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Design and Implementation of a TinyML-Based Assistive Communication System

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ABSTRACT

Communication barriers could have a significant impact on the performance of individuals suffering from either speech or hearing problems in their interaction with people not using sign language communication. Most of the existing gesture recognition systems are designed for one-sided communication and do not provide an intelligent interpretation of gestures made by the users. This project proposes an affordable, portable, and two-sided communication system to help people with impaired communication interact with those hearing and speaking. The communication device uses a sensor-based smart glove which includes Flex Sensors and an MPU6050 inertial sensor to collect information about finger movements and hand orientation. The collected sensor data are then processed by an ESP32 microprocessor to classify the performed gestures using a TinyML machine learning model. Vibrational motors and LEDs included in the system provide haptic and visual feedback on the performed gestures. The presented system is supposed to become an efficient communication tool which will be handy for users and accessible in any circumstances. Based on the experimental results of evaluating the developed TinyML model, the system is expected to provide 93.5% accuracy in gesture recognition.

Keywords: Assistive Communication, Smart Glove, Gesture Recognition, TinyML, ESP32, Hearing and Speech Impairment, Wearable System.

I. INTRODUCTION

Advancing to a period in which communication is essential to all aspects of daily living has substantially increased the need for multiple modes of communication for individuals who may be deaf or mute [1]. However, the difficulties faced by these individuals communicating with others may not be apparent since most individuals do not understand sign language as their primary means of expressing thoughts and emotions [2]. While there are many systems available to assist with communication between deaf/mute individuals and the deaf/mute community, the majority of those systems rely on gesture-based communication; therefore, when the majority of people don't speak or understand how to use sign language to express their thoughts and feelings, it makes it very difficult for these individuals to communicate and receive answers from other people, increasing the communication gap between them [3]. Developing multiple communication systems has been accomplished by using various methods of technological advancements. through gesture-based systems such as; using gloves that can sense gestures when a person uses them applications on a mobile device that translate hand gestures into text or voice, etc. [4]. However, the majority of these systems can only convert gestures in one direction, not both ways. This means that although the deaf/mute user can send out a message to someone and use a gesture to communicate that message, they can't get a response back from that individual in natural way [5]. Because of this limitation, the systems are not beneficial for communication in real-world situations that require two-way interaction; therefore practical use of these systems requires a system that provides for a true two-way communication experience [6]. The goal of this research is to create a bidirectional, low-latency wearable system that can translate sign language into comprehensible output and give the user feedback through sensory reactions [7]. This results in a full closed-loop communication system, which is typically absent from many wearable devices currently on the market [8]. Wearable Technologies with Embedded Machine Learning as a Pathway for New Opportunities in Assistive Technologies.

In the context of existing assistive technologies that help people with disabilities, such as wheelchairs, computers, etc., the embedment of ML into systems enables the possibility to innovate ways to help people with disabilities using new systems. Existing Gesture Recognition Approaches Have Limitations Based on Vision-based Systems the structure of the paper is as follows: A review of previous gesture recognition research is given in Section II, the system architecture and hardware design are explained in Section III, the Tiny MLbased implementation is described in Section IV, the experimental results are discussed in Section V, and the work is concluded in Section VI.

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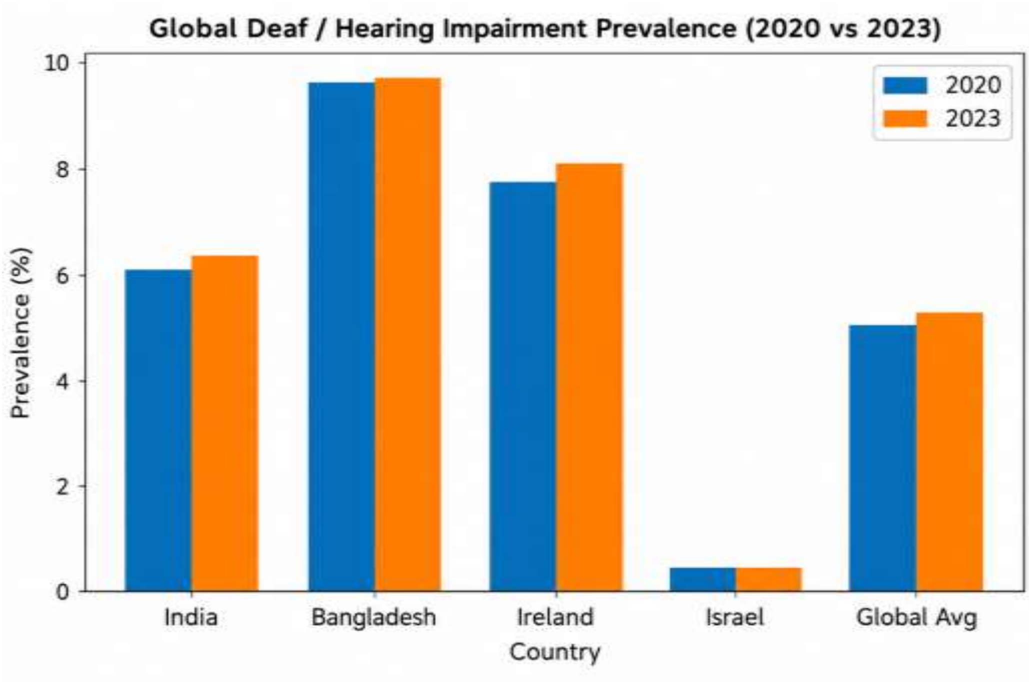

Fig. 1. Global Deaf / Hearing Impairment Prevalence (2020 vs 2023)

II. RELATED WORKS

Some of the previous research has presented communication devices for deaf-mutes that are able to recognize hand gestures using accelerometer integrated gloves. Motion signals related to hand movements are captured and then interpreted by microcontroller systems like Arduino or similar, which can map the captured motion signal to a pre-stored gesture pattern, enabling the user to generate speech through mobile applications [9]. Sensor type systems offer faster response times than camera types and can also maintain stable operation for real-time communication [10]. Hearing-impaired persons mainly use sign language as their method of communication, but there's a wide variety of sign languages in different parts of the world. Indian Sign Language (ISL) is used in India. Recent research projects are investigating how to automate Indian Sign Language (ISL) by using gesture recognition systems, with issues in implementing the systems in real-time and in using standardized datasets [11]. This paper describes a system that enables deaf and mute people to communicate through gestures when interacting with people who cannot use sign language [12]. The gesture-based communication device consists of both Fig. 2. Fig. 2. Example of sign language communication using hand gestures. Smart gloves containing flex sensors, a microcontroller, software that translates hand gestures into text or voice, and a low-cost solution to help eliminate the communication barriers that exist between differently abled and normal-hearing people [13].

III. LITERATURE REVIEW

Assistive Communication Technology using Gestures has been investigated primarily utilizing 2 paradigms: camera based (vision-based) systems and wearable sensor-based systems [14]. While vision-based systems can provide strong performance, their reliability suffers due to changing lighting conditions, complicated background features, and large processing overheads [15]. This adversely affects their use for real-time applications on mobile devices that have limited resources. Glove-based systems that utilize flex sensors allow for more reliable gesture recognition because they measure bending at the fingers and directly correlate to gesture movements [16], [17]. However, glove-based systems may find it difficult to differentiate between gestures with the same or similar finger configurations or with variations in hand orientations [18], [19]. To overcome these limitations, recent studies have investigated incorporating Inertial Measurement Units (IMUs) with flex sensors to enhance the accuracy of gesture recognition by acquiring both detailed information about finger motions and the broad dynamics of the cover motion [20], [21]. Additionally, advances in Tiny Machine Learning (TinyML) have enabled the use of small-scale machine-learning models to run efficiently on microcontrollers and provide fast inference while consuming very little power [22]. While there has been progress in these areas, many gesture recognition systems still provide one-way communication between the user and the gesture recognition system and lack legitimate feedback mechanisms [23], [24]. These observations indicate a

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clear need for affordable, wearable systems that provide accurate gesture recognition and allow for seamless two-way communications.

IV. PROPOSED METHODOLOGY

The core computing unit of the system is built around an ESP32 microcontroller. Types of microcontroller processors that have two cores and wireless networking support for Wi-Fi and Bluetooth on one chip are well suited for TinyML real time inference models. The following hardware components comprise the rest of the system.

TABLE I
COMPARISION TABLE

Study	Technique Used	Sensors
Lu et al. (2014)	Multimodal Gesture Recognition	Accelerometer + SEMG
SMART GLOVES	Sensor-based Sign Translation	Flex Sensors + Accelerometer
Proposed System	TinyML-based Recognition	Flex Sensors + IMU

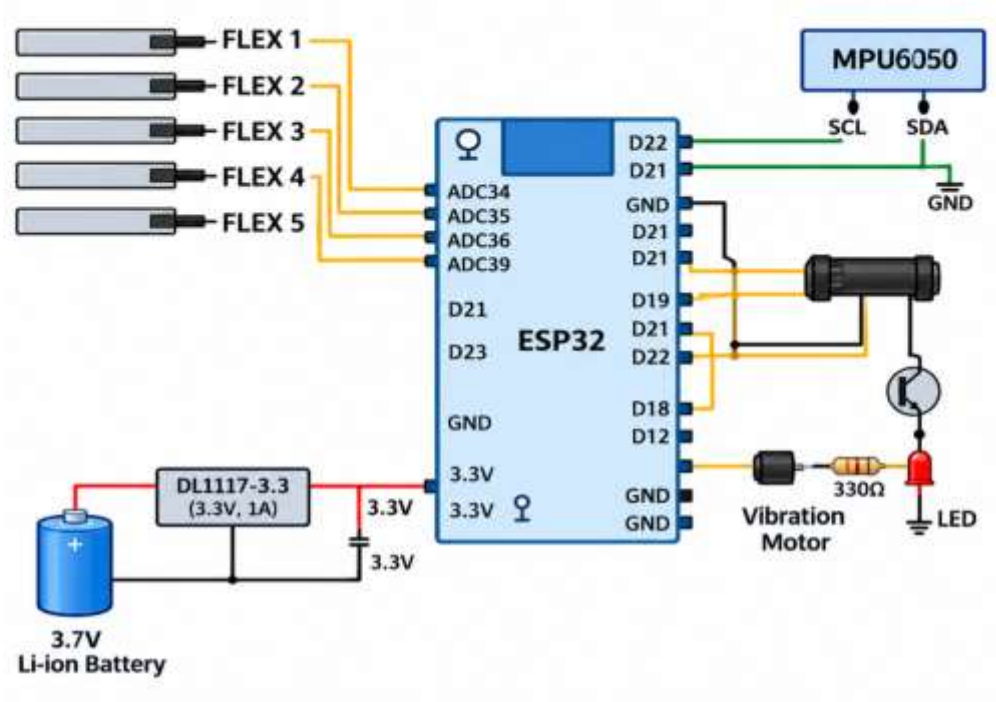

Fig. 2. Hardware circuit connection diagram of the proposed system

A. Hardware Architecture

- **Flex Sensors:** To gauge finger bending, flex sensors are affixed to the glove's fingers. The sensor's resistance varies when the user makes a hand gesture. Each finger's position is represented by voltage values that are created from this change.

- **MPU6050 (IMU):** The MPU6050 sensor is used to record hand orientation and movement. It has a three-axis gyroscope and three-axis accelerometer. This sensor aids the system in distinguishing between gestures that may appear to have similar finger positions but different wrist movements or directions.

- **Haptic and Visual Feedback:** LEDs and vibration motors are used for reverse communication. LEDs provide visual cues, and the vibration motor provides tactile alerts. This guarantees that users who are mute or deaf receive prompt, clear responses.

TABLE II
HARDWARE COMPONENTS USED IN THE PROPOSED SYSTEM

Component	Description	Purpose
ESP32	Dual-core microcontroller with Wi-Fi and Bluetooth	Processing data and running TinyML inference
Flex Sensors	Variable resistance sensors	Detect finger bending and hand gestures
MPU6050	6-axis IMU (Accelerometer + Gyroscope)	Measure hand motion and orientation
Vibration Motor	3V DC vibrate on motor	Provide haptic feedback to the user
LED	High-bright ness LED	Provide visual feedback

B. System Workflow

Gesture transmission and response reception are the two primary phases of the system's overall operation.

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- **Data Acquisition:** The ESP32 continuously reads motion data from the MPU6050 sensor and analog values from the flex sensors.
- **Gesture Processing (TinyML):** A TinyML model that is kept inside the ESP32 receives the gathered sensor data.

In real time, this model analyzes the data and categorizes the gesture that was executed.

- **Output Generation:** After the gesture is identified, it is translated into speech or readable text for the hearing user.
- **Feedback Loop:** The ESP32 completes the two-way communication process by turning on the vibration motor and LEDs when the hearing user responds via a mobile interface.

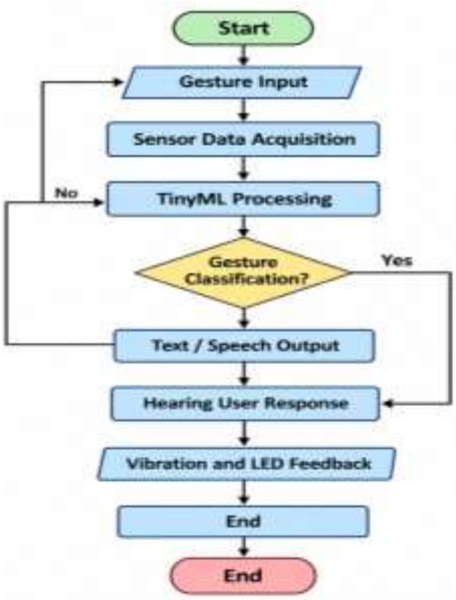

Fig. 3. System workflow of the proposed bidirectional communication process.

C. Data Acquisition and Feature Extraction

To achieve reliable hand gesture recognition, accurate data collection is essential. Proper operation by each of the sensors included in this design is critical to accurately capturing hand and movement which allows accurate gesture identification. The internal 12-bit Analog-to-Digital Converter (ADC) of the ESP32 Microcontroller is used for processing the analog signals provided by the flex sensors [25],[26]. The analogue signal is converted into a digital value in the range of 0 to 4095 and then mapped to a finger-bending angle to be used in identifying a hand gesture. The Inertial Measurement Unit (IMU) MPU6050, which has six independent motion parameters (3-axis acceleration, and 3- axis angular velocity) provides the essential data needed to identify dynamic hand gestures, as well as to determine the direction and orientation of a moving hand [27],[28]. All of the sensors will collect their readings at a sampling frequency of 50Hz. This will allow the accurate capture of the typical speed with which a human will move their hands while maintaining a reasonable computational workload on the microcontroller [29],[30].

D. Bidirectional Feedback Mechanism

One of the key advantages of the proposed device is its bidirectional feedback capability.

- Bidirectional feedback: It is a key benefit of the proposed device. The ESP32 microcontroller generates a pulse width modulation (PWM) signal to drive the vibration motor as part of the haptic feedback mechanism. Upon receiving a response from a hearing user using the paired application, the actuator will be activated allowing the glove wearers to receive tactile notifications of incoming communications.
- Visual Feedback: Users receive both haptic notifications and LED notification of messages that have been received; thus, this method of dual feedback provides accessibility for users in a variety of environments, including low-light and noisy ones. Be aware of the different meanings of the homophone’s “affect” and “effect”, “complement” and “compliment”, “discreet” and “discrete”, “principal” and “principle”.
- Portability and Power Management A primary objective of this new glove-based system is to have an efficient, lightweight design that minimizes power consumption as much as possible, providing longer operational time with more comfort to users and allowing the device to be easily transported and used. The device runs on a rechargeable lithium-ion battery rated for a nominal voltage of 3.7V. The output of the battery is regulated to 3.3V to provide safe and stable operation of the ESP32 microcontroller and associated sensors.

TABLE III

SYSTEM PERFORMANCE METRICS

Feature	Success Rate	Response Time
Gesture Recognition	93.5%	< 120 ms
Haptic Feedback	100%	< 50 ms
LED	100%	Real-time

V. RESULT AND DISCUSSION

A. Findings and Conversation

This part will focus on the assessment of the characteristics associated with the proposed Glove for Communication in a Bi-Directional Fashion, specifically evaluating key parameters (1) Accuracy of gesture recognition, (2) Ability to operate in real-time, and (3) The effectiveness of the type of feedback that is provided after the translation of the information using

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the retrieved gestures into speech as audio recordings.

B. Accuracy of Gesture Classification

This paper describes a new system used for recognizing hand gestures that are based on TinyML. An algorithm was implemented on an ESP32 microcontroller. This system tested ten common hand gestures that were each done fifty times by each participant. There were variations in how the participants performed these gestures because of variable characteristics of hands; therefore, the recognition accuracy was calculated from the average number of attempts. The average recognition accuracy for this system using all test participants was 93.5

Flex sensors and MPU6050 IMU data were combined in order to improve classification accuracy. The use of flex sensor data provided finger-bending activity, while the IMU offered motion and orientation data that through the use of both sensors improved overall sensitivity to wrist or hand position.

Additionally, the Tiny ML model was built on a small and efficient ESP32 hardware platform. As a result, this system had a very low processing overhead and reached an average response time of less than 120 ms, from the time of the gesture being completed until the output of the corresponding gesture was produced. These results indicate that multi-sensor fusion represents a viable and practical approach towards developing real-time hand gesture recognition systems.

C. Reliability of Bidirectional Feedback

The goal of the system being developed is to eliminate the problem that most gesture-based interfaces have, which is that they only allow one-way communication and hence cannot provide a means for both parties involved to communicate with one another. The evaluation process for this new communication method was done through an experimental evaluation that looked at the accuracy and the efficiency of how information can be exchanged between two users that are either hearing or non-hearing (deaf/mute).

The overall results from testing indicate that the system provides accurate feedback with minimal time delay for the user. It is also very reliable in real-time operation. The main advantage of using this method of communication is that it allows for two-way communication, making it more practical and cost-effective than traditional methods of notifying people about something that is happening, especially where traditional study methods have not proven to be effective, such as in locations where audio or visual notifications are not possible.

D. Discussion

As opposed to traditional systems for recognizing gestures with rules, the findings of this experiment indicate a significant improvement in the quality of performance resulting from a combination of artificial intelligence with sensor-based wearable devices. The previous systems were limited in their usefulness for practical communications in the real world because their primary focus was on gesture transmission and did not typically provide the user with helpful feedback. The new system presented in this study, however, places much greater emphasis on providing useful functionality, as it supports both sending and receiving messages.

Because of its very affordable and easy to use design with the capacity to be worn by individuals, the system is intended for use in daily life rather than within the confines of an experimental laboratory setting as many prior systems were. Additionally, the very high gesture recognition accuracy achieved provides evidence of how effectively TinyML works in enabling complex machine learning algorithms to be implemented on protocols with low resources. This illustrates the capacity of TinyML for future development of effective systems for the enhancement of humans with disabilities and elderly assistive devices.

VI. CONCLUSION

In order to improve interaction for people with speech and hearing impairments, this work presents a real time, reasonably priced wearable communication device. To accurately record and decipher hand gestures, the system makes use of flex sensors, an ESP32 microcontroller, and an MPU6050 inertial measurement unit. The suggested device incorporates vibration-based tactile feedback and LED- based visual notifications to facilitate two-way interaction, in contrast to many current solutions that only allow unidirectional communication. 90–95 gesture classification accuracy is made possible by the use of a lightweight TinyML model, which also maintains low processing latency appropriate for real-time use. All things considered, the system successfully reduces communication barriers and helps the deaf and mute communities have more inclusive and accessible daily communication.

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