Guest Editorial
Focused Section on Soft Actuators, Sensors, and Components (SASC)

I. INTRODUCTION

HIGHLY deformable and soft actuators, sensors, and components (SASC) are crucial in the design and development of soft mechatronic and robotic systems that safely interact with humans and delicately handle products through an assembly line. The key advantages of mechatronic systems comprised of SASC are their ability to deform and take on shapes for increased adaptability and better control of forces for enhanced safety. The development of many SASC are often inspired by the form and motion of biological organisms, and often strive to achieve inherently compliant and safe interfaces. The development of SASC for mechatronic and robotic systems presents a number of challenges in materials development, mathematical modeling, mechanism design and fabrication, and control. This area of research has attracted increasing attention from scientists and engineers in recent years.

The objective of this Focused Section is to compile recent research and development efforts contributing to soft actuators, sensors, and components in the context of mechatronic systems. The contributions address the state-of-the-art in associated developments and methodologies, and the perspectives on future developments and applications of SASC.

II. HIGHLIGHTS OF THE FOCUSED SECTION

This Focused Section contains fourteen papers that cover many aspects of SASC, for example, modeling and control of soft actuators, design and development of soft wearable sensing suits, smart footwear, and compact modular soft surfaces, and development of soft wearable sensing suits, smart footwear, and network of numerous soft actuators, where potential applications include shape display and distributed actuation for soft robots.

Soft sensors, due to their stretchability and wearability, are becoming more popular in wearsables as a means of tracking human body motions. Some of the challenges of using such sensors include difficulty with calibration and processing of sensor signals due to inherent nonlinearity and hysteresis of the soft materials and misplacement and displacement of the sensors during motion. The researchers investigate how to compute the required input voltages for programming desired deformations. Experimental results are presented to show different deformation patterns and haptic interaction, and variable surface stiffness tuning. The researchers note that the SRS concept is scalable, space efficient, and features diverse functional potential. The concept will also extend the utility and accessibility of tangible robotic interfaces for future applications from industrial to home and personal use.

Artificial muscles based on dielectric elastomer actuators (DEAs) have been used extensively in various soft mechatronic and robotic applications, including to mimic the motion of the human jaw. However, DEAs show strong nonlinear behavior (such as hysteresis) coupled with rate dependent viscoelastic phenomena, which makes controlling DEAs membranes difficult. Gupta et al. propose a nonlinear dynamic model based on the principles of non-equilibrium thermodynamics to account for viscoelasticity. A feedforward controller is developed based on a viscoelastic nonlinear dynamic model, where they show that the controller can be used to track the sinusoidal, triangular, and staircase trajectory accurately. The advances in modeling and control is applied to a jaw-movement example and video results demonstrate the effectiveness of the work.

Zou and Gu present a new control approach for high-precision tracking of a soft dielectric elastomer actuator (DEA) with inverse viscoelastic hysteresis compensation. Their method divides the viscoelastic response of the DEA into a transition region and a stable region. Next, the viscoelastic response is characterized by creep and hysteresis effects according to the different features of the two regions. Finally, a two-level tracking control approach is developed where first a direct inverse hysteresis compensation controller is designed for the viscoelastic hysteresis behavior. Afterwards, a conventional proportional-integral feedback controller is used to deal with model uncertainty and creep effect. Experimental results are presented to demonstrate effectiveness of the modeling and control scheme.

Chen et al. propose a network of inflated dielectric elastomer actuators, interconnected via a chamber, to create a soft actuator for programmable deformations. The researchers investigate how to compute the required input voltages for programming desired deformations. Experimental results are presented to show different deformation patterns. The work represents an important step toward the integration and network of numerous soft actuators, where potential applications include shape display and distributed actuation for soft robots.

Soft sensors, due to their stretchability and wearability, are becoming more popular in wearsables as a means of tracking human body motions. Some of the challenges of using such sensors include difficulty with calibration and processing of sensor signals due to inherent nonlinearity and hysteresis of the soft materials and misplacement and displacement of the sensors during motion. Kim et al. propose the use of deep learning for full-body motion sensing, which significantly increases efficiency in calibration of the soft sensor and estimation of the body motions. An example sensing suit is made of stretchable fabric and contains 20 soft strain sensors distributed on both the upper and the lower extremities. Three athletic motions were tested with a human subject, and the proposed learning-based calibration and mapping method showed a higher accuracy than traditional methods that are mainly based on mathematical estimation, such as linear regression.

Lee et al. propose a novel wearable cutaneous haptic interface (WCHI) that opportunistically utilizes different types of sensors.
including inertial measurement units (IMUs), force sensitive resistors (FSR) sensors, and soft sensors, to track complex anatomically-consistent multi-DOF finger/hand motion. The device consists of finger tracking modules (FTMs) to estimate complex multi-DOF finger and hand motion and cutaneous haptic modules (CHMs) to convey three-DOF contact force at the finger-tip. They point out that such a device is imperative for truly immersive virtual reality (VR) experience, as many real world tasks involve finger manipulation. Human subject study is performed with a virtual peg insertion task to show the importance of both the multi-DOF finger tracking and the three-DOF cutaneous haptic feedback for dexterous manipulation in virtual environment.

The design and manufacturing of a class of 3D-printable three-chambered actuator modules are described by Drotman et al. The design process is parametric and the actuator modules are fabricated on a commercial 3D printer. A small set of design parameters, with the goal of reducing the design-fabrication cycle time, are related to the actuation characteristics (e.g., bend angle and blocked force). The forward and inverse kinematics are defined for the three-chambered actuator and validated experimentally using a motion capture system. Sensitivity analysis is performed to understand which of the geometric parameters of the bellows have the greatest effect on bending and blocked force.

With recent interest in the robotics community of exploring passively compliant and low inertia systems that can safely make contact with the environment, Hyatt et al. show that a global measurement of orientation for a given soft-robot link using two different types of sensors (not including motion capture) can be achieved. In particular, given the orientation measurement, an estimate of the relative configurations of the soft actuators and joints can be realized. Then, a new method for calibrating the coordinate frames of two unrelated measurement systems are described. Finally, using one of our configuration estimation methods, the researchers demonstrate effectiveness by performing simple behaviors with a large-scale soft-robot platform attached to the K-Rex rover at NASA Ames in an outdoor environment. The results demonstrate effective soft robot configuration estimation and control for large-scale soft robots capable of performing manipulation tasks.

Lê et al. exploit the combination of three linear DEAs to develop soft actuators which can achieve horizontal, vertical and circular motions, for the application of robotic eyeballs. Each DEA is developed with optimal design to achieve large voltage-induced deformation. By combing three DEAs together, the soft actuator can track desired motion trajectories effectively and the results can have an impact on the development of eyeball systems for humanoid robots.

To achieve bi-directional force and motion in a soft actuator, Hassan et al. describe the design and development a pneumatic braided muscle actuator. Finite element modeling is utilized as a design tool in order to study the feasibility of the concept, where a single braid structure is deformed to produce both contraction and elongation. Nonlinear quasi-static simulations are performed using the explicit dynamic solver LS-Dyna, to predict the blocked force and free displacement of the actuator. The effect of varying the end-fittings diameter and the length of the inner chamber, on the mechanical characteristics of the actuator is also analyzed. Simulation results are compared to experimental results from a functional prototype. With an actuation pressure of 1 bar, the actuator is able to produce a contraction force of around 80 N, extension force of around 40 N and an overall stroke greater than 40% of the total length of the actuator. The researchers also describe a case study that utilizes the actuator as main driver for a one degree of freedom variable stiffness joint.

Zhang et al. propose a systemic framework to automatically design and fabricate robots that consist of multiple materials, such as integrated soft actuators and relatively harder materials. Using the framework of topology optimization, the structure and material distribution are obtained simultaneously. To illustrate their approach, a multi-material pneumatic soft finger, modeled as a compliant mechanism, is optimized to achieve its maximal bending deflection. The optimized multimaterial soft fingers are fabricated using molding and 3D printing techniques. Experimental results show that the soft gripper can manipulate a large variety of objects with different shapes and weights, and the artificial hand can perform various gestures.

Wang and Minor describe the design of the Smart Shoe to provide haptic display and terrain rendering for virtual reality applications. Compared to existing physical terrain display devices that focus only on rendering gross terrain features, like slopes and stairs, the proposed bladder-based soft robotic Smart Shoe can render subtle features as well as slopes. New bladder models, including wall mechanics and air behavior, are presented that allow parametric shoe simulations to study design variables, loading scenarios, and user sizes. Pareto optimal design is applied to derive customized shoe designs and experiments validate models and demonstrate significantly improved durability. Subject tests measure biomechanical response and gather survey data, which demonstrate haptic rendering of terrain and the ability to compensate uneven terrain. This article was recently published in December 2018 [item 9] in the Appendix.

Finally, a soft hydraulic actuator is presented by Giorgio-Serchi et al. for pulsed-jet propulsion of soft unmanned underwater vehicles. The device uses elastic energy storage and the actuator consists of a flexible membrane which can be inflated using a micro-pump and the elastic potential energy can be released on demand using a controllable valve. Results show that for equivalent initial elastic energy, the drop in peak thrust is linearly proportional to the decrease in nozzle cross section. They also show that passive elasticity can be exploited in aquatic propulsion that replicates the explosive motion of sea-dwelling animals such as squids and octopuses. This article was recently published in December 2018 [item 10] in the Appendix.

In summary, research and development of highly deformable and soft actuators, sensors, and components continue to grow, where many breakthroughs are currently being made to address major challenges from materials design to modeling and control. Given the present interest in this exciting area, this Focused Section is timely and informative. We hope that the articles contained within are helpful and provide readers with valuable insight to support their research and development efforts.

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APPENDIX

RELATED WORKS


Kam K. Leang received the B.S. and M.S. degrees in mechanical engineering from the University of Utah, Salt Lake City, in 1997 and 1999, respectively, and the Ph.D. degree from the University of Washington, Seattle, in December 2004.

He is an Associate Professor in the Mechanical Engineering Department at the University of Utah, which he joined in July 2014 and directs the Design, Automation, Robotics & Control (DARC) Lab. He is also a member of the University of Utah Robotics Center. Between 2008 and 2014, he was at the University of Nevada, Reno. His current research interests focus on high-speed nanopositioning and scanning probe microscopy, electroactive polymers for applications in soft robotics, and aerial robots for emergency response and environmental monitoring.

He currently serves as an Associate Editor for Mechatronics, and was a Technical Editor for IEEE/ASME TRANSACTIONS ON MECHATRONICS and an Associate Editor for IEEE CONTROL SYSTEMS MAGAZINE. He has been involved with conference organization and editorial work with the American Control Conference (ACC), IEEE International Conference on Robotics and Automation (ICRA), and IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM). He is a member of the ASME and IEEE.

Fumiya Iida received the bachelor’s and master’s degrees in mechanical engineering at Tokyo University of Science in Japan, and the Dr. sc. nat. in informatics at the University of Zurich in Switzerland.

He is a Reader in Robotics at the Department of Engineering, University of Cambridge, the director of the Biologically Inspired Robotics Laboratory, and a fellow of Corpus Christi College. During his doctoral project, he was also engaged in biomechanics research of human locomotion at Locomotion Laboratory, University of Jena in Germany. While working as a postdoctoral associate at the Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, USA, he was awarded the Fellowship for Prospective Researchers from the Swiss National Science Foundation, and then, the Swiss National Science Foundation Professorship hosted by ETH Zurich. His research interests include biologically inspired robotics, embodied artificial intelligence, and soft robotics. He was involved in a number of research projects related to robot locomotion, manipulation, and human-robot interactions leading to some start-up companies. He was a recipient of the IROS2016 Fukuda Young Professional Award, and Royal Society Translation Award in 2017.
Jamie Paik received her Ph.D. at Seoul National University on designing a humanoid arm and hand while being sponsored by Samsung Electronics. This 7-DoF humanoid arm was the lightest in the literature at that time, being 3.7 kg, including the 8-DoF hand.

She is the founder and director of the Reconfigurable Robotics Lab (RRL) of the Swiss Federal Institute of Technology (EPFL) and a core member of Swiss NCCR robotics group. The RRL leverages expertise in multi-material fabrication and smart material actuation for novel robot designs. During her Postdoctoral positions in the Institut des Systems Intelligents et de Robotique in Universitat Pierre Marie Curie, Paris VI, she developed laparoscopic tools that are internationally patented. At Harvard University’s Microrobotics Laboratory, she started developing unconventional robots that push the physical limits of material and mechanisms. Her latest research effort is in soft robotics, including self-morphing Robogami (robotic origami) that transforms its planar shape to 2D or 3D by folding in predefined patterns and sequences, just like the paper art, origami.

Yong-Lae Park received the Ph.D. degree in mechanical Engineering in 2010 from Stanford University.

He is an Associate Professor in the Department of Mechanical and Aerospace Engineering (since 2016) at Seoul National University (SNU). Prior to joining SNU, he was an Assistant Professor in the Robotics Institute at Carnegie Mellon University (2013–2017) and a Technology Development Fellow in the Wyss Institute for Biologically Inspired Engineering at Harvard University (2010–2013). His current research interests include artificial skins and muscles, soft robots, wearable devices and robots, and smart materials and structures. He won the Okawa Foundation Research Grant Award, in 2014, the Best Paper Award from the IEEE SENSORS JOURNAL, in 2013, a NASA Tech Brief Award from the NASA Johnson Space Center, in 2012, and a Technology Development Fellowship for independent postdoctoral research from the Wyss Institute at Harvard University, in 2010. His paper on soft artificial skin was selected as a cover article of the IEEE SENSORS JOURNAL, and his work on soft artificial skin and soft robots was recently featured in Nature, Discovery News, New Scientist, Engadget, PBS NOVA, and Reuters.

Jun Ueda received the B.S., M.S., and Ph.D. degrees from Kyoto University, Kyoto, Japan, in 1994, 1996, and 2002 all in mechanical engineering.

He is currently an Associate Professor and Woodruff Faculty Fellow in the G.W.W. School of Mechanical Engineering at Georgia Institute of Technology. From 1996 to 2000, he was a Research Engineer at the Advanced Technology Research and Development Center, Mitsubishi Electric Corporation, Japan. He was an Assistant Professor of Nara Institute of Science and Technology, Japan, from 2002 to 2008. During 2005–2008, he was a visiting scholar and lecturer in the Department of Mechanical Engineering, Massachusetts Institute of Technology. He joined the G. W. Woodruff School of Mechanical Engineering at the Georgia Institute of Technology as an Assistant Professor in 2008. He served as the Director for the Robotics PhD Program at Georgia Tech for 2015–2017. He received a Fanuc FA Robot Foundation Best Paper Award in 2005, IEEE Robotics and Automation Society Early Academic Career Award in 2009, and Advanced Robotics Best Paper Award in 2015.

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