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An effective methodology to solve inverse kinematics of electroactive polymer actuators modelled as active and soft robotic structures

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ABSTRACT

Electroactive polymers (EAPs) generate highly non-linear deflections when they are used as actuators, which are known as artificial muscles. Though several modelling methods have been proposed before to understand their mechanical, chemical, electrical behaviours or 'electro-chemo-mechanical' behaviour, estimating the whole shape deflection of the EAP actuators has not been studied yet. Therefore, we report on *(i)* an effective methodology to estimate these actuators' whole shape deflection by employing a soft robotic actuator/manipulator approach and *(ii)* an angle optimization method, which we call AngleOPT, to accurately solve the EAP actuators' inverse kinematic problem. Laminated polypyrrole (PPy) EAP actuators are employed to validate the soft robotic kinematic model which has more degrees of freedom than its input. This follows that we have reduced a difficult problem to an easy-to solve inverse kinematic problem (easier to solve) of a hyper-redundant soft robotic system. A parametric estimation model is also proposed to predict the tip coordinates of the actuators for a given voltage. The experimental and numerical results are presented to demonstrate the efficacy of the methodology for estimating the EAP actuators' highly non-linear bending behaviour from the inverse kinematic model. The proposed methodology can be extended to other type of smart structures with a similar topology.

1. Introduction

Electroactive polymers (EAPs) have been receiving the attention of researchers since the mid-1970s. They are usually tailored as actuators (i.e. also known as artificial muscles) and sensors [1]. The EAP actuators are considered to be alternatives to conventional actuation means due to their specific characteristics including compliance, low electrical energy consumption, suitability to miniaturization, biocompatibility, operation ability in air and aqueous environments, and a high force output to weight ratio. Although the EAP actuators have a few configurations, one configuration receiving significant attention recently is a multi-layer laminated-configuration. A multi-layer laminated EAP actuator consists of a passive layer as a cell separator and active polymer layers grown on both sides of the passive layer as electrodes. Such actuators can operate in dry environments as opposed to bi-layer ionic EAP actuators, which have to operate in a certain aqueous electrolyte. In this study, we use the multi-layer laminated ionic EAP actuators. When an electrical input is applied across the two polymer layers, they change their volume due to the movement of electrolytic ions (anions and cations) in and out of the electroactive polymer layers. This volume change generates a mechanical output, in the form of a bending displacement and/or a blocking force when these actuators are

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configured like a cantilevered beam. Besides tailoring the EAPs as actuators, they can be used as sensors; when a mechanical displacement or force is applied, they generate an electrical signal indicating the output [2].

Many applications based on the EAP actuators have been proposed before. These potential applications include swimming devices, crawling robots, micro manipulators, robotic grippers, motion converter mechanisms and many more [3–8]. The EAP actuators are especially suitable for biologically-inspired robotics for which actuators mimicking the characteristics of natural muscles are needed. For instance, these actuators were successfully demonstrated in fish swimming as artificial muscles articulating a caudal fin for propulsion [4].

In addition to utilizing the EAP actuators as artificial muscles in such bio-inspired robotic systems, for more advanced applications, a complete model is required to predict their whole shape behaviour in real time under an electrical input or under a displacement or a force input if the electroactive polymer is used as a sensor. Though there are some significant studies on modelling EAP actuators [8–13,27], majority of them focus on modelling the actuator as a cantilever beam and predict its tip displacement rather than its whole shape or overall configuration. These studies generally follow a linear deflection principle based on small deflections not higher than 20% of the actuator length. However, these actuators can deflect as high as 50% of the actuator length. With this in mind, there is a need for a more accurate approach to estimate the tip deflection and the overall shape or configuration of these active and soft robotic structures.

Soft robotics, which requires soft and hyper flexible components to build a soft robotic device, is an emerging robotics field. Several studies have been conducted on soft and hyper-redundant actuators and manipulators built with conventional materials and components. Whether the soft robotic structure is an actuator or a manipulator with many DoFs, their kinematic model is developed following the same methodology. While a soft robotic manipulator is a continuum system, a hyper-redundant manipulator can be modelled as a discrete system consisting of serially connected rigid links. When the number of links in the manipulator is high enough and link lengths are small enough, the manipulator can be treated as a soft robotic manipulator. There are some studies on such robotic systems inspired from nature in which the working mechanisms of an octopus arm, an eel [14,15], an elephant trunk [16,17] and a snake [20] are mimicked. Following similar modelling principles, Suzumori et al. developed a passive flexible micro-actuator fabricated from a fibre reinforced rubber which is powered by air pressure [19]. These devices are built by conventional actuation means such as tendons, pneumatic actuators, servo motors and joints [20] or a passive material such as a reinforced rubber [16–19]. In the literature, kinematic models are established for such soft and hyper-redundant robotic systems using a so-called *backbone* curve approach [20–24]. The backbone curve approach assumes that the posture of the manipulator is represented by a spatial curve (backbone) and the links of the whole manipulator are fully orientated along (or tangent to) this curve. Formulating the backbone curve of the soft robotic structure is straight forward for a continuum hyper-redundant system. However, obtaining inverse kinematic and/or dynamic solutions of a soft robotic structure can be difficult. In the literature, there are several methodologies such as modal based approach [20,21,24], optimization [22,23] and tractrix based approaches [25,26] to solve the inverse kinematic problem of soft hyper-redundant robot manipulators or actuators. These methodologies can be extended to soft manipulation systems based on EAP actuators.

This paper presents an effective methodology to model and solve the inverse kinematics of a bending type EAP actuator which is treated as an active and soft robotic manipulator with a very large kinematic redundancy. We employ an optimization method (AngleOPT) in order to solve the hyper-redundant inverse kinematic model. We have also employed an image processing technique to measure the tip position of the PPy-EAP actuator as a function of time and used these data as the input to the hyper-redundant inverse kinematic model in order to estimate the angular position, velocity and acceleration (i.e., joint variables) of each segment or each link forming the soft robotic structure (the PPy-EAP actuator). After demonstrating the capability of the AngleOPT for estimating the joint variables, a parametric model is also established in order to obtain a relation between the electrical input (i.e. voltage) and the EAP actuators' tip coordinates as a function of time. This parametric model is then employed to calculate the tip coordinates of the actuators for the whole shape estimation algorithm (the AngleOPT). The parametric model can be used to estimate the tip coordinates when it is not possible to measure or retrieve the tip coordinates of a given actuator for the shape estimation algorithm. The parametric model complements the inverse kinematic algorithm in estimating the whole configurations of a given actuator as a function time.

The primary contribution of this study is to propose an effective methodology for modelling the kinematic behaviour the EAP actuators and employing a constrained optimization method to solve the hyper-redundant inverse kinematic model such that the position of each link in the hyper-redundant structure is physically compatible with the overall shape of the EAP actuator. It must be noted that we have modelled the EAP actuator as an active and soft robotic structure with hyper-redundant degrees of freedom. When solving its hyper-redundant inverse kinematic model, the multiple solutions for the inner links are eliminated by specifying proper upper and lower boundaries and constraints for the joint angular positions reflecting the physical configuration of the actuator during operation. The same controllability over the joint positions, and therefore over the whole shape of the soft robotic structure cannot be achieved with an analytical method or numerical techniques based on inverting the manipulator's Jacobian matrix (pseudo-inverse as the EAP actuator is modelled as a hyper-redundant system).

2. Electroactive polymers: fabrication & operation principles

The electroactive polymers are smart materials derived from monomers; commonly from pyrrole, thiophene and aniline. They have been used to establish various devices including sensors, membranes and materials for energy storage and actuators [2–7].

In this paper, the multi-layer laminated electroactive polymer actuator type is used. Pyrrole monomer is used to fabricate the EAP actuator's active polymer layers by following a number of steps. Firstly, both sides of a non-conductive porous layer