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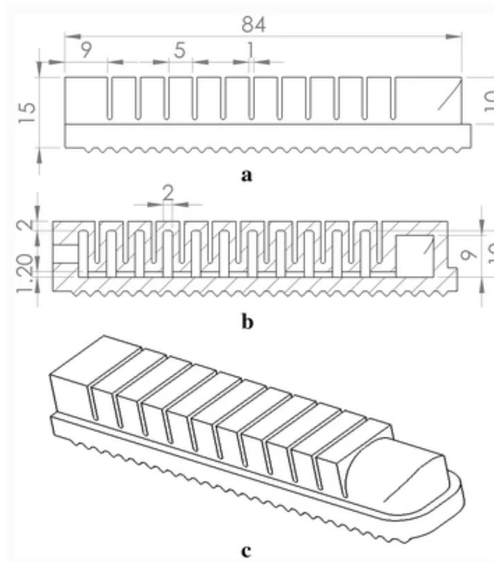
Fabrication of Soft Robotic Gripper

1. Introduction

In the past few years, soft electrometric grippers actuated using pneumatic, hydraulic, or cable systems have revolutionized the field of robotics, offering unparalleled flexibility and adaptability compared to their traditional rigid counterparts. Traditional robotic grippers often face limitations in dexterity and safe interaction with delicate objects.

In contrast, soft grippers, constructed from elastomeric material, exhibit an advantage in handling objects of varying shapes, sizes, and fragilities, making them ideal for applications ranging from surgical procedures to dynamic manufacturing processes. Its distinct flexibility and compliance characteristics give it the functionality of adaptive and delicate manipulation of its grasping motion and it requires less precise positioning, allowing a simplified control algorithm while increasing its reliability.



2. Design

The chain-like granular jamming mechanism and chamber structure of the soft robotic gripper are crucial aspects that define its flexibility and functionality. The chambers are arranged longitudinally along the length of the grip, each separated by the inner wall, allowing for substantial volume change during actuation and even distribution of actuation force. The outer wall is the continuous layer that encases the entire structure of the gripper, providing overall integrity and maintaining the shape of the gripper.

When inflated, the internal pressure causes the chambers to expand, and the expansion pushes against the inner walls, causing them to bend outward and increase their overall length, allowing them to wrap around an object.

When deflated, the chamber contracts back to its original shape. The elasticity of the material helps the chamber return to its initial configuration, releasing the grip on objects.

3. Methods

Soft robotic grippers can be fabricated using various techniques, each with its own advantages, limitations, and suitability for specific applications. The three common methods include injection molding, compression molding, and additive manufacturing (3D printing).

Injection molding has not been a practical manufacturing method for soft robots due to machine costs, the large volumes of liquid silicone required, and the inability to change materials quickly between shots. Injection molds are typically machined from metals to allow for high pressure and clamping forces, which further limits the ability to rapidly prototype and produce in low volume when molds could cost thousands of dollars to design and manufacture. When designing single-cavity molds for injection, material flow and air escape paths are critical considerations. To prevent trapped air from creating voids in the molded part, risers need to be strategically placed to allow air and material to escape when material is injected through the sprue, gate, and then throughout the mold until finding an escape path through open risers.

The general steps of injection molding include cartridge preparation, mold release application, pre-molding assembly, mixing, degassing, injecting, post-molding assembly, demolding, process time, and wet modeling time. In the process flow of injection molding, the mold is fully assembled and clamped with other internal inserts before introducing material. This allows the user time to properly place any inserts, such as soft cores, fabrics, mesh inserts, mounting, and rigid inclusions.

Soft cores, which can be removed after the injection, ensure alignment and proper spacing to be in the exact center of each alignment and proper spacing to be in the exact center of each bellow cavity. A two-part liquid silicone elastomer is commonly chosen as the material for the softcore because of its high elongation to failure, allowing large stretches during the removal process while avoiding plastic deformation so that the cores can be reused. Moreover, fabric and mesh inserts play a key role in serving as strain-limiting materials; they can be used to reinforce boundaries between successive layers of rubber that would otherwise be at risk of delamination. They also serve as a way to anchor rigid inserts, such as embedded magnets or nuts, by first adhering to the rigid insert and then impregnating it with the surrounding silicone.

While the pressure-induced flow from injection molding eliminates bubble-related defects and enables higher-resolution modeling with complex arrays of features and embedded components, this fabrication method is extremely cost- and time-ineffective for prototypes and low-volume production.

Alternatively, traditional compression molding has lower initial tooling costs since it uses simpler female and male molds that are typically less expensive, require less complex setup, and are easier and less costly to modify molds, making it suitable for iterative prototypes and customization, making it cost-effective for low-volume production. While injection and compression molding are very similar in their fabrication process, one key difference is that compression molding makes use of a two-step molding technique where the actuator is molded in halves, which are partially cured and then wet-bonded together. The seam form of wet bonding is a common source of actuator failures, and the operating pressures demonstrated with that process were less than half of the operating pressures that have been achieved with actuators modeled with soft cores.

Lastly, additive manufacturing, commonly known as 3D printing, is rapidly advancing and becoming increasingly popular due to its versatility and accessibility. Modern 3D printers are now capable of handling a wide variety of materials, including flexible and conductive thermoplastics, which are essential for creating soft robotic structures with embedded sensors. Techniques such as fused-deposition modeling (FDM) are particularly popular for fabricating these intricate devices. For instance, thermoplastic polyurethane (TPU) filaments are commercially available and can be optimized for consistent printing. Optimal printing conditions, such as a nozzle temperature between 220°C and 235°C, are critical to avoid issues like under-extrusion or over-extrusion. Additionally, a printing bed temperature above 45 °C is necessary for proper adhesion, while an extrusion multiplier of 1.7 ensures sufficient flow for TPU's higher elasticity.

Additionally, techniques such as stereolithography (SLA) and selective laser sintering (SLS) offer significant advantages over FDM. For instance, SLA's ability to create highly detailed and intricate designs is beneficial for this application, which often requires complex geometries and fine features to mimic the flexibility and adaptability of natural grippers. Furthermore, SLA can utilize flexible resins that offer the necessary softness and elasticity for soft robotic applications. These materials can be optimized for different levels of stiffness and flexibility, allowing for tailored mechanical properties of the grippers.

Similarly, SLS can process a variety of materials, including flexible thermoplastics like thermoplastic elastomers (TPE) and nylon blends, which are ideal for soft robotic applications. SLS-produced parts often have superior mechanical properties and durability compared to those made with FDM. This is important for soft robotic grippers that need to withstand repeated mechanical fatigue from inflation and deflation. This versatility allows for the production of durable, elastic, and wear-resistant grippers.

Overall, while FDM remains a cost-effective and accessible option for rapid prototyping, SLA and SLS are better suited for producing high-quality, durable, and complex soft robotic grippers.

4. Materials

Commonly the material used for both molding techniques is silicone rubber, which is a durable and highly resistant elastomer. It is composed of silicone (a polymer) containing silicon together with other molecules. These molecules include carbon, hydrogen, and oxygen. Its chemical structure consists of a siloxane backbone (silicon-oxygen chain) and an organic moiety bound to the silicon.

The most common types of this material used are Mooth-Sil 950 and Elastosil M4601, which differ in hardness, viscosity, and tear strength. Sil 950, with a Shore hardness of 50A, is harder and less flexible than the softer M4601, which has a Shore hardness of 33A. Sil 950 has a medium viscosity, allowing for easy mixing and pouring, while M4601's low viscosity ensures smoother pouring and better detail capture. In terms of durability, M4601 offers superior tear strength and resilience due to its platinum-cured composition, making it more durable for continuous use compared to Sil 950, which still has high tear strength but not to the same exceptional degree. Additionally, M4601 is usually biocompatible, making it suitable for medical and skin-contact applications.

Moreover, for additive manufacturing, the most common type of material is thermoplastic polyurethane (TPU) filaments, which are ideal for soft robotic grippers due to their exceptional flexibility, elasticity, and tear resistance. TPU can reach elongation of up to 700%, allowing it to conform to various shapes, while its elasticity enables it to stretch and return to its original form without deformation.

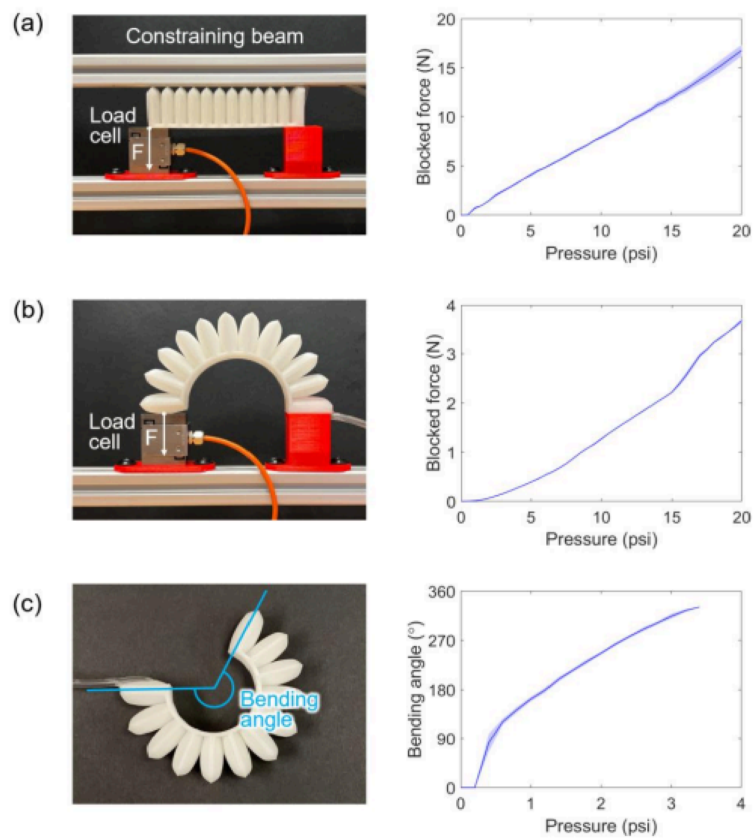
Similarly, SLA can utilize flexible resins that offer the necessary softness and elasticity for soft robotic applications. These materials can be optimized for different levels of stiffness and flexibility, allowing for tailored mechanical properties of the grippers.

5. Testing

Testing the gripper is crucial to validating the design and ensuring it performs as intended. In the diagram to the right, test (a) is set up to measure the blocked force of the curved actuator in its original shape. The actuator is supported by a load cell and fixed support, with a beam constraining the top side to prevent bending deformation. Pressure is applied in increments of 0–20 psi, and the blocked force is recorded, considering only the bending force.

Test (b) is set up to measure blocked force at 180° bending strain, the actuator is mounted vertically, and the load cell records force as pressure increases past 1 psi.

Lastly, test (c) is set up to measure the characterization of free strain, which involves placing the actuator horizontally, applying different pressures, and measuring bending angles. These tests are performed to help verify the gripper's force and strain capabilities, ensuring its effectiveness and reliability.



6. Conclusion

In the field of robotics, silicone rubber soft grippers stand out for handling delicate materials. This research explores their advanced design and fabrication, emphasizing their flexible chamber structure and durable materials like Smooth-Sil 950 and Elastosil M4601. Comparing manufacturing techniques—such as injection molding, compression molding, and additive manufacturing—reveals each method's unique benefits. TPU's use in 3D printing enhances functionality. Rigorous testing confirms the gripper's precision and reliability. Overall, this study highlights the potential of soft robotic grippers in diverse applications, from surgery to manufacturing, showcasing their adaptability and effectiveness.

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