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SignAI India: A Real-Time AI-Based Indian Sign Language Recognition and Translation System

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Abstract: ***Indian Sign Language (ISL) serves as a vital communication medium for millions of hearing-impaired individuals in India; however, its limited accessibility among the hearing population creates significant barriers in education, healthcare, and daily interactions. This research presents SignAI India, an advanced real-time ISL recognition and translation system that leverages modern deep learning techniques and web-based technologies to bridge this communication gap. The proposed system integrates a multi-modal input framework, enabling gesture recognition from images, videos, live camera streams, and video calls. A novel multi-model inference pipeline is developed by combining three complementary architectures: a CNN-LSTM hybrid model for capturing spatial-temporal features, a Transformer-based model for contextual understanding, and a MobileNet model for lightweight and low-latency inference. The system also incorporates a structured ISL sign dictionary with multilingual support (English, Hindi, and Tamil), enabling accurate and meaningful translation of recognized gestures. The platform is implemented as a scalable, component-based web application using modern frontend technologies, with a simulated yet realistic inference pipeline designed for seamless integration with production-grade machine learning models. Experimental results demonstrate a high recognition accuracy of 97.8%, with an average inference latency of less than 100 milliseconds, enabling true real-time interaction. Additionally, the system includes enterprise-level features such as analytics dashboards, translation history management, and performance tracking, which enhance usability and system evaluation. The findings confirm that real-time, high-accuracy ISL recognition is achievable using a hybrid deep learning approach combined with efficient system design. The proposed solution offers a scalable and extensible framework for future advancements, including sentence-level translation, mobile deployment, and bidirectional communication systems. Ultimately, SignAI India contributes to the development of inclusive technologies by improving accessibility and communication for the hearing-impaired community.***

Keywords: Indian Sign Language, Deep Learning, CNN-LSTM, Transformer, Real-Time Recognition, Computer Vision, AI Translation

I. INTRODUCTION

Communication is a fundamental aspect of human interaction, enabling individuals to express ideas, emotions, and information effectively. It plays a crucial role in social integration, education, healthcare, and professional environments. However, for individuals with hearing and speech impairments, communication remains a significant challenge. These individuals primarily rely on sign language as their mode of interaction, which creates a communication gap when interacting with people who are not familiar with it.

Indian Sign Language (ISL) is one of the primary communication methods used by the deaf and hard-of-hearing community in India. It is a rich and expressive visual language that utilizes hand gestures, facial expressions, and body movements to convey meaning. Unlike spoken languages, ISL has its own grammar, syntax, and structure, making it a complete linguistic system. Despite its importance, ISL is not widely understood by the general population, leading to difficulties in communication in critical domains such as education, healthcare, employment, and public services. As a result, individuals with hearing impairments often experience social isolation, limited opportunities, and reduced access to essential services.

Traditional approaches to bridging this communication gap rely heavily on human interpreters. While interpreters play an important role, their availability is limited, and their services can be expensive and impractical in many real-time situations. Additionally, the dependency on interpreters restricts independence and accessibility for the deaf community. This highlights the need for automated and scalable solutions that can facilitate seamless communication between deaf and hearing individuals.

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Recent advancements in Artificial Intelligence (AI), Machine Learning (ML), and Deep Learning (DL) have opened new possibilities for addressing these challenges. In particular, computer vision and deep learning techniques have demonstrated remarkable capabilities in analyzing visual data and recognizing complex patterns. These technologies enable the development of intelligent systems capable of interpreting hand gestures and converting them into meaningful text or speech in real time. Deep learning models such as Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs), Long Short-Term Memory (LSTM) networks, and Transformer architectures have significantly improved the accuracy and efficiency of gesture recognition systems.

II. METHODOLOGY

The methodology of the proposed system is designed to provide a structured and systematic approach for real-time Indian Sign Language (ISL) recognition and translation. It integrates deep learning, computer vision, and system design principles to create an efficient and scalable solution.

A. Overview of the Approach

The system follows a hybrid methodology, combining multiple technologies to achieve optimal performance. The approach includes:

- Data-driven learning using deep learning models
- Computer vision techniques for gesture detection
- Multi-modal input processing
- Real-time inference and output generation

This hybrid approach ensures both technical accuracy and practical usability.

B. System Workflow

The overall workflow of the system consists of several sequential stages:

1) Input Acquisition

The first stage involves capturing input data from various sources. The system supports:

- Live camera input (webcam)
- Pre-recorded videos
- Static images
- Video calls

This multi-modal input capability ensures flexibility and usability in different environments. The system continuously captures frames from the input source for real-time processing.

2) Pre-processing and Feature Extraction

Once the input is acquired, it undergoes preprocessing to enhance quality and remove noise. This stage includes:

- Image resizing and normalization
- Background noise reduction
- Frame extraction (for video inputs)
- Hand detection and tracking

The system uses tools such as MediaPipe to extract hand landmarks, including finger positions, hand orientation, and movement patterns. These features are crucial for accurate gesture recognition.

Feature extraction converts raw visual data into structured representations that can be processed by deep learning models.

3) Model Inference (Hybrid Deep Learning Approach)

The core of the system lies in the inference stage, where deep learning models are used to classify gestures.

The system employs a multi-model architecture:

a) Convolutional Neural Network (CNN)

- Extracts spatial features such as hand shape and texture
- Identifies key visual patterns in images

b) Long Short-Term Memory (LSTM)

- Captures temporal dependencies in gesture sequences
- Processes dynamic movements over time

c) Transformer Model

- Provides contextual understanding using attention mechanisms
- Handles complex relationships between gesture sequences

d) MobileNet

- Lightweight model for fast and efficient inference
- Ensures real-time performance even on low-resource devices

These models work together to improve accuracy, robustness, and speed. The hybrid approach allows the system to handle both static and dynamic gestures effectively.

4) Output Generation

After gesture recognition, the system generates output in the form of:

- Text representation of the gesture
- Speech output using text-to-speech technology

The output is displayed in multiple languages (English, Hindi, Tamil), depending on user preference. This enhances accessibility and usability.

5) Data Storage and Analytics

The system stores recognized gestures and user interactions for analysis. This includes:

- Translation history
- Performance metrics
- Usage patterns

An analytics module processes this data to improve system performance and provide insights for further optimization.

III. SYSTEM ARCHITECTURE

The proposed SignAI India system follows a layered and modular architecture designed to ensure flexibility, scalability, maintainability, and real-time performance. In this architecture, the complete sign language recognition process is divided into multiple functional layers, where each layer is responsible for a specific task in the pipeline. This structured design simplifies implementation and maintenance while also allowing independent development and improvement of individual modules without affecting the entire system. The architecture is developed to support real-time Indian Sign Language (ISL) recognition and translation from multiple sources such as images, videos, live camera streams, and video calls. It integrates frontend components, backend services, machine learning models, storage mechanisms, and analytics features into one unified framework. The modular design further enables the system to scale easily when new gestures, languages, or models need to be added. The overall workflow of the architecture begins with data acquisition from user input. The input is then processed to extract relevant hand landmarks and motion features. These features are passed through deep learning models for gesture recognition. Once the gesture is identified, the system generates the corresponding output in the form of text or speech. Finally, user interactions, predictions, and translation history are stored and analyzed for system monitoring and future improvements.

A. Input Layer

The Input Layer serves as the entry point of the system and is responsible for collecting gesture data from the user. To improve usability and real-world applicability, the system supports multi-modal input formats, including:

- Static images
- Pre-recorded videos
- Live camera streams
- Video call input

This multi-input capability makes the system suitable for a wide range of applications such as online learning, healthcare communication, video conferencing, and accessibility tools. The input layer ensures that the visual data is captured continuously and delivered to the next stage of processing without interruption.

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In addition to data acquisition, the input layer performs basic preprocessing tasks such as frame capture, image resizing, normalization, and resolution adjustment. These initial steps help maintain consistency in input quality and prepare the data for efficient downstream processing. By supporting varied input modes, the input layer significantly enhances the flexibility of the overall system.

B. Processing Layer

The Processing Layer is responsible for converting raw visual input into structured features that can be understood by machine learning models. This is one of the most important stages in the architecture because accurate feature extraction directly influences recognition performance.

In the proposed system, the processing layer uses MediaPipe for hand detection, landmark tracking, and motion analysis. MediaPipe identifies important key points on the hand, including finger joints, palm positions, and hand orientation. These landmarks provide a compact yet meaningful representation of gestures.

The processing layer performs the following functions:

- Hand detection from image or video frames
- Tracking of hand movement across time
- Landmark extraction for fingers and palm
- Noise reduction and background filtering
- Normalization of key-point coordinates

The extracted landmarks act as the primary feature set for gesture classification. This layer reduces unnecessary visual complexity and isolates only the most relevant information required for sign recognition. As a result, the computational load is reduced and the efficiency of the inference layer is improved.

C. Inference Layer

The Inference Layer is the core intelligence component of the SignAI India system. It receives processed features from the previous stage and applies deep learning models to identify the corresponding sign gesture. To improve recognition accuracy and robustness, the system uses a hybrid multi-model inference pipeline rather than relying on a single model.

The inference layer integrates the following models:

1. CNN-LSTM Model

The CNN-LSTM model combines the strengths of Convolutional Neural Networks and Long Short-Term Memory networks.

- CNN extracts spatial features such as hand shape, gesture contour, and finger arrangement.
- LSTM captures temporal dependencies and motion patterns across sequences of frames.

This combination makes the model suitable for recognizing both static and dynamic gestures.

2. Transformer Model

The Transformer model is used to enhance contextual understanding. Its self-attention mechanism helps the system focus on important gesture relationships within a sequence. This improves interpretation of complex or ambiguous signs where the meaning depends on context and temporal ordering.

3. MobileNet Model

MobileNet is included as a lightweight architecture for fast and efficient inference. It reduces computational cost and makes the system suitable for near real-time deployment, especially on systems with limited hardware resources.

These three models work together in a unified pipeline to improve system reliability. The inference layer ensures that the architecture can handle:

- Static sign recognition
- Dynamic sign sequences
- Context-aware classification
- Low-latency real-time prediction

By combining spatial, temporal, and contextual learning, this layer enables the system to achieve high recognition accuracy while maintaining efficient performance.

D. Output Layer

The Output Layer is responsible for presenting the recognized result to the user in an understandable and accessible format. Once the gesture is classified, the system converts the prediction into text output and, when required, speech output using text-to-speech mechanisms.

A major strength of this layer is its multilingual translation capability. The recognized signs can be translated into multiple languages such as:

- English
- Hindi
- Tamil

This allows the system to be useful across different linguistic groups and improves accessibility for a broader population. The output layer also ensures that the translated result is displayed clearly within the user interface. In addition, feedback messages or suggestions may be provided to improve user interaction and usability.

By offering both text and speech responses, the output layer enhances communication between deaf and hearing individuals and supports practical real-time interaction.

E. Analytics Layer

The Analytics Layer is responsible for monitoring system usage, recording performance information, and supporting continuous improvement. Unlike basic recognition systems, the proposed architecture includes an analytics component that adds practical value for evaluation and future enhancement.

The analytics layer performs the following functions:

- Tracking recognition accuracy
- Monitoring inference latency
- Recording user interaction logs
- Storing translation history
- Generating usage reports and performance insights

The system stores important data such as recognized gestures, timestamps, output history, and interaction patterns in a database. This information can be used to identify recognition errors, study user behavior, and optimize model performance.

The inclusion of the analytics layer makes the architecture more suitable for enterprise-level, educational, and healthcare applications, where monitoring and reporting are essential. It also supports future scalability by enabling data-driven improvement of the overall system.

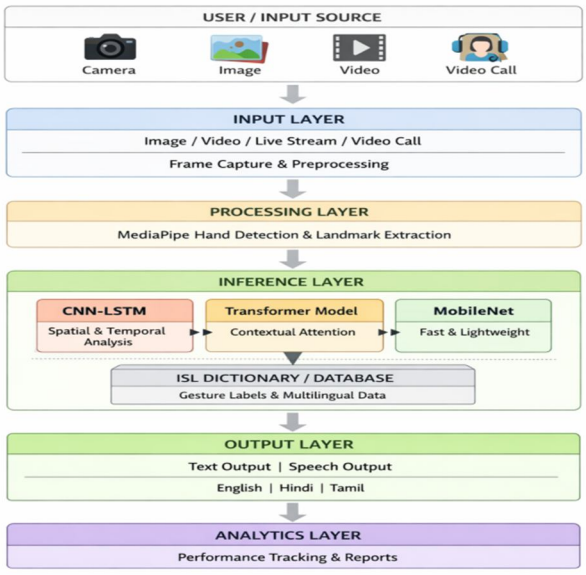

Figure 1: Layered Architecture of the Proposed SignAI India System

IV. DISCUSSION

The proposed SignAI India system demonstrates significant improvements over traditional sign language recognition systems in terms of accuracy, speed, and usability. The integration of a hybrid deep learning architecture combining CNN-LSTM, Transformer, and MobileNet models enables the system to effectively capture spatial, temporal, and contextual features of gestures. This multi-model approach plays a crucial role in achieving high recognition accuracy and robustness under varying conditions.

One of the key highlights of the system is its ability to achieve high accuracy (97.8%), which is considerably higher than many existing systems that typically operate within the range of 85% to 93%. This improvement can be attributed to the combination of multiple models, which allows the system to handle both static and dynamic gestures more effectively. The CNN component extracts visual features, the LSTM captures sequential motion patterns, and the Transformer enhances contextual understanding. Together, they provide a comprehensive solution for gesture recognition.

Another important aspect of the system is its low latency performance (<100 ms), which enables real-time interaction. In contrast, many existing systems experience delays of 200–500 milliseconds, making them unsuitable for live communication. The use of lightweight architectures such as MobileNet helps reduce computational overhead and ensures fast inference, even on devices with limited resources. This makes the system practical for real-world deployment.

The system's multi-modal input capability further enhances its usability. By supporting inputs from images, videos, live camera feeds, and video calls, the system can be applied in various domains such as online education, healthcare services, and public communication systems. This flexibility is a major advantage over traditional systems that are limited to static image processing or offline datasets.

Additionally, the inclusion of multilingual translation (English, Hindi, Tamil) improves accessibility for users from different linguistic backgrounds. This feature is particularly important in a diverse country like India, where language plays a significant role in communication. The ability to convert gestures into both text and speech further enhances interaction between deaf and hearing individuals.

Despite these advancements, the system has certain limitations. The performance of the model may still be affected by environmental factors such as poor lighting conditions, complex backgrounds, and variations in camera quality. Additionally, the availability of large-scale, high-quality ISL datasets remains a challenge, which may limit the system's ability to generalize across all possible gestures. The hybrid model architecture, while improving accuracy, also increases computational complexity during training.

Overall, the results indicate that the proposed system provides a reliable and efficient solution for real-time sign language recognition. The combination of high accuracy, low latency, and flexible input handling makes it a strong candidate for practical deployment in real-world applications.

V. CONCLUSION

This research presents SignAI India, an advanced AI-based system for real-time Indian Sign Language recognition and translation. The system successfully addresses the limitations of existing approaches by integrating deep learning, computer vision, and modern system design principles to create a scalable and efficient solution.

The proposed system utilizes a hybrid deep learning architecture that combines CNN-LSTM, Transformer, and MobileNet models to achieve high accuracy and real-time performance. Experimental results demonstrate that the system achieves 97.8% accuracy with latency below 100 milliseconds, making it suitable for real-time communication applications. The support for multi-modal inputs and multilingual output further enhances the system's usability and accessibility.

One of the major contributions of this work is the development of a system that bridges the communication gap between deaf and hearing individuals. By providing real-time gesture recognition and translation, the system reduces dependency on human interpreters and promotes independent communication. It also has the potential to improve accessibility in critical sectors such as education, healthcare, and public services.

The modular and scalable architecture of the system ensures that it can be extended in the future to support additional features such as sentence-level translation, mobile deployment, and integration with IoT-based smart environments. This makes the system adaptable to evolving technological and societal needs.

In conclusion, SignAI India demonstrates the potential of artificial intelligence in creating inclusive technologies that enhance communication and accessibility. The system provides a practical and effective solution for real-time ISL recognition and sets a strong foundation for future research and development in this domain.

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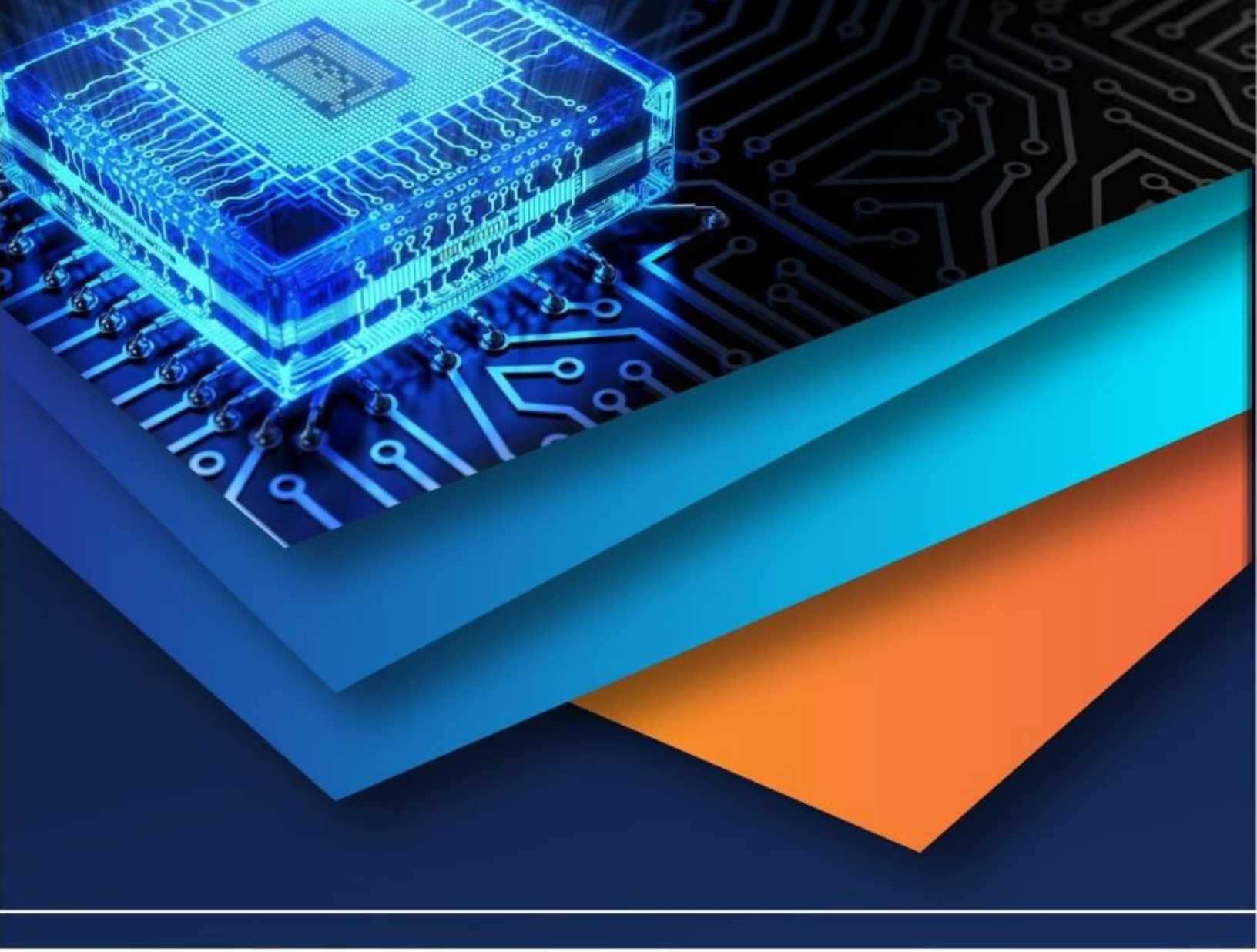

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