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BYOE: Wacky-Waving-Non-Inflatable-Arm-Flailing-Tube-Man for Teaching Soft Robotics

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BYOE: Wacky-Waving-Non-Inflatable-Arm-Flailing-Tube-Man for Teaching Soft Robotics

Abstract. The emerging field of soft robotics has a wide range of applications in many different fields. Due to its recent emergence and development, it is important to formally expose students interested in STEM to this rapidly developing interdisciplinary field. We have addressed this issue by assembling the undergraduate engineering students to create a hands-on experience for college-level engineering students, allowing them to become familiar with a subset of soft-robotics-relevant scientific concepts and exciting them about the field. Students introduced to this project will be exposed to various topics of soft materials, magnetism, and parametric design that interplay in the design of soft robotic systems. This paper presents a "Wacky-Waving-Non-Inflatable-Arm-Flailing-Tube-Man" that undergraduate students can design, build, analyze, and test. The project can be tailored as a classroom activity, a laboratory exercise, or a group project. Students will design several tests to determine the best design to achieve a tailored flailing configuration. The two major elements of their designs that students will be able to modify include: 1) a selection among a subset of provided silicone elastomers that they will select based on their material properties (modulus of rigidity, hyperelasticity, etc.) and 2) the integration of ferromagnetic particles into the elastomer matrix or embedding a magnetic structure inside their design as a magnetic core. Once students have selected their design parameters and constructed their 'Flailing-Tube-Man', their design will be driven by external electromagnets also designed by the students. Through an iterative design process, the students can fine-tune their design and control the flailing parameters defined by the instructor. The motivation for this activity is to reinforce students' knowledge of soft material properties and electromagnetics concepts. The knowledge and skills used in this project form the building blocks for various soft robotic applications. By using an iterative design aimed at meeting the 'flailing' criteria of a customer (their instructor), this project also endeavors to teach students elements of parametric design and control principles by having them conduct their own tests to determine the best way for their design to flail about. The combination of electromagnetics and materials science is also an excellent opportunity to reinforce concepts taught within a typical engineering program. This paper details the supplies needed, possible methods of construction, and suggested learning outcomes associated with the activity.

Motivation

Soft robotics enables a shift in teaching paradigms, due to its use of multi-disciplinary and integrative knowledge, "The Soft Robotics community takes inspiration from nature and employs a highly multi-disciplinary approach involving several disciplines such as Materials Science,... Physics,... and Computer Science, etc" [1]. Therefore, it opens up new opportunities for educators to teach a combination of physics concepts (i.e., magnetism), material properties, and coding in the same project in a fun and engaging way for students. This project accomplishes this by creating a wacky-waving-non-inflatable-arm-flailing-tube-man that students might recognize as a fun and exciting object. This paper describes such activities of constructing a flailing soft structure that will engage students in a fun way while meeting several learning objectives achieved during activities. Knowledge gained may transfer to fields beyond soft robotics that include control, magnetism, actuator design, and mechanics of materials. We expect the project will unleash students' creativity as it goes beyond the mechanical and rigorous math-heavy control aspects of traditional mechanical engineering projects and introduces a fun way to learn about soft robotics.

An additional factor which may facilitate this is that the project was developed by undergraduate students for undergraduate students, which demonstrates that the project is feasible and interesting for undergraduates. Additionally, it should be noted that this project has not actually been run in classes as a consequence of the people proposing it being undergraduate students. The following explains the general process behind the project.

Project Overview

The main goal of this project is to produce a table-top wacky-waving-non-inflatable-arm-flailing-tube-man using 3D printing, silicone molding, and electromagnets controlled by a microcontroller. This project's initial inspiration of a common inflatable-tube-man, from [2], can be seen in Figure 1A. An example of a final product can be seen in Figure 1B, which includes a magnetically sensitive silicone tube hanging upside down from a test rig and three spatially arranged electromagnets controlling its flailing motion. This flailing motion is encouraged by instructors to be paired with some sort of song; both to make the project more enjoyable and to have students demonstrate a high level of control with their suspended tube. This project consists of four distinct phases: the tube-man phase, the electromagnet phase, the enclosure phase, and the control program phase. Each phase should take approximately 2 academic weeks for students to complete. Students should also be encouraged to infuse their creative spirit into their projects. This along with the other grading considerations are seen in the rubric found in Appendix A.

(A) (B)

Figure 1. (A) An example of the inflatable-tube-man that inspired the project [2]. (B) A demonstration of a non-inflatable-tube-man for this project, which includes a silicone tube, a test rig, and electromagnets.

Educational Context

This project is intended for engineering undergraduate students. The four phases listed above are implemented to help students pace their progress on this project. While the primary student audience for this project is sophomore mechanical engineering majors, the project may also appeal to chemical, electrical, and civil engineers at a similar point in their academic careers. Prior student knowledge on electricity, magnetism, and 3D modeling is helpful but not required as it can be introduced by the instructor. However, students might not be familiar with all of the concepts used in soft robots. Proof can be found in [3], "A pneumatic clamp makes it easier for people with motor disabilities to safely wield kitchen knives. Prostheses utilize shape memory polymers to better replicate the range of motion of a limb… these concepts fall under the category of 'soft robotics,' a field that uses strings, magnets, air, water and other non-rigid elements to design robotic solutions for biomechanical or industrial challenges". While it is likely for students to understand the physical forces behind certain objects, sophomore undergraduate students may not be familiar with the materials used in soft robotics and how they can be mechanically operated. For creating the magnetic silicone tube structure, the instructor has a choice to provide the physical molds or CAD design files to students beforehand, or introduce 3D modeling to students and ask them to prepare molds for generating the silicone tubes. The same practice can be applied to the design and 3D printing of the test rig.

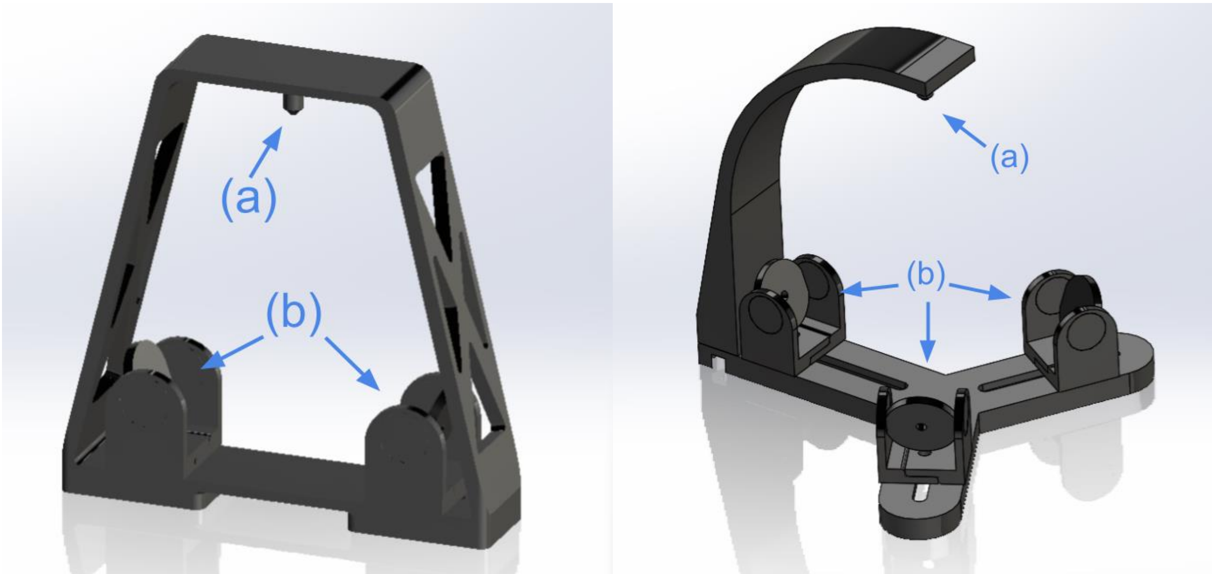
Learning Outcomes

By participating in this project, the students will…

- Use CAD modeling packages to design 3D-printed parts for assembly and production.
- Understand silicone materials and produce silicone structures using molding.
- Develop Arduino-based codes to control the flailing motion.
- Apply their electrical circuit and magnetism knowledge to develop a driving mechanism.

Instructor Preparation

The materials required to run this activity are provided in the Bill of Materials (see Appendix B). Care must be taken on material selections to avoid electrical interference with the electromagnets. Test rigs can be supplied by the instructor at the beginning of the project or can be designed and manufactured by students as part of project activities. Depending on the instructor's desired complexity in the flailing motion (e.g., a motion in which the robot reaches an angle of deflection greater than 15 degrees and oscillates between two or more configurations when the music is played), students can choose to produce double-electromagnet or triple-electromagnet test rigs seen in Figure 2A and 2B, respectively.



(A) (B)

Figure 2: (A) Double-electromagnet test rig with (a) a peg for the tube-man to be suspended upside down and (b) double mounts for electromagnets. (B) Triple-electromagnet test rig with (a) a peg for the tube-man and (b) triple mounts for electromagnets.

To guide students through this four-phase process, sample structures or devices of each phase (discussed in the Running the Activity section) should also be prepared by the instructor before the class. Students will be able to check out these samples at the start of each phase (a tube-man mold, a magnetic silicone tube, electromagnets, etc). This will allow the planned activity to be run in shorter time frames as students will be able to apprehend the ideas quickly or build their designs off the provided sample structures. Additionally, a sample rubric along with some framing for the project is provided in Appendix A which should help guide instructors in running the activity.

Running the Activity

The suggested process below is based on what has been done by our undergraduate design team. As a test run of the project, these hands-on activities, as well as the resulting physical components, are developed for the creation of a soft robot prototype. Further changes can be made to the original prototype to improve the learning experience of the participating students.

Tube-man

During this phase, students will learn the basic concepts of silicone rubber molding and the material properties of various silicone options. After practicing with the molding process and different silicone products, students will choose one design to create a negative mold for their desired tube-man shape and one silicone material for their desired mechanical properties. Figure 3A shows the CAD parts that can be used to make the mold, which include a lid (top closure), a dowel rod (for stirring and later for permanent magnet insertion), a shaft (main tube shape), and a base (bottom closure). Except for the dowel rod (wood or metal), other parts can be created using 3D modeling software, such as SolidWorks, and then printed using a 3D printer. Figure 3B shows an assembled mold with a silicone cast inside the chamber. The detailed engineering drawings can be seen in Appendix C.

(A) (B)

Figure 3: (A) CAD designs of mode components, including (a) a lid, (b) an example dowel rod, (c) a shaft, and (d) a base. (B) An assembled negative mold with silicone inside.

The dowel rod in Figure 3A is only an example of what students should expect to make. There will not be any CAD components that the student will have to design. It can be made out of wood or metal as these materials will not stick to the silicone, making it easy to stir the silicone inside the shaft chamber. Its length is dependent on the dimensions of the silicone tube as the rod needs to fit inside the shaft chamber without falling inside. Students can 3D print the individual components and assemble them into an enclosed negative mold. Screws will be used to secure these components into a single, leak-free structure. The information for the screws and nuts we used can be found in Appendix B. The other materials needed are the silicone kits of the instructor's choice (Smooth-On Ecoflex 00-20 was used in this demonstration), a plastic cup, and a digital scale. Students can follow the procedures recommended by the vendor of silicone kits to mix the liquid silicone parts in the correct proportions. The liquid silicone can be injected into the negative mold, further mixed using the dowel rod whenever needed, and cured at room temperature (or at an elevated temperature if other silicone products are used). The dowel rod must be wide enough so that a permanent magnet can fit comfortably in the finished mold. By the end of the curing process, students will be able to disassemble the negative mold and take the silicone tube out, as demonstrated in Figure 4.

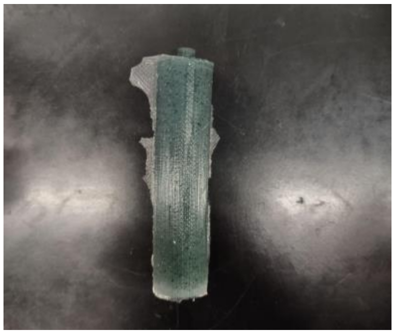


Figure 4: A silicone tube dyed with green food coloring.

The magnetic sensitivity of the silicone tube can be enabled in two different ways. The first option is to use a magnetic composite material, where the entire tube is made of a silicone base with dispersed magnetic particles. In this approach, students can add magnetic particles (e.g., carbonyl iron powder (CIP)) into the liquid silicone and mix them thoroughly before pouring the mixture into the mold. The second option is to insert permanent magnets into a fully cured silicone tube. With the dowel rod removed from the center of the tube, students can insert a few small permanent magnets into the hollow channel at the center of the tube. In our demonstration, we used the later option using permanent magnets for simplicity (a cross-section illustrating this is seen in Figure 5), due to focus on demonstrating the functionality.

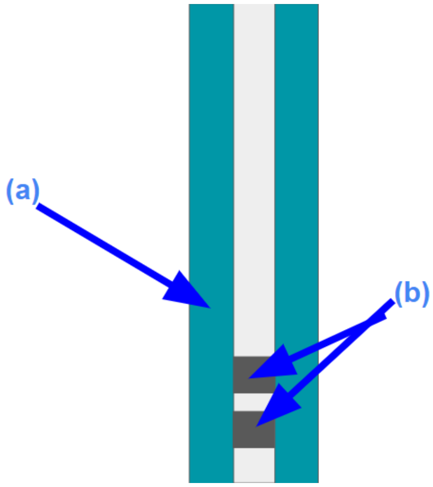


Figure 5: Depiction of the cross-section of (a) silicone tube showing where (b) permanent magnets were placed.

Electromagnet Design

The spatially arranged electromagnets are used to generate an electromagnetic field to control the flailing motion of the tube. The electromagnets should ideally produce a high magnetic flux density (B), which is defined as [4]:

$$B = \mu \times \mu_0 \frac{NI}{l} \quad (1)$$

where B is the flux density (T), μ is the relative permeability of the material chosen for the core (unitless), μ_0 is the magnetic constant (H/m), N is the number of turns of the wire around the core (unitless), I is the electric current running through the coils (A), and l is the length of the coil of the electromagnet (m). All of these variables (except for the magnetic constant) can be manipulated to increase or decrease the magnetic flux density, giving students options to change the parameters used in their designs.

Commercially available permanent magnets were used in our prototype as the magnetic core inside the silicone tube. As a result, there was no CAD file developed for the structure of the magnet. The specifications of the magnets can be found in Appendix B. To generate the electromagnetic field, hand-wound coil-based electromagnets are fabricated, with an example shown in Figure 6. The electromagnet is composed of two main parts, the coil (the wire wrapped around the bolt) and the magnetic core (a metal bolt). Looking back to equation (1), the term N refers to the number of times the wire is wrapped around the core, the term l refers to the length of the coil (or the solenoid; in Figure 6, the length denoted by (L)), the term I refers to the supplied current to the coil, and the relative permeability refers to a material property of the core (the bolt) that can be easily found (e.g., carbon steel has a relative permeability of 100) according to [5]. Relative permeability refers to how much more permeable the material is in comparison to the permeability of free space (which is given by the magnetic constant). It should be noted that electromagnets (with a similar magnetic core) have an upper limit of flux density produced (approximately 2 Tesla), and as such, students should attempt to increase the flux density in their designs to be close to the upper limit. This will give them a finer control over their electromagnets in later stages of the project. With this knowledge, students can then use a rearranged form of the magnetic energy equation found in [6] to find the force produced by their electromagnets:

$$F = \frac{B^2 A}{2\mu_0} \quad (2)$$

where A is the cross-sectional area of the electromagnet (m^2).

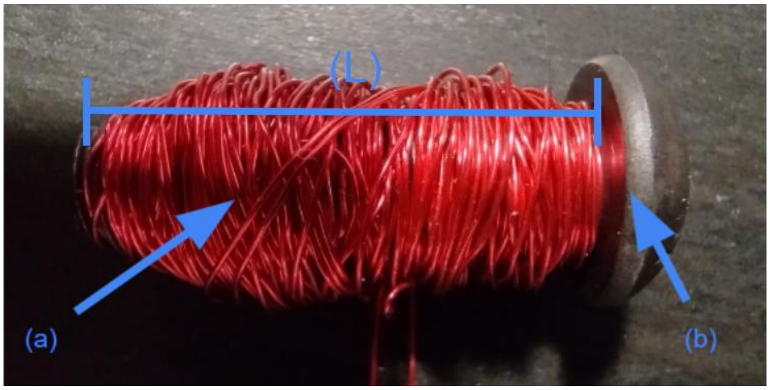


Figure 6: An example of an electromagnet with (a) a hand-wound coil and (b) a magnetic core of a length (L).

After performing these calculations, students should then be able to produce their own electromagnets by wrapping the provided wire around the ferrous cores. It should be noted that the magnetic flux density produced by the electromagnet follows the inverse square law, so the flux density's magnitude rapidly decays over distance. To validate that students' electromagnets can function properly, the instructor can run a progress check at the end of the electromagnet manufacturing process. This check can be done by using a magnetic field sensor to record the magnetic flux density created by the device or by asking students to use the electromagnet to pick up a ferrous object of a certain mass.

Enclosure Design

During this stage, students will be asked to create their own test rig to replace the instructor-provided rig (examples shown in Figure 2) for their set of electromagnets and tube-man. Students should be able to consider the large number of factors (distance, current source, material properties of their elastomer, etc.) that can impact their design. They will then create a test rig considering these factors as well as the flailing motion criteria defined by the instructor. For example, since the magnetic fields produced by their electromagnets decrease over distance (and likewise the pulling/pushing force), students could implement a component that allows them to move their electromagnets to and away from their tube-man within their design so that they can fine-tune the movement of their tube-man later on. Additionally, students should be adding their creative flair or theme to their design as per the provided rubric in Appendix A.

Control Program

At this stage, students should have a fully assembled tube-man setup and should design a control algorithm to execute the flailing motion outlined by instructors with their developed codes (using Arduino or Raspberry Pi). Students will first set up a control circuit, as demonstrated in Figure 7. They can choose to use batteries (4 AAA batteries, as shown in the figure) or a 12 V power supply to provide power to the circuit. Afterwards, students can use Arduino IDE (or other microcontrollers) to program their microcontroller and motor driver. A sample code is provided for instructors in Appendix D. It is encouraged for instructors to provide this sample code to students so that they can quickly and easily modify it for their desired tube-man dance. The main parameters that can be controlled with their motor driver are the current supplied to their electromagnets as well as the direction of the current supplied. This can be seen in the sample code shown in Appendix D in lines such as “analogWrite(EnA, 230); digitalWrite(Pin1, HIGH); digitalWrite(Pin2, LOW)” where the value of EnA controls the current supplied to the electromagnets on a scale from 0 to 255 via the motor driver and setting Pin1 and Pin2 to high or low determines the flow of current for the electromagnet. The flow of current in the electromagnet is important as it can flip the direction of its force (pushing instead of pulling and vice-versa). A motor driver is used for its ability to handle higher currents than a microcontroller, and it has the capability to control two motors, or in this use case, two electromagnets. Students should be encouraged to experiment with their codes to see how these different decisions will impact the dance motions of their tube-man, reminding students that they aim to meet specific angles of deflection, oscillations to a specific beat rate, etc., as outlined in the provided rubric. Since this is the last section of the project, students should then present their tube-man dancing along to the song listed in the rubric.

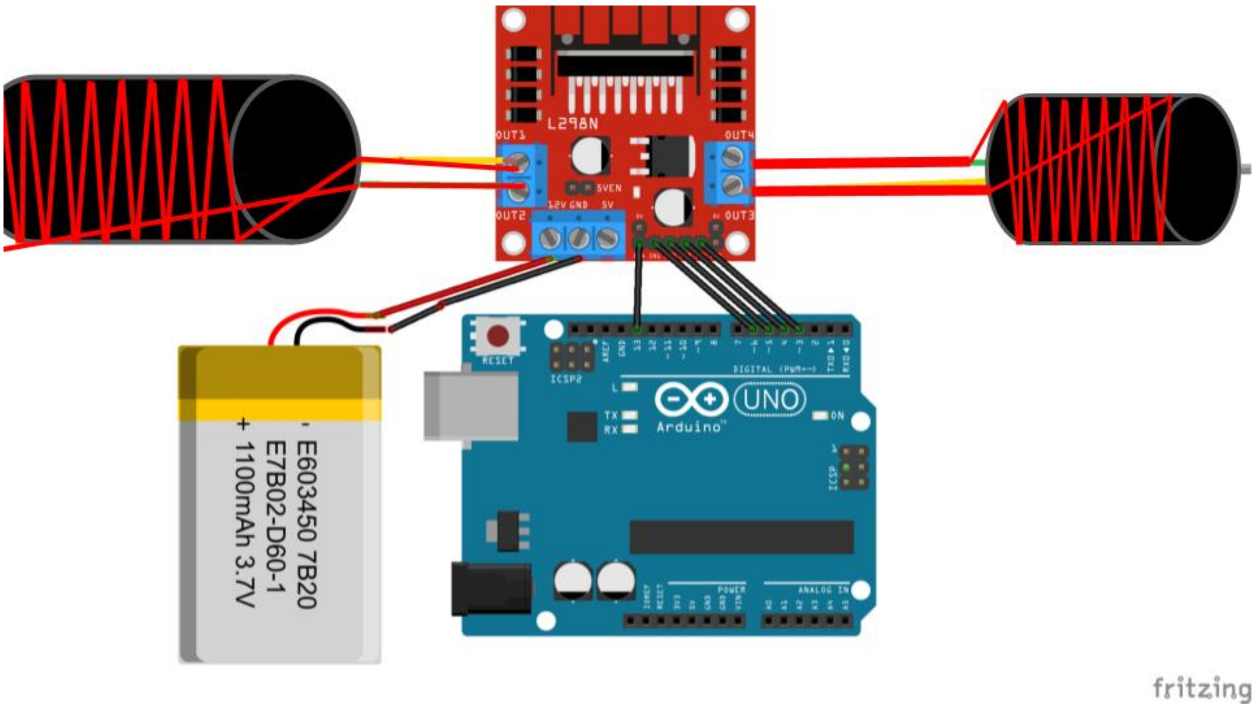


Figure 7: Circuit diagram for the motor driver and microcontroller (a) Red and black elements represent electromagnets. Generated and adapted using [7].

Student-Made Prototype Evaluation

Based on the provided rubric, the produced prototype would have received a 66%. Although the prototype did have a decorative element (being dyed green and having a tongue) the mold itself was not modified and therefore did not have a unique shape placing it in the 4 points category. While the electromagnets themselves did reach a high flux limit, they were not manufactured by the team, so there were only 2 points awarded in this category. The enclosure was not excessively large, so it met the size requirements; however, it did not have unique design elements incorporated into it. This resulted in it only receiving 4 points. Lastly, the tube-man reached an angle of deflection of 25°, so it received 6 points

There are several reasons for the poor grade received by the produced prototype. The final working prototype was developed in approximately two weeks, and as a result, the grading rubric for the project was not finalized until a very late point in development. Previous work conducted was on a separate design for a magnetic soft robot that was not transferable to this design, and so many aspects of the project are lacking due to time constraints (not enough time to redesign the enclosure, redesign the molds, and produce electromagnets ourselves).

If this were to be attempted again, appropriate time and a finalized rubric from the outset would be instrumental in ensuring a project that fulfills the outlined requirements. Particularly the creativity aspect was developed later in the project, and as a result, the produced prototype did not adhere to the rubric well. With these in mind from the start, a more creative magnetic soft robot could have been developed (e.g. an ocean-themed tentacle robot).

Conclusion

The learning outcomes for this soft-robotics-themed project address several needs of the engineering education space. This tube-man project can teach engineering students about designing and creating a soft robot that reinforces key engineering skills. To facilitate the implementation of the project in an undergraduate-level class, the instructors are encouraged to develop and demonstrate key components of a magnetically controlled tube-man. Students will be able to learn critical skills such as working with silicone materials, molding development, CAD drawing, 3D printing, electromagnetic actuation, microcontrollers, and programming. The project will also entail an iterative approach with appreciable troubleshooting opportunities. It is recommended that the project be divided into four phases where specific goals are made in each phase to help students pace the project and ensure they can make sufficient progress. Having the project split in this form also gives instructors the ability to constrain, modify, and emphasize specific aspects of the project. Ultimately, this project presents a unique way to introduce engineering concepts in an engaging way with the potential to get students excited about the emerging field of soft robotics.

Acknowledgments

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References

[1] S. M. H. Sadati, P. Maiolino, F. Iida, T. Nanayakkara, and H. Hauser, "Editorial: Current Advances in Soft Robotics: Best Papers From RoboSoft 2018," Frontiers in Robotics and AI, vol. 7, 2020.

[2] Tricia. (2006). Wacky waving inflatable arm-flailing tube man. Available: https://www.flickr.com/photos/elvissa/294517115

[3] M. Goisman. (2024). A world of soft robotics: Harvard Biodesign Lab brings back international competition. Available: https://seas.harvard.edu/news/2024/02/world-soft-robotics

[4] R. Martin, E. Neary, J. Rinaldo, and O. Woodman, "Section 22.3 Ampere's Law," in Introductory Physics: Building Models to Describe Our World, ed: Queen's University, 2020.

[5] (2016). The Engineering ToolBox: Permeability. Available: https://www.engineeringtoolbox.com/permeability-d_1923.html

[6] R. Fitzpatrick. (2006). Magnetic energy. Available: https://farside.ph.utexas.edu/teaching/em/lectures/node84.html

[7] “Fritizing: Electronics Made Easy.” Accessed: May 01, 2024. [Online]. Available: https://fritzing.org/

Appendix A - Rubric

Criteria	6.0	4.0	2.0	0.0
Molding Phase	Unique shape and decorative element	One or the other	Successfully creates a silicone product	Meets none of the given criteria.
Electromagnet Phase	Flux density within 5% of technical limit	Flux density within 15% of technical limit	Flux density within 50% of technical limit	Meets none of the given criteria.
Enclosure Phase	Meets size constraint, 3D, unique shape/ dec element	Meets size constraint and is 2D	Meets size constraint	Meets none of the given criteria.
Coding / Circuit	Reaches an angle of deflection of 25° & oscillates between two or more configurations when the music is played	Reaches an angle of deflection 15° & Oscillates for at least one movement when the music is played	Functional and documented code	Meets none of the given criteria.
Total /24				

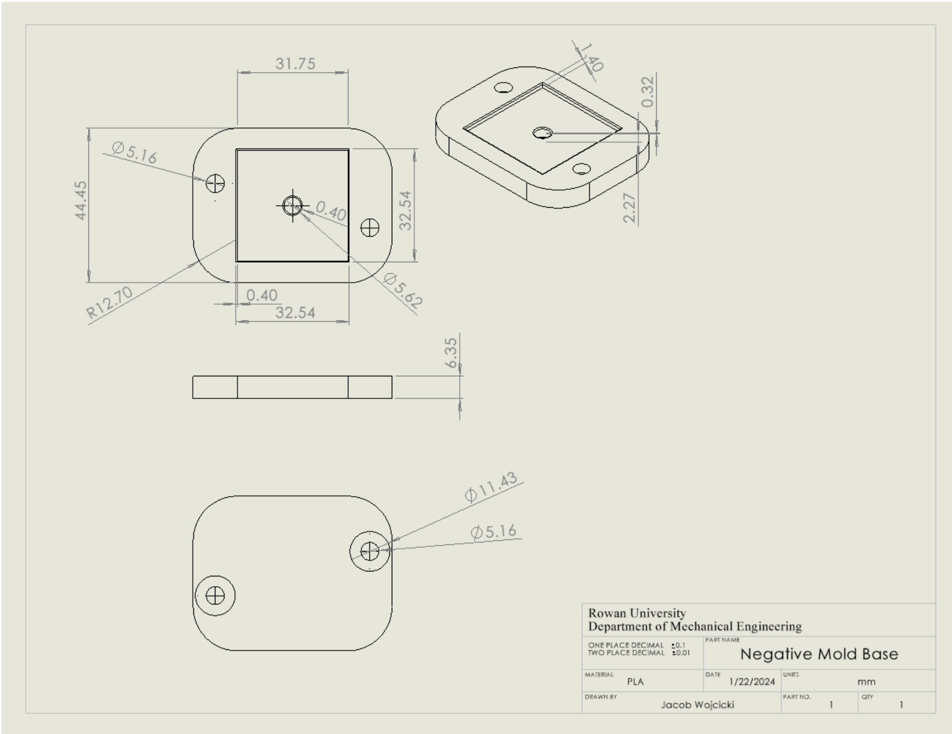
Appendix B - Bill of Materials

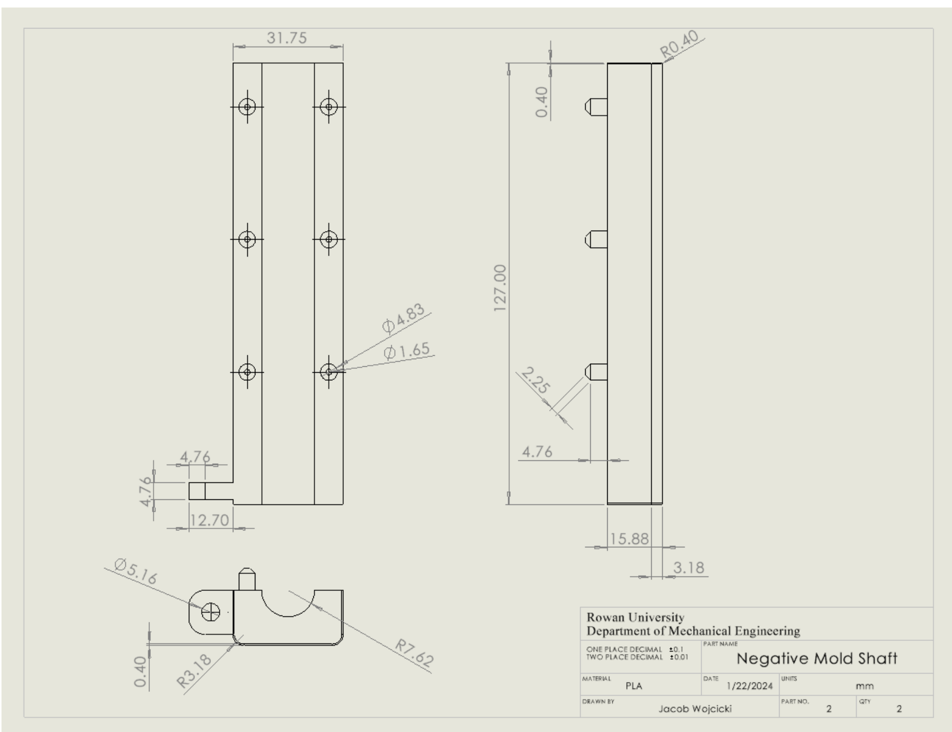
Item	Rec Qty	Materials	Vendor	Price	Description	Notes
1	3	Creality Ender 3 Pro (3D printer)	Creality	$150	Will be used to create mold and rig.	A large number of 3D printers is recommended due to the potentially high volume of prints.
2	2	PLA filament 1.75 kg	Overture	$18	Used in 3D printers.	Any PLA filament will work fine.
3	2	BNTECHGO 28 AWG Magnet Wire - Enameled Copper Wire - Enameled Magnet Winding Wire - 4 oz - 0.0122" Diameter 1 Spool Coil Red Temperature Rating 155℃ Widely Used for Transformers Inductors	BNTECHGO	$11.45 (0.02 cents per foot)	Used in electromagnet.	Thinner wire is recommended since less voltage will be required to generate a higher current.
4	2	M6-1.0 x 35 mm Socket Head Cap Screws, 12.9 Grade Alloy Steel, Allen Socket Drive, Black Oxide Finish, Machine Thread, 40 PCS	Kongki	$13	Used in making electromagnet.	As long as the bolts are made of some sort of steel or iron they should be okay.
5	2	Smooth-On Ecoflex 00-20 Super Soft Silicone Rubber - Pint Unit	Smooth-On	$38	Used in creating the tube-man.	

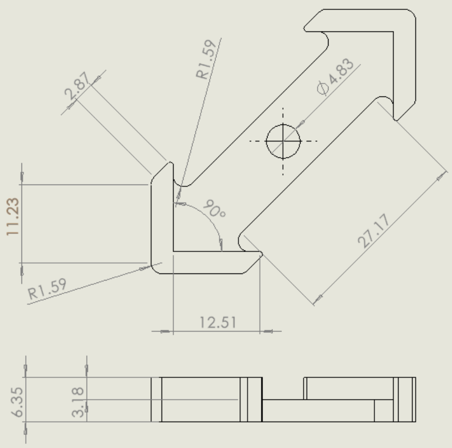
6	2	Smooth-On Dragon Skin 20 Mold Making Silicone Rubber - Trial Unit	Smooth -On	$38	Used in creating the tube-man.	
7	1	ELEGOO UNO Project Super Starter Kit	ELEGO O	$30	Programma ble Microcontro ller along with other useful electronics.	This was selected due to having multiple necessary components (cables, breadboard, microcontroller) in one package. Jump wires and an UNO board are used in Figure 6.
8	1	L298N Motor Driver	Qunqi	$7	Controls the strength and direction of current supplied.	This is recommended since it can handle higher voltages than those that come (L293D) with project kits. This is used in Figure 6.
9	1	Plastic Cups	Comfy Package	$8.49	An 80-pack of plastic cups.	This was selected to help hold the silicone needed for the tube.
10	1	Digital Scale	Amazo n Basics	$10.70	A digital scale with an LCD display. Can weigh up to 11 pounds.	This was selected to help measure the amount of silicone needed for the tube.
11	1	12V DC Power Supply	ABLEG RID	$10.99	A 12V DC Power supply adapter.	This was used to supply power to the Arduino and electromagnets. It can be used instead of 4 AAA batteries in Figure 6.
12	2	CENTROPOW ER 20 Pcs DC Male Plug Connector 12 V 5 A 2.1 mm	CENTR OPOW ER	$8.59	Allows the 12V power supply to be connected to the motor	

		5.5 mm DC Power Adapter Connector			driver with wire from the starter kit.	
13	1	Hillman #10-32 × 1/2-in Phillips-Drive Machine Screws (10-Count)	Lowe’s	$1.38	Important fasteners for assembling reverse mold seen in the technical drawings and paper.	
14	1	RHINOCATS 60 pcs Refrigerator Magnets, Magnets for Nail Clippers, Small Round Fridge Magnets, Tiny Magnet, Multi-Use for Office, Hobbies, Crafts and Science, Tiny Size: 5 mm x 3 mm (DxH)	RHINO CATS	$4.99	Is placed in the silicone tube to allow for electromagnetic attraction.	
15	4	Powermax 24-Count AAA Batteries, Ultra Long Lasting Alkaline Battery, 10-Year Shelf Life, Reclosable Packaging	Powermax	$6.15	AAA batteries that can be used as a power source.	If the instructor decides to use batteries instead of the power source, this is what should be purchased.
16	1	BHM-4A3	Twin Industries	$3.52	The battery holder for the AAA batteries.	

Appendix C - Drawings of Negative Mold







Rowan University Department of Mechanical Engineering			
ONE PLACE DECIMAL ±0.1 TWO PLACE DECIMAL ±0.01	PART NAME Negative Mold Lid		
MATERIAL PLA	DATE 1/22/2024	UNITS mm	
DRAWN BY Jacob Wojcicki		PART NO. 3	QTY 1

Appendix D - Sample Code in Arduino IDE for the tube-man

```
// By: William Heil-Heintz
//Last Modified: 2/8/24
// Notes:
// Although you can set your EnA and EnB to values of 255, this is not encouraged.
// For one, the current might simply be too much for the board to handle causing it to short
// For two, student's produced electromagnets may not even be able to safely handle a high amount of current

const int Pin1 = 2; // Leads to one of the terminals of e-mag one
const int Pin2 = 3; // Leads to one of the terminals of e-mag one
const int Pin3 = 4; // Leads to one of the terminals of e-mag two
const int Pin4 = 5; // Leads to one of the terminals of e-mag two
const int EnA = 6; // Leads to EnA of the motor driver this controls how much current electromagnet 1 receives on a scale of 0:255 with 255 being the max current that can be supplied
const int EnB  = 10; // Leads to EnB of the motor driver this controls how much current electromagnet 2 receives on a scale of 0:255 with 255 being the maximum current that can be supplied

// This section defines different variables to correspond to the different digital pins on the arduino unit

void setup() {

pinMode(Pin1, OUTPUT);
pinMode(Pin2, OUTPUT);
pinMode(Pin3, OUTPUT);
pinMode(Pin4, OUTPUT);
pinMode(EnA, OUTPUT);
pinMode(EnB, OUTPUT);
// This section defines the different variables as outputs for the arduino
}
```

```
void loop() {
 analogWrite(EnA, 230); // Setting the strength of electromagnet 1
  digitalWrite(Pin1, HIGH); // Current is sent into this pin
  digitalWrite(Pin2, LOW); // Current is not sent into this pin
  // The direction in which your current flows determines whether or not your
electromagnet will pull or push
 analogWrite(EnB, 230);
  digitalWrite(Pin3, HIGH);
  digitalWrite(Pin4, LOW);
  delay(500); // This is a delay in milliseconds that instructs your arduino to wait to execute
the next line
  analogWrite(EnA, 200);
  digitalWrite(Pin1, LOW);
  digitalWrite(Pin2, HIGH);
  analogWrite(EnB, 230);
  digitalWrite(Pin3, LOW);
  digitalWrite(Pin4, HIGH);
  delay(500);
}
```