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Advancing Indian Sign Language Translation: A Comprehensive System for Punjabi Text Using Synthetic Animations

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Abstract
In the changing realm of technology-based education, efficient communication tools for diverse language groups are crucial. This work presents the automated translation system for Punjabi text to Indian Sign Language (ISL) using synthetic animations, addressing a critical gap in regional language inclusivity. Unlike prior systems (e.g., Hindi/English-centric tools with static images), our approach integrates rule-based methodologies with Punjabi-specific NLP tools a part-of-speech (POS) tagger and stemmer to resolve morphological complexities unique to Punjabi.The system incorporates a bilingual dictionary of 3,500 Punjabi-ISL words, validated against the Indian Sign Language Research and Training Centre (ISLRTC)'s standardized 10,000-word corpus, with dynamic gestures accounting for regional variations. Synthetic animations generated via the HamNoSys framework were rigorously evaluated by 125+ deaf students, instructors, and Indian Sign Language (ISL) experts across Punjab, achieving 80% accuracy for basic sentences (1,000 tested) and 70% for complex/compound sentences (500 tested). Designed for practical deployment, this system empowers Punjabi-speaking parents of deaf children, educators, and public services to bridge communication gaps. Future work will expand the dictionary using active learning and integrate transformer-based models (e.g., PunjabiBERT) for enhanced contextual accuracy.

Keywords: ISL, HamNoSys, NLP tool for Deaf, Natural Language Processing.

Introduction
Sign language is a gesture-based language that is employed by individuals who are deaf to communicate with hearing individuals and one another (Dhanjal, A., & Singh, W., 2018). Since deaf individuals are unable to communicate directly with hearing individuals, they can utilise sign language to interchange their thoughts, emotions, ideas, and feelings with those who are hearing (Irving, A., & Foulds, R. ,2005). Individuals who suffer from speech and auditory impairments engage in sign language (Nasr, M.M., 2010). Prior systems (Chakladar et al., 2021) focused on English/Hindi and lacked regional language support. By integrating Punjabi NLP tools and ISL grammar rules, our work bridges this gap, enabling context-aware translations for Punjabi-speaking deaf communities. In India the language used by Hearing Impaired people to communicate with each other is called Indian Sign Language. Unlike previous systems that focused on static dictionaries of 200 words without grammar integration, our work introduces the first Punjabi-ISL system combining 3,500 words with 20 validated grammar rules and NLP tools like a Punjabi stemmer (98.66% accuracy). This addresses Punjabi's morphological complexity, a gap in prior Hindi/English-centric systems.

1.1 Important Facts about Indian Sign Language.
- ISL is the primary sign language utilised by the deaf community in India, which is a unique characteristic. It is distinct from spoken languages such as Hindi, Punjabi, or English in terms of its grammar, syntax, and structure (Goyal, L., & Goyal, V. , 2016).
- In India, approximately 2 million deaf individuals utilise ISL; however, there is a scarcity of comprehensive data regarding its precise user base because of inadequate documentation and awareness.
- The grammar of ISL is not derived from spoken or written Indian languages. It employs visual and spatial grammar, utilising hand gestures, facial expressions, and body language to communicate its message (Dasgupta, T., & Anupam, B. ,2008).
- India does not recognise ISL as a national language. The Indian Sign Language Research and Training Centre has been working to standardise and promote ISL.
- In 2018, ISLRTC produced the first official ISL dictionary, featuring thousands of words and signs, with the objective of standardizing ISL and increasing its usage statewide.
- Unlike ASL or BSL, ISL differs somewhat throughout India, making standardisation difficult.

- Punjabi's rich morphology and SOV structure pose unique challenges for ISL translation, compounded by the lack of resources for its 2.8 million hearing-impaired speakers in Punjab (Census 2021).

1.2 Objectives

To address the facts and research gaps, our study aims to achieve the following objectives:

- To comprehend Indian Sign Language (ISL) and its grammatical structure.
- To create diverse ISL grammatical rules for Punjabi text.
- To create a bilingual dictionary for translating Punjabi text into Indian Sign Language.
- To integrate a variety of Punjabi NLP tools that are essential for the system, current tools will be adapted to meet specific requirements.
- To design an algorithm for converting Punjabi text into Indian Sign Language via synthetic animations.

1. HamNoSys (Hamburg Notation System)

Sign language needs a distinct written form for accurate representation and comprehension. The Hamburg Sign Language Notation System (HamNoSys) is a specialised framework used for the transcription of signs across several languages. It employs phonetic symbols to delineate signing criteria, including hand forms, orientation, location, gestures, and positioning (Dhanjal, A.S., & Singh, W., 2022).

HamNoSys enables the transcription of signing motions but necessitates proficiency in both HamNoSys and Indian Sign Language (ISL), since it needs users to comprehend its notation system and associated semantics. The HamNoSys syntax systematically delineates certain parameters for precise representation as shown in Fig. 1.

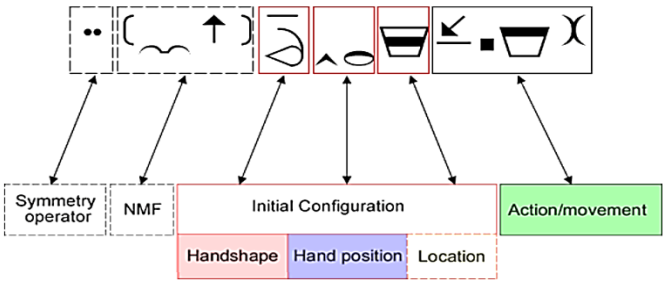

Fig. 1: HamNoSys General Structure

2. Signing Gesture Markup Language (SiGML)

SiGML is a scripting language that is employed to represent HamNoSys symbols in XML tag format. A database for American Sign Language (ASL) and British Sign Language (BSL) is included in the eSiGN Editor, which is based on SiGML. A system has been devised to translate HamNoSys symbols into SiGML, as each sign language is distinct, including Indian Sign Language. This system converts SiGML files into a SiGML client for subsequent processing. The following is an example of a SiGML file.

```
<sigml>
<hns_sign gloss="ਹੈਲੋ">
<hamnosys_nonmanual>
<hamextfingerol/>
<hampalmu/><hamchest/>
<hamparbegin/>
<hamreplace/><hamflathand/>
<hamthumboutmod/>
<hamfingerstraightmod/>
<hamextfingeru/><hambetween/>
<hamextfingero/><hamshoulders/>
<hambetween/>
<hamchest/><hamclose/>
<hamparend/>
<hamrepeatfromstart/></hamnosys_manual>
</hns_sign>
</sigml>
```

3. Literature Survey

Indian Sign Language (ISL) has become a significant research area in computer science in recent years. The development of systems that translate Indian language text into ISL across India's 22 official languages is the subject of numerous research initiatives. Table 1 and Table 2 contain summaries of a variety of ISL translators.

Table 1: Different ISL Translators

Author	Language
Kar, P., Reddy, M., Mukerjee, A., & Raina, A. (2006).	Hindi
Verma, A., & Kaur, S. (2015)	Punjabi
Vij, P., & Kumar, P. (2016)	Hindi
Nair, M.S., Nimitha, A.P., & Idicula, S.M. (2016)	Malayalam
Goyal, L., & Goyal, V. (2016)	English
Dhanjal, A., & Singh, W. (2018)	Punjabi
Chakladar, D., Das, K., Mandal, S., Roy, P.P., Iwamura, M., & Kim, B.G. (2021)	English
Dhanjal, A.S., & Singh, W. (2022)	English
Sharma, P., Tulsian, D., Verma, C., Sharma, P., & Nancy, N. (2022)	English
Bhagwat, S., Bhavsar, R., & Pawar, B. (2023)	Marathi
Aasofwala, N., Verma, S., & Patel, K. (2023)	Gujrati
Rajesh, S., Bhagwat, R.P., Bhavsar, B.V., & Pawar, B.V. (2024)	Marathi

Kar, P., Reddy, M., Mukerjee, A., & Raina, A. (2006) utilised HamNoSys notation to correspond Hindi sentences to ISL gestures in the development of INGIT for the Indian Railway Reservation System. Using a corpus of 230 sentences, it generates ISL identifiers for 3D animations. Although beneficial for deaf individuals at railway stations, it only translates the clerk's voice, necessitating that deaf users respond through forms.

Verma, A., & Kaur, S. (2015) translator converts Gurumukhi script to ISL, but their concentration is solely on translating Punjabi to English, disregarding ISL grammar standards. This instrument is a straightforward dictionary-based system that operates with a restricted database of 200 fundamental words. It is unable to manage complex or sentence-level translations, however, as a result of the absence of grammar rule integration.

Vij, P., & Kumar, P. (2016) have created a Hindi-to-ISL translator that employs WordNet to identify synonyms in the event that the input words are unavailable. It struggles with negative, complex, and compound sentences due to incomplete rule implementation, despite applying ISL grammar rules based on POS labelling.

Nair, M.S., Nimitha, A.P., & Idicula, S.M. (2016) created a technique to convert 100 fundamental Malayalam words into Indian Sign Language using synthetic animation. Although it functions as a sign language instructional resource for Kerala, it fails to include ISL grammatical principles in its translations. Goyal, L., & Goyal, V. (2016) implemented synthetic animation to create a real-time English-to-ISL translator. The animations featuring a robotic avatar are generated using HamNoSys code, SiGML tags, and ISL grammar constraints. It is effective in public spaces; however, it encounters difficulties with complex sentences, non-manual signs, and time-intensive animation generation.

Dhanjal, A., & Singh, W. (2018) proposed a system that utilises synthetic animations to translate Punjabi text into ISL, which is based on VisiCAST. A database of 100 words is currently in use, and endeavours are being made to expand it. The system is advantageous for sign language training; however, it is deficient in the incorporation of ISL Punjabi grammar and contemporary technologies such as machine learning.

Chakladar, D., Das, K., Mandal, S., Roy, P.P., Iwamura, M., & Kim, B.G. (2021) introduced a 3D avatar system that translates speech or text into sign language, enabling continuous sign movement. The method employs sophisticated animation techniques to improve the precision of communication. The paper is innovative in that it emphasises continuous signature; however, it lacks comprehensive insights into the incorporation of grammar for specific languages.

Sharma, P., Tulsian, D., Verma, C., Sharma, P., & Nancy, N. (2022) designed a system that converts voice into Indian Sign Language using natural language processing methodologies. The work uses NLP to enhance translation efficiency but does not thoroughly explore the integration of ISL grammar rules or the management of complicated sentence structures.

Bhagwat, S., Bhavsar, R., & Pawar, B. (2023) tackled the issue of managing concurrent morphology in sign languages for cross-modal machine translation from Marathi to Indian Sign Language. The work emphasises linguistic intricacies but need more refinement to tackle grammatical regulations and scalability for wider applications.

Aasofwala, N., Verma, S., & Patel, K. (2023) automated the process of translating the Gujarati script into the Gujarati Sign Language by use of computer-generated animations. Despite the method's usefulness for translating letters, it is unable to translate sentences or include grammatical rules.

Rajesh, S., Bhagwat, R.P., Bhavsar, B.V., & Pawar, B.V. (2024) developed a low-resource Marathi-to-Indian Sign Language machine translation system. While promising, the technology might improve with improved ISL grammar processing and complicated phrase translation.

Table 2 : Summary of different ISL translators

References	Year	Grammar rules follow or not	Database	Output type	Testing	POS tagger name	Accuracy
Kar, P., Reddy, M., Mukerjee, A., & Raina, A. (2006).	2006	Yes	230 Sentences used in railway by the clerk	Synthetic Animation	ISL experts	Input Parser only for Indian Railway corpus	_
Verma, A., & Kaur, S. (2015)	2015	No	200 basic words used in the Punjabi language	Synthetic Animation	Compared with ISL Dictionary by ISLRTC	_	_
Vij, P., & Kumar, P. (2016)	2016	No	_	Synthetic Animation	ISL experts	Hindi Dependency Parser	_
Nair, M.S., Nimitha, A.P.,	2016	No	100 basic words of the Malayalam language	Synthetic Animation	ISL experts and deaf students of the National	_	80%

& Idicula, S.M. (2016)					Institute of Speech and Hearing, Trivandrum		
Goyal, L., & Goyal, V. (2016)	2016	Yes	1818 most commonly used English words	Synthetic Animation	By Sign Language Expert	Stanford Parser	82%
Dhanjal, A., & Singh, W. (2018)	2020	No	100 basic words used in the Punjabi language	Synthetic Animation	ISL experts and Teachers of deaf school Patiala	_	_
Chakladar, D., Das, K., Mandal, S., Roy, P.P., Iwamura, M., & Kim, B.G. (2021)	2021	No	200 basic English sentences	Synthetic Animation	ISL experts	_	Sign Error Rate (SER) of 10.50 during tests
Dhanjal, A.S., & Singh, W. (2022)	2022	Yes	English, Punjabi, Hindi (100 words for each)	Synthetic Animation	ISL experts	_	_
Sharma, P., Tulsian, D., Verma, C., Sharma, P., & Nancy, N. (2022)	2022	Yes	200 Basic sentences of English	Synthetic Animation	ISL experts	_	_
Bhagwat, S., Bhavsar, R., & Pawar, B. (2023)	2023	Yes	Marathi Sentences	Synthetic Animation	ISL experts	_	_
Aasofwala, N., Verma, S., & Patel, K. (2023)	2023	Yes	Gujrati Sentences	Synthetic Animation	ISL Experts	_	_
Rajesh, S., Bhagwat, R.P., Bhavsar, B.V., & Pawar, B.V. (2024)	2024	No	Marathi Sentences	Synthetic Animation	ISL Experts	Marathi language-specific tools	_

4. Methodology

This section describes the methods used to develop the Indian Sign Language (ISL) Translation System, which converts Punjabi text into Indian Sign Language (ISL) using synthetic animations. Our system uses rule-based methods instead of AI/ML models because (1) data scarcity—there aren't enough Punjabi-ISL datasets to train reliable models; (2) linguistic complexity—Punjabi's unique grammar precise, handcrafted rules; and (3) validation needs—experts and deaf communities helped refine the system to ensure accuracy for real-world use. For now, rules work better with limited resources, but we'll explore AI as datasets grow. The translation process is structured into several modules, each handling a specific function such as text preprocessing, POS tagging, word elimination, stemming, and SiGML file generation. These modules collaboratively convert input text into corresponding Indian Sign Language (ISL) gestures through well-established linguistic mappings and syntactic rules. The dataset comprises 1,000 simple and 500 complex Punjabi sentences sourced from educational materials and ISLRTC's standardized corpus, covering domains like healthcare, education, and daily communication. The following subsections detail these critical components of the system, and Fig. 2 illustrates the overall architecture.

5.1 System Overview

This proposed system aims to translate Punjabi text into Indian Sign Language (ISL) synthetic animation videos. The architecture consists of several stages, as illustrated in Fig. 2, and each stage plays a crucial role in the overall process. Below is a step-by-step explanation of the system:

Stage 1: Pre-processing

1. **Cleaning the Input Text**

- Extra spaces within the sentence are removed to ensure a clean structure.
- Non-Punjabi characters, except numerals, are filtered out.

2. **Purpose**
   - These steps enhance the input data quality for subsequent processing.

Stage 2: Part of Speech (POS) Tagging

1. **Assigning POS Tags**
   - A POS tagger assigns grammatical tags (e.g., noun, verb, adjective) to each word in the input sentence.
   - Subcategories like proper nouns or transitive verbs may also be identified.
2. **Existing POS Tagger**
   - The system uses a pre-existing Punjabi POS tagger to simplify this task.

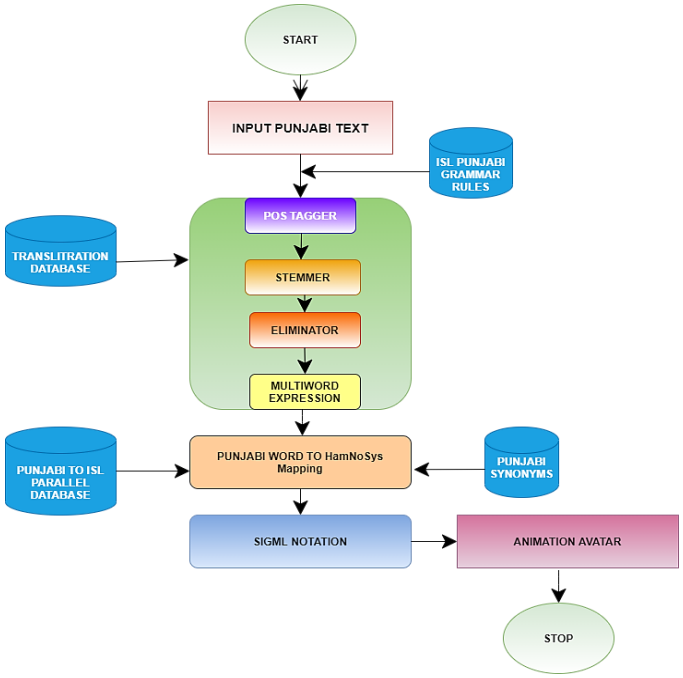

Fig. 2: Architecture of Punjabi Text to ISL Synthetic Animation System.

Stage 3: Eliminator

1. **Elimination of Unnecessary Words**
   - Words like articles, conjunctions, prepositions, suffixes, modals, and certain adverbs are omitted.
   - These words do not contribute to ISL sentence structure.
2. **ISL Sentence Formation**
   - The remaining words are rearranged based on ISL grammar rules, ensuring proper order and structure.
3. **Outcome**
   - A reduced sentence with only meaningful words is prepared for the next stage.

Stage 4: Stemming

1. **Extracting Root Words**
   - Stemming algorithms convert words into their root or base forms.
   - For example, "running" would be reduced to "run."
2. **Purpose in ISL**
   - ISL sentences use root words to convey meanings effectively.
   - Words with suffixes, inflections, or gerunds are stemmed into their base forms.
3. **Integration of Punjabi Stemmer**
   - The system incorporates a Punjabi stemmer for this purpose.

Stage 5: SiGML File Generation

1. **Filtering Punjabi Text**
   - The processed text from earlier stages is matched with the SiGML (Signing Gesture Markup Language) database to retrieve corresponding files.
2. **Handling Missing Words**
   - If no SiGML file exists for a word, its synonym is retrieved from the synonyms database.
   - If neither the word nor its synonym is available, the Punjabi-to-English database provides an English equivalent.
   - The avatar performs fingerspelling for English words or named entities.
3. **Output**
   - The SiGML file generated here is used to produce ISL synthetic animation. The animated avatar presents the translation in ISL, completing the process.

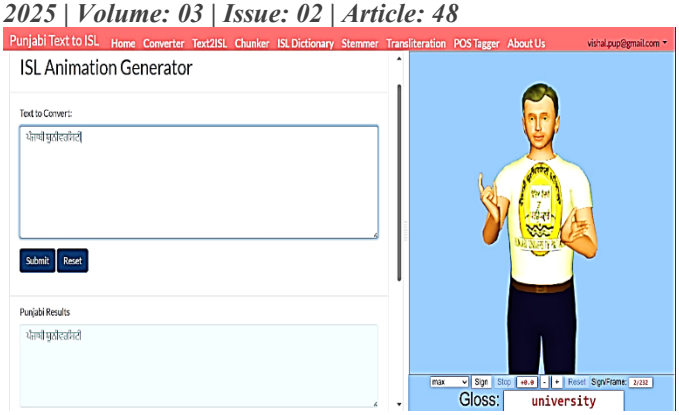

Fig. 3: The developed Translation System View

5.2 Key Modules of the System

The primary components of the developed system are the ISL Dictionary for Punjabi text, ISL grammar rules for Punjabi text, Punjabi Stemmer, Punjabi-to-English transliteration, and the Punjabi Part-of-Speech (POS) tagger, among others. This section presents an overview of essential technologies that are pivotal in translating Punjabi text into Indian Sign Language.

5.2.1 Indian Sign Language Dictionary for Punjabi Text

The development of a comprehensive bilingual dictionary is foundational to enabling robust Punjabi-to-Indian Sign Language (ISL) translation. This dictionary was systematically developed in three incremental phases: an initial lexicon of 774 terms, followed by expansions adding 1,026 words (Phase II) and 1,700 words (Phase III). Currently, the dictionary encompasses 3,500 Punjabi-ISL entries, organized into different domain-specific categories. Each sign is rigorously validated against the Indian Sign Language Research and Training Centre (ISLRTC) standardized video dictionary to ensure linguistic accuracy, regional variation compliance, and alignment with ISLRTC's nationally recognized benchmarks.

To enhance usability, the dictionary integrates a user interface where selecting a lexical entry triggers a synthetic avatar to demonstrate the corresponding ISL gesture (Fig. 4). Future expansions will align with ISLRTC's 10,000-word ISL dataset (2023), incorporating advanced morphological derivations and semantic categories. This ongoing effort prioritizes collaboration with ISL linguists and leverages ISLRTC's evolving corpus to address gaps in low-resource domains.

Fig. 4: Indian Sign Language dictionary for Punjabi Text using Synthetic Animations

5.2.2 Punjabi Stemmer and POS Tagger

The Stemmer and the Part-of-Speech (POS) Tagger are two linguistic tools that are vital to the translation process for the Punjabi language. These tools have been incorporated into our system effectively. Fig. 5 shows the results of the Stemmer's rigorous testing using a 1,000-word dataset, where it attained an outstanding accuracy rate of 98.66%. The system's capacity to efficiently handle complicated language tasks is greatly improved by this integration.

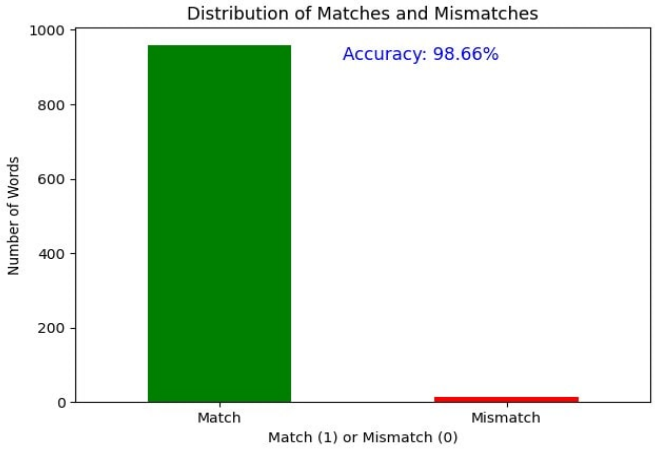

Fig. 5: Distribution of Matches and Mismatches in Stemmer Module with an Accuracy of 98.66%

5.2.3 Punjabi Text to English Transliteration

Our system incorporates the transliteration module without any hitches. Quickly and accurately, this module converts named things from Punjabi to English. With a corpus of 500 distinct named things, it attained an accuracy rate of 79.10%, as shown in Fig. 6.

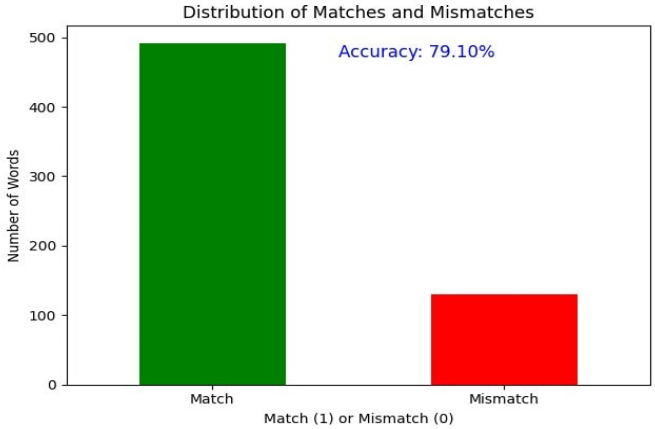

Fig. 6: Distribution of Matches and Mismatches in Transliteration System with an Accuracy of 79.10%

5.2.4 Indian Sign Language Grammar Rules for Punjabi Text

This method applies particular principles of ISL Punjabi grammar to convert Punjabi text into ISL (Indian Sign Language). After then, the user receives the output. Due to a lack of interpreters and hearing-impaired people who are fluent in both Punjabi and ISL, it is difficult to develop these grammatical rules.

With the help of ISL interpreters and instructors from the Deaf School in Saifdipur Patiala, 2000 Punjabi phrases were analysed, and 20 rule for ISL grammar have been put into practice so far. Below are the first two rules developed for translating Punjabi text into Indian Sign Language (ISL), derived through collaboration with ISL interpreters and educators and validated by the deaf community. These rules address syntactic simplification and alignment with ISL grammar.

Rule 1: When Punjabi simple sentences are converted into Indian Sign Language during translation helping verb is removed like '**ਹੈ**', '"ਹਨ", "ਹਾਂ ",**"ਹੋ**",

Example:

Punjabi text	Indian Sign language (ISL)
ਮੈਂ ਸਕੂਲ ਜਾ ਰਿਹਾ ਹਾਂ ।	ਮੈਂ ਸਕੂਲ ਜਾ ਰਿਹਾ ।
ਬੱਚਾ ਬਿਮਾਰ ਹੈ ।	ਬੱਚਾ ਬਿਮਾਰ ।
ਤੁਸੀਂ ਕੀ ਕਰ ਰਹੇ ਹੋ ?	ਤੁਸੀਂ ਕਰ ਰਹੇ ਕੀ

Rule 2: When Punjabi Interrogative sentences are converted into Indian Sign Language then 'Questions' word like "**ਕੀ**", "**ਕਿੱਥੇ**", "**ਕਦੋਂ**", "**ਕਿਹੜਾ**", "**ਕਿਸੇ**", "**ਕੌਣ**", "**ਕਿਵੇਂ**", "**ਕਿਉਂ**" will be added at the end of the sentence and we will neglect the helping verb like "**ਹਾਂ**", "**ਹੈ**", "**ਹਨ**", "**ਹੋ**", "**ਸੀ**", "**ਸਨ**"

Example:

Punjabi text	Indian Sign language (ISL)
ਅਸੀਂ ਕਿੱਥੇ ਜਾ ਰਹੇ ਹਾਂ ?	ਅਸੀਂ ਜਾ ਰਹੇ ਕਿੱਥੇ
ਤੁਸੀਂ ਕੌਣ ਹੋ ?	ਤੁਸੀਂ ਕੌਣ
ਤੁਸੀਂ ਘਰ ਕਦੋਂ ਜਾਣਾ ?	ਤੁਸੀਂ ਘਰ ਜਾਣਾ ਕਦੋਂ
ਤੁਹਾਡਾ ਸ਼ਹਿਰ ਕਿਹੜਾ ਹੈ ?	ਤੁਹਾਡਾ ਸ਼ਹਿਰ ਕਿਹੜਾ

5. Results and Discussion

The system's accuracy was rigorously tested by ISL experts, hearing-impaired students, and their teachers from various schools across Punjab. Their evaluations provided crucial insights into the system's performance. The system achieved an average rating of 4.0 out of 5 and 80% accuracy with basic sentences, which was a significant improvement. It is possible to attribute this success to the reduced variability in linguistic patterns and the simplicity of grammatical structures. In contrast, complex/compound sentences presented more difficult challenges, as evidenced by an average rating of 3.5 out of 5 and a reduced accuracy of 70%. These challenges were the result of the inability to comprehend nuanced sentence structures, conjunctions, and clauses. We sincerely appreciate the feedback regarding the limitations in non-manual sign execution (e.g., facial expressions, body posture) by the synthetic avatar and reduced accuracy for complex/compound sentences. These observations align with our internal evaluations and are critical areas for improvement.

Sentence Type	Number of Sentences	Average Rating (out of 5)	Accuracy (%)
Simple Sentences	1,000	4.0	80%
Complex/Compound Sentences	500	3.5	70%

Several areas necessitate consideration in order to enhance the system's performance:

- Improvement of Linguistic Tools: To more effectively manage intricate grammar and linguistic variability, it is necessary to use advanced AI model like PunjabiBERT and enhanced rule-based systems.
- Enhancing Non-Manual Sign Representation: The current HamNoSys-to-SiGML pipeline focuses primarily on manual gestures (handshapes, movements), underrepresenting non-manual markers like eyebrow raises (for questions) or head tilts (for negation).
- Dictionary Expansion: To ensure precise translation, it is imperative to have a more comprehensive ISL dictionary that encompasses synonyms, idiomatic expressions, and a diverse vocabulary.
- Contextual Awareness: The system's capacity to interpret and translate nuanced sentences effectively can be improved by incorporating context-aware translation mechanisms, such as machine learning models.
- Expertise Collaboration: It is imperative to maintain ongoing communication with linguistic experts and ISL interpreters to enhance the system's knowledge base and refine grammar rules.
- The system will be able to more effectively manage linguistic complexity and provide more accurate translations across a variety of sentence types because of these enhancements.

6. Applications and Impact

Improving the quality of life for the deaf and their families is only one of many potentials uses for the newly created Punjabi-to-ISL translation system. Because it bridges

Punjabi and Indian Sign Language, the system is a crucial tool for instructors in deaf schools, allowing them to communicate effectively with pupils. Both student participation and the quality of what is learnt in class are improved by this. This method ensures that people who are deaf are able to communicate with service providers in public places including hospitals, train stations, and government offices. For parents of deaf children who are only fluent in Punjabi and not English, the system's usefulness is one of its most notable benefits. By improving their communication skills, these parents are able to strengthen the bonds within their families. The system fosters inclusion and contributes to the creation of a more accessible and equitable society for the deaf population by removing crucial communication hurdles.

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