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Muscle Sensor Driven 3D Printed Prosthetic Arm

[1]Prof. Nitinkumar P. Padghan , [2]Mr. Kuldip N. Sapekar, [3]Mr. Mayur S. Sonakneur , [4]Mr. Nilesh M. Masram, [4]Mr. Sanjay R. Lolure, [5]Mr. Saurabh C. Madavi

Mechanical Engineering Department, Suryodaya College of Engineering and Technology, Nagpur

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Abstract

Over the past decade, humanity has pushed beyond its physical and cognitive boundaries, a movement recognized as transhumanism. In the fields of robotics and biomimetics, researchers are leveraging the intricate designs of biological structures to develop highly advanced, human-like artificial appendages. While lower extremity prosthetics have reached a stage where amputees can compete with professional athletes, upper limb prosthetics still lag significantly behind natural human hands in terms of functionality and dexterity.

This paper presents the development of an affordable, lightweight, and durable 3D-printed prosthetic arm designed to bridge this gap. It details the mechanical design, actuator development, and full-motion integration of the prosthetic limb. Furthermore, the study introduces an innovative classification approach that enables intuitive prosthetic control through electromyography (EMG) signals from the residual arm muscles.

By advancing the synergy between humans and machines, this research contributes to the ever-evolving landscape of human augmentation. Additionally, it aims to inspire students and researchers to explore transhumanist studies, utilizing emerging technologies such as bio-signal processing, AI-driven prosthetics, and adaptive control strategies to enhance prosthetic functionality

Introduction

The evolution of prosthetic limbs has seen remarkable progress in recent years, driven by technological advancements and material innovations. Among these breakthroughs, 3D printing has emerged as a transformative technique for crafting customized prosthetic devices, allowing for the creation of lightweight, cost-efficient, and ergonomically optimized limbs tailored to individual user requirements. This method not only meets the increasing need for affordable prosthetics, particularly in underserved regions, but also improves the overall functionality and comfort of the devices.

A fundamental component of contemporary prosthetic systems is the incorporation of electromyography (EMG) sensors, which detect electrical activity produced by muscle contractions. By harnessing EMG signals, prosthetic limbs can achieve intuitive control, enabling users to operate them with enhanced ease and precision. In the proposed 3D-printed prosthetic arm system, an Arduino microcontroller functions as the primary processing unit, interpreting EMG signals and converting them into executable commands for robotic mechanisms. The integration of servo motors facilitates crucial movements, including gripping, clasping, and rotation, effectively replicating the natural hand's capabilities.

This innovative fusion of 3D printing, EMG technology, and servo motor actuation marks a substantial advancement in prosthetic development. It promotes a more seamless interaction between the user and the device while providing a flexible solution that can adapt to evolving user needs.

As prosthetic technology advances, the convergence of these elements represents a crucial milestone in enhancing the quality of life for individuals with limb loss, empowering them to regain independence and efficiently perform daily tasks. The ongoing refinement of this 3D-printed prosthetic arm system aims to bridge the gap between cutting-edge technology and practical application, contributing to the future of accessible and effective prosthetic solutions.

Aim & Objectives

The study on robotic arm control using human forearm EMG signals aims to propose a non-invasive and intuitive control method for robotic systems.

The primary objective is to design and develop a low-cost, lightweight, and functional 3D-printed prosthetic arm that utilizes electromyography (EMG) sensors for precise and intuitive control. By integrating an Arduino microcontroller and servo motors, the system is designed to replicate essential hand movements such as gripping, clasping, and rotating, thereby enhancing the user's ability to perform daily tasks. Additionally, the project seeks to address challenges related to affordability and accessibility, particularly for individuals in developing regions.

Surface electrodes are used to capture EMG signals from forearm muscles, ensuring accurate signal acquisition for effective prosthetic operation.

The system's performance is evaluated based on its ability to control the robotic arm with high accuracy and precision under various conditions, including different levels of muscle fatigue and varying arm positions. Ultimately, the goal is to improve the quality of life for amputees by providing a prosthetic solution that is not only functional but also customizable to meet individual needs. Furthermore, the study demonstrates the potential of using EMG signals as a non-invasive and intuitive control method for robotic systems, with broader applications in rehabilitation, assistive devices, and industrial automation.

Literature Survey

Several research studies have explored the development of cost-effective and functional prosthetic arms using 3D printing, electromyography (EMG) signals, and advanced control mechanisms. In [1], a 3D-printed prosthetic arm was designed to provide an affordable and lightweight alternative to traditional prosthetic devices, addressing accessibility challenges for amputees in developing regions.

The study integrated EMG signals for intuitive control and highlighted future improvements using machine learning to enhance adaptability. Additionally, [2] presented a myoelectric prosthetic arm utilizing an Arduino-based control system with muscle sensor modules to detect EMG signals. The system featured a cable-driven actuation mechanism, enabling intuitive control but requiring refinements to improve grip stability.

Another study [3] introduced a wireless EMG-controlled robotic arm leveraging the nRF24L01 transceiver module for improved mobility and reduced wiring constraints. The system utilized threshold-based signal interpretation to activate servo motors for gripping and releasing functions, with future enhancements focused on refining signal processing for precise movements. Similarly, [4] proposed an EMG-based robotic arm control system incorporating machine learning for signal classification. The system demonstrated high accuracy in movement control, highlighting potential applications in rehabilitation, assistive devices, and industrial automation.

Furthermore, [5] developed a cost-effective haptic prosthetic hand controlled via flex sensors and voice commands. The system employed a five-degree-of-freedom (DOF) design for natural hand movements, though it relied on basic control algorithms, with future advancements aimed at integrating sophisticated sensing technologies. Additionally, [6] introduced a low-cost EMG-based prosthetic hand with multifinger control, addressing limitations of existing high-cost commercial solutions by offering improved dexterity and user adaptability.

These studies demonstrate the effectiveness of 3D printing, EMG signal processing, and machine learning in prosthetic development, emphasizing affordability, functionality, and real-time control. The proposed prosthetic system builds upon these findings, integrating advanced technologies to enhance precision, accessibility, and user experience.

Problem Statement

Developing the most affordable prosthetic hand while ensuring ease of customization and usability is a primary objective.

Cost: Careful selection of components and their quantities plays a crucial role in minimizing expenses without compromising functionality.

Customization: The prosthetic arm must be designed based on the dimensions of the amputated limb for bilateral amputees or the functional arm for unilateral amputees. This ensures a natural fit, helping the user accept and adapt to the prosthetic seamlessly.
Usability: The prosthetic must be user-friendly to enhance the daily life of the amputee, making it intuitive and effortless to operate. [4].

Methodology
A. Electronic Circuit Design
The electronic circuit was initially designed to determine its size, as this information was essential for developing the prosthetic arm. A sensor was incorporated to enable muscle-based control, while motors were chosen based on their size, programmability, and accuracy to facilitate finger movements. The selection process then focused on identifying a suitable microcontroller, followed by the final choice of a battery to power the system.

1. Signal Acquisition
Electromyography (EMG) Sensors: The system begins with the placement of EMG sensors on the user's forearm. These sensors detect electrical signals generated by muscle contractions, which are indicative of the user's intention to move their hand or fingers.
Signal Filtering and Amplification: The raw EMG signals are often noisy and require filtering to eliminate interference. An EMG amplifier circuit processes the signals to enhance their clarity and strength for better analysis.
2. Signal Processing
Analog-to-Digital Conversion: The filtered and amplified EMG signals are then converted from analog to digital format using the Arduino microcontroller's built-in analog-to-digital converter (ADC). This conversion allows the microcontroller to interpret the signals for further processing.
Threshold Detection: The Arduino is programmed to monitor the digital EMG signals. A predefined threshold value is established to determine when the muscle activity is sufficient to trigger specific movements of the prosthetic arm.
3. Control Logic
Control Algorithms: The control logic implemented in the Arduino consists of algorithms that interpret the processed EMG signals. Based on the muscle signals received, the Arduino decides which action to perform, such as gripping or releasing an object.
Movement Mapping: Different patterns of muscle activation correspond to specific movements (e.g., gripping, open hand, pointing). The system is programmed to map these EMG patterns to the desired movements of the prosthetic arm
threaded through the machine, ready to be fed into the knitting mechanism.
4. Actuation Mechanism
Servo Motors: The prosthetic arm is equipped with multiple servo motors that provide the necessary movement for the hand and fingers. Each servo motor is responsible for a specific joint or movement, allowing for intricate motion control.
Real-Time Control: Upon detecting a muscle signal that exceeds the threshold, the Arduino sends signals to the corresponding servo motors to actuate the desired movement.
5. User Training and Feedback
User Calibration: Users may need to undergo a calibration process to fine-tune the sensitivity and responsiveness of the EMG sensors. This ensures the system accurately reflects the user's muscle signals.
Feedback Mechanism: Continuous feedback from the user allows for adjustments in the control algorithms and mapping of movements. This iterative process enhances the user experience and ensures the prosthetic arm meets their specific needs.

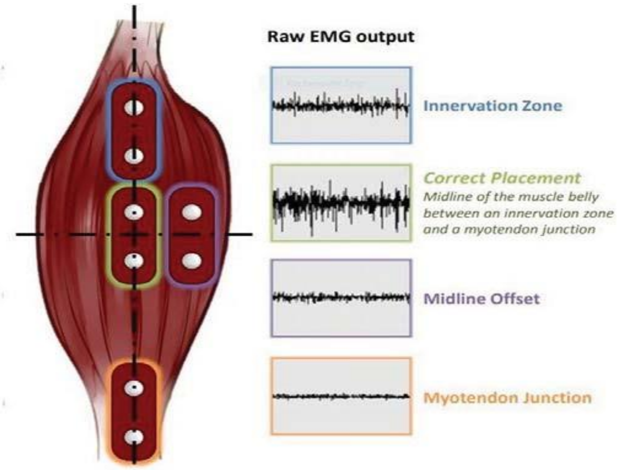

Fig 1: Input of Raw EMG

A servo motor was chosen due to its small size, high power, ease of programming, and accuracy—making it a suitable option for robotics. Initially, 14 motors were assigned, with one for each joint of every finger. To optimize weight and cost, the number was reduced to five motors (one per finger) and later further minimized to just two motors—one for the thumb and one for the remaining fingers. This modification significantly decreased weight and cost while maintaining essential functionality.

A. Selection Of Microcontroller:

The Arduino development board was chosen for its ease of acquisition, coding, and usability. Among the available options, the Arduino Nano was selected due to its compact size, lower cost, and minimal functional difference from the Arduino Uno.

B. Selection of Battery :

An 11.1V, 2200 mAh battery was chosen to meet the system's power requirements, ensuring efficient and reliable operation.

C. Mechanical Design:

To achieve a realistic mechanical design, the exact hand dimensions of team member were used. The design needed to incorporate movement functionality and sufficient space for electronic components while maintaining a natural appearance.

3D-printed parts were chosen over mass-produced factory parts due to their customizability. While factory-produced parts might lower costs, they lack flexibility in adjusting dimensions to meet individual user needs.

CAD Modelling: A software called DesignSpark was used for CAD Modelling. According to the person's hand dimensions and requirements, the CAD files are very adaptable. As seen in Fig 2 and 3.

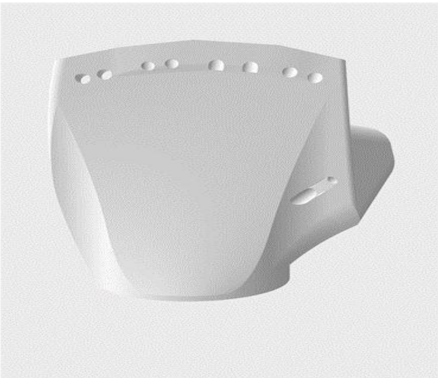

Fig 2: Plam Design

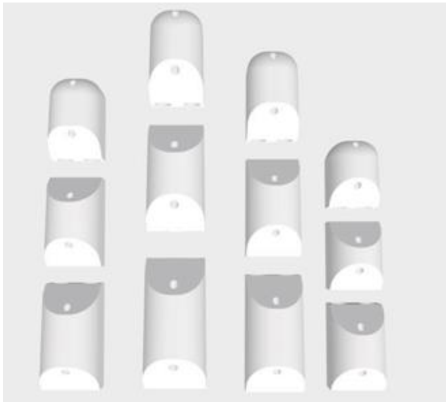

Fig 3: Design of Finger

I. 3D Printing: 3D printed parts are preferred over mass-produced factory parts due to easy customization. A component called PLA, which is a biodegradable polymer, was used. As seen in Fig **5.** This is a lightweight and environmentally friendly material which is cheap and helps to maintain the build cost in the budget. An FDM 3D printer, developed by Stratasys, was used to print the material. The print time was around 50 hours, and the components required only 75 meters of the material. Thus, this method is rapid, efficient, and mass friendly.

Block diagram of system

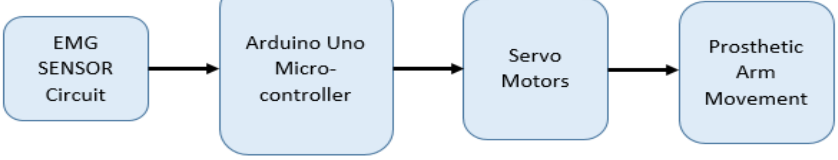

Fig 4: Basic Block Diagram

Project Requirements

1. Hardware Requirements

EMG Sensor: Capable of detecting and amplifying muscle electrical signals. Should support multiple channels to capture signals from various muscle groups.

Arduino Microcontroller: A suitable model (e.g., Arduino Uno or Mega) with sufficient I/O pins for interfacing with the EMG sensor and servo motors. Must support real-time processing of signals and control commands.

Servo Motors: Adequate torque and speed specifications to enable realistic movements of the prosthetic arm joints. At least three servo motors for controlling different joints (e.g., shoulder, elbow, and wrist).

Robotic Arm Structure: A lightweight, durable, and ergonomic design for the arm, preferably made from 3D-printed materials. Mechanisms for easy attachment and removal from the user.

Power Supply: A reliable power source for the Arduino and servo motors (e.g., rechargeable batteries). Voltage and current ratings must meet the requirements of the components.

2. Software Requirements

Arduino IDE: To program the Arduino microcontroller with appropriate control algorithms for processing EMG signals and generating control commands.

Signal Processing Algorithm: Software for feature extraction from EMG signals (e.g., filtering, normalization). Algorithms for real-time classification of muscle signals into corresponding movements.

Control Algorithm: Logic to convert processed signals into control signals for servo motor actuation. Implementation of a Pulse Width Modulation (PWM) control system for precise movement of the robotic arm.

These requirements form the foundation for developing a functional, reliable, and user-friendly 3D-printed prosthetic arm system that utilizes EMG signals for control. Adhering to these requirements will ensure that the system meets the needs of users and functions effectively in real-world applications.

Applications

The 3D-printed prosthetic arm system utilizing EMG sensors and Arduino microcontrollers has a range of significant applications across various fields:

Assistive Technology:

Primarily designed to assist individuals with upper limb amputations, allowing them to regain functionality in daily tasks, such as gripping, holding, and manipulating objects.

Rehabilitation:

Used in rehabilitation settings to help patients regain motor control and improve muscle strength through targeted exercises. The system can provide feedback on muscle activation and performance, aiding in therapy.

Research and Development:

Serves as a platform for researchers and engineers to explore advanced control algorithms, prosthetic designs, and human-machine interaction, contributing to the ongoing development of bio-inspired robotics.

Education and Training:

Offers educational opportunities for students and professionals in fields such as robotics, biomedical engineering, and assistive technologies. The system can be used in academic settings to teach principles of EMG signal processing and robotic control.

Disaster Response and Recovery:

In scenarios where limb loss may occur, such as in combat or industrial accidents, this technology can provide immediate assistance, enhancing the quality of life for affected individuals in emergency situations.

Customization and Personalization:

The ability to 3D print the prosthetic arm allows for customization according to individual user needs, preferences, and anatomical measurements, making it a viable option for users in developing countries where access to conventional prosthetics is limited.

Implementation

Mechanical System:

The mechanical system comprises fishing line, nylon paracord, servo motors, and 3D-printed components such as the hand and fingers. Servo horns attached to the motors are linked to the fingers using fishing line, which is glued to the servo horns. Due to tension in the fishing line, the fingers move when the servo motors rotate. To ensure bidirectional movement, 180-degree rotation motors were selected instead of 360-degree rotation motors.

When the hand closes, the fingers follow suit, but upon opening, they may not fully return to their original position. To retain the natural shape, nylon paracord is used due to its strength and flexibility.

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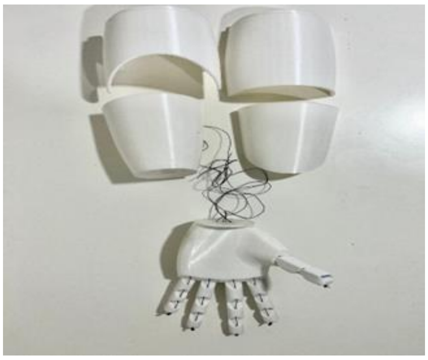

Fig 5: 3D Printed Arm Parts

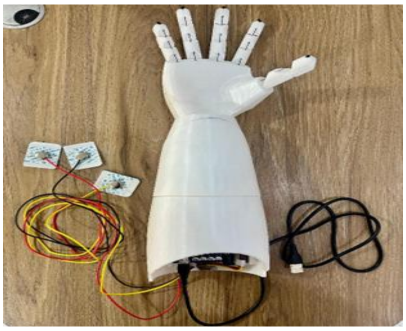

Fig 6.1: Final Assembly

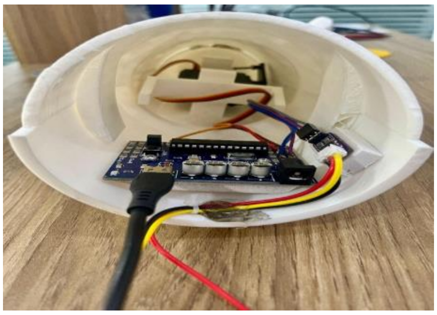

Fig 6.2: Final Assembly

Conclusion

A microcontroller-based bionic arm utilizes electromyography (EMG) signals from skeletal muscles to execute supportive movements, ultimately aiding in the restoration of nerve functions to enable arm movement.

A 3D-printed, Arduino-based bionic arm offers a cost-effective and adaptable solution for individuals with upper limb amputations. 3D printing technology enables the creation of customized prosthetic components, tailored to the user's specific needs and preferences. The Arduino microcontroller ensures precise control and feedback for smooth arm movements.

Furthermore, the open-source nature of both 3D printing and Arduino programming allows for continuous development and improvement as more contributors share their expertise. While challenges remain in enhancing durability and functionality, this technology presents significant benefits, particularly for those who previously lacked access to affordable prosthetic solutions.

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