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ORIGINAL ARTICLE

The Soft Robotics Toolkit: Shared Resources for Research and Design

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Abstract

This article describes the development of the Soft Robotics Toolkit, a set of open access resources to support the design, fabrication, modeling, characterization, and control of soft robotic devices. The ultimate aim of the toolkit is to support researchers in building upon each other's work, and thereby advance the field of soft robotics. An additional aim is to support educators and encourage students to pursue careers in engineering and science by making the resources as accessible as possible. The toolkit was developed and refined through a series of pilot studies and user tests. Specifically, the resources were used by students in a project-based medical device design course; volunteers from a variety of backgrounds tested the toolkit and provided feedback, and soft robotics researchers used the collection of resources and contributed to its development. Throughout all user studies, qualitative data were collected and used to guide improvements to the toolkit. This process of testing and refinement has resulted in a website containing design documentation describing general hardware control platforms and specific soft robotic component designs. The online documentation includes downloadable computer-aided design (CAD) files, detailed multimedia protocols for the fabrication of soft devices, tutorials and scripts for modeling and analyzing soft actuators and sensors, and source code for controlling soft devices. Successive iterations of qualitative data gathering and redesign have confirmed that the toolkit documentation is sufficiently detailed to be useful for researchers from a wide range of backgrounds. To date, the focus of the toolkit has primarily been fluid-actuated robotic systems, but the plan is to expand it to support a wider range of soft robotic-enabling technologies. The toolkit is intended as a community resource, and all researchers working in this field are invited to guide its future development by providing feedback and contributing new content.

Introduction

Current challenges in soft robotics include a need for new classes of soft devices, new simulation and analysis tools, and new soft sensing and actuation methods.[1,2] Overcoming these challenges requires the development of shared design tools and standards to ease knowledge transfer.[1,3] While research articles provide a useful medium for sharing scientific knowledge, they are limited by space constraints that prevent detailed descriptions of procedures, and bias that prevents unsuccessful experiments from being published.[4,5] For these reasons, research articles alone are not sufficient.

Recently, there has been a growing interest in adopting an ''open notebook'' approach to scientific practice and technology development. Projects such as OpenWetWare and UsefulChem allow researchers to augment their published research by publicly sharing their experimental protocols, raw data, and unsuccessful experiments.[6,7] Concurrently, there is a movement in the robotics community to make systems open source, with common hardware and software platforms emerging that are highly modular in nature. Platforms such as the Robotic Operating System (ROS),[8] the Arduino microcontroller,[9] the OpenHand project,[10] and the Takktile pressure sensor[11] are being used by researchers to rapidly implement new robot designs at a much accelerated pace compared to just a decade ago. While platforms exist to support software and electronic hardware design for a wide range of robotics applications, similarly broad platforms to

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support the mechanical design of robotic systems are rare. This is because traditional rigid robotic systems are typically composed of multiple moving parts custom designed for the application at hand, making a universal toolkit unfeasible.

In contrast, the nature of soft robotics makes it ideally suited to the development of shared design tools. For example, the hardware required to operate fluidic soft devices (including pressure source, regulator, valves, and microcontroller) is largely interchangeable between one system and the next with little to no customization. Therefore, a common hardware control platform could support a range of applications, including surgical, wearable, locomotion, and manipulation systems. 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. These molds can be affordably produced because of the increased availability of rapid prototyping technologies such as 3D printers and laser cutters. Given widespread access to these prototyping technologies, a shared database of design files, source code, and fabrication protocols could enable the rapid development of custom soft robotic devices. This proposed collection of hardware and virtual resources would allow the technical community to focus on developing innovative applications rather than dedicating resources to debugging the basic infrastructure of soft robotic systems. Figure 1a is a graphical representation of the design process that would be enabled by these resources.

This article presents the Soft Robotics Toolkit, a website for sharing detailed design information with the soft robotics research community using an open access model. As shown in Figure 1b, the toolkit contains information on the design of soft devices, instructions on fabricating soft components and characterizing their behavior, and design documents describing the assembly and operation of hardware control platforms for use with fluidic soft devices. Given the inherently multidisciplinary nature of the field of soft robotics, it is

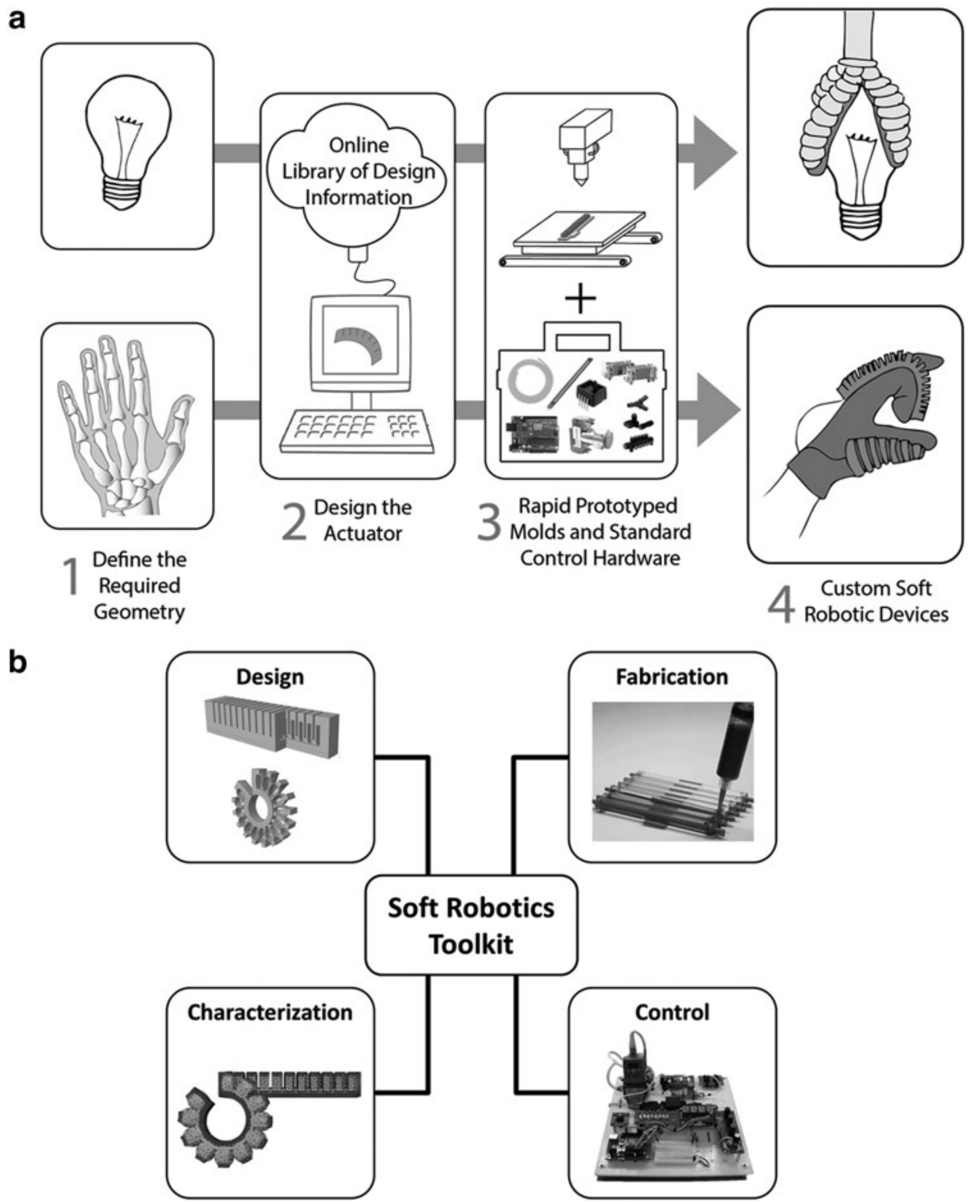

FIG. 1. **(a)** Envisaged design process using common virtual and physical platforms to support a range of soft robotics applications. **(b)** Overview of the Soft Robotics Toolkit.

especially important that shared resources like the toolkit are broadly accessible and useful to researchers from a wide variety of backgrounds. To this end, the toolkit has been developed and refined through a series of pilot studies and user tests involving students and researchers. The next section describes the development of the toolkit and provides examples of its use.

Toolkit Development and Testing

The toolkit was initially developed to meet the needs of students in a project-based mechanical design course with a focus on medical applications of soft robotics. During the course, four student teams, consisting of both undergraduate and graduate students from a variety of science and engineering backgrounds, collaborated with clinicians and soft robotics researchers to develop novel medical devices. Participant observation and interviews were used to document students' experiences in the course. Particular attention was paid to the information and tools that students needed to design, prototype, and test various soft devices. This research was approved by the Harvard University Committee on the Use of Human Subjects in Research.

The results of this qualitative research are summarized here and illustrated with examples drawn from one of the student projects: a ventricular assist device (VAD) intended to restore the heart's pumping function for patients suffering from right ventricular heart failure.[12] The student team worked with a cardiac surgeon to develop a VAD consisting of a soft fluidic artificial muscle anchored in the free wall of the right ventricle and the septum (Fig. 2a). When pressurized, the actuator contracts in length to bring the walls of the right ventricle together (Fig. 2b), thereby contributing to the ejection of blood into the pulmonary artery.

All of the student teams drew heavily on local expertise in soft robotics. In particular, the teams required detailed information regarding the design, fabrication, and testing of soft robotic components. While the students were provided with instructional handouts on actuator fabrication, the level of detail provided was insufficient and, as a result, the teams regularly sought advice and clarifications from soft robotics researchers. For example, the VAD team adopted actuator fabrication processes developed by a group of Harvard researchers working on a soft cardiac simulator[13] and took inspiration from another group's research on shape deposition manufacturing.[14] Results from observations and interviews indicated that, in order to develop new soft robotic devices, students need access to extremely detailed protocols and tutorials.

The course was also used to pilot test some elements of the toolkit, including an early prototype of the pneumatic control board shown in Figure 3. Two of the student teams did not require a control board, as their projects focused on manually operated devices, but for the other two teams, the board provided a means of quickly testing and comparing the performance of device designs. In the case of the VAD team, the

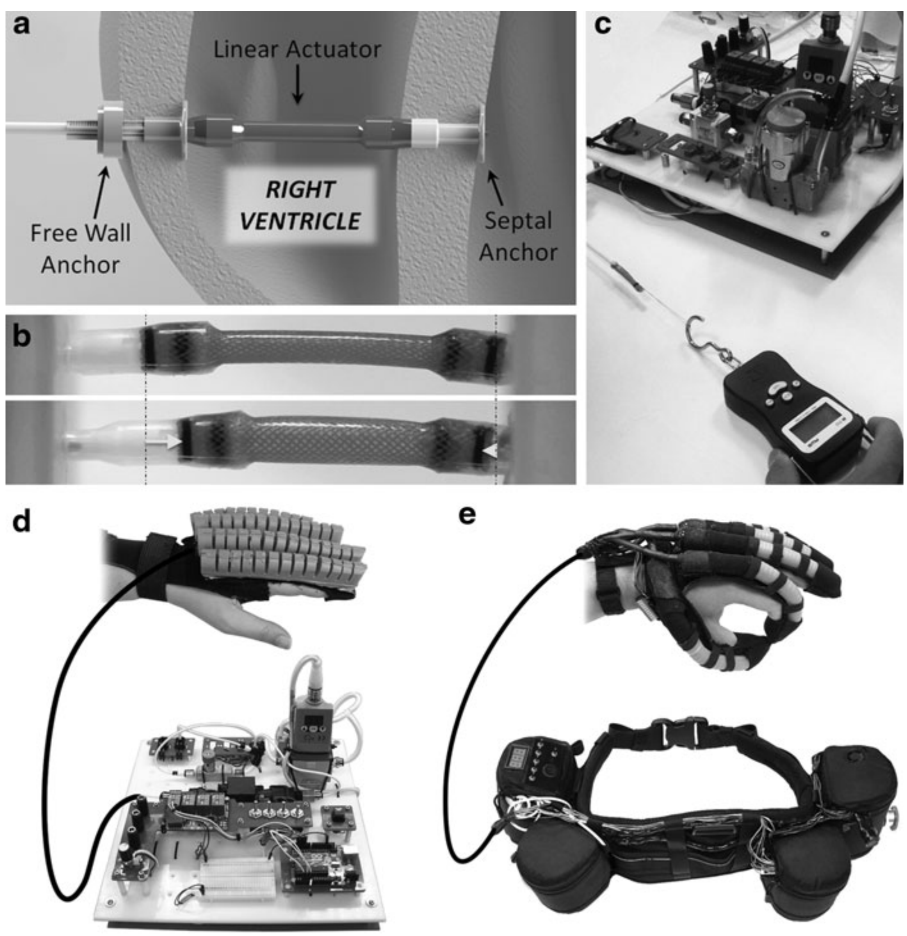

FIG. 2. **(a)** Ventricular assist device (VAD) design. **(b)** Detail of VAD prototype showing soft actuator in uninflated and inflated states. **(c)** Use of the control board to test soft actuators for VAD. **(d)** Soft robotic glove version 1 and control board. **(e)** Soft robotic glove version 2 and control belt.

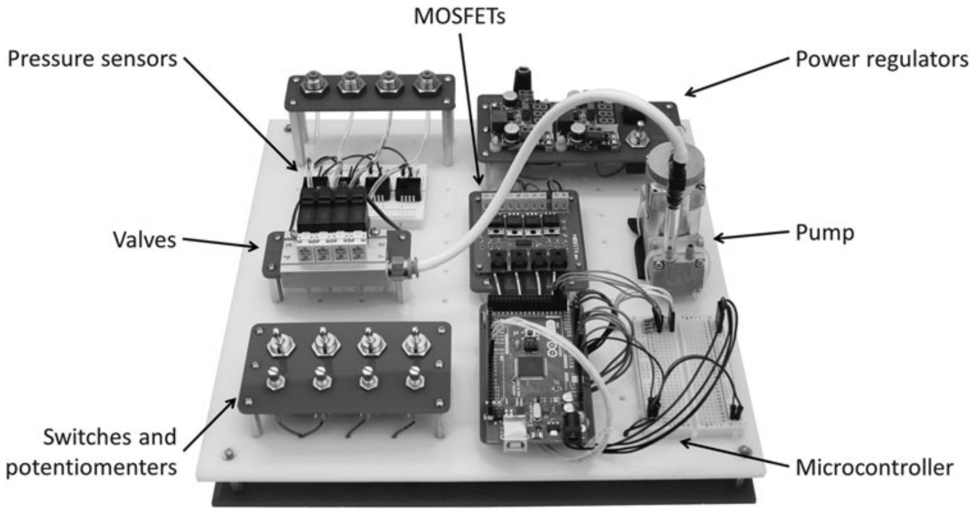

FIG. 3. Fluidic control board.

control board was used to measure the force output of different actuator designs for a given input pressure (Fig. 2c). Access to the board meant that the team did not need to spend time designing a fluidic control system and sourcing the required hardware, allowing them to focus instead on the development and testing of an actuator for their specific application.

The experiences of these student teams were used to guide the subsequent development of the toolkit. The importance of detailed fabrication information to most of the teams indicated that the toolkit should include protocols describing the casting and assembly processes for building soft components such as actuators and sensors. Based on the observation data, which included detailed accounts of the information required by the students during the course, a set of multimedia protocols was created. However, a challenge in documenting bench-level processes is providing all of the information required for replication, in part because researchers often cannot anticipate the importance of minor details to other researchers.[15] In order to ensure that the toolkit contained the necessary level of detail, a series of user tests were conducted with four volunteers from nonengineering backgrounds, who had no experience with soft robotics design or fabrication. Each participant was provided with the materials and equipment needed to build a pneumatic bending actuator, and a multimedia protocol containing verbal descriptions, videos, and images was displayed on a computer. The participants were asked to think aloud as they followed the protocol, noting any confusion or questions they had. All of the participants successfully built an actuator.

During these user tests, the participants highlighted aspects of the protocol that were unclear and made suggestions for specific changes to the videos, images, and verbal instructions. This feedback was used to refine the fabrication protocol to improve clarity, and answers to recurring participant questions were incorporated to ensure that future users could follow the protocol without external assistance. The testing results also led to the development of general guidelines for documentation, which were used to create additional content for the toolkit, including tutorials on the use of software packages to design molds and analyze actuator performance.

The toolkit has subsequently been used for various soft robotics projects by researchers at Harvard, and their work has often fed back into the continued development of the website content. One such project focused on the development of a soft robotic glove intended to augment hand rehabilitation for individuals with functional grasp pathologies.[16] The first version of this glove (Fig. 2d) consisted of ''PneuNets'' (pneumatic networks)[17] bending actuators that assisted the fingers with grasping tasks. To optimize actuator designs for the application at hand, the project team developed finite element method (FEM) models for PneuNets,[16] which were documented and added to the toolkit. In turn, they used the control board component of the toolkit to test actuators and validate these models and also used designs documented in the toolkit to help create new actuators for the glove,[18] which could more accurately mimic the behavior of the fingers and thumb by combining bending, twisting, and extending motions. The project team later returned to the control board, modifying it and reducing the number of components to create a more user-friendly, portable version in the form of a control belt (Fig. 2e). These improvements were then incorporated into the design of the toolkit control board, reducing its cost and complexity.

Soft Robotics Toolkit Description

This section describes the structure and organization of the toolkit, the initial content developed through the testing and refinement process discussed above, and examples of how the resources can be used. The toolkit website (http://softroboticstoolkit.com; Fig. 4) contains documentation for a range of soft component technologies as well as initial embodiments of general control platforms. The components are categorized into broad classes, such as fiber-reinforced bending actuators[19] or soft strain sensors.[20] The documentation for each class contains subsections covering the design, fabrication, modeling, characterization, and control of the component (Fig. 1b). Each of the subsections is described in more detail below.

Design

The design section describes a particular configuration of the component, complete with downloadable solid models and engineering drawings of the component and related molds (Fig. 4a). These files are complemented with tutorials

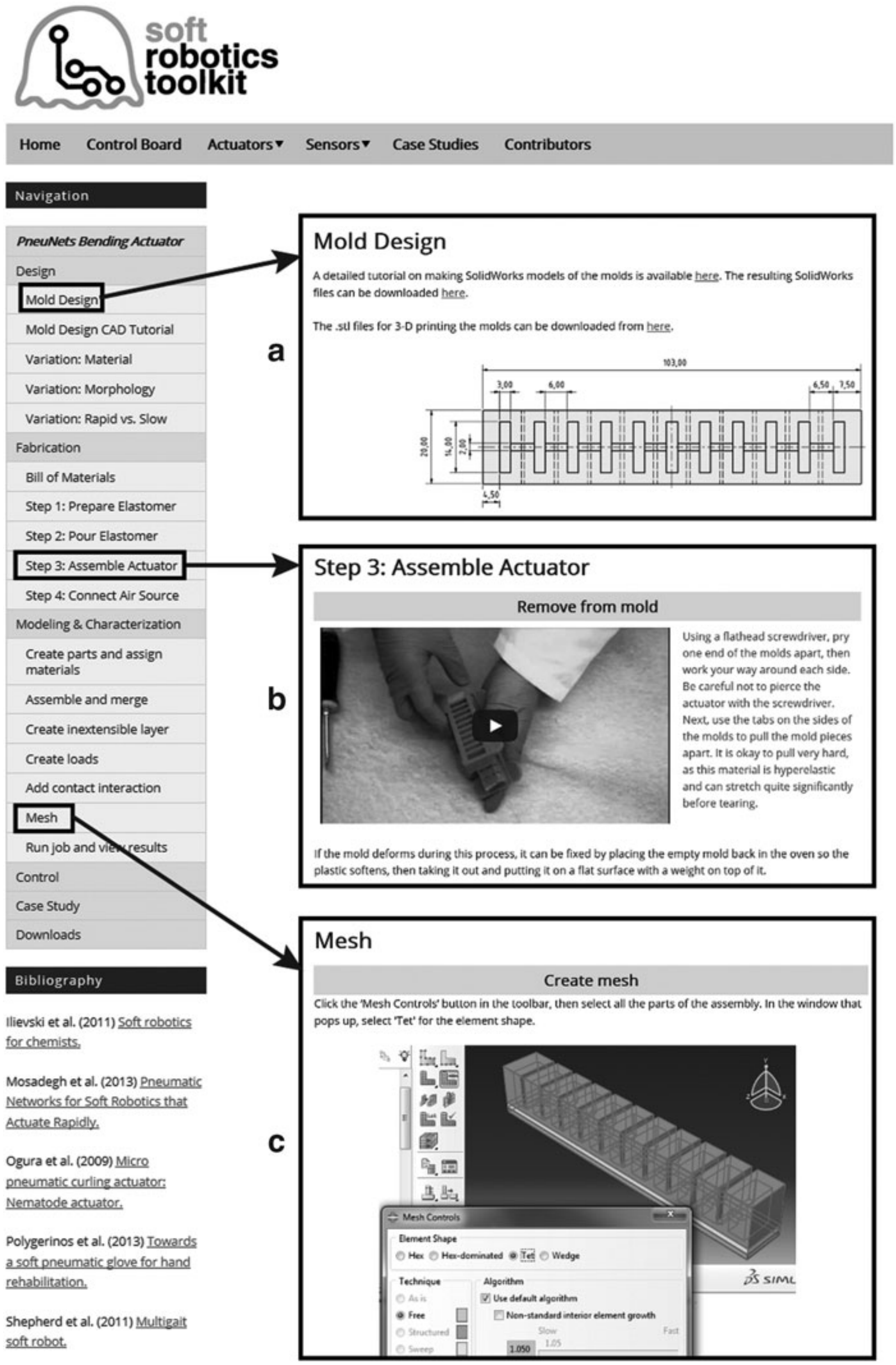

FIG. 4. The Soft Robotics Toolkit website. **(a)** An extract from the section describing the design of the actuator mold. **(b)** A step from the multimedia protocol describing the casting and assembly of the actuator. **(c)** An extract from the tutorial on finite element method (FEM) analysis of the actuator.

for designing mold parts in a solid modeling environment (SolidWorks; Dassault Systèmes). A user with limited mechanical engineering experience can follow the tutorials to design a complete component from scratch, while more experienced users can refer to the tutorial to modify and customize the downloaded computer-aided design (CAD) files to suit their own application. The design section also contains information on material selection, general design principles, and discussions of possible design modifications to vary component performance. This content is based on the observations of student teams, in particular the type of information they sought from more experienced soft robotics researchers. A collection of case studies provides an overview of how other developers have used the component. Since soft robotics allows for infinite customization, these case studies provide insight into the design considerations that need to be made for specific applications.

Fabrication

The fabrication section contains all the information required to build the component. Bills of materials, with links to suggested suppliers, assist users in procuring the required parts and materials. For parts that are not commercially available and need to be custom-made, the provided CAD files can be used to manufacture parts with a machine such as a 3D printer, laser cutter, or CNC mill. Detailed multimedia protocols describe the steps involved in preparing molds, casting parts, and assembling the soft component. In many cases, multiple methods of building the component are described, and the strengths and weaknesses of each method are discussed so that users can make an informed choice about which procedure best suits their needs. Each step of the process is described through verbal descriptions, annotated images, and videos (Fig. 4b).

Modeling & Characterization

Predicting the performance of a soft actuator or soft sensor (such as force output in response to a given pressure) before manufacture is nontrivial because of complex morphologies, nonlinear elastic behavior, and multiple degrees of freedom.[1] Pooling knowledge in this area is especially important for the development of the field. Analytical tools are needed to allow researchers to optimize designs in a deterministic manner and achieve robust control of soft devices. Toward this end, the modeling and characterization section contains general guidelines for analyzing soft components. Descriptions of both analytical and numerical modeling approaches are provided along with detailed derivations or related FEM input files and scripts. Tutorials provide a step-by-step description of using FEM software packages to conduct numerical analyses of particular soft components (Fig. 4c). Users can follow these tutorials to learn about the software and the modeling considerations particular to soft systems so that they can subsequently analyze their own designs.

In order to understand the behavior of soft components, as well as validate FEM and analytical models, researchers must look to experimental data. During the medical device design course, most student teams relied on empirical testing more than modeling to guide their designs, but had difficulty designing and conducting experiments. To assist users in the design of experiments, the toolkit contains examples of empirical tests that have been carried out by other researchers. These examples describe the experimental setup, the type of data that resulted, and how that data were interpreted. The experiments described include fatigue strength tests, force and displacement characterization, and motion studies. Users can modify the examples to guide their own experiments. Many of the experiments described in the toolkit make use of the control board discussed in the next section.

Control

As mentioned previously, much of the hardware required for the operation and control of soft fluidic systems is interchangeable between one system and the next. The website contains documentation for open source fluidic control boards, intended as general purpose tools that can be used for a range of applications (Fig. 3). Users can select between pneumatic and hydraulic actuation and follow the documentation to build and operate their own board. Each board consists of a microcontroller (Arduino Mega), a pressure source, metal–oxide–semiconductor field-effect transistors, solenoid valves, and pressure sensors. These components can be controlled manually via the included potentiometers and switches, or programmatically via the microcontroller. The boards can be used to implement closed-loop control, and the documentation contains source code for proportional-integral-derivative control for particular actuator and sensor combinations that can be downloaded and run on the microcontroller. The base of the control board, a perforated sheet of acrylic, acts as a ''mechanical breadboard'' and allows users to reconfigure the assembly or add new components. An electronic breadboard enables the addition of further sensors. For example, one student team added a gyroscope module to track the orientation of the tip of their actuator during testing. The control boards enable ''plug and play'' of soft devices across a range of applications, allowing proof-of-concept prototypes to be rapidly assembled, tested, and demonstrated. Given the modular nature of the board, its cost depends on the needs of the user. The cost of parts required to build the complete version documented on the website is $800. In the future, toolkit users will be invited to share details of their custom feedback controllers on the toolkit website to support accurate control over device behavior.

Conclusions

This article has presented the Soft Robotics Toolkit, which was developed in response to the needs of engineering students and researchers engaged in the design of soft robotic devices. Successive iterations of qualitative data gathering and redesign have confirmed that the toolkit documentation is sufficiently detailed to be useful to researchers from a wide range of backgrounds. Though the toolkit's main focus is currently fluidic devices, as that has been the most popular application among the toolkit's users and developers, it is hoped that this focus can be expanded in the future as use of the toolkit increases and users from around the world upload new materials. The intention is for this expansion to include new component technology designs and fabrication methods, the use of additional materials such as shape-memory alloys and dielectric elastomers, and control board designs capable of supporting a wider range of actuation methods. To support this, the website contains templates that guide contributors through the documentation process. All interested researchers are invited to make use of the toolkit and to help shape its future by providing feedback and contributing new content.[21]

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Author Disclosure Statement

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