



ADVANCING PROSTHETIC ARM CONTROL: AN EMG-BASED GRASP FORCE ESTIMATION TOWARDS ANTHROPOMORPHIC MOVEMENT

¹M Suresh , ²Sharanya R , ³Pooja S N, ⁴R Noothana Prasad, ⁵Mandara T A

¹Professor , ²Student, ³Student, ⁴Student, ⁵Student

¹Department of Electronics and Communication Engineering,
RajaRajeswari College of Engineering ,Bangalore-560074, Karnataka, India

Abstract: Prosthetic arms have significantly improved the quality of life for individuals with amputations, enabling them to regain functionality. However, a critical challenge persists: controlling the precise amount of force when interacting with objects. This project addresses the issue by integrating Electromyographic (EMG) signals, voice commands, flex sensors, and fire sensors into a prosthetic system. The EMG signals are utilized to estimate the user's intended force, enabling the prosthetic to adapt its grip to handle soft objects delicately and firm objects securely, mimicking natural hand functionality. The voice command interface allows for the execution of complex hand movements with greater accuracy by combining muscle signals and spoken instructions, ensuring seamless and intuitive control. Additionally, flex sensors are incorporated to detect the bending of fingers, providing real-time feedback on hand positioning and enhancing the system's ability to perform intricate tasks. A fire sensor is integrated as a safety feature, enabling the prosthetic to detect and respond to hazardous heat or fire situations, thereby protecting the user from potential injuries. This multifaceted design ensures the prosthetic arm offers users improved control, precision, and safety. By allowing users to perform a wide range of tasks with the appropriate force and accuracy, the system enhances their independence and overall quality of life.

Index Terms - Prosthetic Arm , Electromyographic Signals , Voice Command Control , Force Control, Adaptive Grip Mechanism

I. INTRODUCTION

Prosthetic hands have come a long way in empowering individuals with upper limb disabilities, allowing them to regain functionality and perform daily tasks with increased independence. Modern prosthetic devices are designed to restore mobility and precision while integrating advanced technologies to improve user experience. Despite these advancements, a major limitation persists in many systems—most rely on a single mode of control, such as myoelectric signals or manual input. This restricts their usability, especially for individuals with specific physical impairments or varying needs. This project seeks to overcome these challenges by introducing a prosthetic hand that integrates gesture based, voice-based, and EMG-based controls. These multimodal input options enhance the flexibility and accessibility of the device, allowing users to operate it in a way that best suits their individual capabilities and preferences. Gesture control offers an intuitive approach by recognizing movements from the user's residual limb, while EMG-based control leverages muscle signals to provide precise and responsive operation. Voice-based commands add a hands-free alternative, enabling ease of use in scenarios where physical input may be limited. The project aims to bridge the gap between functionality and accessibility by offering a prosthetic hand that is intuitive, user-

friendly, and adaptable. By focusing on multimodal controls and modular design, this innovation not only enhances usability but also holds the potential to transform prosthetic solutions for a wide range of users.

II.METHOD

A. System Design

The prosthetic control system is designed to ensure intuitive functionality, precise movements, and enhanced safety by integrating sensors, actuators, communication modules, and a power management system, all controlled by the Raspberry Pi Pico. The Raspberry Pi Pico was chosen as the central microcontroller due to its dual-core ARM Cortex-M0+ processor, multiple GPIO pins, low power consumption, and real-time processing capabilities, making it suitable for handling sensor inputs, signal processing, and motor control. The system incorporates three primary sensors: a flex sensor to detect finger bending and angular movements, an EMG sensor to capture muscle activity and translate it into prosthetic movements, and a fire sensor to monitor temperature levels and trigger alerts for safety. Actuation is managed by a DC motor, which provides high-torque movements for overall prosthetic motion, and servo motors, which enable precise control of finger and wrist articulation. A motor driver circuit ensures efficient power distribution and smooth actuator control. To enhance user interaction, a Bluetooth module is integrated for wireless communication, allowing real-time control and feedback through a smartphone or external device, while a display module provides visual updates on system status. The power supply is regulated through a Switch-Mode Power Supply (SMPS) to ensure stable voltage distribution, preventing disruptions in performance, with additional safety features such as fuses and overcurrent protection to safeguard the hardware. The software, developed in Embedded C, processes sensor inputs, executes motor control using Pulse Width Modulation (PWM) for precise movements, and manages Bluetooth-based communication for seamless user interaction. Extensive testing and calibration are performed to ensure sensor accuracy, motor efficiency, and overall system reliability. By integrating these components into a cohesive system, the prosthetic arm achieves natural movement, intuitive control, and improved safety, making it an efficient and user-friendly assistive technology.

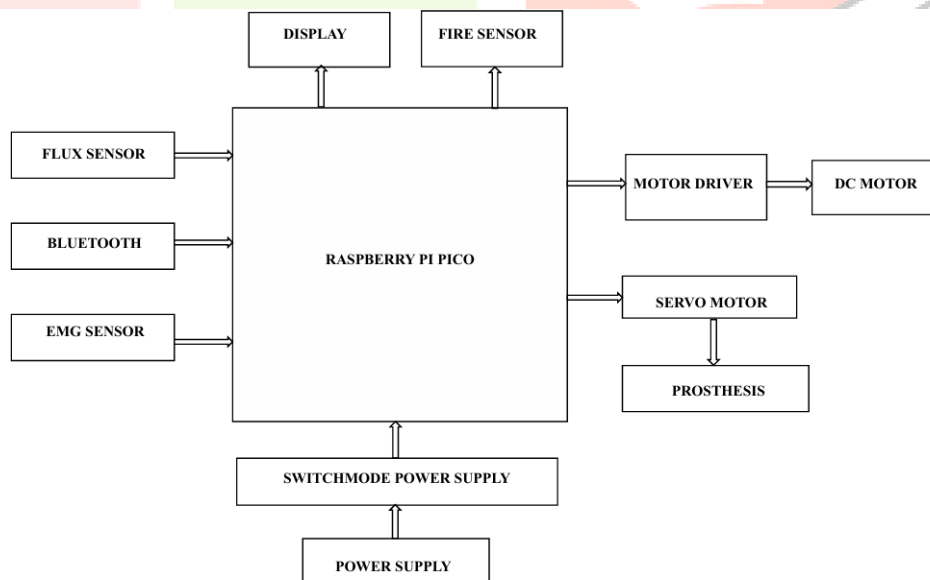


Fig 1. Block Diagram

B. Component Selection and Integration

The prosthetic control system is designed using the Raspberry Pi Pico as the central microcontroller due to its dual-core ARM Cortex-M0+ processor, multiple GPIO pins, and peripheral support, making it ideal for real-time processing and control. The system integrates three primary sensors: a flex sensor to detect bending and angular movements, enabling natural finger motions; an EMG sensor to read muscle activity and provide intuitive control based on user contractions; and a fire sensor to detect high temperatures or fire hazards, ensuring user safety. Additionally, a Bluetooth module is incorporated to enable wireless communication, allowing real-time interaction with external devices. The actuators consist of a DC motor for high-torque

movements and a servo motor for precise control of finger and wrist actions. A motor driver circuit is used to regulate power and control motor operations efficiently. Each sensor and actuator is carefully interfaced with the Raspberry Pi Pico's GPIO pins, ensuring seamless data acquisition and responsive prosthetic movements. The integration of these components creates a robust and efficient control system, enhancing both usability and safety.

C. Signal Processing and Actuator Control

The prosthetic control system relies on efficient signal processing to interpret sensor inputs and generate precise actuator movements. The EMG sensor captures muscle activity by detecting electrical signals generated by muscle contractions. These low-level signals are amplified, filtered, and processed to extract meaningful data that determines the user's intended movement, such as opening or closing the prosthetic hand. The flex sensor detects bending angles and produces an analog output, which is converted into digital values by the Raspberry Pi Pico, allowing for smooth and natural prosthetic motion. The fire sensor continuously monitors temperature levels, triggering alerts and safety mechanisms if hazardous heat conditions are detected. Once processed, these sensor signals are mapped to corresponding motor commands, ensuring intuitive and responsive control.

The system utilizes DC motors for high-torque movements, enabling the prosthetic to perform tasks requiring strength, such as lifting objects. Servo motors are used for precise articulation of fingers and wrist movements, allowing delicate and intricate actions. A motor driver circuit regulates power and control signals, ensuring efficient energy distribution and preventing motor overload. Pulse Width Modulation (PWM) is employed to control motor speed and position, enabling fine-tuned adjustments for smooth and natural movements. The Raspberry Pi Pico continuously processes real-time sensor data, adjusting motor responses dynamically to match user intentions. Additionally, feedback mechanisms help refine motor control, improving accuracy and responsiveness. By integrating robust signal processing with efficient actuator control, the system ensures a seamless, natural, and user-friendly prosthetic experience, allowing for both precision and strength in movement execution.

D. Power Management

The power management system is a critical component of the prosthetic control system, ensuring stable and efficient operation of all integrated sensors, actuators, and communication modules. The system is powered by an external power source, which is regulated using a Switch-Mode Power Supply (SMPS) to provide stable voltage levels and prevent fluctuations that could affect performance. The Raspberry Pi Pico, sensors, and communication modules operate at 3.3V, while the actuators, such as the DC motor and servo motor, require higher voltage levels (typically 5V–12V). A voltage regulation circuit is implemented to distribute the appropriate voltage to each component, ensuring optimal performance without overloading the system.

To handle varying power demands, particularly from high-current actuators like the DC motor, the power supply is designed to deliver sufficient current without voltage drops, maintaining system stability. A motor driver circuit is used to control the power delivered to the motors, preventing excessive current draw and enabling smooth motion transitions. Additionally, power-saving techniques such as PWM (Pulse Width Modulation) are employed to efficiently regulate motor speed and reduce unnecessary power consumption.

For enhanced reliability, safety mechanisms such as fuses, overcurrent protection, and thermal shutdown circuits are incorporated to protect the system from potential faults like short circuits, overheating, or excessive current draw. A battery backup system may also be integrated to ensure continued operation in case of power failures, improving overall dependability.

The power management system is rigorously tested under different load conditions to verify efficiency, ensure uninterrupted operation, and enhance the longevity of the prosthetic device. By implementing a robust and efficient power management system, the prosthetic arm maintains consistent performance, energy efficiency, and long-term reliability, ensuring safe and effective operation for the user.

E. Software and Control Algorithm

The core functionality of the system is governed by the software running on the Raspberry Pi Pico, which processes sensor inputs and generates appropriate outputs for actuator control. The control algorithm is developed in Embedded C, leveraging the microcontroller's real-time processing capabilities. For the flex sensor, the algorithm translates bending angles into corresponding movements, allowing the prosthetic to mimic natural finger motions.

The EMG sensor data is analyzed to detect muscle activity and determine user-intended actions, such as opening or closing the prosthetic hand. The fire sensor is programmed to trigger alerts upon detecting hazardous temperature levels, ensuring user safety. Additionally, Bluetooth communication is integrated, enabling real-time feedback and remote control via an external device.

The motor control logic is implemented using Pulse Width Modulation (PWM) to drive both DC motors for high-torque operations and servo motors for precise finger and wrist movements. The combination of these software components ensures smooth, responsive, and intuitive operation of the prosthetic system, enhancing both mobility and user experience.

F. Flow Chart

The prosthetic control system developed using the Raspberry Pi Pico follows a structured operational flow to ensure real-time responsiveness, accessibility, and safety. The flowchart represents the step-by-step execution of system functions, allowing the prosthetic to process multiple inputs and respond accordingly. The system starts with an initialization phase, where the Raspberry Pi Pico is powered on, and essential components, including sensors (motion, fire detection, etc.), motor drivers, and communication modules, are activated. Voice command processing is also initialized to enable hands-free control. Once initialized, the system enters a continuous monitoring phase, where it actively checks for three main types of inputs: Voice Commands, Motion Sensor Input and Fire Detection

Voice Commands – If a voice command is detected, it is processed using a speech recognition module. The system then maps the command to a predefined action, such as moving the prosthetic in a specific direction or adjusting grip strength.

Motion Sensor Input – If motion is detected, the system interprets the sensor data to determine the intended movement. Based on this input, the motor driver is activated to replicate the required movement in the prosthetic.

Fire Detection – Safety is a critical aspect of the system. If the fire sensor detects potential danger, the system triggers an emergency alert, stops all ongoing prosthetic movements, and may notify the user to take necessary precautions.

The system continuously loops through these steps, ensuring real-time updates and responsiveness to the user's needs. If a shutdown command is received (either manually or due to an emergency), the system safely deactivates all components, ensuring a controlled termination of operations. The modularity of the system allows for customization and adaptability, making it suitable for various user needs. The integration of voice control and sensor-based input ensures accessibility for users with different mobility limitations. The fire sensor adds an extra layer of protection, preventing hazardous situations.

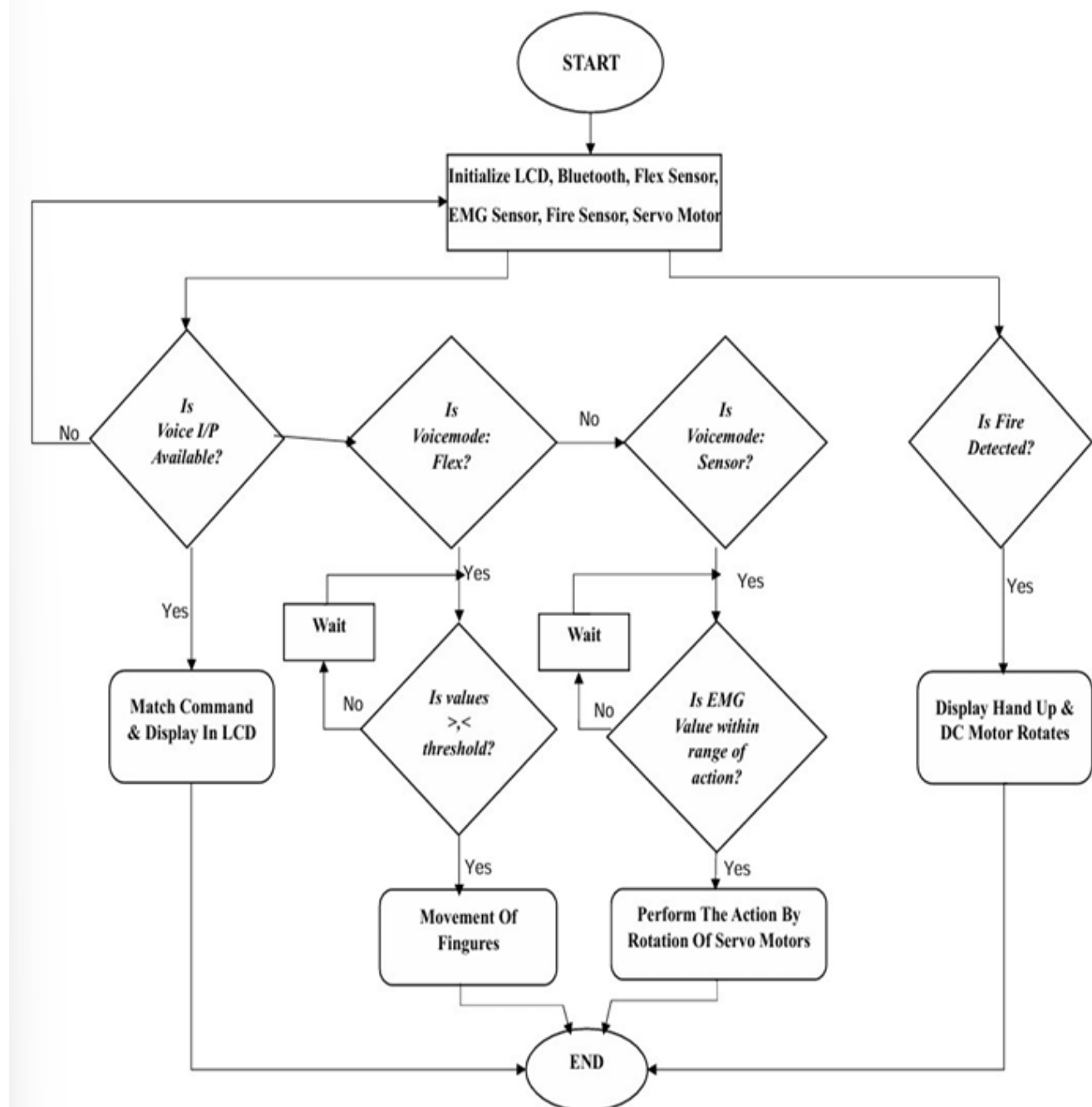


Fig 2. Flow Chart

G. System Testing and Calibration

System testing and calibration are essential to ensure the prosthetic arm operates with precision, reliability, and safety. The testing phase involves validating individual components, performing system integration tests, and conducting user-based evaluations. Sensor calibration is crucial for accurate data acquisition, with the EMG sensor undergoing fine-tuning to detect muscle activity while minimizing noise through gain adjustment and bandpass filtering. The flex sensor is calibrated by mapping its voltage output to specific finger movements, ensuring smooth and proportional articulation, while the fire sensor is tested at various heat levels to set an appropriate activation threshold. Actuator testing ensures that the DC motor delivers the required torque and speed through Pulse Width Modulation (PWM) adjustments while preventing overheating, whereas the servo motor is checked for angular precision and response time to ensure accurate positioning. The motor driver circuit is tested to regulate power distribution and control motor direction efficiently.

Power management testing focuses on the Switch-Mode Power Supply (SMPS), verifying that it consistently supplies stable voltage and current across all components without fluctuations. Safety mechanisms, including overcurrent protection and fuses, are validated to prevent damage during high-power operations. Wireless communication is also assessed by testing the Bluetooth module for stable signal range, low-latency response, and accurate data transmission. Once individual components are validated, system integration tests are conducted to ensure seamless interaction between sensors, actuators, and control mechanisms.

The prosthetic is then evaluated in real-world scenarios, such as gripping objects with varying force and performing delicate tasks to assess fine motor control. Stress testing under prolonged usage is performed to determine the system's durability. Finally, user-based testing is carried out, where individuals operate the prosthetic and provide feedback on comfort, responsiveness, and ease of use. Adjustments are made accordingly to enhance overall performance. By implementing rigorous system testing and calibration, the prosthetic arm achieves high precision, safety, and reliability, offering an intuitive and effective assistive solution for users.

III.RESULT AND OUTCOME

The developed prosthetic hand successfully demonstrates its multi-modal control system, integrating gesture recognition, voice commands, and EMG signal-based operations for enhanced usability and precision. Each input method was rigorously tested for reliability, responsiveness, and accuracy, ensuring real-time actuation of essential hand movements such as gripping, pinching, and releasing. The gesture control system, utilizing flex sensors and an accelerometer, accurately translated hand motions into corresponding prosthetic movements, allowing intuitive control. The voice command interface, implemented through a Bluetooth enabled mobile application, provided seamless execution of commands such as “open hand” or “close hand,” enhancing accessibility for users with limited muscle function. The EMG-based control mechanism effectively detected muscle signals, offering real-time movement execution and high precision, making it particularly beneficial for users with functional nerves.

Beyond control mechanisms, the fire detection system significantly improved user safety by promptly identifying hazardous heat levels and automatically triggering the prosthetic hand to retract in the presence of fire or smoke, preventing potential injuries. The MG90S servo motors played a crucial role in delivering smooth, accurate, and natural hand movements, closely mimicking biological hand functionality. The modular system design facilitated seamless integration of hardware and software components, ensuring a scalable and adaptable architecture. The Raspberry Pi Pico, serving as the system's core, efficiently processed sensor inputs and executed control algorithms, ensuring coordinated and lag-free operation.

The prosthetic hand underwent extensive testing across various real-world conditions, proving its robustness, precision, and ease of use. The ability to combine multiple input modalities provides users with flexibility and convenience, overcoming the limitations of traditional single-input prosthetic hands. Additionally, the system's lightweight design, low power consumption, and affordability make it a practical and accessible solution for individuals with upper limb disabilities. Overall, the project successfully achieved its objectives, offering a highly functional, user-friendly, and safety-enhanced prosthetic solution, significantly improving the quality of life for amputees and individuals with motor impairments.

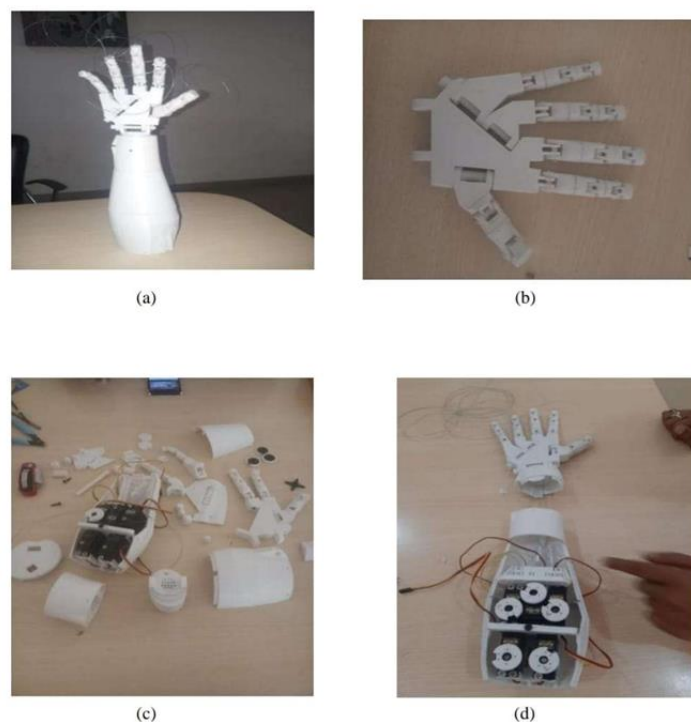


Fig 3. 3D Printed Prosthetic ARM

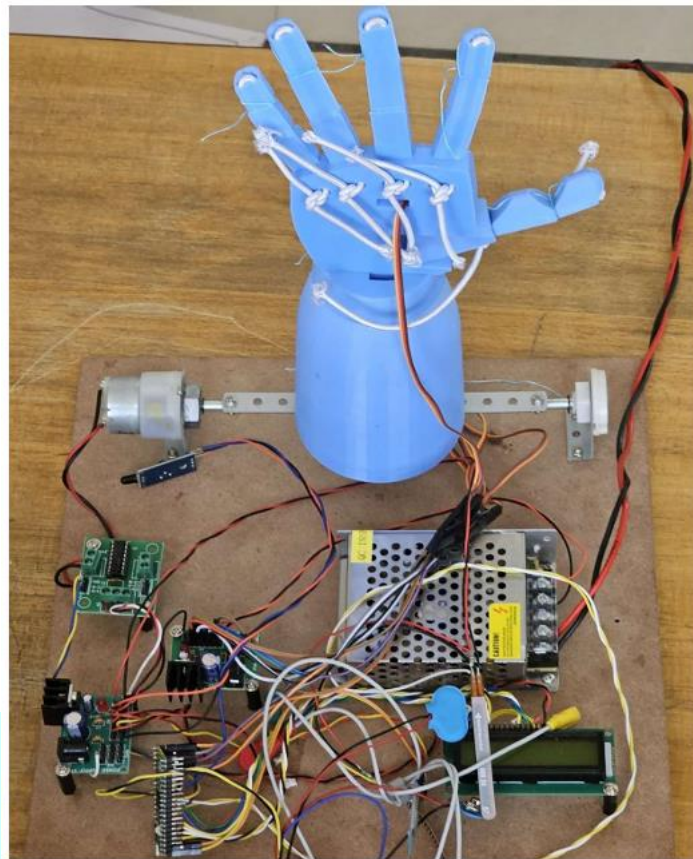


Fig 4. Outcome

IV.CONCLUSION

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