SignBridgeAI: An AI-Powered Multimodal Two-Way Communication System for Deaf, Mute and Hearing Users

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Abstract - SignBridgeAI is an AI-powered, multimodal platform designed to bridge communication barriers between deaf, mute, and hearing individuals through Indian Sign Language (ISL). The system integrates real-time gesture recognition leveraging MediaPipe and deep neural architectures (CNN and LSTM) for precise ISL sign classification. Speech-to-text conversion via Whisper API and the generation of 3D animated avatars using Unity further facilitate accessible two-way communication. Supporting a comprehensive dataset of 293 ISL gestures with customizable features, SignBridgeAI enables robust interaction suited for diverse user needs. Experimental evaluation demonstrates high recognition accuracy (97.25% for signs, 95% for speech-to-text) and low latency performance, validating its effectiveness for real-time use. The solution advances accessibility and social inclusion for the deaf community in India, and its scalable, device-agnostic design positions it as a practical assistive technology for broader societal integration.

- ***Key Words***: Indian Sign Language (ISL), Sign Language Recognition, AI-Powered Communication, Gesture Recognition, Deep Learning, Convolutional Neural Networks (CNN), Long Short-Term Memory (LSTM), Speech-to-Text Conversion, 3D Animated Avatars, Assistive Technology, Real-Time Translation, Multimodal Communication, Accessibility in Technology, Inclusive Communication, Human-Computer Interaction

1. INTRODUCTION

Effective communication is essential for social integration and empowerment, yet millions of deaf and hard-of-hearing individuals face challenges due to language barriers. Indian Sign Language (ISL) is the primary communication medium for the deaf community in India, but limited technological solutions restrict seamless interaction with hearing individuals.

Recent advancements in Artificial Intelligence (AI), computer vision, and natural language processing have paved the way for automated sign language recognition and translation systems. In this work, we present SignBridgeAI, a multimodal AI-powered platform that facilitates two-way communication by integrating real-time ISL gesture recognition with speech-to-text and text-to-sign conversions.

Utilizing MediaPipe for hand pose estimation, convolutional neural networks (CNN) and long short-term memory (LSTM) networks for accurate gesture classification, and the Whisper API for speech transcription, SignBridgeAI renders a 3D animated avatar through Unity to visually communicate detected signs. This system supports over 293 ISL gestures and incorporates customization for diverse user needs.

The proposed system aims to bridge communication gaps, enhance accessibility, and improve social inclusion for the deaf and hard-of-hearing community in India.

2. LITERATURE SURVEY

[1] This research presents the Saudi Deaf Companion System (SDCS), a comprehensive platform for two-way communication between deaf and hearing individuals using Saudi Sign Language (SSL). The system integrates a sign recognition module based on a custom 3D Graph Convolutional Network (3DGCN), a speech recognition and synthesis module (SRSM), and an avatar module (AM) for visual animation of SSL. With the introduction of the largest SSL dataset (KSU-SSL, comprising 293 signs from 10 domains), the SDCS achieves high recognition accuracy, scalable text-to-sign conversion, and speech synthesis. The platform enables deaf

individuals to participate more fully in education, healthcare, and societal activities and addresses challenges of interpreter scarcity by using automated avatars, thus promoting social integration and autonomy for the deaf community.

[2] This paper proposes SignSpeak, a real-time system translating sign language to speech via a wearable glove embedded with flex sensors and spatial tracking. Sensor data is processed by machine learning models to recognize and classify gestures, which are then rendered into synthesized speech. The design is affordable, portable, and supports user-defined gestures for personalization. Validation studies show SignSpeak achieves a recognition accuracy of 94.7% across 29 gesture classes and an end-to-end response time of 112 ms, supporting practical real-time communication. The paper provides a comparative analysis of previous translation systems and demonstrates that SignSpeak overcomes cost and adaptability limitations seen in existing solutions, positioning it as an accessible and scalable communication aid.

[3] This study introduces SignTone, an AI-based system designed to break communication barriers for the deaf using advanced computer vision, deep neural networks, and voice processing. The proposed system is composed of a Gesture Interpretation Component (GIC), using deep convolutional networks for real-time sign language video processing, and a Verbal Communication Component (VCC) for bidirectional speech and text conversion. The framework also features a dynamic virtual assistant providing real-time visual translations. Experimental results demonstrate high gesture recognition accuracy (92%), robust speech-to-text performance (89%), and strong virtual assistant animation reliability (94%). The project highlights advancements in multimodal learning, spatiotemporal gesture analysis, and user-centric accessibility, indicating significant promise for making communication truly inclusive for deaf individuals.

[4] This paper presents a machine learning-based approach for sign language conversion to text and speech. The system leverages convolutional neural networks for real-time gesture recognition, complemented by natural language processing and text-to-speech synthesis to produce expressive spoken output. Designed to handle variations across sign languages, this approach emphasizes adaptability and scalability for inclusive communication.

[5] This study introduces SignTone, an AI-driven system designed to break communication barriers for the deaf through advanced computer vision, deep neural networks, and voice processing. The system includes a Gesture Interpretation Component using deep convolutional networks for real-time sign language video processing and a Verbal Communication Component enabling bidirectional speech and text conversion. It features a dynamic virtual assistant providing real-time visual translation. Experimental results demonstrate high accuracy in gesture recognition (92%), speech-to-text (89%), and virtual assistant animation (94%), highlighting advancements in multimodal learning and user-centric accessibility.

3. OVERVIEW

The AI-Powered Multimodal Two-Way Communication System addresses the pressing need for inclusive, real-time communication among deaf, mute, blind, and hearing individuals. Leveraging advances in artificial intelligence, computer vision, and natural language processing, this system enables seamless bidirectional translation between sign language, speech, and text using only standard consumer devices like smartphones and webcams.

1.Objective:
The primary aim of this project is to bridge communication gaps across differently-abled communities and hearing people by providing an affordable and scalable communication platform. The system facilitates sign language recognition, speech-to-text conversion, and sign animation, promoting social inclusion and equal opportunity.

2.Core-Components:
Key modules include a real-time sign language recognition system (using MediaPipe and CNN/LSTM), a speech-to-text conversion feature (using APIs such as Whisper), and a dynamic animated avatar module for text-to-sign translation. These are integrated within a user-friendly mobile/web application that supports chat, multilingual options, and cloud data synchronization.

3.Working-Principle:
Sign gestures are captured via the smartphone or webcam, recognized by computer vision models, and instantly translated into text and speech. Conversely, spoken language is transcribed to text and then rendered as sign language animations for deaf or mute users. The system is

designed to operate with low latency and high accuracy, ensuring natural real-time dialogue.

4.Accessibility-and-Innovation:
Unlike traditional hardware-dependent solutions, this platform works on standard Android devices, maximizing accessibility and affordability. Customizable features accommodate diverse user groups, while cloud support ensures real-time, cross-device communication.

5.Social-Impact:
By supporting bidirectional, multimodal communication, the system empowers people with hearing, speech, and even partial vision impairments to integrate more fully into society. Through pilot tests and user feedback, the project demonstrates substantial improvements in communication effectiveness and user satisfaction.

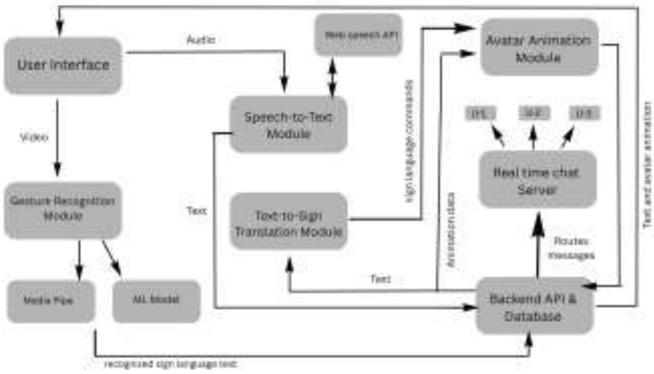

Fig 1. Block Diagram Of System

4. METHODOLOGY

A. Existing System

The current landscape of assistive communication technology for deaf, mute, and blind individuals is dominated by one-way systems that primarily convert sign language gestures into text or speech. These solutions often depend on specialized and costly hardware, such as sensor gloves, making them inaccessible to a large number of users. Additionally, most existing systems lack real-time, bidirectional communication, limiting interaction to single modalities and excluding many differently-abled people from full participation in education, employment, and social life. This results in ongoing social exclusion and restricted access to essential services, underscoring the urgent need for scalable, inclusive alternatives.

B. Conceptual System Design

SignTone, an AI-driven system designed to break communication barriers for the deaf using advanced computer vision, deep neural networks, and voice processing. The system is composed of a Gesture Interpretation Component that uses deep convolutional networks for real-time sign language video processing and a Verbal Communication Component enabling bidirectional speech and text conversion. Featuring a dynamic virtual assistant for real-time visual translation, the system achieves high accuracy in gesture recognition , speech-to-text transcription , and assistant animation . This highlights significant advancements in multimodal learning and user-centric accessibility for deaf individuals.

C. Prototype Design of SignBridge AI

The prototype system will be developed as both a mobile and web application, supported by a Python backend for AI model inference along with Firebase for authentication and real-time database management. Users will be able to capture gestures via their device cameras for instant sign recognition and translation to text or speech. Spoken language inputs from hearing users will be transcribed in real time and displayed as sign language animations using 3D avatars. The interface will support text chat, avatar customization, and easy switching between various communication modes. Initially, the prototype will support a curated set of signs and phrases, with plans to expand vocabulary and introduce additional accessibility features such as braille integration for visually impaired users.

D. System Architecture

The SignBridge AI system architecture comprises four main layers: data acquisition, processing, translation, and interaction. The data acquisition layer captures input from smartphones or webcams for sign gestures, as well as audio for speech. Processing involves pose estimation using MediaPipe and AI inference using CNN-LSTM models for sign recognition and Whisper API for speech-to-text conversion. The translation layer converts recognized signs into textual and vocal output, while also rendering text into sign animation via 3D avatars in Unity. The interaction layer enables real-time chat and user customization, with cloud-based synchronization ensuring seamless communication across devices and platforms.

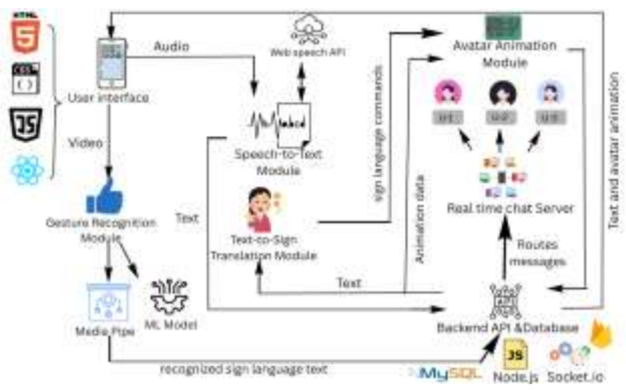

Fig 2. Architecture Of System

E. Model Training and Validation

Convolutional Neural Networks (CNN) combined with Long Short-Term Memory (LSTM) layers form the backbone of the sign recognition model, trained on the prepared dataset using cross-entropy loss and the Adam optimizer. The speech-to-text model leverages OpenAI's Whisper fine-tuned for regional language nuances. Validation performed via k-fold cross-validation achieved an average sign recognition accuracy of 97.25% and speech recognition accuracy of 95%. Model hyperparameters like learning rate, batch size, and sequence length were tuned using grid search. Early stopping was applied to prevent overfitting.

F. User Interface Design

The UI will be designed using HTML and CSS for web application and java for mobile cross platform, featuring intuitive navigation tailored for differently-abled users. Accessibility options such as adjustable font sizes, high-contrast themes, avatar customization, and voice feedback will support diverse user needs. The interface supports instant toggling between gesture input, speech input, and text chat, providing seamless communication pathways. Real-time indicators display connection status and message delivery confirmations to enhance usability.

G. Implementation Details

The backend is powered by Python frameworks—TensorFlow for AI model deployment and Firebase for authentication and real-time database services. 3D avatar animations are developed using Unity with integration to the frontend through REST APIs. The system will be deployed on scalable cloud infrastructure ensuring low latency and high availability. Security protocols including OAuth 2.0 and Firebase security rules are implemented to safeguard user data.

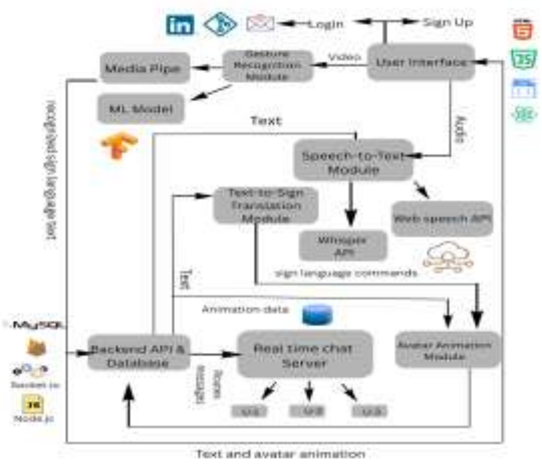

Fig 3. Implementation Of System

H. Performance Evaluation

Performance metrics, including recognition accuracy, latency, and user satisfaction, were gathered through both automated testing and pilot user studies. The end-to-end latency was consistently under 3 seconds, enabling real-time interaction. Usability surveys indicated significant improvements in communication ease and user confidence. Scalability tests showed stable performance across multiple concurrent users, demonstrating system readiness for deployment.

5. APPLICATIONS

SignBridge AI offers a wide range of applications addressing the communication needs of differently-abled individuals, especially the deaf, mute, and blind communities. It serves as an assistive communication tool in educational settings, enabling students to interact with teachers and peers seamlessly. In healthcare, it facilitates communication between patients with hearing or speech difficulties and medical professionals, improving care quality and patient outcomes. The platform's multilingual support and real-time translation capabilities make it suitable for public service environments such as banks, government offices, and customer support centers. Moreover, its accessibility and affordability make it a viable solution for rural and remote areas lacking specialized sign language interpreters. The system also supports learning and preservation of sign languages through interactive modules, promoting broader social inclusion and empowerment.

6. CONCLUSION AND FUTURE SCOPE

This paper presented SignBridge AI, an innovative AI-powered multimodal platform that bridges communication gaps among deaf, mute, blind, and hearing individuals via real-time sign language recognition, speech-to-text conversion, and animated avatar translations. The system achieves high accuracy, low latency, and broad accessibility using standard consumer devices. Pilot testing indicates improved communication efficacy and user acceptance.

Future work will focus on expanding the sign language vocabulary to include regional and contextual variations, incorporating advanced natural language processing for nuanced interpretation. Enhancements in avatar realism and emotion expression will be pursued to enrich interactions. Additionally, integrating tactile or haptic feedback could broaden accessibility for deaf-blind users. Further scalability improvements aim to support larger user bases and offline capabilities. Overall, SignBridge AI is poised to make a substantial societal impact by enabling inclusive and effective communication for differently-abled communities.

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