Design and Fabrication of Sensorized Soft Effectors for Modular Soft Robots

Maliha Kabir [1], Prosenjit Kumar Ghosh [2], Md. Sharif Ahmed [3] , Thinagaran Perumal [4] , Prabha Sundaravadivel [5]
Dept. of Electrical and Computer Engineering, The University of Texas at Tyler [1,2,3,5]
Dept. of Computer Science, Universiti Putra Malaysia, Selangor, Malaysia [4]
mkabir@patriots.uttyler.edu [1], pghosh2@patriots.uttyler.edu [2], mahmed5@patriots.uttyler.edu [3],
thinaragaran@upm.edu.my [4], and psundaravadivel@uttyler.edu[5*]
[*] Corresponding Author

***Abstract*—Biomimicry is a field of study that involves imitating the designs and processes of nature to solve problems using man-made systems. Biomimicry offers an empathetic, interconnected understanding of how life works and where we fit in. In bio-inspired designs, the main challenge is to develop a sustainable and effective framework that can be used in the real world. Most soft robotic designs are state-of-the-art models that cannot be used in real sensing applications. In this research, we propose a sustainable sensor-integrated modular soft robot model that can be used for locomotion and gripping applications. This work presents the steps involved in modeling, designing, and fabricating soft and flexible end effectors that can be used for soft robots with integrated soft stretchable sensors. It also demonstrates the design methodology involved in modeling and simulating the proposed model for robots that would require effectors with increased functionalities.**

***Index Terms*—Biomimicry, Soft robots, 3D models, gripper model**

I. Introduction

Biomimicry is the science of applying nature-inspired designs in human engineering and invention to solve human problems. This paper attempts to achieve a balance with nature to live in harmony with Mother Earth and avoid further contributing to global problems by designing and producing materials, architecture, and systems based on biological materials and processes. A new way of life with sustainable resources, practices, and policies is being used in biomimicry [1]. Innovators turn to biomimicry to achieve a unique product that is an efficient, and effective product. Still, they often gain a deep appreciation of and connection to the natural world. Biomimicry encourages conservation for ecosystems and their inhabitants because they hold the knowledge we need to survive and thrive [2].

Nature is often a source of inspiration for soft robot design given that animals are mostly composed of soft components and appear to exploit the involving movement in complex environments almost everywhere on Earth [5]. Soft robotics is a subfield involving robots constructed with very compliant materials. These robots can be soft and deformable or made of flexible materials [4]. Soft robotics aims to design and construct robots with physically flexible body structures and embedded electronics [15]. Soft robotics is also used with Artificial Intelligence modeling to design more efficiently.

There are multiple mechanisms have been used for the soft robotic control process. Gas or liquid controls the chamber inflation or deflation for the actuation [19]. In this research, we propose soft models that can be actuated based on the mechanics and the environment around them. Our proposed reconfigurable soft effectors are attached to soft robots with spring-like structures that can help them provide flexibility in the degree of freedom. The sensor-integrated soft effectors, a.k.a. sensorized soft effectors, can help change the course of action for the proposed models based on the desired applications [16].

A. Novel Contribution of This Paper

In this research, soft modular robots are proposed that can be used for gripping and locomotion. To achieve this, it must be ensured that the proposed model has different pressure points to enable gripping and crawling activities. Our proposed model can have numerous applications and benefits, including the following:

- Form Factor: The proposed soft effectors can be used for small compact soft subsystem design as they can change shape based on the required application. This can reduce the overall form factor, as we will be using the same design for different modes of operation.
- Sustainable Design: As the bio-inspired design will be printed with environment-friendly materials and used for different applications, it will lead to a sustainable monitoring framework.
- Low Maintenance: The proposed framework will require low maintenance as it reduces the need for frequent repairs and replacements.
- Real-time sensing: The proposed sensor and actuators can be used for various real-time sensing applications, including agriculture, bio-medical and environmental sensing [18].

B. Organization of this paper

In this paper, Section II shows the Related Prior Research for bio-inspired soft robots. Section III explains this paper's novel contributions and the benefits of the proposed model. Section IV presents the basic working principle of the proposed modular soft robot. Section V details the implementation

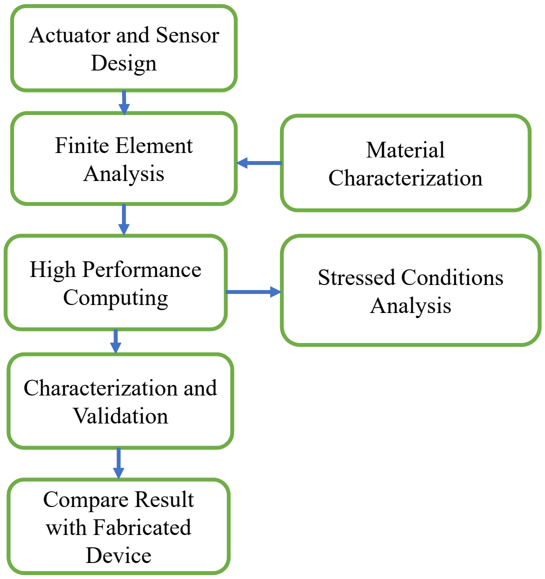

Fig. 1. Design and Fabrication Flowchart for the proposed Sensorized Soft Effectors

and validation results for the sensorized soft effectors. Section VI concludes the research with directions for future work.

II. Related Prior research

Development of an anthropomorphic soft robotic hand integrated with multiple flexible force sensors in the fingers has been demonstrated for the Grasp Stability Estimation [6], [7]. Researchers have developed bio-inspired designs for sensors and actuators based on animals. Such models can be used for analyzing the environment and real-time monitoring of species distribution models [8], [9]. Closer observations of such tetrapods can provide more insights into weather and climate changes [10], [11], [13]. In our previous research, we have developed soft stretchable sensors that can be integrated into any existing framework with a single or swarm of robots [17].

III. Basic Working Principle

Soft robots require sensors that can help them in changing the degrees of freedom and conform to various target areas as applicable. In this research, the proposed soft effectors are made of flexible materials that can be used for bi-directional bending. The wall i.e. the outer layer, is designed with a fixed degree of the wedge so that it is favorable to increase the bending angle when it needs to bend backward. Moreover, the same design is used for the inner chamber, and the thickness of the wall is constant when the air pressure is increased. The proposed model is integrated with stretchable sensors in the bottom layer. Figure 1 shows the steps involved in designing and fabricating the customized soft robot. To demonstrate the versatility of the proposed model, we have designed a soft gripper and a soft bend leg. In both models, the stretchable sensors are integrated to automate their change of position and structure depending upon the application.

IV. Design and Fabrication of proposed Soft Flexible Effectors

A. 2D modeling and Simulation

As the proposed model consists of actuation points along the length of the flexible structure, the feasibility of such a design was first modeled and simulated using the physics-based software, Aglodoo. In the 2D model, the structure and stress points were thoroughly evaluated. Figure 2 shows the 2D modeling and simulation of soft, flexible hind legs that need to be embedded with springs and motors.

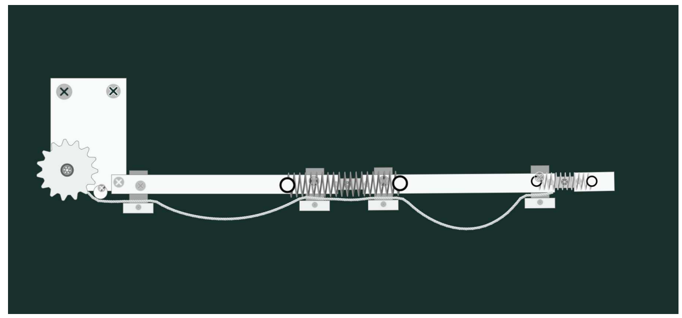

Fig. 2. 2D modeling and simulation of soft and flexible legs

B. 3D modeling

Based on the evaluated design from the 2D modeling, the proposed framework is evaluated using 3D modeling software, Fusion360. In the 3D modeling, the number of layers required for the soft robot along with room for the stretchable sensors, motors, and springs are taken into consideration. Figure 3 shows the 3D model of the custom-designed soft flexible legs.

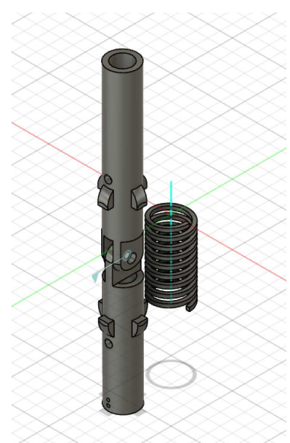

Fig. 3. 3D modeling of the proposed soft and flexible legs

C. Materials

Silicone rubbers are the most common materials for fabricating soft pneumatic actuators. The main reason behind this selection is that they are highly flexible and can undergo a large deformation during high pressure. Hyperplastic models are used for the characterization of soft robotic behavior modeling. For silicone rubber, it is assumed that the material is isotropic and incompressible, and the viscoelasticity and stress-softening are neglected. Soft pneumatic robot has a bending motion that can be approximated as multiple tangent constant sections or small piecewise structures. Elastomer-based soft effectors in soft robots show great promise for handling delicate objects, which makes them suitable for sensitive applications. The soft grippers can have multi-layer and multi-segment, making them inconvenient for high-precision manipulation.

V. Implementation and Characterization

A. 3D Printed Models for Soft Grippers

1) Material Testing and Curve Fitting: Considering the coefficients in the hyperplastic models for material testing is essential for modeling the stretchable sensors and actuators to be integrated into the gripper. The coefficients, such as uniaxial, biaxial, and shear test data, are determined by hyperplastic models. Moreover, most of the studies are considered to use uniaxial testing due to their high availability. To observe the behavior of the elastomers, it is obvious to calculate the multiaxial stress states where the pressure of actuators is significant. In this experiment, the Yeoh model has been used for the actuator characterization concerning different pressure. The Yeoh model can predict elastic behavior with an extensive range of stress and strain. From this model, it is easy to observe the stress-stretch mechanism in different deformation modes. The main problem of the Ogden model is that this model uses a limited number of testing data like uniaxial tension.

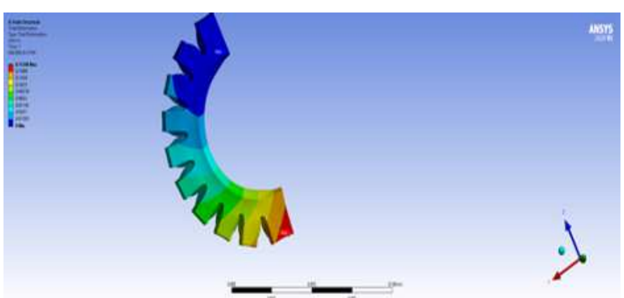

Fig. 4. FEM simulation of Soft Pneumatic gripper (Pressure 100KPa)

In this work, a computational Finite Element method (FEM) is created to observe the performance of the soft pneumatic actuator. At first, the actuator is designed using Autodesk (Fusion-360), and the geometry is appropriately described for the analysis. To determine their geometrical parameters and supplementary materials, tests such as blocked force and displacement are done using the FEM computational modeling. The characterization and inputs are commanded in the ANSYS simulator. This modeling tool can automate different simulation parameters such as part, interactions, meshing, and boundary conditions for command. Additionally, the computational model has enabled to make the design iteration before the actual fabrication of the prototypes.

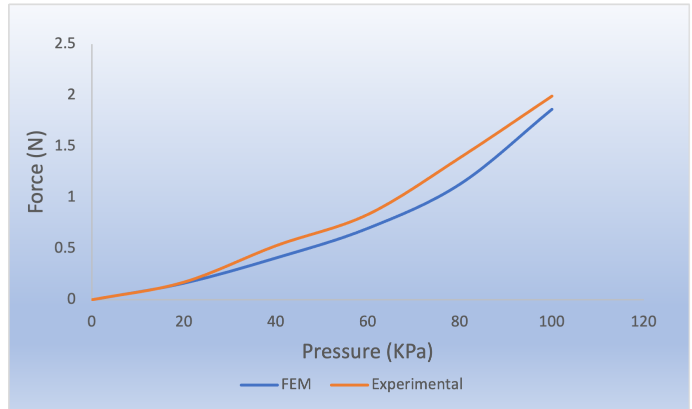

Fig. 5. Soft pneumatic actuator: FEM vs Experimental result of load with respect to applied pressure.

2) Output Validation of the Sensor: Figure 6 shows the resistivity changes in the custom-built sensor for various degrees of pressure. The custom-built sensors were developed as electronic skin that can be integrated along the walls of the soft effectors.

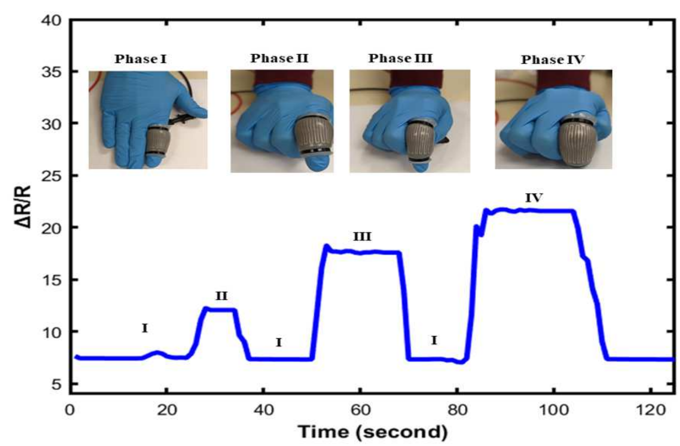

Fig. 6. Output feedback of the 3D printed stretcahble sensor integrated in gloves.

B. 3D Printed Models for Soft Flexible Legs

Figure 7 (a) shows the Lychee Slicer model of the adjustable legs and the spring required for obtaining different degrees of freedom in the legs. Figure 7 (b) shows the individual components, including the spring and legs with holes for along the joints for integrating the springs. In addition to this, we used Ultimaker Cura for slicing the design. Figure 8 shows the tested model of the legs printed using Thermoplastic filament (PLA). Figure 9 shows the final printed legs with at least 3 degrees of freedom. The custom-designed legs were designed both using the thermoplastic (PLA) filament for the flexible legs and Superflex F39 resin.

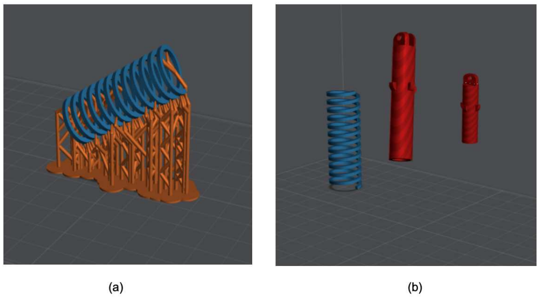

Fig. 7. Lychee Slicer Model for (a) the Spring and (b) the flexible legs

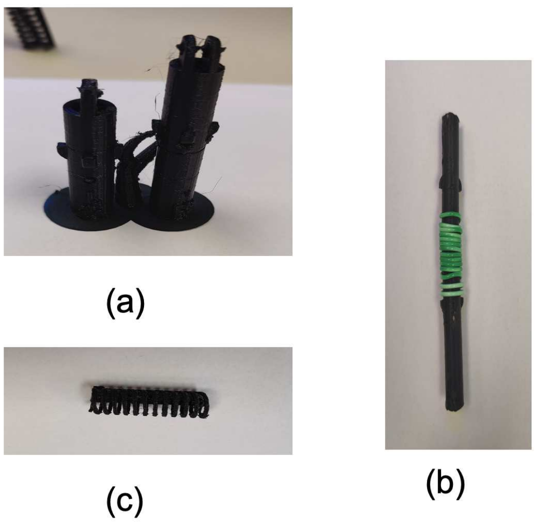

Fig. 8. Tested 3D model of the legs using PLA. (a) PLA-based legs along with the joints, (b) Complete form of the leg along with the spring, (c) PLA-based spring that can be attached to the leg joints

VI. Conclusion and Future Work

In our proposed design of modular sensorized soft robots, we have integrated stretchable sensors along the flexible legs and gripper that can help change the mode of operation from locomotion to gripping based on the desired application. The proposed model is easily integrated to any existing framework where gripping and locomotion are essential. As the next steps in this research, the pressure points required for the flexibility skill of the effectors will be validated such that the mode of operation can be automated.

Fig. 9. Final 3D printed flexible bent leg (a) using PLA and (b) flex resin with attached spring.

VII. Acknowledgment

This research is supported in parts through the National Science Foundation under Grant No. OAC-1924117. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

[1] Editors, B. D. (2017, June 14). Biomimicry - definition and examples of biomimetics. Biology Dictionary. Retrieved February 27, 2023, from https://biologydictionary.net/biomimicry/
[2] What is Biomimicry? Biomimicry Institute. (2023, February 21). Retrieved February 27, 2023, from https://biomimicry.org/what-is-biomimicry/
[3] How does humidity affect air pollution? Conserve Energy Future(2022, July 28).
[4] Soft Robotics 101: Definition, examples, and Soft Robotics applications. Moosmosis.(2022, December 4) Retrieved February 28, 2023, from https://moosmosis.org/2021/06/29/soft-robotics-definition-examples-and-applications/
[5] Sangbae Kim, Cecilia Laschi, Barry Trimmer, Soft robotics: a bioinspired evolution in robotics, Trends in Biotechnology, Volume 31, Issue 5, 2013, Pages 287-294, ISSN 0167-7799, https://doi.org/10.1016/j.tibtech.2013.03.002.
[6] Khin P. M., Low Jin H., Ang Marcelo H., Yeow Chen H., "Development and Grasp Stability Estimation of Sensorized Soft Robotic Hand", Frontiers in Robotics and AI JOURNAL, VOLUME 8,2021, doi=10.3389/frobt.2021.619390.
[7] Bellis, E. D. (1962). The Influence of Humidity on Wood Frog Activity. The American Midland Naturalist, 68(1), 139–148. https://doi.org/10.2307/2422640.
[8] SHELFORD, V. E. 1913. The reactions of certain animals to gradients of evaporating power of air. A study in experimental ecology. Biol. Bull., 25: 79-120.
[9] Polineni S, Shastri O, Bagchi A, Gnanakumar G, Rasamsetti S, Sundaravadivel P. MOSQUITO EDGE: An Edge-Intelligent Real-Time Mosquito Threat Prediction Using an IoT-Enabled Hardware System. Sensors. 2022; 22(2):695. https://doi.org/10.3390/s22020695.
[10] How does weather affect mosquito activity? Mosquito Squad. (2018, July 10). Retrieved February 28, 2023, from https://www.mosquitosquad.com/central-illinois/about-us/blog/mosquitoes-facts-more/how-does-weather-affect-mosquito-activity-/
[11] Yamana, T.K., Eltahir, E.A.B. Incorporating the effects of humidity in a mechanistic model of Anopheles gambiae mosquito population dynamics in the Sahel region of Africa. Parasites Vectors 6, 235 (2013). https://doi.org/10.1186/1756-3305-6-235.
[12] Ahmed EM. Hydrogel: Preparation, characterization, and applications: A review. J Adv Res. 2015 Mar;6(2):105-21. doi: 10.1016/j.jare.2013.07.006. Epub 2013 Jul 18. PMID: 25750745; PMCID: PMC4348459.
[13] Barik, Lal. (2019). IoT-based Temperature and Humidity Controlling using Arduino and Raspberry Pi. International Journal of Advanced Computer Science and Applications. 9. 494-502. 10.14569/IJACSA.2019.0100966.
[14] Bellis, E. D. (1962). The Influence of Humidity on Wood Frog Activity. The American Midland Naturalist, 68(1), 139–148. https://doi.org/10.2307/2422640.
[15] P. Sundaravadivel, P. Ghosh, B. Suwal. IoT-enabled Soft Robotics for Electrical Engineers. In Proceedings of the Great Lakes Symposium on VLSI (GLSVLSI), 2022, 329–332.
[16] P. Ghosh, SZ. Riam, MS. Ahmed, P. Sundaravadivel. CMOS-Based Memristor Emulator Circuits for Low-Power Edge-Computing Applications, Electronics, 2023, 12, 1654.
[17] P. Sundaravadivel, A. Fitzgerald, P. Ghosh, MS. Ahmed. Hapt-Edge: Haptics in Soft Effectors for Smart Interactive Assistive Frameworks, Journal of Biomedical Sciences Instrumentation, 2022, 3, 162–167.
[18] Kabir, M., Mummadi, T., Sundaravadivel, P., Poster: Towards Edge-Intelligent Drowning Detection System, In Proceedings of the 16th International Conference on Underwater Networks and Systems, Boston, MA, USA, 14–16 November 2022.
[19] P.K.Ghosh, P.Sundaravadivel, Stretchable Sensors for Soft Robotic Grippers in Edge-Intelligent IoT Applications. Sensors 2023, 23, 4039. https://doi.org/10.3390/s23084039.