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Prototyping of Pneumatic Hand Glove for Finger Joint Rehabilitation

Summer Research Internship Report

Submitted by

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1 Introduction

PneuNets actuators, a type of soft robotic actuator, can mimic natural movements. Their design often involves interconnected air chambers that inflate and deflate to generate motion. This research focuses on the development of a soft robotic glove utilizing PneuNets actuators for finger joint rehabilitation.

Our objective for this project is to make a prototype of a pneumatic hand glove for finger joint rehabilitation. The first question that comes to our mind is who are the intended customers for this product. According to the Indian Council of Medical Research, stroke is regarded as the sixth leading cause of disability in India, and significantly impacts the physical health and abilities of a person. Patients who have had a stroke or other brain trauma frequently experience flexion spasm, loss of active grasping, flexion/extension of hands, finger opposition movement, trouble extending their metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, as well as perform activities of daily living (ADLs).

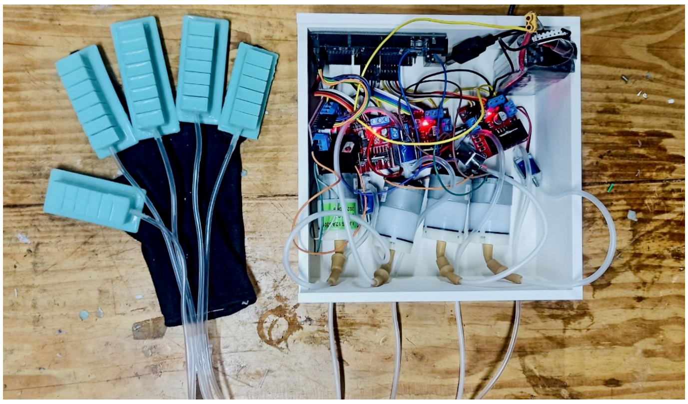


Figure 1: Final Prototype

Clinical physical therapy typically uses assistance from a physiotherapist to passively decrease spasticity in order to treat hand dysfunction by moving the joints of the afflicted hands. However, this rehabilitation process can be labor intensive and needs the availability of the therapist. Thus, an increasingly popular method of delivering such therapy is with the help of robot-assisted glove/hand, which is yet another use of soft robotics outside of training tools, that acts as a daily assistive gadget that positively impacts the functional independence of people with disability. Although the field of prosthetics and orthoses has seen considerable development in the past decades, the technology has not been able to reach the masses due to its high cost, non-portability, and heavyweight.

Our research focuses on bringing a solution to this problem by designing a soft robotic glove using advanced materials and techniques that make it comfortable and reliable. The body of the glove will be manufactured by using silicone due to its flexibility and high performance.

2 Design of Actuators

The PneuNet actuator that we designed using CAD softwares like SolidWorks / Fusion consists of a series of chambers arranged in a row, where the thinnest wall sections are those between each chamber and the next. The strain-limiting layer is a piece of paper embedded in the base. When the device is inflated, the chambers expand, and the thin walls between the chambers bulge out the most. This would cause the actuator to expand in the axial direction, but since the strain-limiting layer does not expand, the actuator bends instead. The actuator consists of two parts: the main body, which expands when inflated, and a base containing the inextensible paper layer embedded in elastomer. To build this actuator, the main body and the base are cast separately and then glued together. The base of the actuator is a simple rectangular plate. The more complex main body is cast in the two-part mold. we designed CAD models of actuators with 8 air chambers for middle finger , 7 for Ring and Index finger , 6 for Ring Finger and 5 chambers for thumb such that min. 2 degrees of freedom is provided by the actuators

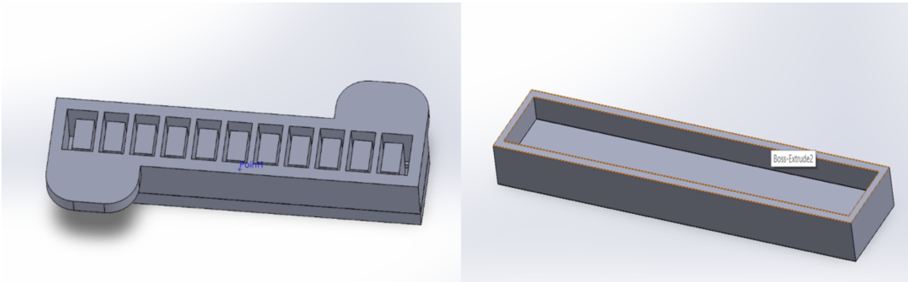


Figure 2: CAD model

2.1 Material Selection

Material stiffness affects how much pressure is required to make the actuator bend. High strain/low durometer (stretchy) materials will deform more for a given pressure than low strain/high durometer (rigid) materials.

Figure 3: Mold Star 15

2.2 Fabrication

An overview of the fabrication process that we followed is listed below:

- **Prepare Elastomer**: We use Mold Star 15 (Silicon Rubber Material) for the fabrication of PneuNet actuators. It is mixed in 1:1 ratio (by weight) of Part A and Part B. For first sample , we poured into cup 50 g each of part A and Part B of mold star. Weighed the material using Weighing machine so that to get each part amount in exact amount. And then mixed the two parts for 5 minutes uniformly to remove air bubbles.

- **Pour Elastomer**: Then Slowly poured the mixture into the main chamber mold, making sure that each chamber fills up. Then filled the base mold to half of its depth with Mold Star tilting the mold until it is evenly spread out. Then degassed the mold to remove the bubbles or used the tip of a spatula to pop the bubbles that have been drawn to the surface ,as unpopped bubbles may cure and show up in the final product. Then added the piece of paper on top of the mold star of base mold (act as strain limiting layer). Then left it to cure for 4 hours at room temperature.

- **Assemble Actuator**: Once the elastomer is cured, slowly pull the mold pieces apart and remove the main body from it. This material is hyperelastic , so it didnt teared easily when pulled out from the molds. Then filled the remaining half of the base mold with uncured elastomer and using this uncured elastomer as glue, we bonded the main body piece to the base. Then left the two pieces to cure for 4 hours and when it was cured , demolded the final actuator.

- **Connect Air Source**: Then made a hole for tubing at the one end of actuator using a thin metal rod and aim the rod slightly downwards to reach the central channel without puncturing any of the actuators walls. Then inserted silicon tubing of 2mm inner diameter . At one end and tested it using air pump of 5V. Also repaired the leaks present in some actuators with some extra mixed elastomer.

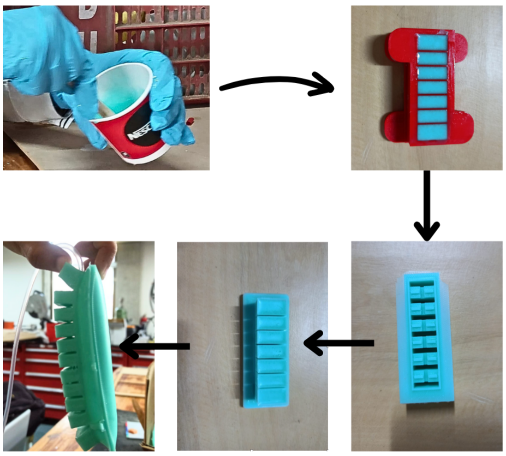


Figure 4: Fabrication Process

2.3 Assembly with Glove

To interface with the patients, the five pneumatic actuators were strategically placed on the cotton glove to align with the finger positions, ensuring each actuator can replicate the bending and extension of the corresponding finger. The actuators were securely fixed onto the glove using the Silpoxy glue.

Figure 5: Assembly with Glove

3 Hardware Overview

We used a combination of microcontroller units, motor drivers, air pumps, and air valves to control the actuators for finger joint rehabilitation. Below is a detailed overview of the hardware components used:

- **Arduino ATMega 2560**: The Arduino Mega 2560 is the central microcontroller used in this project. It provides the necessary processing power and I/O capabilities to control the various components of the pneumatic hand glove.
- **L298N Motor Drivers**: Five L298N motor drivers are used to control the air pumps and valves. Each motor driver is responsible for driving one air pump and one air valve. The L298N is a dual H-Bridge motor driver that can control the direction and speed of two DC motors independently.
- **12V DC Air Pumps**: Five 12V DC air pumps are used to generate the necessary air pressure for actuating the pneumatic components of the glove. Each air pump is controlled by an L298N motor driver and is responsible for one actuator.
- **12V DC Air Valves**: Five 12V DC air valves are used to regulate the airflow to the actuators. Each air valve is paired with an air pump and controlled by an L298N motor driver. The air valves ensure precise control of air pressure to the actuators, enabling accurate finger joint movements.

Figure 6: Hardware Used

4 Hardware Configuration

The hardware connections are designed to ensure seamless communication and power distribution across all components. The Arduino Mega 2560 microcontroller is at the heart of the system, providing control signals to each of the five L298N motor drivers. Each motor driver is responsible for one actuator, consisting of an air pump and an air valve. The air pumps and valves are connected in pairs, with the motor driver regulating their operations based on the control signals from the Arduino. The battery provides the power supply, connected to the motor drivers and subsequently to the pumps and valves, ensuring they receive the necessary 12V for operation. The air pumps are connected to the air valves, which are then connected to the actuators in the glove. This configuration allows the Arduino to control the inflation and deflation of the actuators, enabling precise and coordinated movements of the fingers for rehabilitation purposes. .

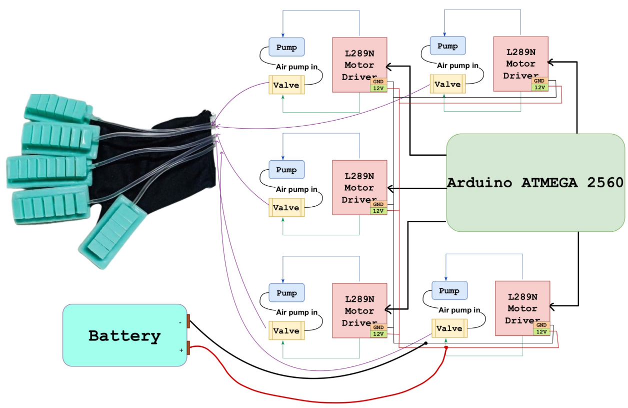


Figure 7: Block Diagram

5 Assembly of Control Unit

The assembly of the control unit for the pneumatic hand glove involves integrating all the hardware components into a compact and organized system. The control unit is housed in a robust enclosure, which contains the Arduino Mega 2560 microcontroller, five L298N motor drivers, five 12V DC air pumps, five 12V DC air valves, and a switch for controlling the power supply.

The Arduino Mega 2560 is securely mounted in the enclosure, with its pins connected to the respective motor drivers. Each motor driver is also firmly placed inside the enclosure, with connections made to both the air pumps and air valves. The air pumps and air valves are positioned to ensure efficient airflow and minimal obstruction. The air tubes from the pumps and valves are routed neatly to connect to the actuators in the glove.

A switch is included in the system to control the power supply, enhancing the usability and safety of the device. The switch allows for easy powering on and off of the control unit, providing an additional layer of control for the user.

Power supply connections are made to the battery, which is also housed in the enclosure, providing a stable and uninterrupted power source to the entire system. Wiring is carefully managed to avoid tangling and ensure clear paths for signals and power.

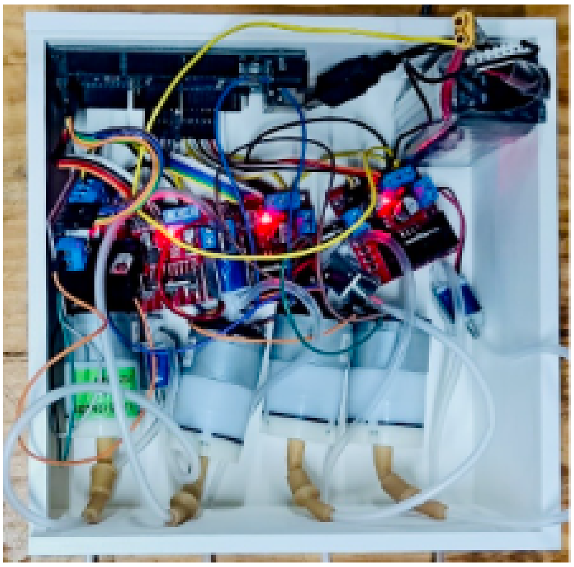


Figure 8: Control Unit

This organized assembly not only ensures the reliability and efficiency of the control unit but also facilitates easy maintenance and troubleshooting. The compact design allows for portability and ease of use, making the pneumatic hand glove an effective tool for finger joint rehabilitation.

6 Testing

The grasping force of elastic pneumatic finger can easily be controlled by adjusting the flow control valve to change the supplied air pressure. We performed the experiment to check the ability of the soft pneumatic robotic glove to hold objects. We tested the pneumatic glove by holding and grasping the objects of different sizes and shapes , weighing from 30 grams to 200 grams. Experimental results showed that the soft pneumatic robotic glove lifts small and medium-sized objects from 30 grams to 180 grams. However, for a heavy target weighing ¿280 grams, we can still maintain lifting the object for a short time (about 5 seconds) since its weight is larger than the soft fingers pressure force.

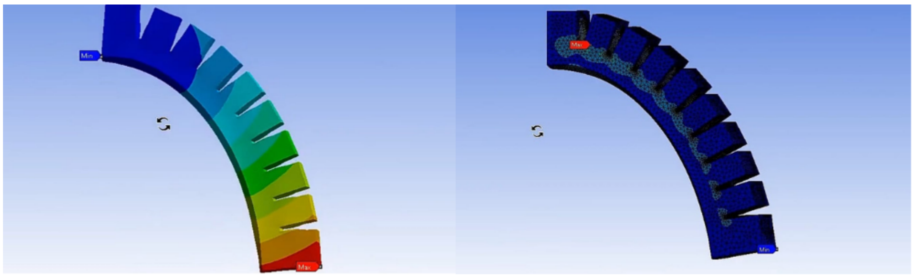
Figure 9: Testing

7 Results and Analysis

7.1 FEM Analysis

Finite Element Method [FEM] analysis has been conducted in ANSYS environment, on a 3D model of the actuator created with CAD modelling software SolidWorks. This method proved to be a valid approach for testing the soft actuator motion, forces and stresses, before its actual physical production, i.e., in the design phase.

- For the analysis purpose, 2 materials which are chosen are Elastosil Silicon Rubber and Paper. It was tested under two loads: Gravity and Pressure and Yeoh hyperelastic model is utilized for studying the behaviour of an elastomer under external forces.
- Results-The max. Deformation value computed is 9,4023e-002 m. The max. Value of equivalent elastic strain is 0,38154 m/m.



(i) Total deformation (ii) Equivalent Elastics strain

Figure 10: FEM Analysis

7.2 Trajectory of tip of the Actuator

In a test scenario, one actuator of the glove was supplied with air pressure, and the trajectory of the tip of the glove was plotted using video analysis software (Tracker). The analysis involved capturing the movement of the glove's tip as the actuator inflated and deflated, and then plotting the trajectory based on the video frames. This allowed for a detailed study of the actuator's performance and the resulting movement of the glove, providing valuable insights into the behavior of the pneumatic system.

Figure 11: Trajectory

7.3 Maximum Bending Angle

To quantify the performance of the pneumatic actuators in the glove, the maximum bending angle was measured under a pressure of 80 kPa. Using OpenCV, a computer vision library, the bending angle was calculated by analyzing the curvature of the actuated glove finger. In the experiment, one of the actuators was inflated to 80 kPa, and its resulting deformation was captured.The analysis focused on the trajectory of the finger tip and the overall curvature of the actuator. By processing the captured image, OpenCV detected the key points along the bend and computed the angle between the base and the tip of the actuator.
As shown in the above image, the actuator achieved a maximum bending angle of **79**°.

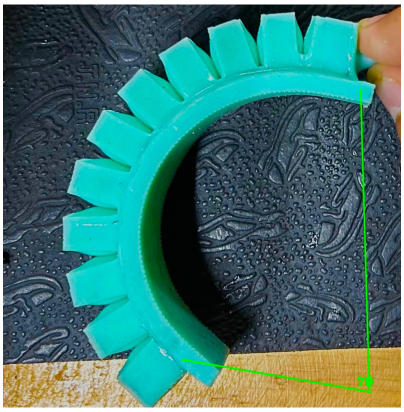


Figure 12: Maximum Bending Angle

8 Code Implementation

The control unit for the pneumatic hand glove is programmed using the Arduino IDE. The code begins with defining the pin assignments for the pumps and valves, which are connected to the Arduino Mega 2560. Each pump and valve is controlled through specific pins, and these pins are declared as outputs in the setup function to prepare them for sending control signals. The loop function contains the core logic for the operation of the glove. Initially, all pumps and valves are turned on by setting the respective enable pins to high and low, respectively. The direction of the pumps and valves is controlled by setting the direction pins accordingly. A delay is introduced for testing purposes, after which all pumps and valves are turned off to complete one cycle of operation. This setup allows for precise control of the pneumatic actuators in the glove, facilitating effective finger joint rehabilitation through controlled inflation and deflation of the actuators.

8.1 Code Snippet

```
// Pin definitions for the pumps and valves
const int pumpIn1 = 9;
const int pumpIn2 = 10;
const int valveIn1 = 11;
const int valveIn2 = 12;
const int pumpIn3 = 3;
const int pumpIn4 = 4;
const int valveIn3 = 5;
const int valveIn4 = 6;
const int pumpIn5 = 28;
const int pumpIn6 = 30;
const int valveIn5 = 24;
const int valveIn6 = 26;
const int pumpIn7 = 40;
const int pumpIn8 = 42;
const int valveIn7 = 36;
const int valveIn8 = 38;
const int pumpEnable1 = 8;
const int pumpEnable2 = 2;
```

```
const int pumpEnable3 = 32;
const int pumpEnable4 = 44;
const int valveEnable1 = 13;
const int valveEnable2 = 7;
const int valveEnable3 = 22;
const int valveEnable4 = 34;

void setup() {
  // Set motor driver pins as outputs
  pinMode(pumpIn1, OUTPUT);
  pinMode(pumpIn2, OUTPUT);
  pinMode(valveIn1, OUTPUT);
  pinMode(valveIn2, OUTPUT);
  pinMode(pumpIn3, OUTPUT);
  pinMode(pumpIn4, OUTPUT);
  pinMode(valveIn3, OUTPUT);
  pinMode(valveIn4, OUTPUT);
  pinMode(pumpIn5, OUTPUT);
  pinMode(pumpIn6, OUTPUT);
  pinMode(valveIn5, OUTPUT);
  pinMode(valveIn6, OUTPUT);
  pinMode(pumpIn7, OUTPUT);
  pinMode(pumpIn8, OUTPUT);
  pinMode(valveIn7, OUTPUT);
  pinMode(valveIn8, OUTPUT);
  // Set enable pins as outputs
  pinMode(pumpEnable1, OUTPUT);
  pinMode(valveEnable1, OUTPUT);
  pinMode(pumpEnable2, OUTPUT);
  pinMode(valveEnable2, OUTPUT);
  pinMode(pumpEnable3, OUTPUT);
  pinMode(valveEnable3, OUTPUT);
  pinMode(pumpEnable4, OUTPUT);
  pinMode(valveEnable4, OUTPUT);

  // Initialize serial communication
  Serial.begin(9600);
}

void loop() {
  // Turn on all pumps
  digitalWrite(pumpEnable1, HIGH);
  digitalWrite(pumpEnable2, HIGH);
  digitalWrite(pumpEnable3, HIGH);
  digitalWrite(pumpEnable4, HIGH);

  // Turn on all valves
  digitalWrite(valveEnable1, LOW);
  digitalWrite(valveEnable2, LOW);
  digitalWrite(valveEnable3, LOW);
  digitalWrite(valveEnable4, LOW);

  // Control the direction of the first pump and valve
  digitalWrite(pumpIn1, HIGH);
  digitalWrite(pumpIn2, LOW);
  digitalWrite(valveIn1, HIGH);
```

```
  digitalWrite(valveIn2, LOW);
 // Control the direction of the second pump and valve
  digitalWrite(pumpIn3, HIGH);
  digitalWrite(pumpIn4, LOW);
  digitalWrite(valveIn3, HIGH);
  digitalWrite(valveIn4, LOW);
 // Control the direction of the third pump and valve
  digitalWrite(pumpIn5, HIGH);
  digitalWrite(pumpIn6, LOW);
  digitalWrite(valveIn5, HIGH);
  digitalWrite(valveIn6, LOW);
 // Control the direction of the fourth pump and valve
  digitalWrite(pumpIn7, HIGH);
  digitalWrite(pumpIn8, LOW);
  digitalWrite(valveIn7, HIGH);
  digitalWrite(valveIn8, LOW);

  // Add a delay for testing purposes
  delay(4000);

  // Turn off all pumps and valves
  digitalWrite(pumpEnable1, LOW);
  digitalWrite(pumpEnable2, LOW);
  digitalWrite(pumpEnable3, LOW);
  digitalWrite(pumpEnable4, LOW);

  digitalWrite(valveEnable1, HIGH);
  digitalWrite(valveEnable2, HIGH);
  digitalWrite(valveEnable3, HIGH);
  digitalWrite(valveEnable4, HIGH);

  // Add a delay for testing purposes
  delay(4000);
}
```

9 Drawbacks

The following are the drawbacks in the present design of the glove:

- The finger movements after wearing the glove is limited to only flexion-extension and it does not provide support for abduction-adduction.
- The thumb actuation was unsuccessful due to unavailability of an air pump and air valve.
- As this glove provides assistance passively, it can be used for patients who have lost their complete hand function to regain hand movement and perform grasping task.
- The glove cannot be used for rehabilitation exercises that target movement of a single digit or combination of two-three digits.

- The control system is an open loop system, thus not supporting real-time feedback functionality.

10 Work Contribution

In this project, I played a pivotal role in designing the control unit for the pneumatic glove. I ensured the work was equitably distributed among all team members, fostering an efficient and collaborative environment. I conducted the analysis to determine the maximum bending angle of the actuator under 80kPa using OpenCV, and I meticulously plotted the trajectory of the actuator tip using Tracker software. Additionally, I assisted in the documentation process and contributed to creating the poster for the final presentation, encapsulating the project's key findings and developments.

11 Future work

The present project can be modified by the actuators design specifically for each finger joint and then actuating each of them with an air supply, thereby increasing the Degree of Freedom. Thus, on a digit there will be three small actuators each assigned to move metacarpophalangeal joint(MCP), Proximal interphalangeal joint(PIP), Distal interphalangeal joint(DIP), separately. Further research can be done on minimising the control system by reducing the number of motor drivers and using a single air source with high supply capacity. Sensors can be incorporated to provide real-time feedback ensuring effective control over air supply and for providing important data on force generated and bending angle, which can be useful for the medical supervisor to determine the patient's progress. Rotating actuators can be designed and connected, to support different hand movements thereby, increasing the Degree of Freedom (DOF).

12 Conclusion

The work provides a cost-effective, portable and customizable pneumatic hand glove design which can be further refined for its application in the medical field. The cost effectiveness of the solution can be explained in terms of the fabrication of PneuNets actuators, which was done using silicon rubber that is widely available in the market at low-cost. The mold design for fabricating the actuators can be modified as per requirements thus making it customized for different finger sizes. The project also emphasizes the effectiveness of soft-robotics as a light-weight, flexible, and safe solution to mimic human movements and satisfy various needs in the field of rehabilitation.

13 Acknowledgement

We would like to express our heartfelt appreciation to our advisor, Prof. Aniruddh Mali, for his invaluable guidance and assistance throughout our internship. His insights and support were instrumental in the successful completion of this prototype.

We are also deeply grateful for the facilities provided at Maker Bhawan, which played a crucial role in the completion of our project. The resources and environment at Maker Bhawan significantly contributed to our learning experience and the development of our prototype.

Furthermore, we extend our thanks to IIT Gandhinagar and Maker Bhawan for offering us this Research Internship Program. The opportunity to participate in this program has been an enriching and rewarding experience, and we are grateful for the knowledge and skills we have gained.

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