which axially contract during activation (Figure 2b). While this configuration is extremely interesting because the actuation of device is remarkably similar to the contractile motion of the biological muscles, the fabrication of multilayer stacks presents manufacturing difficulties. Despite the rolled actuators, the geometry of the electrodes applied to the layers of the stack is intrinsically discontinuous. Moreover, in order to obtain an appreciable contractile motion (in the millimeter range), a high number of thin layers of elastomer film are needed, and particular manufacturing equipments are required to accomplish the stacking process \cite{8}\cite{9}.

In order to fulfill the requirements in terms of range of motion, without the manufacturing difficulties of a multilayer stack composed of several hundreds of layers, a simple rolled configuration was chosen for the fabrication of the actuators used in this work. A commercially available dielectric EAP material, PolyPower (by Danfoss Polypower A/S) was employed for the fabrication of the rolled actuators. This material has the peculiarity of employing a compliant...
electrode technology constituted of metal electrodes deposited onto corrugated microstructures imprinted on a silicone elastomer [10]. This wavy pattern makes the electrodes compliant along the axial direction of the elastomer roll and make possible for the actuator to elongate when electrically activated. About 4 m of PolyPower film were manually rolled in order to obtain two actuator rolls, each of them 150 mm long.

After the rolling phase and the connection of the power lines to the electrodes, the actuators were boxed in a protective plastic frame. Miniature linear ball bearings (by IKO Nippon Thompson) were employed in order to make one extremity of the actuator free to move with the minimal possible friction. The ball bearings were also used to integrate a displacement feedback system composed by a linear encoder (fixed) and a multi-pole magnetic strip (attached to the free extremity of the actuator). A hall-effect integrated digital sensor (AS5311 by austriamicrosystems) was employed as contactless linear encoder, in order to monitor the elongation of the actuator and provide position servoing. The resulting resolution of the device, which employs multipole magnetic strips 20 mm long with of pole-length of 1 mm, is 0.488 μm (12 bit over 2 mm). The free extremity of the actuator also provides a mechanical attachment for a sensorized tendon tensioning system, described in the following sections.

2. THE MECHANICS

The setup consists of two parallel artificial muscles moving a bar. On one side, the actuators are linked to a fixed base. On the other side, the movement of the muscles is transmitted to a pulley through a stainless steel tendon. An aluminum bar is rigidly linked to the pulley. The actuation of the rotational degree of freedom of the bar (Figure 3) recalls the design of a tendon-driven parallel manipulator [11] [12].

![Figure 3](image)

Figure 3: Sketch (a), and picture of the experimental setup (b). Two dielectric elastomer actuators arranged in antagonistic configuration are employed to move a pulley, on which a link is attached. Position sensors and tension sensors are employed to measure the displacement and the forces developed by the actuators.

Even if far from being a close reproduction of the human musculoskeletal system, this structure has some analogies with its typical arrangement (Figure 4), in which the position of one joint is controlled through the activation of two (or more) muscles. In our simplified artificial system, the two actuators have the functionality of an antagonistic pair of muscles, whose levels of activation determine the angular position of the inertia bar. However, as previously mentioned, one major difference between the developed artificial system and a biological one relies on the operating principle of the rolled actuators employed in this setup which elongate when electrically activated, and not contract as muscles do. Moreover, since the elastomeric muscles are made of soft silicone material, and the rotational joint is actuated by tendon cables, the actuators are completely unable to develop a pushing force on the inertia bar. For this reason, both the actuators require a suitable preload and the controller needs to use an “inverse” control strategy to actuate the joint, commanding the elongation of the artificial muscle opposite to the direction of movement of bar. These concepts are clarified in the next sections.
2.1 Dynamical formulation

From a dynamical point of view, the activation of the two dielectric elastomer actuators generates a variation of the overall torque acting on the pulley. This torque is the effect of the superimposition of the force generated by each actuator over the pulley. The two forces produce the movement of the bar along the only degree of freedom of the system. The equations of motion of such a system are:

\[
\begin{align*}
I \ddot{q} + mg \sin(q) &= \tau \\
\tau &= (F_1 - F_2)r = [r - r] \begin{bmatrix} F_1 & F_2 \end{bmatrix}^T = J^T \cdot F \\
F_i &= -f(V_i) + K_i(x_i)(rq - x_{i,0})
\end{align*}
\]

Where $q$ is rotational degree of freedom, $I$ is the inertia of the bar, $\tau$ is the overall torque acting on the pulley, $F_i$ is the force which each actuator transmit to the pulley through each tendon, $r$ is the radius of the pulley, and $J$ is the Jacobian of the system. Let us also call $K_i(x_i)$ the nonlinear elastic coefficient of the muscle, $x_{i,0}$ the rest length of the muscle, and $f(V_i)$ the commanded force, function of the input voltage.

2.2 The redundancy of the actuation

A tendon-driven system with open-ended tendons (i.e. tendons that can exert tension but not compression) requires more tendons than DOFs to be fully controllable. Therefore, to independently control $n$ DOFs, $n + 1$ tendons (and actuators pulling the tendons) are needed [13].

In our setup, the position of the pulley is a one dimensional variable, $q \in \mathbb{R}$. This variable is controlled by the voltage applied to the actuators, $V_i \in \mathbb{R}^2$. Remarkably, given a certain configuration of the system, there are mechanical (and practical) constraints which prevent the actuator positions $x_i$ from being chosen arbitrarily. In practice, there is an ideal muscle configuration $\hat{x}$ which distributes the stresses over all the two tendons in an optimal way. Given the elasticity of
the structure, the actual elastomer actuator configuration $X$ can differ from $\hat{X}$, but the more the distance $X - \hat{X}$ increases, the higher is the risk of compromising the actuation structure (see also [11] and [12]). Ideally, high tendon tension might break the tendon and low tension might misalign the tendon with respect to its capstan. In order to reduce the risk of compromising the actuation system, a preload force is used, measured through the sensorized tension system reported in next subsection.

2.3 The tension system

A sensorized tendon tension system has been used to adjust the preload of the muscles. The mechanical preload is necessary for several reasons: the first obvious reason is that if there is not sufficient tension on the cables, the actuation system might not work properly because of misalignment of the tendons and the capstans. Secondly, a certain amount of preload is required for the elastomer actuators to operate correctly. It can be noticed, in fact, that using the expanding configuration, the actuators elongate when electrically activated. This means that if both the actuators are activated at the same time, the overall tension of the tendon system reduces. For this reason, a suitable pre-tensioning must be applied to the system, taking in account the maximum and minimum tension forces that are expected to act on the system. To avoid the described inconveniences, custom tensioning devices with integrated force sensing elements have been developed, allowing both to apply tension and to measure the current force acting on the tendons.

Figure 5a shows the developed devices. Each tensioner has a length of 25mm along its axis, with a diameter of 14mm. It is made of an aluminum-zinc-magnesium-copper alloy named Ergal7075. A cover protects the electronics and provides for a mechanical hard stop, in order to prevent from high deformation which might damage the sensing elements. The tensioners have been designed to operate in the range of 0-100N, which is the maximum force that can be applied to the polymeric actuators without mechanical damaging the elastomer. It must be noticed, however, that even 25N of applied force can cause an excessive elongation of the actuator, damaging the continuity of the compliant metal electrodes.

Semiconductor strain gauges (SSGs by Micron Instruments) have been employed to obtain an indirect measurement of the force acting on the tensioners by sensing the deformation of a part that transmits the force: under the hypothesis of linear elasticity, force is directly proportional to the sensed deformation. In order to obtain high resolution and good signal-to-noise ratio the sensing part have been designed to generate the highest possible strain. The tension of the tendons is thus estimated from the flexion of a beam structure. Such deformation is measured by two semiconductor strain gauges placed in a Wheatstone bridge configuration, which gives a high signal-to-noise ratio. Figure 4b shows the operating principles of such devices. Finite element analysis (FEA) has been used to validate the calculation of the stresses and strain for the maximum applied load of 100N along the axial direction. The stress field computed as a result of one of the analyses is shown in Figure 5b. As it can be seen, the maximum Von Mises stress is around 198MPa, which lead to a strain of 1000$\mu$-Strain which is under the maximum allowable stress before the nonlinearities of the employed SSGs (non lineairities arise over 2000 $\mu$-Strain; the safety factor can be estimated to be around 2.0).

![Figure 5](image-url)
3. CLOSED-LOOP CONTROL

The linear position encoders placed at the moving side of the elastomer actuators and the force sensing system described in Section 2 are here employed to provide feedback information to a closed-loop controller. The controller was implemented on a custom DSP board, based on the microcontroller 56807 by Motorola. Control signals to the elastomer actuators were generated through the DSP’s PWM output interface, connected to a high voltage power amplifier (model 609E-6 by Trek). All the sensory data, locally converted in digital form in order to minimize the transmission noise, are transferred to the DSP via CAN bus. The frequency of the control loop of the DSP, implemented in optimized C-language, is 1 KHz.

3.1 Analysis of the response of the two actuators (independently controlled)

In order to investigate the properties of the system, preliminary experiments on open loop and closed loop control of independent actuators (i.e. not arranged in the agonist-antagonist configuration) were performed. In particular, three experiments were performed on each actuator: open loop control, closed loop position control and closed loop force control. Taking advantage of the integrated hall-effect linear encoders and the force sensors mounted on the extremities of the elastomer actuators it was possible to obtain measurements of the stress-strain relationship of the actuator. In particular, it can be noticed in Figure 6 that the actuators exhibit a non-linear stress-strain characteristics which varies as a function of the applied voltage. Moreover, the operative range of the actuators is dependent on the applied load. As an example, if no load is applied, the range of movement of the actuator is 0-2 \( \text{mm} \), while with an applied load of 5 \( \text{N} \), the movement range shifts to 8-10.5 \( \text{mm} \) (Figure 6c-d). This information should be taken into account during control.

![Figure 6](image_url)

Figure 6. Voltage-elongation and force-elongation relationship of one of the two elastomer actuators, expressed as a function of an externally applied load and an externally applied voltage respectively.
3.2 Position control of a single actuator

This first experiment shows the closed loop performances of an elastomer actuator during position control. In this experiment, the two actuators are not linked through the tendons and each actuator is considered independent from its antagonist. Position measurement is obtained using two linear hall-effect sensors on the moving side of the elastomer. A PID control scheme (Figure 7) is used to control the position of the actuator, tracking a desired position reference signal. The control signal \( V_{\text{out}} \) sent to the actuator is thus:

\[
V_{\text{out}} = k_p e + k_d \frac{d}{dt} e + k_i \int e dt
\]

Where \( e(t) \) represents the error between the current position of the actuator and the reference position, and \( k_p \), \( k_d \) and \( k_i \) are the proportional, derivative and integral gains. The values of the control gains are derived from an optimization of the step response using the classical control theory of gain tuning.

![PID control scheme](image)

Figure 7: The PID control scheme implemented for the closed loop control of the position of one single actuator.

Weights have also been applied to the moving side of the actuator, in order to evaluate the response of the controller under the influence of an external load. Figure 8a shows the time response of the controlled system to track a square wave reference signal under different load conditions (0 g, 10 g, 20 g, 30 g). As shown in Figure 8a, the controller was able to successfully track only the first two loading conditions. The reason to this has been mentioned in the previous section. Here, the application of a load to the sliding side of the actuator biases its rest position, causing a shift of the admissible range of positions that the actuator can reach. The effect is clearly described also in Figure 8b, where the saturation of the controller occurs (0V). Additionally, since the amplified controlled output voltage may also reach values which are out of the operating range the actuator (2000V), causing the ultimate failure of the dielectric material, software saturation was implemented in the controller, together with an anti-windup control scheme that allows the controller to quickly recover from a saturated state.

![Graphs](image)

Figure 8: a) measured position during the tracking of a square wave reference signal. b) plot of the control variable.
3.3 Force control of a single actuator

Experiments performed using a force closed-loop controller are here shown. To test this regulator, the actuator was preloaded with a certain force and linked to the ground. Also here, the considerations about the admissible range of reference signal hold. In fact, since the actuator can only elongate when a voltage is applied, values of force higher than the initial preload condition can not be tracked. Moreover, due to limited maximum elongation of the actuator, also low values of tension may be out of range.

![PID control scheme](image)

Figure 9: The PID control scheme implemented for the force closed-loop control of one single actuator.

As in previous experiment, the reference signal is tracked using a PID regulator (Figure 9). Figure 10 shows the response of the controlled system to a step of commanded force. It can be noticed from Figure 10a that, after 0.25s, the system reaches the steady-state. The equivalent input voltage for the step force trajectory tracking is shown in figure 10b. In Figure 10c-d, instead, a plot of the response to a chirp signal reference from 0 to 20Hz is shown.

![Response graphs](image)

Figure 10: a) response of the controlled system to a step of commanded force. b) plot of the control variable. c) tracking of a chirp signal, d) plot of the first seconds.
3.4 Passive behavior of the agonist-antagonist mechanism

Considering the agonist-antagonistic mechanism of section 2, where the joint is actuated by two elastomer actuators which elongate (and not contract like human muscles) when activated, we show here some preliminary considerations about the mechanic properties of the system and the effects of the applied preload by studying its passive behavior. If the system is not actuated (i.e. no voltage is applied to the two dielectric elastomer actuators), the stiffness experimented at the rotational joint only depends on the preload applied to the actuators. This is due to the fact that the two actuators exhibit non-linear stress-strain relationships (as pointed out in the previous sections). This means that the stiffness of the joint will depend on the working point of the two actuators, in their stress-strain characteristic.

![Figure 11](image1.png)

Figure 11: a) passive force-elongation relationship of the two actuators in three cases: low (3.2N), medium (5.6N) and high tendon tension (8.2N). b) The tendon tension can be considered constant in the whole range of motion of the joint.

According to the specific operating configuration of the two dielectric elastomers, which elongate when external voltage is applied, the stiffness of the joint slightly increases by increasing the preload level of the actuators (Figure 12). On the contrary, the co-elongation of the two muscles decreases the stiffness of the joint. It must be pointed out, however, that in the explored operating range of the system (i.e. 10 N of maximum applied tension to the tendons), the change of stiffness of the joint is barely noticeable. Therefore, for this actuating configuration, the only way to substantially increase the stiffness of the system is by changing the intrinsic stress-strain relationship of the actuators, using different materials (e.g. harder silicones) or modifying the geometry of the actuators.

![Figure 12](image2.png)

Figure 12: a) Plot of the resulting torque on the joint. b) Rotational stiffness at the joint estimated at three different preload levels.
3.5 Closed loop control of the antagonistically actuated joint

A closed loop scheme for controlling the position of the antagonistically actuated joint is proposed in Figure 13. The angular position of the joint is obtained through an optical encoder placed on the revolute joint. Its measurements are employed, together with the desired position, by the PID regulator to generate the control $V_{\text{out}}$. Due to the redundancy of the actuation system (i.e., two muscles are used antagonistically to command one revolute joint), different activation levels of the two artificial muscles can command the same angular position of the joint. For example, in an equilibrium position of the system, if the same variation of force is generated by the two muscles on the tendons, the actual angular position does not change, regardless if the actuators are at rest length or fully activated.

![Diagram of closed loop control scheme for an antagonistically actuated joint.](image)

Thus, the problem of controlling the position of the joint becomes an issue of coordinating the two muscles. This issue is obviously simplified when only one actuator is commanded at a time. In the controller scheme of Figure 13, the output of the PID regulator, $V_{\text{out}}$, is the input of a logical switch that activates one HV amplifier at a time, according to the simple rule:

$$V_{\text{out}} \geq 0 \rightarrow \begin{cases} V_1 = |V_{\text{out}}| \\ V_2 = 0 \end{cases}$$

$$V_{\text{out}} < 0 \rightarrow \begin{cases} V_1 = 0 \\ V_2 = |V_{\text{out}}| \end{cases}$$

One inconvenient of this approach is that it is not possible to control the load that the muscles generate on the tendons, resulting in the possible loose of preload, rather than the misalignment of the tendons and the pulleys. Next section shows a control strategy for over-actuated tendon driven systems, proposed in [12], which exploits the optimization of a constrained cost function, to control the position of the system, while guaranteeing the preload of the tendons.

3.6 Position control of a joint with internal feed-back of the muscles force

A more advanced control scheme can be adopted considering not only the position feedback but also the force measurements, which are provided by the aforementioned tension system of section 2.3. Figure 14 shows the control scheme, which is composed of two PID regulators for independent tendon tension control, and an external joint position control loop, which generate the reference input signal for the previous force controllers. This control scheme generates a coordinated motion of the actuators which achieves the primary task of position control of the joint, while guaranteeing a minimum tendon force.

The proposed control scheme is structured as follows: firstly, the position error $e = q - q_d$ is converted into a fictitious instantaneous reference torque $\tau_d$ using a standard PID regulator. Given the geometry of our setup, the desired joint torque comes out to be related to the tendon forces as $\tau_d = r (F_{1d} - F_{2d})$. Moreover, the desired tendon forces should not be less than the minimum force $F_{\text{min}}$.

One possibility is to calculate the vector $F_d = [F_{1d}, F_{2d}]$ as the solution to the following optimization problem:

$$\min_{F_d \in \mathbb{R}^2} \| F_d \| \quad \text{s.t.} \quad F_d \geq F_{\text{min}}$$

where the operator $\geq$ indicates that each component of the vector $F_d$ should be larger or equal to the desired minimum force vector $F_{\text{min}}$, whose components are $f_{\text{min}} \in \mathbb{R}$, and $F_d \in \gamma(\tau_d)$ represents the set of all the possible forces $F_d$. 

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belonging to the subspace $\gamma(\tau_d)$, which contains all possible tendon forces able to generate the joint torque $\tau_d$. It can be demonstrated [12] that the solution to this problem is:

$$\begin{align*}
F_d &= (J^T)^\dagger \tau_d + \lambda u \\
u &= \begin{bmatrix} 1 & 1 \end{bmatrix}^T \in \ker(J^T) \\
\lambda &= f_{\min} - \min\left((J^T)^\dagger \tau_d\right)
\end{align*}$$

Where $\min(\cdot)$ represents an operator that return the smallest component of a vector and $u$ is the vector spanning the null space of the jacobian matrix $J$.

Finally, $F_d$ is tracked by the independent internal force regulators and guarantees both the primary and the secondary task of the optimization problem.

![Diagram](image)

Figure 14: position and force control scheme for an antagonistically actuated joint.

The performances of the proposed controller are presented in Figure 15. The controller was commanded to track a desired square wave position trajectory (Figure 15a). The resulting desired and actual tendon forces required to track the trajectory are shown in 15b. It can be noticed from the plot that the minimum force during the tracking task was never less than $f_{\min} = 2.3N$, as expected.

![Graphs](image)

Figure 15: Plot of angular position tracking experiment (a) and the resulting commanded and actual tendon forces (b)
4. CONCLUSIONS AND FUTURE WORK

In this paper we analyzed a mechanical system composed by a rotational joint, which is actuated by two antagonistic dielectric elastomer actuators. A preload is given to the two actuators in order to improve their electromechanical performances and keep tension in the tendons connected to the end-effector. The actuators elongate when a controlled high voltage input is given to them, releasing part of the initial preload. In order to monitor the force developed by the actuators and the corresponding change of tensions of the tendons, custom force sensors were fabricated and experimented on the system. Different closed loop techniques were implemented into a DSP microcontroller and the performances of independently controlled actuators were evaluated when tracking position and force reference signals. Finally, a closed loop control scheme which allows to tracking of a reference position while maintaining a desired minimum tension in the tendons was implemented for the agonistically actuated system.

Future work will focus on the investigation of adaptive control schemes with parameter estimation as an alternative to the classical PID control approach. Moreover, the actuating characteristics of stacked contractile elastomer actuators will be investigated and compared to the expanding configuration analyzed in this paper.

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