Introduction to the themed articles on ionic polymer–metal composites

Over the past two decades, we have observed an explosive growth in the field of electroactive polymers (EAPs), polymers that respond to external stimuli by changing their shape or size or even when mechanically stressed produce a measurable charge [1–6]. Specifically, the research on the ionic EAP, such as ionic polymer–metal composites (IPMCs), has attracted international attention. The IPMC material has the ability to function as an actuator or a sensor in both air and wet environments, and generally IPMCs require low voltages (<5 V) for actuation. When an IPMC is subjected to a voltage, deformation occurs due to the migration of ions and polar solvents within the polymer material. Typically, an IPMC is created by plating a noble metal (e.g., platinum) on both sides of a thin ionomeric membrane, followed by a process that neutralizes the material with a certain amount of cations to balance the electrical charge of the anions covalently bonded to the backbone polymer. The two commonly used ionic membranes are the perfluorosulfonic acid type (Nafion [7]) and the carboxylic type (Flemion [8,9]). Because of its soft and flexible structure, an IPMC is most suited for developing soft biomimetic actuators [1,10], artificial muscles [4,5,11–13], and sensors [14,15]. Compared to conventional metal- or ceramic-based actuators, such as shape memory alloys [16] and piezoelectric ceramics [17], IPMCs are lightweight, low power, fracture tolerant, and easily manufactured and configured into complex shapes. Furthermore, the properties of IPMCs can be tailored for specific applications.

Pioneering work on IPMCs began in the early 1990s [18–20]. The IPMC manufacturing process involves two basic steps for commercially available ionomeric membranes: (1) neutralizing the membrane with the desired cation and (2) plating the membrane surface with a noble metal electrode [21,22]. The effect of different backbone ionomers and various cation forms are studied in [23]. Commercially available Nafion membrane for fabricating IPMCs such as N115, N117, and N1110 have nominal dry thicknesses of 127, 178, and 254 µm, respectively [24]. By exploiting solution casting [25] and more novel manufacturing techniques [26,27], thicker IPMC actuators have been produced that lead to improved force output [28]. In addition, by incorporating nanoparticulates into the polymer matrix to control the water uptake and loss, an increase in blocking force has been observed [13,29]. The blocking force is also shown to increase significantly with the use of dispersing agents in the reduction process [21]. Other work on performance-enhancing methods for IPMCs include boosting the capacitance of the composite material [30,31]. The IPMCs are traditionally manufactured into thin film or plate-like structures, but recent work has focused on disk shape [32], rod shape [33], and other complex geometries and configurations [34–36]. Furthermore, by patterning the electrodes on the surface of an IPMC, a monolithic structure can be created for both sensing and actuation [37], and even for realizing complex actuation patterns [38–40].

Models for IPMCs have been developed using a number of techniques, such as finite-element methods [41] and exploiting the underlying physics, where the latter approach...
K.J. Kim and K.K. Leang considers the electrostatic forces, osmotic pressures, charge imbalances, transport of materials, and effect of local strains [42–49]. The physics-based modeling approach offers valuable insight on the physical behavior of the composite material. The results of the modeling can be used to help guide the development of the material on many levels, such as materials development and performance optimization. Despite being more realistic—and sometimes more accurate—the physics-based model is more computationally demanding to solve [50]. Equivalent electrical circuit models have been proposed to characterize the electrical dynamics of the IPMC [51]. These models can be coupled with simplified mechanical models to create input–output models for design and control applications [45].

Due to the inherent nonlinearities (such as back relaxation), dynamic effects, time-varying behaviors caused by solvent evaporation, and external disturbances in IPMCs, control is needed for high-performance operation. Control approaches for IPMCs include traditional feedback-based methods [52–54], robust and adaptive control [55,56], and feed-forward control [25,57], as well as neural networks [58].

The interest in IPMCs over the last two decades has resulted in significant advances in the manufacturing and materials processing [59–61], characterization [62], modeling [63–65], design [66], control [67], and application of IPMCs for actuation in soft bio-inspired systems [68], sensing [69], and even energy systems [70–72]. This issue and issue 4(4) contain eight papers that cover current research interest of IPMC technologies.

The paper entitled A compliant surgical robotic instrument with integrated IPMC sensing and actuation by Aw, McDaid, and Xie focuses on IPMCs for surgical applications. The paper entitled Influence of conductive network composite structure on the electromechanical performance of ionic electroactive polymer actuators by Montazami, Wang, and Heflin examines the effects of a conductive network on IPMC performance. Oh, Jeon, and Jo describe work on Nonlinear dynamics of curved IPMC actuators undergoing electrically driven large deformations in the paper that follows. A novel application of IPMCs to create a bio-inspired sensor is presented by Abdulsadda and Tan in their paper entitled An artificial lateral line system using IPMC sensor arrays. The remaining four articles will appear in Issue 4(4) of the Journal.

Kwang J. Kim a,b and Kam K. Leang a

aDepartment of Mechanical Engineering, University of Nevada, Reno, NV 89557-0312, USA
bDepartment of Mechanical Engineering, University of Nevada, Las Vegas, NV 89154-4027, USA

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