Additively Manufacturing Molds for Soft Robots with Complex Internal Geometries

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ABSTRACT

Almost all moving creatures have soft bodies in nature. Soft bodies give them flexibility, smooth motions, silent actions, and allow them to travel through small openings. The robotics community turned their attention to the robots with soft bodies with the help of newly available manufacturing methods, actuators, sensors, and electronics. Flexible bodies have been used in many systems from medical to space applications. Soft robots have been implemented as grippers already. These grippers are incorporated into industrial robotic arms to grab, lift, or move fragile items such as live animals, produce, or sharp items. In this study, additive manufacturing technology was used for the manufacturing of molds for soft body actuators. Implementation of additive manufacturing allows for the creation of small custom plastic molds which would be very difficult to make with using conventional methods. The additive manufacturing machine used in our study is as shown in figure 5. The actuator shown in figure 11 shows the internal cavity which is designed inversely through a 3-D printed inner insert, as shown in figures 8, 9, and 10. These alterable inserts are housed as part of a complete 3-D printed mold, as shown in figure 4, that in turn gets casted with silicone to obtain these actuators. The developed parts had complex internal geometries which created the desired motions which were designed. This initial mold created an 80 mm actuator with 7, 3 mm ridges, in its internal cavity and had a minimum wall thickness of 1.75 mm, as shown figure 11. These standard ridges successfully made the actuator create a deflection of 48° from an input of 72 ml of air, as shown in figure 13. These molds can be designed in a variety of ways to achieve a desired motion, and can only be casted once, since it has to be broken into pieces for the precise removal of each actuator. This technique has been further implemented for the creation of full robotic crawlers. Beyond just making the complex parts which cannot be manufactured at affordable costs with conventional methods, price and convenience to manufacture tens of molds, until the desired characteristics are implemented, are achieved.

Keywords

Soft Robotics, Additive Manufacturing (AM), Internal Geometries

1. INTRODUCTION

The field of Soft Robotics is a fairly new industry. Currently, there are few patents out in the market with most scholarly journals discussing ongoing studies [4][6]. As such, most articles discussed are theoretical by nature and are trying to find the feasibility of a soft robot. Most of the breakthroughs of Soft Robotics are thanks to the original studies conducted by Harvard University [1]. Harvard researched and ultimately patented the “Soft Robotic Actuator”, a robot molded from a flexible, elastic, and malleable material [4]. The body of the robot consisted of multiple chambers that when filled by a fluid (whether it be liquid or gas) caused the robot to move [4]. Simple in design, the most efficient movement that can be emulated by these robots are bending and curling.

Harvard expanding on their research created the “Multigait Soft Robot” [6]. Inspired by invertebrates, animals with no skeletal structure, Harvard opted to create a locomotive robot out of their discovery. Creating a starfish like shape consisting of internal chambers, allows for the robot to move in a curling motion [4]. Optimizing the shape, the “Multigait Soft Robot” was able to curl and grab objects [6]. Its further optimization allows the fluid that passes through the robot to vary at different pressures, via using multiple channels. Using this method, the robot was capable of walking slightly [4-6].

Harvard’s research paved the way to the brand-new industry of Soft Robotics. In the current market, the only commercial use of these patents are grippers. “Soft Robotics Incorporated” is one of the few companies that have built upon the patent in Soft Robotics [2]. “Soft Robotics Actuator Enhancements” uses soft robots as the claws in an industrial gripper [5]. The benefit is that the material the gripper is made from, is non-invasive and soft to the touch. These grippers are capable of interaction with delicate material, such as food products including eggs, as well as fragile objects in general [2][5].

Further research on the subject is the theme for the all other scholarly articles in the industry. Though one industry that Soft Robotics is trying to be incorporated into is the medical field. There are many ongoing research projects in the field trying to find a practical medical use for soft robots. Since these robots are non-invasive, many researchers are trying to incorporate them into surgical implants, medical equipment, rehabilitation assistance, and so on. Harvard is in the forefront of this research using their robot as a specialized robotic glove to assist the daily lives of stroke survivors [1]. Overall, all research currently being done now are grippers, hard framed soft covered robots, as well as soft robotics with exoskeletons and electronics; However, most of these research projects are still ongoing with no conclusions yet [1][2][4-6].

The scope that this experiment aimed to achieve is to further develop proper innovative techniques to design and manufacture additively manufactured molds, for Soft Robotics applications. Silicone bodies were in turn created to be actuated with pressurized air, validating the geometric variations approach presented in this paper. This new approach to the overall design within Soft Robotics is different from existing designs, incorporating internal geometric changes, single piece designs, and a single port of actuation. Current approaches use external variations, two or more-piece designs, and multiple actuation ports, that are not practical. In the following sections, theoretical background, manufacturing processes, proposed geometric variations, results, and concluding remarks will presented.

2. THEORETICAL BACKGROUND

Soft bodies when actuated are subject to an elongation of the entire body due to the inflation of its walls. The soft bodies discussed throughout this paper are made from Silicone Rubber. When actuated these bodies change from original shape to an inflated balloon like structure. These bodies, even though difficult, were simulated through the 2016 Dassault Systèmes SolidWorks software using the SolidWorks Simulation Extension. This Static loading of internal pressure within each soft body was performed using Finite Element Analysis (FEA). This analysis used a Solid Standard Mesh, as shown in figure 1 and detailed in tables 1 and 2, focusing on a high quality four-point Jacobian analysis. A series of simulation and numerical analyses were performed to validate the proposed designs.

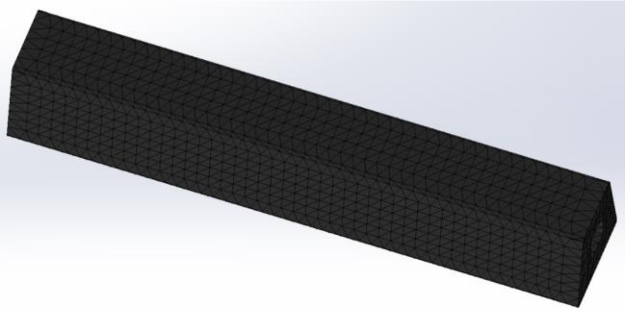

Figure 1: Actuator FEA Mesh Simulation

Table 1: FEA Mesh Information

Mesh type	Solid Mesh
Mesher Used:	Standard Mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian Points	4 Points
Element Size	1.70719 mm
Tolerance	0.0853594 mm
Mesh Quality	High

Table 2: FEA Mesh Detailed Information

Total Nodes	29178
Total Elements	18595
Maximum Aspect Ratio	12.959
% of Elements with Aspect Ratio < 3	99.6
% of Elements with Aspect Ratio > 10	0.0215
% of Distorted Elements (Jacobian)	0
Time to Complete Mesh (HH:MM:SS):	00:00:02

3. MANUFACTURING PROCESS

In these experiments, three-piece molds were created for design concept and casting, as shown in figures 2 and 3. These molds were first designed utilizing SolidWorks as the main 3-D CAD modeling software, as shown in figure 4. After each of the three parts of the mold were designed, they were saved as STL files, and put into the QIDIPrint Slicing software to be sliced for printing. It then was sent to print with the QIDI Technologies X-Pro Dual Extrusion 3-D Printer, as shown in figure 5, this printer has the capacity of 270 mm by 150 mm by 150 mm, in length, width and height, respectively. This printer can print multi-material parts with its unique dual extruding head, that has a precision between 0.05 mm and 0.4 mm. Each part was printed with a layer height of 0.2 mm and a tri-hexagonal infill density of 12%. These parts were printed at a nozzle temperature of 200°C and a bed temperature of 70°C, using Hatchbox Polylactic Acid (PLA) plastic filament; with a 1.75 mm diameter.

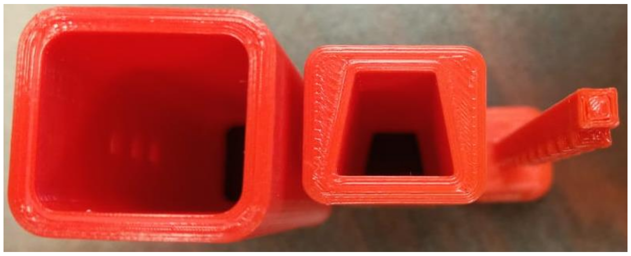

Figure 2: Actuator Mold Parts Top View

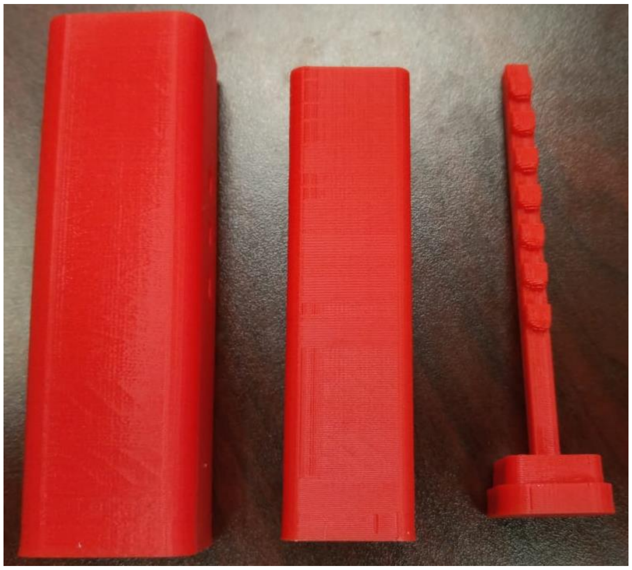

Figure 3: Actuator Mold Parts Side View

Figure 4: Complete 3-D Model for Mold

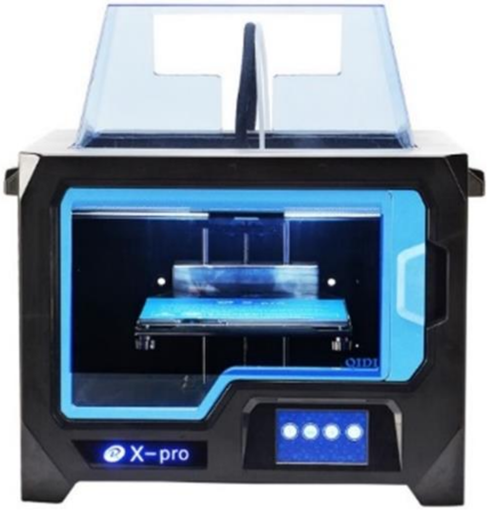

Figure 5: QIDI TECH X-PRO 3-D Printer [3]

After additively manufactured, these pieces were press-fitted together to create a single piece castable actuator mold, as shown in figure 6. This mold was then completely casted with Ecoflex 00-30 Super Soft Platinum Silicone. After curing for four hours, the actuators were demolded from the two outer molds, then the inner insert was removed. When done, the actuator is ready to be leak tested by inputting 20 ml of air through a standard air pump, as shown in figure 7. Finally, once passed it is ready for actuation, testing, and validation of design.

Figure 6: Actuator Mold Assembled Top View

Figure 7: Casted Actuator for Proposed Design

4. PROPOSED INTERNAL GEOMETRIC DESIGNS

The internal cavity of each actuator can be developed in such a way that different ranges of motion can be obtained through inversely designing an inner insert with complex geometries. A variety of different variations are expressed in figures 8, 9, and 10. Using this proposed method allows for a new approach to designing and manufacturing in Soft Robotics. These inner inserts are alterable in design, in which ridges are implemented on a rod, which acts as a space filler that will turn into a custom cavity inside the actuator, as shown in figures 11. This technique for the internal cavity allows for a single piece actuator through the use of multi-piece molds. These actuators also consist of a design with a single port of actuation. Keeping this way of manufacturing as is, allows for user error free actuators, as well as replicability and consistency of each casted actuator. Overall, this method is proven valid as expressed in the results section.

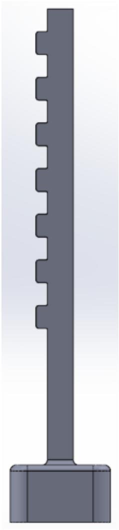

Figure 8: Standard Inner Insert Design

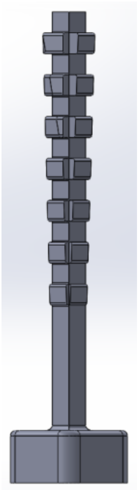

Figure 9: Altered Inner Insert Design

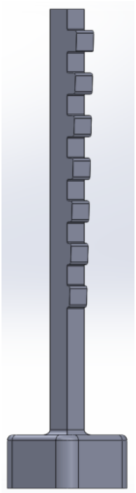

Figure 10: Altered Inner Insert Design

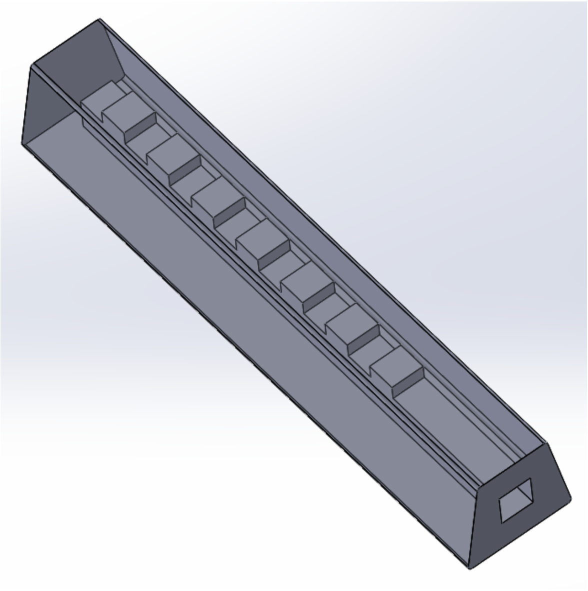

Figure 11: Actuator Design with Transparent Walls to Show Internal Design

5. RESULTS

To initially validate the proposed internal geometric design approach, a series of SolidWorks deflection, stress, and flow simulations were performed. Using the design further discussed, simulated with standard silicone rubber material properties, resulted in a 24 mm deflection from an inputted 2 PSI, as shown in figure 12.

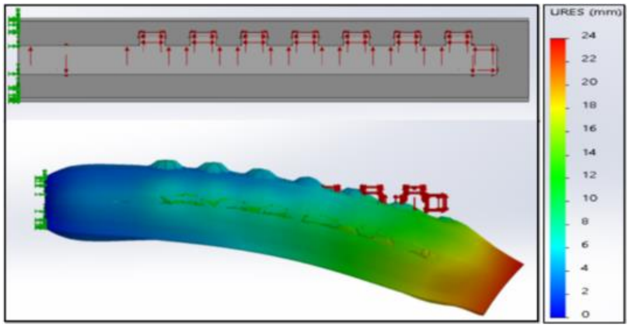

Figure 12: Simulation Results for Proposed Design

Further validating the proposed design approach, a standard mold was created to make an actuator. This mold, when casted, created an actuator with an external trapezoidal shape with dimensions of 15 mm by 13 mm by 80 mm of base, length, and height, respectively, as shown in figure 11. The overall mold size consisted of a rectangle of 22.5 mm by 19.5 mm, and with a total height of 84.5 mm, as shown in figures 3 and 4. The internal cavity where the air flowed had square dimensions of 4.5 mm by 4.5 mm and a height of 75.5 mm, as shown in figure 12. This internal cavity also included 7, 3 mm ridges, which faced the top part of the actuator, where the smallest side of the outer trapezoid is located. They were also designed without sharp edges, by the implantation of filets and chamfers, for easier extraction and rupture prevention. These ridges were designed to aid the actuator curve towards the opposite side of their location and had a minimum wall thickness of 1.75 mm. When actuated with 72 ml of air, this standard designed actuator resulted in a deflection of 48°, as shown in figure 13. These molds can be designed in a variety of ways to achieve a desired motion ranging from curves, twits, and bends in different directions.

Figure 13: Casted Actuator Inflated

After designing and additively manufacturing close to a hundred pieces, incorporating a variety of design variations, resulting sustainability analyses were performed. These analyses were broken into two different categories: quality and success rate, to determine if the design is replicable. First, the quality of each additively manufactured item was observed to determine if the print was usable for casting, without any layer delaminations. After casting, the quality of the cast, without any micro or macro bubbles that will in turn cause a premature rupture, was also observed. Overall, it was determined that 86% of all printed pieces and casted actuators were successful in its replicability and sustainability of design and manufacture.

6. CONCLUSION

Through this research, an internal geometric design approach was proposed and validated with actuators. This technique has been further implemented for the creation of full robotic crawlers, as expressed in a paper titled, "Implementation of Customizable Inner Geometries in Soft Robotics Using Additive Manufacturing" which is also in this published proceeding.

In this study, additive manufacturing technology was used for the manufacturing of molds for Soft Robotics. The implementation of additive manufacturing allows for the creation of small custom plastic molds which would be very difficult to make with using conventional methods. When taking into account the variations designed, tested, and validated; it was determined that the size and location of the internal ridges inversely affected the overall success rate of each actuator close to 62%, while the rest was determined by the quality of manufacturing. These dimensions and location placement were key to the deserved deflected outcomes.

All research that was conducted aids to the furtherment of Soft Robotics and it allows for a new approach to designing fully soft, non-robust, robots for a variety of applications. Not only does this bring new techniques for design and manufacturing, but it aids to global replicability, allowing for research groups worldwide take part in this uprising technology.

7. ACKNOWLEDGMENTS

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