model checking or other formal verification tools. In the months leading up to the competition, the organizers created an open source infrastructure for generating problem instances and interacting with submitted controllers. This included deciding problem specification formats and parameters of each problem domain that would be varied during trials. Teams submitted robot operative system packages that interacted with this competition's infrastructure in simulation. Trials were run using Amazon Web Services, and evaluations were based on predefined metrics for each domain. Dry runs prior to the competition date helped set reasonable metrics for the final evaluation.

Of the four teams, Caltech, CMU and WPI participated in the chains-of-integrators domain with WPI winning. Caltech and Cornell participated in the road-network domain, with Caltech winning. In the aftermath of the challenge, each team will summarize its approach for publication. Several teams have also offered to make their implementations open source, so that future participants may build on their successes and learn from their failures.

The FMRC has sparked broad interest and recognition of its importance and uniqueness; teams of key researchers at several universities are already planning to participate in future competitions. Future FMRCs will also include a physical variant for the road-network domain, where teams execute their controllers on real robots. Other problem domains that test capabilities not covered by the current domains are also being explored.

Further details including links to the competition infrastructure are available at https://fmrchallenge.org.

Acknowledgment

Scott C. Livingston has been instrumental in creating and developing the FMRC.

The 2015 Soft Robotics Competition

By Dónal P. Holland, Gareth J. Bennett, George M. Whitesides, Robert J. Wood, and Conor J. Walsh

In the past decade, there has been a growing interest in soft robotics, or the development of electromechanical systems composed at least partially of low-modulus materials. A community of researchers and designers working on soft robotics has emerged, supported by events such as the Soft Robotics Week that is held annually in Livorno, Italy, and several workshops at international robotics conferences [1]. In 2015, a competition was launched to contribute to the ongoing development of a soft robotics community.

The competition was organized through the Soft Robotics Toolkit (Figure 1), an open-access collection of resources to support design and research in this growing field [2]. The website is an intellectual, rather than physical, tool kit and contains design documentation, downloadable resources, tutorials, and case studies to support students and researchers in learning about the field. The tool kit was originally developed for use by undergraduate engineering students in robotics classes, and it was launched publicly in September 2014. In the first year after its launch, the website was visited over 93,000 times by almost 60,000 people in 158 countries. The tool kit is intended as a vehicle for robotics research groups to share details about their work, thereby accelerating advances in the field. To date, the website hosts material from ten research groups, with

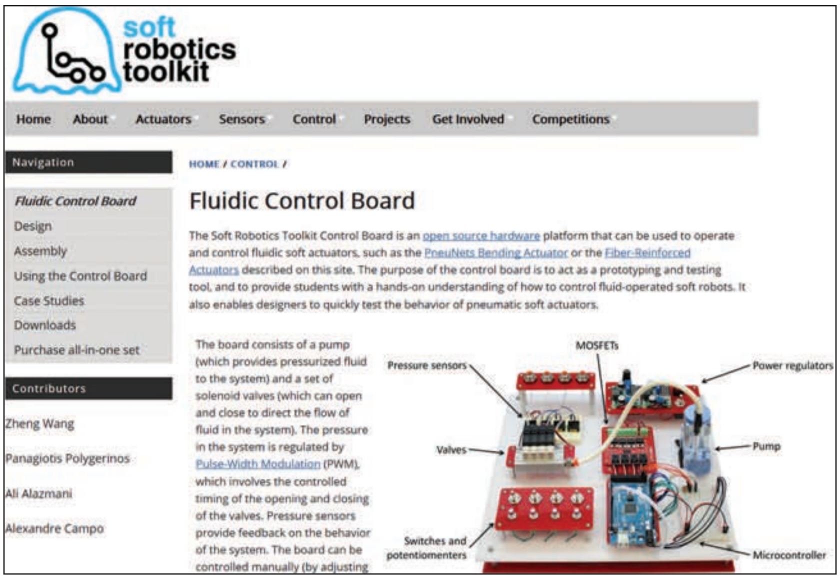

Figure 1. The Soft Robotics Toolkit website.

Digital Object Identifier 10.1109/MRA.2016.2587959
Date of publication: 13 September 2016

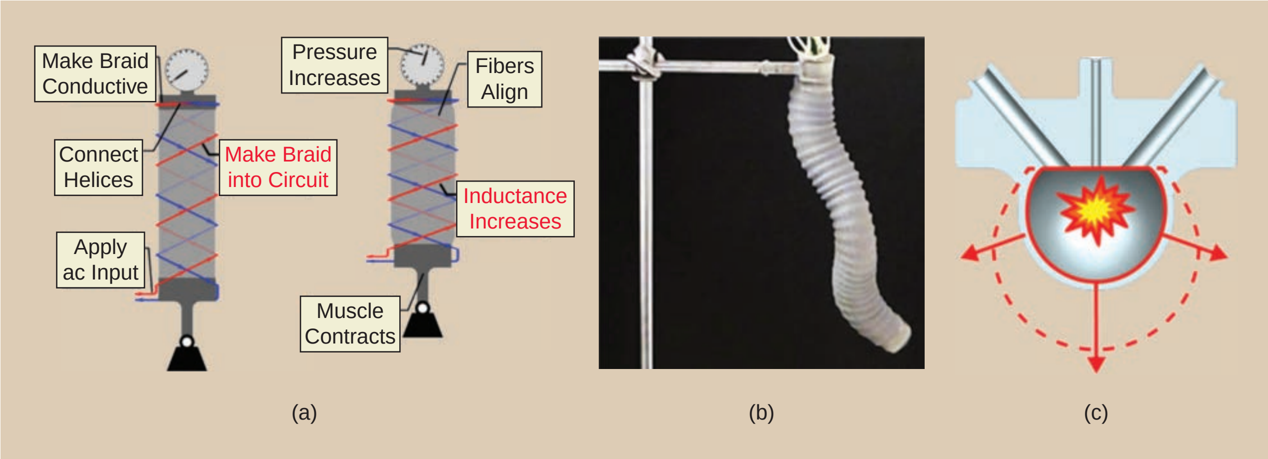

Figure 2. The entries in the research category of the competition: (a) the Smart Braids project [3], (b) a multimodal variable-stiffness manipulator [5], and (c) a combustion-driven actuator [4].

more contributions under way. The tool-kit contents describe the design, fabrication, modeling, and testing of soft actuator and sensor component technologies. The website also contains design documentation for open source fluidic control hardware that can be used to operate a wide range of soft actuators and devices.

The 2015 Soft Robotics Competition contained two categories: a design competition and a research award. Where most robotics competitions specify a predefined task to be completed and participants may choose their own technological approach to accomplishing this task, the soft robotics competition took the opposite approach. Participants were asked to address a problem of their own choosing, and any entry was eligible as long as it made use of soft robotic technology. The goal of this open-ended approach was to engage competition participants in finding new applications for soft robotics and to showcase the creativity of the soft robotics community.

The design competition asked participants to develop new devices that made use of soft component technologies documented on the tool-kit website. It was aimed at students and hobby roboticists, and it was intended to publicize and encourage use of the materials that research groups were sharing via the tool kit. The research competition awarded the most significant recent contribution to soft robotics research and was geared toward robotics research groups. The research competition was intended to support and promote research that advances the field of soft robotics, while incentivizing researchers to contribute to the tool-kit website.

The competition was announced in November 2014, with registration taking place during January and February 2015. A total of 31 teams consisting of 68 individual participants registered for the design competition, and 51 teams consisting of 175 people signed up for the research competition. Upon registration, each team was provided with their own private website hosted on the Soft Robotics Toolkit domain. Each team was tasked with documenting their project on the website, following a provided template. During the competition, teams could not see each other's webpages. In June, the project web pages were frozen to allow judging to take place. Twenty-six entries were found to have met the eligibility requirements. In each competition category, an international panel of expert judges evaluated the projects and assigned scores based on a rubric. Entries to both categories were judged on the novelty of their work as well as the quality of the submitted documentation. The original plan was to award prizes to one entry in the research category and to one winner and two runners-up in the design category. However, the quality of the entries was of such a high standard that prizes were awarded to more runners-up in each category.

The winning entry in the research competition was Smart Braids, submitted by C.D. Remy, W. Felt, K.Y. Chin, and K. Green from the Robotics and Motion Lab at University of Michigan [Figure 2(a)] [3]. Many fluidic soft actuators, such as pneumatic artificial muscles, consist of elastomeric bladders that expand when inflated. By adding reinforcing fibers to these bladders, the motion of the actuator in response to fluid pressurization can be controlled. The innovative contribution from the Smart Braids team was to construct these reinforcing fibers from conductive materials, thereby providing a way of sensing the deformation and force output of fiber-reinforced actuators without any external transducers. This is achieved by sensing a change in resistance and inductance, which corresponds to movement of the fibers.

Runner-up entries in the research category included work on combustion-driven actuators, which use the ignition of combustible mixtures to drive actuation, submitted by M. Loepfe, C.M. Schumacher, and W. J. Stark from the Functional Material Laboratory at ETH Zürich [Figure 2(c)] [4]. A multimodal variable-stiffness manipulator that

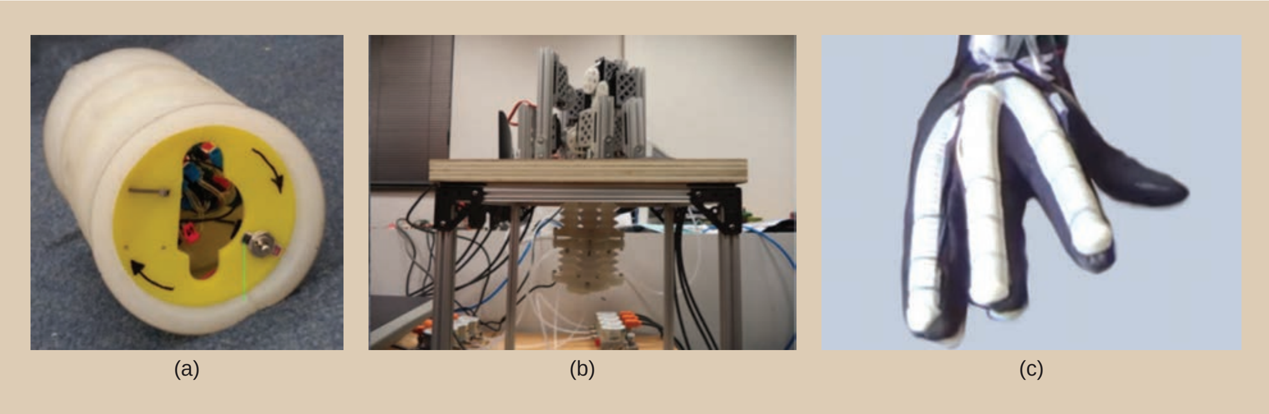

Figure 3. Entries in the design category of the competition. (a) A soft wheel robot from Cornell University. (b) The FeTCH Mark 1 manipulator from the Lille University of Science and Technology. (c) A glove that detects and reduces hand tremors from Olympia High School, Washington.

mimics the elongation, omnidirectional bending, and stiffness variation capabilities of an octopus tentacle was submitted by I. De Falco, M. Cianchetti, and A. Menciassi from the BioRobotics Institute at Scuola Superiore Sant'Anna in Pisa, Italy [Figure 2(b)] [5]. In keeping with the theme of the Soft Robotics Toolkit, U. Çulha, F. Giardina, S. Nurzaman, and I. Fumiya from the Machine Intelligence Laboratory at the University of Cambridge in the United Kingdom submitted the Hot Glue Kit, which includes an actuation unit and modeling tools to enable the rapid prototyping and analysis of soft robot designs based on hot melt adhesives [6].

The winning entry in the design competition was the Soft Wheel Robot submitted by O. Farias Jr., N. Nieminen, C. Strock, H. Kress-Gazit, and R. Shepherd from Cornell University in New York [Figure 3(a)]. This device consists of a cylindrical plastic shell with elastomeric channels on the exterior. By selectively inflating these channels, the rolling speed and direction of the robot can be controlled up to a maximum speed of about 6 m/min. The electropneumatic components that control the inflation of the channels are contained within the plastic shell, and the robot is not tethered to any external pressure or power source.

Runner-up entries in the design competition included the FeTCH Mark 1 manipulator, a soft robotic arm that makes use of a hybrid actuation system composed of pneumatic and tendon-based actuators, submitted by T. Bieze, F. Largillière, S. Hage Chehade, M. Sanz Lopez, and C. Duriez from the Lille University of Science and Technology in France [Figure 3(b)]. K. Uyama from Waseda University in Japan and E. Akanuma from the University of Tokyo submitted a design for a compact actuation system for soft fluidic robots. A project titled Soft Robotics for the Hobby Roboticist by A. Terranova consisted of a robotic hand and an electropneumatic control system, and it aimed to make soft robotics more accessible by using common tools and affordable materials. S. Mundaba, a student at Olympia High School in Washington, designed and built a glove that detects and reduces hand tremor, using flexion sensors and pneumatic actuators [Figure 3(c)]. Another team of high school students, D. Depriest, S.J. Lee, and S.Y. Song from the Barstow School in Missouri, received an honorable mention for an unpowered child's teddy bear. Squeezing the bear's torso inflated the bending actuators inside its arms, causing it to hug you back.

At the time of writing, the 2016 competition was under way, and 96 teams have registered. The competition again includes categories for design and research, and a new category for high school participants has been added to recognize the quality of submissions from younger students. The soft robotics competitions will continue to be an annual event taking place between January and June. For more information, please see http://softroboticstoolkit.com/.

References

[1] L. Margheri and C. Laschi, "The soft robotics week: A new yearly event for the community of soft robotics," *Soft Robotics*, vol. 2, no. 2, pp. 88–90, 2015.

[2] D. P. Holland, E. J. Park, P. Polygerinos, G. J. Bennett, and C. J. Walsh, "The soft robotics toolkit: shared resources for research and design," *Soft Robotics*, vol. 1, no. 3, pp. 224–230, 2014.

[3] W. Felt, K. Y. Chin, and C. D. Remy, "Contraction sensing with smart braid McKibben muscles," *IEEE/ASME Trans. Mechatron.*, vol. 21, no. 3, pp. 1201–1209, 2016.

[4] M. Loepfe, C. M. Schumacher, and W. J. Stark, "Design, performance, and reinforcement of bearing-free soft silicone combustion-driven pumps," *Ind. Eng. Chem.*, vol. 53, no. 31, pp. 12519–12526, 2014.

[5] I. De Falco, M. Cianchetti, and A. Menciassi, "STIFF-FLOP surgical manipulator: design and preliminary motion evaluation," in *Proc. 4th Workshop Computer/Robot Assisted Surgery (CRAS)*, Genoa, Italy, 2014, pp. 131-134.

[6] X. Yu, S. G. Nurzaman, U. Culha, and F. Iida, "Soft robotics education," *Soft Robotics*, vol. 1, no. 3, pp. 202–212, 2014.