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Yoseph Bar-Cohen
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Contents

DIELECTRIC ELASTOMERS

APPLICATIONS OF DIELECTRIC ELASTOMERS

EAP FABRICATION PROCESSES

APPLICATIONS OF EAP I

APPLICATIONS OF IPMC

CONDUCTING POLYMERS

EAP SENSORS

APPLICATIONS OF EAP II

APPLICATIONS OF EAP III

APPLICATIONS OF EAP IV

POSTER SESSION

Authors

Numbers in the index correspond to the last two digits of the seven-digit citation identifier (CID) article numbering system used in Proceedings of SPIE. The first five digits reflect the volume number. Base 36 numbering is employed for the last two digits and indicates the order of articles within the volume. Numbers start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B...0Z, followed by 10-1Z, 20-2Z, etc.

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1 EAP as Emerging Actuators
Yoseph Bar-Cohen, Jet Propulsion Laboratory (United States)
Iain A. Anderson, The University of Auckland (New Zealand)

2 Field-Activatable EAP I
John D. W. Madden, The University of British Columbia (Canada)
Jonathan M. Rossiter, University of Bristol (United Kingdom)

3 Advances in EAP Materials
Kwang Jin Kim, University of Nevada, Las Vegas (United States)
Andreas Tairych, The University of Auckland (New Zealand)

4 IPMC
Ray H. Baughman, The University of Texas at Dallas (United States)
Geoffrey M. Spinks, University of Wollongong (Australia)

5 Modeling EAP Materials
Christoph Keplinger, University of Colorado Boulder (United States)
Ji Su, NASA Langley Research Center (United States)

6 Dielectric Elastomers
Ron Pelrine, SRI International (United States)
Minoru Taya, University of Washington (United States)

7 Field-Activatable EAP II
Qibing Pei, University of California, Los Angeles (United States)
Ron Pelrine, SRI International (United States)

8 Applications of Dielectric Elastomers
Brian Trease, The University of Toledo (United States)
Anthony Griffin, University of Illinois (United States)

9A EAP Fabrication Processes
Mircea Badescu, Jet Propulsion Laboratory (United States)
Holger Böse, Fraunhofer-Institut für Silicatforschung ISC (Germany)

9B Applications of EAP I
E.-F. Markus Henke, The University of Auckland (New Zealand)
Thomas Wallmersperger, Technische Universität Dresden (Germany)

10A Applications of IPMC
Jian Zhu, National University of Singapore (Singapore)
Lenore Rasmussen, Ras Labs., LLC (United States)

10B Conducting Polymers
Rocco Vertechy, University degli Studi di Bologna (Italy)
Yang He, Harbin Institute of Technology (China)

11A EAP Sensors
Samuel Rosset, Ecole Polytechnique Fédérale de Lausanne (Switzerland)
Liwu Liu, Harbin Institute of Technology (China)

11B Applications of EAP II
Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)
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12A Applications of EAP III
Adrian Koh, National University of Singapore (Singapore)
Caleb Christianson, University of California, San Diego (United States)

12B Applications of EAP IV
Gabor Kovacs, EMPA (Switzerland)

Introduction

The SPIE Electroactive Polymers Actuators and Devices (EAPAD) conference continues to be the leading international forum for presenting the latest progress, challenges and potential future directions for the EAP field. The conference this year was chaired by Yoseph Bar-Cohen, JPL/Caltech, and co-chaired by Iain A. Anderson, The Univ. of Auckland (New Zealand). This Conference has been the 20th since its start in 1999 and the invited talks focused on reviewing the accomplishments, challenges and potentials of the various types of EAP known today (**Figure 1**). Presented papers reported the significant progress made in topics including: theoretical modeling and analysis of EAP mechanisms; improved EAP materials, processes, fabrication (including 3D printing) and characterization techniques; emerging EAP actuators (including ionic, shape memory polymers, and dielectric EAP); applications of EAP materials including power generation and energy harvesting, robotics, haptic, tactile, and various sensors.

Figure 1: Some of the Session co-Chairs of the EAPAD Conf. From left to right: Ji Su, NASA Langley Research Ctr. (United States), Iain Anderson, The Univ. of Auckland (New Zealand), Gabor Kovacs, EMPA (Switzerland), Qibing Pei, Univ. of California, Los Angeles (United States), Ron Pelrine, SRI International (United States); Yoseph Bar-Cohen, Jet Propulsion Lab. (United States), Qiming M. Zhang, The Pennsylvania State Univ. (United States), Herbert Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland), John D. W. Madden, The Univ. of British Columbia (Canada) and Jonathan M. Rossiter, Univ. of Bristol (United Kingdom)

The Conference included 94 presentations and was well attended by internationally leading experts in the field including members of academia, industry, and government agencies from the United States and overseas. The efforts described in the presented papers are showing significant improvements in understanding the electromechanical principles toward better methods of dealing with the challenges to the materials applications. Researchers are continuing to develop analytical tools and theoretical models to describe the electro-chemical and -mechanical processes, nonlinear behavior as well as methodologies of design and control of the activated materials. EAP with improved response were described including dielectric elastomer, hydraulically amplified self-healing electrostatic, IPMC, conducting polymers, gel EAP, carbon nanotubes, and other types. Specifically, there seems to be continuing trend toward using dielectric elastomers as practical EAP actuators for commercial applications.

At this EAPAD conference, the Keynote speaker was Brian Trease, (**Figure 2**), the Univ. of Toledo (United States). Brian Trease spent eight years working at JPL/NASA, Pasadena, California, after he graduated from the Univ. of Michigan. His specialties include mechanism design, optimization, flexible systems, and deployable structures. At JPL, Brian was a research technologist in compliant mechanisms, printable spacecraft, rover mobility, and solar sail development. His current research interests at the Univ. of Toledo include origami inspired design, biomimicry, swarm robotics, and autonomous robotics for environmental remediation.

According to Brian, the engineering world has exploded with recent interest in the craft of origami. This traditional art form, most often associated with Japan, has become fertile ground for inspiration of devices with applications ranging from medicine to aerospace. In his talk, Brian presented an overview of the prominent figures and applications that are currently driving innovation in the field. He pointed out that engineers and artists alike have come together to develop new techniques that take the practice from paper curiosities to practical engineered devices and systems. Foldable tools are now entering the human body during minimally invasive surgery, and foldable optical structures are being designed for the next generation of space-based telescopes. Mathematicians, material scientists, roboticists, architects, and mechanical designers are all investigating classical origami patterns and inventing new ones, benefiting from the insights and craftsmanship of partnering artists. The resulting software tools are accessible by engineers, tinkerers, and artists alike, some of who then leverage laminated manufacturing techniques to fabricate fully-operational systems with embedded electrical components and smart material actuation. While engineering is often influenced by external disciplines, such as biology or aesthetics, the melding of engineering and origami

Figure 2: The Keynote Speaker, Brian Trease, the Univ. of Toledo (United States).

has been uniquely synergistic. The interaction of scientists and artists has mutually benefited both sides. Beyond the novel advancements in engineering, the artists themselves are taking back the numerical tools and material innovations, using them to produce revolutionary pieces of balanced complexity and elegance.

The invited papers in the 2018 EAPAC Conference were:

- John D. W. Madden, The Univ. of British Columbia (Canada), "25 years of conducting polymer actuators: history, mechanisms, applications, and prospects" Paper 10594-2
- Qiming M. Zhang, The Pennsylvania State Univ. (United States), "Molecular machine: how ferroelectric polymers generate giant electrostriction", Paper 10594-3
- Ron Pelrine, Roy D. Kornbluh, SRI, International (United States); Qibing Pei, Univ. of California, Los Angeles (United States), "Dielectric Elastomers past, present, and potential future", Paper 10594-4
- Ray H. Baughman, The Univ. of Texas at Dallas (United States), "Stronger, faster, and more powerful artificial muscle yarns and fibers" Paper 10594-6
- Gabor M. Kovacs, EMPA (Switzerland), "Manufacturing polymer transducers: opportunities and challenges", Paper 10594-7
- Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States), "Last twenty-five years of effort in developing fabrication-methods of IPMCs", Paper 10594-9
- Minoru Taya, Univ. of Washington (United States); and Kevin Kadooka, Pacific Northwest National Laboratory (United States), "Review talk on viscoelastic behavior of dielectric elastomer actuators", Paper 10594-19
- Ji Su, NASA Langley Research Ctr. (United States), "A review of electrostrictive graft elastomers: structures, properties, and applications", Paper 10594-23
- Jian Zhu, Hareesh Godaba, National Univ. of Singapore (Singapore), "Review on soft robots using dielectric elastomer actuators", Paper 10594-26
- Nicholas Kellaris, Vidyacharan Gopaluni-Venkata, Garrett Smith, Shane K. Mitchell, Eric Acome, Christoph Keplinger, Univ. of Colorado Boulder (United States) , "The Peano-HASEL actuator: a versatile electrostatic actuator that linearly contracts on activation", Paper 10594-80

In the 2018 EAP-in-Action Session 14 demonstrations were presented by teams from China, Germany, New Zealand, Singapore, Switzerland, and United States (see Appendix for the details).

In closing, we would like to extend a special thanks to all the conference attendees, paper presenters, Session Chairs, EAP-in-Action demo presenters, and the members of the EAPAD Program Committee. In addition, special thanks are extended to the SPIE staff who helped make this conference a great success.

Yoseph Bar-Cohen
Iain Anderson

APPENDIX: THE 2018 EAP-IN-ACTION PROGRAM

Moderator:

Yoseph Bar-Cohen, Jet Propulsion Lab.

The EAP-in-Action Session of the EAPAD Conference/SPIE Smart Structures/NDE Symposia is highlighting some of the latest capabilities and applications of Electroactive Polymer (EAP) materials where the attendees are given demonstrations of these materials in action. In addition, the attendees are given opportunity to interact directly with the presenters as well as given "hands-on" experience with the presented technology. The first Human/EAP-Robot Armwrestling Contest was held in 2005 during this session.

Best EAP-in-Action Demonstration Award
As of 2017, as part of the EAP-in-Action Session, a selection is made of the "Best EAP-in-Action Demonstration". This selection is intended to encourage excellence in developing EAP materials and accelerate the transition of EAPs to practical and commercial technologies. A judging committee, consisting of leading EAP experts, selects the award winner(s) among the presenters of the demonstrations at the EAP-in-Action Session. The judges assess the presenters' performance as well as the quality and content of the demos. The top ranked three are recognized and are being awarded with a certificate during the Symposium.

<u>Evaluation criteria</u>: The demo presenters are ranked based on the following criteria:
1. Originality/creativity
2. Use of EAP to drive the demo
3. Performance of the demo
4. Potential impact

Scores: 4 excellent; 3 Good; 2 Fair; 1 Reasonable; 0 no show

The 2018 judges were:
1. Gabor Kovacs, EMPA (Switzerland)
2. John D Madden, The Univ. of British Columbia (Canada)
3. Qibing Pei, Univ. of California, Los Angeles, (United States)
4. Jonathan Rossiter, Univ. of Bristol (United Kingdom)
5. Brian Trease, Univ. of Toledo, Ohio (United States)

The 2018 Session included 14 demonstrations with presenters from China, Germany, New Zealand, Singapore, Switzerland, and United States. The presenters consisted of professors and their students as well as engineers from industry. The top three best demonstration presentations (**Figure 3**) were:

- **First Place (Figure 4):** "HASEL: Hydraulically amplified self-healing electrostatic actuators with muscle-like performance". The recipients are Eric Acome, Shane K. Mitchell, Timothy G. Morrissey, Nicholas Kellaris, Vidyacharan Gopaluni Venkata, Madison B. Emmett, Claire Benjamin, Madeline King, Garrett Smith, Miles Radakovitz, and Christoph Keplinger, Univ. of Colorado (United States).
- **Second Place (Figure 5):** "Haptic feedback demonstrators based on strip dielectric elastomer actuators", Philipp Loew (on the left in the photo), and Daniel Bruch, Univ. des Saarlandes, Lehrstuhl für Intelligente Materialsysteme, Intelligent Material Systems Lab (Germany).
- **Third Place:**
    1. "Dielectric elastomer energy harvester autonomously primed by piezo- and tribo-electricity", Koh Soo Jin Adrian (shown in the photo on the left), Liu Chong, Ahmed Haroun, Anup Teejo Mathew, National Univ. of Singapore (Singapore) - **Figure 6**
    2. "An untethered swimming robot powered by dielectric elastomer actuators" Mihai Duduta (shown in the photo on the left), Florian C. Berlinger, Hudson Gloria, Radhika Nagpal, Robert J. Wood, and David R. Clarke, Harvard Univ. (United States) - **Figure 7.**

Figure 3: The recipients of the top three places of the best 2018 EAP-in-Action Demonstrations.

Figure 4: The recipients of the 1st place Best EAP-in-Action Demo – "HASEL: Hydraulically amplified self-healing electrostatic actuators with muscle-like performance". The recipients are Eric Acome, Shane K. Mitchell, Timothy G. Morrissey, Nicholas Kellaris, Vidyacharan Gopaluni Venkata, Madison B. Emmett, Claire Benjamin, Madeline King, Garrett Smith, Miles Radakovitz, and Christoph Keplinger, Univ. of Colorado (United States)

Figure 5: The recipients of the 2nd place Best EAP-in-Action Demo - "Haptic feedback demonstrators based on strip dielectric elastomer actuators", Philipp Loew (on the left in the photo), and Daniel Bruch, Univ. des Saarlandes, Lehrstuhl für Intelligente Materialsysteme, Intelligent Material Systems Lab (Germany).

Figure 6: The recipient of one of the two 3rd place EAP-in-Action Demo - "Dielectric elastomer energy harvester autonomously primed by piezo- and tribo-electricity", Koh Soo Jin Adrian (shown in the photo on the left), Liu Chong, Ahmed Haroun, Anup Teejo Mathew, National Univ. of Singapore (Singapore)

Figure 7: The recipient of the second of the two 3rd place EAP-in-Action Demo - "An untethered swimming robot powered by dielectric elastomer actuators" Mihai Duduta (shown in the photo on the left), Florian C. Berlinger, Hudson Gloria, Radhika Nagpal, Robert J. Wood, and David R. Clarke, Harvard Univ. (United States)

The 2018 EAP-in-Action demonstrations included innovative devices and potential new products that are driven by EAP and they were as follows:

1. Christopher R. Walker, Samuel Rosset, and Iain Anderson, The Univ. of Auckland (New Zealand) – "Capacitive coupling as an underwater signal transmission interface" (**Figure 8**): Capacitive coupling was showcased as a signal transmission method to interface a capacitive strain sensor with electronics underwater. This signal transmission interface has the potential to simplify strain sensor integration into underwater wearables. The demonstration technology could be useful in diver health monitoring, human-interaction, and performance sport coaching applications.

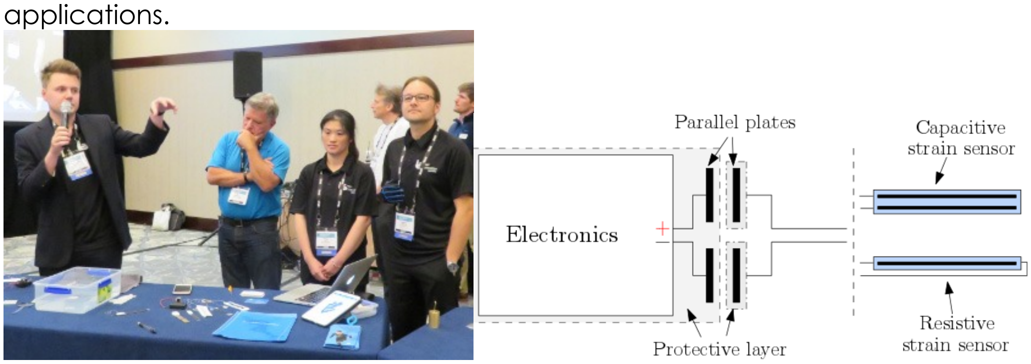

Figure 8: The demonstration of the Capacitive coupling as an underwater signal transmission interface

2. E.-F. Markus Henke, Katherine E. Wilson, and Iain A. Anderson, Biomimetics Lab., The Univ. of Auckland (New Zealand) – "Autonomous soft robots without electronics" (**Figure 9**): Multifunctional dielectric elastomers possess outstanding characteristics for future developments in soft robotics. Large actuation combined with piezo-resistive switches enables new fast elements of dielectric elastomer logic that can directly drive soft robotic structures. Combining soft DE

electronics with silicone skeletons enables the design of entirely soft, autonomous robots. This demo presented the design of soft skeletons (see example below) that is able to undergo large actuations and simultaneously maintaining necessary pre-strains in DE membranes. It allows integration of multifunctional DE electronics for autonomous signal generation using integrated DE oscillators and design that uses DE electronics, soft skeletons, and electro static adhesion for locomotion.

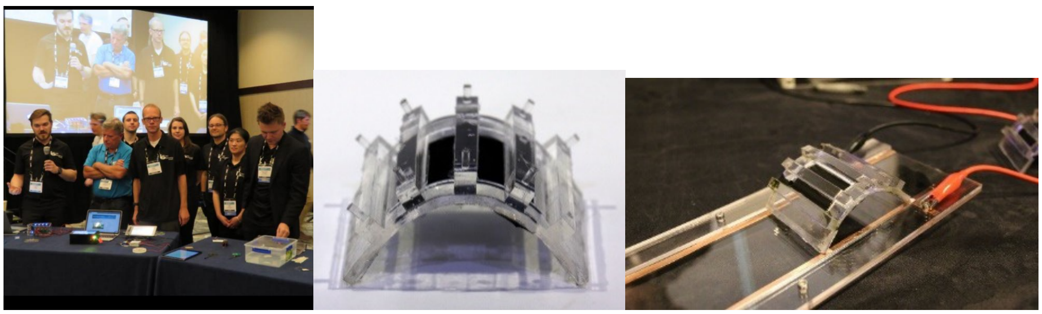

Figure 9: The demo of the autonomous soft robots without electronics

3. Samuel Rosset, Biomimetics Lab, The Univ. of Auckland (New Zealand) and Ecole Polytechnique Fédérale de Lausanne (Switzerland); Patrin Illenberger, Biomimetics Lab, The Univ. of Auckland (New Zealand); Samuel Schlatter Herbert Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Iain Anderson, Biomimetics Lab, The Univ. of Auckland (New Zealand) – "Single channel high voltage power supply with integrated touch screen" (**Figure 10**): Completely independent high-voltage power supply was demonstrated to drive dielectric elastomer actuators. It can generate a user-programmable voltage between 0 V and 5 kV, either continuously or as a square signal between 1 mHz and 1 kHz. It integrates a large 7'' LCD touch screen and a user-friendly graphic user interface. Its integrated battery makes it possible to use the power supply.

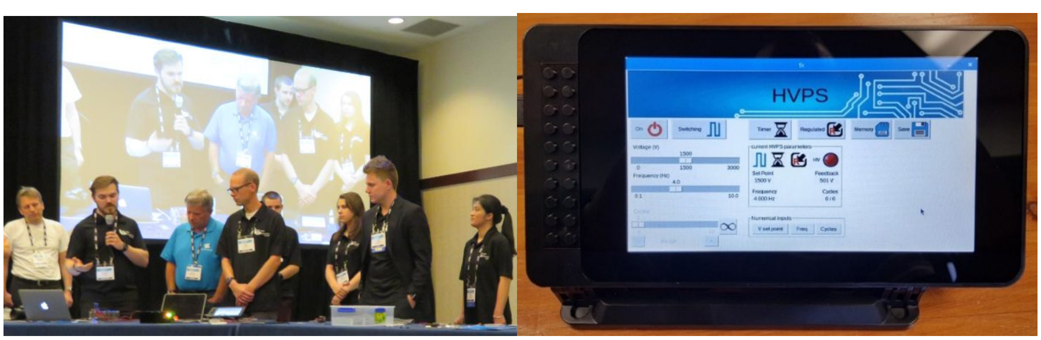

Figure 10: The demo of a single channel high voltage power supply with integrated touch screen

4. Eric Ambos, Iain Anderson, StretchSense Ltd. (New Zealand) – "The latest offerings in wearable electroactive polymer technology from StretchSense Ltd." (**Figure 11**): This will include a glove that transmits via Bluetooth to phone or

computer hand kinematic data from embedded stretch sensors with on-board inertial measurement. Uses include gaming, virtual reality, and good old fashioned air guitar (or violin). The new application software can depict a live 3D rendering of your hand.

Figure 11: The demo of a wearable electroactive polymer technology.

5. Mihai Duduta, Florian C. Berlinger, Hudson Gloria, Radhika Nagpal, Robert J. Wood, and David R. Clarke, Harvard Univ. (United States) – "An untethered swimming robot powered by dielectric elastomer actuators" (**Figure 12**): DEAs are rarely used in untethered robots because their force output is too small to enable locomotion via crawling or swimming. A multilayer assembly technique was developed to fabricate stronger bimorph actuators capable of outputting 20 mN of thrust when flapping in water at 1-8 Hz. A 10 cm long robot encapsulating the high voltage power supply that swims at 0.2 body lengths / second was demonstrated (***Tie in 3rd place***).

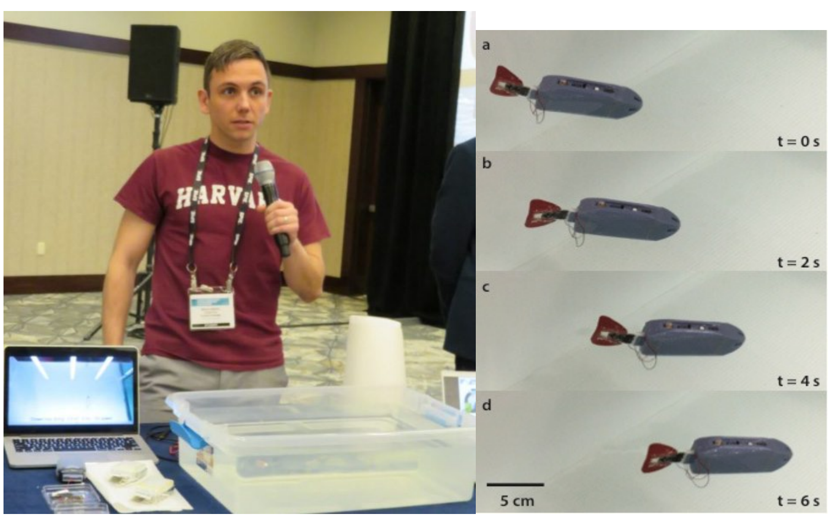

Figure 12: An untethered swimming robot powered by dielectric elastomer actuators

6. Tim Helps, Majid Taghavi, Univ. of Bristol (United Kingdom) – "Towards electroactive gel artificial muscle structures" (**Figure 13**): Electrostatic

phenomenon has been used for decades in the form of variable capacitors to build electro-active actuators. Dielectric elastomers are an example of electrostatic actuators and can produce high forces and specific energies. However, can only be created using soft materials and are strain-limited because of dielectric breakdown at high compression. The presenters are investigating the opportunity for improved performance and alternative actuator arrangements, which could allow for real world applications.

Figure 13: The demo of electroactive gel towards becoming artificial muscle structures

7. Eric Acome, Shane K. Mitchell, Timothy G. Morrissey, Nicholas Kellaris, Vidyacharan Gopaluni Venkata , Madison B. Emmett, Claire Benjamin, Madeline King, Garrett Smith, Miles Radakovitz, Christoph Keplinger, Univ. of Colorado (United States) – "HASEL: Hydraulically amplified self-healing electrostatic actuators with muscle-like performance" (**Figure 14**): Soft electrostatic actuators that provide muscle-like performance was demonstrated. These electrically controlled devices are based on a new class of soft actuators, termed hydraulically amplified self-healing electrostatic (HASEL) actuators, which recover from electrical failure while also combining the benefits of pneumatic and dielectric elastomer actuators. Key attributes were presented including the ability to deliver large actuation force, achieve large actuation strain, output high power, and self-sense deformation for controlled actuation (***1st place***).

Figure 14: The demo HASEL: Hydraulically amplified self-healing electrostatic actuators with muscle-like performance

8. Sarah Trabia, Robert Hunt, Taeseon Hwang, Qi Shen, Zachary Frank, Justin Neubauer, Zakai Olsen, Tyler Stalbaum, Blake Naccarato, Kwang Kim, Active Materials and Smart Living Lab., Univ. of Nevada Las Vegas (United States) – "Multiple mode ionic polymer-metal composite array for the use in travelling wave actuators and sensing" (**Figure 15**): In nature, there are teams of actuator-like limbs that move together (such as cilia). By producing a travelling wave effect, they can transport items, generate flow, and act as sensors. It would be ideal for researchers to be able to reproduce something similar to create more biomimetic systems. Presented was an Ionic Polymer-Metal Composite (IPMC) array that has the ability to work as a team of actuators moving in a travelling wave or a team of sensors, being able to give a reading of the flow across the surface of the array. In this demo an IPMC array that works as an actuator and sensor was presented.

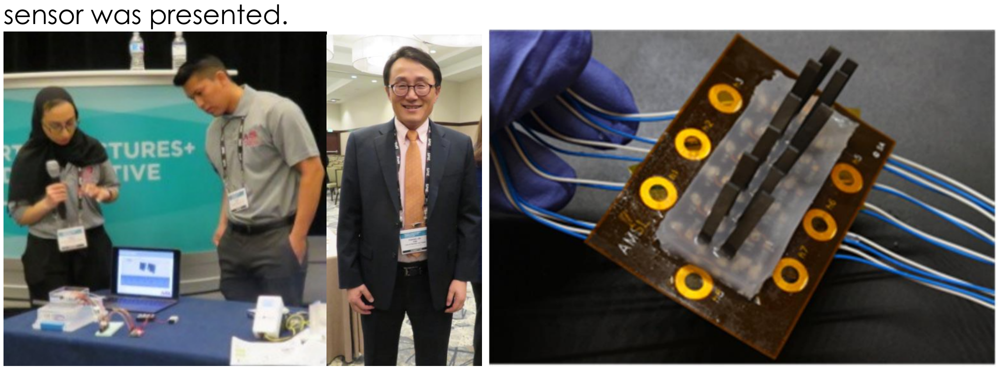

Figure 15: the demo of multiple mode ionic polymer-metal composite array for the use in travelling wave actuators and sensing

9. Liwu Liu, Xiongfei Lv, Qinghua Guan, Jinrong Li, Yanju Liu and Jinsong Leng, Harbin Institute of Technology (China) – "Applications of smart polymers and their

structures" (**Figure 16**): This demonstration will show smart polymers and their structures in action taking advantages of their being light weight, fast response, and large deformation. The demonstration will include the applications of EAP, shape memory polymer (SMP) and other smart structures. Specifically, a smart gripper, based on EAP and SMP materials, will be presented. Different soft actuators with various structures could achieve bend, elongation, contraction and other types of movements.

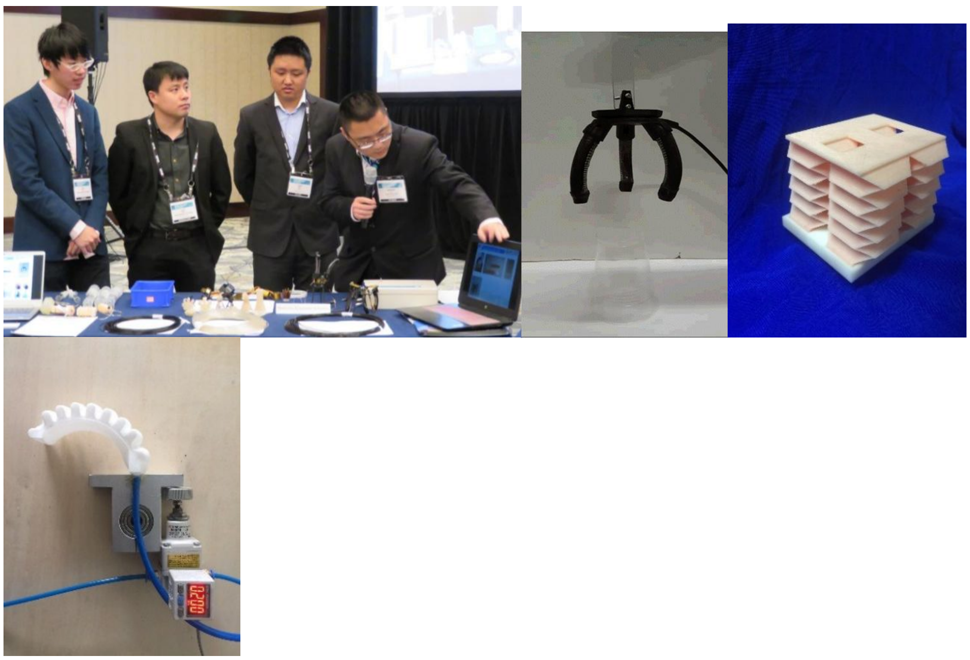

Figure 16: The demo of applications of smart polymers and their structures

10. Lenore Rasmussen, Simone Rodriguez, and Matthew Bowers, Ras Labs, Inc. (United States) – "Synthetic Muscle™: Shape-morphing EAP based materials and actuators" (**Figure 17**): Ras Labs Synthetic Muscle™ is a class of electroactive polymer (EAP) based materials and actuators that contract, and with reversed electric input polarity, expand. Several actuators and sensors will be presented including a thick shape-morphing EAP pad that controllably contract or expand and is being used to prototype self-adjusting extremely comfortable prosthetic socket liners and other void-filling continual-fit applications, such as ear buds.

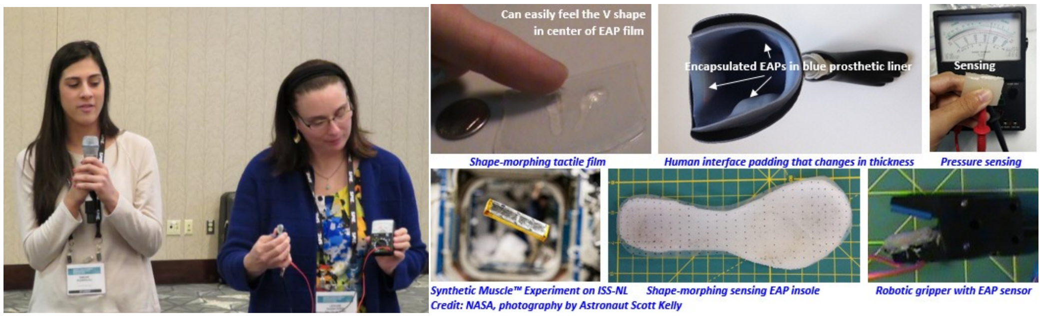

Figure 17: The demo of the Synthetic Muscle™: Shape-morphing EAP based materials and actuators.

11. Philipp Loew, and Daniel Bruch, Univ. des Saarlandes, Lehrstuhl für Intelligente Materialsysteme, Intelligent Material Systems Lab (Germany) – "Haptic feedback demonstrators based on strip dielectric elastomer actuators" (**Figure 18**): In times where touchscreens become more and more present in our daily lives, a haptic feedback based on the image that is being received from the screen is helpful to operate a touch device without looking at it. The haptic feedback demonstrator, which is based on strip dielectric elastomer actuators is, is designed to perform this task, especially simulating buttons and rough surfaces. (***2nd place***)

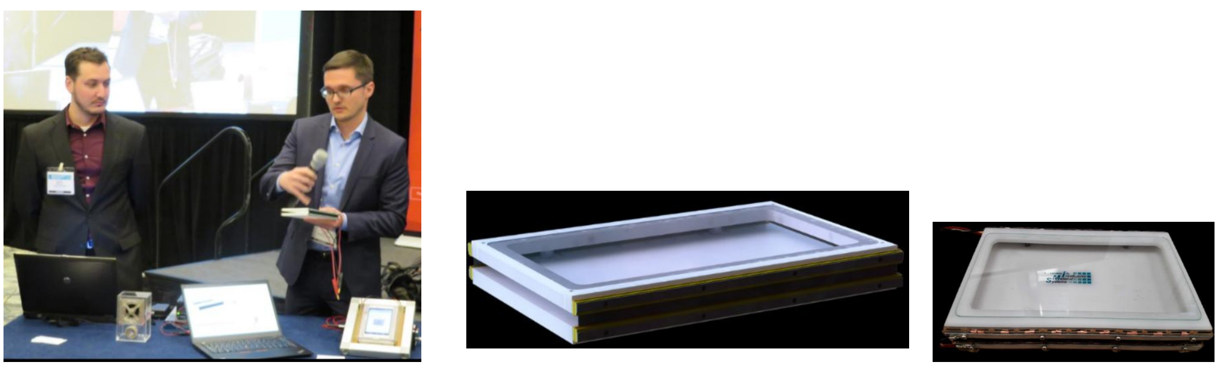

Figure 18: Haptic feedback demonstrators based on strip dielectric elastomer actuators

12. Philipp Loew, and Daniel Bruch, Univ. des Saarlandes, Lehrstuhl für Intelligente Materialsysteme, Intelligent Material Systems Lab (Germany) – "Loudspeaker based on cone shaped out-of-plane dielectric elastomer actuators" (**Figure 19**): Due to their advantages, such as lightweight, energy efficiency, low cost, compactness and freedom in design, dielectric elastomers are suited to substitute commercial loudspeakers. The presented demonstrator supplies the overall driving motion by an out-of-plane biased cone shaped dielectric elastomer actuator. In contrast to conventional loudspeakers, sound is generated by the active membrane surface.

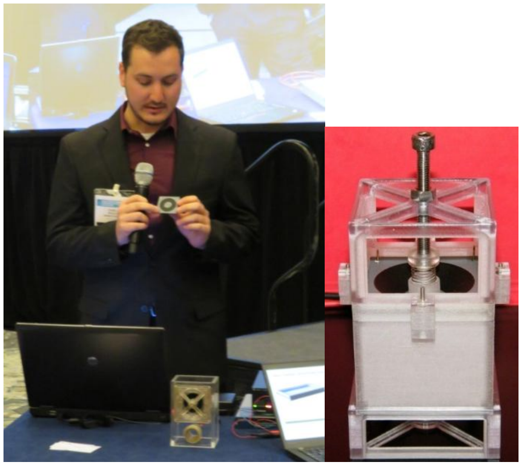

Figure 19: The demo of loudspeaker based on cone shaped out-of-plane dielectric elastomer actuators

13. Koh Soo Jin Adrian, Liu Chong, Ahmed Haroun, Anup Teejo Mathew, National Univ. of Singapore (Singapore) – “Dielectric elastomer energy harvester autonomously primed by piezo- and tribo-electricity” (**Figure 20**): A Dielectric Elastomer (DE) Energy Harvester that is autonomously primed with a piezo- and a tribo-electric source will be demonstrated. The similar nature of piezo- and tribo-electric primers with DE allows a DEG to operate autonomously without the need of an external source of electricity. We present an assembly of a piezo-DEG and tribo-DEG energy harvester. The piezo- and tribo- sources will provide a voltage prime of about 100 V. The DE film then takes over the electrical charges from the piezo- and tribo- source, and amplifies the voltage (**Tie in 3rd place**).

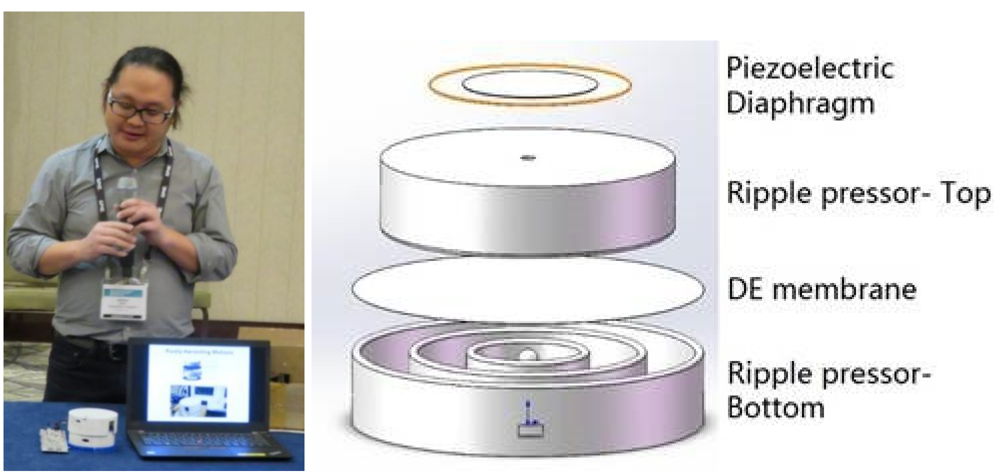

Figure 20: The demo of dielectric elastomer energy harvester autonomously primed by piezo- and tribo-electricity

14. Tino Töpper, Bekim Osmani, Sebastian Buchmann, Matej Siketanc, Biomaterials Science Center, DBE, Univ. of Basel (Switzerland); Dominik Bachmann, Transport at

Nanoscale Interfaces, EMPA (Switzerland); Bert Müller, Biomaterials Science Center, DBE, Univ. of Basel (Switzerland) -- "Enhancing the capabilities of artificial muscle implants using low-voltage dielectric elastomer sensors" (

Figure 21): The Swiss BRIDGE Proof-of-Concept initiative aims for dielectric elastomer sensors (DES) operated at battery voltages. The DES prototype was equipped with electronics built by EMPA. The capacitive sensor is based on a polydimethylsiloxane (PDMS) elastomer layer covered by flexible electrodes. The high-vacuum-based thin-film technology reliably enables the fabrication of sub-micrometer-thin elastomer and nanometer-thin conducting films. Compression is resolved with a sensitivity better than 4 kPa-1, which can be adjusted to the physiological pressures of interest, i.e. from Pa to MPa. The resting capacitance of hundreds of pF/cm2 only requires conventional electronics. The total DES thickness of maximal 20 µm opens the path for a wide variety of applications in medical implants and devices. An energy consumption below 1 nW and the self-healing capabilities enable long-term stability and reliability.

Fabricated on flexible polymer substrates the DES can be directly attached to the skin or implant surface for monitoring with millisecond response. In particular, the team is going to integrate the DES to an artificial muscle implant for incontinence treatments, which is under development at the Wayne State Univ. in Detroit, Michigan. The leading medical expert Nivedita Dhar envisions a reliable force feedback for a substantially improved and biomimetic urinary incontinence treatment.

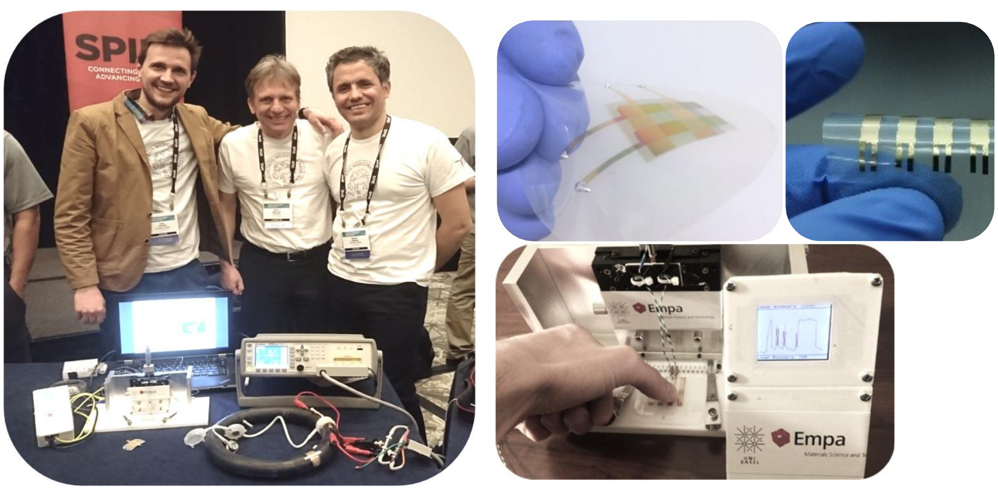

Figure 21: Left: The dielectric elastomer sensor prototype on flexible substrates. Right: The team from the Biomaterials Science Center at the Univ. of Basel T. Töpper, B. Müller and B. Osmani.