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Electro-mechanical modelling and identification of electroactive polymer actuators as smart robotic manipulators

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ABSTRACT

Electroactive polymer (EAP) actuators, also known as artificial muscles, have remarkable properties such as low energy consumption, low weight, low actuation foot-print, compliance and bio-compatibility. Several methodologies have been proposed to model and analyse their quasi-static bending behaviour with negligible attention paid to their dynamic behaviour. We, therefore, report on an enhanced methodology to model their highly non-linear bending behaviour by treating them as smart and soft robotic manipulators. The methodology consists of an inverse kinematic model and a dynamic model. The proposed methodology accurately estimates the EAP actuator's whole shape deflection using optimization-based inverse kinematic solutions integrated with an electro-mechanical dynamic model. The experimental and numerical results are presented to show the effectiveness of the soft robotic manipulator model in estimating the highly non-linear bending behaviour of the polypyrrole electroactive polymer (PPy-EAP) actuators. The proposed methodology can easily be extended to other bending type actuators and active smart manipulators.

1. Introduction

Over the last decade, smart materials such as electroactive polymers (EAPs) have drawn significant attention due to their interesting properties offering the possibility of new actuation and sensing schemes. These properties include low energy consumption, low weight, low actuation foot-print, compliance, noiseless operation, bio-compatibility and the ability to work in both air and aqueous environments. EAPs have a significant potential for building more efficient robotic applications, sensing or actuating devices or a combination of both. A number of potential devices have been articulated by EAPs: microrobotic gripping systems, energy converters, swimming devices, crawling robots, micromanipulators, stiffness regulators, motion converter mechanisms and many more [1–9] -thanks to their natural muscle-like working principles and their remarkable properties. EAPs, as soft actuators, are especially suitable for biologically-inspired robotics where it is necessary to mimic certain characteristics of natural muscles. For instance, these smart actuators were successfully demonstrated in a swimming robotic fish as artificial muscles powering the caudal fin [4,5]. EAPs have been used as actuators in this paper and their modelling and characterisation process have been explained by employing a soft robotic manipulator modelling approach.

Since EAPs were proposed as actuators, several methodologies have been presented in the literature in order to analyse and model the EAP actuators' behaviours based on their chemical, electrical and mechanical properties. In most of these studies, the EAP actuators were treated as a cantilever beam to which an electrical stimulus was applied at its fixed end and its output is measured, at its free end. Pei and Inganas [10] used Timoshenko's classical bending beam theory to estimate the bending displacement of the bi-layer polymer actuators. When the EAP actuator is stimulated, this stimulation produces some strain and therefore, a bending along the actuator. The radius of the curvature formed by the EAP actuator is then measured and used to calculate the magnitude of the strain. This approach was adopted by Benslimane et al. [11], Madden [12] and Alici et al. [13] for tri-layer EAP actuators, however this approach is based on the assumptions of a small strain and constant modulus of elasticity. Alici [14] also applied the classical beam theory, taking non-linear effects into account to estimate the non-linear bending displacements of the PPy-EAP actuators. While these studies focus on the quasi-static bending behaviour of the EAP actuators, they do not consider the dynamic effects. Those studies which rely on quasi-static modelling of an EAP actuator as a

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cantilever beam assume that the EAP actuator's elastic properties are constant. EAP actuators, however, are materials which exhibit change in their properties due to a number of reasons: geometric parameters, substrate synthesis conditions, the type of electrolyte used, the molarity of electrolyte used etc. Therefore, an accurate modelling of the EAP actuators is crucial if they are to be employed in advanced applications such as medical devices, microrobots and artificial organs/muscles. As far as the EAP actuators are concerned, there is still a lack of a reasonably accurate dynamic model which not only estimates the tip position but also predicts their whole bending behaviour as a function of time. One can find several methods to model a system dynamically, but in general, two major methods are commonly used: (i) identifying a transfer function based on the system's input/output behaviour or (ii) analysing the dynamics of the system by a mathematical model using the Newton–Euler method, the Lagrangian or the Hamilton formulations based on the system's physics [15]. While the first method is more suitable for modelling single input single output (SISO) systems, the latter is followed in this study on modelling the EAP actuators as a soft robotic manipulator with a hyper degrees-of-freedom. It must be noted that we are not proposing to construct a soft serial robotic manipulator made of EAPs, but to model the EAP actuator as a hyper-redundant soft robotic manipulator using this analogy.

Following the configuration estimation of the EAP actuators based on the inverse kinematic model, the electro-mechanical modelling and the dynamic parameter estimation of the EAP actuator are reported. In our previous papers [16,17], the inverse kinematic shape estimation process was explained in detail in which the EAP actuator's bending curvatures were estimated by solving the EAP actuator's hyper-redundant inverse kinematic model employing an optimization-based method (we introduced and referred to that optimization-based inverse kinematic solution as AngleOPT: angle optimization). We experimentally validated the proposed electro-mechanical model which can be employed for (i) identifying the stiffness and damping parameters of an EAP actuator's soft robotic model and (ii) controlling the EAP actuator's whole shape deflection under an electrical stimulus without requiring any position and/or deflection feedback information. We establish the dynamic model and identify its parameters experimentally so that the kinematic and dynamic models can be employed to control the output displacement of the EAP actuators using a feedforward control method which does not require external feedback data. Accurate kinematic and dynamic models are needed to estimate the actuator configuration for a given voltage input so that its positioning ability can be improved without using external sensors. It is not practical to use an internal or external sensor to measure the actuator displacement for feedback control. The ideal solution is to have accurate dynamic models and invert these models to control the displacement output.

The main contributions of this paper are developing an explicit electro-mechanical model for an EAP actuator based on the soft robotic manipulator approach and estimating the whole shape behaviour of the EAP actuator dynamically, rather than estimating only its tip position for a given electrical input dynamically or in quasi-static form, as in the previous studies mentioned above. This study also contributes to understanding the behaviour of the EAP actuator's variable dynamic properties (i.e. variable elasticity) by introducing whole actuator modelling and identifying these variable dynamic parameters. It is not straightforward to analyse and model the kinematic and dynamic behaviours of the cantilevered-type EAP actuators used in this paper as their operation principle based on the electrical, chemical and mechanical parameters is not yet fully understood but the electro-mechanical model developed in this paper contributes a greater understanding of these smart and soft actuators' condition-dependent dynamic properties.

2. Fabrication and operation principles of multi-layer EAP actuators

In this study, pyrrole monomers are used to fabricate the tri-layer laminated EAP actuator's active polymer layers by following a number of steps. First, both sides of a non-conductive porous layer (i.e. polyvinylidene fluoride, PVDF) were sputter coated with gold to prepare a conductive (<20 Ω) surface for polymerisation. We used lithium triflouromethanesulfonimide (Li.TFSI) as the electrolytic ions. The PVDF layer acts as an electrochemical cell separator and also stores $Li^{+}TFSI^{-}$. The commercially available PVDF layer, which is 110 μm in thickness, is used as received. A pyrrole monomer (0.1 M) containing polymer growth solution, $Li^{+}TFSI^{-}$ (0.1 M) and 1% water in propylene carbonate (PC) was prepared for the polymerisation process. Then the gold-coated PVDF was placed in the solution. The polypyrrole (PPy) layers were galvanostatically grown from the growth solution at a current density of 0.1 mA cm^{-2} for about 12 h on the gold-coated PVDF. This polymerisation process provides ∼30 μm thickness of a PPy layer on each side of the gold-coated PVDF. The laminated PPy-based EAP actuator will be called the PPy-EAP actuator throughout the paper. The PPy-EAP actuator's laminated (tri-layer) configuration and operation principle are depicted in Fig. 1.

The PPy-EAP actuator's operation principle is based on the energy conversion from an electrochemical process to a mechanical output. An electrical input applied to the PPy layers stimulates counter-ions to move in and out of the PPy layers. When the positively charged polymer layer is oxidised, the negatively charged polymer layer is reduced. The $TFSI^{-}$ anions move from the electrolyte into the positively charged PPy layer and an opposite reaction happens in the other PPy layer in order to neutralize the charge in the PPy layers. This ion migration causes a volume expansion in the positively charged PPy layer and a volume contraction in the other PPy layer. This electro-chemo-mechanical process therefore generates a mechanical bending in the PPy-EAP actuator, as illustrated in Fig. 1.

3. Kinematic analysis of EAP actuators as soft robotic manipulators

Bending behaviours of the EAP actuators can be analysed using the classical beam theories as they have a cantilevered topology, however the classical beam theories assume that material properties such as elasticity modulus are constant. The modulus of

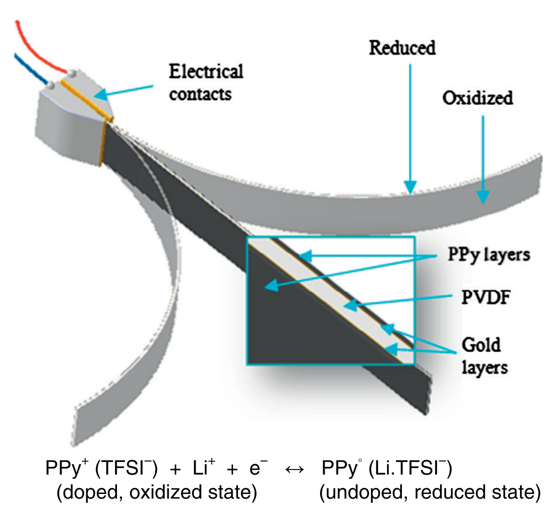

Fig. 1. Structure and the operation principles of the laminated PPy-EAP actuator.