Air-Powered Soft Robots for K-12 Classrooms

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***Abstract* – This paper outlines the development of an affordable, sustainable K-12 outreach program based pneumatically-powered soft robots. Recent advances in low-cost 3D printers have helped make these robots available to hobbyists and K-12 classrooms. This paper is intended to serve as a reference for interested students, parents and educators, and a model for other researchers to develop similar outreach programs.**

Index Terms – engineering, outreach, robotics

INTRODUCTION

I. Background

In the last decade, afterschool robotics programs have become widespread, largely thanks to the popularity of commercial kits such as LEGO® Mindstorms® [1] and competitions like the FIRST® robotics leagues [2]. Such programs are beneficial in sparking student interest in science, technology, engineering and math (STEM) at a young age, as part of a longer-term plan to improve K-12 STEM education and to develop a highly educated, scientifically literate workforce so the United States can remain competitive in a global 21st-century economy [3],[4].

Despite the success of these programs, there are some limitations. Individual kits are typically expensive (e.g. $280 for a LEGO® Mindstorms® NXT 2.0 set), and despite very user-friendly interfaces, do require a minimal amount of programming knowledge to operate. This "barrier to entry" results in many competitions and afterschool clubs relying heavily on volunteer engineers and computer scientists for mentoring and coaching.

This paper presents a low-cost, low-tech robotics outreach program intended as a supplement or alternative to, and **not a replacement for**, existing robotics programs. In particular, this project involves no programming and focuses on building simple, air powered robots (discussed in more detail below) from scratch with cheap materials. We believe this will lower the barriers to entry into robotics activities, particularly for **very young students** (elementary school) and adults without technical backgrounds. The project is scalable: young students can follow simple directions to successfully build their own robots, and advanced users (e.g. hobbyists or high school students) can expand the basic directions and come up with their own designs.



FIGURE 1
A SOFT ROBOTIC GRIPPER LIFTING A SMALL BOX.

II. Air-Powered Soft Robots

"Soft robots" are a recent trend in the robotics community. Instead of using "traditional" materials such as metals and hard plastics, and traditional actuators (e.g., DC motors and hydraulic pistons), these robots are made from highly flexible and stretchable materials (such as rubber). They are powered by a variety of methods, ranging from compressed air to chemical reactions or "electroactive" materials that change shape in response to electrical voltage or current.

In [5], the authors developed a method to create highly flexible, silicone rubber robots with embedded air channels using a 3D-printed mold. As these channels inflate, the robot's geometry changes drastically (e.g., a flat "leg" can become curved). This body morphing allows the creation of the soft "grippers" in [5] (shown lifting a raw egg in [6]) and the walking robot in [7] (see [8] for video). The same technology can even be used to create camouflaged robots [9] and jumping robots [10]. An example "gripper" robot, made with the procedure outlined in the "Fabrication Process" section, is shown in Figure 1.

III. 3D Printing

3D printing technology has existed for decades, but only recently has it become affordable to users outside of industry. Numerous "desktop" 3D printers in the $1,000-$2,000 range are now available [11]-[13] that can print durable materials such as ABS plastic, typically available in spools for roughly $50/kg. In addition, online 3D printing services allow users to upload, share, sell, and order printed copies of their own designs [14], [15]. Relative to industrial machines that cost tens or even hundreds of thousands of

dollars, these new avenues make 3D printing available to general consumers, hobbyists, schools and STEM educators.

FABRICATION PROCESS

I. Overview and Materials

Fabrication of the robots is based on a two-step molding process. A cross-section of each step is shown in Figure 2. In the first step, two separate molds are used to make "top" and "bottom" halves of the robot. The top mold has ridges that form negative cavities in the silicone rubber, and the bottom pieces is flat. The silicone rubber cures in 4 hours at room temperature or 10 minutes at 150°F. In the second step, the (now cured) top piece is removed from its mold and bonded to the flat (now cured) bottom piece with a new (uncured) layer of silicone rubber.[1] This gluing step embeds and seals the air channels. After a second curing step, the structure is punctured with an air tube, which inflates the channels and actuates the robot.

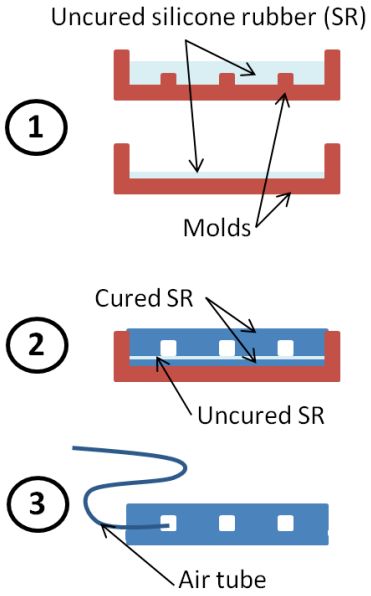


FIGURE 2
CROSS-SECTIONS OF THE MOLDS AND SILICONE RUBBER AT EACH STEP OF THE FABRICATION PROCESS.

In a laboratory setting, this process was completed using a $35,000 commercial 3D printer (Dimension by Stratasys Inc.), an air compressor [6] and system of computer-controlled solenoid valves [7]. However, the fundamental process is simple enough that the molds can be produced by a low-cost 3D printer or online printing service [11]-[15], and powered by a rubber squeeze bulb (commonly used to remove dust from camera lenses or computer parts). This drastically lowers the infrastructure cost required to make the robots, and the materials themselves (silicone rubber and plastic tubing) are very cheap. The process we have developed is affordable for a home or classroom setting. The required materials are listed in Table I (see Appendix A for recommended vendors). The non-renewable materials required to make one robot are (approximately): 0.2lbs silicone rubber mix, 1ft polyethylene tubing, 1" rubber tubing, and one squeeze bulb.

Not including the cost of a 3D printer (assuming a printer would not be purchased exclusively for this project, thus its cost would be spread over a longer period of time and many projects), and assuming one spool of ABS plastic is consumed printing molds (which are reusable), this project costs **approximately $10 per student for a classroom of 30 students**.

TABLE I
MATERIALS AND COSTS

Item	Cost
Desktop 3D printer	$1,000-$2,000
ABS plastic	$50/kg
3D printed mold (online vendor)	$30-$50
Silicone rubber mix	$15/lb
Polyethylene tubing	$0.05/ft
Rubber tubing	$0.70/ft
Squeeze bulb	$4 each
Metal baking pan	$5each

II. Step-by-Step Process

The step-by-step fabrication process (assuming you have either printed your own or ordered the necessary molds) is described here:

1. Mix parts A and B of the silicone rubber mix in a 50:50 ratio by volume in a plastic or paper cup. A straw or popsicle stick can be used to stir.
2. Slowly pour the mixture into the mold, filling the silicone to the top edge of the mold. Also pour a thin sheet of silicone onto your baking pan (approx. 2-4 mm thick). See Figure 3.
3. Let the silicone rubber sit for 4 hours and it will cure at room temperature. (Optional): The process can be accelerated by baking it in an oven at 150°F for 10 minutes. The materials are non-toxic, but **as a general scientific safety practice, do not use an oven that is used for cooking food!**
4. After 4 hours (or 10 minutes in the oven), check that the silicone is cured by poking the top with a pencil or pen. If it is solid and rubbery, the material is cured. If it is still gooey and sticks to the pencil, it needs more time.
5. Carefully remove the silicone rubber from the plastic mold (Figure 4), but do *not* peel the flat sheet off the baking pan.

[1] Best practices are to wear gloves when handling the uncured silicone rubber. The material is non-toxic and does not have any hazardous ingredients according to the MSDS, but it does have a warning label that it can be a mild skin irritant from repeated or prolonged exposure.

6. Mix a fresh batch of silicone rubber, again in a 50:50 ratio. Spread a thin layer (approx. 1mm) of the fresh silicone on top of the cured flat sheet in the baking pan (Figure 5). **Important**: this step is the most critical. If you use too much silicone, it will clog the air channels and your robot will not properly inflate. If you do not use enough, the two layers will not bond and you may have air leaks. Make sure you have an even layer of "glue".
7. Take the cured piece of silicone you removed from the mold in step 5, and carefully place it on top of the new layer of silicone **with the air channels facing down** (Figure 6)**.** Pour/spread a small amount of additional silicone around the outer perimeter of the shape (to help seal the bond and prevent air leaks). Check the top layer for air bubbles that may have been trapped during curing – these are vulnerable "weak spots" that can pop. Pour a small blob of silicone on top of any air bubbles that you see.
8. Let the silicone cure for 4 hours at room temperature, or 10 minutes at 150°F.
9. Carefully peel the silicone off of the baking sheet. Use scissors to cut around the outer perimeter, removing excess rubber from the sheet. Be careful not to cut into the body of the robot or puncture the air channels (Figure 7).
10. Cut roughly 12" of polyethylene tubing. Use one end of the tube to puncture the robot, in order to access an inner air chamber (Figure 8). This may be easier if you use a pushpin or paper clip to create the puncture, then insert the tubing. Use rubber tubing as necessary to adapt the polyethylene tubing to the nozzle of the squeeze bulb.
11. Squeeze the bulb and your robot should begin to inflate. It will probably require multiple squeezes to get the gripper to inflate fully.
12. Troubleshooting: if your robot does not inflate, it could be (a) air leaks or (b) clogged channels; both of which will prevent the robot from operating properly.



FIGURE 3
POUR UNCURED SILICONE RUBBER INTO THE MOLD AND BAKING SHEET. ALLOW TO CURE FOR 4 HOURS AT ROOM TEMP.

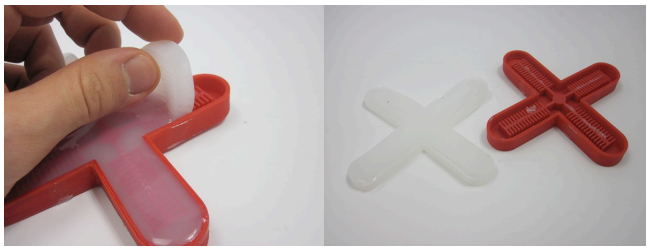


FIGURE 4
CAREFULLY REMOVE THE CURED SILICONE RUBBER FROM THE PLASTIC MOLD.

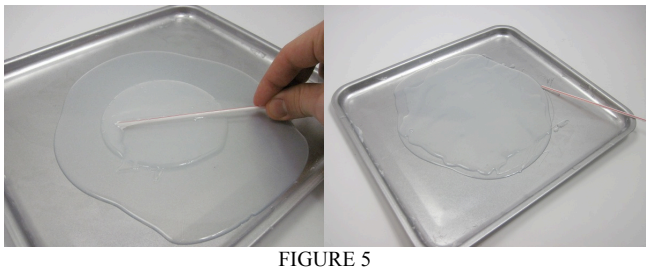


FIGURE 5
SPREAD A NEW LAYER OF UNCURED SILICONE ON TOP OF THE CURED SHEET ON THE BAKING PAN.

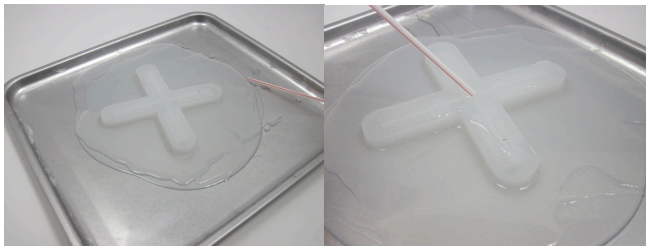


FIGURE 6
PLACE THE TOP PIECE ON TOP OF THE NEW LAYER, AND SEAL AIR BUBBLES AS NEEDED WITH FRESH SILICONE. LET SIT FOR 4 HOURS.

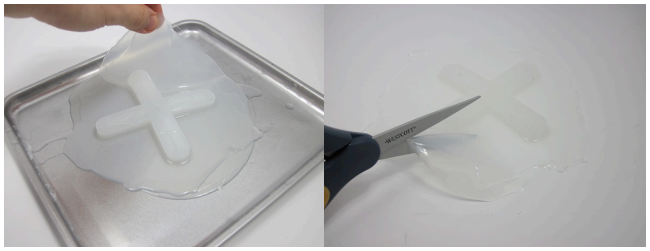


FIGURE 7
REMOVE ROBOT FROM THE BAKING SHEET AND CUT AWAY EXCESS MATERIAL

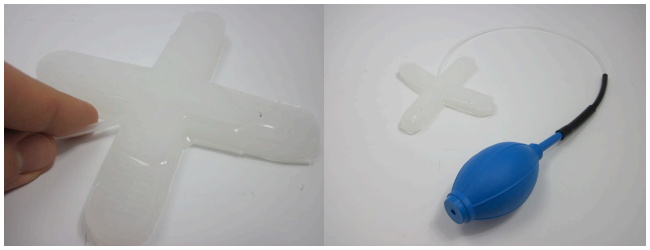


FIGURE 8
PUNCTURE ROBOT WITH POLYETHYLENE TUBING AND ATTACH SQUEEZE BULB.

OUTREACH PROGRAM

Through a partnership with a local "Maker Space", we ran a soft-robotics workshop open to families and children. Approximately 25 participants (including parents) ranging from elementary to high school students attended. The majority of the attendees found the project very engaging, and even very young children could complete the activity with some adult supervision. The workshop was a learning experience both for participants and the authors, as we identified critical steps in the procedure and problem areas that require future improvement (e.g. using too much or too little adhesive in Step 6). It also gave us a chance to show videos and discuss real-world applications of the robotics research with interested audience members. Some pictures from the workshop are shown in Figure 9.

We currently have a second workshop scheduled, in addition to a series of after-school science club activities through a partnership with a local science museum. We plan to iteratively improve the fabrication process until it is robust enough to be widely disseminated to parents and educators, at which point it will be made freely available through online platforms such as Instructables.com and MakeProjects.com.

This round of workshops does not include any formal learning assessments, although we hope to collaborate with education researchers on such assessments in the future. For now we have collected qualitative feedback from parents, which included comments like "The concept was very good & the kids had fun. Good hands-on program" and "Very hands-on! Great! Kids loved it."



FIGURE 9
PICTURES FROM THE FIRST SOFT ROBOTICS WORKSHOP.

CONCLUSION

This paper describes a preliminary outreach program based on soft robots. We believe the program has two primary strengths that give it value in STEM education: (1) it is low-cost, low-tech and sustainable, and (2) it gives children access to current, cutting-edge robotics research with real-world applications.

We plan to make the program widely available through additional local workshops and freely available online directions. We hope this program can serve as an inspirational model for other scientists and engineers, especially those in robotics, to use their research as a platform for outreach programs and educational STEM activities at the K-12 level.

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APPENDIX A – MATERIALS

- **STL files for mold** – contact the first author (bfinio@gmail.com).
- **3D printer**: we used an UP! printer, available at http://www.pp3dp.com/. There are numerous other desktop 3D printers available, such as the Makerbot (http://www.makerbot.com/) and Cube (http://cubify.com/cube/)
- **3D printing service:** There are many 3D printing services available, such as http://www.shapeways.com/ and http://i.materialise.com /. Be sure to order a plastic mold **with a smooth surface finish**. A rough finish will make it impossible to remove your part from the mold.
- **Silicone rubber:** Ecoflex 00-30 from Smooth-On Inc., available at http://www.smooth-on.com/Ecoflex%3D-Superso/c1130/index.html?catdepth=1
- **Polyethylene tubing:** 1/16" inner diameter, 1/8" outer diameter. Available at http://www.mcmaster.com/#catalog/119/138/=lhm57k, McMaster-Carr product number 5181K15.
- **Silicone rubber tubing:** 1/8" inner diameter, ¼"outer diameter.. Available at http://www.mcmaster.com/#catalog/119/128/=lhm6m1. McMaster-Carr product number 5236K832. **Note:** depending on the squeeze bulbs you purchase, you may need to purchase additional, larger-diameter tubing to use as an adapter.
- **Squeeze Bulb:** Polaroid Super Blower with Hi Performance Silicon Squeeze Bulb. Available from Amazon.com, ritzcamera.com, and other vendors. **Note:** this blower has a small rubber tip at the end of the plastic nozzle. Remove this tip and the plastic will mate directly with the 1/8" ID silicone rubber tubing.

APPENDIX B – LARGER IMAGES

This appendix contains larger versions of some of the images for crucial steps of the fabrication process. (Figures 3A, 4A, 5B, 6B, 7B, and 8A).



FIGURE 3A

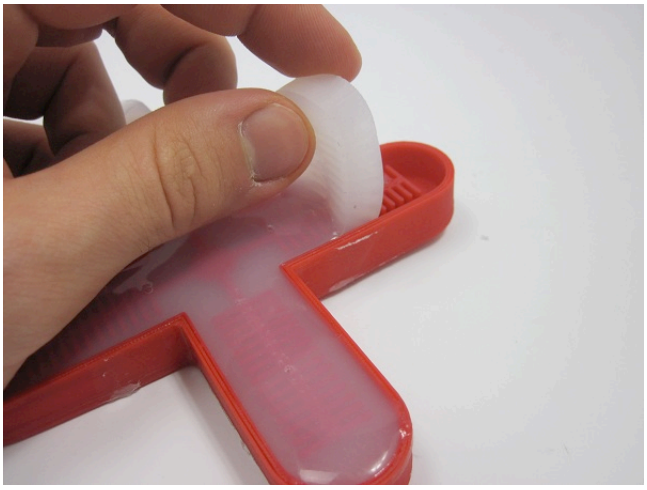


FIGURE 4A

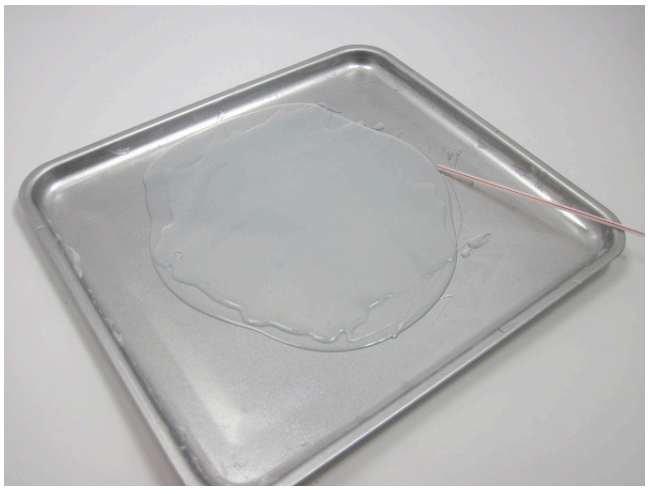


FIGURE 5B

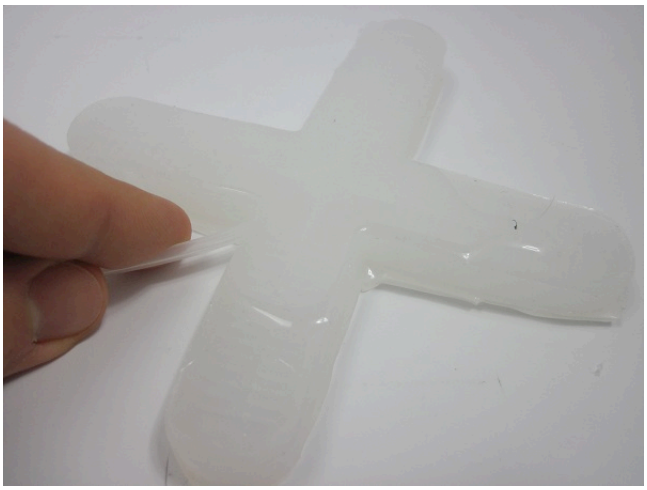


FIGURE 8A

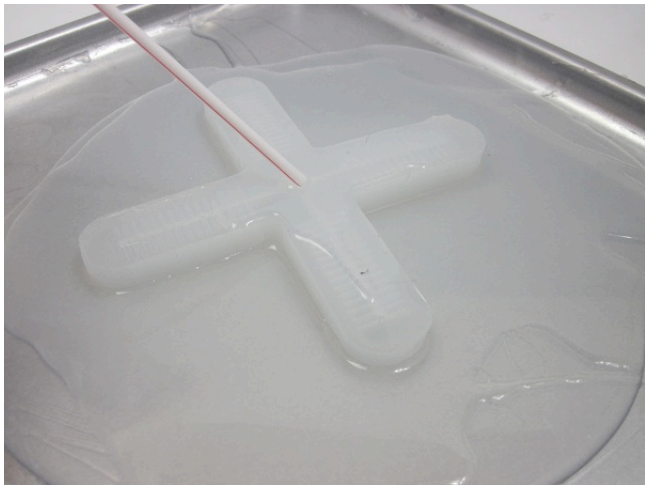


FIGURE 6B

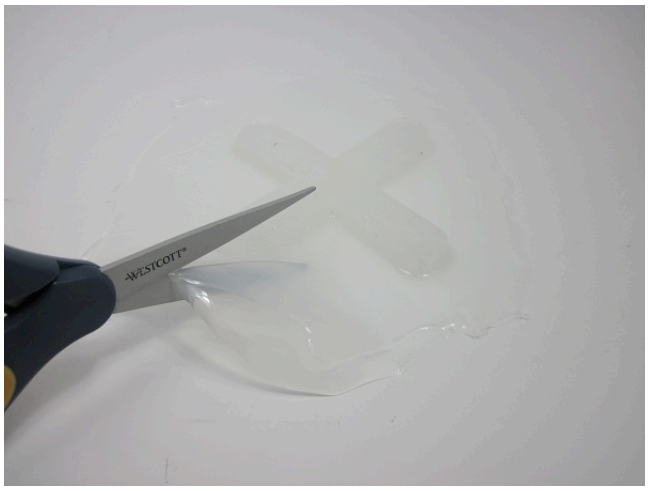


FIGURE 7B