# The Soft Robotics Toolkit

## Strategies for Overcoming Obstacles to the Wide Dissemination of Soft-Robotic Hardware

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The Soft Robotics Toolkit (SRT) is an open-access website containing detailed information about the design, fabrication, and characterization of soft-robotic components and systems (Figure 1). Soft robotics is a growing field of research concerned with the development of electromechanical technology composed of compliant materials or structures. The SRT website hosts design files, multimedia fabrication instructions, and software tutorials submitted by an international community of soft-robotics researchers and designers. In this article, we describe the development of the SRT and some challenges in developing widely disseminated robotic-hardware resources. Our attempts to overcome these challenges in the development of the toolkit are discussed by focusing on strategies that have been used to engage participants ranging from K–12 grade students to robotics research groups. A series of design competitions encouraged people to use and contribute to the toolkit. New fabrication methods requiring only low-cost and accessible materials were developed to lower the entry barriers to soft robotics and instructional materials and outreach activities were used to engage new audiences. We hope that our experiences in developing and scaling the toolkit may serve as guidance for other open robotic-hardware projects.

The SRT was originally conceived as a resource for undergraduate engineering students in project-based robotic design classes. In our research on engineering design education, we found that students require access to detailed documentation of previous designs [1], [2], because the interpretation and reuse of previous design solutions is an important element in design activity in general and in design education in particular. Professional designers rely on a repertoire of previous problems and solutions to guide their work, and that requires an ability to make analogies between past experiences and

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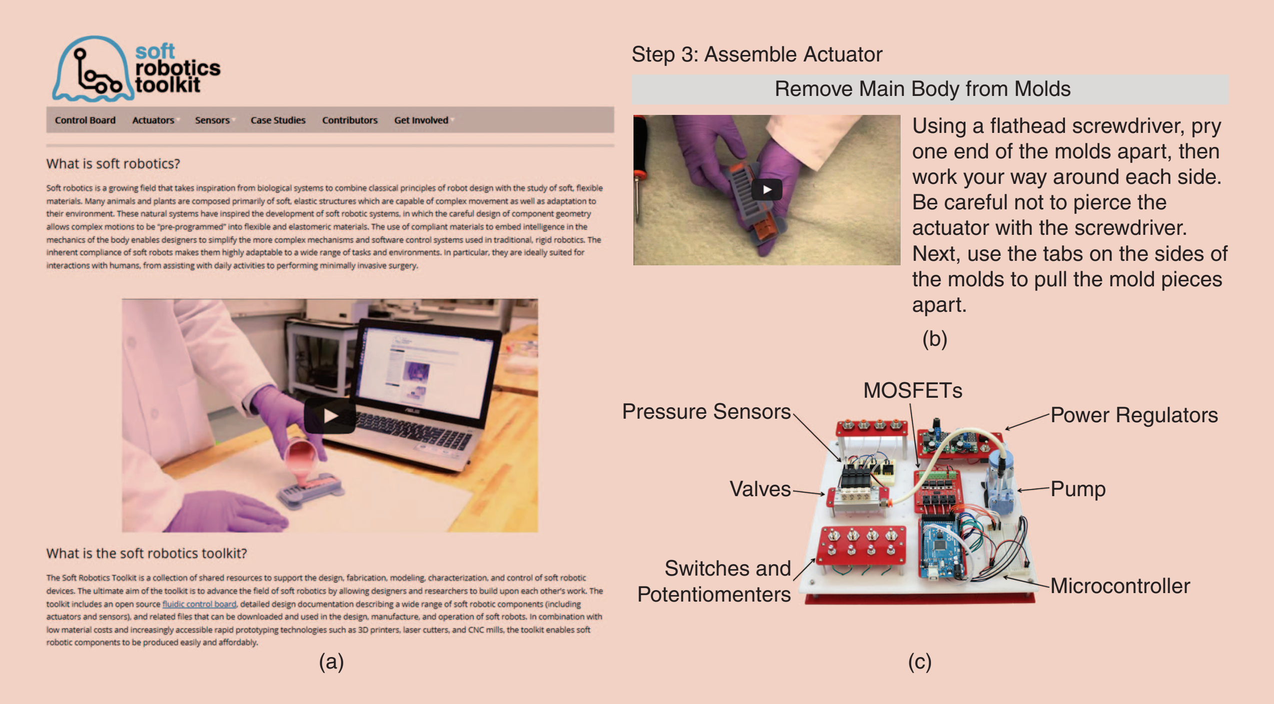

What is soft robotics?

Soft robotics is a growing field that takes inspiration from biological systems to combine classical principles of robot design with the study of soft, flexible materials. Many animals and plants are composed primarily of soft, elastic structures which are capable of complex movement as well as adaptation to their environment. These natural systems have inspired the development of soft robotic systems, in which the careful design of component geometry allows complex motions to be "pre-programmed" into flexible and elastomeric materials. The use of compliant materials to embed intelligence in the mechanics of the body enables designers to simplify the more complex mechanisms and software control systems used in traditional, rigid robotics. The inherent compliance of soft robots makes them highly adaptable to a wide range of tasks and environments. In particular, they are ideally suited for interactions with humans, from assisting with daily activities to performing minimally invasive surgery.

What is the soft robotics toolkit?

The Soft Robotics Toolkit is a collection of shared resources to support the design, fabrication, modeling, characterization, and control of soft robotic devices. The ultimate aim of the toolkit is to advance the field of soft robotics by allowing designers and researchers to build upon each other's work. The toolkit includes an open source fluidic control board, detailed design documentation describing a wide range of soft robotic components (including actuators and sensors), and related files that can be downloaded and used in the design, manufacture, and operation of soft robots. In combination with low material costs and increasingly accessible rapid prototyping technologies such as 3D printers, laser cutters, and CNC mills, the toolkit enables soft robotic components to be produced easily and affordably.

(a)

Step 3: Assemble Actuator

Remove Main Body from Molds

Using a flathead screwdriver, pry one end of the molds apart, then work your way around each side. Be careful not to pierce the actuator with the screwdriver. Next, use the tabs on the sides of the molds to pull the mold pieces apart.

(b)

(c)

**Figure 1.** The SRT. (a) The home page of the toolkit website. (b) An excerpt from a multimedia fabrication protocol describing the casting and assembly of a soft pneumatic actuator. (c) An open-source fluidic control board which allows users to control and test a wide variety of soft actuators.

current problems and to use that knowledge to generate new solutions [3]. Comparisons of expert and novice designers have found that experts are more likely to refer to previous designs than novices [4]. Reusing previous designs is not a matter of simply copying a design from one situation to another. It requires an understanding of the similarities and differences between the current and previous contexts and an ability to use that understanding to identify potential issues that must be addressed [5]. However, this type of context-dependent judgment is underserved by most engineering education programs, which tend to focus on abstraction and generality [6]. Therefore, it is essential that students have opportunities to rehearse interpreting and using previous designs. A primary motivation in developing the SRT was to address these needs by providing students in project-based robotics courses with example designs to use when tackling their own projects.

In the past decade, there has been an increase in the availability of online databases containing design documentation that is relevant to robotics. Open-source software is computer software provided under a license that allows users to run, study, modify, and redistribute the software source code as they wish. Open-source projects such as the Robot Operating System (ROS) provide a modular and reconfigurable platform to support the rapid implementation of new designs [7]. Open hardware takes a similar approach to the distribution of design information related to physical artifacts. The Arduino microcontroller is a project that combines open-source software and open electronic hardware in a tool that was originally developed for use by design students and has become extremely popular in the robotics community. In our research with engineering design students, we found that open-source software and open electronic hardware projects provided an ideal source of the detailed design information required for meaningful learning. We therefore decided to meet the needs of our students by developing a comparable resource focused on the mechanical design of robotic systems.

## Challenges in the Wide Dissemination of Mechanical Designs

Compared to open-source software and open electronic hardware, there are challenges to sharing mechanical hardware designs in a way that supports wide adoption and modification. Our research in mechanical design classrooms revealed that students rarely make use of resources such as online libraries of solid model files. Our research participants reported that, unlike software source code files or electronic circuit schematics, engineering drawings or solid model files alone are rarely useful. Mechanical design is concerned with particular morphologies that depend on factors that are external to the design itself. Using a previous design inevitably involves making modifications, but modifying a solid model file can be a complicated task because interoperability between different computer-aided design environments remains an issue, and information about how to actually manufacture a design cannot typically be inferred from such documentation.

As a result, open mechanical hardware projects typically involve sharing a larger quantity of information, including models, drawings, bills of materials, and written fabrication instructions. Examples of open hardware projects that successfully share mechanical designs include the RepRap, a low-cost three dimensional (3-D) printer, and the Yale OpenHand Project, a robotic hand [8], [9]. However, these projects have a very particular focus. Whereas the ROS and Arduino can support software and electronic design for a wide range of devices and applications, similarly broad hardware platforms to support mechanical design are rare. This is because mechanical design typically involves specialized parts that are selected or customized to suit a particular application. Thus, modifying complete mechanical system designs to create new devices or applications is not a straightforward task.

Rather than focusing on a specific device or application, the SRT is intended as a broad platform comparable to some open-source software and electronic hardware projects. Our approach to achieving this has been to focus on design at the component, rather than system, level. The nature of soft robotics is amenable to this approach. The behavior of soft-robotic devices is determined by the morphology of custom-made actuators and sensors that are typically made from low-cost elastomers cast in molds created with rapid prototyping technologies. By providing an online database of design information related to soft component technologies, we aim to support a broad range of design activities. The aim is not just to let a user replicate a particular design but to also provide a platform to enable them to design their own soft components and devices based on the designs on the site. The documentation set for each component contains downloadable design files, tutorials describing the mold design process, multimedia fabrication protocols, testing case studies, and finite element method modeling tutorials [Figure 1(b)] [10]. Thus, the SRT empowers users to vary both the design of the component itself and the system that incorporates the component. The hardware required to operate fluidic soft devices (including the pressure source, pressure regulator, valves, and microcontroller) is largely interchangeable between systems. The SRT website includes an open-source control board that can be used to control a wide variety of soft-robotic devices [Figure 1(c)].

To ensure clarity of the content, the tutorials and protocols were evaluated with undergraduate students enrolled in nonengineering majors. Feedback from these trials was used to improve the documentation. The SRT was then used by a cohort of students in an electromechanical design class, and website analytics data and weekly surveys were used to track student use of the resource [2]. Throughout their semester-long projects, the students rated the SRT as more useful than both textbooks and other online databases. The website analytics data indicated that students made frequent short visits to the website when first learning about soft robotics and defining their design concepts and less frequent but longer visits during the detailed design of their devices. This indicates that the SRT can support multiple types of design activities.

## The Role of Community in Open Mechanical Hardware

The success of open-source software and open electronic hardware is due in large part to active online communities of users who contribute to the resources and make use of them. When a large amount of users make small modifications to a design and these changes are accumulated, it leads to rapid progress in the development of a technology. A necessary component in developing such a resource is therefore a community of "user producers." Thus, an important question in developing the SRT was how to build a community of engineers around the project.

The growth of soft robotics as a research field is a relatively recent phenomenon, and there are many technical challenges that must be addressed for the field to develop [11]. Soft-robotics researchers have acknowledged a need for shared design tools and standards to ease knowledge transfer. The SRT was developed as a platform that could meet these needs while also addressing the educational needs of engineering students. Framing the toolkit as a resource to support the soft-robotics research community—rather than solely as an instructional tool—was intended to provide the incentive required to build a community of user producers.

The initial content of the SRT website was developed in collaboration with six soft-robotics research groups at Harvard. Interviews and observations were used to understand the design, fabrication, testing, and modeling required for soft component technologies. The fabrication process was decomposed into steps, and for each step, a verbal explanation was written and a video demonstrating the step was made. Supplementary images, including labeled photographs and diagrams, were also created. In September 2014, the resulting SRT website was publicly launched. In its first four months, the website had over 149,000 page views by 29,382 users in 158 countries and received substantial media coverage. However, during that time, only one external research group contributed material to the website. In addition, the approach used to develop the initial website content, which involved the SRT team working intensively with robotics groups to create documentation, was not scalable due to the severe time requirements. A new approach was required to expand the community of user producers, who are essential to the success of the project.

## Expanding the Community Through Competitions

A series of soft-robotics competitions were hosted on the SRT website with the aim of encouraging participation by user producers. The first competitions took place in 2015 and consisted of a design category and a research category. The design category was aimed at a general audience, and it asked participants to use the materials on the website to develop a novel device for the application area of their choice and to document their results for inclusion in the SRT. The aim of the design category was to encourage use of the resource and to produce a collection of case studies describing soft-robotic systems based on the component technologies documented on the SRT. The research award was intended to incentivize research groups to contribute to the website. It rewarded the most significant recent contribution to soft-robotics research documented on the toolkit website as determined by an international panel of experts recruited from leading soft-robotics research groups. For both categories, cash prizes were offered, and the judging of entries was based entirely on documentation submitted to the website.

The first year of the competitions saw 82 projects submitted by 243 participants. Entries in the design category included work completed by undergraduate students as part of robotics classes, projects undertaken by high school students for science fairs, and low-cost robotic systems designed by and for hobbyists. Applications included assistive devices, functional apparel, children's toys, architectural features, locomotion, and electropneumatic control hardware [Figure 2(a)–(f)]. The winning entry described the design and fabrication of an untethered pneumatic wheel robot. Fifty-one robotics research groups registered for the research category. Applications included new approaches for modeling and controlling soft actuators, new manufacturing methods, and novel designs for soft sensors and actuators [Figure 2(g)–(i)]. The winning entry consisted of a self-sensing technique for pneumatic artificial muscles [12].

During the second year of the competitions, the categories were modified to better reflect the demographics of the entrants. For example, some of the most original entries to the design category in the first year came from high school students. However, most high school students do not have access to the same facilities and knowledge as their undergraduate competitors, which puts them at a disadvantage. The 2016 competitions therefore consisted of three categories: one was for design by high school

**Figure 2.** The example projects from the 2015 SRT competitions. (a) An untethered soft wheel robot. (b) A glove for detecting and reducing tremor. (c) A shape-changing insulator for architecture. (d) AirStrap: an actuator-based sandal. (e) A pneumatic control board and soft robotic hand. (f) A low-cost electropneumatic control board. (g) The combustion-driven soft actuators [13]. (h) The smart braids for self-sensing artificial muscles [12]. (i) The methods for modeling and manufacturing soft robotics constructed from hot glue [14].

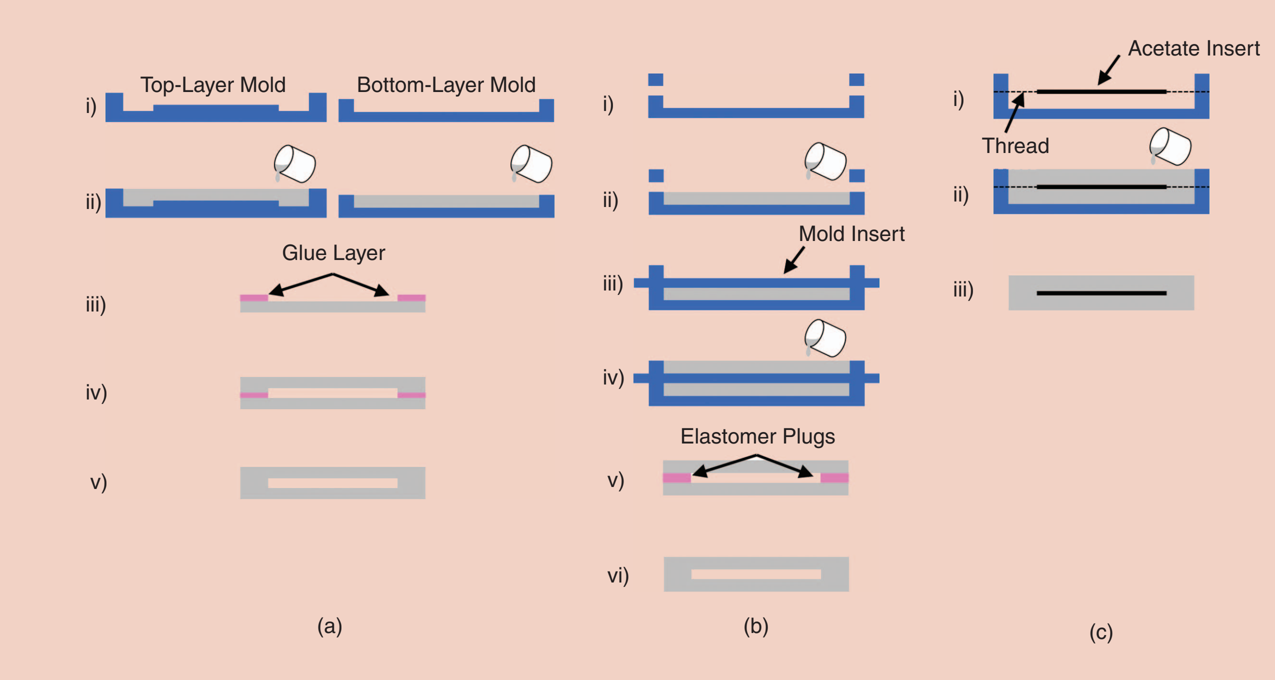

**Figure 3.** The comparison of three methods for manufacturing of soft fluidic actuators. (a) The two layers are cast separately and then glued together using a layer of silicon rubber. (b) A mold with an insert is used for casting. The insert is later removed and the bladder is plugged at both ends to create an airtight chamber. (c) A sacrificial acetate layer is held in the middle of the mold with thread, and it acts as a zero-thickness air chamber.

students, another was for "college-level" design that included students and hobbyists, and the last was for a research award that aimed to attract contributions from robotics labs.

The second year of competitions attracted 96 entries from 228 participants. Entries in the high school category included a novel locomotive robot and new types of soft sensors. Projects in the college-level category included a bioinspired manta ray robot and a novel soft manipulator. Submissions for the research award included a 3-D-printed tactile sensor, as well as a new type of soft actuator that harnesses the power of instability to trigger instantaneous movement [15], [16].

While the response to the competitions has been positive, it has also highlighted some entry barriers faced by potential community members. In particular, high school participants have reported difficulties in using the toolkit information due to complex manufacturing methods and a requirement for specialized machine tools and expensive consumables. Thus, we identified a need for new instructional materials based on manufacturing methods that are less complex, more reliable, and require only low-cost and easily-accessible materials.

## More Accessible Manufacturing Methods and Instructional Materials

Our focus in developing new manufacturing methods has been on actuators rather than sensors or control hardware and, in particular, on fluidic soft actuators. Such actuators can achieve complex motions due to mechanical programming using only fluidic pressure as a simple input. Soft fluidic actuators consist of airtight chambers surrounded by materials of varying stiffness. Upon pressurization, the channels in the soft actuator expand in the direction of lower stiffness. A variety of motions, including extension, contraction, bending, and twisting, can be programmed into the actuator through the morphology and materials used in the construction of the fluidic chambers.

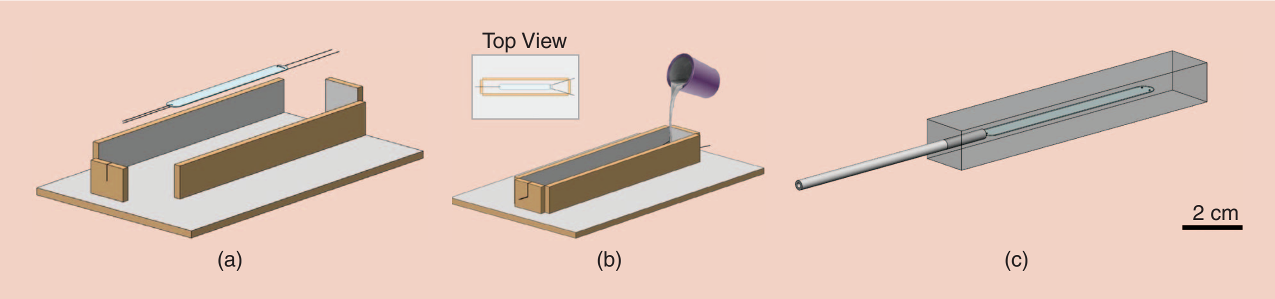

**Figure 4.** The description of our low-cost bladder casting method. (a) A mold is assembled from cardboard pieces and an acetate insert is suspended from thread in the center. (b) The mold is filled with silicone rubber. The rubber does not bond to the acetate insert, creating a zero-thickness air chamber. (c) The final bladder with embedded acetate layer and pneumatic tubing.

Most of the actuators documented in the SRT consist of silicone rubbers cast in complex, multipart molds produced using 3-D printers or other rapid manufacturing tools. The silicone rubbers themselves, which are commonly used in model-making and special effects, are affordable and easy to obtain. However, the requirement for rapid prototyping equipment remains to be a barrier for many. To address this issue, we have designed molds that can be built from accessible materials such as paper and cardboard. One advantage of this approach is that mold designs can be shared via two-dimensional templates that can be printed on paper, adhered to a sheet of cardboard, and cut out to create components that can then be assembled into 3-D molds. This approach has the potential to drastically lower the entry barriers to soft robotics and to thereby support the wide dissemination of robotic-hardware designs.

The challenge when designing molds for fluidic actuators is creating airtight chambers. Common approaches include

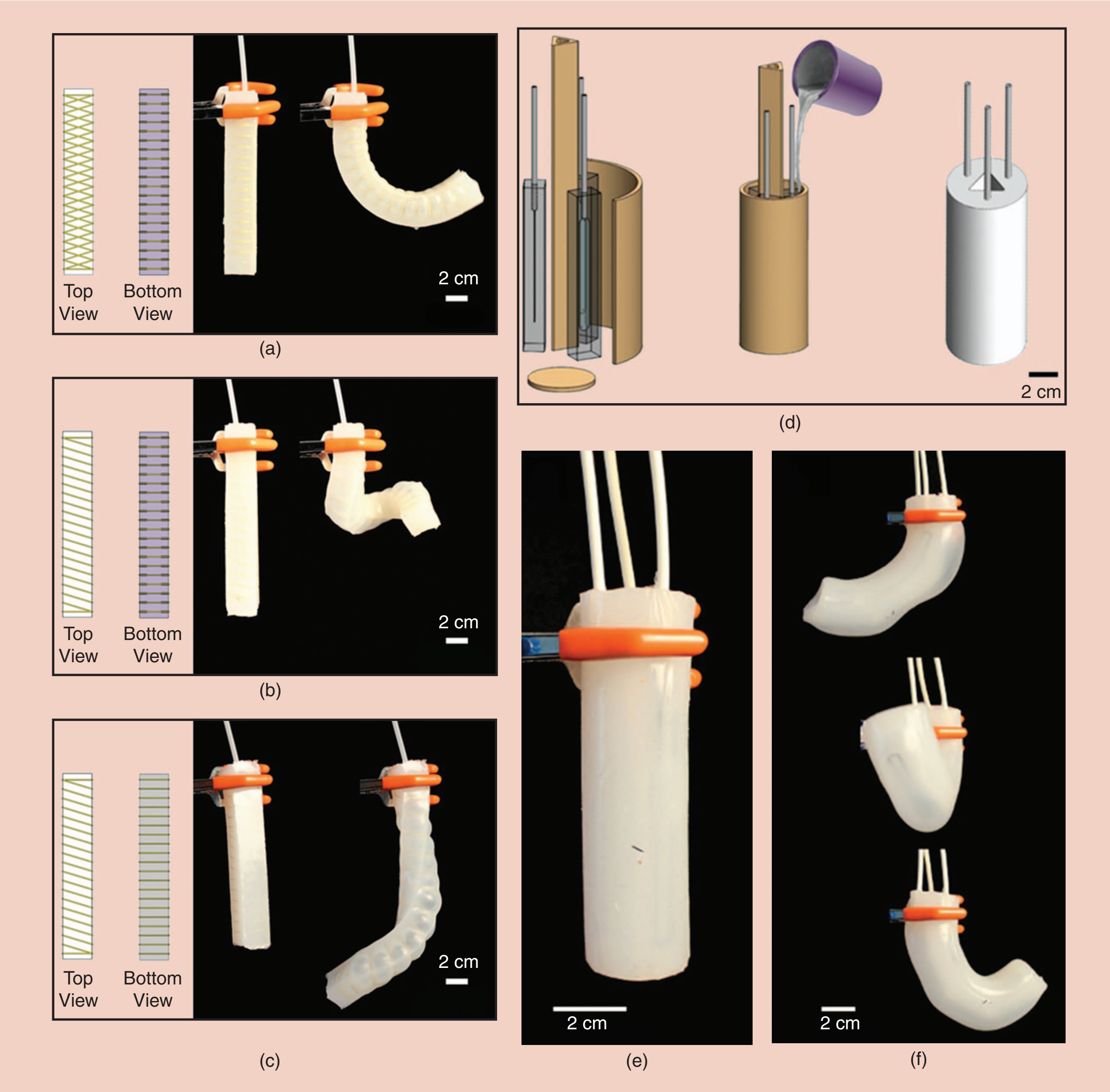

**Figure 5.** The example fluidic actuators. (a)–(c) The different patterns of fiber reinforcement pattern (top view) and the fabric layer locations (bottom view) result in different motions in response to an increase in fluid pressure in the inner chamber. (a) The double helix fiber reinforcement with a fabric layer along one side, resulting in a bending actuator. (b) The single helix fiber reinforcement with a fabric layer along one side, resulting in a bending and twisting actuator. (c) The single helix fiber reinforcement with no fabric layer, resulting in a twisting and extending actuator. (d)–(f) A two-degrees-of-freedom actuator consisting of three airtight bladders. (d) The overview of the fabrication process: a cylindrical cardboard mold is used to cast a silicone rubber matrix around three premade bladders. (e) The resulting actuator. (f) The selective inflation of each bladder allows the free end of the actuator to trace a spherical cap.

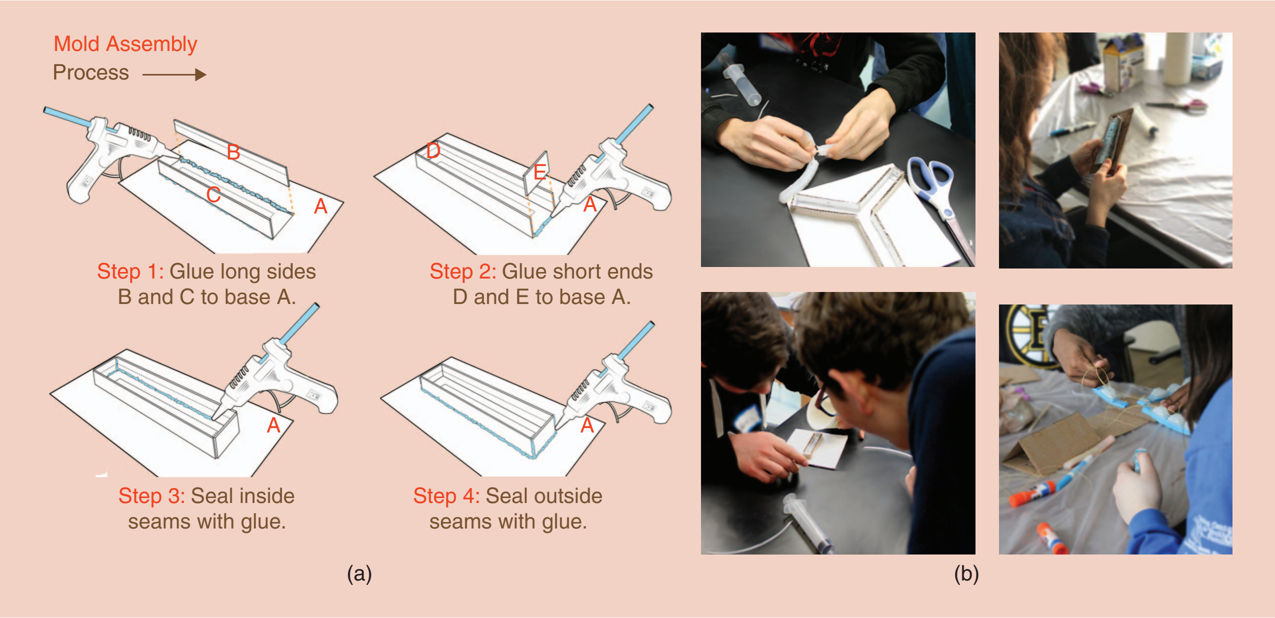

**Figure 6.** The methods of disseminating the new manufacturing techniques. (a) An extract from an illustrated instruction manual describing the assembly of the low-cost mold. (b) The middle and high school students using the new manufacturing technique to build their own soft robotic devices.

casting layers separately and subsequently gluing them together [Figure 3(a)] or using a mold insert during casting that can be removed and plugged afterward [Figure 3(b)]. Both methods require multiple casting steps and are time-consuming. The molding technique presented here requires fewer steps and is more accessible for novice users [Figure 3(c)]. This technique produces simple airtight bladders that serve as building blocks for more complex actuators. Our approach uses a sacrificial insert made of acetate sheet that creates a zero-thickness air chamber. The acetate layer is suspended between cardboard walls using thin thread (Figure 4). A two-part silicone rubber is cast in the mold. Once the silicon rubber is cured, the thread is removed. The sacrificial acetate layer remains in the bladder but does not stick to the walls of the bladders, thereby creating the fluidic chamber.

The bladders produced using this technique can be assembled in different combinations to create a variety of actuators. For example, external reinforcement layers can be used to mechanically program the motion of an actuator in response to internal fluid pressure [17]. Kevlar thread wrapped around the circumference of the actuator restricts its radial expansion. Layers of fabric prevent axial expansion in parts of the actuator. Figure 5(a)–(c) shows three examples of actuators that can be achieved from identical bladders simply by varying the placement of these reinforcement layers. These variations can take place along the length of a single bladder, yielding multiple segments that each perform different motions. This technique has been used to produce patient-specific actuators that mimic the motions of human fingers for an assistive soft orthotic glove [18]. Other approaches involve combining multiple bladders in assembly to create a single actuator. In the example shown in Figure 5(d)–(f), three identical bladders are cast in a surrounding matrix of silicon rubber. By selectively inflating individual bladders, it is possible to trace a spherical cap with the free end of the actuator as shown in Figure 5(f). By assembling N such actuators in a series, it is possible to achieve a tentacle with 2N degrees of freedom [19]. In addition to the two examples discussed here, it is possible to use this molding technique as a low-cost and easy means of replicating a wide variety of component technologies from the soft-robotics literature.

The new manufacturing technique was developed to meet the needs of educators and students who wanted to develop their own soft-robotic devices. The approach presented here eliminates the need for specialized equipment and substantially reduces the cost and time required to construct soft-robotic components. It allows a user to create a mold and actuator in less than one hour, while the methods previously documented on the toolkit site take at least three hours. To share the new methods with potential users, we have developed a collection of instructional materials and created a new “Education” section on the SRT website. The instructional resources consist of illustrated descriptions of the manufacturing techniques, printable mold templates, and suggested class projects accompanied by soft robot case studies to serve as examples for students. Figure 6(a) shows an extract from a student handout describing soft actuator fabrication using a cardboard mold. The instructional materials have been tested and refined through robotics workshops with over 100 students in the United States, Peru, and Ireland [Figure 6(b)].

## Conclusions

This article describes the development of the SRT and efforts taken to address issues commonly faced by open mechanical hardware projects in robotics. The wide dissemination of mechanical design information is not a straightforward task because of the level of detail required to enable a wide audience to replicate a physical design. To ensure that the project documentation was sufficiently detailed, it was developed to meet the needs of students and tested with novice roboticists. This approach allowed us to identify the essential information that must be shared, which is often not intuitive for domain experts. Involving nonexperts in the development and pilot testing of design documentation can help to improve its clarity for all users.

Mechanical design typically involves multiple parts that are custom-designed for a particular application and is not conducive to the development of broad platforms for varied applications. The SRT addresses this issue by focusing on component-level design and separating general hardware from parts for particular applications. While soft robotics is particularly well-suited to this strategy, other open hardware projects may also benefit from a similar approach.

The success of an open-source project depends in large part on its ability to attract a community of user producers who review and contribute to the shared resources. Convincing robotics experts to contribute the documentation of their mechanical designs is a challenge given the level of detail required. Hosting design competitions related to the project has proven to be an effective means of engaging participants ranging from high school students to research groups. Again, other open hardware projects may benefit from adopting this strategy.

Finally, the emergence of low-cost rapid prototyping technologies has the potential to accelerate the growth of open mechanical hardware projects, but it should be recognized that these technologies are still beyond the reach of many potential users. Developing alternative design and manufacturing methods that do not rely on specialized equipment or materials could enable open hardware projects to increase their impact and expand their communities.

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