IPMC Mechanoelectrical Transduction Review

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Abstract

This paper presents a comprehensive review of using Ionic Polymer-Metal Composite (IPMC) materials as mechanoelectrical transducers. Recently more and more emphasis has been put on the research of IPMCs as displacement or velocity sensors for different applications. This has resulted in different theories and models to describe the mechanoelectrical transduction phenomenon. The paper gives an overview of the proposed transduction principles, developed models and the latest applications. In more detail, the history of IPMC materials, the physics and the electrochemistry behind the mechanoelectrical transduction, different black and grey box models, and novel real-world applications are discussed throughout the paper. However, despite of the latest advancements in the research of IPMC transduction, there is still some controversy in regard to some of the IPMC sensorial properties. For instance, it has been noticed by several authors that a signal delay which occurs in case of bending an IPMC. The general understanding of the physical principles about regular IPMC mechanoelectrical transduction is rather good. In the last section of the paper the novel results are presented for Cu-coated IPMC materials. Apparently the electrochemistry behind the transduction for Cu-coated IPMCs is significantly different. Besides the ionic diffusion, chemical reactions on the electrodes occur as well and dominate the actuation process. The experimental results show some promising opportunities for designing new Cu coated IPMC based sensors.

# Introduction

Ionic Polymer-Metal Composite (IPMC) type of materials has been extensively researched during the last two decades. Low voltage bending of a Nafion-based IPMC was reported in 1992 by Oguro . From there on, many studies have considered IPMC electromechanical properties . The IPMC materials consist of a thin ionomeric membrane with thickness of approximately 200 μm. The typical membrane materials are Nafion, Teflon, Flemion[7]. The membrane is coated with a thin layer of noble metal electrodes, such as platinum. Sometimes an additional layer of gold is added on the surface to improve the electric conductivity of the electrodes. As there are anions fixed to the polymer backbone, the membrane also consists of freely movable cations, so the overall charge of the material is balanced. Typical cations are Na+, Ka+, Li+ and Cs+ in water solution. The dry form of IPMCs has also been studied, where the ionic liquid (e.g TBA+) is used [7].

General conceptual design of IPMC was first described by Shahinpoor in 1992. The swimming robotic structure based on the IPMC actuators was proposed. The discussed kinematic equations were based on the work of Segalman et al, who presented a number of papers about modeling the IPMC materials . The diffusion equation describing the evolution of the solvent concentration and therefore the strain of polymeric gel material was proposed in 1991. In 1993 and 1994 Segalman et al also published the finite element analysis of the polymeric gel materials . In the following years attempts to formulate the electromechanical theory for IPMC materials were made. Shahinpoor presented a non-homogeneous large deformation theory of ionic polymer gels in electric and pH fields. The proposed model considered the spatial distribution of cations and anions inside the material due to the applied electric field. The deformation of IPMC was defined as a function of electric field strength, dimensions and the material physical parameters . In 2000, De Gennes and his coworkers presented the first phenomenological theory of sensing and actuation of IPMC. Nemat-Nasser and Li presented a model of the electromechanical response of IPMC, which considered the electrostatic forces inside the material. The cluster morphology of Nafion was also considered in the model . In 2002, Nemat-Nasser stressed the role of hydrated cation transport within the clusters and polymeric networks of IPMC . Couple of years later, Weiland and Leo published a model, where the rotation of individual dipoles within a cluster was studied and related to the actuation of IPMC . In 2003 Nemat-Nasser presented an extensive study of actuation properties of IPMC with different membrane materials and type of cations . To summarize the study, typical Nafion based IPMC in most cation forms, when subjected to a small potential, undergoes a fast bending towards the anode, followed by a slow relaxation towards the cathode. However, when some large alkyl-ammonium cations are being used (e.g TBA+), the initial bending is rather gradual and the back relaxation is only partial. Generally under DC, Nafion-based IPMCs do not maintain their initial displacement towards the anode and relax back towards the cathode. For some cations the back relaxation goes beyond the initial position [7, 20, 21].

In the recent years, research of the IPMC materials has been expanded more in terms of getting higher efficiency, better adaptability to the environment, and applicability. Paquette and Kim investigated the low temperature behavior of IPMC and showed the material capability to operate even below -20 degree C . They also studied IPMC materials in a multilayer configuration and constructed an equivalent circuit model . In 2006, Kim and Kim presented an electrochemical analysis of IPMC. They showed that the performance degradation of IPMC over time is caused due to the Pt oxide formation and they also suggested that the equivalent circuit of IPMC should also include the inductive component . In regard to IPMC applicability, Anton analyzed the usability of the material for real world applications and demonstrated the performance of IPMC using the inverted pendulum control . He also published a detailed description of the quasistatic mechanical behavior of IPMC actuator at large deflection and showed that a short actuator with a rigid elongation behaves more linearly than a long one . In 2007, Kim et al. showed that IPMC operation in a saltwater environment is feasible and possible naval applications could be considered . At the same year, Dogruer et. al showed that when modeling an IPMC, which is subjected to an aqueous environment, the hydrodynamic forces do not significantly affect the performance of the IPMC and could be omitted from the model. In the following years, Kim and Kim conducted an extensive study of IPMC materials exhibiting self oscillations . The mechanism behind this phenomenon was electrochemical reaction on Pt electrodes of an IPMC which was immersed in H2SO4 solution. A year later, Pugal et al published a finite element model to describe this phenomenon . Recently, Dogruer et. al showed that IPMC could be use for energy harvesting purposes. Shortly after, Tiwari studied IPMCs with different electrodes to understand the effectiveness of the process. Platinum IPMC showed better charging in bending and shear mode, gold IPMC showed better battery charging in extension mode . A study of how to increase the efficiency of energy harvesting is still in progress . A comprehensive research in regard to characterization of IPMCs for power harvesting was reported by Brufau-Penella et al. in 2008. The contribution of that research was a generic model that works with the IPMC material in dehydrated conditions.

## IPMC materials as mechanoelectrical transducers

As there are quite many papers about IPMC actuation, the number of papers considering IPMC mechanoelectrical, or voltage/current sensory properties is much smaller. However, during the last decades, several authors have focused their research on the mechanoelectrical transduction properties of IPMC and a number of papers have been published[38-58] . The first paper about ionic polymer sensors was published by Sadeghipour et al. in 1992. The system where pressure was applied to the thickness direction of platinum coated Nafion was described. The Nafion was not hydrated but was previously saturated with hydrogen. As the pressure was applied the system generated measurable voltage output. The study brings out that Nafion-base smart materials could successfully be used as vibration sensors due to the high sensitivity and linear characteristics. Couple of years later, Shahinpoor reported the discovery of a new effect in ionic polymeric gels - called the ionic flexoionic polymeric gelectric effect. It means that IPMC strips created the output voltage when was subjected to flexing or loading. Later Shahinpoor and Mojarrad investigated sensing of tip displacement of IPMC strip in cantilevered configuration. They observed that the output voltage was dependent on the orientation of the transducer with respect to the electrodes. In 1998 the first review paper of IPMC materials as biomimetic sensors and actuators was published by Shahinpoor[62]. As was brought out above, De Gennes presented the phenomenological theory of sensing and actuation of IPMC in 2000.

The principle of sensing is believed to be roughly reverse of the actuation. When the material is bent, some of the solvent carrying charged ions are mechanically forced to the vicinity of one electrode. So there forms excess of charges on the expanding side of the material. This in turn results in electric field across the polymer thickness and the corresponding voltage signal can be detected on the electrodes [20, 41, 46, 49, 63]. More recently, Bonomo et al. have done some characterization of IPMC sensors . Their research suggests that the output voltage due to bending is roughly linear to deformation and nonlinear behavior occurs only in particular working conditions – e.g. when material is subjected to a low frequency mechanical input. One of the advantages of IPMC based sensors over their actuation properties is that the wet environment is not the key issue to work well. In fact they do not suffer the same drawbacks as actuators do . However, Chen et al. reported that measured signal of IPCM sensor was weak after immediately taking out of water . The research shows that the amplitude of the sensing signal increased to the maximum at about t=5 minutes, and it started to decrease afterwards. The time-varying response is believed to arise from water evaporation of the IPMC sample. Water evaporation also increases Young modulus, but it is not the dominant factor of sensing response change. It is not clear yet, if the hydration level influences the sensing behavior trough the change of ionic diffusivity and more research in this regard may be needed. This is also important to understand how to make stable IPMC based mechanoelectrical transducers.

Several configurations have been proposed to create IPMC based sensor-actuator systems. Nakadoi [53]has proposed an integrated IPMC actuator-sensor system on a single film and examined the electric interference from actuator phase to sensor phase. Chen et al. have proposed a system where an IPMC sheet is coupled with two polyvinylidene fluoride (PVDF) film[64], bonded to the sides of the IPMC. The authors have overcome the feedthrough problems that they had with the given configuration in past . For the first time, feedback control of IPMC was successfully demonstrated using only integrated sensors showing that one can simultaneously regulating/tracking the bending displacement and monitoring the force output (or vice versa). The actuator/sensor system was verified by measuring forces on tip penetration into a soap bubble. However, only small deformation of IPMCs was assumed. For the large displacements the discrepancies between the bending displacement obtained from the PVDF and from the laser sensors were evident. Several other authors have suggested using the same IPMC strip as a sensor and actuator. For instance, Punning demonstrated a self-sensing actuator. The sensing was based on the voltage drop measurements - half of the IPMC was fixed and another half was able to move and there was an extra wiring at the tip of the IPMC to measure voltage drops. The fixed part provided reference voltage and the voltage of the deforming part was subject to the voltage change due to surface resistance variations. The measured voltages provided some information about bending direction and extent of the sheet. For the given model to work, a surface resistance study was necessary . As the surface resistance acts to the bending as a delicate feedback, more the resistance changes, more the IPMC sensing output of the given system gets disturbed. Farinholt , Konyo[44], and Bonomo have also noted that more the sensor strip is crooked, the more the output signal gets disturbed. Specifically, there exists a certain time delay between the deformation and sensor output. The authors have not discussed the reason for this phenomenon, so more research would be required to investigate the behavior. However, Punning has proposed a circuit model which predicts the delay.

Despite the fact that there is not as much research done about IPMC sensory properties as about the actuation properties, there are already some applications proposed for IPMC sensors. What makes IPMC sensors appealing is their linear output voltage. Bonomo has suggested that the output voltage is not strong enough to produce nonlinear phenomenon . At the same time the current output is shown to scale linearly with the width of the IPMC and inversely with the length, which allows developing simple IPMC based sensors. Bonomo [56]has introduced a prototype of a probe for biomedical applications. The proposed device consists of an IPMC actuator and an IPMC sensor and it is able to recognize the presence of tissues coming into contact with its sensitive part. Also a model which corresponded well to the experimental data was developed. Biddiss has analyzed IPMC materials for using as sensors in hand prostheses. The results look promising and the authors brought out that contrary to many traditional approaches, IPMCs do not require external power supplies or auxiliary mechanism, making them suitable for that kind of applications. However some parameters such as temperature variation and its influence on the sensitivity were not measured above 50C. Chen has demonstrated an application of IPMC/PVDF sensor - micro-injection of living Drosophila embryos. IPMC/PVDF structure and sensing circuit was used. Experimental results showed that the developed IPMC/PVDF sensor-actuator system, together with a model-based compensation algorithm, can perform effective, simultaneous actuation and sensing. Paola has proposed a vibration sensor of an IPMC in cantilever configuration. The single degree of freedom system was modeled with spring/dampener equivalent model. The results showed that IPMC could be used as a vibration sensing transducer with adequate sensitivity and linear characteristics.

When it comes to modeling of IPMC actuation, there are mainly two types of models available - physical models which consider material properties and circuit equivalent models , which are based on the electrical measurements. Both types of models for IPMC mechanoelectrical transduction properties have also been developed. It is noted that the voltage generated by the sensing is not sufficient to produce nonlinear effects; therefore linear approximation in models could be used and an electric circuit model for IPMC voltage sensing was proposed . Chen proposed a dynamic, physics based model, where the infinite-dimensional transfer function relates the short-circuit sensing current to the applied deformation . The model was derived by solving the partial differential equations from . The model involves basic electrostatics and ion migration/diffusion description and goes beyond that. First, it incorporates the effect of the distributed surface resistance, which is known to influence the actuation and sensing dynamics . Simulation comparison with results suggests that the including the resistance makes model more precise. Instead of limiting simulations to the step deformation only, an arbitrary mechanical deformation stimulus was allowed, which is of interest for real applications. The result of the work is a physical model, which also takes into account the surface resistance. Some discrepancies between the model description and the experimental measurements are primarily due non-linear behavior of IPMCs..

The following section provides more insight into the mechanism of mechanoelectrical transduction of IPMC and also the physical models are discussed.

# Mechanoelectrical transduction mechanisms of IPMC

There are several different ways how the physics behind the mechanoelectrical transduction of IPMC is understood. Tadokoro, et al. [74] proposed a model of ionic polymers based on ionic motion. The electromechanical transduction is explained with the forces imposed on the ions as they migrate in the polymer due to an external electric field. Electrostatic interactions produced by ionic motion were also modeled. De Gennes et al, Asaka and Oguro [4, 16, 74] explained the underlying causes of the transduction with solvent fluxes and pressure gradients. Under the electric field the counter ions drift, and they carry with them a certain number of water molecules. When the molecules pile near the cathode, a local overpressure is created, this in turn causes deformation in the membrane. There are two forms of transportation inside the polymer: charge transport (with a current density ) and solvent transport (with a flux ). The standard Onsager relations for such system are

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Here, is the membrane conductance, is the Darcy permeability and is a cross coefficient. The induced electric field is proportional to an applied bending torque , which is the cause of the pressure gradient in the material. Now, when a mechanical torque is applied to the material, there will be a finite water flux, but the electric current remains zero. The magnitude of induced electric field can be calculated using the relation

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where is Poisson’s ratio and is the thickness of the membrane. This model, though, ignores the electrode effects and also the osmotic pressure contribution.

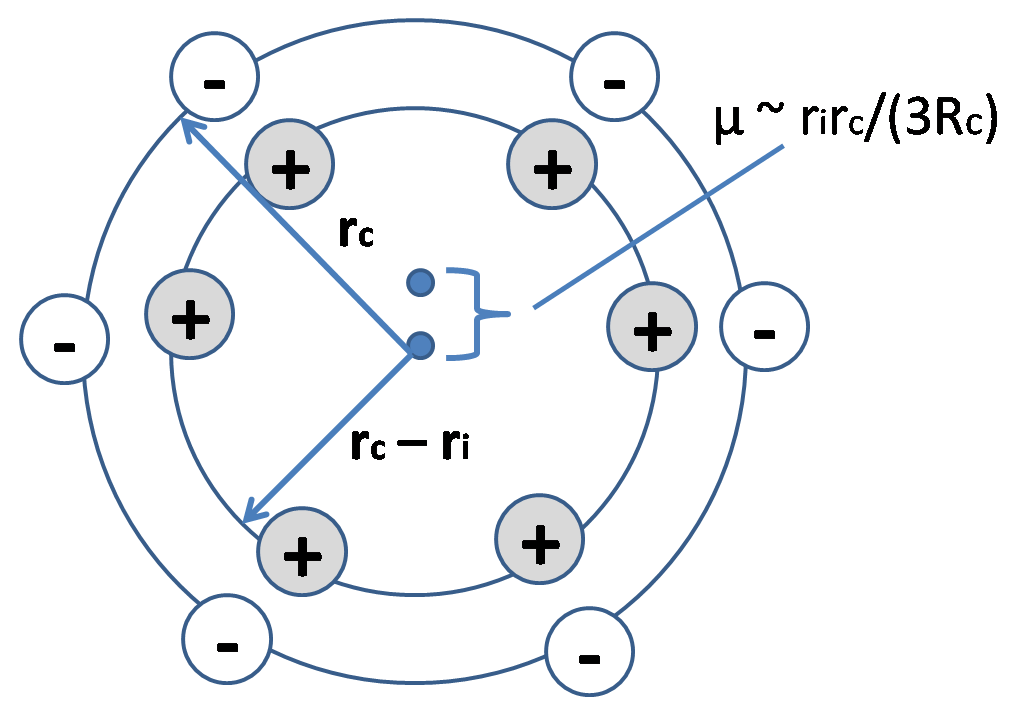


Figure induced electric dipole within a cluster. The dipole is proportional to cluster radius , distance between the ions and inversely proportional to imposed radius of curvature of IPMC (from {{27 Nemat-Nasser,Sia 2006}}).

The different approach to describe the mechanoelectrical transduction is to consider the electrostatic interaction within the polymer. The model was first proposed by Nemat-Nasser and Li[76, 77]. The underlying cause of actuation is explained by the internal stresses induced by interaction between ion pairs inside a cluster. The main components of the stress are the electrostatic stress due to the charge imbalance in the polymer and the osmotic stress, which is due to redistribution of water molecules. The governing equation for counter ion distribution due to applied electric field is:

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where is counter ion concentration, D is diffusion constant, is electric field potential, is fluid pressure, and free water velocity. The term is a combination of water and counter ion molar volumes. The above equation together with an applied time independent electric field gives the stress field inside the polymer as follows

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where is anion density, is a constitutive parameter, which relates the charge density to the electrostatic stress, andis the osmotic stress. Using the same ionic cluster material approach, the induced electric field due to imposed curvature is calculated as well. The electric field is caused by induced electric dipoles in the clusters and the overall field strength is proportional to the sum of “effective” dipole moments. The approximate expression without explicit constants is as follows:

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where is electric dipole and is the distance between the clusters. The electric dipole of a single cluster is illustrated in Figure 1.

When Nemat-Nasser and Li charge sensing model is about ionic dipoles induced in the polymer clusters, Farinholt and Leo, by using the same field equations, presented a hypothesis that the charge density on the surface of the polymer is proportional to the induced stress . This is basically the reverse of actuation model of Nemat-Nasser and Li. The model, though, ignores the convective term of Eq. (3) By assuming linear relation between the stress and the charge density, the induced electric field inside the polymer due to a tip deflection is proportional to the terms and :

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Where and are inverse time constants. The induced electric field at one instant of time after the mechanical deformation is illustrated in Figure 2. The electric field profile is almost identical to the case when external voltage is applied on IPMC.

Chen, while using the same underlying equations as Farinholt and Leo, has expanded the model and added the effects of the surface resistance {{4 Chen,Zheng 2007}}. This resulted in a compact, transfer-function representation of physics-based model. The frequency response analysis shows that considering the resistance improves the model accuracy for higher frequencies. The transfer-function form of the physical model is significant as it could be used in real-time feedback system

The aforementioned models are usable for mechanoelectrical transduction problems. Even though the approaches are different, the practical value for different models remains and much effort has been put in to explain the physics behind the phenomenon. However, there are some areas of mechanoelectrical transduction of IPMC, which remain unclear.

Figure Normalized electric field, calculated using the model proposed in . This is almost identical to the electric field caused by an applied voltage (from {{53 Nernat-Nasser,S. 2000}}).

Different authors have obtained more phenomenological characteristics of IPMC sensors . For many cases, there [45]exists a certain time delay between the imposed displacement and the measured voltage of the IPMC.

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| Figure The figure shows measurement results of prebent sensor. The dotted line is the measured signal at the tip of the sensor. The dashed line is the measured signal at the fixed end of the sensor The solid line in the figures shows the movement of the mechanoelectrical transducer. The graph A is the output of the straight sensor, the graph B shows the output of considerably bent sensor. As it could be seen, there exists a delay between the signals measured at the different ends of the IPMC, and the delay is significantly larger for the prebent IPMC (from ). |

The experimental data suggest that the output signal depends on imposed curvature of IPMC as illustrated in Figure 3. The more the sensor tip is crooked, the more the output signal is disturbed [55]. Somewhat contradicting characteristic of IPMC mechanoelectrical transducer is the stability of the measured output signal. Some experiments suggest that the IPMC characteristics do not change after hours of work and measured voltage is still reliable . Although the wet IPMC produces noisy signal at first, but after the material reaches the state of equilibrium, the signal remains noiseless during many hours of work . For other instances, the sensor signal started to show decrease of the amplitude after only of work [52]. Those areas, though well observed, need some more study to better understand and possibly improve the materials.

## Grey box models

The physical models of IPMC provide the necessary insight to get understanding and visualize what is behind the transduction mechanism. When it comes to controlling of IPMC in real world applications, the gray box models are simpler to design and implement. For instance, a precise white box model was presented by Tadokoro et al. . This was discussed in the previous section as well. However, the model might not be practical to use in design because of its complexity. The model proposed by Kanno et al. is an empirical model, but does not work for IPMC based sensors . Some of the latest grey box models, which would be sufficiently accurate and easy to implement to control an IPMC mechanoelectrical transducer, are considered in this section.

Figure Two port model (from ).

A two-port network model for IPMC transducers was presented by Newbury et al. . It was designed to handle both sensing and actuation properties of the material. The model is based on an equivalent circuit representation of an IPMC transducer and only focuses on the variables that are important for using the polymer transducer as a sensor or actuator. In the two port model (see ), the variables and are the voltage and current at the electrodes, and and   are the external force and the velocity at the tip of the bender transducer and the relation between those is given as:

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where the Zij are Laplace domain expressions. Experimental transducer responses with specific mechanical or electrical boundary conditions were used to identify those terms. The preliminary validation of the model was only done for actuation only. However, the design of the model allows it to use also in linear control systems. Downside of the model is that the parameters are not geometrically scalable.

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| Figure Equivalent circuit for IPMC transducers (from ). | |

The expanded model was presented a year later by Newbury and Leo with a focus to identify a set of fundamental material parameters for electromechanical coupling . The model was developed as a function of these parameters and material geometry. For the extended model, the Eq.(7) becomes

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Where the are the functions of . Those variables are identified in the equivalent circuit graph in . The terms are respectively DC resistance and quantity which shows the ability of the transducer to store electrical charge. denotes the mechanical impedance due to stiffness and is the inertial term. After equivalent circuit analysis, the some simple sensor equations for the input and output terms were obtained. The current over velocity equation is

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For open-circuit voltage, the equation is

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It could be greatly simplified when neglecting the inertial term and assuming the operating frequencies when electric impedance becomes relatively small compared to the DC resistance:

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The last potentially useful relation in regard to sensing is for open-circuit voltage and displacement input:

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In those equations, denotes the distance between the clamped end of the transducer and the point where the force is applied, is the width and is the thickness of actuator. The term represents a piezoelectric coupling term between induced strain and applied electric field and is the complex Young’s modulus. The given equations were also validated in . The value of the model is that it predicts the sensing and actuation behavior within a single framework.

Similar techniques as discussed above were used by Bonomo et al., to create a linear mechanoelectrical model for IPMC transducers {{3 Bonomo,C. 2006}}. The current-deflection relation

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was studied. The term is the Laplace operator. In fact, the main emphasis was put on identifying the complex parameters and The values for both variables were found to be dependent on working environment, i.e. the hydration level of IPMC plays a role. The conclusion of the work was that the need for a wet working environment is not a key issue for IPMC based sensors.

A distributed model for IPMC is proposed by Punning et al. [70]. The basis of the work is the model of Kanno et al. [67]. However, instead of dividing an IPMC into 10 segments and modeling the relation between the input current and tip displacement, the same piece was divided into infinitesimally small segments, allowing treating the system as a RC transmission line. The analytical solution for a voltage-step response of lossy distributed RC lines is presented in [84]. The equations provided in {{62 Punning,A. 2008}} are good for both sensors and actuators. The detailed consideration of the topic is given in [XXX]

# IPMC mechanoelectrical transduction applications

Although the usage of IPMCs as mechanoelectrical transducers is still rather new area, some promising applications have already been demonstrated.

Due to the sufficient sensitivity and linear characteristics, IPMC materials could be used as vibration sensing transducers . To demonstrate IPMC capabilities in the similar area, a system of a cantilever beam was constructed and described with a linear model . The experiments showed that IPMC could be used as a motion sensor as well. Also an interesting quality of IPMC-based sensors was observed: they do not necessarily need a wet working environment, i.e. the characteristics of the material do not change over longer period of time in a dry environment. This is not the case for IPMC-based actuators. This observation is important as it suggests that stable and simple IPMC-sensor based applications could be developed.

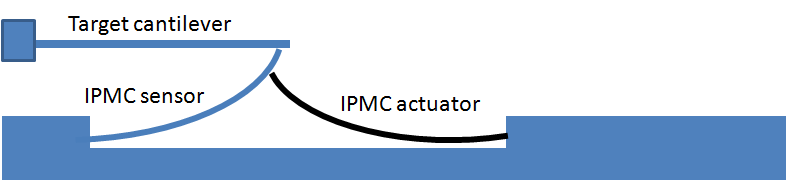


Figure Conceptual scheme of tactile sensor (from {{2 Bonomo,Claudia 2008}}).

Figure Amplitude of the IPMC sensor output voltage in six different surveys when: (a) the probe contact with air only; (b) the probe is in contact with sample (E=100Pa); (c) the probe is in contact with sample (E=300Pa). The dotted lines refer to the mean value (from {{2 Bonomo,Claudia 2008}}).

There is rather significant number of tactile sensors based on piezoelectric effect proposed in the literature [85-89]. Even though the sensors give good results, they are often quite complex in structure and hard to micro-manufacture. A multifunctional tactile sensor based on IPMC materials has been proposed. The advantages of using IPMC are relatively wide displacement and easily adjustable shape. Coupled with an IPMC based actuator, a simple probe has been demonstrated . The device can be used in a medical field as it is designed to recognize difference of the tissue contact with the sensitive part. It consists of an IPMC basedsensor and an IPMC based actuator (see Figure 6 for the conceptual design). A sinusoidal voltage signal is applied to the IPMC actuator which causes it to vibrate, pushing the sensor toward the material that surrounds the device. The IPMC based sensor is able to recognize the presence of the tissue and gives some estimation about the material stiffness. The measured data versus actual stiffness show good correlation (see Figure 7).

Another medical field where the IPMC based transducers are proposed to be useful is in development of hand prostheses . Implementation of a prosthetic hand sets high demands for the materials. For instance, a highly sensitive deflection sensor with fast response and continuously variable output is required. EAP materials in general would be suitable for such applications. IPMC material was investigated due to the relatively novel and exploratory status together with the potential that they have exhibited as transducers. The characterization of the material shows that the attributes of the IPMC could help to achieve the desired deflection sensitivity of hand prostheses in future. However, there are also challenges; the IPMC polymers are responsive not only to bending but also to pressure and stretch as well. This fact must be considered in the system design. Also more research needs to be done about IPMC temperature response. In the range from 5 to 50 degree of C no response was observed though. The material is stable in air, but in a wet environment the characteristics are not that steady. Therefore calibration of the materials for proposed applications is very important.

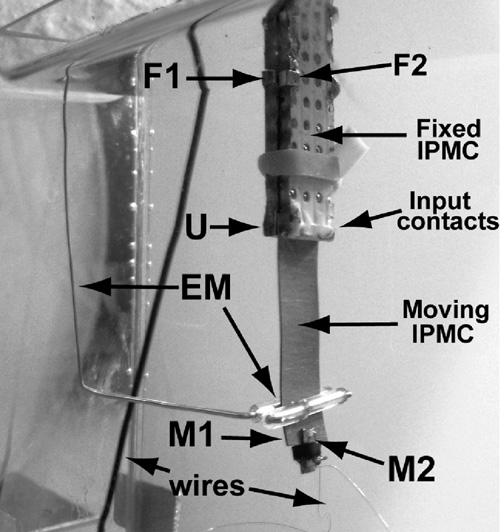


Figure The proposed self sensing actuator. Though somewhat complicated design, the results show that sensor signals are easily detectable and have a good signal-to-noise ratio. The photo is courtesy of A. Punning .

Punning demonstrated a novel self-sensing IPMC actuator . The proposed device consists of a single IPMC strip in cantilever configuration and with additional wiring near the tip of the sheet. The experiments show that the sensor signals are easily detectable and have a good signal-to-noise ratio and no significant signal preprocessing is needed. Besides possible application as an accelerometer, the proposed sensor can be used as a position sensor as well. The disadvantage of the system is that the clamped part is rather long and that increases the energy consumption. Also the contacts at the tip make the device less fault tolerant. However the measurements show that the self-sensing actuator can be used to determine the direction of the bending and to some extent the bending curvature of the actuator as well. Though the design of the system is somewhat complicated (see Figure 8), this is according to our best knowledge, only self-sensing IPMC based solution so far. Park et al. though suggest that the simpler self-sensing actuator based on the IPMC could be potentially achieved, based only signal conditioning technique .

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| Figure Conceptual design of the IPMC/PVDF sensor device for micro injecting living Drosophila embryos. The photos are taken during a real experiment (from {{10 Chen,Zheng 2008}}). | |

Rather than using the sensory capabilities of IPMC materials, PVDF sensors were used in a hybrid IPMC/PVDF sensor-actuator system proposed by Chen et al . A PVDF film was bonded to IPMC with an insulating layer. IPMC was in the role of actuator and the PVDF film worked as a sensor. The challenge of this system was the feedthrough coupling when the actuator was subjected to a voltage. Therefore the system was designed to overcome it by first modeling the coupling effect and then performing the real time compensation. Another problem was that as the hydration level of the IPMC changed, it was necessary to readjust accordingly the feedthrough model. The applicability of the system was demonstrated by using it in micro-injection of living Drosophila embryos. The experimental setup with the snapshots of a successful injection is shown in Figure 9. The designed system allowed the accurate control of the injection force and therefore reducing the failed attempts, which seem to be rather common for the manual process.

# New developments

As discussed in the previous sections of the paper, a significant level of research has been done in regard to Pt plated IPMC materials as mechanoelectrical transducers. We have extended the topic to provide some new insight into characteristics of copper plated IPCM materials, along with the potential usage as transducers.

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| Figure Illustration of Pt electrodes for unbent and bent configuration of IPMC . | |

It is well documented fact, that due to the morphology of Pt electrodes, bending causes rather significant surface resistance changes. For instance, Punning, et al. have characterized the electrodes and during the bending, convex electrode resistivity increases, at the same time, concave electrode resistivity decreases, but not that significantly. This is illustrated in Figure 10. At the same time, it has been reported that the same thing does not necessarily hold true for Cu-Pt electrodes.



Figure 11 X-ray line scan of the Cu-IPMC cross-section after cycling 300 cycles with voltage pulses of 2V magnitude. The image on top shows the Cu and the bottom one is Pt (from {{26 Johanson,Urmas 2008}})

Johanson et al. has done an extensive study of Cu effects on the Pt electrodes and some interesting and novel characteristics, compared to regular IPMC, were recorded . Resistance measurements showed that Cu-coated membranes display an opposite phenomenon compared with the Pt coated materials. When actuated by applying the voltage, the resistance increases at the side to which the material is bended (the anode side) and decreases at the cathode side. The reason for that is that the new layer of Cu is formed between the Pt particles in the electrode and also close to the electrode on the cathode side. At the same time, Cu is depleted from the anode side. The reaction occurs while Cu2+ ions migrate towards the cathode. The positive effect of the Cu2+ migration is the extra water which is dragged along with the ions. The effect is also reversible by switching the polarity of applied voltage. The noteworthy is that the conductivity seems to improve during actuation cycles due to Cu relocation. This must be considered when using the material as electromechanical transducer as the electrode resistance does not only depend on the bending angle. There were also some unwanted reactions observed in . One was that when a voltage is applied, there is a growth of Cu dendrites in the cross-section of IPMC (see Figure 11).

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| bending_ex_1 | bending_ex_2 |
| Figure 12 Cu-Pt covered IPMC (on the left) and regular Pt IPMC on the right – only contact with Cu is due to the electrodes. | |

In order to study Cu-Pt coated IPMC materials in mechanoelectrical transduction context, first the characterization of IPMC with different electrodes was done. One Pt-coated IPMC was covered fully with a copper layer; the second sample was only partially in contact with Cu electrodes (see Figure 12). For both experimental setups, the impedance were measured for five different curvatures, where radius r was 38.3mm, 29.2mm, 21.2mm, 15.9mm and flat. The potentiostat was operated with the following setup: DC voltage of 1000mV and AC voltage of 10mV. The experimental results show some remarkable difference between the Cu-coated and regular Pt IPMC.

Gimpedance

Figure Impedance of the IPMC without Cu-coating with different bending radiuses.

Figure 13 shows the impedance for bent IPMC without Cu-coating. The internal impedance changes due to the bending curvature as well as the surface resistance.

Gimpedance

Figure Impedance of bent IPMC with Cu-coating and different bending radiuses.

Figure 14 shows the impedance plot for the IPMC with Cu-coating. If we compare Figure 13 with Figure 14, the following things could be noticed:

* The impedances Zreal and –Zimaginari increase due to the decrease of the radius of curvature.
* The increase rate of –Zimaginari for the fully covered copper electrodes is smaller than for regular Pt electrodes.
* The differences of impedances due to curvature change could be explained by the change of capacitance inside the IPMC.

Figure 13 and Figure 14 are part of the results we have gotten in regard to characterizing Cu-Pt coated electrodes. However, we can see some connections between the results of Johanson et al. and our measurements. For instance, the capacitance change rate for fully covered Cu-Pt electrode is different and this could be due to the fact that the applied voltage has caused the change of the copper layer inside the IPMC. This opens the way to develop actuators, where the surface resistance is not the key for detecting the position, but instead the capacitance plays the key role. More research would be needed to see, how the Cu-Pt coated sensory properties would change due to certain number of actuation cycles. Also the capacitance change due to that still must be determined.

Considering the research of Johanson et al. and the impedance measurement results shown above, there is a lot of potential for designing novel IPCM mechanoelectrical transducer. Even though the Cu-Pt coated IPMCs have some drawbacks, especially when it comes to actuation, the sensory properties still need to be studied.

References

[1] Oguro, K., Kawami, Y., and Takenaka, H., 1992, "Bending of an Ion-Conducting Polymer Film-Electrode Composite by an Electric Stimulus at Low Voltage," Journal of Micromachine Society, **5**pp. 27-30.

[2] Shahinpoor, M., and Kim, K. J., 2001, "Ionic Polymer-Metal Composites: I. Fundamentals," Smart Materials and Structures, **10**(4) pp. 819-833.

[3] Asaka, K., Oguro, K., Nishimura, Y., 1995, "Bending of Polyelectrolyte Membrane-Platinum Composites by Electric Stimuli I. Response Characteristics to various Waveforms," **27**(4) pp. 436-440.

[4] Asaka, K., and Oguro, K., 2000, "Bending of Polyelectrolyte Membrane Platinum Composites by Electric Stimuli. Part II. Response Kinetics," **480**(1) pp. 186-198.

[5] Adolf, D. B., Shahinpoor, M., Segalman, D. J., 1993, "Electrically Controlled Polymeric Gel Actuators," **902322**(5250167) .

[6] Oguro, K., Takenaka, H., and Kawami, Y., 1993, "Actuator Element," .

[7] Nemat-Nasser, S., and Wu, Y., 2003, "Comparative Experimental Study of Ionic Polymer-Metal Composites with Different Backbone Ionomers and in various Cation Forms," Journal of Applied Physics, **93**(9) pp. 5255-5267.

[8] Segalman, D. J., Witkowski, W. R., Adolf, D. B., 1992, "Theory and Application of Electrically Controlled Polymeric Gels," Smart Materials and Structures, **1**pp. 95-100.

[9] Shahinpoor, M., 1992, "Conceptual Design, Kinematics and Dynamics of Swimming Robotic Structures using Ionic Polymeric Gel Muscles," Smart Materials and Structures, **1**pp. 91-94.

[10] Segalman, D., Witkowski, W., Adolf, D., 1991, "Electrically-Controlled Polymeric Gels as Active Materials in Adaptive Structures," .

[11] Segalman, D. J., Witkowski, W. R., Rao, R. R., 1993, "Finite element simulation of the 2D collapse of a polyelectrolyte gel disk," Proceedings of Smart Structures and Materials 1993: Smart Materials, Anonymous Albuquerque, NM, USA, **1916,** pp. 14-21.

[12] Segalman, D. J., and Witkowski, W. R., 1994, "Two-Dimensional Finite Element Analysis of a Polymer Gel Drug Delivery System," pp. 1055.

[13] Shahinpoor, M., 1993, "Electro-mechanics of bending of ionic polymeric gels as synthetic muscles for adaptive structures," Proceedings of the 1993 ASME Winter Annual Meeting, Anonymous New Orleans, LA, USA, **35,** pp. 11-22.

[14] Shahinpoor, M., 1994, "Continuum Electromechanics of Ionic Polymeric Gels as Artificial Muscles for Robotic Applications," **3**(3) pp. 367-372.

[15] Shahinpoor, M., 1995, "Micro-Electro-Mechanics of Ionic Polymeric Gels as Electrically Controllable Artificial Muscles," **6**(3) pp. 307-314.

[16] de Gennes, P. G., Okumura, K., Shahinpoor, M., 15, "Mechanoelectric Effects in Ionic Gels," Europhysics Letters, **50**(4) pp. 513-518.

[17] Li, J. Y., and Nemat-Nasser, S., 2000, "Micromechanical Analysis of Ionic Clustering in Nafion Perfluorinated Membrane," Mechanics of Materials, **32**(5) pp. 303-314.

[18] Nemat-Nasser, S., 2002, "Micromechanics of Actuation of Ionic Polymer-Metal Composites," **92**(5) .

[19] Weiland, L. M., and Leo, D. J., 2004, "Electrostatic Analysis of Cluster Response to Electrical and Mechanical Loading in Ionic Polymers with Cluster Morphology," **13**(2) pp. 323-336.

[20] Nemat-Nasser, S., and Thomas, C.W., 2001, SPIE, Bellingham, WA, pp. 139, Chap. 6.

[21] Mallavarapu, K., and Leo, D. J., 2001, "Feedback Control of the Bending Response of Ionic Polymer Actuators," **12**(3) pp. 143-155.

[22] Paquette, J. W., Kim, K. J., and Kim, D., 2005, "Low Temperature Characteristics of Ionic Polymer-Metal Composite Actuators," **118**(1) pp. 135-143.

[23] Paquette, J. W., Kim, K. J., Kim, D., 2005, "The Behavior of Ionic Polymer-Metal Composites in a Multi-Layer Configuration," **14**(5) pp. 881-888.

[24] Kim, D., and Kim, K. J., 2006, "Experimental Investigation on Electrochemical Properties of Ionic Polymer-Metal Composite," **17**(5) pp. 449-454.

[25] Anton, M., Kruusmaa, M., Aabloo, A., 2006, "Validating usability of ionomeric polymer-metal composite actuators for real world applications," 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2006, Anonymous Beijing, China, pp. 5441-5446.

[26] Anton, M., Aabloo, A., Punning, A., 2008, "A Mechanical Model of a Non-Uniform Ionomeric Polymer Metal Composite Actuator," **17**(2) .

[27] Kim, K. J., Yim, W., Paquette, J. W., 2007, "Ionic Polymer-Metal Composites for Underwater Operation," **18**(2) pp. 123-131.

[28] Dogruer, D., Lee, J., Yim, W., 2007, "Fluid Interaction of Segmented Ionic Polymer-Metal Composites Under Water," **16**(2) .

[29] Kim, D., and Kim, K. J., 2007, "Ionic Polymer-Metal Composite Actuators Exhibiting Self-Oscillation," **137**(1) pp. 129-133.

[30] Kim, D., and Kim, K. J., 2007, "A Theoretical and Experiment Study for Self-Oscillatory Ionic Polymer-Metal Composite Actuators," **16**(5) pp. 1789-1795.

[31] Kim, D., Kim, K. J., Tak, Y., 2007, "Self-Oscillating Electroactive Polymer Actuator," Applied Physics Letters, **90**(18) pp. 184104.

[32] Pugal, D., Kasemagi, H., Kim, K. J., 2007, "Finite element simulations of the bending of the IPMC sheet," Proceedings of SPIE - The International Society for Optical Engineering, Anonymous San Diego, CA, United States, **6524,** .

[33] Pugal, D., Kim, K. J., Punning, A., 2008, "A Self-Oscillating Ionic Polymer-Metal Composite Bending Actuator," Journal of Applied Physics, **103**(8) pp. 084908.

[34] Tiwari, R., Kim, K., and Kim, S., 2008, "Ionic Polymer Metal Composites as Energy Harvesters," Smart Structures and Systems, **4**(5) .

[35] Dogruer, D., Tiwari, R., and Kim, K., 2007, "Ionic polymer metal composites as energy harvesters," Electroactive Polymer Actuators and Devices (EAPAD) 2007, Anonymous San Diego, CA, United states, **6524,** .

[36] Tiwari, R., and Kim, K. J., 2008, "Improved IPMC sensing by use of cation \& through induced nano-to-micro scale surface cracks," Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2008, Anonymous San Diego, CA, United states, **6932,** .

[37] Brufau-Penella, J., Puig-Vidal, M., Giannone, P., 2008, "Characterization of the Harvesting Capabilities of an Ionic Polymer Metal Composite Device," **17**(1) .

[38] Shahinpoor, M., Kim, K. J., Henderson, K., 2001, "Sensing capabilities of ionic polymer-metal composites," Smart Structures and Materials 2001- Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials, Anonymous Newport Beach, CA, United states, **4328,** pp. 267-274.

[39] Newbury, K. M., and Leo, D. J., 2003, "Linear Electromechanical Model of Ionic Polymer Transducers. Part 1: Model Development," Journal of Intelligent Material Systems and Structures, **14**(6) pp. 333-342.

[40] Newbury, K. M., and Leo, D. J., 2003, "Linear Electromechanical Model of Ionic Polymer Transducers - Part 11: Experimental Validation," Journal of Intelligent Material Systems and Structures, **14**(6) pp. 343-357.

[41] Bonomo, C., Del Negro, C., Fortuna, L., 2003, "Characterization of IPMC strip sensorial properties: Preliminary results," Proceedings - IEEE International Symposium on Circuits and Systems, Anonymous Bangkok, Thailand, **4,** .

[42] Ryu, J., Park, J., Yun, S., 2004, "Design and fabrication of a large-deformed smart sensorized polymer actuator," 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Anonymous Sendai, Japan, **1,** pp. 908-912.

[43] Shahinpoor, M., 2004, "Ionic Polymer--Metal Composites: III. Modeling and Simulation as Biomimetic Sensors, Actuators, Transducers, and Artificial Muscles," Smart Materials and Structures, **13**(6) pp. 1362.

[44] Konyo, M., Konishi, Y., Tadokoro, S., 2004, "Development of Velocity Sensor using Ionic Polymer-Metal Composites," **5385**pp. 307.

[45] Farinholt, K., and Leo, D. J., 2004, "Modeling of Electromechanical Charge Sensing in Ionic Polymer Transducers," Mechanics of Materials, **36**(5) pp. 421-433.

[46] Bonomo, C., Fortuna, L., Giannone, P., 2005, "A Method to Characterize the Deformation of an IPMC Sensing Membrane," Sensors and Actuators, A: Physical, **123**pp. 146-154.

[47] Biddiss, E., and Chau, T., 2006, "Electroactive Polymeric Sensors in Hand Prostheses: Bending Response of an Ionic Polymer Metal Composite," Medical Engineering and Physics, **28**(6) pp. 568-578.

[48] Bonomo, C., Fortuna, L., Giannone, P., 2006, "Improved frequency investigation of IPMC based sensors," Conference Record - IEEE Instrumentation and Measurement Technology Conference, Anonymous Sorrento, Italy, pp. 2338-2341.

[49] Bonomo, C., Fortuna, L., Giannone, P., 2006, "A Model for Ionic Polymer Metal Composites as Sensors," Smart Materials and Structures, **15**(3) pp. 749-758.

[50] Bonomo, C., Fortuna, L., Giannone, P., 2007, "A Nonlinear Model for Ionic Polymer Metal Composites as Actuators," Smart Materials and Structures, **16**(1) pp. 1-12.

[51] Chen, Z., Shen, Y., Xi, N., 2007, "Integrated Sensing for Ionic Polymer-Metal Composite Actuators using PVDF Thin Films," Smart Materials and Structures, **16**(2) pp. S262.

[52] Chen, Z., Tan, X., Will, A., 2007, "A Dynamic Model for Ionic Polymer-Metal Composite Sensors," Smart Materials and Structures, **16**(4) pp. 1477-1488.

[53] Nakadoi, H., Sera, A., Yamakita, M., 2007, "Integrated actuator-sensor system on patterned IPMC Film: Consideration of electoric interference," Proceedings of the 2007 4th IEEE International Conference on Mechatronics, ICM 2007, Anonymous Kumamoto, Japan, .

[54] Punning, A., 2007, "Electromechanical Characterization of Ionic Polymer-Metal Composite Sensing Actuators," .

[55] Punning, A., Kruusmaa, M., and Aabloo, A., 2007, "Surface Resistance Experiments with IPMC Sensors and Actuators," Sensors and Actuators, A: Physical, **133**(1) pp. 200-209.

[56] Bonomo, C., Brunetto, P., Fortuna, L., 2008, "A Tactile Sensor for Biomedical Applications Based on IPMCs," IEEE Sensors Journal, **8**(8) pp. 1486-1493.

[57] Paola, B., Fortuna, L., Giannone, P., 2008, "IPMCs as vibration sensors," Conference Record - IEEE Instrumentation and Measurement Technology Conference, Anonymous Victoria, BC, Canada, pp. 2065-2069.

[58] Punning, A., Kruusmaa, M., and Aabloo, A., 2007, "A Self-Sensing Ion Conducting Polymer Metal Composite (IPMC) Actuator," Sensors and Actuators, A: Physical, **136**(2) pp. 656-664.

[59] Sadeghipour, K., Salomon, R., and Neogi, S., 1992, "Development of a Novel Electrochemically Active Membrane and 'Smart' Material Based Vibration sensor/damper," Smart Materials and Structures, **1**(2) .

[60] Shahinpoor, M., 1995, "A New Effect in Ionic Polymeric Ionic Polymeric Gels: The Ionic Flexogelectric Effect," **2441**pp. 42-53.

[61] Shahinpoor, M., Mojarrad, M., and Salehpoor, K., 1997, "Electrically Induced Large-Amplitude Vibration and Resonance Characteristics on Ionic Polymeric Membrane-Metal Composites Artificial Muscles," **3041**pp. 829.

[62] Shahinpoor, M., Bar-Cohen, Y., Simpson, J. O., 1998, "Ionic Polymer-Metal Composites (IPMCs) as Biomimetic Sensors, Actuators and Artificial Muscles - a Review," Smart Materials and Structures, **7**(6) .

[63] Shahinpoor, M., and Kim, K. J., 2000, "The Effect of Surface-Electrode Resistance on the Performance of Ionic Polymer-Metal Composite (IPMC) Artificial Muscles," Smart Materials and Structures, **9**(4) pp. 543-551.

[64] Chen, Z., Kwon, K., and Tan, X., 2008, "Integrated IPMC/PVDF Sensory Actuator and its Validation in Feedback Control," Sensors and Actuators, A: Physical, **144**(2) pp. 231-241.

[65] Bonomo, C., Fortuna, L., Giannone, P., 2006, "A Model for Ionic Polymer Metal Composites as Sensors," Smart Materials and Structures, **15**pp. 749.

[66] Pugal, D., Kasemagi, H., Kruusmaa, M., 2008, "An advanced finite element model of IPMC," Proceedings of SPIE - The International Society for Optical Engineering, Anonymous San Diego, CA, United States, **6927,** .

[67] Kanno, R., Tadokoro, S., Takamori, T., 1996, "Linear approximate dynamic model of ICPF (ionic conducting polymer gel film) actuator," Proceedings of IEEE International Conference on Robotics and Automation, Anonymous Minneapolis, MN, USA, pp. 219-225.

[68] Bao, X., Bar-Cohen, Y., and Lih, S., 2002, "Measurements and macro models of ionomeric polymer-metal composites (IPMC)," Proceedings of SPIE - The International Society for Optical Engineering, Anonymous San Diego, CA, United States, **4695,** pp. 220-227.

[69] Jung, K., Nam, J., and Choi, H., 2003, "Investigations on Actuation Characteristics of IPMC Artificial Muscle Actuator," Sensors and Actuators, A: Physical, **107**(2) pp. 183-192.

[70] Punning, A., Johanson, U., Anton, M., 2008, "A distributed model of IPMC," Proceedings of SPIE, Anonymous San Diego, CA, United States, **6927,** pp. 69270G.

[71] Punning, A., Johanson, U., Anton, M., 2008, "A distributed model of IPMC," Anonymous SPIE, **6927,** pp. The International Society for Optical Engineering (SPIE); American Society of Mechanical Engineers.

[72] Bonomo, C., Fortuna, L., Giannone, P., 2006, "A Circuit to Model the Electrical Behavior of an Ionic Polymer-Metal Composite," IEEE Transactions on Circuits and Systems I: Regular Papers, **53**(2) pp. 338-350.

[73] Nernat-Nasser, S., and Li, J. Y., 2000, "Electromechanical Response of Ionic Polymer-Metal Composites," Journal of Applied Physics, **87**(7) pp. 3321-3331.

[74] Tadokoro, S., Yamagami, S., Takamori, T., 2000, "Modeling of Nafion-Pt composite actuators (ICPF) by ionic motion," Proceedings of SPIE, Anonymous **3987,** pp. 92.

[75] De Groot, S.R., 1966, "Thermodynamics of irreversible processes," North-Holland, Amsterdam, pp. 242.

[76] Nernat-Nasser, S., and Li, J. Y., 2000, "Electromechanical Response of Ionic Polymer-Metal Composites," Proceedings of the SPIE - the International Society for Optical Engineering, **87**(7) pp. 3321.

[77] Nemat-Nasser, S., 2002, "Micromechanics of Actuation of Ionic Polymer-Metal Composites," **92**(5) .

[78] Farinholt, K., and Leo, D. J., 2004, "Modeling of Electromechanical Charge Sensing in Ionic Polymer Transducers," Mechanics of Materials, **36**(5) pp. 421.

[79] Punning, A., Kruusmaa, M., and Aabloo, A., 2007, "Surface Resistance Experiments with IPMC Sensors and Actuators," Sensors and Actuators, A: Physical, **133**(1) pp. 200.

[80] Konyo, M., Konishi, Y., Tadokoro, S., 2004, "Development of Velocity Sensor using Ionic Polymer-Metal Composites," Proceedings of SPIE, **5385**pp. 307.

[81] Bonomo, C., Fortuna, L., Giannone, P., 2005, "A Method to Characterize the Deformation of an IPMC Sensing Membrane," Sensors and Actuators A: Physical, **123-124**pp. 146–154.

[82] Chen, Z., Tan, X., Will, A., 2007, "A Dynamic Model for Ionic Polymer-Metal Composite Sensors," Smart Materials and Structures, **16**(4) pp. 1477.

[83] Newbury, K. M., and Leo, D. J., 2002, "Electromechanical Modeling and Characterization of Ionic Polymer Benders," Journal of Intelligent Material Systems and Structures, **13**(1) pp. 51-60.

[84] Punning, A., and Jalviste, E., 2009, "Analytical Solution for Voltage-Step Response of Lossy Distributed RC Lines," IEEE Transactions on Microwave Theory and Techniques, **57**(2) pp. 449-57.

[85] Lindahl, O. A., Omata, S., and Angquist, K. A., 1998, "Tactile Sensor for Detection of Physical Properties of Human Skin in Vivo," Journal of Medical Engineering \& Technology, **22**(4) pp. 147-153.

[86] Dargahi, J., Parameswaran, M., and Payandeh, S., 2000, "Micromachined Piezoelectric Tactile Sensor for an Endoscopic Grasper - Theory, Fabrication and Experiments," Journal of Microelectromechanical Systems, **9**(3) pp. 329-335.

[87] Dargahi, J., 2002, "An Endoscopic and Robotic Tooth-Like Compliance and Roughness Tactile Sensor," Journal of Mechanical Design, Transactions of the ASME, **124**(3) pp. 576-582.

[88] Shikida, M., Shimizu, T., Sato, K., 2003, "Active Tactile Sensor for Detecting Contact Force and Hardness of an Object," Sensors and Actuators, A: Physical, **103**(1) pp. 213-218.

[89] Hemsel, T., Stroop, R., Oliva Uribe, D., 2007, "Resonant Vibrating Sensors for Tactile Tissue Differentiation," Journal of Sound and Vibration, **308**(3) pp. 441-446.

[90] Park, I., Jung, K., Kim, D., 2008, "Physical Principles of Ionic Polymer-Metal Composites as Electroactive Actuators and Sensors," MRS Bulletin, **33**(3) pp. 190-195.

[91] Johanson, U., Maeorg, U., Sammelselg, V., 2008, "Electrode Reactions in Cu-Pt Coated Ionic Polymer Actuators," Sensors and Actuators, B: Chemical, **131**(1) pp. 340-346.

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