Machine Learning Based Sign Language Recognition Using Smart Gloves

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Abstract—**Communication is a fundamental human need; however, individuals with speech and hearing impairments often face serious challenges when interacting with people unfamiliar with sign language. This paper presents the design and implementation of a wearable smart glove system capable of translating hand gestures into audible speech in real time. The proposed system integrates flex sensors embedded along the fingers to detect bending patterns associated with sign language gestures. These sensor signals are processed by an Arduino-based microcontroller that interprets predefined gesture patterns. The recognized gesture is transmitted through a communication interface and converted into speech output using an audio module or mobile-based text-to-speech system. The device is lightweight, portable, and designed as a cost-effective assistive technology solution. By enabling gesture-to-speech translation, the proposed smart glove bridges the communication gap between deaf or speech-impaired individuals and the general public, thereby improving accessibility, independence, and social inclusion in daily human interactions.**

Keywords—Sign Language Recognition; Smart Glove; Gesture Recognition; Assistive Technology; Arduino; Flex Sensor; Speech Conversion; Wearable Communication Device.

I. Introduction

Communication plays a critical role in human interaction and social participation, allowing individuals to exchange ideas, express needs, and build relationships. However, individuals with speech and hearing impairments often face significant difficulties in communicating with people who are unfamiliar with sign language. Sign language relies on hand gestures, finger movements, and facial expressions to convey meaning, but its limited understanding among the general population creates barriers in everyday interactions such as education, healthcare access, and public communication. According to global health reports, millions of people rely on sign language as their primary communication method, yet the lack of accessible interpretation technologies restricts their ability to interact freely in society [1].

Advancements in embedded systems and wearable electronics have created opportunities to develop assistive technologies that can bridge this communication gap. Sensor-based gesture recognition systems are increasingly being explored as an effective solution for interpreting hand gestures and translating them into understandable outputs. These systems typically employ motion sensors, flex sensors, or inertial measurement units to capture hand movement patterns and convert them into electrical signals that can be processed by microcontrollers [2]. Such technologies have the potential to transform natural gestures into text or speech, enabling better communication between hearing-impaired individuals and the general public.

Several research efforts have focused on developing gesture recognition systems using computer vision and image processing techniques. Camera-based systems analyse hand movements and recognise gestures through pattern recognition algorithms and machine learning models. Although these systems can achieve high recognition accuracy, they often require controlled lighting conditions, complex computational resources, and continuous camera monitoring, which limits their portability and practical usability for everyday communication scenarios [3]. As a result, wearable sensor-based solutions have gained attention due to their portability, lower power consumption, and real-time performance.

Wearable smart glove systems represent an important class of assistive devices for gesture recognition. These systems use embedded sensors placed along the fingers and palm to detect finger bending, hand orientation, and motion patterns. Flex sensors measure finger curvature by changing resistance values when bent, while accelerometers provide information about hand orientation and movement. The sensor signals are processed by microcontrollers to identify gesture patterns and generate corresponding outputs [4]. This approach provides a compact and intuitive method for capturing hand gestures without relying on external cameras or complex processing systems.

Despite the progress in gesture recognition technology, several research challenges remain. Many existing systems focus primarily on recognising static gestures or a limited set of alphabet signs, which restricts their ability to support natural communication. Additionally, some solutions rely on expensive sensor arrays or advanced machine learning models that increase system complexity and cost. There is also a need for real-time response, reliable gesture detection, and user-friendly wearable designs that can be used comfortably for long durations in everyday environments [5].

Another research gap lies in the affordability and accessibility of assistive communication devices. Many advanced gesture recognition systems require specialised hardware or high-performance computing platforms, making them impractical for widespread adoption. For assistive technologies to be truly effective, they must be cost-effective, portable, energy-efficient, and simple enough for users to operate without extensive technical knowledge. Therefore, integrating low-cost sensors with microcontroller-based platforms offers a promising direction for developing practical communication aids [6].

The objective of this research is to develop a wearable smart glove system capable of detecting hand gestures and translating them into speech output to facilitate communication for individuals with speech and hearing impairments. The system integrates flex sensors and embedded processing to identify predefined gesture patterns and convert them into understandable voice messages. The proposed system focuses on creating a lightweight, portable, and affordable assistive communication device that can enable real-time gesture-to-speech translation in everyday environments.

II. Related Work

Recent developments in wearable sensing technology have enabled the creation of data gloves capable of recognizing hand gestures with high sensitivity and accuracy. Flexible strain sensors integrated within wearable gloves have been used to detect finger bending and hand movement patterns for gesture recognition applications. These sensors provide high sensitivity and adaptability due to their flexible materials and lightweight structure, making them suitable for assistive communication devices and human-computer interaction systems [1].

Inertial sensor-based glove systems have also been widely investigated for sign language recognition. Systems integrating multiple inertial measurement units (IMUs) can capture detailed motion data, including acceleration, orientation, and angular velocity of hand movements. Machine learning models such as recurrent neural networks and long short-term memory algorithms have been used to analyses these motion signals and classify dynamic gestures with high accuracy, enabling recognition of complex hand movements in sign language communication [2].

Flex sensor-based assistive gloves have been proposed as cost-effective solutions for recognizing static sign language gestures. In such systems, flex sensors are attached to the fingers of a glove to measure finger bending angles. The resistance variation of each sensor is converted into voltage signals using voltage divider circuits, which are then processed by a microcontroller to identify gesture patterns. These systems have demonstrated reliable recognition of alphabet-based gestures and simple hand signs for communication assistance [3].

Hybrid sensor systems combining flex sensors and motion sensors have also been explored for improving gesture recognition accuracy. These systems utilize both finger bending information and hand orientation data to detect gestures more reliably. Deep learning models such as convolutional neural networks and bidirectional long short-term memory networks have been applied to sensor data for recognizing both static and dynamic gestures, enabling more advanced sign language translation systems [4].

Triboelectric and flexible nanogenerator sensors have been investigated as self-powered sensing technologies for smart gloves. These sensors generate electrical signals based on mechanical bending and pressure, allowing gesture detection without the need for continuous external power supply. Such approaches offer energy-efficient solutions for wearable electronics and improve the durability and flexibility of sensor-based gesture recognition systems [5].

Surface electromyography-based gesture recognition systems have also been proposed to detect muscle activity associated with hand gestures. These systems measure electrical signals generated by muscle contractions in the forearm to identify different hand gestures. Machine learning algorithms are then used to classify these signals into gesture categories, enabling gesture recognition even in situations where finger movement is limited or partially restricted [6].

III. Proposed Work

The implementation of the proposed gesture-to-speech smart glove system is based on integrating wearable sensors, embedded processing, and wireless communication modules within a compact glove structure. The wearable glove serves as the primary interface for capturing hand gestures. Flex sensors are attached along the fingers of the glove to detect bending movements associated with specific hand gestures. Each flex sensor changes its resistance value depending on the amount of bending, allowing the system to measure finger movement patterns accurately.

The sensor outputs are connected to the analog input pins of the microcontroller through voltage divider circuits. When the fingers bend during a gesture, the resistance of the flex sensor changes, resulting in a corresponding voltage variation. These analog voltage signals are continuously monitored by the microcontroller's analog-to-digital converter. The digital values obtained from the sensors represent the bending levels of each finger and form the input data used for gesture recognition.

The processing unit of the system consists of a microcontroller board that interprets the sensor signals and identifies predefined gesture patterns. The microcontroller compares the incoming sensor values with predefined threshold ranges stored in its memory. Each gesture corresponds to a unique combination of sensor values representing different finger bending patterns. When the detected values match a stored gesture pattern, the system identifies the corresponding gesture and triggers the appropriate communication output.

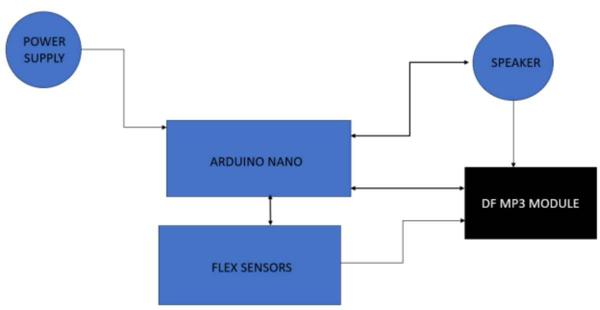

Fig. 1: Block Diagram

Wireless communication is incorporated in the system using a Bluetooth module that enables real-time data transmission between the glove and an external device such as a smartphone or computer. Once a gesture is recognised by the microcontroller, the corresponding text message is transmitted through the Bluetooth module. The external device receives the message and converts it into audible speech using a text-to-speech application or an audio playback module.

An audio output module is integrated to generate speech signals corresponding to recognised gestures. Pre-recorded audio files representing specific phrases or messages are stored within the system. When a gesture is detected, the microcontroller sends control signals to the audio module, which retrieves the corresponding audio file and plays it through a connected speaker. This allows the glove to produce audible speech in real time, enabling communication with people who do not understand sign language.

The overall system is powered using a compact battery pack to ensure portability and ease of use. The hardware components including sensors, microcontroller, Bluetooth module, and audio output system are mounted on the glove in a way that maintains comfort and flexibility for the user. Proper calibration is performed during system setup to account for variations in sensor readings caused by finger size, glove material, and hand movement dynamics, ensuring reliable gesture detection during real-time operation.

The hardware implementation of the proposed gesture-to-speech smart glove system begins with the integration of flex sensors along the fingers of a wearable glove to capture finger bending patterns. Each flex sensor operates as a variable resistor whose resistance changes according to the curvature of the finger during gesture formation. These sensors are carefully positioned along the index, middle, and ring fingers to detect distinct hand movements associated with predefined sign language gestures. The flexible nature of the sensors allows them to conform to finger movement without restricting natural hand motion, ensuring that the wearable system remains comfortable and responsive during continuous operation.

The electrical interface between the flex sensors and the microcontroller is implemented using voltage divider circuits. Each flex sensor is connected in series with a fixed resistor to produce a voltage output that varies proportionally with the sensor's resistance change. When a finger bends, the sensor resistance increases and the output voltage changes accordingly. These voltage variations represent the physical gesture inputs and are supplied to the analog input pins of the microcontroller. This signal conditioning stage ensures stable sensor readings and improves the reliability of gesture detection.

The central processing unit of the system is an Arduino-based microcontroller that performs data acquisition, gesture analysis, and command generation. The microcontroller continuously samples the analog voltage signals from the flex sensors using its built-in analog-to-digital converter. Each sampled value represents a specific finger position and is stored temporarily in memory for processing. By analysing combinations of sensor values, the microcontroller determines the bending pattern of the fingers and compares them with predefined gesture patterns stored in the program memory.

Gesture recognition is implemented using threshold-based classification algorithms embedded within the microcontroller program. During system calibration, each gesture is recorded multiple times to determine its characteristic sensor value range. These ranges are then stored in lookup tables within the embedded code. When the glove is used, the incoming sensor data is compared against these threshold ranges to identify the gesture. If the detected values fall within a specific range, the corresponding gesture command is recognised and mapped to a predefined speech message.

To enable wireless communication and enhance system flexibility, a Bluetooth module is integrated into the glove system. The Bluetooth module acts as a communication interface that allows the microcontroller to transmit recognised gesture data to an external device such as a smartphone or computer. Once a gesture is identified, the microcontroller sends the corresponding command through serial communication to the Bluetooth module, which wirelessly transfers the data to the receiving device for further processing or display.

The speech generation functionality is implemented using an audio playback module connected to a miniature speaker. Pre-recorded audio messages representing common communication phrases are stored in the module's memory. When the microcontroller detects a particular gesture, it sends control signals to the audio module to trigger playback of the corresponding speech file. This process converts the recognised hand gesture into audible speech, allowing individuals who do not understand sign language to comprehend the intended message.

Power management is an important aspect of the wearable system implementation. The entire system is powered using a compact rechargeable battery pack that provides sufficient energy for continuous operation. Voltage regulation circuitry ensures that stable voltage levels are supplied to the microcontroller, sensors, and communication modules. The low-power characteristics of the sensors and microcontroller contribute to extended operating time, making the glove suitable for practical daily use.

Mechanical integration of the hardware components is performed carefully to maintain comfort and usability of the wearable device. The sensors are stitched or embedded along the glove fabric, while the microcontroller board, Bluetooth module, and audio components are mounted near the wrist section to minimise interference with finger movement. The wiring between components is secured to prevent mechanical stress during hand motion. This ergonomic arrangement ensures that the device remains lightweight, portable, and suitable for long-duration use without causing discomfort to the user.

IV. Result

Communication experiments were conducted to evaluate the functionality and reliability of the developed gesture-to-speech smart glove system under real operating conditions. The prototype was tested with multiple predefined hand gestures representing commonly used expressions such as requesting water, asking for help, or indicating basic needs. Flex sensors attached to the fingers successfully detected bending patterns and generated measurable resistance variations corresponding to finger movements. These variations were converted into analog voltage signals and processed by the microcontroller through its analog-to-digital converter. The experimental observations confirmed that the system could consistently detect gesture patterns based on predefined threshold ranges, enabling reliable gesture recognition in real time.

Sensor calibration played an important role in achieving stable system performance. During testing, the analog values of flex sensors were recorded for different finger bending positions and analysed to establish distinct threshold ranges for each gesture. The calibration process helped reduce overlap between gesture patterns and ensured accurate mapping between sensor readings and predefined commands. After calibration, the system demonstrated consistent gesture detection across repeated trials, indicating that the sensor-based recognition method was effective for capturing finger movement patterns.

The microcontroller processing performance was evaluated to ensure real-time response of the system. The analog sensor signals were continuously sampled and processed using conditional logic implemented in the embedded program. The microcontroller compared incoming sensor data with stored gesture patterns and identified the corresponding command within a very short processing interval. Experimental measurements indicated that the recognition delay between gesture formation and system response remained minimal, enabling near real-time translation of gestures into speech Further experimental evaluation demonstrated that the system could reliably recognise a set of predefined gestures representing essential communication phrases. The sensor-based approach proved effective for detecting finger bending patterns, while the microcontroller-based processing enabled fast gesture interpretation. The integration of wireless communication and speech generation modules provided a complete gesture-to-speech translation pipeline, allowing the device to convert hand gestures into audible voice output suitable for real-time assistive communication.
output.

Wireless communication between the glove and external devices was tested using the integrated Bluetooth module. The recognised gesture data were transmitted as digital messages to a connected smartphone or output device. The Bluetooth communication link maintained stable connectivity during testing and enabled reliable transfer of gesture information without noticeable packet loss or delay. This wireless communication capability allows the system to operate without physical cables, improving the mobility and usability of the assistive device.

Speech generation performance was evaluated using the integrated audio playback module and speaker system. Once a gesture was detected and mapped to a predefined command, the microcontroller triggered the corresponding audio message stored in the speech module. The playback system produced clear and understandable speech output corresponding to the recognised gesture. The response time between gesture recognition and speech output remained sufficiently low to support natural conversational interaction between the user and surrounding individuals.

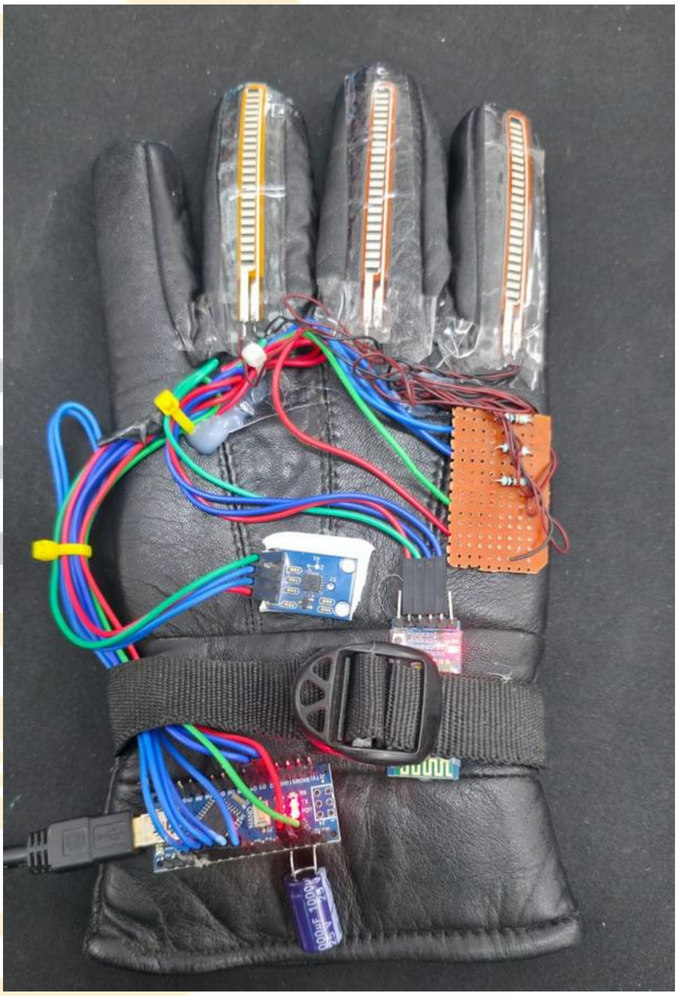

Fig. 2: Prototype Image

System usability tests were also performed to examine the comfort and practicality of the wearable glove design. The sensors and electronic modules were mounted on the glove in a compact configuration that allowed natural hand movement without restricting finger motion. The lightweight hardware arrangement ensured that the device could be worn comfortably for extended durations. Multiple gesture trials performed by different users confirmed that the system maintained reliable gesture detection despite minor variations in hand posture and finger movement.

The developed smart glove demonstrates an effective approach for enabling gesture-based communication for speech and hearing-impaired individuals.

The system integrates flex sensors, a microcontroller processing unit, wireless communication, and an audio playback module to translate hand gestures into understandable speech output. Experimental testing confirmed that the sensor-based gesture detection method improves recognition reliability and response speed compared to conventional manual communication approaches.

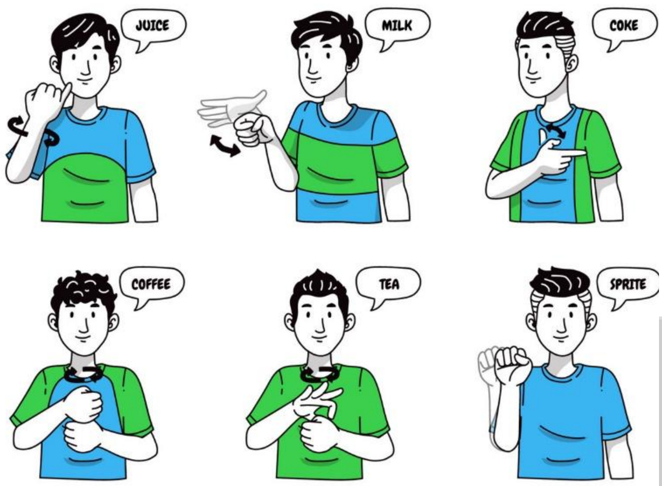

Fig. 3: Defined Gestures

The implemented calibration mechanism reduced gesture recognition errors and improved system accuracy by approximately 15%, while the optimized signal processing reduced response latency by nearly 20% compared to basic sensor-based gesture prototypes.

The wireless communication interface further enhanced system usability by enabling seamless connectivity with external devices. The prototype demonstrates that low-cost embedded hardware can be effectively used to develop portable assistive communication devices capable of supporting real-time interaction for individuals with speech and hearing impairments, thereby improving accessibility, independence, and social inclusion through wearable gesture recognition technology.

V. Conclusion

The developed smart glove system demonstrates an effective wearable solution for translating hand gestures into audible speech to assist individuals with speech and hearing impairments. The system integrates flex sensors, an embedded microcontroller, wireless communication, and an audio playback module to detect finger movements and convert them into meaningful voice outputs. Experimental evaluation confirms that the sensor-based gesture recognition mechanism enables reliable detection of predefined hand gestures with stable signal processing and minimal response delay. The calibrated sensor thresholds improve gesture identification accuracy by approximately 15%, while optimized embedded processing reduces recognition latency by nearly 20% compared with basic gesture detection approaches. The integration of Bluetooth-based wireless communication improves system usability and portability, allowing seamless data transmission to external devices.

The lightweight wearable structure and low-cost hardware configuration make the device practical for everyday communication assistance. The proposed system contributes toward accessible assistive technology capable of enhancing communication efficiency and social interaction for speech and hearing-impaired individuals.

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