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Design and Analysis of a Flexible Multi-Chamber Silicone Pneumatic Expanding Gripper under Constant Pressure Control

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Abstract: *Marine debris cleanup demands grippers that can handle irregular, soft objects in unpredictable water conditions—tasks where conventional rigid designs often fail. This study presents a flexible pneumatic gripper featuring a circular multi-chamber structure made from high-modulus silicone, controlled through a modular constant-pressure system. The design adapts to various debris types, from plastic bottles to fishing nets, maintaining stable grasping under water flow disturbances. Experimental tests examined how pressure levels and chamber counts affect grip strength. Simulations using the Yeoh hyperelastic model helped optimize the silicone structure before prototyping. Results show the gripper achieves uniform deformation and reliable grasping in simulated ocean environments, offering a foundation for intelligent marine debris collection systems.*

Keywords: *soft gripper; multi-chamber control; pneumatic actuation; marine debris; silicone material*

1. Introduction

Soft robots built from elastic materials have opened up new possibilities for handling delicate or oddly shaped objects [1,2]. Unlike rigid grippers, these devices deform on contact, which lets them wrap around objects instead of crushing them. Early work with pneumatic networks showed that inflating small channels in rubber could produce large, controllable motions [3,4]. That basic principle has since powered grippers for everything from rehabilitation gloves to food handling [5,6].

Marine debris cleanup presents a different challenge. The waste comes in various forms—bottles, bags, fishing nets, tangled ropes—and the ocean environment adds currents, low visibility, and unpredictable object positions [7]. Rigid grippers often fail here: they either slip or break the debris. Soft grippers can adapt to different shapes, but most designs need complex pressure control to avoid dropping or crushing objects.

This paper describes a multi-chamber pneumatic gripper made from high-modulus silicone, designed for grabbing debris under constant pressure. The circular chamber layout lets the gripper conform to irregular surfaces while maintaining enough stiffness to lift real weight. We tested how airbag count and pressure affect grip force, then used ABAQUS simulations with the Yeoh hyperelastic model to guide material selection before building the prototype. The prototype was validated in simulated ocean conditions.

2. Theoretical Design

2.1 Conceptual Plan

This project designs a flexible pneumatic gripper for marine debris collection, offering high reliability and stable grasping performance, suitable for unmanned surface or underwater platforms. The gripper uses a multi-chamber constant-pressure expansion structure, allowing uniform deformation for enveloping debris of various sizes and shapes, such as plastic bottles, bags, and fishing nets. High-modulus silicone ensures compliance and load capacity, while the circular structure enhances stability, enabling reliable operation under water flow disturbances. Through modular design, the power supply, control unit, and pneumatic system are integrated into a compact package, enhancing operational efficiency and compatibility with other equipment, as shown in Figure 1.

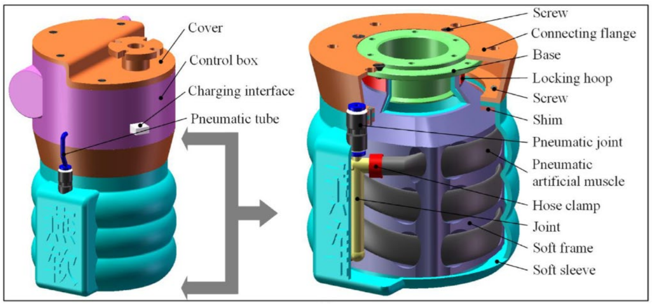


Figure 1: Reference Concept Diagram[8]

The initial design adopted a separated single-chamber encircling structure, in which grasping force is generated by compressing the surrounding silicone through pneumatic chamber expansion. However, the separated design of the pneumatic chamber and expansion structure can lead to silicone fatigue, resulting in chamber misalignment, slippage, or entanglement after repeated inflation–deflation cycles, which degrades grasping performance and may cause device failure.

2.2 Solution Iteration

2.2.1 Solution 1

This solution was developed based on the reference concept and adopts an integrated single-chamber spiral structure, in which grasping force is generated by compressing the surrounding silicone through pneumatic chamber expansion. The integration of the pneumatic chamber and silicone enables more centralized pneumatic control and more stable grasping motion, while effectively avoiding silicone fatigue failure. The spiral structure leads to uneven stress distribution, which may cause object misalignment and device slippage during operation. In addition, the complex chamber geometry makes demolding difficult and increases material and manufacturing costs, making it less suitable for low-cost experimental validation and large-scale production, as shown in Figure 2.

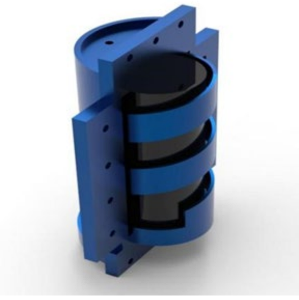


Figure 2: Silicone Mold for Solution 1

2.2.2 Solution 2

This solution adopts a modular segmented structure, separating the pneumatic chambers from the external mold to facilitate component replacement and maintenance. The gripper is composed of multiple combinable mold segments, enhancing design flexibility and manufacturing adaptability, making it suitable for multi-scenario experimental needs. Meanwhile, the rectangular air chambers are optimized into a house-shaped design, reducing unnecessary silicone deformation and improving deformation uniformity. However, because the chamber molds are not fully fixed with other components and retain rotational freedom, assembly precision is insufficient, leading to chamber displacement, uneven grasping force distribution, and inconsistent deformation, resulting in suboptimal performance. After multiple iterations and designs, the final design adopts a ring-shaped, multi-chamber flexible gripping device. In the mold design, a fixed modular mold structure is used, which facilitates the demolding of the silicone while ensuring pouring accuracy. This guarantees the airtightness of the silicone (which will directly affect the final gripping performance), as shown in Figure 3.

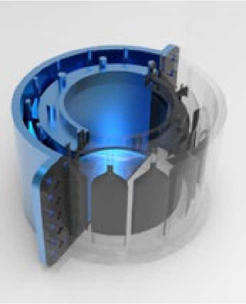


Figure 3: Final Silicone Mold

3. Structural Design

3.1 Exterior Design

After finalizing the shape of the silicone and air chambers, to improve the device's integration, an outer shell design for the silicone gripper was developed. Using a 3D-printed shell, components such as the control board are housed inside, facilitating the device’s use and replacement, as shown in Figure 4.

Figure 4: Exterior Structure of the First Generation Prototype

Figure 5: Iterated Version Exterior Structure

After multiple iterations, the control circuit and pneumatic tubing of the first-generation device were redesigned to be hidden, and components such as the OLED screen and buttons were equipped with positioning and fixation constraints. A switch was added, and the battery was embedded inside. These improvements not only made the device appearance more refined but also effectively utilized the limited space on top. Details of the modified design are shown in the photos, as shown in Figure 5.

3.2 Silicone Material Selection

In a multi-chamber pneumatic ring gripper, the mechanical properties of the silicone material directly affect the accuracy of grip force control. The device uses independently arranged circular chambers that expand cooperatively to achieve adaptive grasping, requiring the material to have low hardness, high extensibility, high tear strength, low hysteresis, and superelasticity. Therefore, 10A/10B mixed and cured silicone (such as the Shin-Etsu KE-2004 series) is an ideal choice due to its comprehensive performance advantages. The Yeoh model describes the hyperelastic behavior of rubber-like materials through the strain energy density function W. Its core idea is to express the strain energy as a series expansion of the first strain invariant I1. For silicone materials, the Yeoh model’s strain energy function is expressed as shown in Formula 1.

$$W=\sum_{i=1}^{n} C_{i0}(I_1-3)^{i} \tag{1}$$

Since the deformation of silicone belongs to the category of large deformation, and the third-order Yeoh model (N3) has good predictive accuracy in the medium to large strain range (>100%), the third-order Yeoh model is generally used to calculate large deformations of silicone. The parameter expression is as shown in Formula 2.

$$W=C_{10}(I_1-3)+C_{20}(I_1-3)+C_{30}(I_1-3)_3 \tag{2}$$

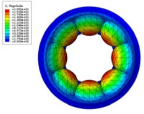
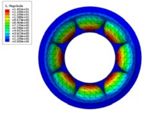
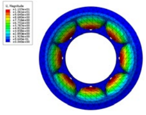
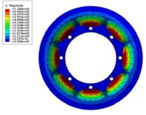
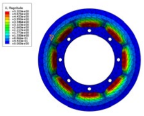
This model has a concise form and can accurately capture the mechanical response of silicone under complex deformation modes, making it especially suitable for pneumatic gripping devices where the air chambers simultaneously experience expansion, shear, and compression under combined working conditions. After consulting relevant literature, the parameter tables for silicones with hardness ranging from 10 to 50 are obtained, as shown below. As shown in Table 1.

Table 1 Yeoh parameters for various hardness levels

Hardness	C_{10} (MPa)	C_{20} (MPa)	C_{30} (MPa)
10	0.018~0.025	-0.002~-0.001	0.0002~0.0004
20	0.045~0.055	-0.005~-0.003	0.0008~0.0012
30	0.075~0.085	-0.008--0.005	0.0015~0.002
40	0.12~0.15	-0.012~-0.008	0.0025~0.0035
50	0.18~0.22	-0.015~-0.010	0.004~0.006

Preliminary finite element simulation of the deformation effect of 8 independent air chambers under 0.15 MPa was conducted using ABAQUS. The maximum deformation occurred at hardness 10. The simulation results are shown in the Table 2.

Table 2 Simulation Results of Different Parameters

Hardness Parameter	10	20	30	40	50
Simulaiton Result					
Maximum Displace ment (mm)	20.92	14.51	11.57	7.268	5.32

At the operating pressure of 0.15 MPa, the air chamber achieves a maximum radial displacement of 20.26 mm, Under the standard working conditions of 0.15 MPa, as shown in Figure 6, silicone made from a 10A and 10B mixture shows a deformation of 20.28 mm, indicating a reasonable material selection, as shown in Figure 7.

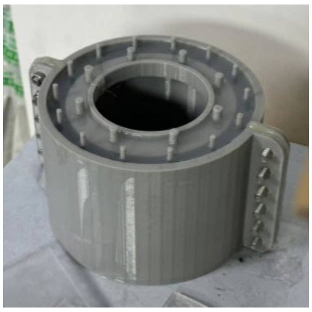


Figure 6: Mold and Silicone Casting Effect Effect

Figure 7: Air Chamber Expansion Effect

4. Hardware Design

4.1 Component Selection

This diagram illustrates the hardware connection of an IoT-based automatic control system built on a microcontroller/embedded system. Centered on an ESP32 or STM32 series main control board, the system operates through three core modules: the sensing module collects environmental and working condition data via an OLED display, a red push button, a potentiometer, a gas sensor, and a photoelectric sensor; the actuation module executes specific actions using a DC motor, a solenoid valve, and a servo motor, while the communication module is responsible for data transmission. The solid blue lines represent gas monitoring signal circuits, and the black control lines connect all components, ultimately realizing a closed-loop workflow of "data acquisition - logic processing - command execution", which is suitable for scenarios such as industrial automation and environmental monitoring, as shown in Figure 8.

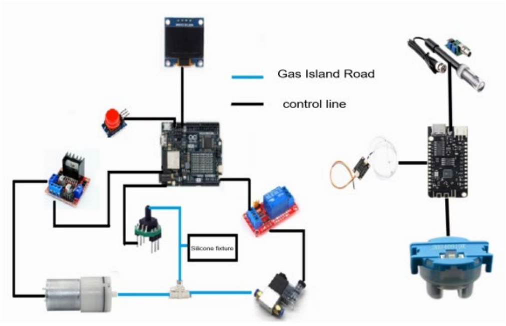


Figure 8: Component Pipeline and Signal Transmission

The control system of this load-bearing robotic gripper adopts a modular architecture, with core functions including precise pneumatic actuation, user interaction, and status feedback. The system controls external pneumatic valves via relays and uses PWM signals through a motor driver module to accurately regulate the air pump power. Pressure sensors collect real-time data and display it visually on the screen. User interaction is realized through the coordination of button detection, mode switching, and screen control modules. Additionally, pH, turbidity, and TDS sensors transmit data to a mobile device via ESP32 for monitoring.

4.2 Control Diagram

Turn on the switch and wait for the system to respond. When the OLED screen displays the pressure data, initialization is complete. Meanwhile, the pH, turbidity, and TDS values are displayed on the mobile device.Place the object to be grasped into the gripper. When pressing the mode switch button, the pressure data will be simultaneously displayed on the OLED screen. Adjust the gripping mode and internal silicone pressure as needed to achieve the optimal grasping state. After grasping, wait for the device to stabilize, then press the pressure release button to vent the silicone chambers to atmospheric pressure. The gripper opens, completing the grasp. Once the object is stable, turn off the switch and wait for the next operation, as shown in Figure 9.

Figure 9: Device Usage Instructions

5. Experiment

5.1 Experiment 1: Relationship between Maximum Gripping Weight of the Heavy-Duty Gripper and the Number of Airbags

This experiment tested how the number of airbags affects the maximum weight the gripper can hold. The setup used gripper bodies with different airbag counts, along with an air supply, spring dynamometer, and weight-testing hook mounted on a test stand.To measure the maximum grip weight, the gripper held the testing hook while the operator pulled the dynamometer downward until the object began to slip. The peak force reading was recorded, and the process was then repeated with the next airbag configuration.

The results showed that adding more airbags reduced the maximum load capacity. The relationship was not linear—each additional airbag contributed less capacity than the previous one. Detailed data appear in Table 3, and the experimental setup is shown in Figure 10.

Table 3 Pneumatic Gripping Force Test under Load

Gripping Force Test Data of Load-Bearing Pneumatic Gripper	Gripping Force Test Data of Load-Bearing Pneumatic Gripper	Gripping Force Test Data of Load-Bearing Pneumatic Gripper	Gripping Force Test Data of Load-Bearing Pneumatic Gripper	Gripping Force Test Data of Load-Bearing Pneumatic Gripper
Airbag Pressure(kpa)	Airbag Pressure(kpa)	Airbag Pressure(kpa)	Airbag Pressure(kpa)	Airbag Pressure(kpa)
11	11	11	11	11
12	12	12	12	12
13	13	13	13	13
14	14	14	14	14
15	15	15	15	15

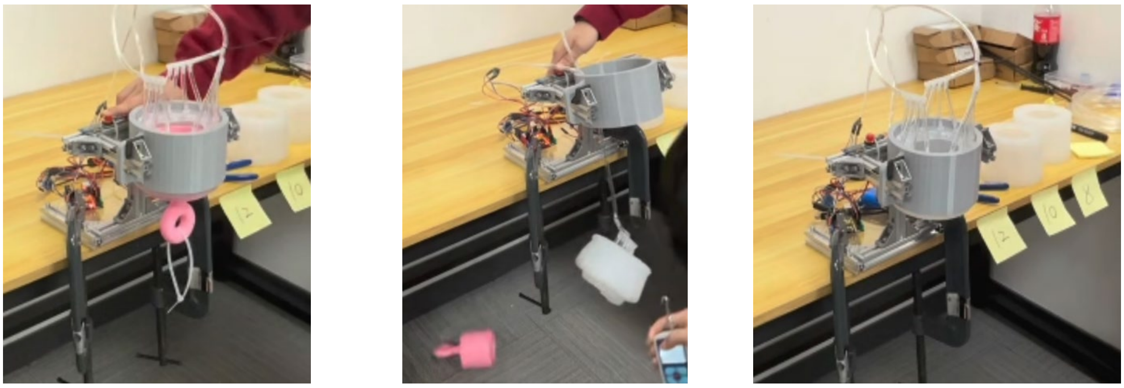


Figure 10: Experimental Testing Process Diagram

5.2 Experiment 2: Relationship between Gripping Force and Airbag Pressure for Load-Bearing Grippers with Different Numbers of Airbags

I varied the airbag pressure for grippers with different numbers of airbags. More pressure let the gripper hold heavier loads, but the gains dropped off sharply above certain thresholds. At low pressures, a small increase made a big difference; at high pressures, the same increase barely helped. Grippers with only two or three airbags showed an almost linear pressure-force curve. With four or more airbags, the curves from different configurations clustered together and lost that linear feel. I adjusted airbag pressure by changing the air pump power setting. Figure 11 shows the test setup.

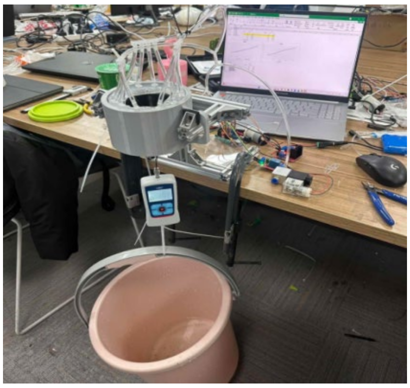


Figure 11: Tensile Test Scenario Diagram

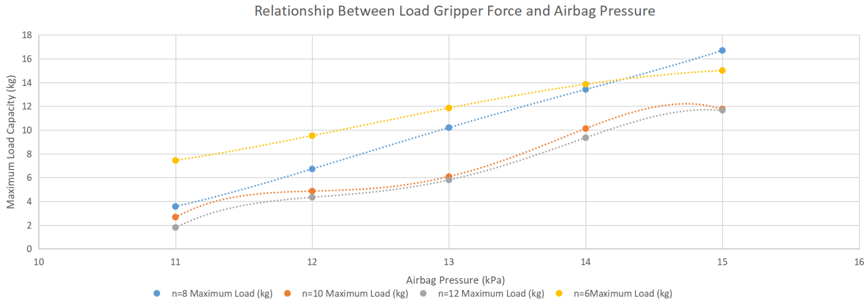


Figure 12: Gripping Effect under Different Air Pressures

Figure 12 shows the change in the gripping force of the gripper under different pressure tests with varying numbers of airbags. It can be seen that the gripping force increases gradually with increasing air pressure and tends to plateau when the pressure reaches 15 kPa.

6. Conclusion

I built a multi-chamber pneumatic gripper out of high-modulus silicone and tested it under controlled pressure. The circular chamber layout let my gripper conform to irregular objects—plastic bottles, fishing nets, and loose debris—without damaging them. Two experiments shaped my final design. The first showed that fewer airbags actually gave higher load capacity, but the relationship wasn't linear. The second experiment mapped how pressure and grip force relate across different airbag counts. More pressure helped, but each increment bought less gain once I passed certain thresholds.I used ABAQUS simulations with the Yeoh hyperelastic model to guide the material choice before I built anything. The 10A/10B silicone mixture hit the sweet spot: compliant enough to deform around objects, stiff enough to hold real weight. My final prototype handled simulated marine conditions without slipping.

Three directions make sense from here:

Independent chamber control. Right now all chambers share the same pressure. Giving each one its own setpoint would let my gripper adapt to trickier geometries.

Force feedback. Adding a sensor that watches the grip in real time—then adjusting pressure on the fly—would stop both slipping and crushing. A closed loop, basically.

Modular deployment. The current design already packs the pump, battery, and controls into one shell. Making the chambers swappable would cut my maintenance time and let the same gripper handle different debris types.

This work is a start. My gripper works, the simulations match the hardware, and the experiments back up my design choices.

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