Supplementary Material: A Modular, Reconfigurable Mold for a Soft Robotic Gripper Design Activity

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A ALTERNATIVE MOLD DESIGNS

The mold kit introduced in this work was developed to increase both design freedom and success rate. Our experience has shown that increasing both of these metrics in parallel is non-trivial. For example, the previously referenced soft robotic gripper activity utilizes a one-piece 3D-printed mold (Finio et al. (2013)), which we produced and show in Figure S1(a). This one-piece mold greatly reduces design freedom, and therefore design learning, by embedding the function in a pre-designed mold that students cannot change. However, use of a one-piece mold also eliminates some common fabrication failure modes, such as liquid elastomeric material leaking through a mold that is made of multiple pieces or non-functional configurations of a multi-piece mold.

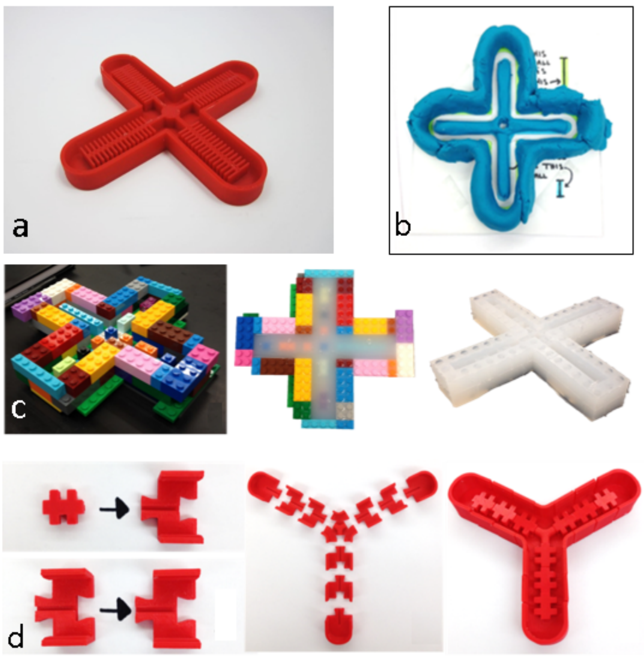


Figure S1. Several previous mold designs. (a) A one-piece 3D-printed mold Finio et al. (2013). (b) A Play-Doh Mold. (c) A LEGO mold. (d) The first iteration of the modular 3D-printed mold.

Other mold designs that we experimented with include molds made from Play-Doh (Figure S1(b)) and molds made from LEGO blocks (Figure S1(c)). Although the Play-Doh approach allows for mold reconfigurations, the dimensions of the mold are very difficult to control, resulting in non-uniform inflation and fewer working grippers. Alternatively, the LEGO mold approach was an effective method that strikes a balance between design freedom and success rate, however consumed a lot of elastomeric material due to the large fixed dimensions, which increased overall activity costs. Figure S1(d) shows a first-generation design for the modular 3D-printed mold kit. Compared to the LEGO mold, the modular 3D-printed mold kit consumes significantly less material and is easier to assemble. Based on several implementations with each of these mold approaches with various age groups, we decided to pursue the modular mold kit and further refine the approach to optimize both design freedom and activity success rate. The modular mold design presented in this work builds upon previous iterations by enabling pneumatic channel reconfiguration and reducing risk of failure modes during fabrication.

B SAMPLE INSTRUCTIONS

The following instructions will guide you through the steps of making a soft robotic gripper. Here we picked Ecoflex as the elastomeric material, but the instructions could also be used with other types of elastomeric material.

For a complete video tutorial, please check out the ”Soft Robotics Gripper Tutorial Video” at `https://www.youtube.com/watch?v=GgJt6vIbiso`.

Curriculum materials, including 3D print mold files, are available for download upon completion of a short survey about intended use of the materials at `https://tiny.cc/SRMolds`.

1. Prepare materials

Gather a set of modular mold pieces or 3D print a set using ABS filament. If printing a set, make sure to sand the mating surfaces of all the modular mold pieces to prevent the mold from leaking. Typically, sanding mold pieces by using a combination of a rough (80 grit) and a finer (220 grit) sand paper will achieve the best result. Slotted spring pins also need to be inserted into the sanded modular mold pieces before use, and they can be purchased from McMaster Carr.

Type of Modular Mold Piece	**Respective Roller Pin Part Number**
Finger caps	92373A106
Middle pieces and hub sides	92373A108
Hub center	92373A110
Coupler	92373A029

The modular mold kit includes 6 types of pieces:

- 1 Hub
- 4 Finger Caps
- 4 End Caps
- 12 Middle Pieces
- 1 Coupler Mold
- About 28 Clips

Besides the modular mold kit, you will need:

- 5 silicone rubber bands
- 1 nail
- 1 sheet of wax paper
- 1 pair of polyethylene gloves
- 1 pair of safety glasses
- 1 measuring cup
- 1 stirring device (such as a plastic knife)

- 1 pair of scissors
- 1 set of Ecoflex (part A and part B)v
- 1 piece of fabric (preferably cotton, at least 6x6 inches)
- 1 squeeze pump

2. Assemble the mold

You can determine what pieces and how many of each kind you need based on your robot design. Slide the pieces into each other to create an enclosed mold and secure the pieces together using a rubber band. Insert however many clips your design requires by clipping them in place on the trunks of the pieces.

TIP 1: Look out for gaps between the pieces; the Ecoflex can leak out of these and cause unequal amounts in fingers or a thinner top layer overall. If you see gaps try cleaning the edges, rearranging your pieces or using a spare piece as a replacement.

TIP 2: If any of the clips are not straight or tight on the trunk, they may tip over or lift up and cause large chambers of air or a thin top layer that leads to ruptures.

Also put together the coupler mold using a rubber band.

3. Prepare silicone elastomer mixture

SAFETY NOTES: Ecoflex is a brand of silicone elastomer used for molding made by Smooth-On Inc. Ecoflex comes in two bottles, containing Part A and Part B. Parts A and B are liquids - when mixed together, they will solidify and form silicone elastomer (in 4 hours at room temperature, or 15 minutes at 150 F). The materials are non-toxic, and harmless once cured. However, according to the Material Safety Data Sheet (MSDS), "repeated or prolonged" exposure to the unmixed materials (Part A and Part B) can cause mild skin irritation. We recommend wearing disposable gloves and eye protection when handling unmixed material. If you do get Part A or B on your skin, just wash it off with soap and water (Finio, 2013).

Mix parts A and B of the Ecoflex in a 50/50 ratio by volume or mass, using a paper or plastic cup for at least one minute. Consult the sheet with volume measurements for each part to calculate the total amount of Ecoflex needed. Put the lids back on your Ecoflex jars, and save the rest of the material to make more robots later.

4. Pour mixture into mold and let it cure

First, prepare a piece of wax paper and lay it down on a flat surface. Then place the molds on top. After that, pour the mixed Ecoflex into your 3D-printed mold. Make sure you have enough Ecoflex to pour to the minimum fill line and also fill the coupler. If you dont have enough Ecoflex return to Step 2 and mix a small amount more.

Ecoflex will cure (solidify) in about 4 hours at room temperature or 15 minutes at 150 F. After deciding which way you will cure your robot, make sure that the area you will leave your robot is level.

Room Temperature Option: Leave your uncured Ecoflex in the plastic mold for at least 4 hours to solidify. Leave the mold on top of wax paper to have easier cleanup after the Ecoflex is cured. Be sure that you leave the mold to cure in a level area. When it is finished the mixture will be rubbery when you touch it and will be somewhat opaque.

Toaster Oven Option: First, make sure that the inside of the toaster oven is flat using a level. If the toaster oven tray is not level, adjust so that its level. Then set it to 150 F or lower (this is the warm setting on most toaster ovens).

Next, place the entire mold (and coupler) together with the wax paper inside the toaster oven for a minimum of 15 minutes.

SAFETY NOTES: Do not use an oven that is also used for food. Do not put a plastic cafeteria tray in the oven. Double-check the melting temperature of the material of your 3D-printed mold. The plastic pictured here is ABS, which will not soften at 150 F. PLA is likely to soften at 150 F. Other mold materials may be different.

TIP: Mixing and pouring introduces air bubbles. If time permits, curing at room temperature or sitting 15-45 minutes prior to oven curing provides time for air bubbles to float to the surface and escape. Air bubbles cured in the silicone increase the risk of weakness and rupture.

5. Remove rubber from mold

Remove the pieces from the rubber. Also remove all the clips from the rubber and remove the coupler from the mold.

TIP: Ecoflex can stretch many times its original size without tearing and will rebound to its original form without distortion so dont be afraid to pull when removing it from the mold.

6. Prepare fabric and attach coupler, let them cure

Cut a square of fabric big enough for your gripper.

Mix another batch of Ecoflex (using measurements from sheet) and use process in Step 2. Then spread the Ecoflex onto the fabric using the tool you used to stir with, such as a plastic knife.

Place the gripper onto the fabric with the channels facing down.

Gently pat the gripper onto the fabric. Using the spreading tool, create a seal of Ecoflex around all sides of the gripper.

Insert the nail into the smaller hole of the coupler. Then put a layer of Ecoflex around the bottom of the coupler (where the bigger hole is).

Insert the nail with the coupler on it in the gripper.

TIP: If you use too little amount of Ecoflex on the fabric the two layers will not bond and there will be leaks. But be careful because if you use too much or press too hard you risk clogging the pneumatic network (or PneuNet).

Use the same process from Step 4 to cure the fabric to the rest of the gripper. If you are using the oven the time may be shortened to 10-15 minutes.

7. Trim off extra fabric

Remove the gripper from the wax paper.

Remove the nail from the coupler and trim around the edges of the gripper.

TIP: When trimming your fabric, be sure not to get too close or you may create a hole.

8. Inflate

There are two ways to use the pump to inflate the gripper. One way is to use the pump without the needle attachment. Inserting the pump into the coupler can be tricky, wedge one side in and pull the coupler up around it. The other way is to use the needle attachment with a rubber band secured around the collar to prevent slipping.

TIP: If you are making an individual finger for testing, use the needle to puncture through the end.

Inflate and test the gripper. If there are any issues, please refer to Table 4 for any troubleshooting.

9. Clean up

Cured Ecoflex can be easily removed from mixing containers, stirrers and table surfaces. Simply let the Ecoflex cure and pull the cured Ecoflex away. Reuse your equipment!!! Speeding the cure by heating is not recommended for mixing equipment.

Uncured Ecoflex is an oil based polymer and can be cleaned up with Lysol wipes, dish soap, simple green or equivalent.

Finally, you should wash your hands with warm soapy water to clean off any Ecoflex.

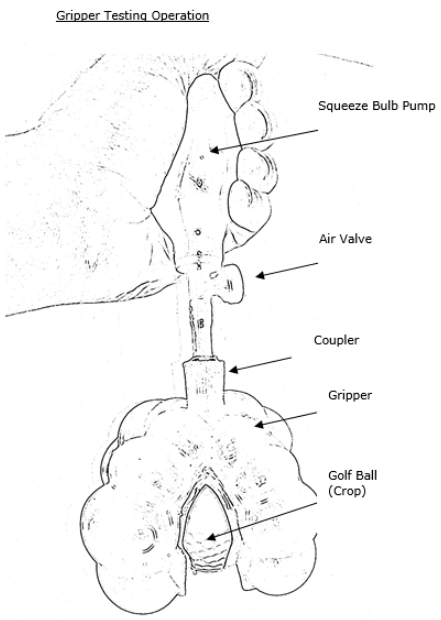
C SOFT ROBOTIC GRIPPER DESIGN BRIEF

Background

Scientists, engineers, and designers know the importance of documenting their work. Ideas, thoughts, experiments, and sketches all have a place in their notebooks. Other names for these notebooks are: Inventors Logbooks, Science Notebook, Engineers Notebook, and others. Thomas Edison documented the details of his ideas and inventions in over 3,500 notebooks.

Design Problem

Worldwide there are more people eating and fewer people producing food; we need to be more efficient and not damage what we have. You have been hired to design a robotic gripper to help a small farm operation be more efficient in picking up fragile produce. They have several different crops but their main yield is tomatoes about the size of a golf ball. Your gripper needs to help a farm worker accurately pick up the crop and sort it, all without damaging the food. Gripper should pick up, hold and release the tomatoes (golf balls). You should also be prepared to give training on your gripper and explain your design decisions (why you made it the way you did). Document your work using your electronic Engineering Design Journal.



Specifications

1. The robot gripper must be able to pick up a golf ball by inflating with the squeeze bulb pump.
2. The gripper must be able to securely hold the golf ball for five seconds.
3. The gripper must be able to release the golf ball by opening the air valve.

Materials

- Soft Robot Gripper Mold
- Ecoflex 2 part silicone
- Squeeze Bulb

Deliverables

1. Students working in groups of two will develop a solution to the soft robotic gripper design brief.
2. The process used to develop the solution should be recorded using the students electronic engineering journals. The journals should include sketches, pictures, and video of the solution.
3. Students will present their solution and electronic engineering design journal to the class.

D SOFT ROBOT PROCESS OVERVIEW

Soft Robot Process Overview

FABRICATING

Mark each step as you complete the process. *F* is for a finger, *G* is for a gripper.

Mold	*F*	*G*
Assemble mold		
Mix equal ratio Ecoflex		
Pour into mold		
Pour into coupler	X	
Cure 4 hours in room (or 15 min at 150° F)		

Fabric	*F*	*G*
De-mold gripper		
Cut fabric		
Mix equal ratio Ecoflex		
Spread Ecoflex on fabric		
Push gripper on to fabric		
Attach coupler with Ecoflex	X	
Cure 4 hours in room (or 15 min at 150° F)		

Sketch your design:

TESTING

Inspect and inflate your robot. For the finger, use the needle to puncture the end of the finger and inflate by squeezing. For the gripper, remove the needle and insert the pump into the coupler opening.

Rate your soft robot on each of the following areas.

	Y	*N*
Top is free of bubbles		
Coupler is attached		
Inner chambers are open		
Fabric is attached well		
Gripper is air tight		
Gripper bends when inflated		
Fingers bend uniformly		

Record results of finger or gripper:

IMPROVING

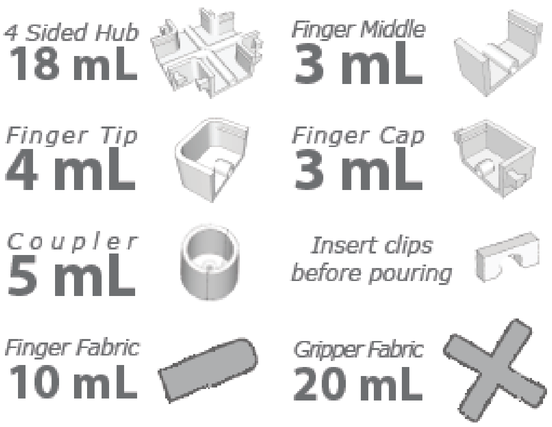
How does the robot compare to your expectations?

What problems do you feel, hear, or see?	What are your plans to solve these problems?

What has been successful about this process? What has not been successful?

VOLUME GUIDE

Use these hints to calculate the mixing volume of Ecoflex required. Each number represents the total estimated volume for each mold. Calculate the total for your design rounding up, and divide by 2 to get the amount of Ecoflex Part A and Part B.



Notes and Questions:

REFERENCES

Finio, B., Shepherd, R., and Lipson, H. (2013). Air-powered soft robots for k-12 classrooms. In *Proceedings of the IEEE Integrated STEM Education Conf.(ISEC)*. 1–6