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Hybrid Dielectric Elastomer Actuator for Biologically Inspired Propulsion

Abstract:

The development of novel methods for underwater propulsion is crucial for advancing underwater exploration. Biologically inspired designs, coupled with soft-robotic technologies, offer promising avenues for creating more efficient propulsion systems. One such promising approach involves dielectric elastomers (DEs), which must be integrated into dielectric elastomer actuators (DEAs) to enhance their performance and practicality. In this study, we evaluated a range of soft-actuation and movement techniques and identified a liquid DE actuated by rotary motion as the optimal design. This approach was selected for its superior energy efficiency, deformability, and the simplicity of motion it affords. Based on this design, we fabricated a liquid DEA and motor housing to assess the validity of our design as well as investigate methods of manufacturing this device.

Introduction:

Developing new methods of movement is a crucial way of exploring the world and moving from place to place faster and more efficiently. However, there are cases where hard bodies cannot be used in a robot and therefore traditional methods of actuation, such as motors, pneumatics, and hydraulics, cannot be used. This replacement of hard-bodied actuation methods is referred to as soft-robotics. This is done by creating methods of actuation that only use soft and highly deformable materials. To make these new actuators as efficient as possible we can take inspiration

and mimic biological motion to create biomimetic robots that are able to explore new places of the world.

Research projects already exist that use both soft and hard-bodied robotics to create biomimetic underwater propulsion with varying benefits and drawbacks in the design. One of the most famous examples is the RoboTuna created by Dr. Triantafyllou et al. at MIT. Their design used hard-bodied components to create a robot that mimicked the motion of a tuna and genetic algorithms to create the most efficient fin motion possible [2]. Despite its revolutionary design the robot could not fully replicate the acceleration of an actual tuna and lacked several biomimetic components that could have improved its efficiency. Another design is done by Shintake et al. where they designed 2 robots that used DEAs and silicone substrates to replicate the motion of a jellyfish and fish [6]. This design proves one way of using DEAs in underwater actuation. However, their low force output and small deformations proved that DEA technology is not yet able to fully replicate muscle force output. From these examples and more [3][4][7][10] it can be gleamed that underwater soft biomimetic robots are good concepts but need much better actuators to achieve the biomimetic motion they set out for.

This project is to study various underwater animal methods of propulsion and then correlate them into design solutions and propulsion methods to help move a robot underwater. Specifically, the hybrid use of liquid and regular dielectric elastomers (DEAs) should be used as DEAs have a high force output per square area, are simple to implement, and replicate muscle movement well. A hybrid design should be used as no papers have been published that use both liquid and regular DEAs to propel a robot as usually only one design is used in the soft-actuator. Additionally, a hybrid model offers benefits as regular DEAs have a high force output, but low displacement and liquid DEAs have the opposite with a lower force output but higher displacement. The hybrid

design seeks to find a cross between these two DEAs to create a balanced actuator that has both high force output and high displacement. With this more biomimetic actuator and analyzing biological motion a new underwater robot can be created that mimics the flapping movement of a snailfish [10] while using a more efficient combination of soft-actuators.

Design Approach:

To create a new underwater soft-robot actuation method a team was assembled of 3, fourth year mechanical engineer majors at Case Western Reserve University. This team then broke down assignments and goals to create the best design possible. Due to the nature of the smaller group, all assignments are shared, and a weekly breakdown of what tasks need to be completed were broken down into a Gantt chart shown in figure 1.

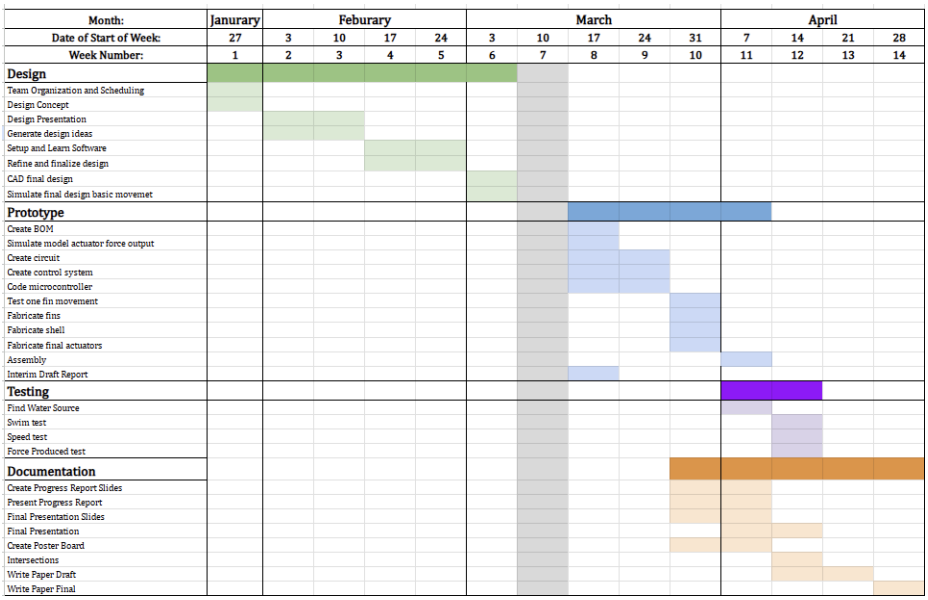


Figure 1: Gantt chart of task breakdown

Once the team was assembled and tasks delegated, investigation into previous soft-robotic designs was done (see Introduction Section). This was essential to allow all designs to not repeat previous experiments and to be a meaningful improvement to current scientific knowledge. From

this information many design iterations were considered and broken down into their respective motor movements and actuation methods. A flapping motion was first considered as the most biomimetic motion compared to fish and cephalopods, this was adapted into both liquid and liquid-solid hybrid designs shown in figure 2. A rotary design was also considered as few designs have been previously created that utilized DEAs, one iteration is shown in figure 2.

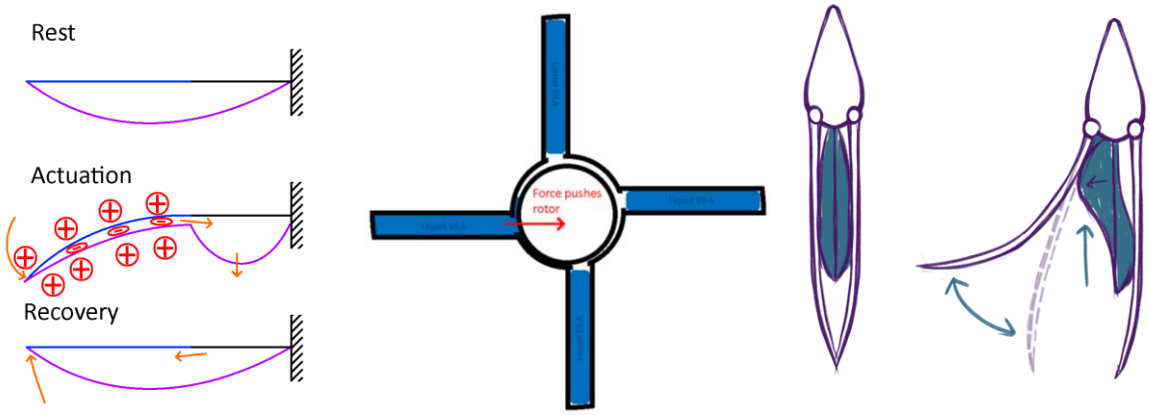


Figure 2: images of previous designs including: Bioinspired Flapping Propulsion (left), Liquid DEA Rotor (center), Liquid-Solid DEA Hybrid (right)

From the design ideas, weighted trade studies were created to break down various design ideas into numerical comparisons based off previous research found in the literature review portion. Two weighted trade studies were done, the first one was used to compare different methods of soft actuation to determine which method would be the best for our design goal. Criteria were broken down with heavy emphasis on energy efficiency, force output, and actuator displacement. Values were then interpreted based on previous research findings and knowledge of how these actuation methods work and their effectiveness.

Soft-Actuation Methods

			Motors		Hydraulics		DEAs		Liquid DEAs	
Criteria	**Specifics**	***Weight (%)***	**Rating**	**Weighted Rating**	**Rating**	**Weighted Rating**	**Rating**	**Weighted Rating**	**Rating**	**Weighted Rating**
Energy Efficiency	W	0.3	3	0.9	2	0.6	4	1.2	4	1.2
Force Output	N	0.2	3	0.6	3	0.6	3	0.6	2	0.4
Displacement	cm	0.2	3	0.6	3	0.6	1	0.2	3	0.6
Simplicity	# of parts	0.1	3	0.3	1	0.1	3	0.3	3	0.3
Cost	$	0.05	3	0.15	1	0.05	4	0.2	4	0.2
Biomimicry	Sim. To SCM	0.05	1	0.05	1	0.05	4	0.2	4	0.2
Stiffness	N/m	0.1	1	0.1	2	0.2	3	0.3	4	0.4
TOTAL		1	17	2.6	13	2	22	2.7	24	2.9

Table 1: weighted trade study of possible soft-actuation methods

From the trade study in Table 1, liquid DEAs are the best choice to be used in our design as they scored highly in all categories except for force output. This is due to the nature of liquid DEAs being extremely deformable and thus their force output being spread out. From this information 3 different methods of creating an actuator were proposed, flapping, rotary, and jetting motion. The flapping motion uses a motion that mimics a cuttlefish's find movement, the fin propagates a sinusoidal wave down the fin and thus displaces and accelerates the water in the opposite direction of the robot, propelling it forward. A rotary motion translates the horizontal motion of a liquid DEA and transfers it into a rotational motion that can be used to spin a propeller

underwater. Finally, jetting propulsion is like a cephalopod's jetting movement as water is pulled inward and then expelled outwards and propels the robot forward.

Movement Methods								
			Flapping		Rotary		Jetting	
Criteria	**Specifics**	***Weight (%)***	**Rating**	**Weighted Rating**	**Rating**	**Weighted Rating**	**Rating**	**Weighted Rating**
Energy Efficiency	W	0.3	2	0.6	4	1.2	2	0.6
Force Output	N	0.2	4	0.8	3	0.6	2	0.4
Displacement	cm	0.2	2	0.4	4	0.8	3	0.6
Simplicity	# of parts	0.1	3	0.3	3	0.3	3	0.3
Cost	$	0.05	3	0.15	3	0.15	2	0.1
Biomimicry	Sim. to Animals	0.05	4	0.2	1	0.05	4	0.2
Stiffness	N/m	0.1	3	0.3	2	0.2	1	0.1
TOTAL		1	21	2.45	20	3.1	17	2.2

Table 2: weighted trade study of movement methods

From the weighted trade study in figure Table 2, the rotary motion was determined to be the best despite it being the least biomimetic. This is due to the setup of the weighted trade study as biomimicry was less of a priority compared to energy efficiency, force, and displacement. From both studies we concluded that a rotary soft-actuator using liquid DEAs would be the best design

idea. This idea was then verified to be new as no published studies have been done that use liquid DEAs to create a rotary actuator meant for underwater propulsion.

After analyzing the best design options in the trade studies above (Table 1 and 2), design drawings were created (figure 2) inspired by the deformable motor done by Minaminosono et al. [14]. Overall dimensions were done in cm and mm to maintain a small form factor at liquid DEAs cannot deform a large amount without increasing material thickness and therefore resistance in the material. The overall radius of the circle frame is 10cm as this was determined to be small enough for liquid DEAs to have a large effect on the motor but small enough to not run into need too large of a force to move.

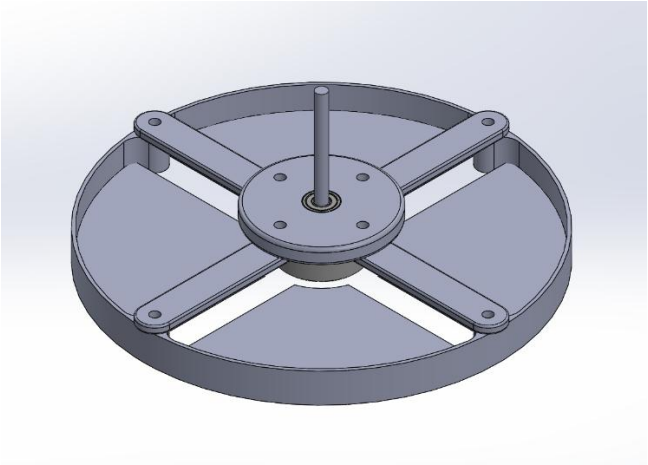


Figure 3: Isometric view of CAD model.

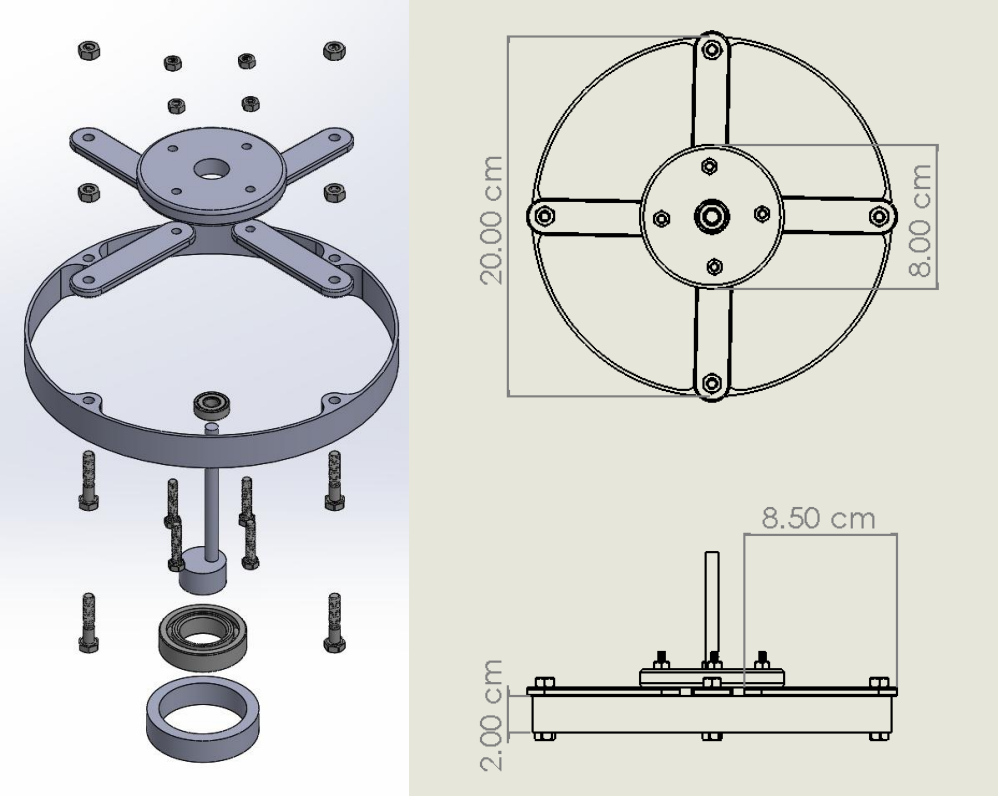


Figure 4: Exploded view of motor (left) and design drawing (right)

The major components in shown in DA-4 include: 4 Peano-Hasel DEAs, 4 support struts, 1 circular frame, 1 eccentric body [14], 1 shaft, 2 shielded ball bearings, and 2 hub rings. The support struts, frame, and one of the hub rings are attached via nuts and bolts. The other hub ring is attached to the 4 Hasel actuators which are further attached to the circular frame with epoxy.

To compare the efficiency of our quarter-circular shaped liquid Hasel DEA and the one outlined by Kellaris et al. [15] we will determine the force output per unit area of our DEA and compare it to the one done by Kellaris et al. to determine if our efficiency has significantly dropped due to the shape differences or changes to manufacturing.

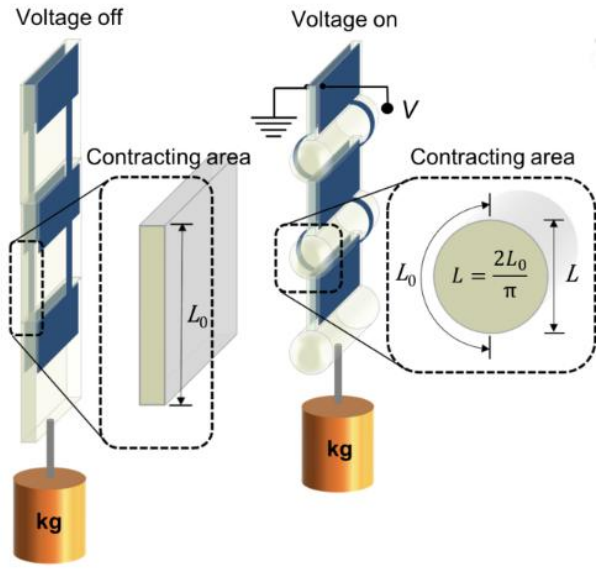


Figure 5: Peano-HASEL Actuator Design (Curtesy of Kellaris et al.)

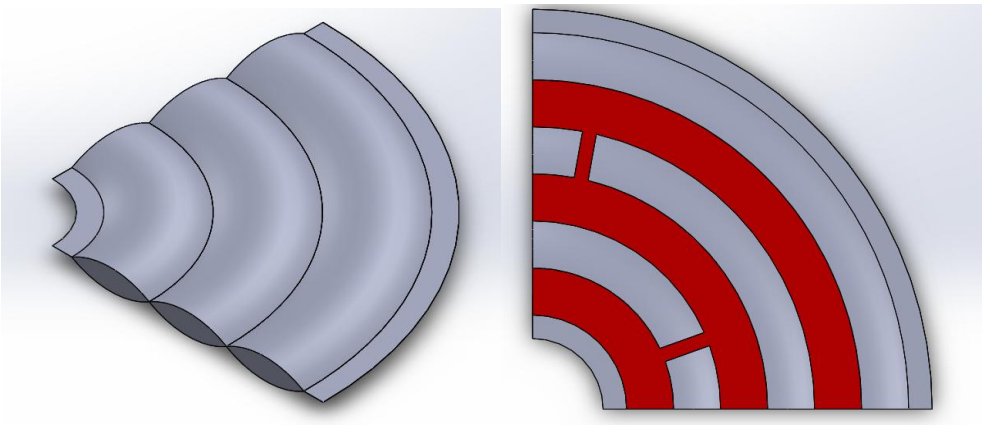


Figure 6: Quarter-Circle Actuator Design (left) and Electrode Layout (right)

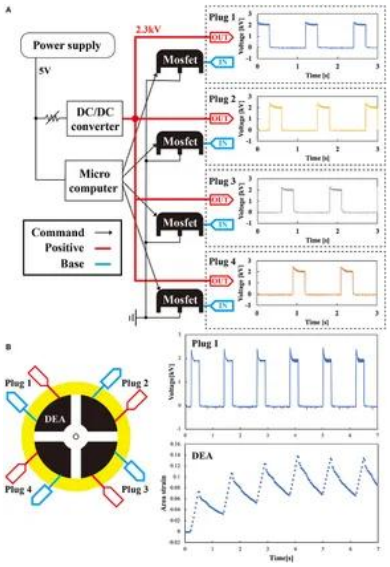


Figure 7: Example circuit design for rotational DEA motion (courtesy of Minaminosono et al. [14])

Due to the high voltage needed to activate a Hazel actuator, about 6-8kV [15], our circuit design will be off board for this design iteration to ensure safety to lab members and efficacy of results. A high voltage DC/DC converter was used to evaluate the devices at 5000, 8000, and 9000V at 30W. This was tested and shown to be able to deform the quarter-circle Hasel actuators without damage or significant heath risks.

Manufacturing Methodology:

Motor Frame:

1. CAD files are converted to STL files and sliced into a GCODE file for 3D printing.
2. Adjust infill to 30%, bed adhesion, and cross fill. Heating should be automatically adjusted for PLA on 3D printer used.
3. After printing, remove it from the heated bed. Removed excess material from bed adhesion.
4. Check for any defects.

Hasel Actuator:

1. A 6” by 6” piece of Kapton film is placed on top of the heated platform. 2 layers of BBOP film are placed, the inside sides facing each other. Attach all films with tape.
2. The pathway is uploaded to the flash forge printer and settings are updated to allow for the correct length between films and heated platform to allow sealing. Start the printer and watch to ensure no melting of the films.
3. Remove BBOP film and cut to desired size.
4. Paint electrode pattern using carbon ink, wait overnight and repeat for opposite sides. Use the oven to expedite drying process.
5. In the breaks of the seal, inject liquid DE (silicone oil in our experiment) to desired volume.
6. Reseal after filling with liquid DE with pouch sealer, soldering iron, or heated metal rod.
7. Wait 1-2 hours to check for any leaking.

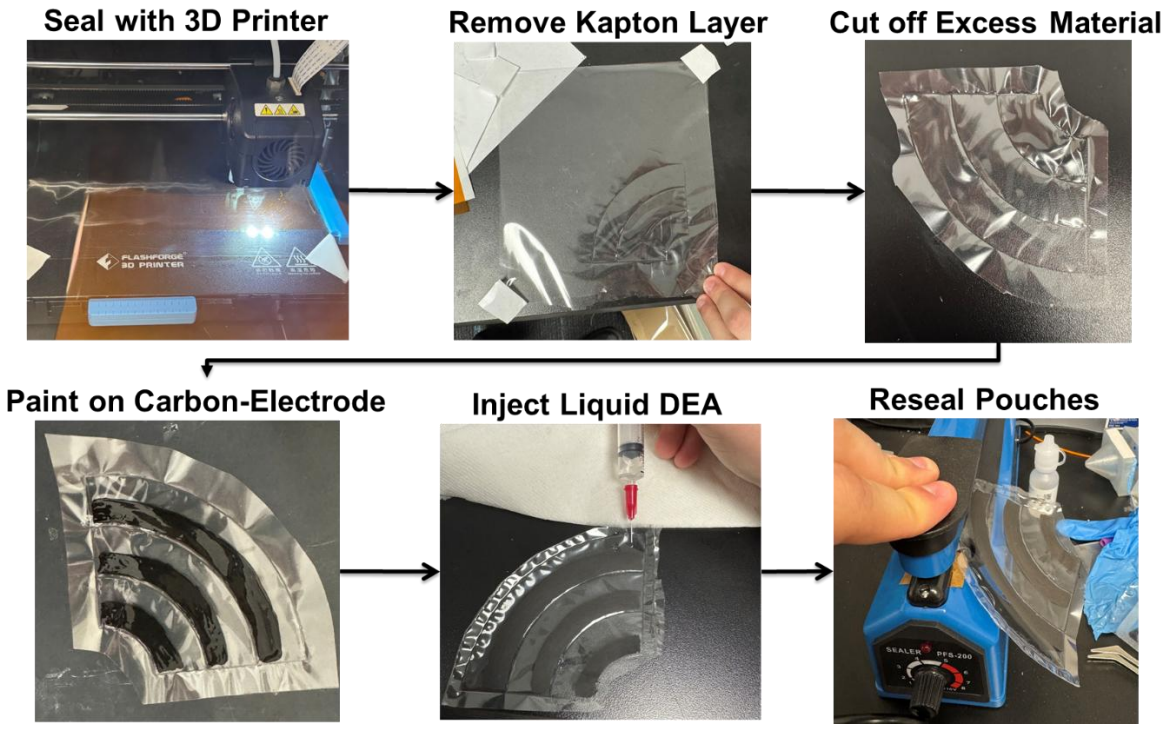


Figure 8: Fabrication process for quarter circle Peano-Hasel actuator

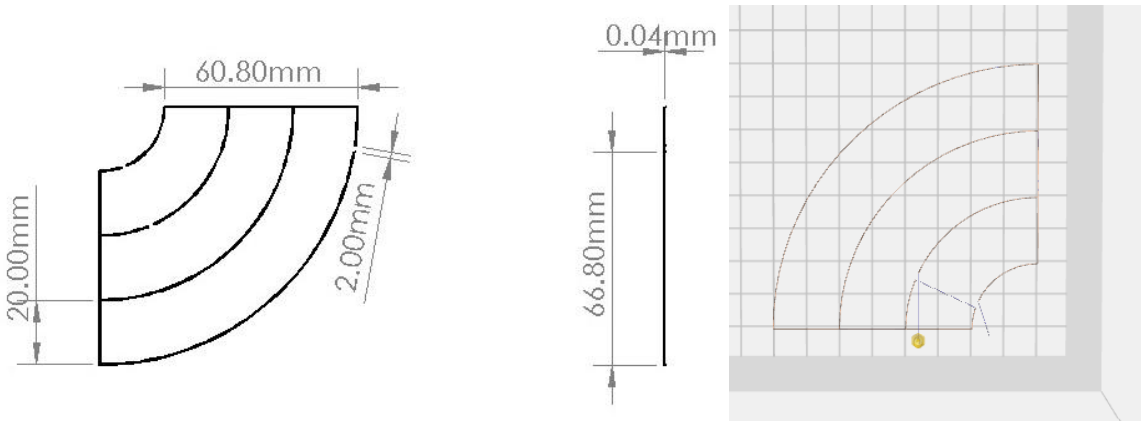


Figure 9: 3D Printer Pathing

Description	Make/Buy	Material	Manufcaturing Methods	Vendor	Vendor ID	Link	Purchase
Liquid DEA	Make	Kapton® Polyimide Film, Elect	3D Printer	McMasterCarr	2271K2	https://v	$18.12
	Make	BBOP Film	3D Printer	N/A	N/A	N/A	N/A
	Make	VHB Tape	3D Printer	McMasterCarr	76665A88	https://v	$63.00
	Make	Carbon Ink	Painting	N/A	N/A	N/A	N/A
	Make	Silicon Oil	Syringe Injection	N/A	N/A	N/A	N/A
Motor Housing	Make	PLA	3D Printing	ThinkBox	N/A	N/A	$12.90
Ball Bearing, Shielded	Buy	Stainless Steel	N/A	McMasterCarr	5972K261	https://v	$12.57
Plastic Ball Bearing w	Buy	Plastic	N/A	McMasterCarr	6455K49	https://v	$21.78
						Total:	$128.37

Table 3: Bill of Materials

Results:

Our design iterations found multiple ways of solving the problem of creating a soft-actuated underwater motor and these design choices were weeded out using weighted trade studies. However, due to the opinionated nature of these studies and our target goals other researchers may find unique designs beneficial. Most issues were found in the manufacturing process as various hiccups in the process caused delays in production that could easily be avoided if known

beforehand. This includes having thicker seal lines on the 3D printer pathing to avoid leaks of the DEA, optimizing injection points, and limiting the amount of air bubbles in pouches.

Due to time constraints testing of our device was limited to ensuring its functionality and the advantages and flaws of our design choices. Future studies should focus on testing our devices against similar papers to ensure that the presented benefits fully overcome the boundaries outlined. This could include testing that the quarter-circle liquid DEA does not limit the liquid DE's movement and that its shape maximizes efficiency and space. Further implementation after optimization testing should include future robot design that would implement this motor with a full robot to test its usefulness in various scenarios. Additionally, multiple Peano-Hasel actuators can be stacked to summarize multiple actuator's power and output an overall larger force to increase the possible speed of the motor.

Appendix:

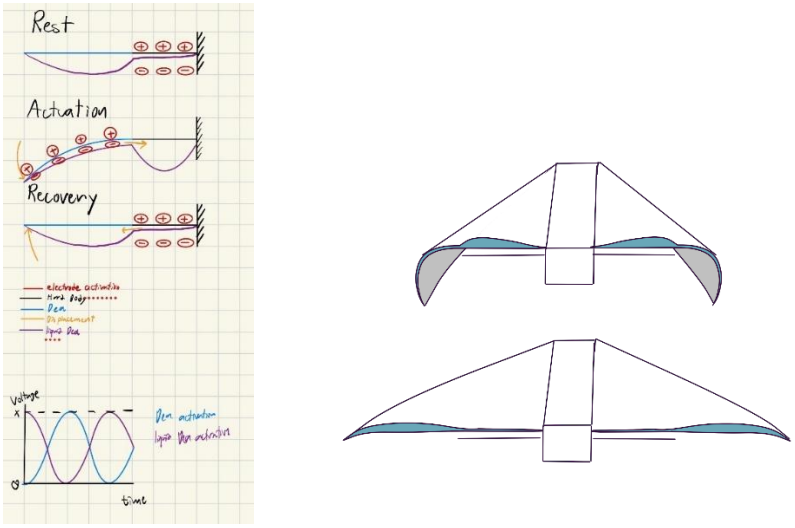


Figure 10: Design drawings of hybrid actuator and robot flapping motion

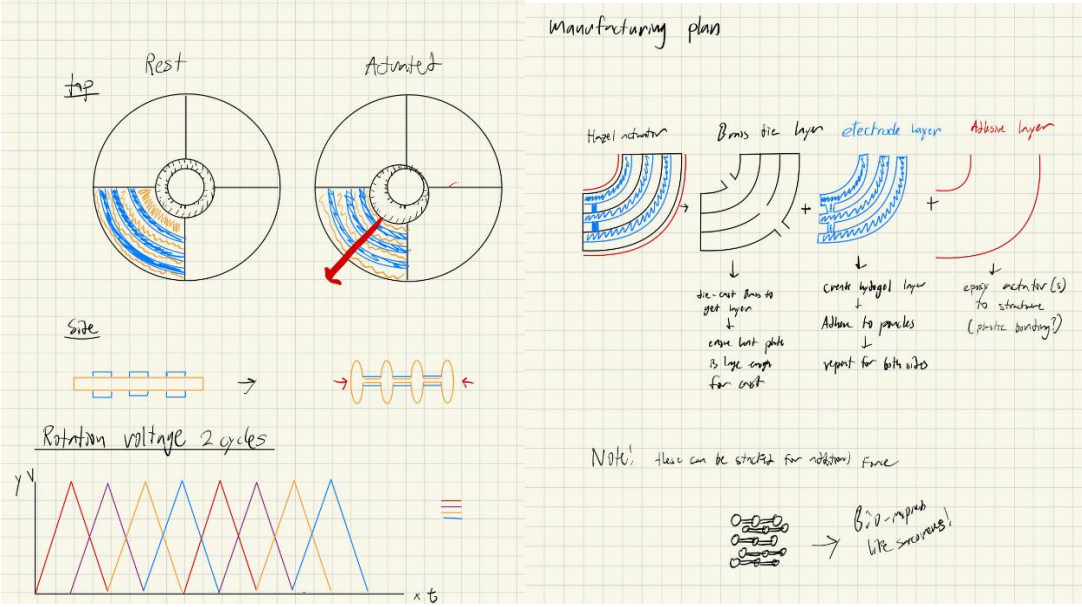


Figure 11: Design drawings of liquid DEA rotational motor manufacturing

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Citations:

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