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Modeling, fabrication, and characterization of motion platform actuated by carbon polymer soft actuator

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ABSTRACT

Carbon polymer composites (CPC) are kind of soft actuators belonging to the category of ionic electroactive polymer transducers. In this work, we present design, modeling, fabrication, and characterization of a novel parallel manipulation system actuated by the CPC actuators. In this system, four actuators are operated in parallel to manipulate an end effector or a platform to generate motion along the different axis. The major advantage of the current system is that the platform and the actuators are fabricated as a single structure using the simple layer-by-layer spray-deposition method with selective masking. The proposed system is highly dexterous and is capable of generating three degrees of motions, namely, roll, pitch, and piston. The initial structural design and its deformation are optimized by modeling and simulating using finite element method and followed by fabrication and characterization to examine its workspace. The experimental results have demonstrated high levels of manipulability from the CPC actuators that are outstanding in the class of soft ionic actuators while keeping the fabrication method simple, scalable and cost-effective. The proposed configuration has potential application in micromanipulation systems that require large deformation in a confined space.

1. Introduction

Ionic electroactive polymer (IEAP) soft actuators are composite smart materials that exhibit deformation along transverse and axial directions in response to an electric field. In general, IEAP materials are composed of a central ion conductive separator membrane, sandwiched between two electronically conductive electrodes on both sides. Under applied electric field the ions pass through the nanochannels of the membrane and congregate on to the surface of the electrode forming an electrical double layer. The imbalanced distribution of ions leads to volumetric expansion of one electrode and the contraction of other, causing deformation of the whole composite [1]. These materials are highly attractive in the field of soft robotic actuators due to their specific characteristics features such as lightweight, noiseless operation, and capability of generating large strains of about 2% at low operating voltages (<3 V). These advantages of the actuators lead to developing numerous soft robotics applications such as six-legged terrestrial walking robot [2], snake-like swimming robot [3], autonomous jellyfish robot [4], IPMC robotic catheter [5], fish-like robot [6], aquatic insectile robot [7] etc.

In this work, we specifically deal with the soft IEAP material with nanoporous carbide-derived carbon (CDC) electrodes, polyvinylidene fluoride-co-hexafluoropropylene (PVdF-HFP) separator membrane and 1-ethyl-3- methylimidazolium trifluoromethanesulfonate ionic liquid (EMIM-Otf, >99.0%) as the electrolyte. Based on the construction we denote this IEAP as Carbon Polymer Composite (CPC). The fabrication process of this kind of actuator is simple, repeatable, scalable and cost-effective [8]. This type of ionic actuators operate in open air and also in a vacuum environment, unlike water-based IPMC actuators [9]. Previously, different applications using this particular type of actuators are explored such as biomimetic soft robot [10], as actuators for space application [11], variable focal lens device [12], linearly actuating device [13], shape adaptive gripping device [14] etc. With this in line, in this work we propose a novel multi-degree motion system that is capable of exhibiting three degrees of motion that includes rotation along two-axis and a linear displacement along one axis namely roll, pitch and piston motion respectively.

Such motion system can be used for wide varieties of applications such as a microscope stage [15], haptic application [16], precision manipulation [17], medical applications [18], and most prominently as an optical mount [19]. Most common actuation

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methods for such systems are usually based on electromagnetic [20], electrostatic [21], electrothermal [22], and piezoelectric actuators [23]. Each of the actuation systems has their own advantages and limitations. Electrostatic actuated system is fast and consumes less power but requires high actuation voltage [24,25], the electromagnetic system can attain large deformations but requires external permanent magnets, which limits packaging and miniaturization [20,26], electro-thermal system have very high power consumption [22], a piezoelectrically actuated system has the advantages of high speed, small size, and low power but is limited to very small strain/displacement [23]. The ideal requirement of such a system is large displacement, low driving voltage, high fill factor, easy fabrication, packaging, size, and cost. The ionic electroactive polymer actuators satisfy these requirements and can be a perfect candidate for such applications.

In the literature, there are several proposals discussing actuators fabricated over a wide range of size scale to obtain titling or linear motion and rarely both using different types of ionic electroactive polymer materials. Yun et al [27] developed IPMC based micromirror that was capable of generating a 0.25 mm linear displacement and the maximum tilting angle of $\pm 11.3^\circ$ on one axis at an input voltage of 4 V. The tunable focusing mirror designed by Tsai et al [28] using three IPMC actuator configuration was able to generate maximum displacement of 45 μm and capable of showing 77.8 m^{-1} optical power change. Another IPMC based optical zoom for the compact camera was able to change the focusing power of 73.8 m^{-1} with 3 V and obtaining a maximum displacement of 200 μm [29]. With reference to linear actuating stages, Mutlu et al [30] developed a spiral arrangement of three actuator configuration with polypyrrole actuators to be used as microscope stage mechanism that was able to generate 1 mm displacement at 1 V. Yamakita et al [31] proposed four IPMC actuator configuration with flexible connector that generates a maximum displacement of 10 mm at 2.5 V, while Lee et al [32] designed a bimorph beam with IPMC that was able to generate free strain of 25% under 2 V. The linear actuator using carbon-based electrode for a mirror application developed by Torop et al [13] was able to generate a stroke of 15 μm at 3 V along lateral direction. The goal of this paper is to present a motion system that can generate large stroke and rotation angles and also capable of generating three degrees of motion in a single configuration. Herein, the electromechanical model, fabrication, and characterization of such a motion system are explored and the possibility of using low voltage driven large deforming CPC actuators for parallel manipulation application is discussed.

2. Actuator description

2.1. Design of motion platform

The schematic representation of the CPC laminate is shown in Fig. 1. In addition to electrode and separator, the actuator consists of a glass fiber cloth as a central reinforcement grid. This grid acts as a support during fabrication and aids in maintaining neutral layer during actuation. Also, the grid is inelastic along the axial direction and hence there is no elongation of the material in that direction during actuation which is desired for applications that require actuation only along the transverse direction.

So far, most of the application of CPC have been limited to bending motion. By appropriate design of multiple actuators connected together or by using the external support mechanism such as gears and pulleys, the bending motion can be converted to obtain the different degree of motion. However, use of external support mechanism with the soft actuators increases the complexity of the system and also fabricating very small lightweight components and joint connections are quite complicated. Hence, configuring the actuators themselves for obtaining the different degree of motion is highly preferred.

For the current study, we propose a novel configuration as shown in Fig. 2**(a)**. It consists of four actuators supporting the square shaped central reinforcement grid at the vertices. The four actuators can be actuated individually or simultaneously in order to move the platform in a desired orientation and position. The main advantage of the proposed system is that it is fabricated as a single structure and it does not require any additional support mechanism to obtain the different degree of motion. Moreover, the working platform is by itself part of the actuator and acts as a load allowing effective use of the available mechanical energy. The different degrees of motion produced by the mechanism is shown in Fig. 2**(b)**.

2.2. Advantages of glass fiber fabric

Apart from acting as a support structure and maintaining neutral layer, the glass fiber plays a major role in the manipulation of the system. During operation, the connection point between the vertex of the central reinforcement grid and the actuator are held through glass fiber strands that act as a spherical joint providing the platform the necessary degree of freedom allowing it to rotate and also move linearly. The number of glass fiber strands at the vertices plays a role in deciding the maximum displacement that can be attained by the system. Finite element method (FEM) is used to optimize this connection point to obtain optimum performance. Also, the thin fiber withstands the stress acting at the joints while undergoing twisting motion without any fracture whereas just a membrane will limit the ductility of the platform and also have a tendency to crack during operation.

3. Fabrication of motion platform

The details of the materials used and the method of fabricating the actuator is described in detail by Kaasik et al [8]. In this section, more specifically the method of fabrication of the motion system alone is described.

3.1. **Step 1:** preparation of reinforcement layer

First, a thin inelastic glass fiber reinforcement grid (18 g/m^2) was tautened to a circular frame. This reinforcement layer form the neutral layer and aids in obtaining controlled and predictable actuation in both the direction.

3.2. **Step 2:** membrane preparation

A mixture of EMIM-Otf (50 wt%) and PVdF-HFP (50 wt%), dissolved in 4-methyl-2-pentanone was applied on the tautened reinforcement grid using the spray-coating technique. The volatile solvents were subsequently evaporated using a hot air gun. The spraying procedure was repeated until the membrane of the desired thickness was achieved

3.3. **Step 3:** creating the masking region

The next step is masking the region of the membrane, which will subsequently become the working platform actuated by the actuators. A 100 μm thick plastic film, which is chemically stable to the solvent is used as a mask in this case. The mask is manually trimmed into appropriate dimensions and shape based on the requirements of the central platform. In this case, the dimensions of the central platform are 25 x 25 mm. The mask is fixed to the membrane with small neodymium magnets on both sides.