Locomotion via soft matter and multi-materials

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***Abstract*— This project focuses on replicating a crawling soft robot developed by Harvard University using 3D multi-nozzle printing. The manufacturing process was adapted to a multi-stage method, utilizing several 3D-printed molds to independently fabricate different parts, which were then assembled either by gluing or by curing one part over an already finished component, depending on the stage. The experiments and gathered data demonstrate a successful outcome, with room for improvement in the alternative manufacturing process and strong performance in the challenges proposed during the course. The locomotion of the robot is presented and analyzed, providing a comprehensive overview of the work conducted. Finally, the paper discusses the drawbacks and outlines potential future work to enhance both performance and manufacturing.**

I. INTRODUCTION

The field of soft robotics has introduced various methodologies for the manufacturing of robots and actuators. [2] provides a comprehensive review of these methods and their characteristics. This paper aims to present the outcomes of replicating a robot designed by a group of researchers at Harvard University [1], with a key modification: replacing the multi-material, multi-nozzle 3D printing process with molding and assembly techniques. The objective is to demonstrate that multiple manufacturing processes can achieve successful results, for the same robot, allowing the adaptation of the process to meet the specific needs and available resources of the group.

II. METHODS

The chosen strategy for completing the project and winning the competition is to re-purpose a soft robot that was created by a team at Harvard University. They managed to create linear locomotion using a series of hollow triangular prisms where one side of the triangle is stiffer than the others. When these hollow structures are deflated they bend to the weaker side of the triangle, and by synchronizing the rows forward motion can be achieved.

A. Manufacturing

The main problem needing solving is the manufacturing process. The team at Harvard managed to 3D print the hollow structures using a multi nozzle silicone printer. This allowed them to create hollow shapes and the required air ways to deflate the triangles. In the case of this project it was decided that a series of silicone molds and gluing operations would make it possible to achieve similar success.

*The contents of this document are adopted from “Writing Good Scientific Papers” by Bridget Hallam and put into the IEEE conference paper format.

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Fig. 1. Independent row

Another change being applied is to make the robot modular. The Harvard solution created the robot as one solid piece. Due to risks of bad adhesion during gluing or air pockets being present, it was important to make sure that if a part was faulty it did not compromise the entire robot. The solution to this is to create identical modules for each each row, figure 1 show on the independent rows. The disposicion central rows is the same as the external ones but rotated 180 degrees. In this way the molds were designed such that we could make each row individually with little time loss if there was an issue with the module.

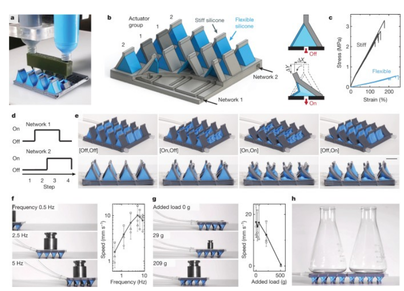

Fig. 2. voxelated soft matter via multimaterial multinozzel 3d printing [1]

The first and probably most important part is to create the hollow triangular prisms. This needs to be done carefully in order to ensure that the structure is airtight. To ensure this the curing process was done naturally, without an oven. As shown in figure 3 the triangles were created using a negative of their shape with an insert places as a cap. This creates a hollow shell of a triangular prism with the top side being open.

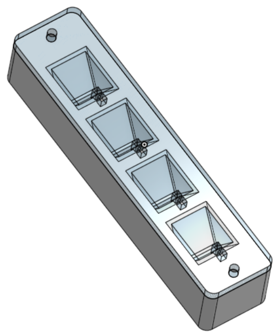

Fig. 3. Mold-1 For Creating Triangular Prisms

Once the triangles were created the stiffer side needs to be created. For this the triangles are moved to a second mold where on one side the negative is slightly thicker. This allows for the stiffer silicone to be poured in and adhere to the softer material.

B. Locomotion

The second challenge was achieving the desired locomotion. The system is pneumatically driven, and its locomotion is accomplished through a specific sequence of inflation and deflation of the triangles, grouped into external rows and internal rows. Both rows in each group perform the same sequence of inflation and deflation throughout the locomotion process.

The locomotion process consists of four stages. For clarity, the term *On* here refers to triangles being contracted under the vacuum effect:

1) **A: On Inners - Off Externals:** The inner triangles contract, causing their tips to displace in the positively in x and y directions.
2) **On Inners - On Externals:** The external triangles contract, lowering the structure along the y-axis.
3) **Off Inners - On Externals:** The robot inflates the inner triangles, recovering its height. However, due to the previous displacement and the orientation of the triangles, this recovery pushes the robot upward, positive y, and forward, positive x.
4) **Off Inners - Off Externals:** Both groups of triangles are inflated, allowing the robot to stabilize after the motion and stand stationary on all its legs.

The different locomotions states can be apreciated on the figures 4, 5, 6, and 7.

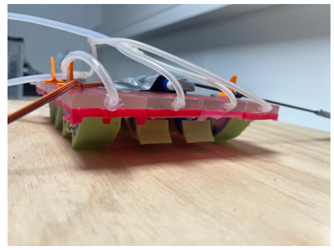

Fig. 4. On Inners - Off Externals

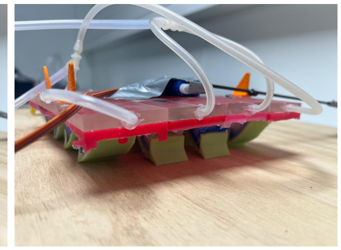

Fig. 5. On Inners - On Externals

Fig. 6. Off Inners - On Externals

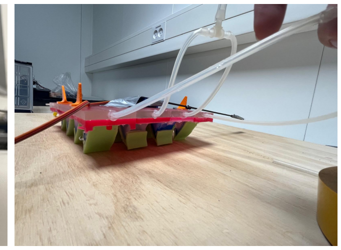

Fig. 7. Off Inners - Off Externals

C. Control and Pneumatic system

The system is powered by two different sources: an external, independent vacuum generator, and two mini pumps controlled and powered by the Arduino. Both pneumatic sources operate continuously, with only the valves states changing to control which group of rows on the robot is powered. Architecture of the pneumatic system is shown on the figure 8

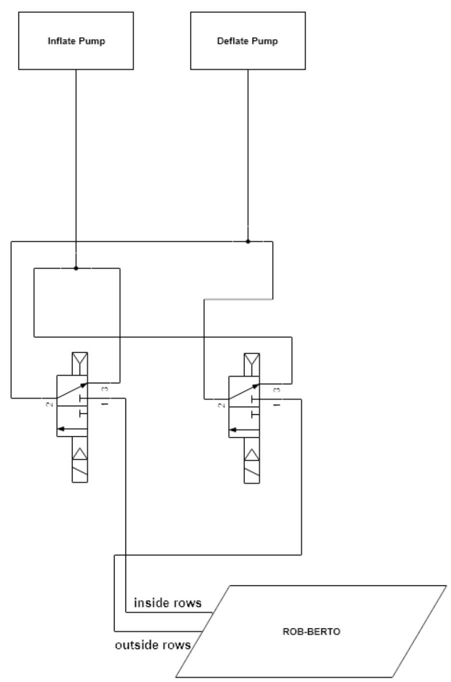

Fig. 8. Pneumatic connections of he system

The code to control the valves is a simple sequence that can be consider a state machine whose change of state is triggered by fixed timers. Each state consists of the

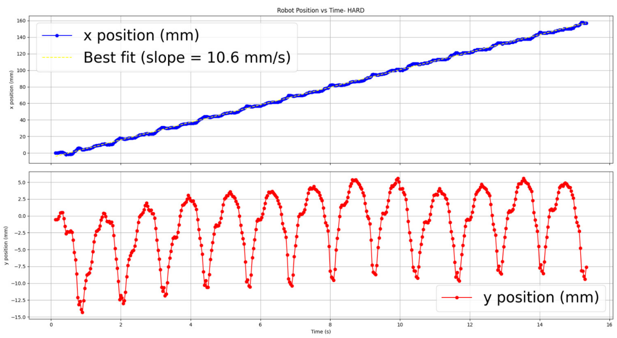

Fig. 9. Robot Surface Speed on Wood

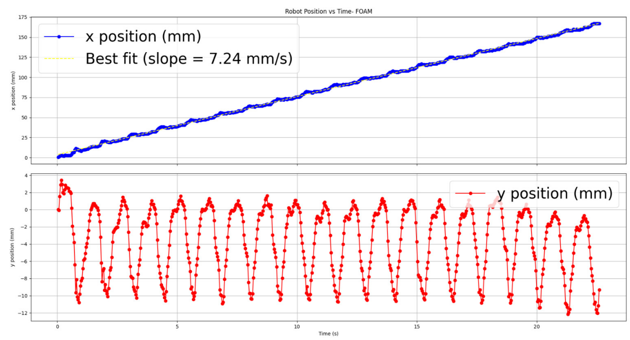

Fig. 10. Robot Surface Speed on Foam

activation or deactivation of the respective valves, followed by the desired delay to maintain the required state. This is implemented as a sequential loop that runs continuously.

III. Results

Success in the creation of the robot was measured in its ability to complete the obstacle course and do so in a controlled manner. The main focus of the design was to create a robot that could robustly traverse the different surfaces. Those surfaces being the wood, wood incline, sand and foam.

The other aspect of traversing the course is the ability to steer. This is something that there were plans for but due to time constraints and other miscellaneous issues, this is something that was put on the back burner for this project. As stated the main goal of this robot was to be able to traverse the different surfaces, and do so in a semi fast and not random manner. To measure this we measured two things, one the ability of the robot to maintain a straight line, and two the speed at which the robot could traverse the different surfaces.

The results in Table 9 and Table 10 illustrate the time required for the robot to traverse two different surfaces: a rigid wooden surface and a foam sheet placed on top of the wood. Using 3D tracking software, the robot's displacement over time was measured in both the X and Y directions, with the X direction representing forward movement and the Y direction representing the displacement up and down over time. The robot's speed was determined by fitting a line to the displacement data. The findings indicate that the robot moved faster on the hard wooden surface with a speed of 7.24 mm/s on foam and 10.6 mm/s on foam. This difference in speed is attributed to the reaction forces from the wood being greater than those from the foam, as the foam deformed under the robot's weight, reducing its ability to provide firm support.

It was also interesting to see the displacement in the Y direction as the robot moved forward. This measurement illustrates how the robot is able to move forward by rising and falling on the rows of feet.

It was also observed that the robot was unable to ascend the inclined surface without the inflation of the center rows. If the robot relied purely on the stiffness of the triangles for reinflation the robot would stall on the hill. Adding the the small inflation pump fixed this issue and gave the robot the ability to climb the hill. However this could be greatly improved by reinflating at the same rate at which the triangles are deflated. It is worth noting that if this upgrade were to happen greater care would need to be taken on making sure the triangles are not over inflated.

IV. Discussion

A. Locomotion

During the fine-tuning of the system, once it was already manufactured, several factors were identified that constrain the level of locomotion achieved:

- **Velocity:** The system's speed is constrained by how quickly it can transition from one state to another. This refers to how fast the system is able to inflate and deflate the triangles. This means that the frequency of the system is the function of the frequency of the inflation deflation cycle. Adding stiffer feet and a larger vacuum greatly increased the robots speed and ability to move. However it is also important that the robot has a surface to push off of to achieve the forward movement. It is because of this that the robot performed so poorly on the sand.
- **Displacement per Cycle:** The amount of movement per cycle is restricted by how much the system can bend the triangles, as this bending is the primary source of displacement along the x-axis.
- **Friction and Stiffness:** The stiffness of the tips of each triangle, which creates friction against the surface, is a critical factor. This prevents the system from sliding or failing during State C, where the body is pushed forward while lifting off the ground. Adding the stiffer feet that were mentioned previously also improved on this.
- **Software Tuning:** Much time was spent on altering the times between the change in state and when the triangles would inflate or deflate. In the future this could be upgraded by incorporating some form of closed loop control in the system. The first iteration utilized no sensors and relied purely on tuning the times between the changes in state.

After a full understanding of these constraints, two enhancements were made:

- **Stiffer Tips:** The production of stiffer tips using Elite Double 32A instead of Dragon Skin 10.
- **Pneumatic System Architecture:** The architecture of the pneumatic system was modified such that the Arduino-controlled pumps focused solely on inflation, powered by an external source. And using a larger external vacuum generator for the deflation of the triangles.

These change resulted in a fivefold increase in the robot's velocity.

B. Manufacturing

During the manufacturing process, several drawbacks arose that necessitated updates or rethinking of the process. These updates led to a successful final process for manufacturing the robot. However, there remains room for improvement:

- **Stiff Tips Manufacturing:** The manufacture of the stiff tips that constrain the bending direction of the triangles can be performed individually and then assembled by gluing afterwards. This approach avoids one of the most critical challenges in the manufacturing process and prevents the cumbersome effect of having stiff silicone on more than one side of the triangles.
- **Injection Process:** Despite degassing the silicone before, and performing carefully the injection process air bubbles remained presents until certain extent on the triangle, additional air exhausts should be added to allow trapped air to escape. Alternatively, a more pressurized method for silicone injection could be used.
- **Weight Reduction:** The upper part of the robot could be reduced in size to decrease its overall weight.
- **Turning Mechanism:** Further modifications could enable the system to turn by altering the morphology of the triangles and the direction in which they bend.

V. Conclusion

This project aimed to replicate the design of an existing robot that achieves locomotion through the deflation and reinflation of hollow triangular prisms. The primary challenge was manufacturing the robot using the materials available. The original design was created using a multi-nozzle, multi-material 3D printer, whereas this project utilized a series of 3D-printed molds to fabricate each module component, which were then assembled by gluing the parts together. The most difficult aspect was ensuring the system was airtight. Ultimately, the method proved successful, and a functional replica of the robot was created.

As noted during initial testing, the stiffer side of the triangular prism required significantly increased rigidity. This led to the development of "shoes" for the feet to enhance stiffness and improve friction with the ground. The improved robot performance stemmed from a comprehensive understanding of its locomotion process and the identification of factors constraining it. This insight also revealed potential future enhancements, such as enabling turning, reducing size, or achieving more complex movements.

The robot demonstrated strong performance across various stages, underscoring the viability of both the design and the adapted manufacturing process.

Appendix

Locomotion performance video on Foam (click →): Team 7: Rob-berto - Locomotion performance over foamed surface.

Locomotion performance video on Wood (click →): Team 7: Rob-berto - Locomotion performance over hard surface.

Appendix

Individual Contributions

- **Conceptual contributions:** David Ospina 45%, Nikolas Neathery 45%, Pauline Boudy 10%.
- **Writing/implementation of control code:** David Ospina 45%, Nikolas Neathery 45%, Pauline Boudy 10%.
- **Design and Manufacturing:** David Ospina 40%, Nikolas Neathery 50%, Pauline Boudy 10%.
- **Production of experimental data:** David Ospina 50%, Nikolas Neathery 50%, Pauline Boudy 0%.
- **Analysis and presentation of experimental data:** David Ospina 50%, Nikolas Neathery 50%, Pauline Boudy 0%.
- **Writing report:** David Ospina 50%, Nikolas Neathery 50%, Pauline Boudy 0%.

References

[1] J. F. Wilson, I. Norio, Bellows-type springs for robotics, Proc. Adv. Spring Technol. JSSE 60th Anniversary Int. Symp., 109–119 (2007).

[2] F. Schmitt, O. Piccin, L. Barbé, and B. Bayle, *Soft Robots Manufacturing: A Review*, Frontiers in Robotics and AI, vol. 5, 2018. Available (click –¿): `https://www.frontiersin.org/articles/10.3389/frobt.2018.00084`. DOI: 10.3389/frobt.2018.00084.