Headless Frankenstein

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I. Project idea synopsis

This report presents the design, modeling, manufacturing, and testing of the Headless Frankenstein, a soft robot utilizing pneumatic networks (pneu-nets) for actuation. The Headless Frankenstein leverages pneu-net technology composed of elastomeric materials like Dragonskin-30 and Ecoflex-30 arranged in a square pattern for enhanced stability. The pneu-nets are designed with semi-hexagonal profiles and optimized air chamber configurations for improved performance.

The rapid prototyping manufacturing approach involved 3D printing molds, curing the elastomeric materials, and assembling the components. Extensive modeling using Abaqus CAE software with Yeoh hyperelastic models accurately simulated the deformation behavior under applied air pressure. Rigorous testing validated the robot's locomotion capabilities, with a 5 cm actuator stroke, 0.981 N maximum actuator force, and the ability to navigate through 7 cm diameter openings with 180° bending angles at 145 kPa pressure.

II. Introduction

Soft robotics marks a significant departure from traditional rigid structures, representing a convergence of engineering, material science, and biology to create machines mirroring living organisms' flexibility. Instead of rigid-body approaches, soft robotics employs compliant and deformable materials, endowing robots with remarkable dexterity and versatility. These pliable machines offer promising applications, from healthcare and manufacturing to human-robot interaction. This report explores soft robotics' principles, including material science, mechanics, and control systems. It delves into diverse applications, from aiding individuals with disabilities to enhancing human capabilities in hazardous environments. Soft robotics heralds a new era characterized by resilience and adaptability, fostering symbiosis with the natural world. This report aims to highlight soft robotics' transformative potential, inspiring curiosity and innovation in this field.

III. Prior Work

Soft robotics has emerged as a promising field in recent years, offering significant advantages over traditional rigid robots in specific environments and tasks.

Addressing the need for agile soft robots, recent research has explored jumping maneuvers as demonstrated by the Agile Soft-Bodied Robot. This untethered robot employs pneumatic and explosive actuators to execute directional jumps remarkably efficiently, showcasing its potential for dynamic tasks such as targeted object manipulation [1]. The development of the Quadruped Soft Rod-Climbing Robot (SR-CR), equipped with flexible bellows and folding air chambers, exhibits exceptional climbing abilities, maneuvering adeptly through environments such as nuclear pipelines and high-voltage cables. Its multifunctional design enables vertical and horizontal movement, showcasing its potential for diverse applications [7]. In addition to climbing prowess, soft robotics has expanded into the realm of locomotion with the creation of the Tetrahedral Soft-Legged Robot for Multigait Locomotion. This compact yet agile robot utilizes pneumatic omnidirectional bending actuators to achieve various locomotion modes, including steering, crawling, and rolling. Experimental validation underscores its capability to traverse challenging terrains, positioning it as a promising tool for search and rescue operations [3]. Furthermore, advancements in material science have led to the development of Enhanced Soft Pneumatic-Network Actuators (SPAs) inspired by fishbone structures. These actuators offer improved gripping capabilities, enhancing stability and firmness in gripping tasks. Their utility has been validated through rigorous simulations and experimental studies, highlighting their potential across various applications [6]

The advent of fully untethered mobile soft robots marks another milestone in the field. Powered by pneumatic systems and equipped with modified Pneu-Net actuators, these robots exhibit autonomy and resilience in adverse conditions. Their capacity to carry up to 8 kg payloads underscores their practicality for real-world deployment, especially in tasks requiring transportation and exploration [2]. Inspired by nature, researchers have also delved into underwater bipedal walking, as exemplified by the Underwater Bipedal Walking Soft Robot. Utilizing a spring-loaded inverted pendulum model, this soft robot achieves notable speeds and adaptability to uneven underwater terrain, presenting opportunities for exploration and research in aquatic environments [4].

IV. Intellectual Merit

Pneu-Net soft robot technology offers unparalleled flexibility and adaptability compared to traditional rigid-bodied robots. Inspired by biological systems, Pneu-Net robots utilize pneumatically actuated soft materials to achieve complex movements and tasks. By mimicking the elasticity and compliance found in living organisms, these robots excel in navigating unstructured environments and interacting safely with humans. The innovative design of Pneu-Net robots opens up a wide range of applications from medical devices capable of delicate surgical procedures to versatile industrial automation solutions. The ongoing advancements in material science and control algorithms open up exciting possibilities for Pneu-Net soft robot technology. By leveraging new materials and sophisticated control strategies, Pneu-Net robots can be designed to exhibit unprecedented levels of adaptability, resilience, and efficiency.

V. DESIGN

The design of the Headless Frankenstein, as shown in Fig.[1] consists of **4** pneu-nets, which are connected to a body plate in a square pattern to have better stability. They are then connected further via tubes for actuation. The design made for this soft robot is parametric, which makes it scalable and versatile for any changes if required. The pneu-nets are designed in such a way that they will yield better performance in the competition. The profile of the pneu-net consists of a semi-hexagon shape with the width of the pneu-net as **3.5cm**, the height of the pneu-net as **2cm**, and the length of the pneu-net as **15cm**, which consists of **12** air chambers.

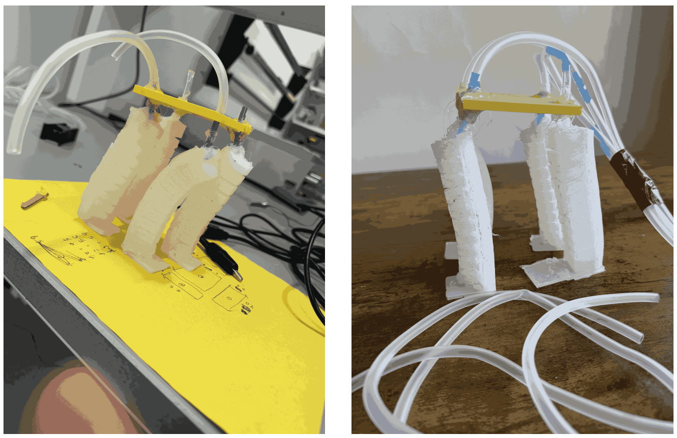

Fig. 1: Headless Frankenstein

The pneu-nets are made from both **dragonskin-30** and **ecoflex-30** material . The use of ecoflex material makes two of the four pneu-net legs inflate more than their counterpart dragonskin legs, making it easy to swim or move in a liquid environment(ex. water)(The proposed movement is such that the ecoflex pneu-nets inflate more than the dragonskin pneu-nets at the same supply of pressure, which creates two circular wheel-like structures in the robot that are filled with air, making the robot float in water. Furthermore, the dragonskin pneu-nets would be used to displace the water, enabling the robot to swim). The method of locomotion is explained in further parts of the report.

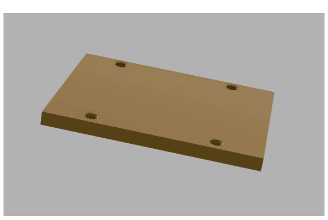

Fig. 2: Connector Plate Design

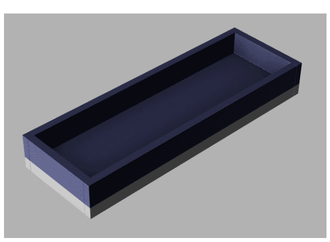

Fig. 3: Strain Limiting Layer Design

The feet of the robot are rectangle shaped, designed to provide better friction while in locomotion and better stability while standing idle. The dimensions of the feet used are **2.4cm** in width and **3.2cm** in length. These feet are made of dragonskin-30 and connected to the pneu-net legs by sticking them with Sil-Poxy. The strain limiting layer as shown in Fig[3] is a thick layer of respective material of pneu-net leg with dimensions of **3.1cm** by width and **10.4cm** by length.

The body which holds these pneu-nets in a square pattern, and from where the tubes extrude and are connected to the syringes, is a simple square shape with dimensions of **80cm** as shown in Fig[2]. It also consists of holes of a diameter of **6cm** to accommodate the tubing coming out from the pneu-net, which is further connected to the syringes.

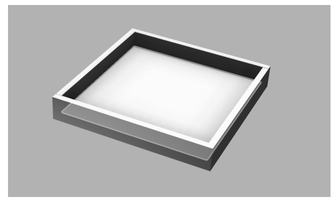

Fig. 4: Initial Mold for feet

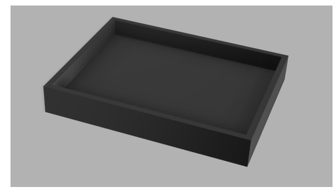

Fig. 5: Improved Mold for feet

VI. MANUFACTURING

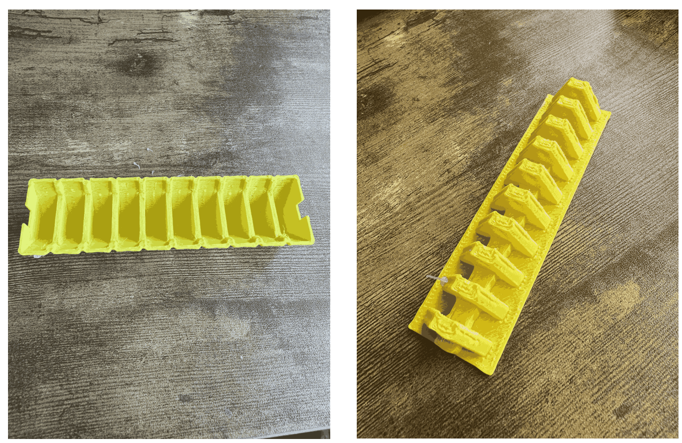

Fig. 6: 3D Printed Components

The manufacturing method used was rapid prototyping, and the way it was done was that the 3D molds were designed, then 3D printed, cured, and tested. The 3D printer used the most was a **Voron 350** 3D printer, which is present in the **Rastic** lab. The initial prototyping 3D prints were printed from **Silab** but were defective due to low infill and low layer thickness. They did not survive the first 3D printing prototype and took time to 3D print, which was nearly eight hours, but apparently, the 3D printers in Rustic were fast and could print at a speed of four hundred millimeters per second, and were used to get more rapid prototyping. The mold designs for the pneu-nets as shown in the Fig[7],[8] were used to obtain the 3D printed molds for curing as shown in Fig[6].

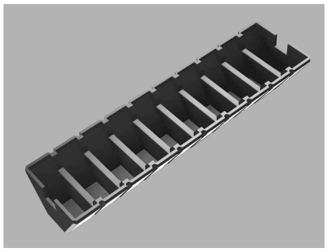

Fig. 7: Mold Cavity for Pneu-nets

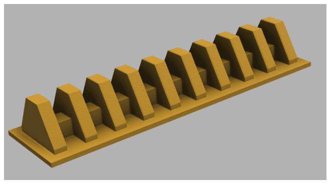

Fig. 8: Mold for Pneu-nets

There were various iterations where I used them and tried to obtain near-perfect results. While the curing of the component was being done, there were some issues regarding the polymers sticking to the mold, and this was resolved using the hair-release sprays, some nail Polish(as shown in Fig[10]), and WD40. The feet were cured and stick to the cured pneu-net using Sil-Poxy. The initial iteration of the 3D print for the cavity mold part resulted in some good results, but it was tough to cure the strain limiting layer, and the molded cured pneu-net as shown in Fig[12],[13]:

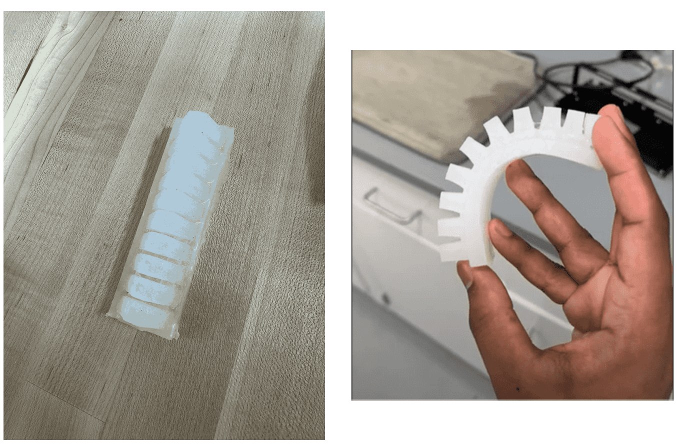

Fig. 9: Manufactured Pneu-Net

Therefore, there were changes made in the mold cavity part as shown in Fig[11] for better curing and better-combined iterations of the pneu-net legs were obtained.

Fig. 10: Nail Polish was applied to seal the space between the 2 layers of 3d printed material and to aid in smoother removal of the cured component

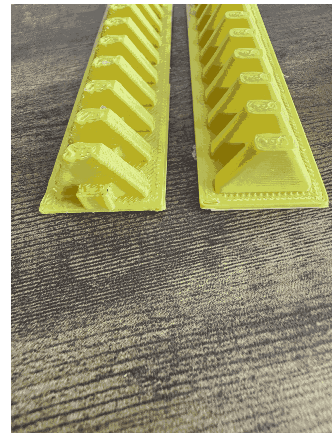

Fig. 11: The left mold was modified to the right mold which removed the extrusion left for connection of air chambers, where the tubing was inserted in the first prototyping, but later the tubing was inserted using a incision in the strain limiting layer and then sealed with Sil-Poxy

The use of hair release spray, nailpolish, and WD-40 resulted in better curing of the pneu-nets yet there was some defective manufacturing resulting in breakage of the pneu-net leg or air leaks in them. To resolve this tweezers dipped in WD-40 were used to carefully extract the cured component from the molds which resulted in creation of perfect pneu-net legs as shown in Fig[9].

Fig. 12: Cured Strain Limiting Layer

Fig. 13: Cured Pneu-Net cavity

The below Fig[14] shows holes of a diameter of 6cm being drilled into the body[2] using a drill press at **EPIC**.

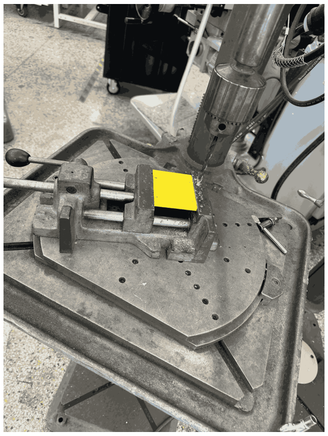

Fig. 14: Drilling Holes of 6cm diameter

VII. Modelling

Modeling was done on **Abaqus CAE** software. The pneu-net and the assembly both were modeled and using the materials dragonskin-30 and ecoflex-30, the hyperelasticity that was used was yeoh hyperelastic with the order of 3rd degree. The Yeoh strain energy potential defined by the coefficients C1 = 0.11, C2 = 0.02, with density of 1130 Kg/m³([Refer here), isotropic was configured in abaqus. The Yeoh strain energy potential for dragon skin defined by coefficients C1 = 0.11488 and C2 = 0.001262 were used(data for dragonskin 30 reffered from [5]). For the meshing of the part the mest controls were defined as follows :

1) Element shape : Tetrahedral
2) Technique : Free
3) Used mapped tri meshing on bounding face turned on
4) Element Library : Standard
5) Family : 3DStress
6) Geometric order : Quadratic
7) Hybrid formulation turned on

The instance for the assembly was created and thereafter boundary conditions were defined. The boundary conditions for pneu-net leg were defined by fixing one end of the pneu-net leg and restrcting all motions in any axes. The boundary conditions were defined for the plate(assembly simulation) keeping it fixed in one axis only and free to move in other axes. Thereafter, steps were defined which include the following steps :

1) Leave the initial step as it is.
2) Create a Gravity step(static, general) which will define the gravity.
3) Nlgeom is turned on.
4) Create another step named as airpressure in which the load(air-pressure) in the pneu-nets was defined.
5) The air pressure load was defined as 100kpa.

The Fig[15],[16] shows the meshing done for the robot assembly and the pneu-net in abaqus cae. After submitting the job and executing the simulation the obtained results are shown in Fig[17] which shows the deformation of the pneu-net leg when air pressure is given to it.

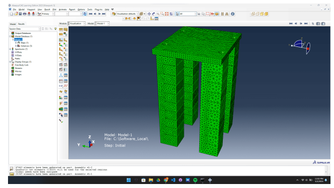

Fig. 15: Meshed Images of Assembly

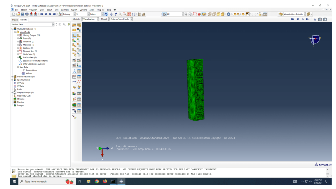

Fig. 16: Meshed Images of Pneu-Net Leg

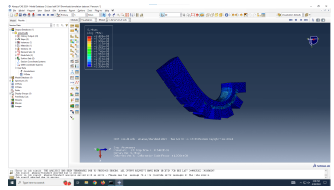

Fig. 17: Deformation of Pneu-Net Leg

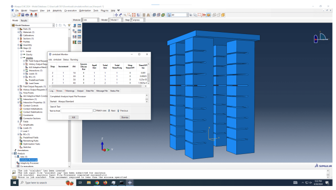

Fig. 18: CAE simulation for robot assembly

VIII. Testing/Validation of Functionality

The following algorithm outlines how the movement of each leg enables locomotion or movement of the robot 1:

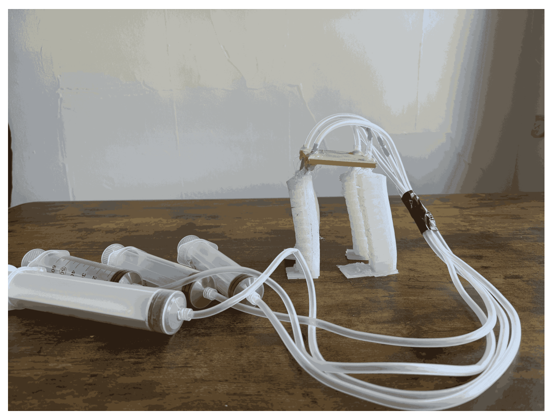

Fig. 19: Headless Frankenstein

Algorithm 1 Headless Frankenstein Locomotion Algorithm

1: Actuate the first leg
2: Actuate the second leg
3: Actuate the third leg simultaneously while deflating the first leg
4: Actuate the fourth leg simultaneously while deflating the second and third legs
5: Deflate the fourth leg
6: Check if the robot has fallen
7: **if** robot has not fallen **then**
8:     Repeat steps 1-5
9: **end if**=0

The actual testing video is included in the submission with the report. The results obtained from the testing of the robot are as follows [I]:

TABLE I: Results

Parameter	Value
Stroke of the actuator	5 cm
Force of the actuators (Max)	0.981 N
Minimum diameter it can squeeze into	7 cm
Max bending angle of Pneu-Net	180°
Max bending angle pressure	145 kPa

IX. Conclusion and Broader Impacts

Soft robotics is an emerging field that combines engineering, biology, and materials science to create flexible, adaptable machines that mimic the dexterity of living organisms. Through the design and manufacturing of the Headless Frankenstein, we have demonstrated some promising capabilities of pneu-net soft robot technology.

The Headless Frankenstein leverages elastic materials like Dragonskin-30 and Ecoflex-30 to achieve remarkable flexibility, resilience, and locomotion abilities. Its ability to move smoothly, navigate tight spaces, and adapt to challenging environments shows the potential advantages of soft robotic systems over traditional rigid robots.

While my work focused on one application, the implications of soft robotics reach far beyond. From surgical applications to search-and-rescue, from underwater exploration to manufacturing, the versatility of soft robots expands what is possible compared to rigid robots. Soft robotics can serve as an exciting educational tool to spark students' interest in this emerging field. By showcasing the capabilities achieved through bio-inspired design and innovative materials, it can inspire students and engineers to explore the world of soft robotics.

References

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