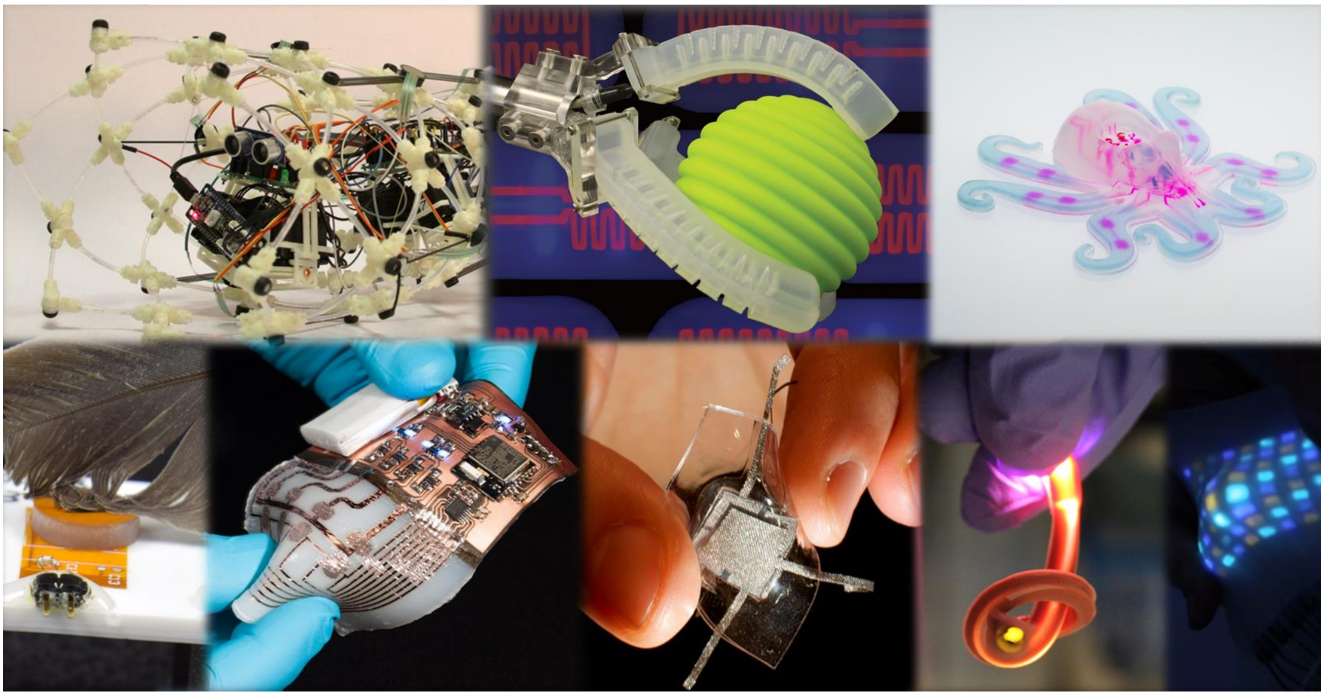


TOWARDS SOFT PERCEPTIVE ROBOTS:

FROM ROBOTIC AND BIOLOGICALLY-INSPIRED SOLUTIONS TO SOFT SENSING TECHNOLOGIES

Full-day Workshop

April 24, 2018

Sala Mascagni, Grand Hotel Palazzo

Livorno, Italy

RoboSoft
The first IEEE-RAS International Conference on
Soft Robotics
LIVORNO, ITALY
April 24-28, 2018

IEEE Robotics & Automation Society
IEEE

Abstract

Exteroception and proprioception are crucial to enable soft robots to discover and react to their surroundings. Through the sense of touch, external cues must be perceived while dealing with exploratory movements, grasping and manipulation of unknown objects. At the same time, body movements in space must be known in order to provide spatial context to exploration and to underlie control policies. All this is highly challenging and leading to a strong interplay among the actuation mechanics of soft bodies, the sensing morphology and functionality, and the soft robotic interaction with the environment.

Our goal is to open a dialogue among scientists from various fields (including material science, robotics, biology, and engineering) to discuss bio-inspired approaches, robotic strategies and sensing solutions towards the development of perceptive soft robots. Challenges related to soft and functional materials, sensing design and emerging technologies will be discussed to shed light on new strategies for filling the gap between the results at material and component level, and what is still missing at robotic level. With the aid of live demos and prototypes, new approaches can be suggested to shape future steps in the field.

Description

Enabling closed-loop control of robotic systems remains a clear challenge in soft robotics. Obtaining autonomy and going beyond open-loop control requires integrating sensors within these soft-bodied systems to provide multiple modes of proprioceptive and exteroceptive feedback. This concerns not only robots and actuators comprised primarily of soft materials (i.e. intrinsically soft), but also those in which the desired deformation is achieved primarily by their architecture (i.e. extrinsically soft). In particular, among many other capabilities soft robots should use mechanosensing in adapting/reacting to unexpected situations. Many results are available today for novel deformable materials for sensing application (e.g. in addition to single elastic sensors, electronic skins are available) however, there is still a gap to overcome to make these results usable in compliant actuated structures and real robotic systems. New flexible/deformable strategies have to be exploited to pursue a full integration of sensing and body, aiming for more sensing functionalities with low computational strategies.

In this vision, the workshop will mainly consist of two highly interdisciplinary parts. In one part, critical examples of sensing in soft bodies will be presented from biology and robotics. Biologically inspired systems for soft locomotion will be presented to shed light on possible simplifying strategies for sensorized robots (of both intrinsic and extrinsic type). Closed-loop soft robotic behaviours will be described, highlighting advantages and challenges associated with sensing implementation, and also drawing input from new fields like soft haptics. In the second part of the workshop, challenges related to soft and functional materials, sensing design and emerging technologies will be discussed, including: soft materials behaviour for sensing mechanical parameters; methods for achieving multimodality in mechanosensing with soft materials; and, 2D and 3D printing technologies for seamlessly embedding sensors within actuated structures.

Topics of interest include, but are not limited to:

- Sensorized soft robots
- Soft robot control
- Biomimetic soft locomotion
- Embodied sensing
- Biomimetic and soft tactile sensing
- Elastic electronics
- Hyperelastic materials for mechanical sensing
- 2D/3D printing of soft materials

The multidisciplinary approach will stimulate creativity and interactions among participants. The audience of the workshop will consist of researchers from different disciplines (robotics, biology, material science, engineering, etc.), and the high technological and scientific level of the topics addressed can make an impact on young researchers and students at Master and PhD level. The discussions during the interactive sessions will be aided by demonstration of robots or components, by using prototypes or videos, and junior researchers will be invited and involved.

Invited Speakers

(In alphabetical order)

#	Name	Affiliation	Country
1	Matteo Cianchetti	Scuola Superiore Sant'Anna	Italy
2	Van Ho	Japan Advanced Institute of Science and Technology	Japan
3	Fumiya Iida	University of Cambridge	UK
4	Unyong Jeong	Pohang Science and Technology University	South Korea
5	Martin Kaltenbrunner	Johannes Kepler University	Austria
6	Rebecca Kramer	Yale University	USA
7	Carmel Majidi	Carnegie Mellon University	USA
8	Robert Shepherd	Cornell University	USA
9	Barry Trimmer	Tufts University	USA
10	Michael Wehner	University of California Santa Cruz	USA
11	Patricia Xu	Cornell University	USA

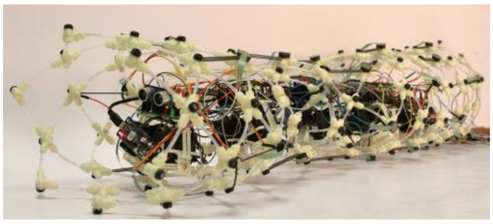
Program

TIME	SPEAKER	TOPICS
09:00 – 09:05	*Welcome - Lucia Beccai & Kathryn Daltorio*	
	BIOLOGICALLY-INSPIRED AND ROBOTIC SOLUTIONS FOR SENSING IN SOFT ROBOTS	
09:05 - 09:30	Kathryn Daltorio	*Sensing for Soft Body Locomotion in Biologically Inspired Robots*
09:30 - 09:55	Carmel Majidi	*Towards Autonomous Soft Robots: Materials, Design Architectures, & Modeling*
09:55 - 10:20	Barry Trimmer	*What Makes Sense? Mechanosensing for Soft Locomotion*
10:20 - 10:45	Rebecca Kramer	*Sensory Skins: A Surface-based Approach to Soft Robot Control*
10:45 - 11:00	*Coffee Break*	
11:00 - 11:25	Matteo Cianchetti	*Stretchable Sensors for Manipulators Working in Wet Conditions*
11:25 - 11:50	Van Ho	*Wrin'Tac: An Active Sensorized Body for Dual-Assessment of Self Deformation and External Interaction*
11:50 - 12:15	Fumiya Iida	*Embodied Intelligence in Soft Sensor Morphology*
12:15 - 13:00	**INTERACTIVE SESSION:** DEMOS/PROTOTYPES/VIDEOS (25 min) PANEL DISCUSSION WITH SPEAKERS OF MORNING SESSION (20 min)	
13:00 - 14:20	*Lunch*	
	DESIGN, MATERIALS AND TECHNOLOGIES FOR SOFT SENSING IN ROBOTS	
14:20 - 14:45	Lucia Beccai	*Mechanosensing for Soft Robotics: Technological Approaches and Open Issues*
14:45 - 15:10	Robert Shepherd	*Bioinspired Design & Additive Manufacturing of Soft Materials, Machines, Robots, and Haptic Interfaces*
15:10 - 15:35	Unyong Jeong	*Printed Tactile Sensors Integrated in Robots*
15:35 - 16:00	Martin Kaltenbrunner	*Imperceptible Plastic Sensor Foils for Soft Electronics and Machines*
16:00 – 16:30	*Coffee Break*	
16:30 - 16:55	Michael Wehner	*Embedded 3D Printing of Autonomous and Somatosensory Soft Robots*
16:55 - 17:20	Patricia Xu	*Continuous Deformation Sensing Using Stretchable Optoelectronic Lightguides for Soft Robots*
17:20 - 18:00	**INTERACTIVE SESSION:** DEMOS/PROTOTYPES/VIDEOS (20 min) PANEL DISCUSSION WITH SPEAKERS OF AFTERNOON SESSION (20 min)	
18:00	*Concluding remarks - Lucia Beccai & Kathryn Daltorio*	

SENSING FOR SOFT BODY LOCOMOTION IN BIOLOGICALLY INSPIRED ROBOTS

Kathryn Daltorio
Case Western Reserve University, Mechanical Engineering, Cleveland, OH
E-mail: kam37@case.edu

Compliance allows a robot to conform to a surface passively. This can give the robot more traction on the ground or more reliable object grasping – even for open-loop behaviors. Thus while rigid robots might need sensors to determine when and if actions successful, it might seem like sensing is less critical in soft robotics. However, when we compare current soft robots with their biological counterparts, we see that animals and plants are out-performing robotic versions. In fact, softness often makes some robots perform worse. This is evident in soft worm robots, like the ones in our lab. We can make very high traction robots, but the softer they are and the higher the friction coefficients the slower they move. This is because worm-like locomotion requires coordinated



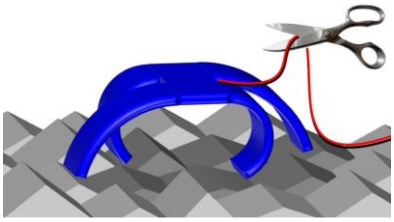
exploitation of softness. I will show the successes and failures with and without off-the-shelf sensor solutions for our worm robots. This highlights some of the problems that we need sensors to solve: shape estimation, terrain classification, traction coordination, decision-making for exploration, and more. Closed-loop behaviors for these problems will be critical for future soft robotic applications in medicine, infrastructure inspection, and search and rescue. In this workshop, our goal is to open a dialogue that connects new possibilities in soft sensor design and in robotic design for soft applications.

Kathryn Daltorio is an assistant professor at Case Western Reserve University in the Department of Mechanical Engineering with a dual appointment in the Department of Electrical and Computer Science Engineering. Her research is in biologically-inspired robotics including climbing robots, decision-making in cockroaches and most recently earthworm robots. Together with interdisciplinary collaborators, she has produced 50 publications. She was awarded fellowships from NSF, NDSEG, and AAUW.

TOWARDS AUTONOMOUS SOFT ROBOTS: MATERIALS, DESIGN ARCHITECTURES, & MODELING

Carmel Majidi
Soft Machines Lab, Carnegie Mellon University, Pittsburgh USA 15213
E-mail: cmajidi@andrew.cmu.edu

Progress in soft lithography, additive manufacturing, biohybrid engineering, and soft materials integration have led to extraordinary new classes of soft-matter sensors, circuits, and actuators. These materials represent the building blocks of soft machines, robots, and bio-inspired systems that will exhibit the rich multifunctional versatility and robust adaptability of soft biological organisms. While there are key challenges in materials and manufacturing that remain to be addressed, further progress in soft robotics now depends on accomplishing a new set of goals: systems-level materials integration, untethered functionality, and robot autonomy. In this talk, I will focus on this latter set of challenges and the new fundamental questions that emerge when exploring the interface of soft multifunctional materials, rigid microelectronics, and robot mobility.



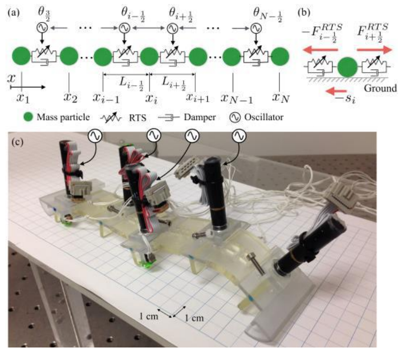
In particular, I will report efforts by my lab to create an untethered soft robot capable of walking in a variety of environments, including rocky terrain and confined spaces. I'll also present recent work on mechanically robust and self-healing electronics that can withstand extreme loading and damage. When used as internal circuit wiring within an electrically-powered soft robot, such materials enable autonomous response to tearing, puncturing, or material removal – damage modes that would be catastrophic for most other soft-bodied robots. I will close by highlighting ongoing efforts to create new computational tools for modeling the motion and surface interactions of limbed soft robots. Based on continuum mechanics, finite element analysis, and emerging techniques in computer graphics, these tools represent another critical requirement for soft robot autonomy by potentially enabling on-board computational intelligence and adaptive decision making.

Carmel Majidi is an Associate Professor of Mechanical Engineering at Carnegie Mellon University, where he leads the Soft Machines Lab. Prior to arriving at CMU, Prof. Majidi had postdoctoral appointments at Harvard University and the Princeton Institute for the Science and Technology of Materials. Prof. Majidi received his doctoral training at UC Berkeley, where he worked with Profs. Ronald Fearing and Bob Full to examine natural gecko adhesion and develop a gecko-inspired shear-activated adhesive. Currently, his research is focused on the development of new classes of soft multifunctional materials for stretchable electronics, sensing, and muscle-like actuation. The purpose of these novel materials is to enable wearable computing and bio-inspired robotics that intrinsically match the mechanical properties of natural biological tissue. Prof. Majidi has received Young Investigator awards from DARPA, ONR, AFOSR, and NASA all for work related to soft-matter robotics and engineering.

WHAT MAKES SENSE? MECHANOSENSING FOR SOFT LOCOMOTION

Barry Trimmer
Neuromechanics and Biomimetic Devices Laboratory, Tufts University, MA
E-mail: Barry.Trimmer@tufts.edu

The types of sensory information necessary to control movements in soft-bodied animals and robots are largely unknown. It is generally assumed that animals monitor strain in most tissues and that this is supplemented by force sensors in muscles and touch sensors on the body surface. Similar capabilities are built into traditional robots to provide feedback for posture control, manipulation and locomotion. However, in the absence of discrete joints and other skeletal elements it is not clear what sensors should be built into deformable robots. We have been studying such sensory-motor integration in the soft scansorial larval insect Manduca sexta. Because Manduca lacks image–forming eyes most sensory feedback for locomotion is mediated by mechanosensors on the body surface and stretch receptors attached to internal tissues. In addition, the internal body wall is tiled by a plexus of sensory neurons whose role in locomotion is poorly understood. Recordings from sensory nerves in the abdomen show that neurons associated with the body wall are sensitive to small amplitude strains, including vibration. The anatomy and response properties of these neurons suggest that they respond to body deformation. The validity of the control strategy is demonstrated with simulation and a soft crawling robot that uses deformation of its body to detect changes in friction on a substrate. This information is used to provide local sensory feedback for coupled oscillators that control the robot's locomotion. One goal of these studies is to determine how mechanical feedback is collected, processed and incorporated into the control of movements by highly deformable climbing animals and robots working in complex environments.



Barry Trimmer is the Henry Bromfield Pearson Professor of Natural Science in Biology at Tufts University. His research focus is on the Neuromechanics of Locomotion, the science of how animals control their movements. In addition to his work on living systems, Professor Trimmer is Director of the Tufts Neuromechanics and Biomimetic Devices Laboratory which specializes in the application of found biological principles to design and fabricate Soft Robots. Dr. Trimmer is also Editor in Chief of the journal Soft Robotics. His lab designs and builds a variety of soft robots that are used to test hypotheses about locomotion and to explore new types of control systems. His interests in living systems and robots converge in his recent research that seeks to "grow" robotic devices using a combination of biosynthetic materials, cellular modulation, and tissue engineering. These Biosynthetic Robots will be versatile, safe, biocompatible and biodegradable.

SENSORY SKINS: A SURFACE-BASED APPROACH TO SOFT ROBOT CONTROL

Rebecca Kramer-Bottiglio
Yale School of Engineering and Applied Science, Yale University
E-mail: rebecca.kramer@yale.edu

During this workshop talk, I will present my group's progress towards sensory skins – distributed sensors over a surface to provide proprioceptive and tactile feedback. I will discuss the merits of both liquid metal-based resistive sensors and conductive composite-based capacitive sensors in terms of manufacturability and robustness in implementation. I will also show demonstrations of sensory skin prototypes being used for soft robot state estimation and control, including the closed-loop control of a soft gripper designed for pack-and-deploy operations.

Rebecca Kramer-Bottiglio is an Assistant Professor of Mechanical Engineering and Materials Science at Yale University. Prior to joining the faculty at Yale, she was an Assistant Professor of Mechanical Engineering at Purdue University for four years. She currently serves as an Associate Editor for Frontiers in Robotics and AI: Soft Robotics, IEEE Robotics and Automation Letters, and Multifunctional Materials. She is the recipient of the NSF CAREER Award, NASA Early Career Faculty Award, AFOSR Young Investigator Award, ONR Young Investigator Award, and was named to Forbes' 2015 30 under 30 list.

STRETCHABLE SENSORS FOR MANIPULATORS WORKING IN WET CONDITIONS

Matteo Cianchetti
The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy
E-mail: matteo.cianchetti@santannapisa.it

The I-SUPPORT soft arm is a manipulator based on soft and flexible materials, conceived to serve as a robotic shower to support elderly people in personal hygiene tasks. Soft robotics represents the most suitable approach to build a new generation of soft modular assistive manipulators for safely come interacting with humans in challenging scenarios (e.g. bathing activities). The design of the robot took into consideration all the constraints imposed to guarantee frail user safety in a wet scenario, but while soft mechatronics technologies intrinsically possess mechanical safety, electrical compatibility becomes a major issue. Moreover, this affects not only the actuation system, but also sensing. In particular, the manipulator needs reliable position and contact information as feedback for the control loop, which is fundamental for an effective interaction with the user. To the best of our knowledge, currently no sensing technology can work in wet

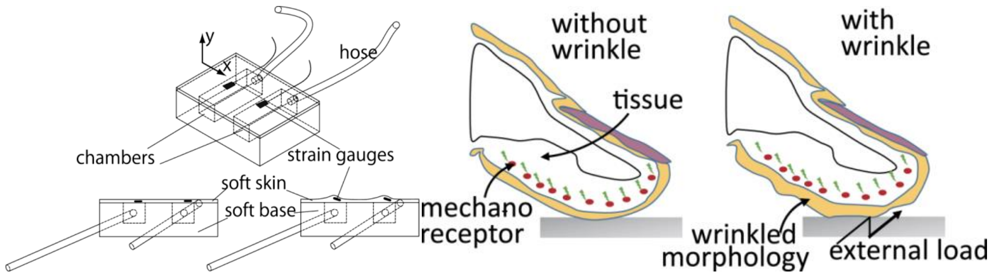
conditions reliably. A first approach was based on completely waterproofing the manipulator, which allowed integrating stretch sensors based on dielectric elastomers. Despite good sensing performances allowing spatial reconstruction of manipulator's configuration, the stiffness of the manipulator module increased remarkably, reducing the working space of the system. This approach was ineffective and introduced undesired mechanical constraints. A more ecological approach involved just fluidic-based technologies. Instead of fighting wet conditions, we decided to move towards an approach that is not influenced by the presence of water. For the spatial configuration, external cameras and colour markers were used, while for the contact information a simple solution based on pressurized fluids has been integrated on the tip of the manipulator. Despite providing only basic knowledge, this ensures a correct interaction with the user and influences neither the workspace nor the dynamics of the manipulator.

Matteo Cianchetti is Assistant Professor at The BioRobotics Institute of Scuola Superiore Sant'Anna (SSSA). He received the MSc degree in Biomedical Engineering (cum laude) from the University of Pisa, Italy, in 2007 and the PhD degree in Biorobotics (cum laude) from SSSA. He is author or co-author of more than 40 international peer reviewed papers and he regularly serves as a reviewer for more than 10 international ISI journals. He has been and currently is involved in several EU-funded projects with the main focus on the development of Soft Robotics technologies (including flexible fluidic actuators, granular jamming based systems, electro-active polymers and shape memory alloys). His main research interests include the study and development of new systems and technologies based on soft/flexible materials for soft actuators, smart compliant sensors and flexible mechanisms.

WRIN'TAC: AN ACTIVE SENSORIZED BODY FOR DUAL-ASSESSMENT OF SELF DEFORMATION AND EXTERNAL INTERACTION

Van Ho
Japan Advanced Institute of Science and Technology, Japan
E-mail: van-ho@jaist.ac.jp

Conventional sensors' sensing abilities are determined by embedded sensing elements, with the number of modalities depending on the number of corresponding sensing elements. Sensing elements are in fixed locations corresponding to specific sensing tasks. In the present study, we utilize a wrinkled morphology to actively change its sensing abilities in interaction with its environment, using single type sensing elements. Our proposed prototype involves integration of an actuator and strain gauge sensing elements. Under air pressurization, wrinkle patterns can be constructed and deconstructed to alter the posture of sensing elements beneath the skin, resulting in changes in sensor outputs. Preliminary results are expected to pave a new way for exploring the application of morphological control in active tactile sensing systems.



Van Ho obtained the PhD degree on Robotics at Ritsumeikan Unviersity, Japan in 2012. He had completed the JSPS Post doctoral fellow in 2013 before joining Advanced R&D Center, Mitsubishi Electric Corp. in Japan. From 2015 to 2017, he worked as Assistant Professor at Ryukoku University in Kyoto, where he led a laboratory on soft haptics. From 2017, he joined JAIST for setting up a laboratory on Soft Robotics. His research interests are soft robotics, soft haptics, grasping and manipulation, bio-inspired robots.

EMBODIED INTELLIGENCE IN SOFT SENSOR MORPHOLOGY

Fumiya Iida
Department of Engineering, University of Cambridge, UK
E-mail: fi224@cam.ac.uk

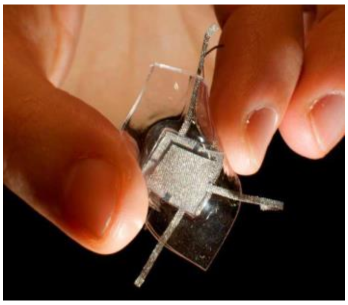
Soft systems (both animals and robots) intrinsically suffer from the lack of sensor resolutions to track their own body motions. On the one hand a soft body usually has a large number of degrees of freedom, if not infinite, while there are always limited resources of sensory receptors and processes available, on the other. Starting from this basic assumption, we have been investigating how the constraints of soft sensing (i.e. sensor morphology in soft systems) can determine overall behaviours of soft systems, or more provocatively, how soft sensors shapes the way robots behave. We will introduce several case studies we have been exploring in my group for discussing some conceptual design principles about embodied intelligence.

Fumiya Iida received his bachelor and master degrees in mechanical engineering at Tokyo University of Science (Japan, 1999), and Dr. sc. nat. in Informatics at University of Zurich (2006). In 2004 and 2005, he was also engaged in biomechanics research of human locomotion at Locomotion Laboratory, University of Jena (Germany). From 2006 to 2009, he worked as a postdoctoral associate at the Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology in USA. In 2006, he was awarded the Fellowship for Prospective Researchers from the Swiss National Science Foundation, and in 2009, he was appointed as a Swiss National Science Foundation Professor for bio-inspired robotics at ETH Zurich. His research interests include biologically inspired robotics, embodied artificial intelligence, and biomechanics, and he has been involved in a number of research projects related to dynamic legged locomotion, navigation of autonomous robots, and human-machine interactions. He has so far published over forty publications in major robotics journals and conferences, and edited two books. Currently he serves on the editorial board of the Journal of Intelligent & Robotic Systems and Frontiers in Neuroscience (Neurorobotics), and as a program committee member for international conferences and workshops. In addition, he has organized a few seminal meetings such as the International Conference of Morphological Computation and International Seminar of Embodied Artificial Intelligence.

MECHANOSENSING FOR SOFT ROBOTICS: TECHNOLOGICAL APPROACHES AND OPEN ISSUES

Lucia Beccai
Center for MicroBiorobotics, Istituto Italiano di Tecnologia, Italy
E-mail: lucia.beccai@iit.it

Tactile sensing is crucial robotics, and soft robotics poses more stringent requirements for design - since it is expected that robots are immersed in the real world moving in vulnerable and undefined surroundings by easily adapting through their soft bodies. Similar to the natural mechanosensitive structures of animals and plants, artificial sensing solutions need to be compliant with the environment, in addition to being conformant to the robot soft body (or human body in case of wearable systems) without compromising sensing functionality. Moreover, external stimuli should be distinguished from mechanical cues originated from the soft body itself during movement. I will



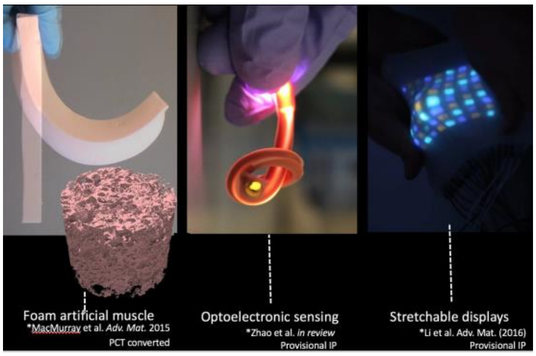
describe the approaches of our group in the area of tactile sensing, and mechanical sensing more at large - i.e. “mechanosensing”, aiming at sensitive but robust and low-cost solutions. We have exploited smart layouts with combinations of soft materials (e.g. elastomers and conductive textiles), to enable detection and discrimination of different mechanical cues (e.g. pressure, strain, multi-directional force) by means of different principles (e.g. capacitive, resistive, optical), and I will also show how some of the results in 2D soft sensing can be successfully applied to develop smart garments for rehabilitation and human assistance. In this workshop we aim at discussing a plethora of possible technologies and methods that can go beyond the classic 2D smart sensing approaches, hence I will mention some preliminary work on soft sensing systems inspired from nature (like for structures from plant sensory organs).

Lucia Beccai is Tenure Track Senior Researcher at the Center for Micro-BioRobotics (CMBR) of the Istituto Italiano di Tecnologia, Pontedera, Italy. She has MSc in Electronic Engineering (University of Pisa) and PhD in Microsystem Engineering (University of Tor Vergata, Rome). She collaborated in many international projects at European and intercontinental level, especially on development of bionic hands and artificial touch. Until 2009, she was Assistant Professor in Biomedical Engineering Institute of Biorobotics of SSSA (Pisa). Then she joined IIT as Team Leader contributing to the start-up of the CMBR and from 2015 she has a Tenure Track position. Her research activities and interests include: smart tactile systems inspired from living organisms, new technologies from milli- to micro-scale for enabling 3D soft mechanical sensing, soft skins, soft robotic systems for investigating active and passive touch, and powerless sensing. Applications are in soft robotics, including wearable devices/human-computer interfaces. She is author and co-author of more than 100 articles on refereed international journals, books, international conference proceedings and serves as AE for Scientific Reports and Frontiers in Robotics and AI, Soft Robotics Section.

BIOINSPIRED DESIGN & ADDITIVE MANUFACTURING OF SOFT MATERIALS, MACHINES, ROBOTS, AND HAPTIC INTERFACES

Robert Shepherd
Organic Robotics Lab, Cornell University., Ithaca, NY
E-mail: rfs247@cornell.edu

This talk will present multidisciplinary work from material composites and robotics. We have created new types of actuators[1], sensors[2], displays[3], and additive manufacturing techniques for soft robots and haptic interfaces[4]. For example, we now use stretchable optical waveguides as sensors for high accuracy, repeatability, and material compatibility with soft actuators. For displaying information, we have created stretchable, elastomeric light emitting displays as well as texture morphing (Pikul et al., in preparation) skins for soft robots. We have created a new type of soft actuator based on molding of foams, new chemical routes for stereolithography printing of silicone and hydrogel elastomer based soft robots, and implemented deep learning in stretchable membranes for interpreting touch (Larson et al., in preparation). All of these technologies depend on the iterative and complex feedback between material and mechanical design. I will describe this process, what is the present state of the art, and future opportunities for science in the space of additive manufacturing of elastomeric robots.



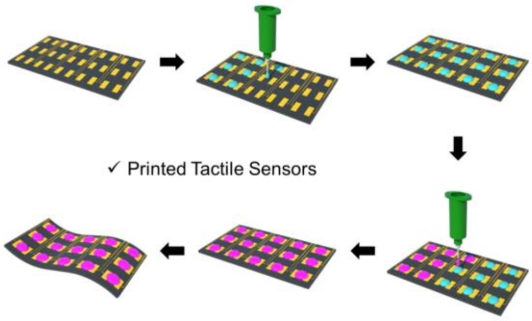
Robert Shepherd is an assistant professor at Cornell University's Organic Robotics Lab (ORL), which focuses on using synthetic adaptation of natural physiology to improve machine function and autonomy. Our research spans three primary areas: bioinspired robotics, haptic interfaces, soft sensors and displays, and advanced manufacturing. We use soft materials, mechanical design, and novel fabrication methods to replicate sensory organs such as dermal papillae, replicate organs that rely on actuation such as the heart, and to power soft actuators and robots. He is the recent recipient of an Air Force Office of Scientific Research Young Investigator Award, and an Office of Naval Research Young Investigator Award. His work has been featured in popular media outlets such as the BBC, Discovery Channel, and PBS's NOVA science documentary series.

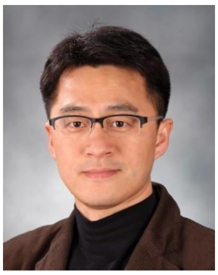
[1] Mac Murray, B.C., et al., *Poroelastic Foams for Simple Fabrication of Complex Soft Robots.* Advanced Materials, 2015. 27(41).
[2] Zhao, H., et al., *Optoelectronically innervated soft prosthetic hand via stretchable optical waveguides.* Science Robotics, 2016. 1(1).
[3] Larson, C., et al., *Highly stretchable electroluminescent skin for optical signaling and tactile sensing.* Science, 2016. 351(6277).
[4] Peele, B., et al., *3D Printing Soft Actuators via Digital Mask Projection Stereolithography.* Bioinspiration & Biomimetics, 2015. 5(055003).

PRINTED TACTILE SENSORS INTEGRATED IN ROBOTS

Unyong Jeong
Department of Materials Science and Engineering,
Pohang University of Science and Technology, Pohang, Korea
E-mail: ujeong@postech.ac.kr

Recent developments in artificial intelligence and service robots have increased the importance of robot development with tactile feedback. Beyond the traditional silicon-based tactile sensors, flexible and stretchable tactile sensors that are able to maintain their function even when deformed, such as human skin, are receiving more attention. In this presentation, I talk about the production of various sensing materials for stretchable tactile sensors. Special emphasis is placed on printed sensors, where bonding to circuits, sensors and flexible substrates are all fabricated in print. I present a stretchable tactile sensor that can be easily attached to and detached from a robot. I also talk about touch-actuated light-emitting sensors for soft robots that simultaneously implement a pressure sensor and luminescence characteristics.



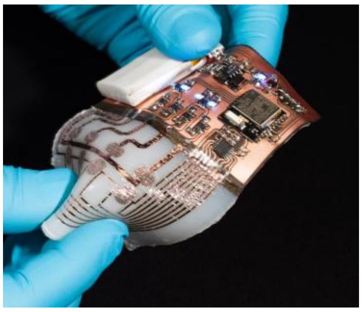


Unyong Jeong received a B.S. degree in chemical engineering from Pohang University of Science and Technology (POSTECH) in Korea (1998). He received a M.A. degree (2000) and a Ph.D. degree (2003) on polymer physics in the same department. He joined Prof. Younan Xia's group as a postdoctoral fellow to study the synthesis and applications of inorganic nanostructured materials. Then, he joined in Yonsei University in Korea (2006) and he moved to Dept. Materials Science and Engineering at POSTECH (2015). His research aims at understanding the mechanical electrical properties of conductive materials and fabricating stretchable electronic devices such as high-resolution tactile sensors for robots. Also, his research includes solution-based synthesis of nanomaterials and their applications.

IMPERCEPTIBLE PLASTIC SENSOR FOILS FOR SOFT ELECTRONICS AND MACHINES

Martin Kaltenbrunner
Soft Electronics Laboratory, Johannes Kepler University, Linz, Austria
E-mail: martin.kaltenbrunner@jku.at

Electronics of tomorrow will be imperceptible and will form a seamless link between soft, living beings and the digital world. This new form of ultra-conformable electronics places severe physical requirements on the active components that constitute modern foil-like electronic systems. Weight and flexibility become key figures of merit for large area electronics such as robotic skin, as they critically influence the mechanical response and perception of the artificial sensory system.



With less than 2 µm total thickness, imperceptible electronic foils are light (≈3-4 g m-2) and unmatched in flexibility, they are operable with radii of curvature below 5 µm, yet highly durable and withstand severe crumpling without any performance degradation. These are prerequisites for intimate contact with soft, biological tissue or organs and complex, arbitrarily shaped 3D free forms that enable applications spanning medical, safety, security, infrastructure, and communication industries.

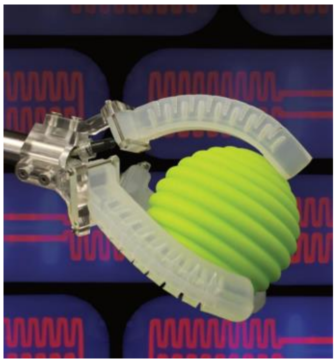
This talk introduces a technology platform for the development of large-area, ultrathin and lightweight electronic and photonic devices, including organic solar cells, light emitting diodes, active-matrix touch panels, implantable organic electronics, imperceptible electronic wraps and "sixth-sense" magnetoception in electronic skins. These large area sensor networks build the framework for electronic foils and artificial sensor skins that are not only highly flexible but become highly stretchable and deployable when combined with engineered soft substrates such as elastomers, shape memory polymers or tissue-like hydrogels. Applications of such sensor foils in soft robotics and in soft machines allow sensing a wide range of stimuli and will be discussed in detail.

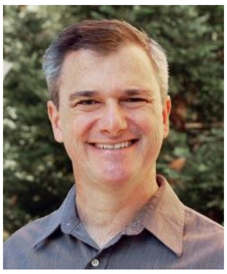
Martin Kaltenbrunner is an associate professor in the Soft Matter Physics Department at the Johannes Kepler University, heading the Soft Electronics Laboratory. He received his master's and PhD degrees in physics from the Johannes Kepler University in 2008 and 2012, respectively. He then joined the Someya-Sekitani Lab for Organic Electronics at The University of Tokyo as postdoctoral researcher prior to his present position. Kaltenbrunner's research interests include soft electronics and machines, photovoltaics, lightning and thin film transistors, flexible and stretchable electronics, and electronic skin.

EMBEDDED 3D PRINTING OF AUTONOMOUS AND SOMATOSENSORY SOFT ROBOTS

Michael Wehner
Jack Baskin School of Engineering, University of California Santa Cruz, CA
E-mail: miwehner@ucsc.edu

Recent advances in soft robotics motivate the need for new fabrication strategies that enable the heterogeneous, programmable assembly of soft matter with disparate mechanical, electrical, and/or chemical properties into functional architectures. Here, I will present a free-form, multimaterial 3D printing technique for manufacturing soft robots. In this approach, known as embedded 3D (EMB3D) printing, functional and fugitive inks are extruded through a nozzle that is translated omnidirectionally within a soft, viscoplastic matrix material that surrounds and supports the printed features (e.g. catalytic, sensing, and pneumatic networks). I will first briefly describe how we have used EMB3D printing to create entirely soft, hardware-free robots and soft sensors. I will then present our work in EMB3D printing soft somatosensitive actuators innervated with multiple conductive features for haptic, proprioceptive, and thermoceptive sensing in soft robotic end effectors. This integrated design, materials, and manufacturing approach can be readily extended to other soft robotic systems that are entirely soft, require somatosensory feedback for improved control, or cannot be made with traditional manufacturing methods.





Michael Wehner is an assistant professor of Computer Engineering at the University of California, Santa Cruz. Michael studies how robots interact with their surroundings, particularly humans, animals, and other biological systems, and extending to general interaction with unstructured environments. Current work focuses on soft systems and soft-rigid hybrid systems including soft sensors for proprioceptive sensing in soft grippers and morphological computation. Michael Wehner earned his Ph.D. from UC Berkeley in 2009, where his research focused on bioinspired systems, human machine interaction, and wearable robotics. In 2011, Michael returned to academia as a post-doctoral fellow at Harvard University, where, he explored soft alternatives to conventional rigid orthotics for disabled children, and developed the first engineered soft exosuit. Working with the labs of Rob Wood, Jennifer Lewis and George Whitesides, he developed Octobot, the first entirely soft untethered robot, replacing rigid battery, pump, and controller with monopropellant fluid power and microfluidic soft logic. Michael has also worked extensively in industry in various engineering, consultant, and management roles in the semiconductor capital equipment, medical device, and consumer goods fields.

CONTINUOUS DEFORMATION SENSING USING STRETCHABLE OPTOELECTRONIC LIGHTGUIDES FOR SOFT ROBOTS

Patricia Xu
Organic Robotics Lab, Cornell University., Ithaca, NY
E-mail: pax2@cornell.edu

In recent years, a variety of flexible and stretchable piezoelectric, capacitive, resistive, magnetic, and optical sensors have been developed for measuring deformations within or over soft structures. Many of them are fabricated into 2D sheets or onto the surface of an object to measure the deformations over their surface. While surface deformations can be used to measure the overall shape of a structure, being able to internally measure the shape of the structure while externally measuring interactions with other objects would be ideal. The 2D sensors are great electronic skins but are hard to adapt to the 3D space inside structures (soft or otherwise). Distributed internal sensors would provide important information on local deformations and possibly failures. Of the many types of sensors, optical strain sensors in particular have great properties such as low hysteresis, high sensitivity, linearity, and low cost fabrications, but each sensor can only measure an overall elongation or force applied. To leverage the properties of optical sensors, we created a system of lightguides that interact with each other through frustrated total internal reflection to localize the positions of the deformations. To integrate this system within a soft structure, we stereolithography 3D print a low modulus, polyurethane scaffold through which we thread each lightguide into place. We will demonstrate that our optical sensor array can be used to localize the placement of both internal deformations and external touches.

Patricia Xu is a second year Ph.D. student in the mechanical engineering department at Cornell University. She earned B.S. degrees in mechanical and materials engineering and is interested in using her multidisciplinary knowledge in the field of soft robotics. Her research involves creating soft machines with sensing abilities, and she currently works on using stereolithography 3D printing to create soft structures with internal optical sensors to measure their deformation state.

Notes

ORGANIZERS

Lucia Beccai

Senior Researcher
Center of Micro-BioRobotics
Istituto Italiano di Tecnologia
Viale Rinaldo Piaggio 34
56025 Pontedera (Pisa), Italy

Kathryn Daltorio

Assistant Professor
Case Western Reserve University
Mechanical Engineering
Glennan 589
Cleveland, OH 44106-7222, USA

Terrazza Mascagni, Livorno, Italy (Photo credit: Antonio Razzauti)