Guest Editorial
Introduction to the Focused Section on Electroactive Polymer Mechatronics

***Abstract*—Mechatronic devices and systems based on so-called electroactive polymers (EAPs) represent a fast-growing and promising scientific field of research and development. EAPs consist of materials capable of changing dimensions and/or shape in response to suitable electrical stimuli. These polymers show unique properties, such as sizable electrically driven active strains or stresses, high mechanical flexibility, low density, structural simplicity, ease of processing and scalability, no acoustic noise, and, in most cases, low costs. EAPs are today studied for applications that so far have been unachievable with conventional actuation technologies, with usage spanning from the micro- to the macro-scale, in several fields, including robotics, automation, prosthetics, orthotics, artificial organs, optics, energy harvesting, and even aerospace. In an effort to disseminate current advances in the field, this Focused Section collects together a selection of papers dealing with a number of topics related to science and technology of EAPs. Following a brief introduction to the field, this Editorial provides an overview on papers dealing with EAPs published in previous issues of this journal, introduces the papers selected for this Focused Section, and highlights future trends in the field.**

***Index Terms*—Actuator, artificial muscle, electroactive polymer (EAP), electronic, ionic.**

I. Introduction

ELECTROACTIVE polymers (EAPs) represent a fast-growing and promising scientific field of research and development. EAPs are studied for mechatronic devices and systems implemented with smart materials inherently capable of changing dimensions and/or shape in response to suitable electrical stimuli, so as to transduce electrical energy into mechanical work. They can also operate in reverse mode, transducing mechanical energy into the electrical form [1]–[6]. Therefore, they can be used as actuators, mechano-electrical sensors, as well as energy harvesters to generate electricity. For such tasks, EAPs show unique properties, such as sizable electrically driven active strains or stresses, high mechanical flexibility, low density, structural simplicity, ease of processing and scalability, no acoustic noise and, in most cases, low costs. Owing to their functional and structural properties, electromechanical transducers based on these materials are usually refereed to as EAP artificial muscles [1]–[6].

EAP materials are typically classified in two major classes: ionic EAPs and electronic EAPs. The former are activated by an electrically induced transport of ions and/or solvent, while the latter are activated by electrostatic forces. Ionic EAPs comprehend polymer gels, ionic polymer metal composites, conducting polymers, and carbon nanotubes. Electronic EAPs comprehend piezoelectric polymers, electrostrictive polymers, dielectric elastomers, liquid crystal elastomers, and carbon nanotube aerogels [1]–[6].

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The rapid expansion of the EAP field has stimulated in Europe the creation of the "European Scientific Network for Artificial Muscles" (ESNAM), which gathers the most active research institutes, and industrial developers and end users [7].

In an effort to disseminate current advances in the field, this "Focused Section on Electroactive Polymer Mechatronics" of the IEEE/ASME TRANSACTIONS ON MECHATRONICS collects together a selection of papers dealing with science and technology of EAPs, with the hope that they could especially stimulate future research directions.

In this Editorial, we highlight some articles related to this field published in previous issues of the IEEE/ASME TRANSACTIONS ON MECHATRONICS, then we introduce the papers selected for this Focused Section, and finally we highlight future trends in the field.

II. Highlights of Related Articles Published in the IEEE/ASME Transactions on Mechatronics

A. Papers on Ionic EAPs

Richardson *et al.* [8] reported on control of ionic polymer–metal composite actuators. Following an analysis of the actuator characteristics in terms of maximum displacement and blocking force, an open-loop position control and a closed-loop position proportional–integral–derivative control were applied to actuator samples. The paper also investigated actuator performance with impedance (force/position) control.

Alici *et al.* [9] reported on the response characterization of ionic-type EAPs as mechanical sensors. Transfer function models of these actuators were experimentally generated using frequency response of these cantilevered mechanical sensors. Their dynamic sensing behavior was characterized through impulse current and voltage responses. An energy-balance approach was proposed to estimate the voltage output. Experimental and theoretical results demonstrated that the EAPs can be used as macro- and microsized mechanical sensors.

Alici *et al*. [10] reported on the performance characterization and quantification of conducting polymer actuators including their nonlinear behavior and their application to articulating a two-finger microgripper. Experimental and theoretical results were presented to demonstrate the ability and suitability of ionic-type EAP actuators in establishing functional macro and microsized robotic devices.

John *et al.* [11] implemented an inversion-based feedforward control algorithm on trilayer conducting polymer actuators, which operated in dry and wet environments. Experimental results demonstrated that the positioning ability and accuracy of these actuators improved significantly without using feedback control, and changing the fabrication and chemistry of the actuators. This was a significant step toward the establishment of functional devices based on EAP actuators.

Chen and Tan [12] developed a physics-based model of ionic polymer–metal composite actuators, represented as an infinite-dimensional transfer function relating the bending displacement to the applied voltage. The model incorporates the effect of the distributed surface resistance and is expressed in terms of fundamental material parameters and actuator dimensions. As an experimental validation of the model, a model-based controller was designed and used for real-time tracking control.

Peterson *et al.* [13] investigated the flow field generated by an ionic polymer–metal composite strip vibrating in a quiescent aqueous environment using planar particle image velocimetry. They estimated the mean thrust generated by the vibrating actuator, with the perspective of miniaturizing underwater propulsion systems. The study was aimed at guiding the optimization of propulsion systems based on ionic polymer–metal composites for miniature biomimetic robotic swimmers.

Chen *et al.* [14] proposed a physics-based model for a biomimetic robotic fish propelled by an ionic polymer–metal composite actuator. The model incorporates both the actuator dynamics and the hydrodynamics, and predicts the steady-state cruising speed of the robot under a given periodic actuation voltage. Experimental validation showed that the model was able to predict the robotic fish motion for different tail dimensions.

John *et al.* [15] reported on the frequency response of ionic-type, but dry, cantilevered conducting polymer actuators and employed the frequency response data in order to identify the resonant frequency and the actuator parameters affecting the resonant frequency. The actuator parameters, which are difficult to measure and estimate directly, such as modulus of elasticity can be estimated using the resonant frequency model.

Aureli *et al.* [16] developed a modeling framework to study free locomotion of biomimetic underwater vehicles propelled by vibrating ionic polymer–metal composite actuators. The motion of the vehicle body was described using rigid body dynamics in fluid environments, and the time-varying actions exerted by the vibrating ionic polymer–metal composite on the vehicle body, including thrust, lift, and moment, were estimated. Model predictions were experimentally validated on a miniature remotely controlled fish-like robotic swimmer.

Fang *et al.* [17] recently proposed a conducting polymer-based torsional actuator. The actuator was obtained by embedding helically wound fibers into a conducting polymer tube during the polymer deposition process. Upon actuation, the electrolyte-soaked tube swells and produces torsion and other associated deformations because of fiber-induced mechanical anisotropy. A model was developed and its capability of capturing torsions, elongations, and dilations was experimentally validated on actuators with different thicknesses, fiber winding angles, and diameters.

B. Papers on Electronic EAPs

Choi *et al.* [18] described a biomimetic linear dielectric elastomer actuator referred to as "Antagonistically Driven Linear Actuator." The actuator was shown to offer cost effectiveness and simple fabrication process. In addition to producing basic bidirectional rectilinear motions, the paper showed the possibility of modulating the actuator compliance, as an advantage for biomimetic applications. Also, the actuator concept was used to demonstrate a microscale robot with annelid-like motion.

Wingert *et al.* [19] proposed bistable dielectric elastomer actuators, also describing their signficant potential for applications tat require large degree-of-freedom (DoF) devices. The proposed actuators consist of thin elastomer films mounted in a flexible frame that incorporates a passive bistable element. The frame prestrains the film and provides a restoring force that allows the actuator to operate bidirectionally. The concept was demonstrated by assembling and testing a prototype 6-DoF binary manipulator.

Rajamani *et al.* [20] reported on fabrication, analysis, and experimental investigation of wound roll dielectric elastomer actuators. They developed a fabrication process for actuators able to reliably work at high linear strain. Also, a nonlinear model was developed and was shown to be useful to predict the actuator displacement and stress.

Carpi *et al.* [21] reported on a study on the magnetic-resonance-imaging (MRI) compatibility of a linear contractile dielectric elastomer actuator made of a silicone elastomer. Phantom tests showed absence of any degradation on both the actuator performance within the MRI environment and the quality of acquired MRI images. Results proved suitability of the considered soft actuation technology as a possible new entry in the class of MRI compatible mechatronic systems.

Carpi *et al.* [22] proposed new types of dielectric elastomer actuators, referred to as "hydrostatically coupled" (HC) dielectric elastomer actuators. The devices use an incompressible fluid to hydrostatically couple a dielectric elastomer based active part to an elastic passive part, which is in contact with the load. The fluid is distributed and sealed between the active and passive parts, transmitting actuation from the former to the latter. This concept was shown to allow for versatility and electrical safety in designing new dielectric elastomer actuators according to different configurations.

Carpi *et al.* [23] described the design of an all-polymer linear peristaltic pump made of dielectric elastomer actuators. The described system is a series of radially expanding elastic tubular modules. Each module consists of a cylindrical hollow dielectric elastomer actuator, working in purely radial mode with specific boundary constraints. Simplified analytical and numerical models, validated experimentally, were developed to obtain a simulation tool, able to predict performance in terms of displaced volume and driving pressure, as a function of the material elastic modulus and applied voltage.

III. Highlights of This Focused Section

This Focused Section collects thirteen papers presenting relevant new models, devices and applications of three families of ionic EAPs (conducting polymers, carbon nanotubes, and ionic polymer–metal composites) and one family of electronic EAPs (dielectric elastomers).

A. Papers on Ionic EAPs

In the paper "*A Dynamic Electromechanical Model for Electrochemically Driven Conducting Polymer Actuators*," Shoa *et al.* presented an analytical electromechanical model to predict the actuation response of electrochemically driven bending conducting polymers. The model is a function of ionic and electronic conductivities, dimensions, volumetric capacitance, elastic modulus, and strain to charge ratio. As compared to existing models, the proposed model represents the two dimensional charging of the polymer, namely through the thickness of the polymer structure and along its length. For this purpose, the model considers both ion diffusion through the thickness and electronic resistance along the length. The model is shown to provide a good description of experimentally assessed bending response, so that it can be effectively used to design electrochemically driven EAP devices.

Application of twisting multiwalled carbon nanotubes (MWNTs) yarns as mechanical force sensors is proposed by Mirfakhrai *et al*. in the paper "*Mechanoelectrical Force Sensors Using Twisted Yarns of Carbon Nanotubes*." Experimental and theoretical results demonstrate that the twisted yarns of carbon nanotubes can be used as mechanical stress sensors with very high transduction efficiency. The sensing ability of these yarns is compared with piezoelectric and conducting polymer sensors that they can not only handle higher loads, but also operate in harsher environmental conditions without degrading. The sensors can be used in high stress and high temperature applications.

The paper "*Modeling and Inverse Compensation of Temperature-Dependent Ionic Polymer–Metal Composite Sensor Dynamics*" by Ganley *et al*. presents the temperature-dependent behavior and modeling of ionic polymer–metal composite mechanical sensors. The transfer function describing dynamic sensing behavior of the actuators contains temperature dependent coefficients which are experimentally identified and subsequently used to estimate sensing dynamics at other temperatures in order to demonstrate the validity of the temperature dependent model. The model is also cross-validated by inverting it; for a given sensor output, the mechanical input is accurately estimated under different temperatures.

B. Papers on Electronic EAPs

The paper "*Dielectric Elastomer Generators: How Much Energy Can Be Converted?*" by Koh *et al*. deals with usage of dielectric elastomer transducers as electrical generators by harvesting mechanical energy from renewable sources, such as human movements and ocean waves. The authors model a generator as a system of two degrees of freedom, represented on either the stress–stretch plane or the voltage–charge plane. They study the maximum energy of conversion, including the following mechanisms of failure: material rupture, loss of tension, electrical breakdown, and electromechanical instability. Results of this study show that natural rubber outperforms the most used acrylic based dielectric elastomer as a generator at strains less than 15%. Furthermore, the authors show that, by varying material parameters, converted energy can be as high as 1.0 J/g.

The paper "*Power for Robotic Artificial Muscles*" by Anderson *et al.* again focuses on dielectric elastomer generators. As a novel contribution, the authors report on the initial low-voltage priming of the generators with a self priming circuit, and they show how this can be used to boost voltage to useful levels for dielectric elastomer actuators. The self-priming circuit can be started using an initial low voltage charge from another energy harvester, such as a solar cell array or a bank of microbial fuel cells, as considered by the authors. The paper also describes the feasibility of using dielectric elastomer generators to generate electric power from the wind without the need for a high-voltage booster. Such achievements might lead to significant advantages, especially for autonomous robots. As a proof-of-concept demonstrator, the authors present a portable self-primed dielectric elastomer generator able to harvest wind energy from a swaying tree branch.

The paper "*Fabrication and Application of Miniaturized Dielectric Elastomer Stack Actuators*" by Lotz *et al.* describes an automated fabrication process of stacked dielectric elastomer actuators. Thin dielectric films of uncured polydimethylsiloxane (PDMS) are spun to a thickness below 100 μm. After curing graphite electrodes are sprayed on the PDMS surface and the next dielectric film can be applied on top. It is shown that the thickness variation within one layer is smaller than 4%. The electrodes are sprayed to have a sheet resistance of 10 kΩ. The technology presented is able to produce dielectric elastomer actuators with layer thicknesses down to 5 μm. Hence, it is possible to design and fabricate actuators which are driven at only 150 V. Arrays of small actuators with a resolution of 1 mm can be produced as well as single actuator elements with a diameter up to 40 mm. The potential of this technology is demonstrated by a vibrotactile display that generates a perceptive vibration of 125 Hz at a driving voltage of 600 V. Also, a peristaltic pump with a maximum flow rate of 12 μL/min is demonstrated. The paper describes the current advanced level of fabrication of dielectric actuators developed over at least a five-year period at TU Darmstadt.

In the paper "*Actuated Microoptical Submount Using a Dielectric Elastomer Actuator*" Jordan *et al.* present an analysis of the operating characteristics of a dielectric elastomer actuator submount for high-precision positioning of optical components, operating in one dimension. The author describe precise alignment of a single mode optical fiber, comparing performance of their dielectric elastomer based system with that of a standard piezoelectric alignment stage.A similar performance in terms of alignment accuracy is demonstrated for the two compared technologies. The paper also presents extensions of the concept to 2 DoFs. Results of this investigation suggest that, with further material improvements, dielectric elastomer actuators could represent a low-cost alternative to currently used manual technologies in overcoming the hurdle of expensive packaging of single-mode optical components.

In the paper "*Fully Coupled Electromechanical Model for Dielectric Elastomer Sheets*," Lassen *et al.* present a fully coupled nonlinear electromechanical model for corrugated dielectric elastomer sheets, be they actuators or sensors. This paper follows the growing trend to develop more sophisticated modelling tools for dielectric elastomers. This paper emphasizes the use of corrugated electrodes, an approach that is of particular importance since such dielectric elastomer sheets are commercially available. Results show that the actuation of dielectric elastomer sheets can be significantly improved by either reducing the period or increasing the amplitude of the corrugations and that changing the shape of the corrugation had only a minor effect on of the actuation. The results also consider the importance of accurately modeling the Young's modulus of the materials as well as show the importance of using fully coupled models at high driving electric fields.

The paper "*Electroactive Polymer Actuators in Dynamic Applications*" by Kaal *et al.* investigates the dynamic behavior of huge rolled dielectric elastomer actuators with the perspective of using them in the field of active vibration control. The nonlinearities in a dielectric elastomer actuator and their consequences for dynamic applications are analyzed on a theoretical level. Based on these findings, two compensation methods influencing the dynamic behavior of the actuators are established. A dielectric elastomer actuator is included in an active closed loop control system and its potential for active vibration control is demonstrated. Furthermore, a MATLAB/Simulink model of the whole system is presented, its general validity is shown, and its potential for future system development processes is highlighted.

The paper "*Optimal Synthesis of Conically Shaped Dielectric Elastomer Linear Actuators: Design Methodology and Experimental Validation*" by Berselli *et al.* presents a mathematical procedure, which makes it possible to optimize conically shaped dielectric elastomer linear actuators for known materials and desired force/stroke requirements. The actuators are obtained by coupling a dielectric elastomer film with a compliant frame which is sized by means of a pseudo-rigid-body model. Depending on the frame design, the actuators can work mono-directionally or bi-directionally. Simulation and experimental results are provided which demonstrate the efficacy of the proposed design procedure and show that better-behaved conically shaped actuators can be conceived and realized. This novel procedure for the optimization of conically shaped dielectric-elastomer-based linear actuators allow for optimizing both films and frame in order to obtain a desired profile of the actuator available thrust.

In the paper "*Electroactive Elastomeric Actuators for the Implementation of a Deformable Spherical Rover*," Artusi *et al.* look at a new type of robotic rover based on dielectric elastomers. The authors present and validate a new conceptual design for future lightweight rolling rovers potentially suitable for exploration and scouting missions. The proposed prototype consisted of an internal rigid frame and an external deformable surface made of dielectric elastomer actuator sectors. Different analytical models were developed to investigate the behavior of the actuators, the dynamics of each sector and the rolling performance of the prototype. Experimental tests were performed to validate the models and evaluate the proposed approach. The maximum angular acceleration of the developed prototype was 0.42 rad/s^2. The prototype shows the potential benefits of the proposed approach with regard to mass and volume. The mass of the prototype was only 75 g and its volume, once inflated, was 660 cm^3. In the folded stowed configuration, the prototype could potentially have a total folded volume of about 30 cm^3.

In the paper "*Controlling Bandgap in Electroactive Polymer-Based Structures*," Gei *et al.* use the large strain capability of dielectric elastomers to essentially create "tunable materials." A novel way to control band gaps in flexural waveguides is proposed. The approach uses the contrast between the soft dielectric elastomer and electrodes applied in a periodic pattern. Voltage-driven actuation changes the spacing of the electrodes. Based on analysis and simulation, the technique proves to be feasible and able to accurately tune the position of band gaps over all frequency spectra. A device able to guide flexural waves, band gap ranges of about one, two hundred hertz has been obtained over frequencies on the order of 1 kHz.

In the paper "*Granularly Coupled Dielectric Elastomer Actuators*," Carpi *et al.* present a new kind of dielectric elastomer actuators, referred to as "granularly coupled" (GC) dielectric elastomer actuators. The devices are analogous to HC dielectric elastomer actuators (see Section II), except for the fact that the working fluid is replaced by fine powder. Usage of powder is shown to allow for reduction of typical drawbacks (such as handling and leakage) arising from fluids, especially when they are liquid, while preserving functionality, at least at millimetre scale. In particular, the paper presents actuation performance of bubble-like GC actuators based on talcum powder, in direct comparison with HC actuators based on silicone grease. GC actuators are shown to exhibit a higher maximum stress, the same maximum relative displacement, the same bandwidth and a higher resonance frequency. The paper discusses advantages and drawbacks of GC actuators, as compared to HC actuators.

IV. Future Trends

After several years of basic research, today the EAP field is just starting to undergo transition from academia into commercialization, with significant investments from large companies [7], [24].

In this context, basic research tasks and technological tasks which still require major efforts are briefly presented below.

A. Basic Research Tasks

For ionic EAPs, the fundamental issue that necessarily requires major improvements is the increase of lifetime and response speed. In fact, short lifetime and high response times significantly limit performance of ionic EAPs today [1], [2],

[4]–[6]. These drawbacks are fundamentally due to the electrochemical driving of the underlying energy transduction mechanisms: this leads, on one hand, to possible material and/or electrode degradations with cycles, and, on the other hand, to a reduction of the response speed, which is conditioned by electrodiffusion of ions and solvent. Limiting such problems would enable greater exploitability of the ionic EAP technologies, whose primary advantage is represented by inherent responsiveness to extremely low driving voltages (order of 1V). For this purpose, using improved electrolytes (especially based on ionic liquids) and more effective electrical driving strategies (e.g., IR compensation) is of primary interest, according to their documented efficacy [1], [2], [4]–[6].

For electronic EAPs, the fundamental task is the reduction of the driving electric fields. In fact, electronic EAPs currently require high driving electric fields (order of 100 V/μm), due to the electrostatic nature of their activation mechanisms [1]–[6]. Lowering their driving fields would expand applicability to areas that are currently precluded, due to the need for high driving voltages (orders of 100–1000 V), although at low power (as electronic EAP actuators are capacitive loads). Lower driving fields would allow superior exploitability of the great potential of electronic EAPs, whose primary advantages are represented by high actuation strains and stresses, fast response and long lifetime. For this purpose, developing new dielectric polymers with increased inherent electromechanical transduction properties, namely higher dielectric constant (while limiting the typical parallel reduction of breakdown strength) is essential. Approaches of primary interest include composites (i.e. polymer matrices mixed with either inorganic or organic particles, such as ceramics or carbon nanotubes), polymer blends (e.g., multicomponent systems including both insulating polymers and semiconductive or conductive conjugated polymers, such as poly(hexylthiophene)), as well as new synthetic systems (e.g., polymer matrices with highly polarizable grafted groups, such as liquid crystal groups) [1]–[6].

B. Technological Tasks

Although addressing the aforementioned basic research tasks is unavoidable, it is not sufficient. In fact, in general, solving fundamental material problems is essential to obtain required breakthroughs, but certainly it is not a guarantee of direct applicability. Actually, scientific achievements cannot neglect parallel developments toward industrialization. For this reason, developing EAP actuators that can be industrialized and mass-produced requires to complement the basic research tasks with technological tasks. The latter mainly deals with technological arrangements and optimizations, as well as manufacturing processes, as mentioned below.

For ionic EAPs, the main technological issue is the development of effective fabrication processes for films and fibers. In fact, manufacturing reliable actuators made of ionic EAPs and shaped in the form of films and fibers using processes that can be industrialized is essential today to move the technology from a lab scale to an industrial dimension [1], [2], [4]–[6]. This requires concentration of efforts to adapt and develop techniques for material processing and packaging that might be applied to ionic EAPs. In particular, their need for a working electrolyte medium (in the form of either a liquid or a solid polymer electrolyte) requires developing specific technological solutions for the overall manufacturing process, especially to properly seal fluids.

For electronic EAPs, the main technological task is the fabrication of polymer films with lower thickness, to reduce their absolute driving voltages. In fact, their current need for high driving fields implies that high voltages have to be usually applied across the thickness of the material sample, as stressed above [1]–[6]. To lower the absolute driving voltages for any given material type (that requires given driving electric fields), a reduction of the sample thickness is essential. Therefore, manufacturing EAP thin films is a must to enable the fabrication of actuators that can be driven at lower voltages and, therefore, can have a broader range of use. For this purpose, a key issue is the development of roll-to-roll processing techniques (e.g., adapted from the web conveying industry), suitable to manufacture and handle continuous and highly stretchable films, which should have a thickness lower than 30 μm (to go beyond the state of the art). Accurate and safe handling of so-thin and highly stretchable films (especially for elastomeric polymers) is fundamental for any future manufacturing system at industrial scale. To prevent damages during manufacturing, industrial efforts should be focused on scalable techniques for film handling, liner removal (if any), and noncontact electrode coating (by means of plotting/spraying of carbon powder or carbon nanotubes, or metal sputtering).

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Federico Carpi, *Guest Editor*
Interdepartmental Research Center "E. Piaggio"
University of Pisa
I-56127 Pisa, Italy

Roy Kornbluh, *Guest Editor*
SRI International
Menlo Park, CA 94025-3493 USA

Peter Sommer-Larsen, *Guest Editor*
Risø National Laboratory
Technical University of Denmark
2800 Kgs. Lyngby, Denmark

Danilo De Rossi, *Guest Editor*
Interdepartmental Research Center "E. Piaggio"
University of Pisa
I-56127 Pisa, Italy

GURSEL ALICI, *Guest Editor*
School of Mechanical, Materials and Mechatronic Engineering
University of Wollongong
Gwynneville 2500, N.S.W., Australia

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Federico Carpi was born in Italy in 1975. He received the Laurea degree in electronic engineering, the Ph.D. degree in bioengineering, and a second Laurea degree in biomedical engineering from the University of Pisa, Pisa, Italy, in 2001, 2005, and 2008, respectively.

Since 2000, he has been with the Interdepartment Research Center "E. Piaggio," School of Engineering, University of Pisa, where he is currently a Postdoctoral Researcher. His research interests include the development of electroactive-polymer-based materials and devices for biomedical engineering and robotics. He is the Chair of the electroactive-polymer-based "European Scientific Network for Artificial Muscles (ESNAM)," a member of the Editorial Board of three international scientific journals, and a member of the Scientific Committees of several international conferences. His scientific publications include more than 40 peer-reviewed papers in international journals, two edited books, and several contributions to books and conferences.

Roy Kornbluh received the B.S. degree from Cornell University, Ithaca, NY, in 1982, and the S.M. degree from the Massachusetts Institute of Technology, Cambridge, in 1984, both in mechanical engineering.

From 1984 to 1991, he was with SRI International, Menlo Park, CA, where he is currently a Principal Research Engineer in the Mobile Robotics and Transducers Group that is a part of SRI International's Robotics Laboratory. He was engaged in a wide range of projects involving robotics, design and analysis of electromechanical systems, smart materials, and sensors. He is one of the inventors of the electroactive polymer technology known as "dielectric elastomers," and has more than 15 years of experience with this technology. He led and participated in projects that developed the artificial muscle technology for a wide variety of applications in robotics, energy harvesting, and other areas. He is the author or coauthor of more than 50 publications in the areas of polymer actuators and robotics including several book chapters and one book. He currently holds approximately 40 patents in these areas as well. He is an Associate Editor for the *Journal of NeuroEngineering and Rehabilitation*. From 1991 to 1994, he was a Water and Sanitation Consultant for the U.S. Peace Corps in Ecuador.

Mr. Kornbluh was a member of the International Program Committees of the Electroactive Polymers and Devices Conference of SPIE, the Actuators 2002, 2004, 2006, and 2008 Conferences, and the International Association of Science and Technology for Development Robotics and Applications Conference.

Peter Sommer-Larsen received the M.S. and Ph.D. degrees in physical chemistry from the University of Copenhagen, Copenhagen, Denmark, in 1985 and 1990, respectively.

He is currently the Head of the Solar Energy Program, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, Kgs. Lyngby, Denmark. He has a background in advanced organic materials, and from 1995 to 2004, he was the Head of research on electroactive polymers at Risø in the ARTMUS project. He has authored or coauthored more than 50 research papers and a number of book chapters, and is a coeditor of the book *Dielectric Elastomers As Electromechanical Transducers* (Elsevier, 2008). He is a member of the coordinating group for the Electroactive Polymer Based "European Scientific Network for Artificial Muscles (ESNAM)."

Dr. Sommer-Larsen is a member of the Scientific Committee ACTUATOR 2002–2008, the Chair of the polymer actuator session of ACTUATOR 2002, 2004, 2006, and 2008, a member of the Scientific Committee for SPIE-Smart Materials and Structures, and Cochair 2004, a member of the International Advisory Board for CIMTEC 2008, and currently, a member of the Editorial Board for the *International Journal of Energy Research*.

Danilo De Rossi was born in Italy in 1949. He received the Laurea degree in chemical engineering from the University of Genova, Genova, Italy, in 1976.

From 1976 to 1981, he was a Researcher at the Institute of Clinical Physiology, National Council of Research, Pisa, Italy. He has had appointments for teaching and research in France, the U.S., Brazil, Japan, and Australia. Since 1982, he has been with the School of Engineering, University of Pisa, Pisa, where he is currently a Full Professor of bioengineering. He was the first President of the Biomedical Engineering Teaching Track of the University of Pisa. He is the author or coauthor of more than 270 peer-reviewed papers in international science journals and peer-reviewed proceedings, a coinventor of 14 patents, and a coauthor of ten books. His current research interests include physics of organic and polymeric materials, and the design of sensors and actuators for bioengineering and robotics.

Mr. De Rossi received the Young Investigator Forum Award from the Biomedical Engineering Society (U.K.) in 1980 and from the American Society for Artificial Internal Organs in 1985. He has been a member of the Editorial Boards of several international scientific journals, and a member of the Scientific Committees of several international conferences.

Gursel Alici received the Ph.D. degree in robotics from the Department of Engineering Science, Oxford University, Oxford, U.K., in 1994.

He is currently a Professor at the University of Wollongong Gwynneville, Australia, where he is the Discipline Leader of mechatronic engineering. He has authored or coauthored more than 160 refereed publications in his areas of research. His current research interests include intelligent mechatronic systems involving mechanisms/serial/parallel robot manipulators, micro/nanorobotic systems for medical applications, and conducting polymers as macro/micro/nanosized actuators and sensors for robotic and bioinspired applications.

Prof Alici is currently a Technical Editor of the IEEE/ASME TRANSACTIONS ON MECHATRONICS, and a member of the Mechatronics National Panel formed by the Institution of Engineers, Australia. He is one of the Chief Investigators of the ARC Center of Excellence for Electromaterials Science (ACES) in the Energy conversion and Bionics programs. He was also the recipient of the Outstanding Contributions to Teaching and Learning (OCTAL) award from the University of Wollongong in 2010.