

DEFORMABLE MEMBRANES ACTUATED BY HIGH MECHANICAL POWER DENSITY COMPOSITE ELECTROACTIVE POLYMERS USING TAILORED ELECTRIC FIELD

Final Report

PF-459

PI: Kaushik Bhattacharya, California Institute of Technology
JPL Lead Investigator, Yoseph Bar-Cohen, NDE and Advanced Actuators (82-105)

A. OBJECTIVES

The objective of the project was to develop a versatile electroactuator based on a specific class of EAP, conductive polymer, that is capable of developing high forces and displacements in both bending and linear contraction/expansion movements. A collaboration between Mechanical Engineering and Electrochemistry was proposed to gain a better understanding of the parameters that control the electroactivation, forces and displacements. The goal was to develop theoretical models that describe the behavior of these materials, to use these models to motivate the designs of polymer-electrode configuration, and fabricate and evaluate representative designs.

B. PROGRESS AND RESULTS

A detailed three-dimensional model that includes electrochemistry, electrostatics and finite deformation was developed. This is the first model that considers the various nonlinear coupling between all these different phenomena. A numerical method to solve these equations has been developed and the implementation of this has been partially carried out.

The model, however, is too detailed and too complicated to be effectively used for design. Therefore, it was specialized to configurations that were experimentally feasible and models for the effective behavior of such configurations were derived. These effective or reduced order models were used to evaluate various polymer-electrode configurations. The actuation of conductive polymers is inherently in bending mode; potential designs to convert it to linear mode by the use of multiple actuators was a topic of particular attention. This led to an understanding of the various trade-offs between mechanical stiffness, electrostatic driving forces and multi-layer couplings in determining actuator performance.

Based on the theoretical considerations various configurations were chosen for experimental evaluation. The first step of this work was to set up the necessary experimental system including the acquisition of the power supply, electrochemical cell, force measurement transducer, signal modulator, ccd camera and computer for data acquisition. [PPy || (SPE) || PPy] trilayers were fabricated and then combined in various configurations.

Construction of [PPy || (SPE) || PPy] trilayers. Polypyrrole films were electrogenerated from 0.2M pyrrole and 0.1M LiClO₄ organic solutions (acetonitrile with a 2% water content). Three AISI 304 stainless steel plates, having a surface area of 3.50 cm², were used as electrodes, one of them as the working electrode and the other two as counter electrodes. The electrogeneration was performed under an inert atmosphere of argon. Potential square waves were applied between -0.300 V (2 s) and 0.850 V (8 s) to control the morphology of the film and its adherence to the metal. A saturated calomel electrode (SCE) was used as reference electrode.

Polymer electrolytes were prepared adding LiClO_4 to a tetrahydrofuran (THF) solution containing 2.5 % (w/w) of [P (ECH-co-EO)]. An elastomeric solid with high ionic conductivity is obtained after evaporation of the solvent (casting). Higher ionic conductivity was attained when the salt concentration, defined as $\eta = [\text{O}]/[\text{Li}^+]$, was fixed at $\eta = 6$.

[PPy || (SPE) || PPy] trilayer was prepared by dripping the electrolyte solution on two polypyrrole films (mass = 3 mg, thickness = 6 μm) grown on two different stainless steel electrodes, followed by evaporation of the solvent under atmospheric pressure at room temperature. Two [steel || PPy || ([P (ECH-co-EO)] / LiClO_4)] systems were obtained. The evaporation of the THF give increasing viscous and adherent films. Once the polyelectrolyte was viscous and adherent enough, the two electrodes covered by the polyelectrolyte film (thickness = 3 μm) were put in contact and a [steel || PPy || ([P (ECH-co-EO)] / LiClO_4) || PPy || steel] system was performed. After 30 minutes the polyelectrolyte is dry and the triple layer [PPy || ([P (ECH-co-EO)] / LiClO_4) || PPy] was then peeled off the stainless steel plates.

The two films of polypyrrole were held at the top with a metallic clamp to allow independent electrical contact to the PPy films. One polypyrrole film was connected as working electrode and the other as counter electrode short-circuited with the reference electrode.

Combination of [PPy || (SPE) || PPy] trilayers in a parallel configuration. This configuration is formed by several [PPy || (SPE) || PPy] trilayers combined in parallel where it is possible to make series or parallel electric connection (Figure 1). The electrical connection could either be in series or in parallel.

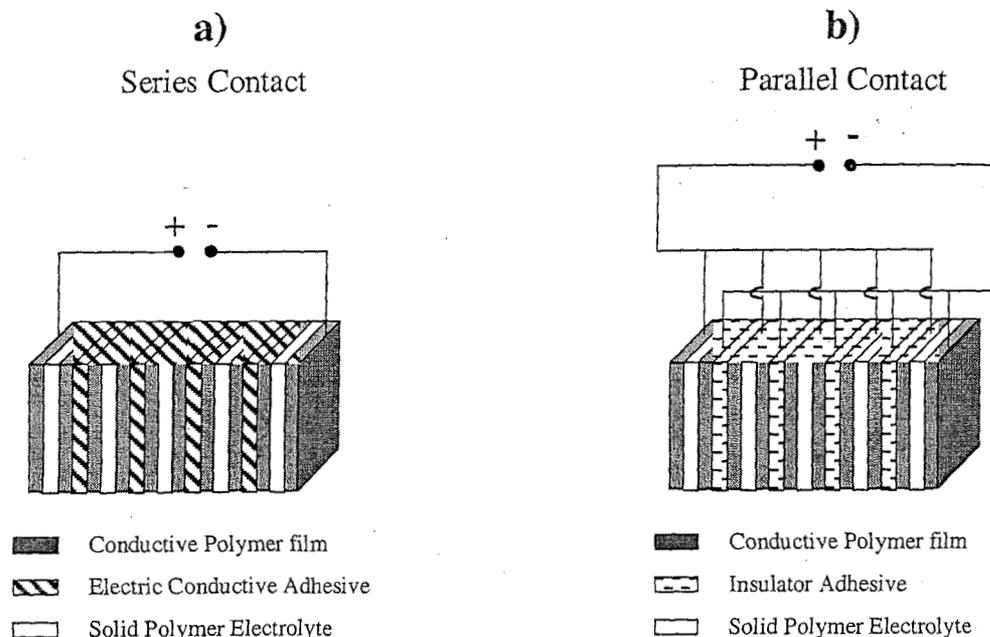


Fig. 1: Parallel configuration of [PPy || SPE || PPy] trilayers connected a): in series; b): in parallel.

Although the goal of this project was to study devices with an increasing number of [PPy || (SPE) || PPy] trilayers, only the movement of a device with two combined trilayers was achieved. We were not able to overcome electrical and structural problems to integrate a higher number of trilayers in the device. The results obtained with the combination of two [PPy || (SPE) || PPy]

trilayers show that this device develops a force double than the force developed by a single trilayer. The parallel connection allowed more uniform movement because it is easier to get the same controlled current flow into all PPy films. Further, the electric energy necessary to move the actuator at a constant angular velocity is higher in the case of the series connection than in the parallel connection as there is a drop of potential along the [PPy || (SPE) || PPy] trilayers with a series electric connection. Therefore, we concluded from this study that a parallel electric connection is more appropriate than the series electric connection to combine an increasing number of [PPy || (SPE) || PPy] trilayers.

Combination of [PPy || (SPE) || PPy]_n multilayer in a series configuration. We also made several attempts to combine trilayers in a series configuration as shown in Figure 2 motivated by theoretical considerations. The theory shows that such configurations should yield linear motion. We have studied different ways to construct this series configuration but it was not possible to get a positive result yet. The experimental procedure has to be optimized in the future to get good adhesion in the interface between [PPy || (SPE) || PPy] trilayers and to avoid the use of wires for the electric connections that limits the movement of the actuator. We think that the utilization of impressed circuitry technology should be a possible solution for the problem of electric contacts.

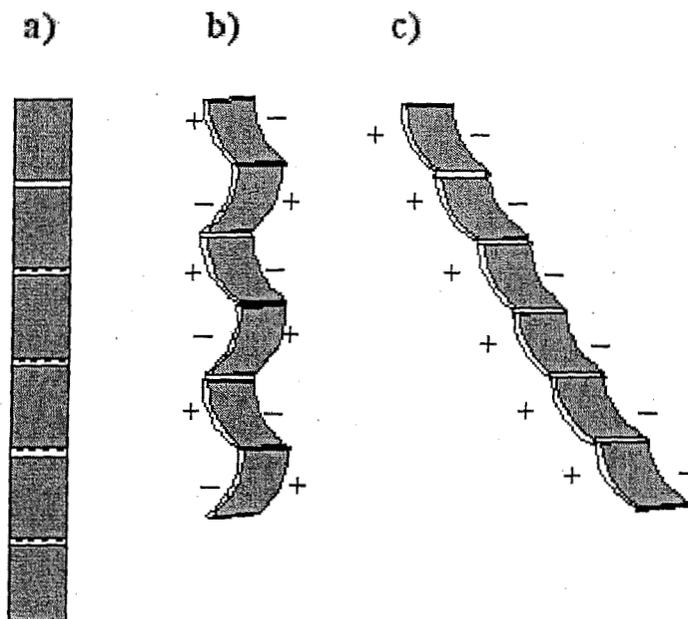


Fig.2: Series configuration of [PPy || SPE || PPy]_n multilayers a): equilibrium position at open circuit; b): linear contraction/expansion movement with an alternated electric polarity; c): bending movement with the same electric polarity.

C. SIGNIFICANCE OF RESULTS

A growing number of NASA programs require mechanical actuators, which can deliver high forces and displacements, with reduced size and mass. Many types of actuator technologies have been studied to develop both micro and macroscopic devices. However, the existing technologies exhibit limitations in one or more performance parameters, such as actuation force and displacement, response speed or electrical potential needed to electroactivate the actuator. The recent introduction of electroactive polymers (EAP) which offer low mass materials that can

induce large strain and forces under electrical activation has led to their consideration as potential actuators. The most attractive feature of EAPs is their ability to emulate biological muscles by the direct conversion of electrical energy to mechanical energy. This similarity gained them the name "Artificial Muscles" with the potential of developing biologically inspired robots, prosthetic devices, sonar projectors and microscopic pumps.

However most EAPs develop small forces and work predominantly in the bending mode. This project clearly demonstrated the feasibility of combining various trilayers in parallel and series manner to increase the force and displacement, and also to convert bending to linear motion. A theoretical model of conductive polymers was developed which guided the experimental efforts.

The project also showed that despite its promise the fabrication of complex configurations remains a significant challenge. This has to be addressed in future work.

D. PERSONNEL

Dr. Virginia Olazábal, post-doctoral fellow in JPL

José-María Sansiñena, post-doctoral fellow in JPL (supported through other sources)

Ms. Yu Xiao, graduate student in Caltech

E. PUBLICATIONS

1. J.M. Sansiñena, V. Olazábal, Y. Bar-Cohen, EAP Fabrication at the JPL's NDEAA Lab, *WorldWide Electroactive Polymers (WW-EAP) Newsletter*, Vol. 2, No. 1, (2000) pp. 10-11.
2. J.M. Sansiñena, V. Olazábal, Conductive polymers in *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*, Y. Bar-Cohen (Ed.), SPIE Press, (2001).
3. Y. Bar-Cohen, V. Olazábal, J.M. Sansiñena, J. Hinkley, Processing and support techniques, in *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*, Y. Bar-Cohen (Ed.), SPIE Press, (2001).
4. K. Bhattacharya, J. Li and Y. Xiao, Electro-mechanical models for optimal design and effective behavior of electro-active polymers, in *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*, Y. Bar-Cohen (Ed.), SPIE Press, (2001).
5. Y. Xiao and K. Bhattacharya, Modeling electromechanical properties of ionic polymers, in *Proceedings of the SPIE symposium on Electroactive polymer, actuators and devices – Smart structures and materials*, Y. Bar-Cohen (Ed.), SPIE Press (2001), pp. 292-300.
6. Y. Bar-Cohen, V. Olazábal, J.M. Sansiñena, Electroactive Polymer Actuator with Selectable Deformation (EAPAS), *NASA Tech Brief Journal*, (NPO-21174), Vol. 26, No. 7 (2002), pp. 1-8.
7. S. Sherrit, V. Olazábal, J.M. Sansiñena, X. Bao, Z. Chen, Y. Bar-Cohen, The Use of Piezoelectric Resonators for the Characterization of Mechanical Properties of Polymers, in *Proceedings of the SPIE's 9th Annual International Symposium on Smart Structures and Materials*, Eds: Yoseph Bar-Cohen, SPIE Press, vol. 4695, (2002), pp. 262-276.
8. Y. Xiao and K. Bhattacharya, A electro-chemico-mechanical model of electroactive polymers, in preparation (2002).

DEFORMABLE MEMBRANES ACTUATED BY HIGH MECHANICAL POWER DENSITY COMPOSITE ELECTROACTIVE POLYMERS USING TAILORED ELECTRIC FIELD

Final Report

PF-459

PI: Kaushik Bhattacharya, California Institute of Technology
JPL Lead Investigator, Yoseph Bar-Cohen, NDE and Advanced Actuators (82-105)

A. OBJECTIVES

The objective of the project was to develop a versatile electroactuator based on a specific class of EAP, conductive polymer, that is capable of developing high forces and displacements in both bending and linear contraction/expansion movements. A collaboration between Mechanical Engineering and Electrochemistry was proposed to gain a better understanding of the parameters that control the electroactivation, forces and displacements. The goal was to develop theoretical models that describe the behavior of these materials, to use these models to motivate the designs of polymer-electrode configuration, and fabricate and evaluate representative designs.

B. PROGRESS AND RESULTS

A detailed three-dimensional model that includes electrochemistry, electrostatics and finite deformation was developed. This is the first model that considers the various nonlinear coupling between all these different phenomena. A numerical method to solve these equations has been developed and the implementation of this has been partially carried out.

The model, however, is too detailed and too complicated to be effectively used for design. Therefore, it was specialized to configurations that were experimentally feasible and models for the effective behavior of such configurations were derived. These effective or reduced order models were used to evaluate various polymer-electrode configurations. The actuation of conductive polymers is inherently in bending mode; potential designs to convert it to linear mode by the use of multiple actuators was a topic of particular attention. This led to an understanding of the various trade-offs between mechanical stiffness, electrostatic driving forces and multi-layer couplings in determining actuator performance.

Based on the theoretical considerations various configurations were chosen for experimental evaluation. The first step of this work was to set up the necessary experimental system including the acquisition of the power supply, electrochemical cell, force measurement transducer, signal modulator, ccd camera and computer for data acquisition. [PPy || (SPE) || PPy] trilayers were fabricated and then combined in various configurations.

Construction of [PPy || (SPE) || PPy] trilayers. Polypyrrole films were electrogenerated from 0.2M pyrrole and 0.1M LiClO₄ organic solutions (acetonitrile with a 2% water content). Three AISI 304 stainless steel plates, having a surface area of 3.50 cm², were used as electrodes, one of them as the working electrode and the other two as counter electrodes. The electrogeneration was performed under an inert atmosphere of argon. Potential square waves were applied between -0.300 V (2 s) and 0.850 V (8 s) to control the morphology of the film and its adherence to the metal. A saturated calomel electrode (SCE) was used as reference electrode.

Polymer electrolytes were prepared adding LiClO_4 to a tetrahydrofuran (THF) solution containing 2.5 % (w/w) of [P (ECH-co-EO)]. An elastomeric solid with high ionic conductivity is obtained after evaporation of the solvent (casting). Higher ionic conductivity was attained when the salt concentration, defined as $\eta = [\text{O}]/[\text{Li}^+]$, was fixed at $\eta = 6$.

[PPy || (SPE) || PPy] trilayer was prepared by dripping the electrolyte solution on two polypyrrole films (mass = 3 mg, thickness = 6 μm) grown on two different stainless steel electrodes, followed by evaporation of the solvent under atmospheric pressure at room temperature. Two [steel || PPy || ([P (ECH-co-EO)] / LiClO_4)] systems were obtained. The evaporation of the THF give increasing viscous and adherent films. Once the polyelectrolyte was viscous and adherent enough, the two electrodes covered by the polyelectrolyte film (thickness = 3 μm) were put in contact and a [steel || PPy || ([P (ECH-co-EO)] / LiClO_4) || PPy || steel] system was performed. After 30 minutes the polyelectrolyte is dry and the triple layer [PPy || ([P (ECH-co-EO)] / LiClO_4) || PPy] was then peeled off the stainless steel plates.

The two films of polypyrrole were held at the top with a metallic clamp to allow independent electrical contact to the PPy films. One polypyrrole film was connected as working electrode and the other as counter electrode short-circuited with the reference electrode.

Combination of [PPy || (SPE) || PPy] trilayers in a parallel configuration. This configuration is formed by several [PPy || (SPE) || PPy] trilayers combined in parallel where it is possible to make series or parallel electric connection (Figure 1). The electrical connection could either be in series or in parallel.

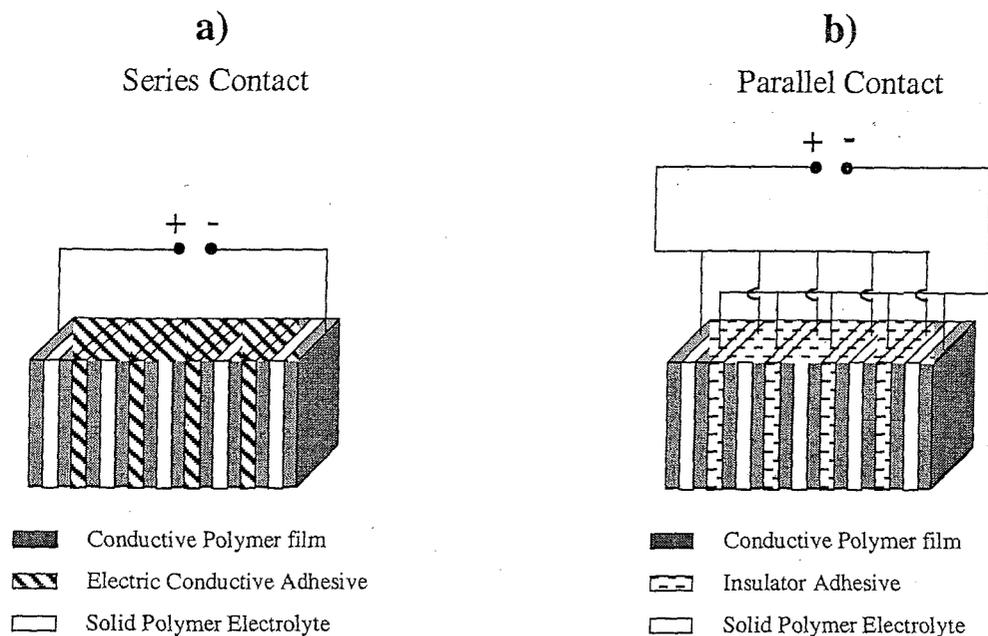


Fig. 1: Parallel configuration of [PPy || SPE || PPy] trilayers connected a): in series; b): in parallel.

Although the goal of this project was to study devices with an increasing number of [PPy || (SPE) || PPy] trilayers, only the movement of a device with two combined trilayers was achieved. We were not able to overcome electrical and structural problems to integrate a higher number of trilayers in the device. The results obtained with the combination of two [PPy || (SPE) || PPy]

trilayers show that this device develops a force double than the force developed by a single trilayer. The parallel connection allowed more uniform movement because it is easier to get the same controlled current flow into all PPY films. Further, the electric energy necessary to move the actuator at a constant angular velocity is higher in the case of the series connection than in the parallel connection as there is a drop of potential along the [PPy || (SPE) || PPY] trilayers with a series electric connection. Therefore, we concluded from this study that a parallel electric connection is more appropriate than the series electric connection to combine an increasing number of [PPy || (SPE) || PPY] trilayers.

Combination of [PPy || (SPE) || PPY]_n multilayer in a series configuration. We also made several attempts to combine trilayers in a series configuration as shown in Figure 2 motivated by theoretical considerations. The theory shows that such configurations should yield linear motion. We have studied different ways to construct this series configuration but it was not possible to get a positive result yet. The experimental procedure has to be optimized in the future to get good adhesion in the interface between [PPy || (SPE) || PPY] trilayers and to avoid the use of wires for the electric connections that limits the movement of the actuator. We think that the utilization of impressed circuitry technology should be a possible solution for the problem of electric contacts.

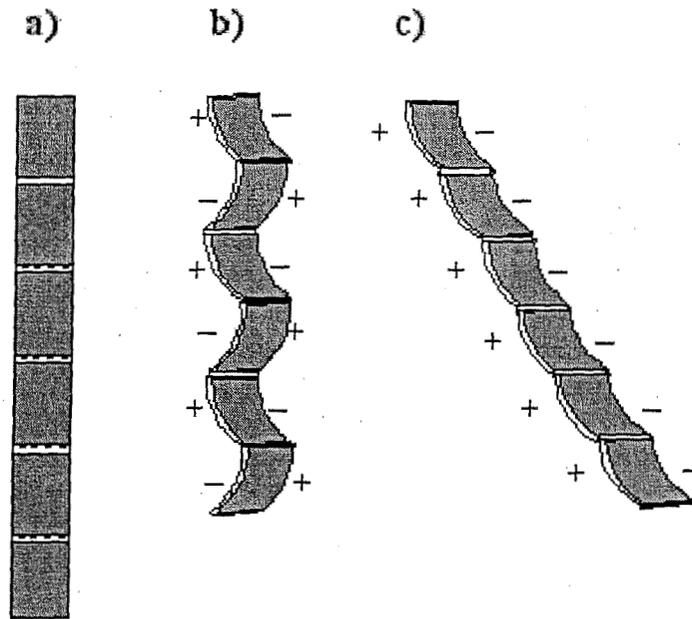


Fig.2: Series configuration of [PPy || SPE || PPY]_n multilayers a): equilibrium position at open circuit,, b): linear contraction/expansion movement with an alternated electric polarity; c): bending movement with the same electric polarity.

C. SIGNIFICANCE OF RESULTS

A growing number of NASA programs require mechanical actuators, which can deliver high forces and displacements, with reduced size and mass. Many types of actuator technologies have been studied to develop both micro and macroscopic devices. However, the existing technologies exhibit limitations in one or more performance parameters, such as actuation force and displacement, response speed or electrical potential needed to electroactivate the actuator. The recent introduction of electroactive polymers (EAP) which offer low mass materials that can

induce large strain and forces under electrical activation has led to their consideration as potential actuators. The most attractive feature of EAPs is their ability to emulate biological muscles by the direct conversion of electrical energy to mechanical energy. This similarity gained them the name "Artificial Muscles" with the potential of developing biologically inspired robots, prosthetic devices, sonar projectors and microscopic pumps.

However most EAPs develop small forces and work predominantly in the bending mode. This project clearly demonstrated the feasibility of combining various trilayers in parallel and series manner to increase the force and displacement, and also to convert bending to linear motion. A theoretical model of conductive polymers was developed which guided the experimental efforts.

The project also showed that despite its promise the fabrication of complex configurations remains a significant challenge. This has to be addressed in future work.

D. PERSONNEL

Dr. Virginia Olazábal, post-doctoral fellow in JPL

José-María Sansiñena, post-doctoral fellow in JPL (supported through other sources)

Ms. Yu Xiao, graduate student in Caltech

E. PUBLICATIONS

1. J.M. Sansiñena, V. Olazábal, Y. Bar-Cohen, EAP Fabrication at the JPL's NDEAA Lab, *WorldWide Electroactive Polymers (WW-EAP) Newsletter*, Vol. 2, No. 1, (2000) pp. 10-11.
2. J.M. Sansiñena, V. Olazábal, Conductive polymers in *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*, Y. Bar-Cohen (Ed.), SPIE Press, (2001).
3. Y. Bar-Cohen, V. Olazábal, J.M. Sansiñena, J. Hinkley, Processing and support techniques, in *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*, Y. Bar-Cohen (Ed.), SPIE Press, (2001).
4. K. Bhattacharya, J. Li and Y. Xiao, Electro-mechanical models for optimal design and effective behavior of electro-active polymers, in *Electroactive Polymer (EAP) Actuators as Artificial Muscles - Reality, Potential and Challenges*, Y. Bar-Cohen (Ed.), SPIE Press, (2001).
5. Y. Xiao and K. Bhattacharya, Modeling electromechanical properties of ionic polymers, in *Proceedings of the SPIE symposium on Electroactive polymer, actuators and devices - Smart structures and materials*, Y. Bar-Cohen (Ed.), SPIE Press (2001), pp. 292-300.
6. Y. Bar-Cohen, V. Olazábal, J.M. Sansiñena, Electroactive Polymer Actuator with Selectable Deformation (EAPAS), *NASA Tech Brief Journal*, (NPO-21174), Vol. 26, No. 7 (2002), pp. 1-8.
7. S. Sherrit, V. Olazábal, J.M. Sansiñena, X. Bao, Z. Chen, Y. Bar-Cohen, The Use of Piezoelectric Resonators for the Characterization of Mechanical Properties of Polymers, in *Proceedings of the SPIE's 9th Annual International Symposium on Smart Structures and Materials*, Eds: Yoseph Bar-Cohen, SPIE Press, vol. 4695, (2002), pp. 262-276.
8. Y. Xiao and K. Bhattacharya, A electro-chemico-mechanical model of electroactive polymers, in preparation (2002).