AI for Real-Time Translation of Sign Language

Durga Prasad Jaiswal[1], Pooja Tupe[2]
[1,2]M.Sc. IT (Artificial Intelligence), [2]Professor
University Department of Information Technology, University of Mumbai, Kalina, Maharashtra, India
[1]dpjaiiswal@gmail.com, [2]ptupe.105@gmail.com

Abstract:

In order to address communication barriers between hearing and deaf people, this paper describes the creation of an AI-based application that enables real-time translation of sign language into speech and text. Convolutional Neural Networks (CNNs), Media Pipe for real time gesture recognition, an easy-to-use user interface, and a feedback loop for ongoing enhancement are all features of the system. The suggested system improves accessibility and inclusivity in fields like public services, healthcare, and education. Future developments will include support for more sign languages and integration with wearable technology.

This paper presents an advanced AI-driven system for Real-time sign language Translation, aiming to eliminate communication barriers between deaf and hard-of-hearing (DHH) individuals and the hearing community. The proposed framework integrates Computer Vision, Deep Learning, and Natural Language Processing (NLP) to enable seamless gesture-to-text and speech-to-sign translation. Utilizing MediaPipe for real-time keypoint detection and a hybrid CNN-LSTM-Transformer architecture, the system effectively captures spatial and temporal patterns of hand gestures and facial expressions. This research contributes to the development of intelligent assistive technologies that promote social inclusion, accessibility, and equality, offering a scalable path toward barrier-free human communication through artificial intelligence.

Keywords: Sign Language Translation, Real-Time Translation, Assistive Technology, Deep Learning, Computer Vision, Natural Language Processing (NLP), Gesture Recognition, MediaPipe, Hybrid Architecture (CNN-LSTM-Transformer), Ethical AI, Accessibility, Low-Resource Languages.

Abbreviations:

AI: Artificial Intelligence, NLP: Natural Language Processing, CNN: Convolutional Neural Network, LSTM: Long Short-Term Memory, ISL: Indian Sign Language

I. INTRODUCTION

Sign language translation (SLT) is the task of translating continuous sign language videos into spoken language sentences. SLT is a challenging multimodal problem that requires both a precise understanding of the signer's pose and the generation of a textual transcription. The current state of the art for automatic SLT is still far away from considering the problem solved [9]. Solving SLT will bring important benefits to the communication between signers and non-signers. Recent advances in SLT have followed a trajectory similar to other computer vision and natural language processing problems: training deep neural networks on large-scale datasets. However, the availability of public sign language datasets is limited and especially reduced when considering parallel corpus of videos and their textual translations, which allow benchmarking the state of the art. [6]

In communication, both spoken words and sign languages serve as vehicles for conveying meaning. However, these elements can have diverse relationships between their form and meaning. Sign languages, for example, have a more visible and direct link between their form and meaning, while spoken languages often exhibit a more arbitrary link between the two. By arbitrary, we mean that the form of a word or sign has no inherent relationship with its meaning. Rather, the meaning of a word or sign arises from societal and cultural conventions. The arbitrariness of spoken language makes it adaptable and flexible, allowing for the introduction of new words and signs to describe new concepts and ideas [16]

1.1 Sign Language and Real-Time Translation

Sign language translators play a crucial role in bridging the gap between the deaf community and the hearing community. They can express themselves in sign language and have the rare capacity to hear spoken language. Deaf people can greatly benefit from the services of translators since they can completely understand and take part in meetings, conferences, and other public events because of the visual representation of spoken messages and the translation of sign language into spoken English. With the help of sign language translators, teachers of deaf students can make their classrooms more accessible to students of all backgrounds. Translators sit in the same class as these students and interpret what their teachers, classmates, and other students are saying. Professional sign language translators ensure that deaf students have the same access to educational content as their hearing peers. Because of this, deaf students can get an education, have their voices heard, and take an active role in class discussions. Furthermore, translators are highly helpful friends to the deaf community. They break down barriers and create new opportunities for progress by improving communication between employees, employers, and customers. Business meetings, job interviews, conferences, and training sessions are just some of the professional contexts where sign language translators may make a difference, allowing deaf people to demonstrate their skills, make valuable contributions, and pursue rewarding careers. Furthermore, sign language translators play a crucial role in guaranteeing that people who are deaf or hard of hearing have access to all necessary services. For example, in the medical field, these experts make sure that patients can ask questions, receive clear answers, and feel confident in the decisions they make regarding their care. A similar service is provided by sign language interpreters, who make it possible for people who are hard of hearing to access legal resources, learn about their rights, and communicate with attorneys. Last but not least, sign language interpreters advocate for the rights of the deaf and hard-of-hearing community. By doing so, they refute myths and promote acceptance in the hearing community by increasing their knowledge of sign language and deaf culture. Sign language interpreters can help society as a whole become more accepting of those with different abilities by spreading information about accessibility and the need for the more widespread use of sign language services. [12]

1.2 Overview of Sign Language

Sign language serves as a mode of communication for individuals with hearing impairments, encompassing a diverse array of components, such as hand gestures, facial expressions, and body movements, to convey meaning. This language employs a distinct grammatical structure and vocabulary, qualifying it as a comprehensive and autonomous language system. Furthermore, sign language usage and interpretation vary across countries and regions, with diverse communities utilizing distinct signs to express similar meanings. Sign language constitutes a valuable instrument that enhances communication between individuals who are deaf or hard of hearing and the hearing community, and it is constantly evolving and gaining more widespread usage and recognition [8]. In their daily interactions, including those with family and friends, people who are deaf or hard of hearing primarily rely on sign languages. It has been established via research that sign languages are actual human languages with unique grammatical structures, vocabularies, and linguistic properties. This insight has boosted awareness of sign languages' significance and contributed to their continued expansion and development. Studies by authors such as Snoddon [9] and Maalej [10] have demonstrated the linguistic complexity of sign languages and the critical role that they play in enabling communication and fostering community among deaf and hard-of-hearing individuals. However, there are a number of differences between spoken and sign languages [11]. Sign languages are visual methods of communication that use hand gestures, facial expressions, and body language to convey meaning. They not only convey linguistic information but also emotions, making them a highly diverse and expressive mode of communication. The vocabulary and syntax of sign languages can vary significantly between different countries and even regions within the same country, as evidenced by research conducted by scholars such as Stokoe [12] and Christopoulos [13]. In order to use sign language proficiently, several factors come into play, including the recognition of hand gestures, movements, facial expressions, and spatial variations, which are linguistically significant. As demonstrated by research conducted by Maalej [10] and Emmorey [5], interpreting sign language is a complex task that requires a deep understanding of the language and its unique features. These studies emphasize the critical role of recognizing sign languages as legitimate human languages and the significant value that they provide in facilitating communication for deaf and hard-of-hearing individuals.

1.3 Challenges in Sign Language

Translation Interactivity is an essential aspect of sign language software programs, as it allows users to actively participate in the learning process and maintain their focus. Sign language, being a visual language, has numerous applications that can effectively aid information sharing and accessibility for the deaf and hard-of-hearing community. In recent years, many tools and applications have been developed to assist individuals in learning sign languages and translating signs into spoken language or text, significantly enhancing communication and accessibility for the deaf and hard-of-hearing community. Studies, such as those conducted in [25], have demonstrated the importance of sign language in enabling communication for those with hearing difficulties, and they emphasize the need for technology to facilitate access to information. [28]

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1.4 Sign Language Translation System Approaches

Sign language recognition systems are typically based on either sensor-based recognition or computer vision technology. Sensor-based recognition systems use a camera to capture hand motion recordings through photographs or videos, which are then processed through image analysis. However, it is worth noting that higher-resolution cameras require more memory space and processing power. Computer vision systems, on the other hand, require high-end sensors and advanced techniques, which can increase the cost and complexity of the system. Additionally, the background must be free from noise and disturbances for the system to function effectively. The software for sign language recognition can be further divided into two approaches: data-glove and visual-based systems [27].

The proposed project focuses on converting sign language into proper sentences as well as developing an application.

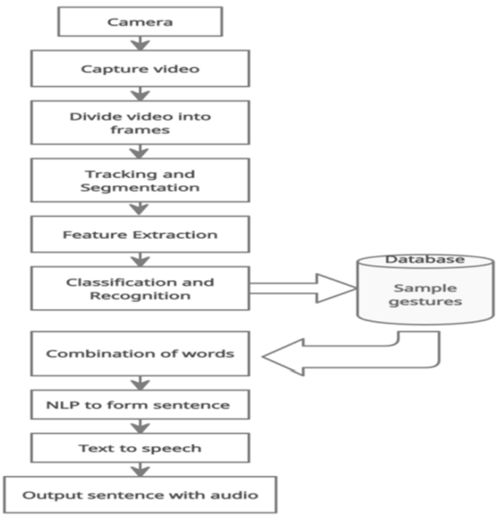

Diagram 1: System Architecture of Real Time Sign Language Interpreter

II. LITERATURE REVIEW

Research on automated sign language recognition has long been a priority. While more recent developments make use of CNNs, RNNs, and transformer-based architectures, earlier techniques depended on manually created features. Among the noteworthy contributions are: Koller et al. (2016) examined the development of methods for recognizing sign language. Transformer-based gesture sequence interpretation was introduced by Camgoz et al. (2018). Hu and Wang (2019): highlighted how well deep learning can identify intricate patterns of visual language. Even with great advancements, problems like real-time performance, multiple sign languages, and dynamic gestures still exist. By emphasizing usability, cultural relevance, and user engagement, our work expands on earlier initiatives. Recent developments in computer vision and deep learning have allowed for real-time sign language recognition using models such as CNNs, LSTMs, and Transformers. OpenPose and MediaPipe enable reliable hand tracking with no additional hardware. Current solutions are mostly unidirectional, only from sign to text or text to sign. Sign All and SL show promising work but are either not scalable or don't implement full bidirectional functionality. This research fills the gap by creating a light, real-time bidirectional sign language translator that translates gestures and also produces visual sign output from text through machine learning. The goal of this paper is to identify the different methods used to translate sign language to text to understand people with disabilities, especially the deaf community. The different creators and innovators used [1] sign language recognition and [2] sign language to text or sign language translation method in their study. The different gathered and filtered studies clustered by publication year with 2019 and 2021 as the highest number of listed used studies in this paper.

III. METHODOLOGY AND SYSTEM DESIGN

The project titled "AI-Based Real-Time Sign Language Translator" adopts a dual-mode, software-centric approach combining computer vision, speech recognition, and text-to-speech technologies. This intelligent system facilitates two-way communication between hearing-impaired individuals and the general public. It operates through real-time gesture detection, voice interpretation, and multimodal output delivery using machine learning pipelines. The methodology involves landmark detection, model training, voice-text conversion, interface development, and end-to-end integration. Each phase is elaborated below. [7]

To realize the Sign Language Translation system, we have meticulously designed and implemented various functionalities to ensure seamless communication between users proficient in sign language and those using spoken language. The implementation is structured around three key modes: Sign Language to Text, Speech to Sign Language, and Learning. To realize the Sign Language Translation system, we have meticulously designed and implemented various functionalities to ensure seamless communication between users proficient in sign language and those using spoken language. The implementation is structured around three key modes: Sign Language to Text, Speech to Sign Language, and Learning. Sign Language to Text: Users have the option to use either a webcam or upload a video, providing

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flexibility in input methods. The application captures video frames in real-time and processes them using MediaPipe's Hand module, ensuring precise hand gesture recognition. Based on the detected gestures, the application identifies sign language letters and displays them on the screen, facilitating instant sign language to text translation. Additionally, a realtime video display of the hand gestures is provided for enhanced user experience. For users who wish to keep a record, the application offers the option to record the video as 'output1.mp4,' enabling them to review their interactions later. Speech to Sign Language: This mode simplifies communication by allowing users to speak into the microphone. The application utilizes the Speech Recognition library to convert spoken words into text, ensuring accurate and real-time speech-to-text conversion. Upon recognizing the spoken words, the application displays the corresponding sign language images, promoting effective communication between speech and sign language users. Learning: The learning mode is designed to facilitate users in learning sign language, focusing on alphabets and numbers. For alphabets, the application provides images and videos for each letter of the alphabet in Indian Sign Language (ISL), serving as a valuable educational resource. Similarly, for numbers, the application offers videos depicting numbers 0 to 9 in ISL, enhancing the learning experience and promoting sign language proficiency. By implementing these functionalities, our Sign Language Translation system empowers users to communicate effectively across different language modalities, fostering inclusivity and accessibility in communication. The methodologies adopted ensure accuracy, real-time processing, and user-friendly interactions, making the system a valuable tool for promoting understanding and integration in diverse communication settings.

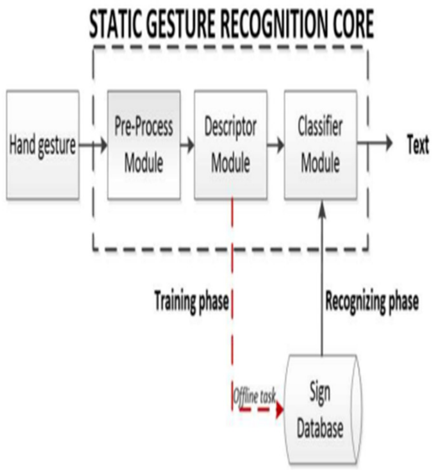
Sign Language to Text:

Sign-to-text translation involves several steps. First, a camera captures sign language gestures, which are then processed using computer vision algorithms. These algorithms analyze the motion, shape, and position of hands and fingers to recognize specific signs. Next, machine learning models interpret these recognized signs based on their context and grammar rules, converting them into corresponding text or spoken language output.

The process requires training the models on large datasets of sign language gestures to improve accuracy and account for variations in signing styles. Deep learning techniques, such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), are often used for robust recognition and translation. Additionally, natural language processing (NLP) algorithms may be

Diagram 2: Sign Language to Text

employed to handle linguistic nuances and produce



coherent text output. Overall, sign-to-text translation systems combine computer vision, machine learning, and NLP technologies to bridge communication gaps between sign language users and non-signing Individuals, facilitating seamless and inclusive interaction. [8]

Speech to Sign Language:

Speech-to-sign language translation involves multiple steps. Initially, the Google Speech API converts spoken language into text, capturing the user's speech input. This text is then processed to identify keywords, phrases, or sentences that correspond to specific sign language gestures. The system compares the extracted text with a database of sign language gestures, which contains mappings between spoken language elements and their corresponding signs.[8]

This database is typically built through extensive data collection and annotation, associating linguistic expressions with their visual representations in sign language. Using this database, the system selects the appropriate sign language gestures that match the recognized text.[15] This matching process can involve algorithms that consider context, grammar rules, and linguistic nuances to ensure accurate translation. Once the matching signs are identified, the system generates a visual output, such as animated avatars or videos, depicting the corresponding sign language gestures. These visual representations are then displayed to the user, providing a realtime translation of their spoken input into sign language. Overall, speech-to-sign language translation systems leverage speech recognition,

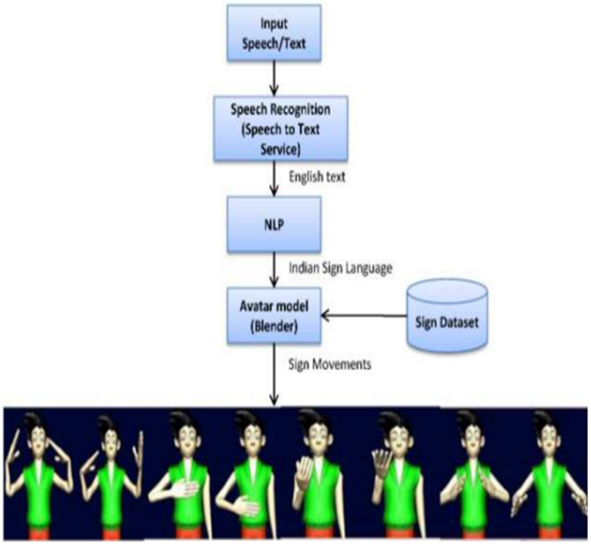


Diagram 3: Speech to Sign Language

database matching, and visualization techniques to facilitate communication between hearing individuals and those who use sign language, enhancing accessibility and inclusivity in communication platforms.[9]

Learning:

Here In the learning mode, users can select from 'alphabets' and 'numbers' to begin learning sign language. For 'alphabets,' the application provides images and videos for each letter of the alphabet in Indian Sign Language (ISL), making it a valuable educational resource. Similarly, for 'numbers,' it offers videos for numbers 0 to 9 in ISL, enhancing the learning experience with visual aids and interactive content. [10]

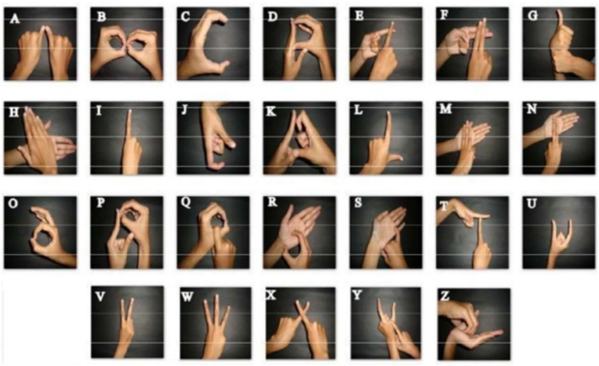


Diagram 4: Alphabets of Indian Sign Languages (ISL)

IV. CONCLUSION AND FUTURE WORK

This Project offers a smart, responsive, and inclusive solution to bridge communication gaps between hearing-impaired individuals and non-signing users. By integrating computer vision, offline speech recognition, and natural language processing, the system provides real-time gesture-to-voice and voice-to-sign translation using accessible hardware and Python-based software. The gesture recognition pipeline, powered by MediaPipe and a Random Forest classifier, demonstrated high accuracy in tracking hand landmarks and predicting gestures across varied lighting conditions. Likewise, the voice module, leveraging the Vosk engine and fuzzy matching, accurately transcribed user commands and mapped them to relevant sign images without internet dependency. Testing validated the system's performance, speed, and multimodal feedback—delivering simultaneous output via images, text, and speech. The interface developed using Tkinter and PIL enabled seamless mode switching, session control, and robust feedback loops, creating an intuitive experience for diverse users. Overall, the translator meets all functional goals and showcases the potential of AI in fostering digital inclusivity through affordable, adaptive, and human-centric design. We conclude that the communication barrier between deaf and dumb people and normal people can be overcome with the help of AI and ML technology. In this work, we used various tools to run an automatic sign language gesture recognition system in real-time. Although our proposed work expected to recognize sign language and convert it to text, there is still plenty of room for future work.

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