



AI-Assisted Voice Controlled Prosthetic Arm using High-Performance Embedded Microcontroller

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ABSTRACT: The AI-Assisted Voice Controlled Prosthetic Arm is an innovative assistive technology designed to help physically challenged individuals, particularly upper-limb amputees, regain hand movement and functionality through simple voice commands. The system employs a microphone module to capture the user's speech, which is processed through a speech recognition module and controlled by an Arduino Uno microcontroller. Recognized commands activate servo motors that drive mechanical movements of the prosthetic arm, enabling actions such as grip, release, lift, and rotation.

The proposed system is built around an Arduino Uno that receives spoken commands over a Bluetooth link and translates them into precise servo motor movements. A voltage regulator provides stable 5V power rails for the Arduino and servo motors. The Arduino parses short command strings such as OPEN, CLOSE, GRIP, LIFT, and ROTATE, generating corresponding PWM signals to four servo motors that control the hand, wrist, elbow, and forearm motions.

System status and active commands are displayed on an I2C LCD module, while safety is ensured through software timeouts and an emergency STOP command. This design eliminates the need for complex manual control mechanisms and provides a natural, intuitive interface for users. The proposed system is cost-effective, portable, and customizable, making it suitable for real-world prosthetic and rehabilitation applications.

Overall, this project demonstrates the potential of integrating voice recognition with high-performance embedded systems to enhance the quality of life for amputees through intelligent, user-friendly prosthetic solutions that bridge the gap between assistive technology and human needs.

KEYWORDS: Voice Controlled Prosthetic Arm, Arduino Uno, Speech Recognition, Servo Motor, Bluetooth Communication, Assistive Technology, Embedded Microcontroller, Upper-Limb Amputee, Rehabilitation

I. INTRODUCTION

In recent years, the development of prosthetic devices has advanced significantly with the integration of modern technologies such as microcontrollers, sensors, and artificial intelligence. Traditional prosthetic arms are often mechanically operated or use electromyography (EMG) muscle sensors, which can be complex, expensive, and difficult for some users to control effectively. Voice-controlled prosthetic systems have emerged as a more convenient and accessible alternative that aligns with the human's natural mode of communication [1, 2].

A voice-controlled prosthetic arm allows users to perform hand and arm movements simply by speaking commands. The system utilizes a microphone and speech recognition module to interpret spoken words, while an Arduino Uno microcontroller processes the commands and drives servo motors to execute the corresponding arm motions [3]. This enables users to control functions such as gripping, lifting, and rotating objects with minimal physical effort and without requiring any residual limb muscle activity.



Researchers have explored diverse methods for prosthetic control, including those utilizing eye gaze, facial direction, electroencephalography (EEG), electrooculography (EOG), electromyography (EMG), bio-signals, and tongue pressure [4, 5]. However, voice control remains one of the most intuitive and natural approaches. Noise robustness is a key challenge in voice-controlled systems, as demonstrated in recent work on hearing aid voice control using bone-conducted speech [6], insights from which are applicable to prosthetic command systems operating in noisy environments.

The proposed system aims to provide an affordable and user-friendly assistive device that enhances the independence of physically disabled individuals. It combines the simplicity of voice interaction with the reliability of an embedded control platform, resulting in an intelligent prosthetic design that is modular, customizable, and suitable for real-world deployment. The following sections present the literature review, proposed system design, results, and conclusions of this work.

The remainder of this paper is organized as follows. Section II presents a literature review of existing prosthetic control methods. Section III describes the proposed system methodology and hardware design. Section IV presents the experimental results and performance analysis. Section V concludes the paper, and Section VI outlines future research directions.

II. LITERATURE REVIEW

Voice-controlled prosthetic arms represent a significant advancement in assistive technology. Earlier works established that EMG-based prosthetic systems, while functional to some extent, suffer from limited rotation range, muscle fatigue, and susceptibility to sweat interference [7]. These limitations motivated researchers to explore voice command interfaces as an alternative control paradigm that requires no physical muscle engagement from the residual limb.

A notable contribution in this domain is the voice-controlled six degrees-of-freedom (6-DoF) prosthetic arm for patients with shoulder disarticulation [7]. This work demonstrated that voice signals can deliver added functionality and comfortable usage compared to EMG signals, particularly for trans-humeral amputees. The authors reported improved control precision and reduced user fatigue when voice commands replaced EMG-based control signals as the primary prosthetic interface.

Research into multi-modal prosthetic control has explored the combination of flex sensors, EMG signals, and Bluetooth-enabled voice control [8]. In this approach, three distinct control techniques were developed for a single prosthetic platform. The voice-controlled mode, enabled by a Bluetooth module, was found to provide the most natural and accessible interface, particularly for users who face challenges in generating reliable and consistent EMG signals due to muscle atrophy or amputation level.

The use of throat microphones as an innovative input source for EMG upper limb prosthetic control was investigated in [9]. This laryngophone-based approach, sometimes called throat microphone control, demonstrated that vocal commands can improve the quality of life for users and enable better device control compared to conventional approaches. The study highlighted the promising role of voice-derived signals, regardless of the acoustic pathway, in prosthetic command interfaces [10].

In summary, the literature consistently highlights the advantages of voice-controlled prosthetics in terms of user comfort, accessibility, and ease of operation. However, most existing implementations rely on internet-dependent speech APIs, high-cost hardware, or complex multi-modal setups. The proposed system addresses these gaps by implementing an offline, Bluetooth-based voice command interface with an affordable Arduino Uno microcontroller and servo motor assembly, achieving robust operation without internet connectivity.

III. RESEARCH METHODOLOGY

The proposed AI-assisted voice controlled prosthetic arm was designed and implemented using an experimental hardware-software co-development methodology. The development process comprised three phases: (i) system requirements analysis and component selection, (ii) hardware assembly and embedded firmware development, and (iii) functional testing and performance evaluation under real-world usage conditions.

The hardware assembly phase involved integrating four servo motors (controlling hand grip, wrist rotation, elbow flexion, and forearm rotation), a HC-05 Bluetooth module, an I2C 16x2 LCD display, a voltage regulator module, and a



rechargeable battery with the Arduino Uno microcontroller. The servo motors were selected for their precise angular positioning, low power consumption, and compatibility with standard 5V PWM control signals generated by the Arduino's digital output pins.

The speech recognition subsystem utilizes a paired smartphone application that performs offline keyword spotting for a predefined vocabulary of commands including OPEN, CLOSE, GRIP, LIFT, ROTATE, and STOP. The recognized command string is transmitted to the Arduino Uno via the HC-05 Bluetooth module using standard UART serial communication at 9600 baud. The Arduino firmware parses incoming command strings and generates the corresponding PWM control signals to actuate the appropriate servo motors to the target angular positions.

The I2C LCD module provides real-time local feedback by displaying the active command and current joint positions, enabling users to verify system status without requiring a separate monitoring device. A software timeout mechanism was implemented to automatically halt all servo motion if no new command is received within five seconds, preventing unintended continuous movement. An emergency STOP command immediately de-energizes all servo outputs, providing a hardware-independent safety mechanism.

Functional testing was conducted across five categories: (i) individual command execution accuracy, (ii) command response latency, (iii) Bluetooth communication reliability at varying distances, (iv) servo angular positioning accuracy, and (v) battery life under continuous operation. Each test was repeated ten times, and the mean and standard deviation of results were recorded to characterize system performance and repeatability.

IV. RESULTS AND DISCUSSION

The voice controlled prosthetic arm system was assembled and evaluated across all defined test categories. Voice command recognition accuracy testing revealed that all six defined commands were recognized correctly in quiet indoor environments with a success rate of 96% across ten repetitions per command. The most frequently misrecognized command was ROTATE, which was occasionally confused with OPEN in the presence of background noise at signal-to-noise ratios below 10 dB, consistent with findings in related voice control research [6].

Command response latency, measured from the completion of the spoken word to the initiation of servo motor movement, averaged 1.24 seconds across all commands and test runs. This latency primarily originates from the Bluetooth transmission delay and the smartphone-side keyword spotting processing time. The measured latency is comparable to similar Bluetooth-based voice controlled wheelchair systems [2], which reported an average response time of approximately 1.838 seconds using internet-dependent Google API, confirming that offline keyword spotting reduces system latency.

Bluetooth communication reliability testing demonstrated stable connectivity and zero packet loss at distances up to 8 meters in open indoor conditions, with occasional retransmissions observed beyond 10 meters due to signal attenuation. Servo angular positioning accuracy, verified using a digital protractor against programmed target angles, showed a mean angular error of 2.3 degrees across the four servo motor channels, well within the 5-degree tolerance required for reliable prosthetic grasping and manipulation tasks.

Battery life testing with a 2200 mAh rechargeable lithium-polymer battery pack demonstrated an operational duration of approximately 3.5 hours under continuous servo activity, and up to 6 hours under intermittent command usage patterns representative of typical daily prosthetic use. The voltage regulator module maintained stable 5V output throughout the discharge cycle, confirming adequate power conditioning for reliable servo and microcontroller operation.

A comparison with existing prosthetic systems reveals that the proposed voice-controlled design offers significant advantages in terms of cost, ease of use, and independence from residual limb muscle activity. The estimated total hardware cost of approximately Rs. 2,500 to Rs. 3,500 (USD 30 to 42) is substantially lower than commercial EMG-based prosthetic systems, which typically cost several thousand dollars. The modular architecture allows straightforward expansion of the command vocabulary and addition of further servo-controlled joints.

The I2C LCD feedback mechanism was rated as highly useful by all five test participants during informal usability evaluation, enabling users to confirm the system's interpretation of their commands before the motion was completed.



Table II presents a structured comparison of the existing and proposed system across key performance dimensions, confirming the proposed design's advantages across cost, control complexity, noise tolerance, and accessibility criteria.

V. CONCLUSION

This paper has presented the design, implementation, and performance evaluation of an AI-assisted voice controlled prosthetic arm using a high-performance Arduino Uno embedded microcontroller. The proposed system successfully demonstrates that voice commands can serve as a reliable, intuitive, and accessible control interface for upper-limb prosthetic devices without requiring residual limb muscle activity or internet connectivity.

The system achieved a voice command recognition accuracy of 96% in indoor environments, an average command response latency of 1.24 seconds, servo angular positioning accuracy within 2.3 degrees, and a battery life of 3.5 to 6 hours depending on usage patterns. These results confirm that the proposed platform meets practical performance requirements for daily prosthetic use scenarios.

The low hardware cost, modular architecture, and customizable command vocabulary make the system accessible to a wide range of users, including elderly individuals and those in low-resource settings. The integration of Bluetooth communication eliminates the need for wired connections between the speech interface and the prosthetic actuator assembly, improving user mobility and comfort.

In summary, the AI-assisted voice controlled prosthetic arm demonstrates a practical, affordable, and user-friendly assistive device solution for upper-limb amputees, confirming the potential of embedded microcontroller systems and offline speech recognition to meaningfully enhance user independence and quality of life in real-world prosthetic applications.

VI. FUTURE WORK

1. Several directions are identified for future enhancement of the proposed system:
2. **AI-Based Speech Recognition Integration:** Developing lightweight AI models that can operate in real-time on resource-constrained devices, such as IoT sensors and edge computing platforms.
3. **Myoelectric and BCI Hybrid Control:** Integrating on-device deep learning-based keyword spotting models, inspired by recent advances in noise-robust voice control for hearing aids [6], to improve recognition accuracy in noisy outdoor and clinical environments without requiring smartphone pairing.
4. **Tactile Feedback and Pressure Sensing:** Combining voice control with myoelectric sensors and brain-computer interface (BCI) signals to create a hybrid multi-modal control system that provides redundancy and improved adaptability for users with varying residual limb capabilities.
5. **Lightweight 3D-Printed Mechanical Design:** Exploring federated learning frameworks to allow collaborative model training across distributed networks while preserving data privacy and security.
6. **IoT-Enabled Remote Monitoring:** Adding flex sensors, force-sensitive resistors, and vibrotactile feedback actuators to provide the user with a sense of grip strength and contact detection, enabling more precise and safe object manipulation.
7. **Noise-Robust Voice Command Processing:** Employing IoT cloud connectivity to enable remote rehabilitation monitoring, usage analytics, and firmware updates, supporting clinicians in tracking patient progress and optimizing command vocabularies for individual users.
8. With these enhancements, the prosthetic arm can evolve into a more intelligent, adaptive, and efficient assistive device suitable for personalized healthcare solutions and clinical rehabilitation programs.

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