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An active-compliant micro-stage based on EAP artificial muscles

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An Active-Compliant Micro-Stage Based on EAP Artificial Muscles

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***Abstract*—Electroactive Polymer actuators (EAPs), also known as EAP artificial muscles, offer a great potential for soft robotics. They are suitable for bio-inspired robotic applications due to their built-in actuation property within the mechanical body. In this paper, we report on a fully compliant micro-stage with built-in actuation. It has been fabricated as one piece inspired from twining structures in nature. We have employed a soft robotic modeling approach and finite element modeling to predict the mechanical output of the stage as a function of the input voltage. Experiments were conducted under a range of electrical inputs (0.25 - 1.00 V). For a given electrical stimulus, the compliant mechanism results in a linear motion in the middle of the active compliant mechanism, as expected. Experiments and simulation results are in good correlation. The active compliant mechanism can be used as a micro stage as well as an optical zoom mechanism for mobile phone cameras and similar devices.**

I. INTRODUCTION

A fully compliant and active mechanism intelligently hiding or incorporating all of its components of mechanical structure, actuation, sensing, and control into its monolithic body will be able to replace its biological counter-part, like a living willow structure. Such a mechanism will no longer require a complex mechanical design and fabrication to activate a functional system. Soft robotics, as a new and exciting area of robotics, focuses on soft and smart materials which can combine multi-disciplinary concepts or methodologies in order to build novel robotic systems with high dexterity and adaptability to un-structured environments. One of the primary challenges in soft robotics is to establish new actuation concepts with a low foot-print power source. Smart actuators such as pneumatic artificial muscles (PAMs), shape memory alloy (SMA), electroactive polymers (EAP) typified by conducting polymers (CPs), ionic polymer metal composites (IPMCs) and dielectric elastomers (DEs) can exhibit natural muscle-like behaviors suitable for articulating soft robotic devices. These soft robotic devices can be miniaturized for micro domain applications [1, 2].

Several interesting soft robotic studies can be found in the literature where the soft robotic structures (generally manipulators) are modeled as a continuum structure or as their hyper-redundant substitutes. Those soft robotic studies were inspired from nature to abstract and implement the working principles of an octopus arm [3], an eel [4], an elephant trunk [5-7] or a snake [8]. In addition to this, some significant efforts have been devoted to modeling of these biologically inspired soft robotic manipulators [9-16]. Most of these soft robotic manipulators in the literature have been built by employing conventional means such as serially connected rigid parts driven by pneumatic actuators, electric motors or cables, or a combination of them in order to obtain the bio-inspired motion of the soft manipulator or robot. Regardless of the materials used, building the soft robotic structure driven by pneumatic artificial muscles or by a cable system, the topology of a soft robot is similar where continuum materials have higher dexterity and better bending and adapting capabilities. On the other hand, a hyper-redundant version of a soft robotic system produces similar kinematic configurations generated by a soft robotic system with the continuum body. Therefore, both approaches use a same analogy to model a soft robot kinematically and dynamically. The most commonly used modeling approach is the backbone curve approach where a special curve represents the kinematics of the real soft robot and that curve is mathematically formulated adapting formulas from differential geometry. The backbone curve of a soft robot can be modeled as a continuum or a discrete system. While a continuum model would be more accurate to obtain the exact shape of the soft robot, it will have a high computational cost. On the other hand, the model can be developed in a discretized form (i.e. hyper-redundant model).While a reasonably accurate shape correspondence is obtained between the discretized model and the real soft robot, it will also serve better for motion control purposes. We have adapted the backbone curve approach in order to model a cantilevered EAP actuator as a soft robotic actuator kinematically [17] and dynamically [18] where the EAP actuator highly soft bending properties are estimated.

Most of the soft robotic applications have been focused on developing a soft robotic limb or manipulator inspired by nature, particularly by elephant trunk, octopus limbs, snake, caterpillar and similar motion generating species. Besides, soft robotic applications can exploit soft and smart materials not only to mimic a biological counterpart to re-produce such motion by a human-made robot but also can articulate those innovative materials in order to produce novel mechanisms with higher compliance. In other words, soft robotics can benefit from bio-inspiration to develop new devices that those devices can be optimized to adapt to its environment like their soft bodied biological counterparts.

In this paper, we propose to exploit soft actuators, particularly bending type EAP actuators, in order to develop a fully compliant mechanism which can be used as a micro-stage, micro-auto-focusing mechanism or motion converter (from bending to linear motion). The fully compliant EAP mechanism distinguishes from compliant

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mechanisms [19] studied in the literature, which are made of passive flexible materials that the mechanism is fabricated with flexural joints. We propose to use bending type EAP actuators to design a fully compliant mechanism that flexural joints are not required –thanks to EAP actuator's whole structure softness. Unlike a passive compliant mechanism which generates motions for given displacement and/or force inputs, the EAP compliant mechanism is fully compliant and active due to its operation principle that the motion of the mechanism is generated under an input voltage as small as 1.0 V. We are inspired by a type of bacteria (e.g. Escherichia coli) swimming, where the bacterium forms its flagella filament(s) into helical shapes in order to propel itself [20]. This twining motion was studied and demonstrated in our previous studies by articulating bending type EAP actuators [21, 22]. The EAP compliant mechanism has been designed based on the same principle of twining motion from nature where the EAP compliant mechanism has four spiral-arcs actively deforming to move a so-called stage in the middle of the mechanism and it is fabricated as one-piece.

II. Bending Type Electroactive Polymer Actuators

EAPs are commonly categorized as ionic or electronic. While conducting polymers (CP), ionic polymer metallic composites (IPMC), hydrogels and carbon nanotubes can be included in the ionic EAPs, dielectric elastomers, electrostrictive paper, liquid crystal elastomers are electronic EAPs [23]. The ionic EAP actuators can produce a lower stress but larger strain requiring less energy for actuation compared to electronic EAPs. The electronic EAP actuators can generate a higher stress but they operate under a high input voltage which limits their application. In this paper, we consider the ionic bending type EAP actuators (i.e. conductive polymer actuators) and they will be referred as EAP actuators throughout the paper. A number of different monomers, including polypyrrole (PPy), polythiophene (PTh) and polyaniline (PANi) [24], can be used to synthesize ionic bending type EAP actuators. The EAP compliant mechanism has been fabricated using PPy monomers where the EAP actuator has tri-layer configuration as illustrated in Fig. 1.

A. Operation Principles and Fabrication Process of Ionic Bending Type EAP Actuators

Operation principle of an ionic bending type EAP actuator relies on an energy conversion from the electrochemical domain (Eq. 1) to the mechanical domain. An electrical potential applied to an EAP sample results in a volume change in the polymer layers due to the transfer of the mobile ions in and out of the polymer layer(s) where the electrical contacts are connected to the active polymer layers. The electrical potential starts the electrochemical reactions (reduction and oxidation) in the PPy layers of the EAP. In these electrochemical reactions, cations or anions can be the mobile ions depending on the electrolyte type.

$$\underset{\text{oxidized state}}{PPy^{+}(TFSI^{-}) + Li^{+} + e^{-}} \leftrightarrow \underset{\text{reduced state}}{PPy^{\circ}(Li.TFSI^{-})} \quad (1)$$

When the mobile ions leave a layer, this layer shrinks, and when the mobile ions enter a layer, this layer swells. These volume changes in the active polymer layers produce a mechanical bending in the laminated ionic EAP actuators.

The tri-layer laminated EAP actuators considered in this study are synthesized by following a number of steps. Pyrrole is used as polymerization monomer. Both sides of a porous layer (i.e. polyvinylidene fluoride, PVDF), as received (110 µm in thickness), were sputter coated with gold to produce a conductive surface for polymerization. Lithium trifluoromethanesulfonimide (Li.TFSI) is used as the electrolytic ions, $Li^{+}TFSI^{-}$, which are stored in the PVDF layer. Polymerization solution was prepared containing 0.1M pyrrole monomer, $Li^{+}TFSI^{-}$ (0.1 M) and 1% water in propylene carbonate (PC). The gold coated PVDF was placed in the polymerization solution. Polypyrrole (PPy) layers were galvanostatically grown from the solution at a current density of 0.1 mA cm^{-2} for 12 hours on the gold coated PVDF. 12-hr polymerization process provides ~30 µm thickness of a PPy layer on each side of the gold coated PVDF. The PPy based EAP actuator was cut from the bulk sheet fabricated which we call the PPy-EAP actuator throughout the paper. The PPy-EAP actuator's laminated structure and operation principle (Eq. 1) are depicted in Fig. 1.

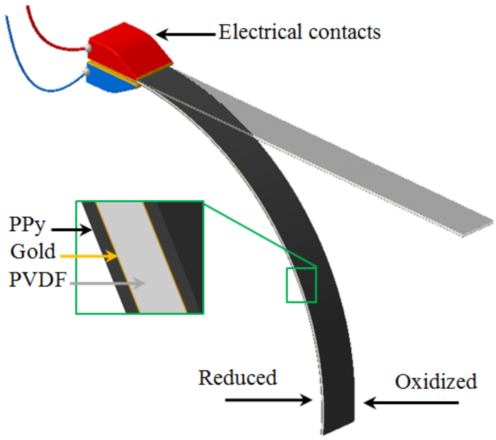

Figure 1. Structure of a bending type multilayer EAP actuator.

III. Modeling an EAP Actuator in 3D: A Soft Robotic Modeling Approach

Modeling a soft EAP actuator is quite challenging due to its multi-physics properties and some of these properties are condition-dependent. For instance, the PPy-EAP actuator's elastic properties depend on the fabrication parameters as well as the type and amount of chemical solution used for actuation. Beside variable properties, the PPy-EAP actuator can be kinematically modeled, adapting the soft robotic modeling approach. Such modeling approach can be utilized for a single PPy-EAP actuator [17, 18] or it would be quite sophisticated to mathematically describe a compliant mechanism made of an active and smart material. However, soft robotic modeling approach can be partially used in modeling procedure of the PPy-EAP actuators.

Compliancy and smartness in mind, we have designed an active and fully compliant soft mechanism made of the PPy-EAP actuator. Within design process, 4 spiral-arcs are used as actively-working parts of the active compliant mechanism, as illustrated in Fig. 2.

Figure 2. Design configuration of active compliant mechanism (the PPy-EAP active compliant mechanism samples cut by a laser on the left and computer design is on the right).

The spiral-arcs, which represent the backbone curve of actively working part of the compliant mechanism, are generated by using a parameterized position vector formulation of a spiral/helix [25] in the cylindrical coordinates as

$$\mathrm{R}(s) = [\mathrm{x}(s),\ \mathrm{y}(s)]^T \qquad (2)$$

where

$$\mathrm{x} = (\mathrm{r}_1 + \frac{\gamma(\mathrm{r}_2 - \mathrm{r}_1)}{2l\pi}) \cos\gamma \qquad (3)$$

$$\mathrm{y} = \mathrm{q}(\mathrm{r}_1 + \frac{\gamma(\mathrm{r}_2 - \mathrm{r}_1)}{2l\pi}) \sin\gamma \qquad (4)$$

where $\gamma \in [0, 2\pi]$, l is the number of helix cycles (i.e. spiral/helical coils) and $q = +1$ for right-handed helix. r_1 and r_2 are the starting radius and final radius of the spiral / helix, respectively. The code is implemented in MATLAB to obtain the coordinate points, $\mathrm{R}(s)$, along the backbone curve which is then imported to a CAD software in order to design the final form of the active compliant mechanism. The CAD design and real active compliant mechanism assembled are exhibited in Fig. 3.

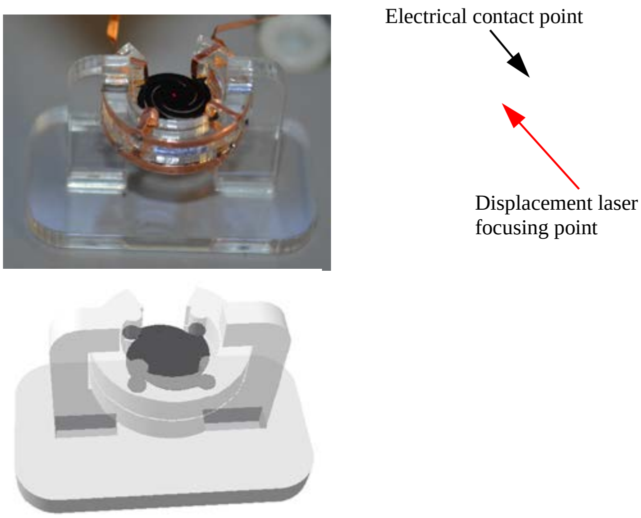

Figure 3. The PPy-EAP active compliant mechanism assembly (real mechanism is on the left and its CAD design on the right).

IV. Finite Element Analysis of The Compliant EAP Mechanism

We have developed a finite element model of the PPy-EAP active compliant mechanism in order to assess its bending behavior, in other words, its whole structure deformation. Distributed load analogy is used in the finite element model [26]. The elasticity modulus (E) of the PPy is set to 200 MPa and the elasticity modulus of the PVDF is set to 117 MPa [27]. The finite element analyses are developed in ANSYS. Along with experimental measurements, corresponding distributed load was obtained for a given electrical input generating similar displacement rates by the PPy-EAP active compliant mechanism, as illustrated in Fig. 4.

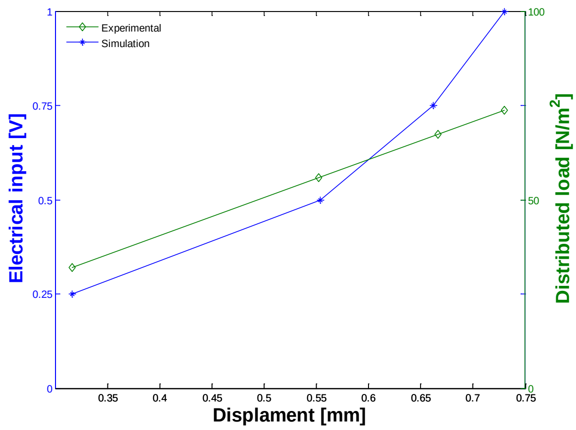

Figure 4. Stage displacement (probed at the middle of the PPy-EAP active compliant mechanism) comparison of the experimental data (blue) and the theoretical data (green) from the finite element model.

Simulations using the static structural analysis are performed based on two assumptions: (i) one end of the beam is fixed and (ii) a uniformly distributed load (electrical input triggers a series of multi-physics reactions resulting in a bending behavior produced by a similar distributed load) is applied to the top surface of the polymer actuator, as illustrated in Fig. 5. A set of simulations are conducted in order to obtain simulated displacement results corresponding to the experimental displacement results under a range of input voltages.

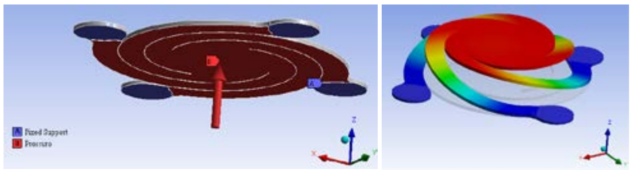

Figure 5. Finite element model with fixed points and distributed load applied points (on the left) and deformed mechanism (on the right)

V. Experimental Results and Discussion

Experiments were conducted under various voltage inputs (0.25-1.00 V with 0.25 V incremental electrical inputs at each test) applied to examine the displacement output of the active PPy-EAP compliant mechanism which was built by following a number of steps. These steps are (i) designing the compliant part of the mechanism (the PPy-EAP actuator) in a spiral configuration, (ii) fabricating the fixtures and their assembly with appropriate electrical contacts, (iii) actuating through Simulink and data analysis to obtain the experimental results, and (iv) comparing experimental and simulation results.

B. *Design and Fabrication Process of Active-Compliant EAP Mechanism*

Geometrical design of the compliant PPy-EAP actuator (spiral-arcs) is done using Eqs. 2-4. The spiral data was imported to a CAD software to craft the final design. Drawings were generated to fabricate the compliant part of the mechanism using a laser cutting process. The fixture

parts of the mechanism were also fabricated using the same design and laser cutting process. The fixture parts are cut from Acrylic (PMMA) sheet 3mm in thickness. The fixture material should not have a chemical reaction with the electrolyte used for the PPy-EAP. For the electrical contacts, a copper tape was cut and soldered appropriately.

A laser cutting process was used due to its accuracy in cutting materials. Achieving a complex profile cut, which is a customized design including irregular shapes, cannot be possible with other fabrication processes. The laser cutting process used in this study has a number of steps which starts obtaining the cutting profile in AutoCAD. The laser cutting machine (Universal Laser Systems, Model: VLS 3.50, graphics (pixel) and CAD (vector) based) used for the laser cutting process does not require converting the cutting contours into G-codes (CNC codes). The laser cutting machine cooperates with AutoCAD software so that the vector based CAD drawing contains the contours of the PPy-EAP part of the active compliant mechanism. Finally, the laser cut complaint PPy-EAP part was assembled between glass slides containing some actuation solution (electrolyte) which was then placed between the electrical contacts.

C. *Actuation and Displacement Measurement*

The PPy-EAP compliant part was actuated from 4 contact poi+nts as illustrated in Fig. 3. To obtain the displacement output of the active PPy-EAP compliant mechanism, we combined a laser based displacement measurement with an image processing system. The actuation signals were generated in SIMULINK environment (MATLAB) and passed through a NI-DAQ card (NI PCI-6221) to a potentiostat (eDAQ, Model: EA164). The electrical input supplied from the potentiostat was applied to the PPy-EAP actuator through the copper electrical contacts fixed on the clamping part of the fixture. Clamping a PPy-EAP is essential for its actuation. The laser displacement sensor (Micro-Epsilon ILD1700-50) was focused in the middle of the compliant mechanism. The motion of the active PPy-EAP compliant mechanism was also recorded using a digital camera (Nikon D5100).

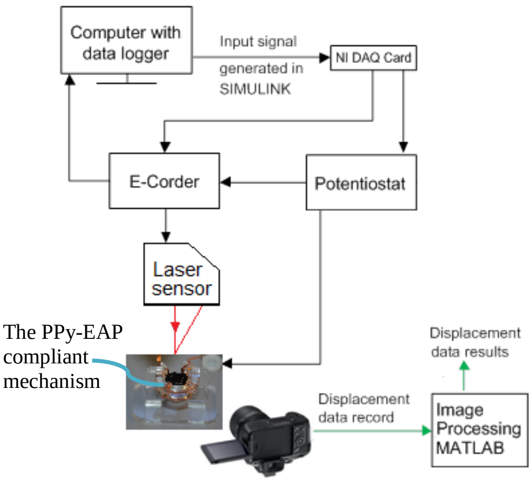

Figure 6. Schematic of experimental set-up.

The PPy-EAP compliant mechanism were stimulated long enough to observe their maximum bending for an applied electrical stimulus, from its neutral state (the actuator is straight and not activated) to the fully charged (maximum bent) state. After the displacement data acquisitions by e-DAQ data logger, the displacement results were analyzed and compared with the displacement results obtained from the finite element analysis simulation results. The experimental set-up including the actuation of the PPy-EAP compliant mechanism and the displacement measurement system are shown in Fig. 6.

D. *Experimental Validation*

Prior to each test, the PPy-EAP compliant mechanism was actuated by a sine wave input voltage. The amplitude of the voltage input is increased incrementally from 0-1.25 V. This procedure is performed prior to main experiments of PPy-EAP actuators after fabrication in order to enhance the bending capability of the PPy-EAP material as well as reduce hysteretic behaviors. The data acquired and recorded under a sine wave input voltage applied prior to test is presented in Fig. 7.

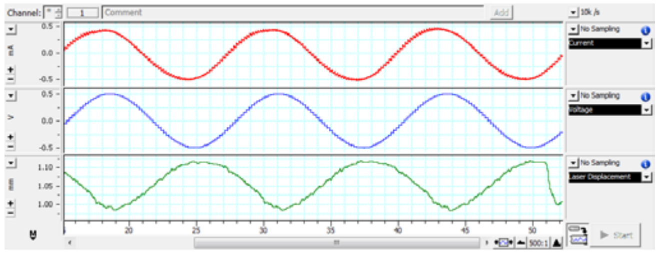

Figure 7. Typical displacement results of PPy-EAP compliant mechanism.

The experimental displacement output of the PPy-EAP compliant mechanism is given in Fig. 8, which was measured using a laser displacement sensor. Also, the experimental and simulation results are compared and presented in Fig. 9. Although the spiral-arc design of the active and fully compliant mechanism typified by the PPy-EAP is preliminary prototype, it has produced quite encouraging results. Such an active compliant mechanism can be optimized to increase its displacement capabilities. The displacement output seems low compared to a single PPy-EAP actuator in cantilevered-beam configuration with similar dimensions. This might have been due to design parameters which includes spiral-arc shapes and dimensions. It was observed that the spiral-arc parts of the compliant mechanism constraints the other parts of the mechanism while bending which reduces or blocks the mechanism to move.

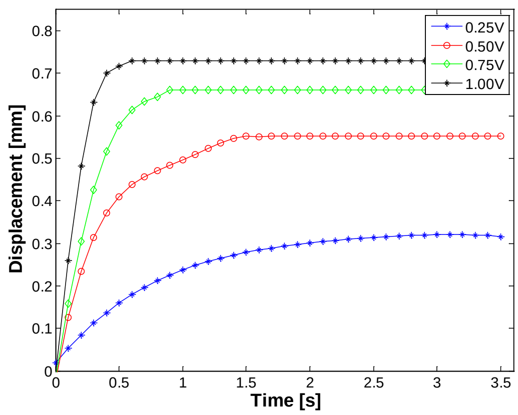

Figure 8. Experimental displacement output of the PPy-EAP compliant mechanism under 0.25-1.00V.

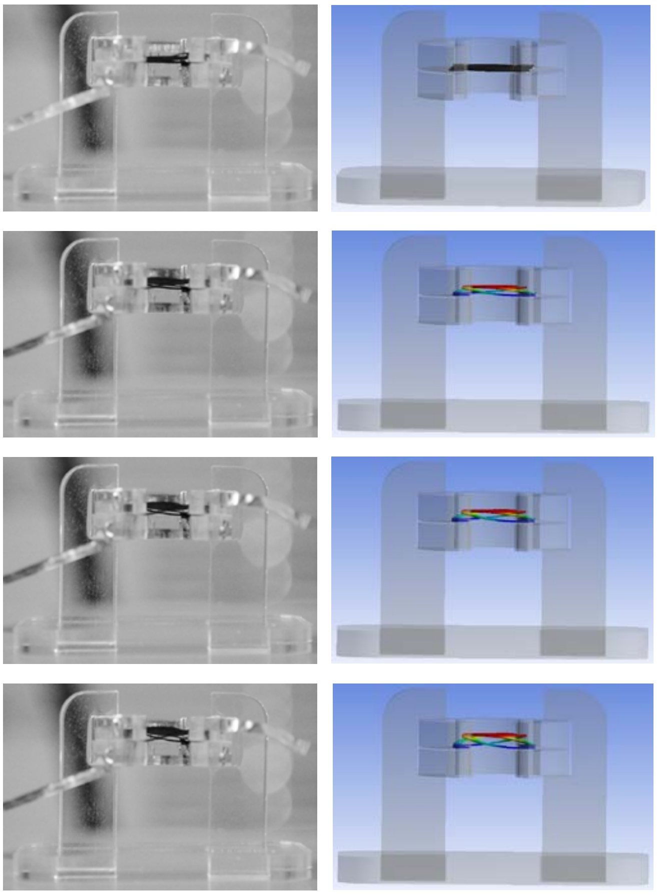

Figure 9. Comparison of the PPy-EAP compliant mechanism (left column) and finite element model (right column) under a range of electrical input (0-1.0 with 0.25 V increments from top to down).

The active compliant mechanism made of the PPy-EAP actuator or other bending type EAP actuators can be used in many positioning and manipulation applications including a micro stage or an auto-focusing mechanism with an optical zoom capability for mobile phone cameras or a soft robotic gripper with twining fingers to secure an object through its soft handling.

VI. Conclusion and Future Work

An active and fully compliant mechanism seamlessly articulated with PPy-EAP actuators has been established and its preliminary experimental evaluation results are presented. The active compliant mechanism was fabricated as one piece and actuated from the contact points at the outer sides of the compliant mechanism by applying various electrical inputs ranging from 0.25 to 1.00 V. To the best authors' knowledge, this compliant mechanism is novel where the mechanism has its own deformation capabilities and can be fabricated in a smaller size without requiring a sophisticated fabrication process. The active compliant mechanism has also been modelled using a soft robotic modelling approach and finite element analysis. This active compliant mechanism is a preliminary prototype, articulated through its twining spiral-arc parts.

Future work will include an optimization of the active compliant mechanism in order to increase its bending capabilities in single direction or tilting to various directions depending on the actuation gait applied where a FEM approach can be employed in shape optimization process. We plan to generate an initial shape (e.g. spiral-arc with mathematical description such as a spline) as a starting shape for the shape optimization process in which the parameters (data points of the curve) will be optimised for maximum bending output of the compliant mechanism within the dimension constraints.

Also, we plan to actuate the active compliant mechanism with 4 electrical inputs applied to each spiral-arc whose stage can be controlled more effectively. The mechanism will have 4 electrical inputs applied individually to each spiral arc. Further, we will actuate the mechanism from 2 contact points and use other 2 spiral-arcs to receive displacement feedback data. As a whole such a system will be a bio-inspired soft robotic device combining actuation, mechanism, sensing and control all in one structure—a truly soft robotic system.

Acknowledgments

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