Integrated IPMC sensor-actuator devices for walking robots

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Abstract

Ionic Polymer Metal Composites (IPMC) are dual purpose flexible materials capable of converting electrical energy to mechanical force for actuation, or converting mechanical movement to electrical signals for sensing force and/or displacement. The paper presents a methodology to design integrated IPMC sensor-actuator devices (iSADs) to realise force/displacement feedback for IPMC actuators. Two IPMC strips are used, one to provide the actuation and the second for the sensing. In this way multiple IMPC strip devices can be designed for sophisticated iSAD elements that could have potential use in various CLAWAR robot applications. One such application to construct walking robots based on iSAD components is discussed.

Keywords: Ionic polymers, IPMC devices, iSAD, sensors, actuators, integrated sensor-actuator, beam theory, walking robots.

1 Introduction

Electroactive polymeric materials (EAP) are a class of material that have been the subject of intensive research since 1992. Ionic polymer-metal composites (IPMC) are a class of EAPs that can be used as either a sensor or an actuator in small robot/mechatronic applications. IPMCs consist of an ion exchange membrane (e.g. Nafion®) which have a metal layer deposited on their two sides that act as electrical contacts. Their low density, low voltage requirements, mechanical flexibility and ease of processing offer several advantages over traditional electroactive materials [1]. These advantages of IPMCs have led to consideration of such materials in various applications [2]-[5]. As an actuator, they exhibit a bending motion in their transversal direction when a voltage is applied across the metal coatings. As a sensor, a charge is generated when the IPMC is deflected providing an electrical signal depending on the deflection. The forces produced by IPMC actuators are extremely small (around 1-5mN) and hence their use is limited to micro-applications.

The dimensions of the IPMCs influence the performance of the sensor or actuator. For example, maximum actuator tip deflection is achieved when the IPMC is long, whilst maximum force is achieved when a short IPMC strip is used. The range of usable validated working dimensions of current IPMC strips is 10-60mm (length), and 3-6mm (width) and they are available in only a few thicknesses. For example, DuPont supply IPMCs in the following thicknesses: Nafion 112 (50μm), Nafion 1035 (89μm), Nafion 105 (127μm), Nafion 115 (140μm), Nafion 117 (178μm), Nafion 350 (254μm) and Nafion 417 (432μm). If other thicknesses are needed it is necessary to produce them by purchasing Nafion resin.

A further factor to consider are the hydration levels of the IPMCs. IPMC actuators work best when wet, whilst sensors operate better when dry. Hence for operation in air, the actuator needs to be coated appropriately to prevent dehydration or else they have a very limited working life (of approximately 1-3 minutes) due to drying out and require hydration for further operation.

Presently IPMC actuators are mainly used in an open loop fashion with no feedback to regulate the deflection achieved. To overcome this, it has been proposed to integrate a second element onto an IPMC actuation strip to act as a sensor for the actuator strip. In this way an IPMC integrated sensor-actuator device (iSAD) can be realised. As the actuation forces are small, the deflection of the actuator in these cases will be affected not only by its own characteristics but also by those of the integrated IPMC sensor and the integration/attachment mechanism. A design methodology for integrating sensor-actuator devices has been produced to realise the required closed-loop actuator specifications and initial results have been presented in [6]. This paper extends these results and presents a potential application for using the iSAD devices in realising micro-walking robots.

An EC funded research project "Ionic polymer-metal composite as sensor and actuator: Application in motion control" (ISAMCO, EC contract FP6-505275-1, see www.mediainnovation.it/progetti/isamco/) aims to fabricate IPMC devices for sensing and actuation applications. To achieve this, dedicated Matlab software has been developed to assist in the design of individual IPMC actuator and IPMC sensor devices. This design software has been used in conjunction with beam theory [7] to realise a design methodology for producing iSAD components. The overall approach is as follows:

1. Design required IPMC actuator via ISAMCO software.
2. Design required IPMC sensor via ISAMCO software.
3. Determine portion of actuator's performance that is needed to deflect the sensor via beam theory.
4. If performance degradation is too severe and not acceptable, repeat steps 1-3 until satisfied.

Taking a simplistic view, it seems obvious that when an sensor strip needs to be added to an IPMC actuator, the sizing of the actuator should just be increased to accommodate the parasitic force required to deflect the sensor strip. However this may not be easily possible due to the small output forces that can be generated by IMPCs and so it is important to consider the design of iSADs in the integrated manner as described above to determine a suitable algorithm.

The final algorithm developed can be used to size the sensor-actuator pair in a sensible manner and to reduce the interaction effects between the actuator and sensor to an acceptable level. Beam theory has been used in the design procedure in a straightforward manner because each IMPC strip can be viewed as a simple beam vibrating as a cantilever. The Euler-Bernoulli (E-B) equation for the deflection of such a beam can be used to determine the force required for an IPMC strip of length l to cause a specific deflection (although this can be used to calculate the deflection at any point along the beam, we assume this is measured at the end point for convenience). It is sensible that in determining good design rules the actuator IMPC has to be sized to provide sufficient force for "real actuation" and not simply to deflect the sensor IPMCs. Hence a sufficient safety margin must be introduced to size the actuator and sensor elements in a holistic iSAD design approach.

From an engineering perspective we can assume that the sensor IPMC should not "consume" more than 10% of the actuator's force during normal operation while providing a reasonable output signal.

2 Design of iSAD devices

In this section we summarise the methodology for analysing and modelling of the integrated sensor-actuator devices. In order to do this we first consider the IPMC actuator model. This can be viewed as a simple single input – single output system as shown in Figure 1. The input is the applied voltage $v(t)$ and the output can be either the force generated $g(t)$ or the deflection of the IPMC strip $d(t)$ (in some cases both force and deflection may be necessary but for convenience we assume only one output is needed here.

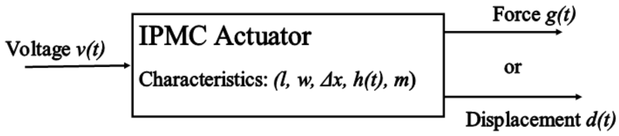

Figure 1: Block diagram of an IPMC actuator

The work carried out in the EC ISAMCO project [8] has shown that the model for the IMPC actuator is given by $d_a(t) = g_1(w,l,h(t),m,\Delta x,v(t))$ where $g_1(\cdot)$ is a function of the variables inside the brackets. These variables depend on the characteristics of the IPMC strip used to make the actuator, namely, w is the width, l is the length, h is the hydration level, m is the type of material used and Δx is the thickness of the strip. Also the "a" subscript represents the fact that the IPMC is being used as an actuator. A similar equation holds for the force generated by the actuator, namely $f(t) = g_2(w,l,h(t),m,\Delta x,v(t))$. The IPMC modelling details are presented in [10] where it can be seen that a high order non-linear time varying model is needed to adequately represent the behaviour. For convenience this model can be simplified to $d_a(t) = K_1(t)v(t)$ and even to $d_a(t) = K_a v(t)$ if the time varying aspects of the IPMC strip are ignored. In this way a simple constant of proportionality can be used to determine the output deflection of the IPMC actuator for a particular situation.

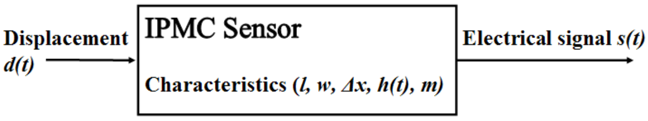

Figure 2: Block diagram of an IPMC sensor

The IMPC sensor model has also been modelled within the ISAMCO project [8] and an appropriate block diagram is shown in Figure 2. In a similar way as above, the single input – single output model to determine the electrical signal obtained from the IPMC sensor is given by the $s(t) = g_3(w,l,h(t),m,\Delta x,d_s(t))$, where $s(t)$ represents the output signal and "s" subscript represents the fact that the IPMC is being used as a sensor. This model can be simplified to $s(t) = K_2(t)d_s(t)$ and $s(t) = K_s d_s(t)$ when the time varying aspects are ignored. In this way a simple constant of proportionality can be used to determine the output signal from the IPMC sensor as it is actively deflected.

In order to determine a design methodology for integrated sensor-actuator devices, the two single input – single output models presented above need to be combined so that we have a two input – two output model. It is straightforward to see that the model for this situation is as shown in Figure 3 which gives the multivariable model for the integrated sensor-actuator IPMC device as

$$\begin{bmatrix} d_a(t) \\ s_s(t) \end{bmatrix} = \begin{bmatrix} K_a & C_{as} \\ C_{sa} & K_s \end{bmatrix} \begin{bmatrix} v_a(t) \\ d_s(t) \end{bmatrix}.$$

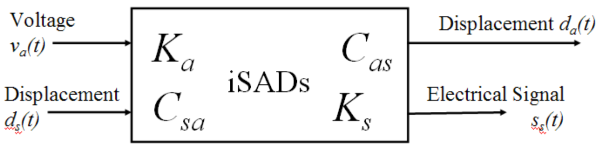

Figure 3: Block diagram of an IPMC iSAD device

It is clear that when the cross coupling terms C_{as} and C_{sa} are non-zero, they will effect the performance of the integrated sensor-actuator device and so it is not possible to design iSADs to the required specification by designing the sensor and actuation elements separately.

As the sensor and actuator are physically connected together to their tips and have equal lengths, the two end point deflections are identical, that is, $d_s(t) = d_a(t)$. Hence we have $\begin{bmatrix} d_s(t) \\ s_s(t) \end{bmatrix} = \begin{bmatrix} K_a & C_{as} \\ C_{sa} & K_s \end{bmatrix} \begin{bmatrix} v_a(t) \\ d_s(t) \end{bmatrix}$ and the equation for d_s gives the following:

$$\begin{aligned} d_s(t) &= K_a v_a(t) + C_{as} d_s(t) \\ &= \frac{K_a v_a(t)}{1 - C_{as}} = d_a(t) \end{aligned}$$

Therefore it can be seen that the actuator deflection changes from $d_a(t) = K_a v_a(t)$ when only an IPMC actuator is designed to $d_s(t) = d_a(t) = \frac{K_a v_a(t)}{1 - C_{as}}$ when an iSAD is built. It is clear that we need C_{as} to be as small as possible so that the actuator deflection is affected as little as possible due to the addition of the sensor IPMC.

It is also plausible to assume that $C_{sa} = 0$ because the electrical signal generated will be due entirely to the deflection of the overall sensor-actuator strip and the sensor IPMC will be insulated from the applied voltage. Hence the model for designing integrated IPMC sensor-actuator devices when the two strips have equal length and identical end points is given by $\begin{bmatrix} d_s(t) \\ s_s(t) \end{bmatrix} = \begin{bmatrix} K_a & C_{as} \\ 0 & K_s \end{bmatrix} \begin{bmatrix} v_a(t) \\ d_s(t) \end{bmatrix}$ with C_{as} designed to be "as small as possible" so that the effect of the sensing IPMC is small on the iSAD element.

2.1 Beam theory for IPMCs

The design aspects can be investigated by assuming that the motions of IPMC strips can be approximated by flat beams to which standard beam theory [7] can be applied. It is well known that the Euler-Bernoulli equation gives the deflection of a flat beam of length l as $d = \frac{Fl^3}{3EI}$, where F is the force, E is Young's modulus, and the moment of inertia, $I = \frac{w(\Delta x)^3}{12}$.

Rearranging this we get $F = \frac{Ew(\Delta x)^3}{4l^3} d$ where Δx is the thickness and w is the width of the beam.

It is straightforward to see that the force needed to deflect the sensing IPMC by some specified amount can be reduced if the width and thickness of the strip is reduced and/or its length increased. Another approach that can be adopted is to oversize the actuator as stated above so that it can perform as required with the extra load due to the integration of the IPMC sensor. However, this option may not be available.

The strip dimensions effect the bending force in the following way:

- beam width – linear variation
- beam thickness – cube law variation
- beam length – inverse cube law variation

From a design point of view, varying the beam thickness and length will have a more pronounced effect on the bending force and, hence, these should be used in the first approach when designing iSADs.

Varying strip length is easy because IPMCs are available in small sheets and the required strip sizes can be simply cut out. Varying strip thickness is not so straightforward and hence IPMC strips of various thicknesses are required so that thick ones can be used for actuators and thinner ones for sensors. At present only a limited range of thicknesses is available as stated above and hence the design of iSADs needs to focus on increasing strip length and reducing strip width to reduce the force to required levels.

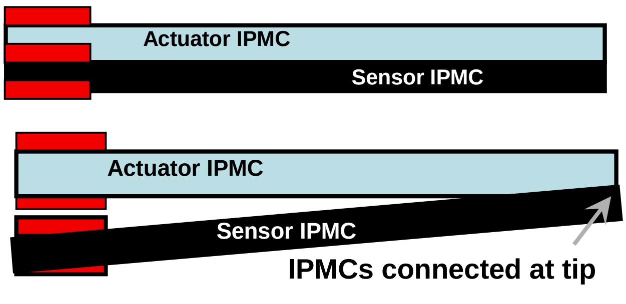

Figure 4: Configurations of Case 1 iSAD devices

Varying the IPMC strip dimensions in this way leads to several configurations of iSAD devices e.g. those with equal length and width strips but different thicknesses; equal length and thickness strips but different widths, etc. We will consider two cases here.

2.2 Case 1: Equal l, Δx, diff w IPMCs

A few configurations for this set up are shown in Figure 4 where the lengths and thickness of the actuator and sensor IPMCs strips are the same but the widths are different (not shown). From above the force is given by $F = \frac{Ew(\Delta x)^3}{4l^3}d$. As l and Δx are fixed (equal to the dimensions of the IPMC actuator) the only parameter varied in this case in designing the IPMC sensor is reducing its width to reduce the force. As stated above this has a linear effect only which may be insufficient to give the required design flexibility. From a generic viewpoint, increasing the length has a greater effect (cubic order) than reducing the width in reducing the force needed to move the sensor IPMC. This leads to the Case 2 type iSADs.

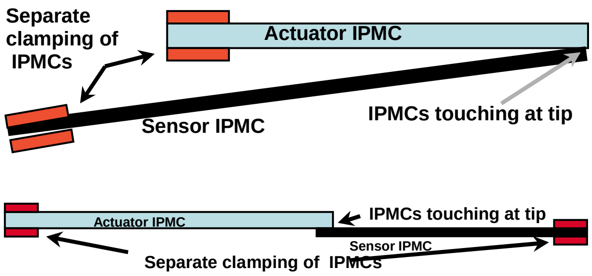

Figure 5: Configurations of Case 2 iSAD devices

2.3 Case 2: Equal Δx, w, diff l IPMCs

The discussion above for Case 1 iSADS has indicated that changing IPMC length has a more significant effect in varying the bending force (inverse cubic order); hence increasing strip length will reduce the force by a third order. However the configurations of iSADs with different lengths of actuator and sensor require specific design to suit the application so that the two IPMCs can move as required. Figure 5 shows two configurations. Separate clamping for the sensor and actuator elements is needed but this leads to a more profound capability of reducing the bending force needed by the sensing IPMC.

3 Experimental validation

3.1 Test rigs

The design procedure is experimentally validated by building and testing individual IPMC sensor and actuator strips as well as integrated sensor-actuator devices (iSADs). A number of test rigs have been developed for this purposes and they are briefly presented here.

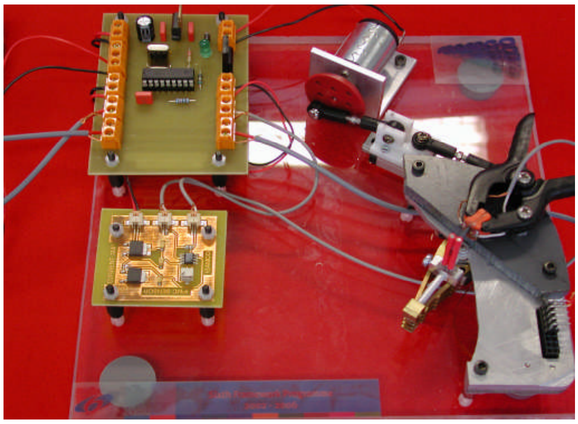

Figure 6: IPMC sensor test rig

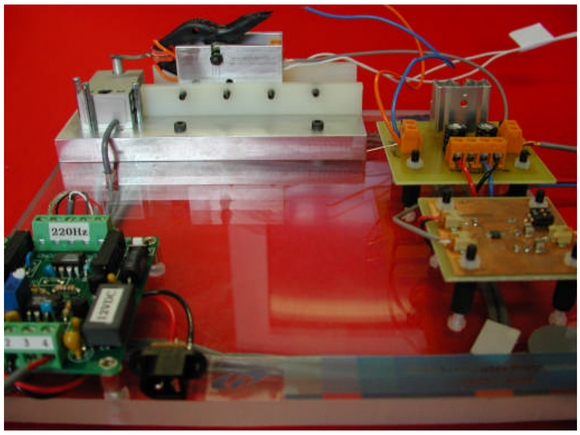

Figure 7: IPMC actuator test rig

Figure 6 shows the sensor test rig which allows an IPMC to be clamped at one end to provide electrical contacts, whilst the other end is attached to an oscillating arm. The oscillating arm is shown in the lower right corner of the photograph. The arm is attached to a slider-crank mechanism whose speed is controlled using the electronics in the top left of the photo. The signal conditioning circuitry of the sensor is shown in the lower left of the photo. The actuator test rig is shown in Figure 7. The IPMC can be seen in the top left of the photo. One end is clamped into the clamp to provide electrical contacts, whilst the free end is positioned on a force sensor. The IPMC is powered using the electronics on the right hand side of the figure. Applying a voltage to the IPMC causes it to bend pushing down on the force sensor. The conditioning circuit for the force sensor is shown in the lower left of the photo.

These test rigs were used to monitor and verify the effect of integrating an IPMC sensor strip onto an actuator in a quantifiable way, based on the design approach and examples that have been presented in the previous sections. It is conceivable that different methods of attaching the sensor strip will need to be investigated to minimise the impact of integration.

3.2 Validation of results

The theoretical results produced by the iSADs design approach have been validated by building and testing actual IPMC strips. An example of an iSAD device design and experimental validation procedure is given here.

3.2.1 Individual IPMC actuator design

1. IPMC actuator force required = 3mN (say)
2. ISAMCO software gives the result that a Nafion 115 Li IPMC of length=15mm, width=5.2mm is required to form the actuator. The software predicts a deflection of 2mm and an actuation force of 3mN.

3.2.2 Individual IPMC sensor design

1. Use sensor deflection of 2mm and that a sensor output of 0.5µA (say) is required.
2. ISAMCO software gives the result that a Nafion 117 Na IPMC of length=15mm, width=3.2mm is required.

3.2.3 Assessment of designed iSADs

1. Beam theory gives the force needed to deflect the IPMC sensor designed by 2mm as 0.9mN.
2. This parasitic force is 30% of the actuator's force which is felt to be excessive (if we assume that 10% is what we are aiming for) and hence the design needs to be improved. For this we can go back to redesign both the actuator and the sensor but for convenience, here we focus on redesigning only the sensor so that it needs a lower bending force.
3. We repeat the IPMC sensor design by assuming a deflection of 2mm and that it outputs a lower signal of 0.2µA (say). In this case, the ISAMCO software gives the result that a Nafion 117 Na IPMC of length=15mm, width=1.2mm is required.
4. Beam theory in this case gives the force needed to deflect the improved IPMC sensor designed by 2mm as 0.34mN.
5. This sensor bending force for this second sensor is 11.3% which is felt to be low enough for the 3mN actuator and so the design has been completed.

The following iSAD has therefore been designed to give an actuation force of 3mN and a defection of 2mm:

- Actuator: Nafion 115 Li IPMC of length=15mm, width=5.2mm
- Sensor: Nafion 117 Na IPMC of length=15mm, width=1.2mm

The above data is used to cut and shape the two IPMCs for experimental validation of the iSAD designed. The experimental results use the rigs that have been developed for the IPMC research. These latest results are presented in the next section.

3.3 Experimental validation

The full experimental validation of the design methodology is current under progress but the following initial results have been achieved:

- Actuator tests: Two IPMC actuators have been produced. A force of 3.4mN has been measured in both actuators and the following deflections have been measured
  - Actuator 1: 2-7.5mm
  - Actuator 2: 1-5mm
- Sensor tests: Three sensors have been produced. For a deflection of 2mm these were found to produce an output signal of 1µA, 0.75µA and 0.5µA.

The results are in broad agreement with what is predicted by the theoretical models. This gives us confidence to continue the research. However it is clear that there is a wide variation in the experimental results obtained; this is not a surprise as the methods of manufacturing IPMC strips are rather crude and prone to considerable human error. The IPMC elements are extremely small, delicate and "fiddly" to handle and the measurements have to be carried out manually. This introduces considerable errors in the quality of the strips produced. Hence the work needs to be repeated several times to reduce these human errors of measuring, cutting and handling the small IPMC strips in a reliable and repeatable manner. It is clear that specialised tools may also be needed .

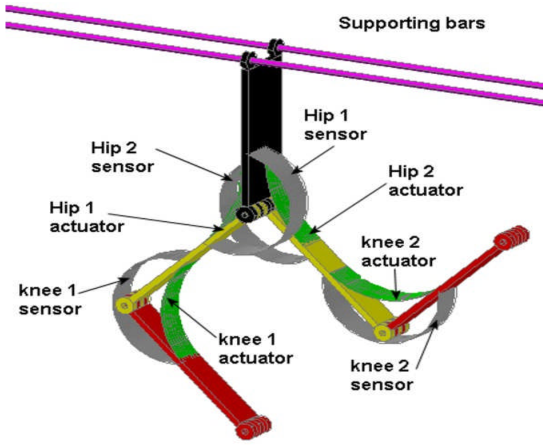

Figure 8: Concept drawing of IPMC walking robot

4 Walking robot application

In this section we present the use of iSAD elements in realising miniaturised walking robots. Work is currently underway for this and only the initial results are included here. The iSAD elements are to be used as active elements in realising a walking system and precise motion control of the strips is needed in order that the system is able to move itself in a walking manner. Precise trajectory following in this way allows us to perform different walking gaits. A concept diagram for the walking system is shown in

Figure 8 which has been designed to allow the IPMC actuator to move the walking system.

4.1 Modelling and control of iSADs

In order to control the behaviour of systems comprising iSAD devices it is necessary to model IPMC actuators and sensors. A step response of the IPMC actuators used in our research is shown in Figure 9; the response exhibits an interesting behaviour in that the IPMC strip deflects quite rapidly initially in direct response to the step input but is then see to slowly relaxes to its original state even though the step input signal is still present. In other words the IPMC strip is unable to maintain its DC position. This behaviour indicates that such IPMC cannot be used for maintaining a stationary position but actuation for a walking system could be possible if the dynamics of the walking is kept within the "fast dynamics" of the IPMC.

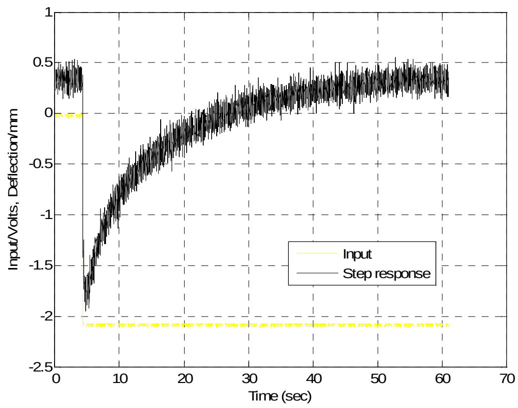

Figure 9: Step response of IPMC actuator

Pseudo random binary signal excitation experiments are currently being carried out on IPMC actuators and sensor strips to enable good dynamic models of iSAD devices to be obtained. These models are then expected to be used for motion control of the walking links used in the robot depicted in Figure 8.

5 Conclusions

The paper has presented a design methodology to produce IPMC integrated sensor-actuator devices so that feedback of the position of the IPMC actuator can be provided. The ISAMCO models and design software is used to develop a methodology to allow integrated sensor-actuator devices to be produced to the desired specifications. The theoretical results are being validated experimentally by using them to build and test the iSAD units. This work is continuing to design and validate the results on a miniaturised walking robot. The results obtained to date indicate that various configurations of iSAD devices can be designed. For good designs, it is necessary that sensor IPMC strips are longer and thinner than the actuator IPMC strips so that parasitic forces are reduced as much as possible.

6 Acknowledgements

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7 References

[1] H. Tamagawa, K. Yagasaki and F. Nogata, Mechanical characteristics of ionic polymer-metal composite in the process of self-bending, Journal of Applied Physics, Volume 92, Number 12, pp 7614-7618, 15th December 2002.

[2] Shahinpoor and K.J. Kim, Novel ionic polymer-metal composites equipped with physically loaded particulate electrodes as biomimetic sensors, actuators and artificial muscles, Sensors and actuators, A 96(1), p125 – 132, 2002.

[3] Z. Chen, M.S., Xiaobo Tan, Quasi-static positioning of ionic polymers-metal composite (IPMC) actuators, in IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Monterey, CA, 2005.

[4] M. Shahinpoor, K.J. Kim, Ionic polymer–metal composites: IV, Industrial and medical applications, Smart materials and structures, Vol 14, p197–214, 2005.

[5] M. Shahinpoor, K.J. Kim, Ionic polymer–metal composites: III. Modelling and simulation as biomimetic sensors, actuators, transducers, and artificial muscles. Smart materials and structures, Vol 13, p1362–1388, 2004.

[6] G.S. Virk, D.R. Harvey, I. Chochlidakis and S. Dogramadzi, Design of integrated sensor-actuator ionic polymer-metal devices, Proceedings of the 9th International Conference on Climbing and walking robots (CLAWAR'06), Brussels, Belgium, 12-14 Sept 2006.

[7] S.S. Rao, Mechanical Vibrations, 4th edition, Chapter 8, pages 525-550, ISBN 0130489875, Upper Saddle River, N.J.; London: Prentice Hall, 2004.

[8] Arena P., Bonomo C., Fortuna L., Giannone P., Graziani S., Strazzeri S., ISAMCO Deliverable 3.2: The electromechanical properties of IPMC materials, EC Contract # NMP2-CT-2003-505275, Dipartimento di Ingegneria Elettrica, Elettronica e dei Sistemi, University of Catania, Catania, Italy, 2005.