feature article

soft robotics as emerging technologies:

preparing students for future work through soft robot design experiences

Students prepared with strategies for learning now will be able to apply the same strategies when faced with new situations in the future.

by Andrew Jackson, Nathan Mentzer, and Rebecca Kramer-Bottiglio

In our field of technology and engineering education, we are limited by our inability to predict what is coming; as the saying goes, we are preparing our students for jobs that don't even exist yet. Two adaptive approaches can help prepare students for this uncertainty: teaching broad skills that can be applied in new situations and exposing students to recent technological developments that hint at the future. Soft robotics is an emerging technology with advantages to traditional robotics in some circumstances. In this article, we describe several emergent applications of soft robotics and how they align with the *Standards for Technological Literacy* (*STL*) domains of technology. We also share an overview of our approach to implementing a soft robotics design and fabrication experience focused on integrating design and inquiry skills. These resources may be used by technology and engineering teachers to grow student confidence for emerging engineering careers.

Preparing Students for the Future

Integrating 21st century skills development—problem solving, creativity, and communication, among others—in our classrooms is one way to prepare students for an uncertain career landscape. Learning these types of skills "allows the individual to transfer what was learned to solve new problems" (Pellegrino & Hilton, 2012, p. 6). Open-ended and design-based teaching are effective pedagogies for fostering these skills: they support critical thinking, mega-cognition, and collaborative learning, allow students to draw on authentic information sources to make decisions, and "highlight the process of thinking" (Pellegrino & Hilton, 2012, p. 10), which is transferrable to future situations. They also engage students in questioning and self-directed learning. Voogt and Roblin (2010, p. 13) likened these competencies to "learning-to-learn" competencies, noting that pedagogical approaches for 21st century skills can include student involvement in pacing and assessment. In this way, students prepared with strategies for learning now will be able to apply the same strategies when faced with new situations in the future. Though the skills are not new, they are called upon at an increasing rate and in broadening types of careers. As career options broaden, especially in technology and engineering, we need to be aware of and communicate the nature of these fields to our students. Looking at recent technological developments is critical:

> Looking forward to further changes in science and technology, perhaps revolutionary changes, we are limited by our inability to see the future… Turning to reality, though, the best we can do is look at recent and emergent advances…to provide a possible template of the changes engineering will need to contend with [in the future]. (National Academy of Engineering, 2004, pp. 9-10).

Showing these new innovations to students, letting them explore the advantages of these technologies and learn their intricacies in a structured environment, and having students try the technology for themselves are all important steps in growing understanding of the core ideas. In order to develop further technological solutions, the ideas of these recent solutions will need to be leveraged and improved; "industry requires a workforce that is equally nimble at adapting to changing conditions so they can utilize available technologies and generate innovations of their own" (Brophy, Klein, Portsmore, & Rogers, 2008, p. 369).

Trends of student interest in STEM decline during secondary school: about 28% of students begin with STEM interest, about half of those lose interest, yet fewer students experience a gain in interest, so there is a failure to offset these losses (Munce & Fraser, 2013). Therefore, we need ways to recapture, even grow, student interest. Ensuring that our teaching strategies include 21st century skills and cutting-edge technology designed to meet societal challenges may be one such way.

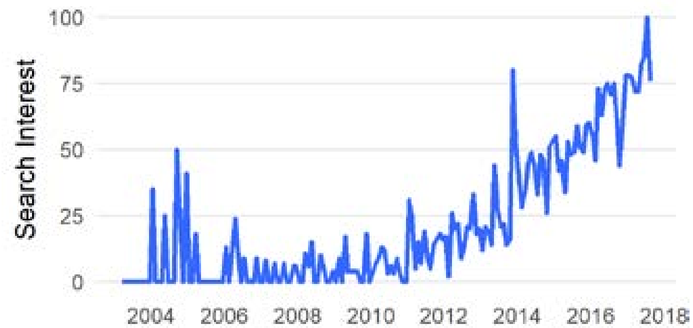


Figure 1. Search interest of "soft robotics" by year. Obtained from Google Trends (www.google.com/trends). The y axis represents relative interest for the search during the period of time.

Soft Robotics: Advantages and Applications

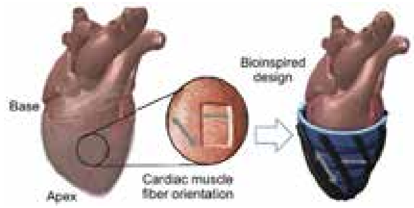
Soft robotics is one example of an emerging technology with novel applications in areas where traditional robotics may struggle. Soft robotics has direct societal impacts and tangible outcomes, such as safety at the material level and appropriateness or direct human interaction, that we might explore in our classrooms. Soft robotics is of growing interest to the engineering community, media, and the public, as indicated by rising interest in the search topic (Figure 1). Soft robots are controllable systems made from soft, flexible materials that are designed to perform a task. Soft components of these systems include actuators and sensors (for movement and feedback, respectively), which are often integrated into one body. Power and pneumatic control may even be connected internally, though that is not often the case for testing.

In the design phase of a robotics project, a decision might be made to pursue soft robot use, based on the affordances of soft robot systems (Table 1). There is inherently a tradeoff: soft robots are less forceful and less accurate; however, their compliance in new environments and delicate interaction with objects may be necessary for the success of the project. Wang, Chen, and

Table 1. Comparison of soft robot and traditional rigid robot characteristics.

Soft Robot Design	Traditional Rigid Robot Design
Made of soft, flexible, stretchable materials (e.g., fabric, rubber, or foam)	Made of rigid materials (e.g., plastics, wood, or metal)
Naturally compliant to the environment	Compliant via control systems
Safe for human-machine interaction	Unsafe for human-machine interaction
Highly biologically inspired systems	Slightly biologically inspired systems
Low force and accuracy	High force and accuracy

Soft Robot Heart Sleeve Vignette



Roche, et al. (2017) designed a soft robot sleeve with layers to mimic the function of the heart. The device could be used to help medical patients with heart failure. Compared to traditional assistive devices, it does not contact blood, meaning it is simpler and less expensive.

Design: pneumatic artificial muscles

Domain: medical technology

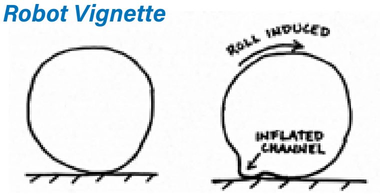
Learn More: www.wired.com/2017/01/robots-coming-heart/

Image from Roche, E.T., Horvath, M.A., Wamala, I., Alazmani, A., Song, S.-E., Whyte, W., . . . Walsh, C.J. (2017). Soft robotic sleeve supports heart function. *Science Translational Medicine, 9*(373). doi: 10.1126/scitranslmed.aaf3925. *Reprinted with permission from AAAS.*

Yi (2015, pp. 93-94) summarized three main applications of soft robots that are intrinsic to their material properties. First, handling deformable, fragile, or changing objects. Because soft robot materials are compliant relative to the environments they are in, they are able to conform to and grasp a variety of objects, even of different shapes. Second, resemblance to natural systems, namely biomimicry. Numerous soft robot designs have drawn from biological inspiration for fabrication including the octopus, jellyfish, and caterpillars. And third, human-centered applications such as wearables or medical devices. Examples of soft robots intended for interaction include a glove for hand rehabilitation and a device to assist with heart rhythm.

These advantages of soft robotics are being leveraged in a variety of ways, including the applications previously mentioned. Within the framework of seven technology areas for K-12 study identified in *STL* (ITEEA, 2007), we identify prototype examples of the use of soft robotics to address a number of problems, described in these vignettes. There are many more applications being investigated, and these have been chosen on the basis of their direct connection to the technology areas, clarity in mechanisms for construction, and accessibility of resources for further investigation. We share the design need and affordances of soft robotics in each context, the type of soft robot construction, the *STL* domain, and a website to begin research. Through further investigation, technology and engineering teachers can build understanding of these applications and incorporate these as technological examples or design challenges in their own classrooms.

Soft Wheel Robot Vignette



Farias, Nieminen, Strock, Kress-Gazit, and Shepherd (2015) won the Soft Robotics Toolkit design competition with their idea for a self-contained soft robot that could drive and turn. Air channels along the side of the robot would inflate, propelling the robot forward, then deflate to allow it to keep rolling.

Design: cast silicone with air channels

Domain: transportation technology

Learn More: https://softroboticstoolkit.com/soft-wheel-robot

Image from Farias, O., Jr., Nieminen, N., Strock, C., Kress-Gazit, H., & Shepherd, R. (2015). Soft wheel robot, submission from Cornell University. Retrieved from Soft Robotics Toolkit Projects website (above). *Reprinted with permission from Soft Robotics Toolkit.*

Soft Acoustic Tile Vignette

Decker (2015) described soft robot research to dynamically respond to and minimize sound. In its deactivated state the robot is flat; in its activated state it expands to a rough surface to affect sound reflection.

Design: pneumatic actuators

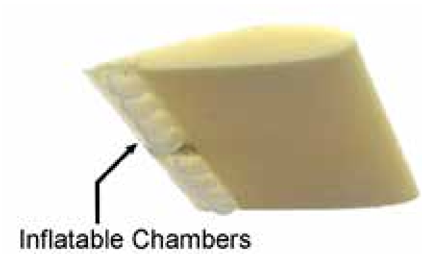
Domain: construction technology

Learn More: www.architectmagazine.com/technology/q-a-material-dynamics-lab-director-martina-decker-on-the-intersection-of-design-and-science_o

Image of soft acoustic tile test environment (deactivated and activated system) courtesy of Material Dynamics Lab at the New Jersey Institute of Technology, Ryan Berg, Paulo Guerreiro, and Jesus Vasquez.

In addition to the growing body of research related to soft robotics, there is a growing community designed to share insights, including for educators. Teachers are encouraged to look for more information on the projects in these vignettes and others. A useful repository is the Soft Robotics Toolkit, http://softroboticstoolkit.com/, which contains information on design, fabrication, and testing soft robot components. The design of soft robots

Soft Robotic Airfoil Design Vignette



Xie, et al. (2015) demonstrated using soft actuators to change lift and drag of an airfoil by changing its shape. The soft, morphable airfoils are lighter and simpler than rigid mechanisms to achieve the same shapes.

Design: pneumatic actuators

Domain: transportation technology

Learn More: http://mae.rutgers.edu/elastomeric-actuators-airfoils-aerodynamic-control-lift-and-drag

Image from Xie, J., McGovern, J. B., Patel, R., Kim, W., Dutt, S., & Mazzeo, A. D. (2015). Elastomeric actuators on airfoils for aerodynamic control of lift and drag. *Advanced Engineering Materials, 17*(7), 951-960. doi: 10.1002/adem.201500036. © 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. *Reprinted with permission.*

Soft Robotic Glove Vignette

Polygerinos, Wang, Galloway, Wood, and Walsh (2015) have been developing a soft robotic glove to assist in hand rehabilitation. Because the materials are more compliant than rigid robotic systems, it is safer, less expensive, and more comfortable and customizable for users.

Design: fiber-reinforced actuators

Domain: medical technology

Learn More: https://wyss.harvard.edu/technology/soft-robotic-glove/

Image of soft robotic glove from Wyss Institute at Harvard University and Harvard Biodesign, http://wyss.harvard.edu. *Reprinted with permission.*

Soft Robot Gripper by Soft Robotics, Inc. Vignette

Soft Robotics Inc. has created a commercial system that uses pneumatically actuated grippers to handle a variety of objects, especially delicate objects like food. The system can also adapt to objects of different shapes and sizes.

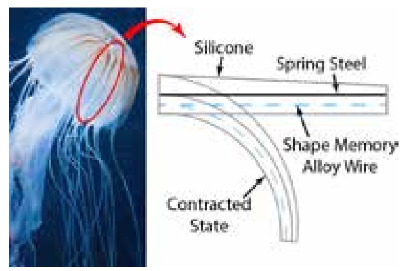
Design: pneumatic actuators

Domain: agricultural and biotechnology, manufacturing technology

Learn More: www.softroboticsinc.com

Image from Soft Robotics, Inc. *Reprinted with permission.*

Robojelly Vignette



Villanueva, Smith, and Priya (2011) created a bioinspired soft robot jellyfish for underwater movement. The design was based on anatomy of several jellyfish species and used 3D printing and silicone for construction.

Design: shape memory alloy wires

Domain: agricultural and biotechnology

Learn More: www.fastcompany.com/1679544/robojelly-a-robotic-jellyfish-to-monitor-the-oceans

includes the application of scientific principles in pneumatics, materials, biology, and other disciplines. It also necessarily includes problem solving and reflection on the process, as we describe in the curriculum experience shared next. Exploring these soft robot applications ourselves as technology and engineering educators is a step toward incorporating soft robot design in our own classrooms and unfolding these 21st century skills through experience.

Implementing Soft Robots in High School Design

In an effort to increase student interest in engineering and expose students to novel engineering contexts, we have developed and tested a soft robot design experience for high school classes. In contrast to traditional robotics systems, with which students are likely familiar, soft robots are new and unfamiliar. Changing the materials for construction may encourage participation from all students in exploring this new context. The experience has come from a four-year research partnership between Purdue

University, Yale University, and the International Technology and Engineering Educators Association (ITEEA), with support from the National Science Foundation. The research project was situated in the 9th grade *Foundations of Technology* course as a two-week unit. Based on the positive results, we have adapted the learning experience for the Grade 10-12 Engineering byDesign™ *Advanced Technological Applications* course offered by ITEEA's STEM Center for Teaching and Learning. Here, we describe the design experience, as adapted for the 2018 release of the *Advanced Technological Applications* course and share resources to enable teaching these lessons. In the experience, students fabricate and redesign soft robot fingers using provided materials before designing and fabricating their own gripper.

Our use of soft robotics is situated in an agricultural context. The advantages of a soft gripper here include the ability to grasp a variety of objects, to do so without damaging the produce, and to alleviate ergonomic concerns from the repetition of the task. Playing to the strengths of soft robots to handle delicate objects without damage, we challenge student pairs to design a pneumatically inflatable soft gripper that can pick up simulated produce (a golf-ball to represent a tomato). The gripper is made of a silicone rubber, cured (solidified) by mixing two parts together and waiting the prescribed time. Fabrication steps are described in more detail in the next section, and more details can be found in Jackson, Mentzer, Kramer, and Zhang (2017).

To begin design, students build a foundational understanding of necessary scientific principles through instruction related to pneumatics and conducting research related to soft robotics. The growing prevalence of soft robotics research means that students can find information by searching online, though we specifically direct them to the Soft Robotics Toolkit pages about "pneunets bending actuators" and "fiber-reinforced actuators." We do acknowledge that there are other approaches that may also be successful in a classroom application, but using pneunets (short for pneumatic networks) with cloth fiber reinforcement has been successful in our grant project. Two structural aspects of the robots will enable it to curve around the tomato to pick it up: the configuration of the inner air chambers, and an "inextensible layer" of fabric that constrains inflation (Figure 2).

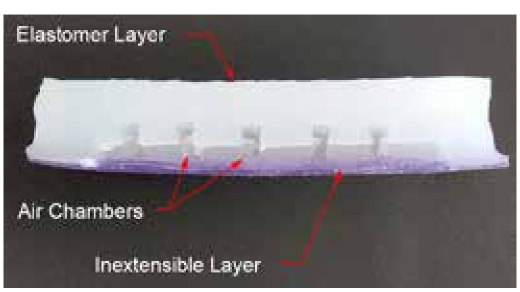


Figure 2. Cross-section of soft robot finger showing air chambers and inextensible fabric layer.

As part of their research to understand how the soft robot will behave in various configurations, students use a 3D printed mold to test various soft robot finger designs for their effect on robot movement. Students focus on understanding the design and fabrication process using this mold. The reconfigurable mold for the *Advanced Technology Applications* course has had several iterations in our research, allowing students to adjust the placement of clips to change the configuration of the inner air chamber (Figure 3). The performance differences, based on a few key variables, can also be discussed as a class. In our classes, such considerations directly relate to the constraints and criteria we encourage students to develop while designing and testing. Furthermore, it is necessary for students to document their design ideas and test results as research evidence to inform their final gripper design.

Designing and making successful soft robot fingers is an iterative process—it is harder than it seems, and the first attempts may not produce robots that inflate, or they may not curve in a desirable way. One of the difficulties of soft robot design is the precision required—a complication of the nature of the materials and manual fabrication process (Wang, et al., 2015). One expert observed, "if you have small structures, a small difference in fabrication makes a big difference for the behavior of the materials and the whole mechanisms" (Trimmer, et al., 2013, p. 68). It is therefore important that students carefully document and reflect on their process. Group discussion and failure analysis are useful to identify principles for successful fabrication and design of the grippers. With soft robotics, failure analysis is relatively simple and begins with observation, hypothesis, and testing in a future iteration. For instance, failure to inflate might be because of a leak that becomes obvious by listening for the air escaping or submerging the soft actuator in water to identify air bubbles. Further insight can be realized by cutting the actuators and observing a cross section as shown in Figure 2. Students are able to make observations and discuss their theories. They can create tests to confirm their thinking—for example, students might speculate that inconsistences in thickness cause one finger to inflate before another. By allowing their silicone to cure in a mold that is not level, they can create extreme differences in thickness between two fingers and observe the results to confirm or challenge their hypothesis. Whole-class discussions can be rich with scientific argumentation as students use evidence to support their claims. Students can try again, as needed, based on viable class time because the process is iterative and relatively cheap and fast.

Through phases of making several soft robot fingers with the provided mold and the fabrication process described further later in this article, students build a conceptual understanding of soft robot actuators. After students have this understanding and curiosity about how other variables impact the design, they are challenged to design their own gripper mold using CAD software and a 3D printer. Ultimately, students follow similar fabrication steps to make the gripper as they did to make the fingers. One difference between the finger and the gripper is the amount of silicone used (since it is a larger product) and another difference is the addition of a coupler through which to inflate the gripper. Third, the gripper is a little more complex because of balancing the inflation of multiple fingers.

We conclude the design challenge by having students demonstrate their design and present about their process, decision-making, and ideas for improvement. The full curriculum in the *Advanced Technological Applications* course provides teachers with a lesson about the soft robot fingers and a gripper design challenge that includes suggestions for extensions as well as troubleshooting support. The process, while challenging, is conceptually simple, and we describe it here as nine fabrication steps.

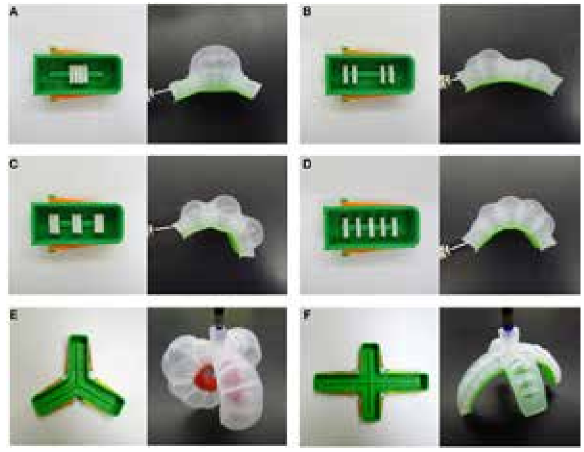


Figure 3. Demonstration of clip arrangement impacts on soft robot actuation. A) A single large chamber made by placing clips next to each other; B) two slightly separated clips; C) three pairs of clips; D) five evenly spaced clips; E) a three finger gripper design; and F) a four finger gripper design with different finger lengths. Figure originally included in Zhang, J., Jackson, A., Mentzer, N., & Kramer, R. (2017). A modular, reconfigurable mold for a K-12 soft robotic gripper design activity. *Frontiers in Robotics and AI, 4*, 1-8. doi: 10.3389/frobt.2017.00046.

Fabrication of Pneumatically Actuated Soft Robots

1. Gather the necessary materials. Supplies include the 3D printed mold components (image, page 8 – finger mold shown above, gripper mold shown below), silicone (Ecoflex 00-30 by Smooth-On), disposable gloves (polyethylene—not nitrile or latex), safety glasses, measuring cups, a stirring stick, parchment paper for a work surface, scissors, fabric, and a soccer or volleyball pump for testing. If using heat in Step 4 or Step 5, be sure the plastic mold is resilient to the needed temperatures—we use Acrylonitrile Butadiene Styrene (ABS) for printing for this reason.

2. Design the soft robot. This includes arranging the clips in the provided finger mold or CAD work for the gripper design.

3. Mix and pour silicone. Mix the desired amount of Ecoflex using a 1:1 ratio of Part A and Part B. Stir gently for at least 1 minute, then, on a piece of parchment paper, fill the mold.

4. Cure and demold. Allow the silicone to cure for 4 hours at room temperature, or 15 minutes at 150° Fahrenheit. After the material is cured, pull it out of the mold.

5. Attach the fabric. Mix enough Ecoflex to saturate a piece of fabric and attach the top half of the robot. The layer of Ecoflex on the fabric should be deep enough that there is a good connection. We suggest looking at the layer from an angle and seeing that the surface is smooth and reflective—but not so deep that it clogs the air chambers. If the layer of silicone is so thin that the threads of fabric are visible, it is too thin and may not adhere sufficiently. The gripper should be laid on the fabric, and the silicone can be welled up around the edges to reinforce the connection. For a gripper, attach the coupler on top in the center. Then let this cure with the same process as Step 4.

6. Testing. Peel your robot off the parchment paper and insert the pump. Inflate it to watch the finger or gripper actuate because of the air chambers and fabric. Consider the curvature patterns of the fingers.

7. Iterate. Did the robot work the way you expected it to? How do you think changing your design would change the functionality? To be most effective, iteration should be deliberate: test your robot, identify problems, and brainstorm ways to address the problem through a different design or fabrication process. Systematically change some design variables and try again.

8. Troubleshoot. There may be a few reasons your robot didn't work: Was there a hole in the silicone? Did it stay attached to the fabric? Did it inflate evenly? Think critically and change your design or fabrication process.

9. Demonstrate your design solution. Use your completed gripper and design journal to share your process. Share your design and why you made those decisions. Demonstrate how your gripper works.

Conclusion

This work demonstrates that, as educators, we can identify an emerging technology and bring it into the classroom to help prepare students for jobs that don't even exist yet. In our project, we identified soft robotics as a developing technology that has many varied applications, from agriculture to prosthetics and from acoustic dampening to wheeled motion and flight. Current examples of soft robotics provide visible benefits in human-centered applications, which research indicates is engaging for students. Furthermore, closely examining these uses of soft robotics can reveal the underlying mechanisms and cultivate ideas for futuristic problem-solving and innovation. We propose that our approach may be a model for teachers and other curriculum developers to identify emerging technologies and transfer them into the classroom.

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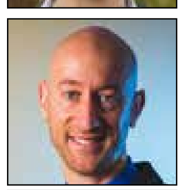

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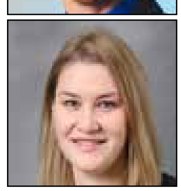

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