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DESIGN AND TEST OF BIO-INSPIRED UNDERWATER SOFT GRIPPING ROBOT

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ABSTRACT

This project is part of a collaboration between Rochester Institute of Technology and Boeing in an effort to research and develop underwater robotics technologies. The goal was to design and build an underwater soft robotics gripping device as a proof of concept that could be used to handle fragile samples or a wider range of geometries than traditional grasping devices. An underwater soft robotics gripper was designed and built using hydraulically controlled soft bending actuators for the gripping device, and a servo motor driven scissor mechanism to extend and retract the gripping device. In testing, the device is able to successfully grasp objects and proves that soft robotics are viable for use in underwater applications.

INTRODUCTION

The Starfish Gripper project is a bio-inspired underwater grasping robot designed using soft robotics, mimicking the function of a starfish to achieve a grasp on an object. The main goal of this project is to prove the viability of using a soft robotic gripper underwater. This has been done by developing an efficient, reliable, gripper device which is capable of effectively deploying from a container and successfully capturing a range of target objects. The project builds upon the principles of multiple soft-robotics related MSD projects that were focused on gripper technology as well as mimicking a fish swimming.

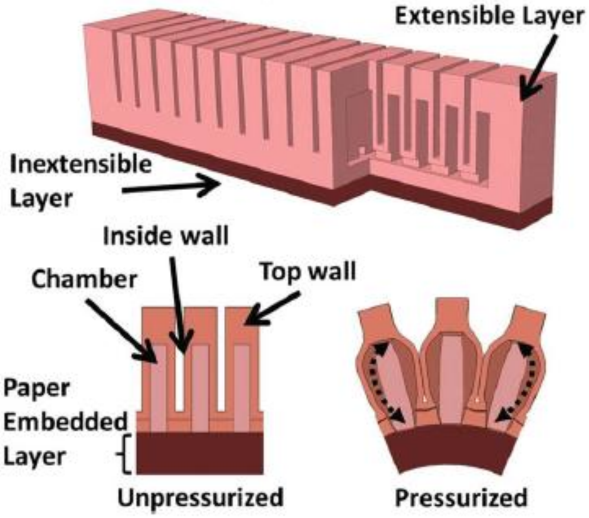

Figure 1. Soft robotics bending actuator design. Adapted from [1].

Soft robotics is an emerging field with constantly growing interest and research. To be considered soft robotics, a robot must use actuators made with a flexible material. Many of these actuators, including the ones used in this project, use a molded silicone or other elastomer to create a geometry that moves in a desired fashion when pressurized. For this project, PneuNets style bending actuators, as shown in figure 1, were molded from a two-part silicone rubber compound. These have an internal chamber that is hydraulically pressurized, and an inelastic material integrated into the wall of one side of the actuator. When pressurized, one side of the actuator expands, while the other is forced to remain the same length, causing a bending motion [1].

While soft robotics is a somewhat recent field, there are several products already in use that utilize these principles. Soft Robotics Inc., a company that specializes in making soft robotic grippers for the food industry, has a wide variety of products that are designed to grip delicate foods of varying size and shape. Also, a team at Harvard University has developed an underwater soft robotics gripper for ocean exploration and collection of fragile coral reef specimens [2]. An overview of a number of other soft robotics gripping devices are given by Rus & Tolley [3].

PROJECT REQUIREMENTS

Being a proof of concept project, there were a limited number of quantitative requirements to hold. However, there were a number of qualitative operational requirements, such as the use of soft robotics in the gripping mechanism, the ability to pick up a variety of objects underwater, the ability to extend and retract the gripper, and the ability to pull fluid from the surroundings rather than having a dedicated hydraulic reservoir. These requirements were translated to specifications to meet by the team, as shown in Table 1 below.

Table 1. Project engineering requirements.

rqmt. #	Importance	Source	Engr. Requirement (metric)	Unit of Measure	Marginal Value	Ideal Value
ER1	3	CR1	Percentage Soft Material in Gripper	%	80	100
ER2	3	CR2	Spherical Object Mass	kg	0.5	3
ER3	1	CR2	Spherical Object Diameter	cm	5-10	1-15
ER4	1	CR4	Container Volume	cm^3	8000	1000
ER5	3	CR7	Number of Cycles Before Failure	cycles	120	1000
ER6	9	CR6	Successful Capture Rate From Standard Position and Orientation	%	75	100
ER7	3	CR9	Deployable Depth	m	1	5
ER8	3	CR10	Fits Budget	$	<750	<500

MECHANICAL DESIGN

Soft bending actuators were fabricated utilizing the Smooth-On Dragon Skin 20 silicone polymer, which has a 100 percent elastic modulus of approximately 340 kPa, with slight additions of the Smooth-On polymer thinning agent to assist during molding. A hybrid design inspired by the PneuNets design shown in figure 1 was created. This hybrid has relief slots that extend halfway through the width of the actuator, balancing rigidity when not pressurized with ability to bend when pressurized. Previously, many soft bending actuators integrated a layer of paper into the base to create an inextensible layer. However, paper is prone to ripping under load, so the team integrated a flexible mesh drywall tape into our design, which has a much higher tensile strength, but is still quite flexible. The mesh also allows the silicone polymer to intersperse and bond around the mesh. This method proved to be quite effective and created very robust actuators.

A manifold was designed and machined to fit the soft body actuators, as well as accommodate all fittings associated with both the hydraulics systems and the extension system, as the manifold would act as the base from which all the primary actuation hydraulics was divided, and also it would serve as the solid plate surface from which the actuators could be extended and retracted from the system housing.

Figure 2. Hybrid soft bending actuator design with inlayed mesh tape.

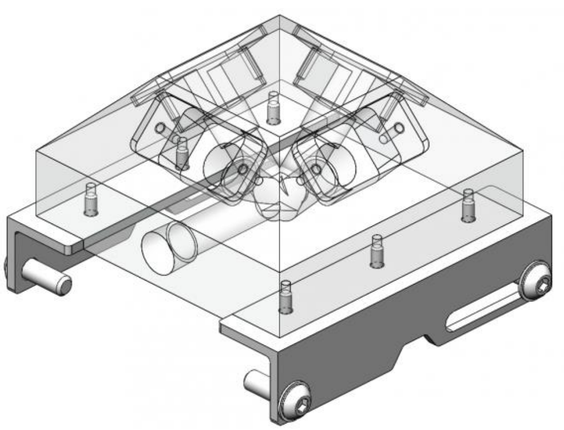

Figure 3. Manifold design.

To ensure that the soft bending actuators stayed in place on the manifold, thin retaining plates were fastened to the manifold, as shown in figure 4, which interlock with slots that were molded into the actuators.

For extending and retracting the gripper, a scissor mechanism design, as shown in figure 5 below, was chosen for both its relatively compact footprint and low cost compared to other linear actuators that can be used underwater. A servomotor was chosen to drive the mechanism through a linkage originally, but this design was modified during the build and test phase to use a GT2 timing belt driven by the servomotor.

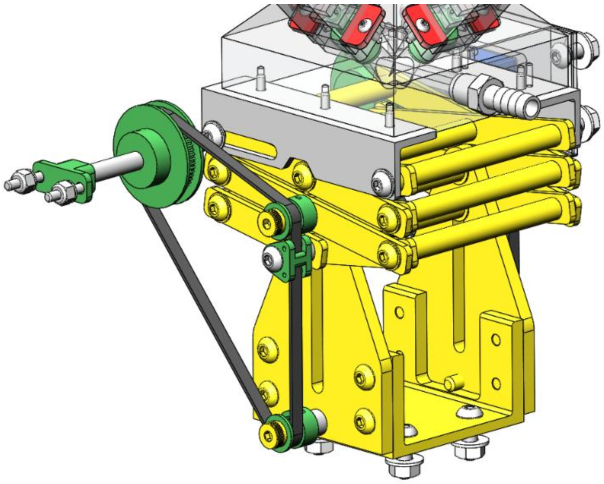

Figure 5. Scissor mechanism with belt drive system.

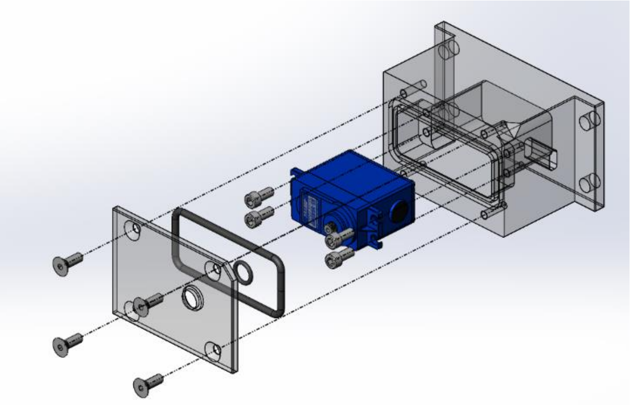

Figure 6. Servo motor waterproof enclosure exploded view.

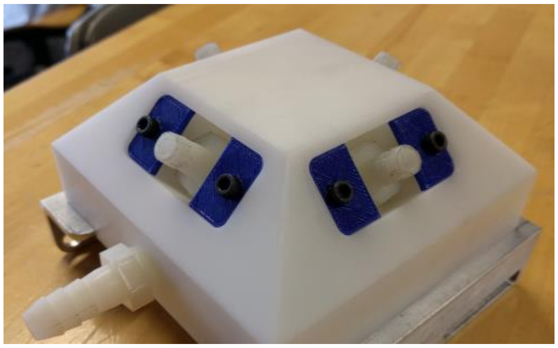

Figure 4. Soft actuator retaining plates on manifold.

A Hitec HS-5646WP servo motor was chosen for use due to its high torque output and IP67 waterproof rating, and was kindly donated by Hitec. The IP67 rating does not guarantee waterproofing below 1m and for longer durations, so an enclosure was designed to provide further waterproof protection to the motor. An aluminum enclosure and lid were machined with a channel for an o-ring between the enclosure and lid, as well as a channel around the output shaft of the servo, as shown in figure 6.

To drive the hydraulic system, a Seaflo 21-series diaphragm pump was chosen. It was determined to generate enough pressure, with a maximum output of 35 psi at its 12V operating voltage. The pump was also quite cost effective. Some consideration was also taken to ensure the pump would not overheat in a semi-sealed enclosure.and can be run dry.

To ensure that the pump, battery, Arduino microcontroller, and other electronics were protected from water, an Integra Enclosures IP68 rated polycarbonate enclosure was chosen. Integra Enclosures was gracious enough to donate one of their Premium line enclosures.

In order to accommodate the inlet and outlet of the pump, as well as wires, holes were drilled in the container and IP68 rated cord grips were installed in the holes to provide a seal against any interface running through the holes. Stainless steel tubing was run through two of these cord grips for the inlet and outlet of the pump. Epoxy was then applied to the interfaces between the container and the cord grips and injected through a syringe in between wires.

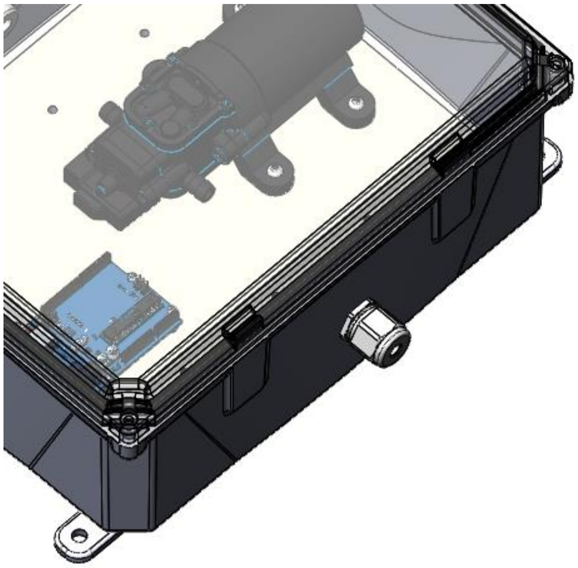

Figure 7. Cord grip installed in side of waterproof enclosure, tubing not shown.

The hydraulic system is fairly simple, using one solenoid valve as a pressure release valve, which vents to the surrounding fluid. A pressure sensor was also added to the system to monitor pressure, and cut off the pump when a certain pressure is reached.

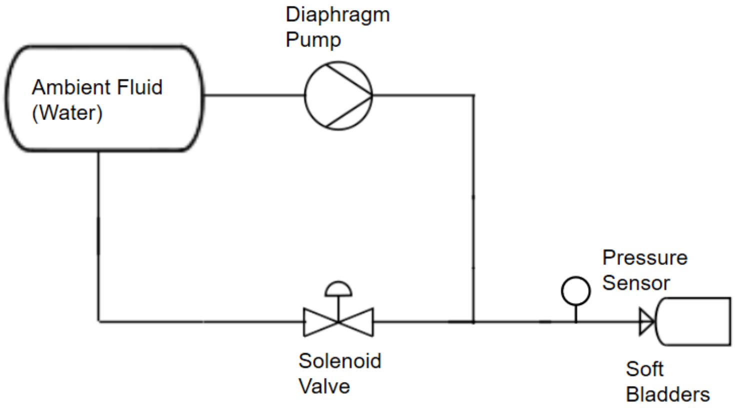

Figure 8. Schematic of hydraulic system.

ELECTRICAL DESIGN

An Arduino Uno microcontroller was chosen to control the electronics for this project. The Arduino activates the pump, valves, and servo motor and receives signals from the pressure sensors and control switches.

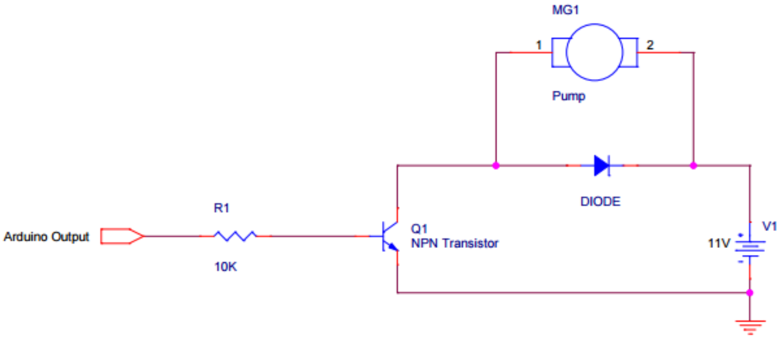

Figure 9. Transistor schematic for pump.

NPN transistors are used to give control the pump and valves through the Arduino, while allowing them to draw power directly from the battery.

The MS5803-14BA pressure sensor uses the I2C protocol to communicate with the Arduino. To prevent over pressurization of the soft actuators, an absolute maximum allowable pressure of 13 psi relative to the atmosphere has been set. Due to the shallow depth the robot will be exposed to, the team is not concerned with the additional pressure underwater. Future projects may consider adding a second pressure sensor to measure the relative pressure in the gripper, rather than the absolute. The sensor was used during initial testing to determine pressure during actuation and determine the limits used in the code.

A control panel was designed with three switches; a power switch, along with a switch to control the pump/valve and one to control the servo motor. DPDT (double pole double throw) toggle switches were used to control the pump, valves, and servo motor, and an SPST (single pole single throw) toggle switch was used to provide power to the system.

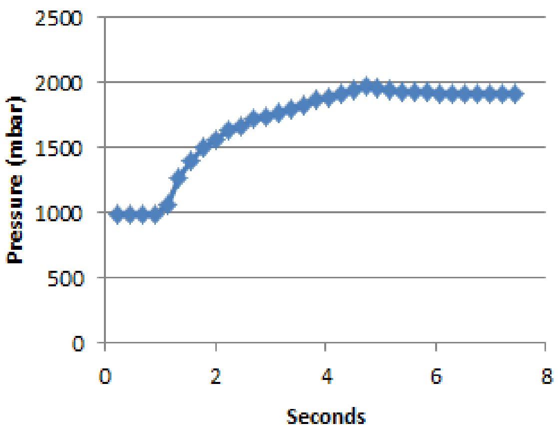

Figure 10. Graph of pressure vs time during one gripper actuation. Pump was turned off around 5 seconds.

The Arduino program runs using a simple polling loop. Due to this, it is not possible to retract or extend the gripper while the pump is activated. Likewise, if the gripper is being opened or closed, extension/retraction functionality is disabled. This was by design to minimize risks to the actuators. The following flowchart shows the general program flow used to control the gripper. Note that initial setup code is not included in the flowchart.

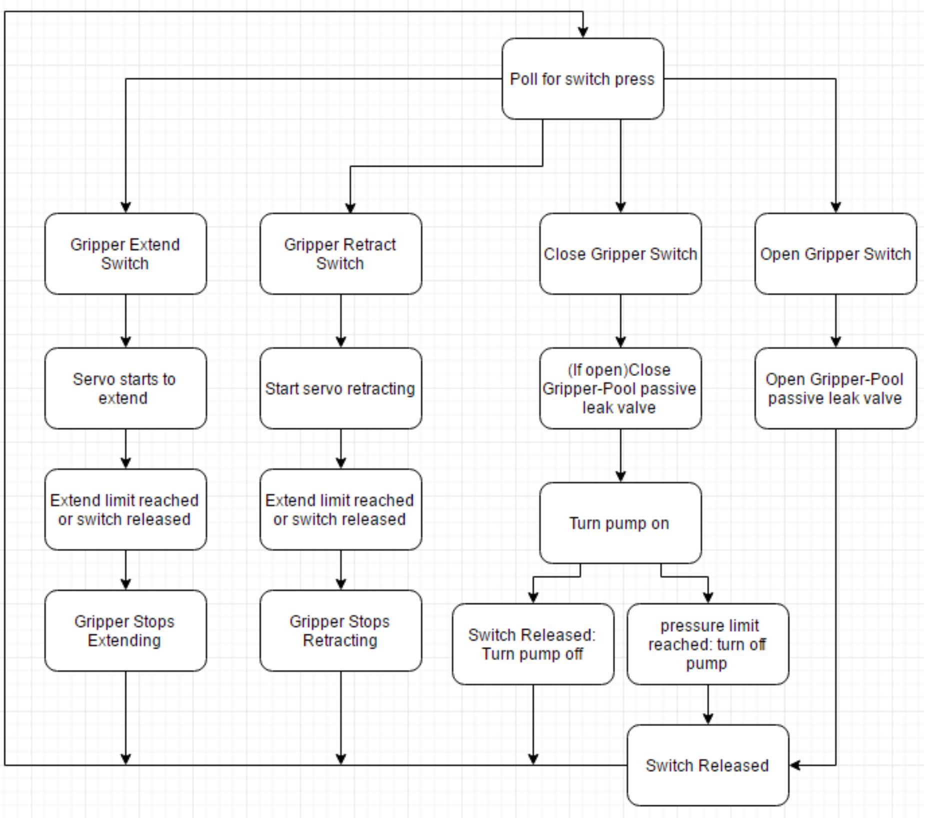

Figure 11. Arduino program flowchart.

The servo utilizes the Arduino Servo library, and the pressure sensor utilizes the Wire library for I2C communications and the SparkFun_MS5803_I2C library to report absolute pressure.

TESTING

To test the depth that the robot is still waterproof and able to function, the robot was submerged underwater in increasing depth increments, and timed for 3 minutes. The robot was inspected after each increment of 1m to ensure that no water had entered the electronics enclosure and that the device was still operational. The robot was submerged to a maximum depth of 2.4 m, where it was limited by the length of the tether to the control panel. After 3 minutes underwater at 2.4 m, there were no signs of water infiltration, which exceeds the engineering requirement for the project.

To test the reliability and durability of the soft bending actuator gripping device, the device was subjected to a trial of 120 gripping cycles underwater, and the robot completed the test without issue. This was determined to be the number of actuation cycles needed to demonstrate throughout the day during Imagine RIT. At the end of 120 cycles, there were no signs of degradation or fatiguing, meeting the engineering requirement.

To test the percentage of time that the gripping device successfully grasped an object, the robot was subjected to 30 trials underwater of attempting to grasp an object from a set location. The number of successful object grasps were recorded. From this test, the robot successfully grasped the standard object for 100 percent of the trials, meeting the engineering requirement.

In testing, we found that the robot was able to reliably grip objects approximately 8-15 cm in diameter, and up to approximately 1 kg in mass. Heavier objects had the potential to cause actuators to pull out from the manifold.

RESULTS AND DISCUSSION

The robot was successfully able to hydraulically actuate the soft bending actuators, and was very reliable in doing so. The actuators worked well underwater, and there is definitely promise for their use as grasping devices for fragile specimens in underwater explorations or other similar use cases. The 12V pump was able to fully pressurize them in a few seconds, which was fast enough for our purposes, but if faster actuation is desired, a more powerful pump would be required. Overall, the grasping of the device was not as effective as desired. The geometry of the manifold and bending actuators made it difficult to grasp object that were much smaller or much larger than the designed size. However, benchmarked devices also use a variety of different geometry actuators to grasp a range of objects, so this constraint is to be expected.

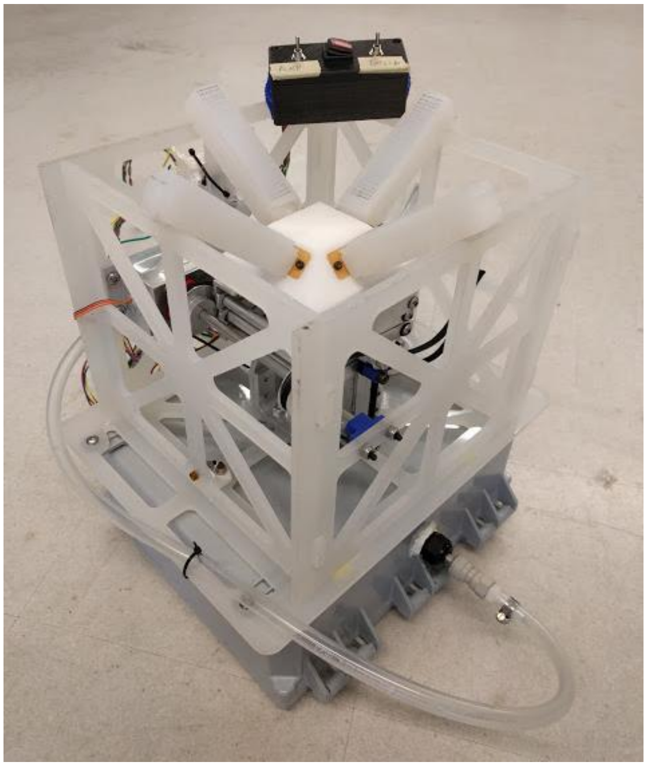

Figure 12. Final assembly of robot.

The Integra Enclosures IP68 rated enclosure that housed the pump, battery, and other electronics was very effective for waterproofing. Also, the cord grips installed through the sides of the enclosure worked flawlessly, and were an effective strategy for creating a waterproof inlet and outlet for the pump. The size of the enclosure created a large amount of buoyancy, which was difficult to overcome without adding a cumbersome amount of weight, so we recommend minimizing enclosure size for future underwater projects.

The scissor lift style extension mechanism proved to be more difficult to fabricate and actuate than originally thought. Maintaining tight tolerances and parallel faces is required for smooth sliding actuation, and our fabrication time and resources made this difficult. The team ran into some issues with the mechanism sticking and the servo motor not being able to provide enough torque to overcome the friction. Using a premade mechanism may be an option, but we would recommend using other mechanisms and actuators for further underwater projects.

Actuating the scissor mechanism with a servo motor underwater proved difficult, as there were no IP68 rated servo motors on the market, requiring the fabrication of a custom waterproof enclosure. This was difficult to retrofit around the servomotor and maintain a waterproof seal around a rotating shaft. In the end, the enclosure was mostly successful at waterproofing the servo motor, but if a linear actuator is required for a future project, hydraulic cylinders are highly recommended.

Several difficulties in fabrication of the custom-molded soft actuators were encountered as well. The liquid silicone rubber used is prone to air bubbles forming within the limb bodies, compromising the strength of the limb and ability to be pressurized. A new curing process was developed to mitigate the size and number of present bubbles, which involves popping any noticeable bubbles, placing the mold in a vacuum chamber for a short period of time, and then allowing the mold to cure open to the atmosphere.

CONCLUSIONS AND RECOMMENDATIONS

This project successfully showed that soft robotics can be taken underwater and used to grasp objects. The grasping device operated reliably throughout testing and demonstration. With further development and exploration of gripper geometry, this technology could be attached to an underwater exploration vessel and successfully used to collect fragile specimens underwater or other similar use cases.

The main point where this project did not operate as intended was with the extension mechanism, which did not actuate as smoothly as intended. The servo motors used did not provide enough torque to overcome the friction from the scissor mechanism. To improve this design, use of a double-acting hydraulic cylinder is recommended, as it can be driven from the same pump as the soft bending actuators. Since this is a very low load application, an industrial hydraulic cylinder is not recommended due to cost, but rather a low-cost design that would be easy to fabricate. Another option is to mold the extension mechanism out of a soft material as well, with a bellows style design, but this could present issues with the capacity that the robot could lift.

Also, the robot was limited in the size and weight of objects it could grasp due to the geometry of the manifold and actuators. Any design will have similar limitations, but to make the design more adaptable without having to fabricate multiple manifolds, it is recommended to mold the entire end effector out of a single mold, with a single hydraulic inlet. Similar designs have been pursued by the Whitesides research group at Harvard [4]. This would not only make fabricating a variety of gripper geometries simple, but would reduce cost and prevent potential issues with connection between the manifold and actuators.

Future improvements to this technology would allow the robot to grasp objects with a wider range of geometries and weights, as well as sense when an object is grasped. Integrating sensing into the gripper device by molding sensors into the base layer of the soft bending actuators would allow object grasping feedback. Also, attaching the gripping device to a multiple DOF arm would increase its usefulness in underwater applications.

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