Optimized Soft Actuator Design for Delamination-Efficient Lamprey-Inspired Suction Cups in Robotics

Liyan Luo

Faculty Advisors: Prof. Cameron Aubin

Department of Robotics, University of Michigan

1. ABSTRACT

This report presents the design, fabrication, and testing of a novel bio-inspired suction cup mechanism based on the suction capabilities of sea lampreys. Leveraging the active control and efficient delamination characteristics observed in lampreys, the proposed suction cup integrates an additional air chamber to enhance detachment control. The suction cup is composed of two parts, with the primary air chamber providing strong adhesion and the secondary chamber facilitating easy, energy-efficient detachment. The design utilizes silicone rubber for durability and cost-effectiveness. A series of experiments were conducted to optimize the size, volume, and location of the secondary chamber, leading to significant improvements in adhesion and detachment performance. Instron pulling force tests were employed to evaluate suction performance under both air and underwater conditions, demonstrating competitive results compared to existing suction cups. Our results highlight the key factors influencing suction cup performance, such as the chamber's volume, area, and membrane thickness, offering insights for future engineering applications in underwater environments.

2. INTRODUCTION

Bio-inspired adhesion mechanisms, such as mechanical interlocking, chemical bonds, and electrostatic adhesion, offer remarkable adhesion abilities observed in the natural world. Numerous animals utilize suction force, where a pressure difference between an internal chamber and ambient pressure allows them to achieve significant adhesion on various surfaces, including the skin of other animals. This principle, as exemplified in the physics of suction cups, demonstrates the capability to adhere to both smooth and rough, non-planar surfaces, and even surfaces with gaps, both in-air and underwater.

Sea lampreys are recognized for their active attachment control, efficient delamination management, and soft, compliant mouth suction capabilities. Inspired by these distinctive suction traits, lamprey-based suction cup mechanisms have potential applications in various engineering fields, including underwater construction maintenance, environmental inspection, and more. Sea animals demonstrate remarkable control abilities to grasp and release objects, attach and detach from surfaces, and adapt to complex underwater environments. Sea lampreys show great ability living in the ocean. Using their large oral sucking disc, they attach to larger underwater bodies, actively sucking with sharp, horn shaped teeth and rasping tongues. In this paper, inspired by the lampreys, we introduce an innovative design featuring an additional fluidic chamber mimicking their teeth on the edge of the suction cup to actively attach and detach the suction cups from the surfaces.

Suction cup mechanisms can be broadly categorized into two types: active and passive suction cups. There are various types of active suction cups that have been widely studied, including pneumatic, mechanical, and magnetic suction cups, etc. These devices are designed to actively attach and detach from surfaces to fulfill their engineering purpose. However, the suction performance of some of these suction cups is insufficient for certain applications.

Pneumatically actuated suction robots are widely used for gripping, food harvesting, inspection, and cleaning in air. However, their bulky systems present challenges for manipulation and movement underwater, as the air outlet compromises their sealed integrity. Researchers like Frey et al., have developed pneumatic suction cups, but these often lack robustness in suction performance and are sensitive to environmental factors [1]. Song et al., have created mechanical suction cups that improve upon certain aspects but still do not entirely resolve the detachment issues and require complex designs [2].

Passive suction cup designs are simple and typically generate a strong suction force. However, forcefully pulling them off a surface can cause permanent damage to the cup. A more effective method is to peel the suction cup from the edge, breaking the seal and equalizing the pressure between the air chamber and the external environment. Peeling is the most energy-efficient way to detach suction cups. Addressing these issues requires innovative designs that can bridge the gap between strong adhesion capabilities and ease of detachment without compromising the integrity of the suction cup or requiring complex additional power sources.

A new soft actuator is created to be the analogy of the peeling process to delaminate the suction cups with less effort. Integrated with a soft actuator, our suction cups have strong suction force and can actively attach and detach from the surface. The use of silicone rubber made this suction cup design very durable, low hysteresis, cost efficient, and reusable.

In this paper, we propose a novel suction cup integrated with an air chamber, as illustrated in Figure 1. The suction cup demonstrates strong adhesion and enables simple controlled detachment via an air chamber located at its base. By modulating the air pressure, the chamber could deform readily and disrupt the vacuum seal, thus facilitating active Detachment.

Fast prototypes of varying air chamber shapes, sizes, locations, and membrane thickness were fabricated using Dragon Skin 20, which were produced employing mold injection method designed in SolidWorks and subsequently produced by FDM 3D printing.

A series of experiments were conducted to optimize the size, volume, and shape of the air chamber to improve the suction cup's performance, particularly its normal adhesion force and ratio of air volume required for attachment and detachment. The performances were verified by characteristic experiments and the results were then compared with suction cups of similar dimensions but different detachment

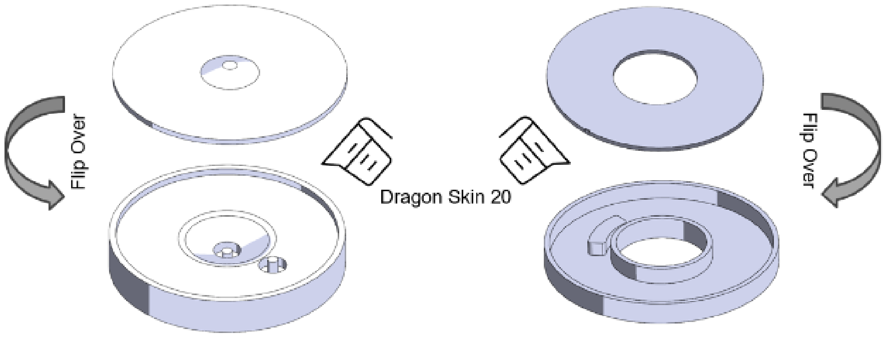


Fig. 1. CAD and assembly guide

3. DESIGN

Current market-available suction cups vary significantly in size and shape. The primary mechanism of suction force in these cups is the negative pressure generated within the suction cup chamber. Generally, a larger contact area between the suction cup and the surface results in greater negative pressure and, consequently, higher suction force. Therefore, direct comparisons between small and large suction cups are inherently unfair. To facilitate a fair comparison, we normalize the suction force by dividing it by the contact area, resulting in the normalized suction force. A comprehensive table is provided, listing existing suction cups along with their corresponding suction forces and contact areas. Both air and underwater conditions were tested using Instron pulling tests. Our suction cup's performance was evaluated against these normalized suction forces, demonstrating competitive results. The actively controlled suction cup system consists of two primary components: an upper part and a bottom part. The upper part features a conical center with a diameter of 29 mm and a flat peripheral area to accommodate a secondary air chamber located in the bottom part. The bottom part is a hollow cylinder, 5 mm in height, with an inner diameter of 29 mm and an outer diameter of 64 mm. An air chamber is positioned in the bottom part, 18.5 mm from the suction cup center. Placing the air chamber closer to the contacting ring of the suction cup allows it to inflate and facilitate easier delamination from the surface. Three critical factors significantly impact suction performance and ease of detachment from the surface. This study investigates various air chamber heights and volumes, ensuring consistent comparison by altering only one variable at a time to analyze performance differences across designs. 1. the design of the suction cups, geometries 2. three parameters 3. the test designs 4.

4. METHOD

According to Tolley et al., the clingfish-inspired suction cup demonstrates excellent suction performance underwater [3]. The primary source of suction force is the negative pressure generated within the contacting ring. To achieve this, a syringe is used to drain fluid from the primary chamber. The fluid flows through a one-way valve into the syringe. When the barrel is pushed, the fluid is transferred into the secondary chamber, causing a bump in the air chamber. This bump aids in delaminating the suction cup from the surface. By creating a slit in the air chamber, the fluid can escape, penetrate the contact ring, and break the seal, allowing the suction cup to detach from the surface.

A. Manufacturing

The two suction cup components were created using injection molding in 3D-printed PLA molds. Dragon Skin 20 silicone (Smooth-On) was utilized to fabricate the suction cup. After mixing the two parts of the Dragon Skin silicone in a central mixer, the solution was poured into the PLA mold. The suction cup parts were degassed in a vacuum chamber for 10 minutes and cured in an oven at 70 degrees Celsius for 25 minutes. The two parts were then bonded together using Dragon Skin 20 solution. Two 3-inch long silicone tubes with an outer diameter of 1/8 inch and an inner diameter of 1/16 inch were inserted into pre-set locations and sealed with Sil-Poxy (Smooth-On). These tubes were connected to two one-way valves. The one-way valves were joined at the top by a predesigned Y-shaped connector, created using Formlabs. At the top of the Y-shaped connector, a silicone tube was connected, leading to a syringe that was inserted and sealed into the setup.

B. Experiment Setup

First, we implemented the Instron Test to get the pulling force of the suction cup. We designed two 3D printing clamps to hold the suction cup. And we use the Instron features to clamp the 3D printing components. (Shown on Fig. 2). We ran 8 pulling force tests.

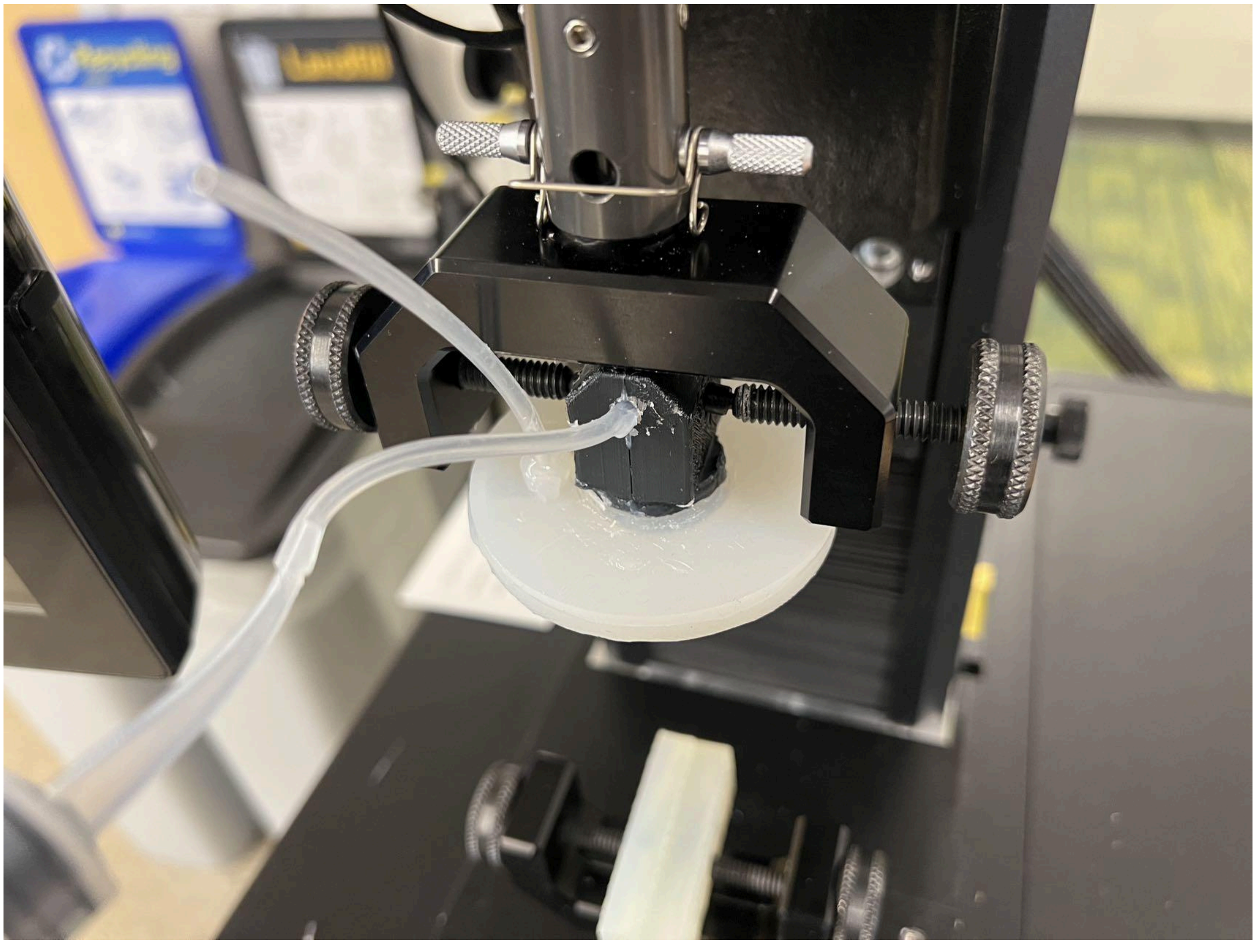


Fig 2. Instron Test Setup

All test trials were conducted under identical conditions. The experimental setup utilized a pulley system to generate a normal force. A nylon string was attached to the suction cup, with the opposite end connected to a 300g load. Three 100 gram weights were applied as preload to ensure full contact between the suction cup's contacting ring and the surface. A syringe was connected to the primary chamber, and 5mL of air was drawn from the primary air chamber into the syringe. Two methods were investigated to assess the necessity of a secondary air chamber for easy detachment of the suction cup. In the first method, the 5mL of air that was drawn into the syringe was released back into the primary chamber to determine the volume of air required to detach the suction cup from the surface. In the second method, the 5mL of fluid was drawn into the syringe, held in the barrel. Another syringe with 10mL of air was connected to the secondary chamber and pushed into the secondary chamber to determine the volume of air needed for detachment. We designed 5 sets of experiments as Fig 3 shows. 1) Same area with different volume. 2) Different area with the same volume. 3) Different area with different volume. 4) Same area and same volume with different location 5) Same area and same volume with different membrane thickness. For each set of experiments, we tested 8 times for each data and chose median as the final data.

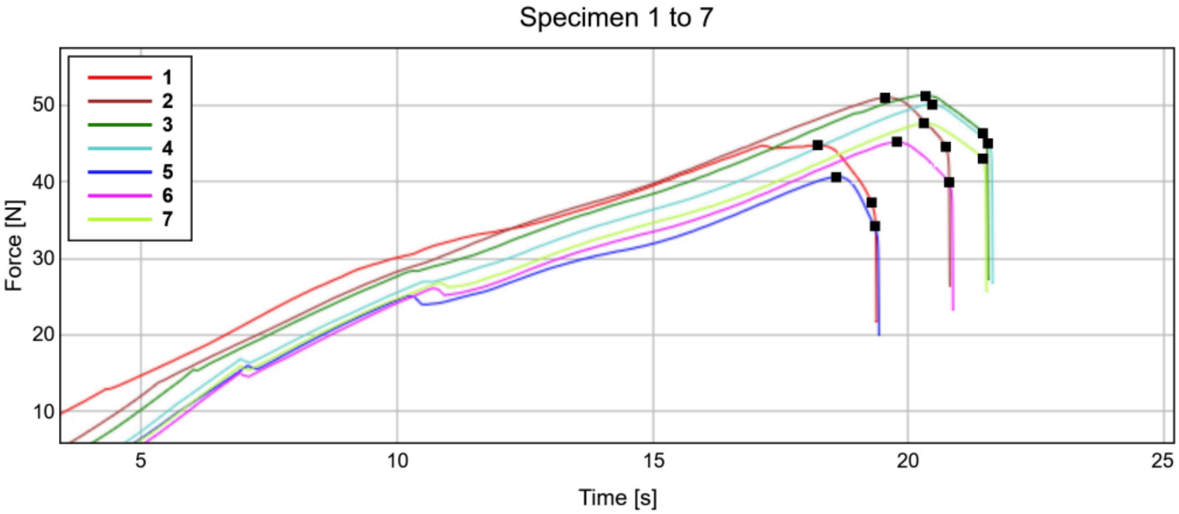
Fig 3. Experiments Design for Detaching Performance of Suction Cup with Different Designs of Secondary Chamber

5. RESULT AND CONCLUSION (Continuing)

For the Instron Tests, we got our average pulling force is 47.5 N as Fig. 4 shows. And we compared the Pulling force vs. Area of our suction cup with Pulling force vs. Area from other papers (As Fig. 5 shows). We defined three categories. 1) Mechanical (Active) Suction Cup: Utilizes a mechanical device to create a vacuum by physically removing air from between the suction cup and the surface, ensuring a secure attachment. 2) Pneumatic (Active) Suction Cup: Employs compressed air to generate a vacuum. 3) Passive Suction Cup: Operates by manually pressing the cup against a surface, which deforms to expel air and create a vacuum seal. The preload from this deformation, coupled with atmospheric pressure, maintains the suction without any active mechanisms or external power. The pink cross is our design. We concluded that our suction cup has a fair sucking performance.

We are looking for the secondary chamber which has less detached volumeIn terms of bottom membrane thickness, 1 mm is the best. The curve is parabolic. Thin membranes could not produce a strong force. Thick membrane was less likely to deform. (As Fig. 6 shows)

In order to find what factors really impact the detaching performance of suction cups, we made a 3D plot to show the factors trends (Fig. 7). The Z axis is the detached volume of the secondary chamber minus detached volume of the primary chamber (Delta-the smaller, the better). X axis is Area. The Y axis is the Volume of the secondary chamber. And the gray plane is a horizontal plane when Z=0 for more clearly showing the Delta value (Under the plane is better (delta is less than zero) because this means we only need smaller volume to detach the suction cup. 1) red line - constant area changing volume, 2) blue line - constant volume changing area, and 3) green line - changing area and volume. Fig. 7 shows that when volume of the secondary chamber is around 154.9 mm^3 mm height and area is around 92.94 mm^2, detaching performance of the suction cup is the best. There is no linear relation between detaching performance and area or volume of secondary chamber.



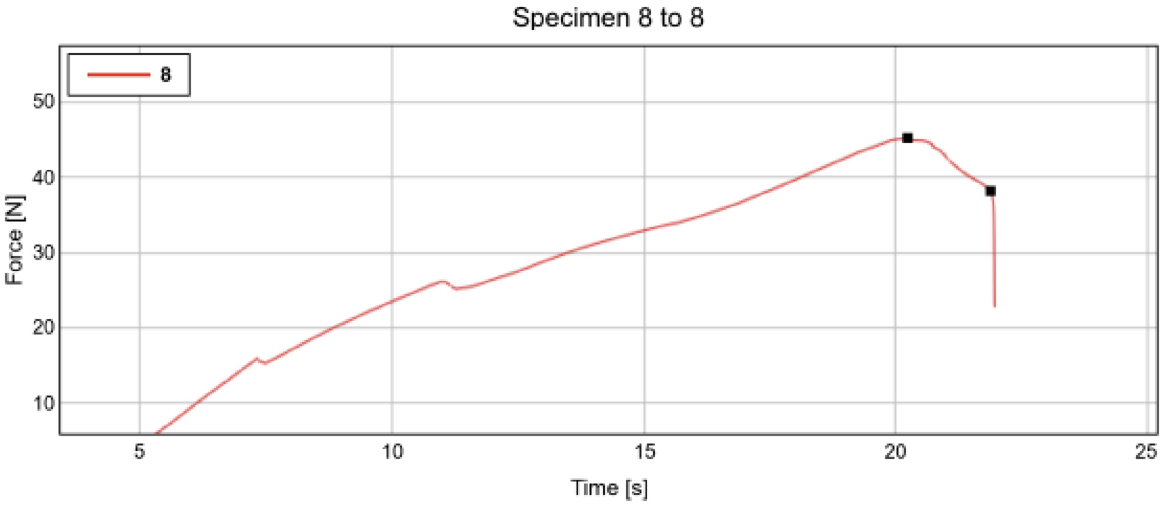


Fig 4 Instron Test of Our Suction Cup

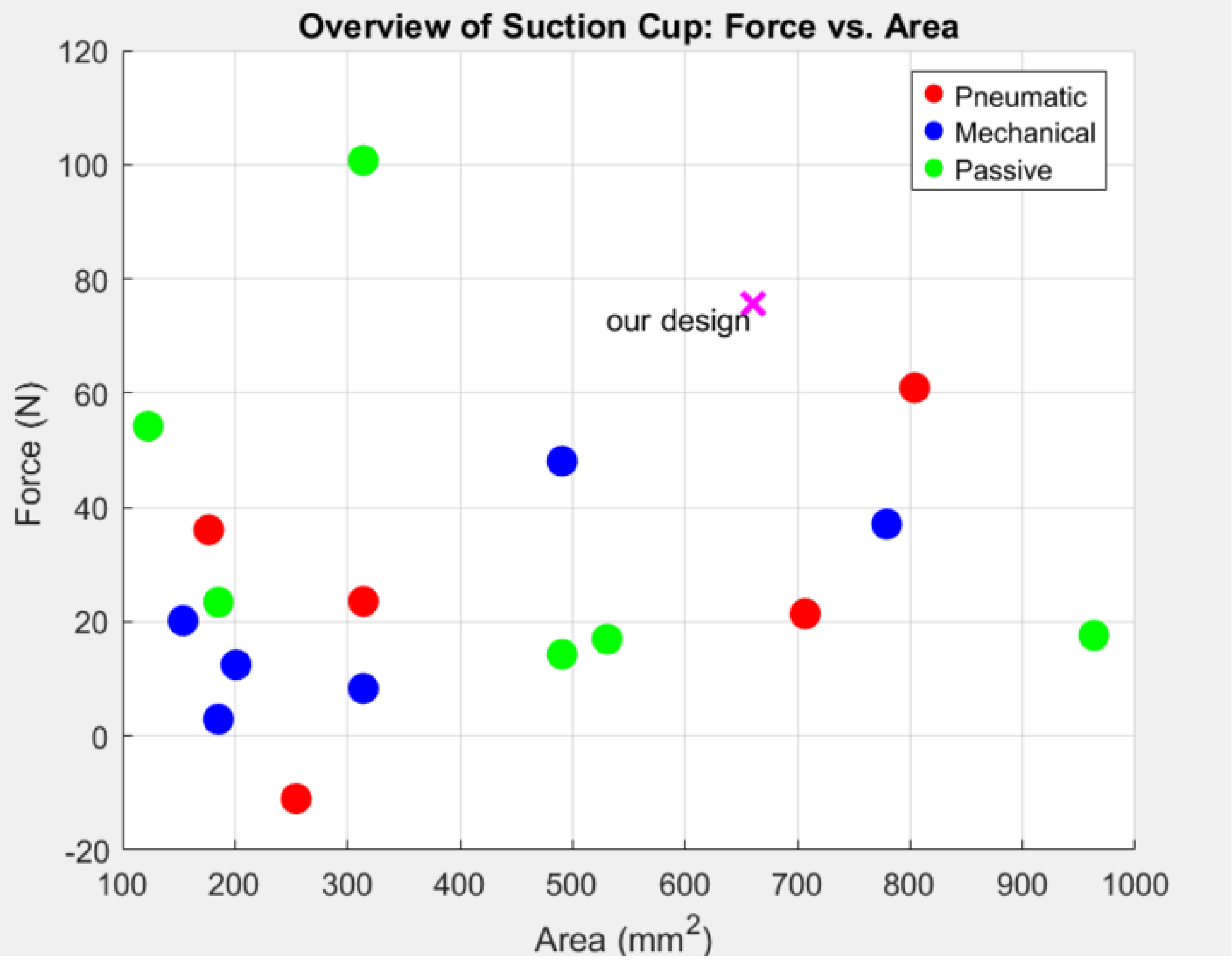


Fig. 5 Normalized Suction Force Table [4]-[13]

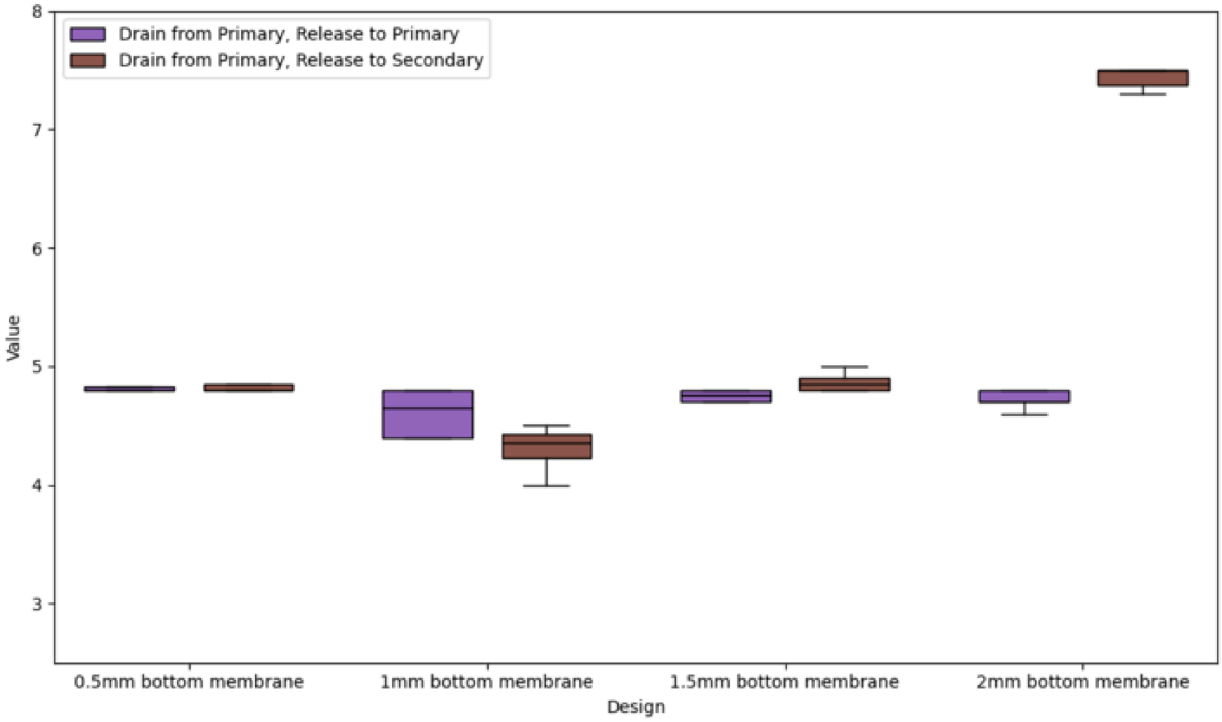


Fig. 6 Comparison of Detached Volume of Primary and Secondary Chamber

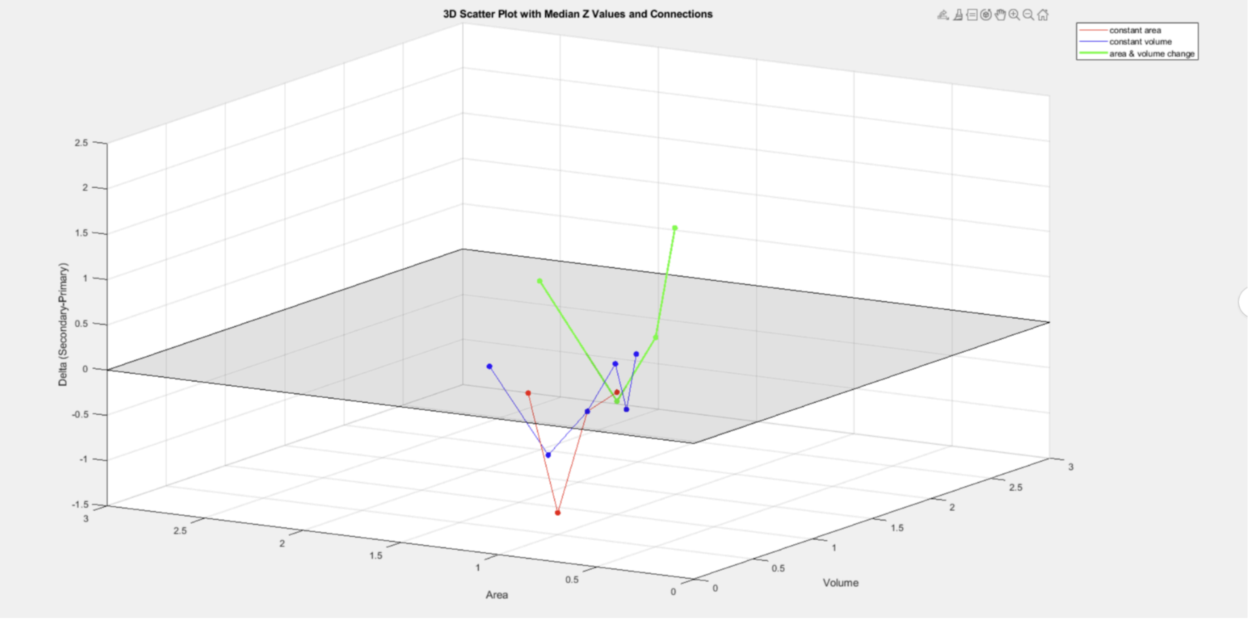


Fig. 7 The Factors Trends of Our Suction Cup

6. FUTURE WORK

In future developments, the actively controlled suction cups hold significant potential for various underwater robotic applications, including as a gripping tool for robotic arms and a locomotion mechanism for underwater robots. These applications would benefit from further optimization of the suction cup design, particularly to enhance its performance in environments with shear forces, which are commonly encountered in dynamic underwater settings.

One promising direction is to modify the current suction cup design to incorporate features that counteract shear forces while maintaining strong adhesion. This could involve the integration of additional mechanical interlocking elements or surface texture modifications that improve grip on slippery or uneven surfaces. Additionally, exploring materials with higher flexibility and durability under shear stress could enhance both the lifespan and reliability of the suction cup in real-world underwater operations.

Further research could also focus on improving the suction cup’s detachment control mechanisms. Refining the air chamber design, exploring different geometric configurations, and adjusting membrane thickness could lead to even more energy-efficient and reliable detachment. Incorporating sensors to monitor pressure and force distribution in real time may offer enhanced feedback control, allowing the suction cup to adapt dynamically to changing environments or surface conditions.

ACKNOWLEDGMENTS

Thank you to Prof. Cameron Aubin for providing me the opportunity to conduct research in the Zeotic Laboratory.. I wish to extend my sincere gratitude to Mr. Tony Wang for his generous support. This award has granted me the opportunity to continue making progress on research projects and pursue my academic interests in the field

REFERENCES

[1] S. T. Frey, A. B. M. T. Haque, R. Tutika, E. V. Krotz, C. Lee, C. B. Haverkamp, E. J. Markvicka, and M. D. Bartlett, "Octopus-inspired adhesive skins for intelligent and rapidly switchable underwater adhesion," *Science Advances*, vol. 8, no. 28, Jul. 2022. doi: 10.1126/sciadv.abq1905.

[2] S. Song, D.-M. Drotlef, D. Son, A. Koivikko, and M. Sitti, "Adaptive self-sealing suction-based soft robotic gripper," *Advanced Science*, first published Jul. 3, 2021. doi: 10.1002/advs.202100641.

[3] J. A. Sandoval, S. Jadhav, H. Quan, D. D. Deheyn, and M. T. Tolley, "Reversible adhesion to rough surfaces both in and out of water, inspired by the clingfish suction disc," *Bioinspiration & Biomimetics*, vol. 14, no. 6, p. 066016, Oct. 2019. doi: 10.1088/1748-3190/ab47d1.

[4] X. Gu, Z. Li, Y. Liu, and S. Sun, "Adaptive Self-Sealing Suction-Based Soft Robotic Gripper," *Advanced Science*, vol. 18, p. 254.47, 2021. doi: 10.1002/advs.202100641.

[5] J. Park, H. Lee, and S. Kang, "Soft Hybrid Suction Cup Capable of Sticking to Various Objects and Environments," *Actuators*, vol. 10, no. 3, p. 2375.83, 2021. doi: https://doi.org/10.3390/act10030050.

[6] T. Yamazaki, M. Shibata, and K. Okamoto, "A Suction Cup-Based Soft Robotic Gripper for Cucumber Harvesting: Design and Validation," *Biosystems Engineering*, vol. 12.51, p. 122.91, 2024. doi: https://doi.org/10.1016/j.biosystemseng.2024.01.008.

[7] S. Chen, Y. Yang, and X. Wang, "A Contact-Triggered Adaptive Soft Suction Cup," *IEEE Robotics and Automation Letters*, vol. 30, p. 706.86, 2022. Doi: 10.1109/LRA.2022.3147245.

[8] P. Martin, D. Torres, and L. Navarro, "3D-Printed Pneumatically Controlled Soft Suction Cups for Gripping Fragile, Small, and Rough Objects," *Advanced Intelligent Systems*, vol. 20, p. 314.16, 2021. doi: https://doi.org/10.1002/aisy.202100034.

[9] A. Wright, E. Smith, and C. Turner, "Glowing Sucker Octopus (Stauroteuthis syrtensis)-Inspired Soft Robotic Gripper for Underwater Self-Adaptive Grasping and Sensing," *Advanced Science*, vol. 73, p. 4185.39, 2021. doi: https://doi.org/10.1002/advs.202104382.

[10] H. Kim and J. Zhou, "Constraint-Based Simulation of Passive Suction Cups," *Proceedings of ACM SIGGRAPH*, vol. 50, p. 1963.50, 2022. doi: https://doi.org/10.1145/3551889.

[11] A. Barnes, R. Taylor, and L. Walker, "Locomotion via Active Suction in a Sea Star-Inspired Soft Robot," *IEEE Robotics and Automation Letters*, vol. 16, p. 201.06, 2022. doi: 10.1109/LRA.2022.3191181.

[12] J. Huang and M. He, "Octopus-Like Suction Cups: From Natural to Artificial Solutions," *Bioinspiration & Biomimetics*, vol. 20, p. 314.16, 2020. doi: 10.1088/1748-3190/10/3/035004.

[13] K. Lee, F. Zhang, and S. Cho, "A Soft Bioinspired Suction Cup with Tunable Adhesion Force Using Shape Memory Alloy," *Journal of Physics D: Applied Physics*, vol. 73, p. 4185.39, 2023. doi: 10.1088/1361-665X/ad6cbb.