Robotics and Autonomous Systems 62 (2014) 53–60

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

A bio-inspired multi degree of freedom actuator based on a novel cylindrical ionic polymer–metal composite material

Seong J. Kim [a,1], David Pugal [a], Johnson Wong [a], Kwang J. Kim [a,*], Woosoon Yim [b]

[a] University of Nevada, Reno, NV, USA

[b] University of Nevada, Las Vegas, NV, USA

ARTICLE INFO

Article history:
Available online 23 August 2012

Keywords:
Ionic polymer
Actuator
IPMC
Finite element method
FEM

ABSTRACT

In this work, we explore a promising electroactive polymer (EAP), called ionic polymer–metal composite (IPMC) as a material to use as a multi degree of freedom actuator. Configuration of our interest is a cylindrical IPMC with 2-DOF electromechanical actuation capability. The desired functionality was achieved by fabricating unique inter-digitated electrodes. First, a 3D finite element (FE) model was introduced as a design tool to validate if the concept of cylindrical actuators would work. The FE model is based upon the physical transport processes—field induced migration and diffusion of ions. Second, based upon the FE modeling we fabricated a prototype exhibiting desired electromechanical output. The prototype of cylindrical IPMC has a diameter of 1 mm and a 20 mm length. We have successfully demonstrated that the 2-DOF bending of the fabricated cylindrical IPMCs is feasible. Furthermore, the experimental results have given new insight into the physics that is behind the actuation phenomenon of IPMC.

1. Introduction

Ionic polymer–metal composite (IPMC) material is one of the most promising active (smart) material for developing novel soft biomimetic actuators and sensors [1–4]. It typically consists of an ionomeric membrane that is coated with a thin layer of a noble metal electrode, such as platinum. The advantages of the IPMC include low driving voltage (<5 V), relatively large strain, soft and flexible structure, and the ability to operate in an aqueous environment (such as water). Due to the softness and flexibility of the material, it can be used to mimic the flexible bending behavior as seen in the nature. For instance, a number of robotic applications based on the IPMCs have been proposed. Among others, the list includes an active fish fin for propulsion with sophisticated control model [5,6], jellyfish based on the soft materials [7], and snake-like swimming robot [8].

A lot of effort has been put into formulating the electromechanical theory of IPMC materials. Shahinpoor et al. developed a non-homogeneous large deformation theory of ionic polymer gels [9,10]. In 2000, De Gennes et al. presented the first phenomenological theory of sensing and actuation of IPMCs [11]. Li and Nemat-Nasser presented a fundamental model of electromechanical response of IPMC — it considers the cluster morphology of the material [12]. In the follow-up work, the role of the hydrated cation transport within the clusters and polymer network was stressed [13]. Weiland and Leo presented a model where the individual dipole rotations within a cluster were calculated and related to the deformation of IPMC [14]. Akle et al. studied both numerically and experimentally large electrode surface area effect on the induced current [15]. Wallmersperger et al. proposed a finite element model to incorporate these effects [16]. Porfiri studied the charge dynamics and capacitance of IPMC [17]. Davidson and Goulbourne studied ionic liquid transport in the polymer and boundary layer interactions on the actuation of IPMC [18,19]. A comprehensive review of the state-of-the art understanding of IPMC materials was written by Tiwari and Garcia [20]. Although the materials have been extensively studied, some shortcomings still remain. For instance, water solvent based IPMCs tend to dry off and lose performance when actuated in air [21]. Also, back relaxation under a DC applied voltage is observed in the case of typical solvent cations such as Na^+, Li^+ [22]. Regardless of the shortcomings, the appealing mechanical properties make IPMCs promising materials to be used in the biomedical field. Applications for active endoscopes [23] and smart catheters [24–26] have been proposed. Also, strips of IPMCs can be used as sensors in hand prostheses [27].

Whereas the flat, beam-shaped IPMCs have been extensively studied for different applications, cylindrical IPMCs have not yet been investigated. This is primarily due to the difficulties related to the fabrication process and a small deflection angle that is mainly

* Corresponding author. Tel.: +1 775 784 7522; fax: +1 775 784 7522.
E-mail address: kwangkim@unr.edu (K.J. Kim).

1 Current address: Samsung Electronics, South Korea.

0921-8890/$ – see front matter
doi:10.1016/j.robot.2012.07.015

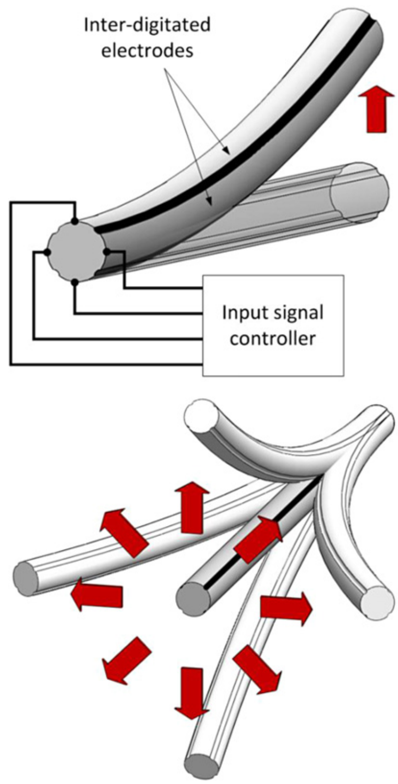

Fig. 1. Schematic drawing of a cylindrical IPMC with four inter-digitated electrodes (top) and illustrated actuation (bottom).

caused by the high mechanical rigidity. However, the cylindrical IPMC is a promising candidate to be used as, for instance, an active catheter platform if it can show 2-DOF actuation capability. A way to achieve this is to inter-digitate the surface electrodes into 4 sections and apply appropriate combinations of input signals as illustrated in Fig. 1.

Furthermore, different electrode configurations of the cylindrical actuator possibly allow the undulatory actuation that is more common in the nature [28,29].

In this study the 2-DOF actuation capabilities of the cylindrical IPMCs was numerically simulated with a physics-based 3D Finite Element (FE) model. The model simulates the important underlying physical processes, including the ionic migration and concentration of the cations inside the membrane. The results helped to confirm beforehand that the concept of the cylindrical IPMCs is feasible.

The cylindrical ionic polymers were fabricated using hot pressing process and the surface electrode of the IPMC was inter-digitated by a mechanical process. Various methods to inter-digitate flat IPMCs have been developed [30,31], however, we propose a method to pattern the electrodes on the cylindrical IPMC.

The mechanical process is a significant upgrade compared to the process discussed in [32] — namely, the new process results in very clean cut electrodes compared to the previous method. As a result, the experimental data including the bending angle and blocking force of the 2-DOF bending of the cylindrical IPMC with a diameter of 1 mm and a length of 20 mm are presented.

2. Initial FE analysis

Analysis on the geometry of the cylindrical IPMC and the combination of the input signal were carried out using a 3D FE model. The model is based on the calculations of the ionic migration and diffusion, which are directly related to the bending of the IPMC. The cation concentration in the IPMC is calculated using the system of Nernst Planck and Poisson equations [33]:

Table 1
Simulation constants.

Constant	Value	Unit
Diffusion constant D	12e−12	m^2/s
Dielectric permittivity ε	2e−3	F/m
Force coupling A	8e4	–
Force coupling B	6e7	–

$$\frac{\partial C}{\partial t} + \nabla \cdot (-D\nabla C - z\mu F C \nabla \phi) = 0, \tag{1}$$

$$-\Delta \phi = \frac{F\rho}{\varepsilon}, \tag{2}$$

where C is cation concentration; D diffusion constant; ϕ electric potential; F the Faraday constant; μ mobility; and ε absolute dielectric constant. In the initial analysis, the calculated local charge density, ρ, was coupled to the local stress by using the force relation [34]

$$F_x = A\rho^2 + B\rho, \tag{3}$$

where F_x is a body force in the longitudinal direction. The detailed model, including the details about the Navier's equation is described in [33]. The equations were implemented in COMSOL Multiphysics software package. As a full calculation in a 3D domain is very resource demanding, the Poisson–Nernst–Planck system of equations was solved in a circular 2D domain where applied voltages were used as the boundary condition for Eq. (2). In order to minimize computational error, very fine mesh was used near the electrode boundaries (for detailed explanation, see [35,36]). The calculated cation concentration C was then extruded to a full-scale 3D domain where Eq. (3) was calculated. The main simulation constants are shown in Table 1.

In this study, the diameter and the length of the actuator were set to 1 mm and 20 mm, respectively. The 1 mm diameter was chosen due to manufacturing considerations.

For a beam-shaped conventional IPMC the input signal is rather straightforward because it simply bends toward the anode (electrode where a positive voltage is applied) direction. In case of a cylindrical IPMC, which has at least 4 independent electrodes, the input signal can have more combinations to potentially actuate in arbitrary number of different directions. However, given that constant voltage signals are used to simplify the control of the actuation, 8 different directions of can be achieved.

There are two ways of actuating the cylindrical IPMC in the vertical/horizontal directions with constant voltage signals — three positive signals and one positive signal as shown in Fig. 2. On the other hand, there is only one way to actuate the cylindrical IPMC in the diagonal direction, which is by applying positive signals to coinciding electrodes.

A set of simulations was carried out for a cylindrical IPMC. The results showed that the 8 directional bending is indeed possible. The model predicted reasonable diagonal bending and the bending in case of three positive signals. It is illustrated in Figs. 3 and 4. However, the model was not able to estimate the bending in case of one positive signal. The calculation results in case of 4 V applied voltage are shown in Fig. 5.

The simulations results were sufficient to move onto the next step, namely to fabricate and characterize the cylindrical IPMCs. Thereafter, based on the experimental data, the force coupling Eq. (3) was redefined and another set of simulations was carried out. More calculated data are presented in Section 5 — results and discussion.