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On the multiobjective optimization of conjugated polymer based trilayer actuators

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ABSTRACT

The main focus of this study is the multiobjective optimization of a trilayer actuator comprising two layers of polypyrrole and a PVDF membrane core. Since the performance of these actuators is difficult to predict due to their mechanical and chemical properties, optimizing their output behaviors such as their generated tip displacement and blocking force is of crucial importance. The optimization process leads to exploit the full potentials of these trilayer actuators, and more significantly, increase their performance predictability. Considering mechanical and chemical characteristics of the bending actuators, two mathematical models are developed to capture their performance in terms of tip blocking force and vertical displacement. Results obtained from both models explicitly indicate the trade-off between the two designated outputs. The optimization models include a system of nonlinear equations along with their corresponding constraints. A multiobjective genetic algorithm and a nonlinear programming solver in MATLAB were employed to solve the mathematical models. Ultimately, the results obtained from the two developed optimization methodologies were experimentally verified. For this purpose, a trilayer PPy based actuator was fabricated and related measurements were performed.

1. Introduction

Conducting polymers (CPs), also known as conjugated polymers, are a class of electroactive polymers (EAPs) which are categorized into electronic and ionic depending on their charge carriers [1,2]. CPs have shown great potential for a wide range of applications in both engineering and bioengineering fields such as biomimetic robotics, biomedical and micromanipulation systems. They can electrically be stimulated by applying a low driving voltage, and therefore, can be utilized in the structure of actuating devices [1,3–5]. Some of the most prominent features of these actuators are namely their low operating voltage, simple construction, light weight, and biocompatibility. In addition, some of their properties can be reversibly manipulated such as color, conductivity, volume, and porosity [1,3,6]. Recent studies on conjugated polymers have noticeably contributed in further development of several aspects of CP based actuators such as their maximum attainable strain, operating stress, work per cycle, and operating lifetime. However, these improvements have been reported in different types of CP actuators under dissimilar conditions. Hence, attaining one single conducting polymer actuator that simultaneously produces high blocking force, low response time, and high strain rate is now of critical importance [6]. To be more specific, different research groups have investigated polypyrrole (PPy) actuators, one of the most applied CP based trilayer actuators with key properties such as low actuation voltage, large and mechanically stable strain, high strength, high reversibility, and scalability to micro-scale [1,7]. PPy actuators are also biocompatible and light in weight, operating in air and liquid environments [8].

Despite all aforementioned remarkable properties of PPy actuators, there are also a few shortcomings in their performance entailing further considerations. For instance, their actuation response time is not as fast as desired due to the movement of ions into or out of the polymer during actuation [1,9]. Another drawback of PPy actuators is the decrease of their electronic conductivity by two or three orders of magnitude due to the reduction process of the polymer. As a result, only a small part of the polymer would actively be actuated [10]. This can be one of the main causes of the low response speed which noticeably restricts the performance of

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the actuator. In order to overcome or alleviate this limitation, an additional electron conductor such as an ultra-thin layer of gold or platinum can be added to the actuator structure [11–13].

CP based actuators are categorized into different types, two of which are trilayer and bilayer actuators. Comparing a trilayer actuator with a bilayer one, the former is capable of operating in aqueous and non-aqueous environments while the performance of the latter is confined to liquid mediums [14–16]. In terms of their structure, a trilayer structure consists of two CP films with an inert layer in the middle which acts as an ion tank as well as an insulator between the two layers [17]. Alternatively, a bilayer actuator only has one CP layer on a substrate, and therefore, it requires a separate counter electrode inaccessible to the actuator.

During the actuation process, one of the CP layers is oxidized as the other one is being reduced. When the oxidation of the polymer initiates due to the anodic current flowing through the CP, the removal of electrons from the chains of the polymer modifies the allocation of the double bonds and bond angles. Consequently, this process induces a positive charge through the polymer backbone [18]. In order to maintain charge neutrality, the structure which has been positively charged pulls the negative anions and solvent molecules, existing in the electrolyte, into the conducting polymer [2]. As a result, the conjugated polymer layer will expand and contract during oxidization and reduction process, respectively. On the other hand, if the anions are large and immobile, the cations will drive the movement, and the response of the CP layer would be reversed [19]. Both positive and negative ions existing in the electrolyte salt are capable of moving through the polymer due to the induced charge. Considering this fact, one of them (i.e. positive and negative ions) should be small in size while the other one is large so that the large ions are immobile and the small ones manage the volume change of the polymer. Otherwise, both ions can diffuse into and out of the CP layer, and the effects of their influx and outflow will be canceled out, therefore, the maximum attainable volume change cannot be occurred [20]. The oxidation and reduction (redox) of the active layers are processed in a continuous and reversible manner, which results in a rocking chair motion. Furthermore, the bending moment generated by the actuator is due to the fact that the active layers have been constrained by the middle electrolyte layer, and in turn it acts like a cantilevered multi-layer structure [21]. Redox process leads to some concurrent changes in some properties such as conductivity [22], color [23], and volume. All these changes are associated with the flow of ions and solvent into and out of the conducting polymer layer.

In order to fabricate more comprehensive CP actuators, in terms of their applications and performance predictability, a realistic mathematical model is required to investigate, and consequently, improve the determining characteristics of the trilayer actuators [24]. Hence, in recent years, several research groups have proposed various mathematical models along with their experimental analyses. Most of these models are designed to calculate the tip displacement of the actuator as well as the blocking force in response to a stimulus. Fabrication and analysis of microactuators based on conducting polymers have been comprehensively studied by Alici et al. [24]. They reported a lumped-parameter mathematical model to describe bending mechanics of PPy actuators. The results obtained from this model can predict the bending angle and bending moment of these actuators for a range of applied voltages. This model can be used to optimize the geometry of the polymer layers in order to design and fabricate an actuator with efficient performance. Another multilayer model was introduced by Shapiro and Smela [25] as well as Du et al. [26] based on the classic beam bending theory. In this proposed approach, the thickness of the beam is considered small compared to the lowest radius of curvature reached by the actuator. Furthermore, the relationship between the strain and stress was assumed to be linear. In another work, Alici and Huynha [19] developed a model in order to predict the force output of trilayer conducting polymer actuators. Two specific cases were described in their force model, free deflection and zero deflection. The developed model was experimentally verified through the fabrication of a robotic finger. Their results were promising and in good agreement with their mathematical model. Study of the shape, tip deflection, angle, and deflected length of a trilayer PPy actuator was then further pursued in another model in which it was suggested to apply a non-linear least square optimization algorithm in order to estimate the deflected length and the tip deflection angle [27]. Minato et al. investigated the influence of different actuator geometries (i.e., non-uniform thicknesses for a uniform width and length) [21]. It was found that higher PPy thicknesses in certain areas of the trilayer actuator length results in more enhanced performances. Therefore, it was claimed that a polymer actuator with an optimized geometry could be synthesized in order to be employed for various applications. Furthermore, Alici et al. [18] demonstrated that the thickness of the actuator root (i.e., the clamped end of the actuator) has a significant effect on its bending moment. Having a constant length and width, a higher thickness of the actuator root leads to a larger bending moment compared to a trilayer actuator with a uniform thickness.

The abovementioned models only considered the electromechanical behavior of the trilayer actuators while their electrochemical properties have a major impact on their output as well. Consequently, it is of critical importance to have a model that describes the electrochemomechanical behavior of the actuator along with prediction of its outputs under different actuating conditions. Madden [22] developed a diffusive elastic metal (DEM) model to illustrate the impedance of CP based actuators. In the equivalent circuit of this model, the diffusive impedance and a double layer capacitor were assumed to have a parallel connection. The resistance of the middle polymer layer containing the electrolyte was in series with the two former elements. Ultimately, the relationship between the current across the CP layer and the input voltage was characterized. Different mathematical models have been formulated based on DEM model including the one developed by Fang et al. [28]. They designed a self-tuning regulator considering the simplified DEM model for conjugated polymer actuators. In another study conducted by Nguyen et al. [29], the tip curvature and the current response of a conducting polymer trilayer actuator was captured through a model developed based on the diffusive impedance and the double layer capacitance along with its charge transfer resistance.

Since the linear elasticity theory is only applicable for low actuation voltages, the DEM model may not be adequately accurate in predicting the mechanical outputs of the actuator with relatively larger strains. In this regard, Fang et al. [30] developed a nonlinear mechanical model based on the nonlinear elasticity theory. The results were compared with their counterparts obtained from the linear model showing that their nonlinear approach is capable of demonstrating the actuator performance under a wider range of applied voltages.

The behavior of a multifunctional conjugated polymer based artificial muscle was captured through a physical-chemical equation proposed by Martinez and Otero [31]. This system of artificial muscles mimics the haptic functions of the brain muscles and their feedback communication. Their sensing-actuating model originates from the basic polymeric and electrochemical principles describing the key features of the system some of which are its moving rate, position, as well as the mechanical perturbations and working temperature. Using different steel masses attached to the bottom of the muscle, a constant angle was maintained by the muscle through the flow of a constant anodic or cathodic charge. It should also be noted that CP based artificial muscles are considered as electro-chemo-positioning devices, the movement rate of which