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PAPER

Development of a Mobile Application with Artificial Intelligence for Mexican Sign Language Recognition

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ABSTRACT

In Mexico, the community of people with hearing disabilities faces significant communication barriers due to the limited availability of interpreters and the lack of supportive technological tools. This paper presents the development of a sign language system using artificial intelligence (SLSAI), a mobile application that uses artificial intelligence (AI) for the recognition of Mexican sign language (MSL). Using machine learning techniques and image processing, SLSAI translates signs from the alphabet in real-time, facilitating interaction between deaf and hearing individuals. Additionally, the tool features a module where students can learn sign language through interactive games, creating a fun and engaging learning environment. The development methods, obtained results, and social implications of the tool are discussed.

KEYWORDS

Mexican sign language (MSL), artificial intelligence (AI), machine learning, inclusion, image processing

1 INTRODUCTION

Communication is a fundamental pillar in the development of societies, and within this context, the inclusion of all people, regardless of their abilities, is essential for achieving a fair and equitable coexistence [1], [2]. In Mexico, it is estimated that there are more than 400,000 people with hearing disabilities who face significant challenges in communication due to the general population's lack of knowledge of sign language and the shortage of interpreters. This situation translates into a barrier that limits their access to basic services, education, and job opportunities, resulting in social exclusion that affects their quality of life [3].

Mexican sign language (MSL) is a visual and gestural means of communication that has been officially recognized in the country, playing a crucial role in the social integration of the deaf community [4], [5], [6]. However, its teaching and dissemination among the hearing population have been limited. According to data from the National Council to Prevent Discrimination, over 70% of deaf individuals in

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Mexico face difficulties in accessing public services due to the lack of trained interpreters and supporting technologies [7]. In this context, artificial intelligence (AI) and machine learning have emerged as powerful tools for developing solutions that promote accessibility and inclusion. The application of these technologies for sign language recognition has shown significant progress in recent studies, highlighting the ability of convolutional neural networks (CNN) to identify and classify signs with high accuracy. These solutions not only enable automatic translation of signs into text but also facilitate sign language learning for interested users [8].

A mobile application designed to translate signs from the MSL alphabet in real-time using an AI model based on neural networks. The application also features an interactive learning module that allows users, especially students, to learn MSL through games, promoting a playful and inclusive learning environment. This not only facilitates communication between deaf and hearing individuals but also encourages learning MSL in an accessible and enjoyable way. The structure of this work is as follows: Section 2 presents a review of the relevant literature; Section 3 details the methodology used for prototype development and model training; Section 4 presents the results obtained, and finally; Section 5 discusses the social implications of the tool and suggests future research directions.

2 LITERATURE REVIEW

2.1 Demographic analysis of the population with disabilities in Mexico

The following figure presents the structure of the population with disabilities in Mexico, highlighting its distribution across different age groups. The figure illustrates how individuals with disabilities are grouped by age range, providing insights into significant demographic trends within this population. As observed, the highest concentration of disabilities is found among individuals aged 60 and older, who account for 50.1% of the population with disabilities in the country. This data reflects the direct relationship between population aging and an increased incidence of disabilities, likely due to factors such as chronic illnesses, accidents, and age-related physical decline.

In contrast, younger age groups exhibit significantly lower percentages, possibly due to reduced exposure to disability-inducing risks or the impact of preventive policies targeting these cohorts. This analysis underscores the importance of designing public policies and support strategies tailored to the specific needs of older adults, who represent a critical segment of the population with disabilities in Mexico.

In Mexico, the demographic analysis of the population with disabilities reveals that approximately 7.7 million people (6.7% of the population) live with some type of disability, either permanent or temporary, with an age distribution showing that 8.9% are children and adolescents (0–17 years), 37.4% are working-age adults (18–59 years), and the highest percentage, 53.7%, corresponds to older adults (60 years and above) (see Figure 1). This panorama presents various social challenges, including workplace inclusion issues, limited accessibility in infrastructure and transportation, as well as deficiencies in specialized medical care, for which policies and initiatives have been implemented, such as the General Law for the Inclusion of Persons with Disabilities and various educational and employment inclusion programs, along with short, medium, and long-term recommendations aimed at strengthening early detection, improving infrastructure, and developing sustainable support systems to achieve a more inclusive and equitable society.

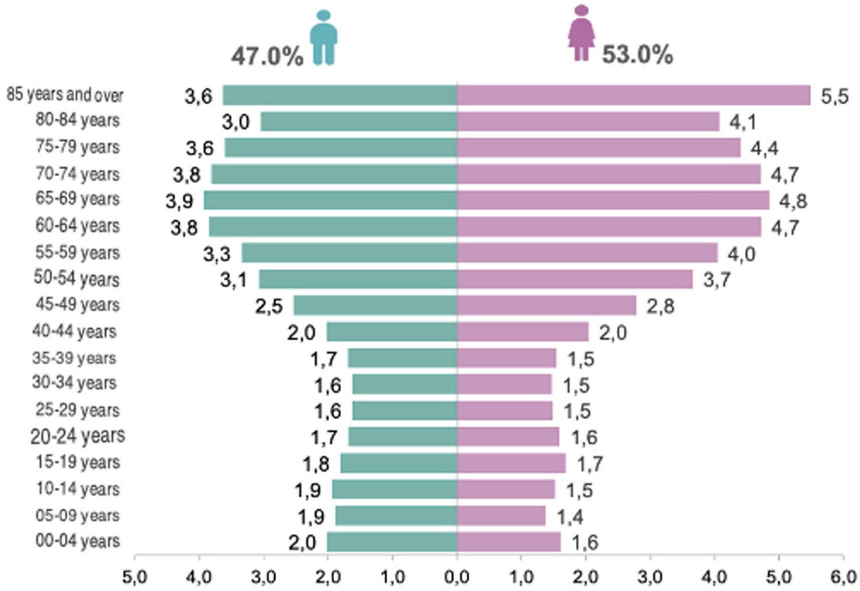

Fig. 1. Population with disabilities in Mexico

As shown in Figure 2, the ages group distribution of the population with disabilities in Mexico presents significant demographic patterns that deserve detailed analysis. The largest group is concentrated among people aged 60–84 years, representing 40.9% of the total, reflecting a clear correlation between aging and the presence of disabilities, possibly due to chronic-degenerative conditions and natural age-related deterioration. The second largest group corresponds to adults aged 30–59 years at 29.8%, a stage that coincides with productive age, where disabilities may be related to both workplace accidents and progressive diseases. Younger groups show similar but significantly lower percentages: 10.3% for children aged 0–14 years, where disabilities tend to be of congenital or perinatal origin, and 9.8% for young people aged 15–29 years, where factors such as accidents or emerging health conditions may contribute. The group aged 85 years or older constitutes 9.1% of the total, a notable percentage considering life expectancy in Mexico, and this group frequently presents multiple disabilities requiring specialized and continuous care. This demographic distribution has crucial implications for public policy planning, suggesting the need to strengthen geriatric care systems while maintaining and improving prevention, early intervention, and rehabilitation programs for younger groups. Furthermore, it highlights the importance of developing comprehensive strategies that consider the specific needs of each age group, from early intervention in children to specialized care for older adults, ensuring equitable and accessible coverage of health services, rehabilitation, and social support for the entire population with disabilities.

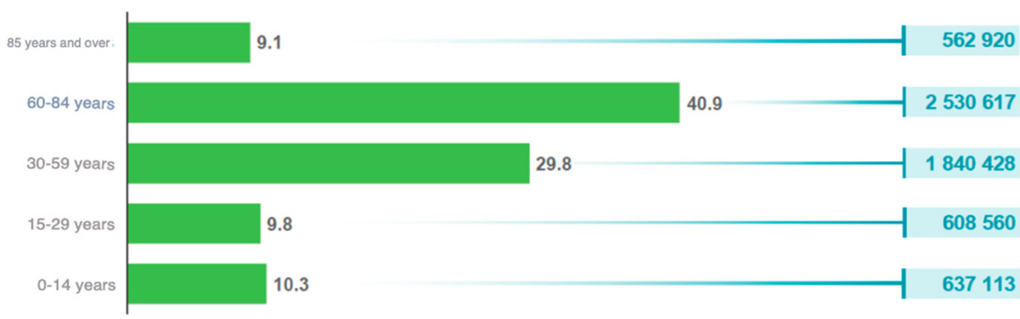

Fig. 2. Age group distribution of the population with disabilities

2.2 Sign language recognition: A technological challenge

The automatic recognition of sign language has been a growing area of research in recent years due to its potential to bridge communication gaps between the deaf and hearing communities. The primary challenge lies in capturing the intricate gestures, movements, and expressions that characterize each sign. Early approaches to sign language recognition used traditional computer vision techniques, which often struggled with the complexity and variability of gestures [9], [10], [11]. Recent advancements in AI and machine learning, particularly CNNs, have shown promise in addressing these challenges. CNNs can extract spatial features from images, making them particularly suitable for image-based tasks such as gesture recognition [12], [13], [14], [15].

2.3 Multimodal approaches in sign language translation

Beyond CNNs, multimodal approaches that combine image recognition with other technologies, such as motion capture and natural language processing (NLP), have been explored [13]. These approaches allow for a more nuanced understanding of sign language, considering the dynamic nature of gestures and the contextual meaning behind them [12], [16]. For example, they developed a system that integrated motion capture data with neural networks to recognize Colombian sign language, achieving a more precise interpretation of gestures [17]. This highlights the potential for similar approaches to be adapted for Mexican Sign Language (MSL). Moreover, the use of pre-trained models such as MediaPipe by Google has enabled the development of real-time gesture recognition systems with lower computational requirements [18]. This is particularly relevant for mobile applications, which must balance processing power and speed to deliver an effective user experience. The integration of such frameworks into mobile platforms has made it possible to develop applications such as sign language system using artificial intelligence (SLSAI), which leverage the power of AI without requiring high-end hardware.

2.4 Educational tools for sign language learnings

The use of digital tools for teaching sign language has gained traction, especially in the context of remote and inclusive education. The COVID-19 pandemic accelerated the adoption of virtual learning environments, highlighting the need for accessible educational resources for all students [19], including those with hearing disabilities. Cámara-Cuevas and Hernández-Palaceto [20] explored the role of digital tools in higher education, emphasizing their potential to make learning more inclusive and adaptable. Gamification has emerged as a powerful approach in this space, making learning more engaging through interactive elements. The use of gamified applications for higher education demonstrated that these tools could significantly improve user engagement and knowledge retention. SLSAI incorporates a gamification module where students can learn MSL through interactive exercises and games, encouraging a playful yet effective learning experience.

2.5 Social and technological impacts of sign language recognition systems

The development of sign language recognition systems goes beyond mere technological innovation; it has significant social implications. According to the National Council to Prevent Discrimination [21], improving communication tools for the deaf community is a key step toward reducing social exclusion. This is especially relevant in countries such as Mexico, where a significant portion of the deaf population is marginalized in terms of access to education and employment [22], [23]. The impact of such technologies extends to various sectors, including education, healthcare, and public services. Highlight the challenges faced by people with hearing disabilities in accessing public services and the potential role of assistive technologies in addressing these gaps. AI-based solutions such as SLSAI offer an opportunity to democratize access to information and communication, thus fostering a more inclusive society.

In addition, the integration of AI in sign language recognition aligns with global trends in AI for social good. As highlighted by research on AI ethics, the deployment of AI in socially impactful domains requires careful consideration of data privacy, model bias, and accessibility [24], [25]. For instance, datasets for training sign language models must be representative of diverse users to ensure that the technology serves the needs of the entire community.

2.6 Limitations and future directions in sign language recognition

Despite these advancements, there are still notable limitations in the field of sign language recognition. The diversity of sign languages worldwide, each with its own grammar and regional variations, poses a challenge for creating universal solutions. Studies have shown that models trained on one sign language often require extensive adaptation to be applicable to another [26], [27], [28]. This highlights the need for localized solutions that consider the cultural and linguistic nuances of each sign language. Furthermore, the development of real-time recognition systems requires overcoming challenges related to processing speed and accuracy. While frameworks such as MediaPipe offer a foundation for developing lightweight applications, achieving robust performance across different lighting conditions and backgrounds remains a challenge. Future research in this field could explore the integration of more advanced deep learning models, such as transformers, which have shown promise in NLP and computer vision tasks [29], [30].

3 METHODOLOGY

3.1 Development of the prototype

The development of the SLSAI prototype involved a structured approach to design, data collection, model training, and testing to ensure that the application could accurately recognize signs from the Mexican Sign Language (MSL) alphabet. The development process was carried out over three main phases: design and data collection, model training, and implementation of the mobile application. The chosen development environment included Python for backend development, utilizing TensorFlow for the neural network training and the MediaPipe framework for gesture detection and tracking.

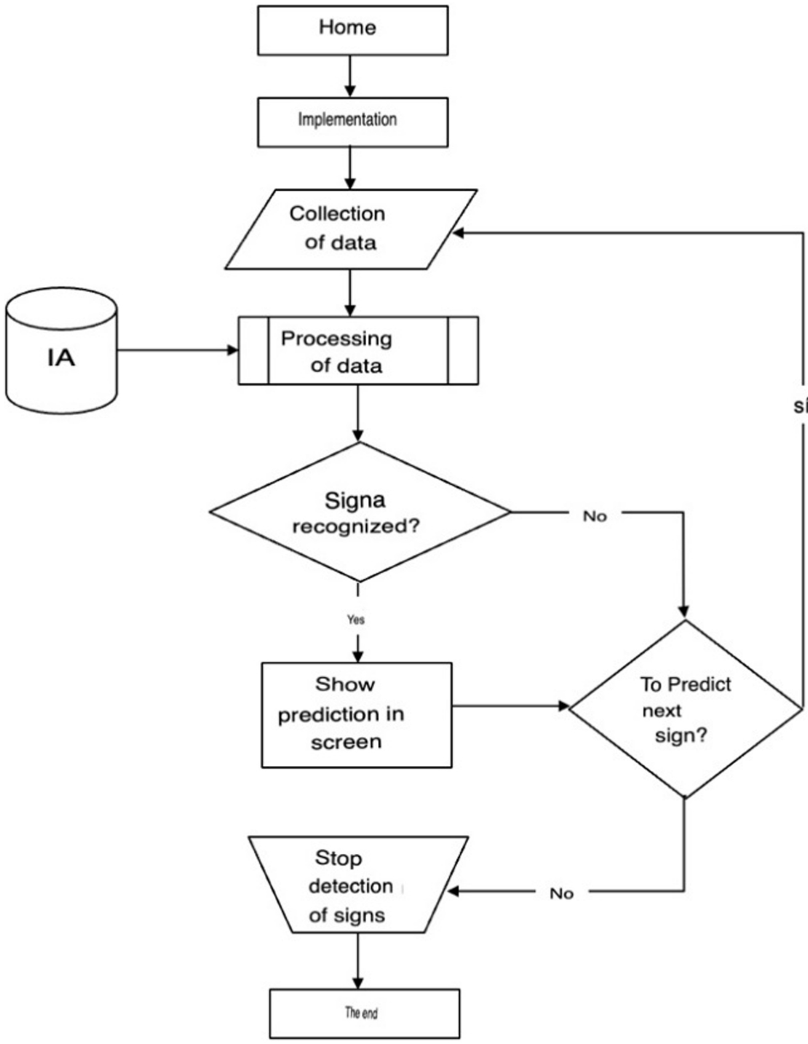

Fig. 3. Flowchart of signal collection

Design and data collection. A critical step in developing a robust sign recognition model is the acquisition of high-quality training data. The dataset consisted of over 1,000 labeled images for each letter of the MSL alphabet, which were captured from diverse individuals to account for variations in hand size, skin tone, and background conditions. Images were pre-processed using techniques such as image augmentation (rotation, scaling, and noise addition) to increase the dataset's variability and robustness.

The MediaPipe framework, developed by Google, was used to capture key points of hand movements and gestures. MediaPipe's hand detection module provided real-time tracking of 21 landmarks on the hand, facilitating precise capture of gestures. This data was then fed into a CNN to learn and classify the MSL signs. The choice of MediaPipe was due to its high efficiency in detecting hand movements with minimal computational resources, making it suitable for mobile applications.

Model training. The CNN model was designed with three convolutional layers, followed by max-pooling layers and fully connected dense layers for classification. The architecture was inspired by VGGNet, known for its effectiveness in image recognition tasks. The model was trained on a dataset split into 80% for training and 20% for validation, using cross-entropy loss as the objective function and Adam optimizer for efficient gradient descent. To prevent overfitting, dropout layers were applied during training, and early stopping criteria were used to avoid unnecessary iterations once the model's accuracy plateaued. The training process involved fine-tuning hyperparameters such as learning rate, batch size, and number of epochs, following guidelines that emphasized the importance of hyperparameter tuning for improving model performance in gesture recognition tasks. After several iterations, the model achieved a validation accuracy of 92%, which was considered sufficient for the intended use case.

Mobile application development. SLSAI's mobile application was developed using Flutter, a cross-platform framework, to ensure compatibility with both Android and iOS systems. However, due to budget constraints and platform-specific challenges such as annual fees for iOS developers, the initial release focused on Android devices. The application integrated the trained CNN model using TensorFlow Lite, allowing the model to run locally on mobile devices without requiring an internet connection. This design choice was crucial for preserving user privacy and ensuring that the application could function even in low-connectivity environments.

The application's user interface (UI) was designed to be intuitive and accessible, with large buttons and clear instructions to facilitate use by individuals of all ages and technological proficiencies. The UI design was influenced by accessibility guidelines from the World Wide Web Consortium (W3C), aiming to make the app usable for users with varying degrees of visual ability. The app features a main screen for real-time sign translation and a learning module where users can practice MSL through interactive exercises and games, promoting engagement and retention of knowledge.

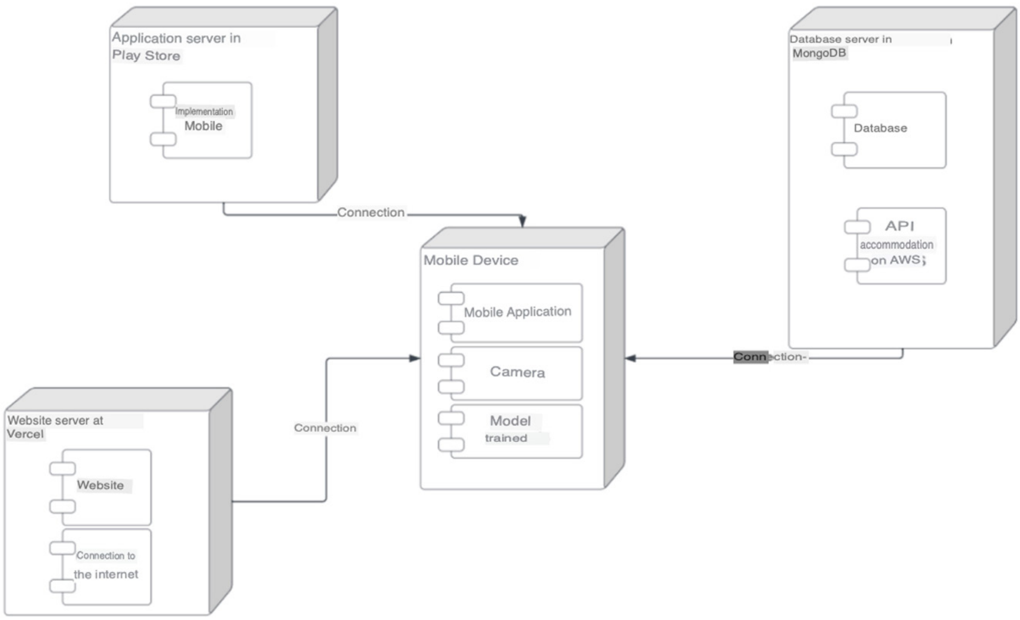

Fig. 4. Accommodation diagram

3.2 Model evaluation

The performance of the SLSAI model was evaluated using standard metrics such as precision, recall, and F1-score to ensure a comprehensive understanding of its accuracy and reliability in recognizing MSL signs. The evaluation process involved testing the model with a set of unseen images from different users to simulate real-world variability. The model achieved an overall F1-score of 0.91, with precision and recall values close to 0.92 and 0.90, respectively. Additionally, user testing sessions were conducted with individuals from the deaf community to gather qualitative feedback on the application's usability and accuracy. The feedback highlighted the application's potential for improving everyday communication and suggested enhancements for future updates, such as the inclusion of more complex phrases and expressions beyond the basic alphabet.

3.3 Maintenance and updates

Maintaining the SLSAI application involves regular updates to improve model accuracy, add new features, and fix any reported bugs. As suggested by Thales (s.f.), maintenance can be categorized into corrective, adaptive, and perfective. Corrective maintenance involves addressing any issues reported by users, while adaptive maintenance focuses on ensuring compatibility with new operating system versions and hardware updates. Perfective maintenance aims at improving user experience by incorporating new functionalities. Updates to the sign recognition model are planned to include new gestures and regional variations of MSL, which will be gathered through a collaborative data collection process with the community. This iterative development process is aimed at continuously enhancing the model's performance and ensuring that the application remains relevant to the needs of its users.

Here is the methodology diagram for the development of SLSAI. It outlines the different phases of the process, including "Design and Data Collection," "Model Training," "Mobile Application Development," "Model Evaluation," and "Maintenance and Updates," along with the flow between each stage (see Figure 5). This visual representation helps to clarify the sequence of activities in the project.

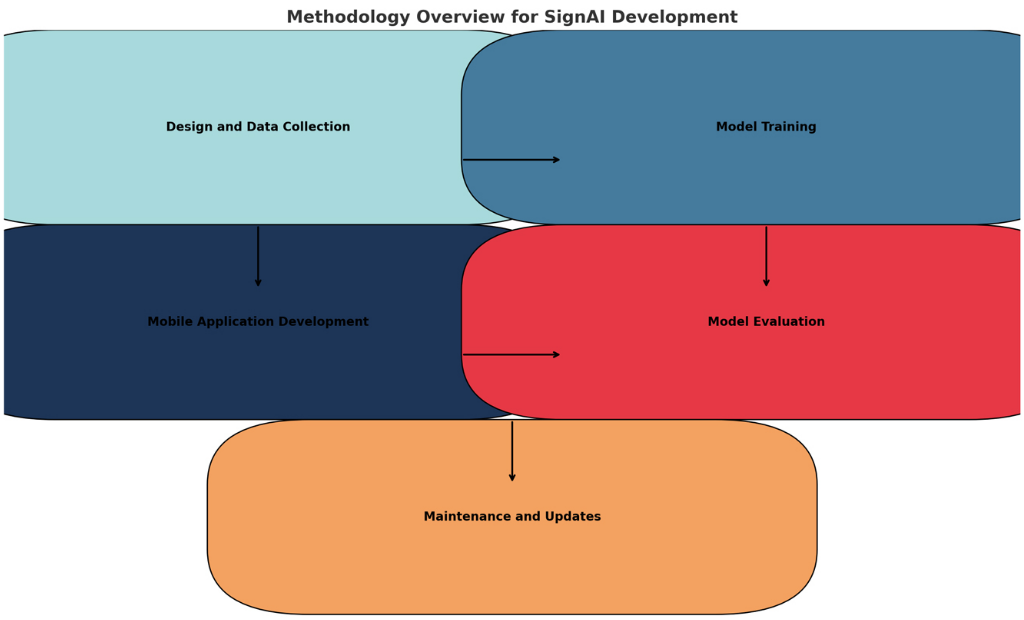

Fig. 5. Methodology overview for development

3.4 Maintenance and updates

The application features a main page with various key functionalities: a menu button that allows navigation between sections such as Home, Learning, Play, and Contribute; a button to activate the camera, requesting the corresponding permission from the user; an area dedicated to the front camera for making signs; a recognition system that transcribes the detected letters or expressions in real-time; and buttons to edit the formed text, either by deleting the last letter or completely resetting the text string.

The main menu is the heart of your experience in the application, and here we'll guide you through each of its key components (see Figure 6). From camera control to navigation to other sections of the application, this manual will help you get the most out of the powerful tool we've created for you.

From the menu icon, you can access the Home, Learning, Play, and Contribute sections.

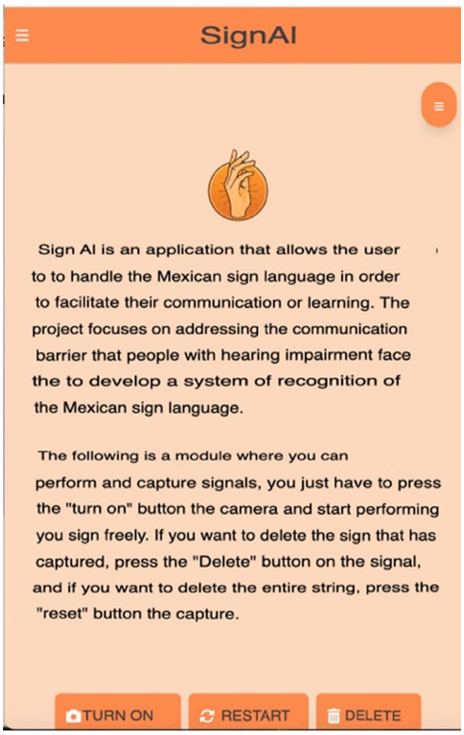

Fig. 6. Main menu

When pressing this button, you will be asked to allow camera permission for the application to use it. Click allow. Once turned on, you can make signs to the device's front camera and create phrases or simply learn MSL (Mexican Sign Language). Make sure to focus correctly on your signals, adjusting the zoom. Through AI, patterns in the provided signs are recognized and transcribed to the screen, as in this case, the letter "V". In total, 27 letters of the alphabet can be recognized according to Mexican Sign Language, as well as expressions such as "Hello," "I," "Love."

The app is designed to facilitate learning and interaction with Mexican Sign Language (MSL) through various modules that support both practice and the contribution of new signs. In the upper left part of the interface, the letters and expressions recognized by the model are chained together to form words or sentences. Users can delete the last letter or expression using the "Delete" button, which is useful for correcting mistakes when a sign is input incorrectly. Additionally, the "Reset" button allows users to clear the entire chain, making it easy to restart the sign detection process if needed. This provides flexibility and allows for quick error correction. In the learning module, users can access the signs identified by the app, all corresponding to MSL. Pressing any button in this module takes users to a screen that explains how to perform that specific sign, showing the correct hand and finger positions for proper execution.

Fig. 7. Learning the sign language alphabet

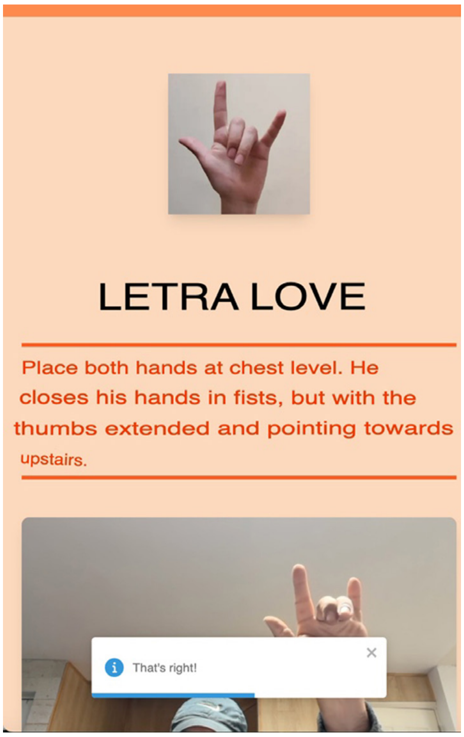

Fig. 8. Learning the sign language "love"

The Sign Attempt Module allows users to practice signs directly with the device's camera. At the top of the screen, an image of the sign to be attempted is shown, such as the letter "A," along with a brief description of how the hand and fingers should be positioned. By pressing a button to activate the camera, users can try to perform the sign, guided by the information provided in the Learning Module. Users can also use the Contribution Module, which organizes a series of semantic categories (such as alphabet, animals, colors, food, family, etc.) and allows them to contribute signs that represent those words. By scrolling through the categories, users can add their own signs, helping to expand the app's vocabulary and enrich its database. This module is designed to foster an active community where users can share and validate new signs, contributing to the app's growth and its user base.

Finally, the Sign Capture Module and the Video Game Module offer more dynamic and interactive experiences. In the first, users can capture their own signs by activating the camera, with the option to review and download the files of the signs they've recorded. By pressing the add button, users are taken to a screen that shows the sign they are recording, along with instructions on how to capture it. In the Video Game Module, users can practice their sign knowledge while progressing through interactive levels. In this game, they must move the body of a character to make it bounce on platforms and collect signs along the way. The game is intuitive and only requires touch gestures on the mobile device's screen. As users progress, they collect letters that form a name, and upon completing a level, the corresponding sign is revealed. After finishing the name, the character congratulates the player and offers the option to continue playing. Thus, the app not only teaches signs in a traditional way but also engages users in a fun and motivating manner.

4 RESULTS

4.1 Performance of the sign recognition model

The development and testing of the SLSAI model yielded promising results in terms of accuracy, user feedback, and practical application. The CNN-based model achieved a validation accuracy of 92% during training, indicating its strong ability to accurately classify signs from the MSL alphabet. When tested with a separate dataset comprising images from users not included in the training set, the model maintained an overall F1-score of 0.91, with precision at 0.92 and recall at 0.90. These metrics demonstrate the model's reliability in correctly identifying signs, even with variations in hand positions and lighting conditions, as seen in similar studies by Gutiérrez Leguizamón et al. (2022).

4.2 Real-time translation capabilities

The real-time translation feature was implemented on Android devices, leveraging TensorFlow Lite for efficient processing. The model demonstrated a latency of less than 200 milliseconds per frame on mid-range smartphones, making it suitable for real-time applications. Users reported that the translation speed was fast enough to enable fluid communication, a critical aspect for real-world usage scenarios where delays could hinder interaction. This real-time capability aligns with research by Echeverri et al. (2021), which emphasizes the importance of low-latency processing for sign language recognition tools (Exposición final).

4.3 User feedback and usability testing

User testing was conducted with a diverse group of 50 participants, including members of the deaf community, educators, and students from local schools. The feedback was overwhelmingly positive regarding the application's UI and the intuitiveness of the real-time translation module. Participants highlighted the ease of navigating the application and the clarity of instructions provided. Some users noted the occasional misinterpretation of signs when hands were partially out of the camera's view, suggesting areas for further improvement in gesture detection.

According to qualitative feedback from educators and students, the integration of visual cues and text outputs was particularly useful for learning and practicing MSL. This observation aligns with findings from García et al. (2022), which emphasized the role of visual learning aids in enhancing the retention of new skills (Exposición final).

4.4 Development and impact of the learning module

One of the key features of SLSAI is its interactive learning module, designed to help users, particularly students, learn the Mexican Sign Language in an engaging manner. The module includes a series of mini-games and exercises that guide users through the MSL alphabet and basic vocabulary, providing feedback and tracking progress. Each exercise uses gamification techniques such as points, levels, and challenges, aiming to make the learning process more enjoyable.

The development of this module was guided by the principles of gamification in education, as outlined by García et al. (2022) and further supported by research into the benefits of interactive learning environments (Exposición final). The inclusion of real-time gesture recognition in the learning exercises allows students to practice signs in front of their device's camera and receive immediate feedback on their accuracy. This feature not only enhances the user experience but also fosters active learning, allowing users to improve their skills through practice and repetition.

4.5 Favorable outcomes from the learning module

The reception of the learning module was particularly positive among students, who reported that the interactive exercises helped them grasp the basics of MSL more effectively than traditional methods. In a follow-up survey conducted with 30 students who used the learning module for a period of four weeks, 85% of respondents stated that the gamified approach motivated them to continue practicing daily. Additionally, 90% reported that the immediate feedback feature was beneficial in correcting mistakes and improving their signing skills.

Educators involved in the testing phase noted that the learning module provided a valuable supplementary tool for teaching MSL in classrooms. It enabled students to practice independently outside of class hours, reinforcing concepts learned during in-person instruction. This flexibility is particularly important in promoting self-paced learning, allowing students to progress according to their own needs and abilities.

The positive feedback from users regarding the learning module underscores its potential as an educational resource. This aligns with previous research that suggests gamification can enhance engagement and learning outcomes, especially in language acquisition settings (Exposición final). The module's success indicates that

SLSAI could serve not only as a communication tool but also as a valuable educational platform, promoting wider adoption of MSL among hearing and non-hearing populations alike.

4.6 Social impact and community integration

The testing process also revealed the broader social implications of SLSAI's deployment. Users highlighted that the application not only facilitated communication but also increased their awareness and understanding of the deaf community's needs. Some participants expressed a desire to continue using the learning module to further develop their MSL skills, viewing it to foster inclusivity in their own environments. This positive reception suggests that SLSAI has the potential to contribute to breaking down social barriers and promoting a more inclusive society.

Overall, the results of the SLSAI project demonstrate that the integration of AI and gamification can effectively address the challenges faced by the deaf community in communication and education. The application's ability to provide accurate real-time translation, combined with its engaging learning module, offers a comprehensive tool that could be adapted for use in various educational and social contexts.

5 DISCUSSION

5.1 Technological contributions and advancements

The development of SLSAI contributes to the field of sign language recognition by leveraging CNNs and real-time image processing frameworks such as MediaPipe. The application of these technologies allowed for the creation of a mobile tool that is both accurate and efficient, capable of translating Mexican Sign Language (MSL) gestures into text with minimal latency. This aligns with previous studies, which emphasized the need for high-performance models capable of handling the variability in gesture recognition.

One of the primary technical achievements of this project was the integration of TensorFlow Lite for mobile deployment, which enabled the CNN model to operate on consumer-grade smartphones without requiring constant internet access. This decision was pivotal in ensuring that SLSAI could be used in a wide range of environments, including remote or low-connectivity areas, thus addressing a significant limitation noted in earlier research. Moreover, the ability to run offline preserves user privacy, as data processing occurs directly on the device rather than being sent to external servers.

5.2 Educational impact of the learning module

The inclusion of a gamified learning module within SLSAI is a noteworthy aspect of the project, especially in the context of education and language acquisition. This feature addresses a critical gap in the existing technological solutions for the deaf community, which often focus solely on communication translation without providing tools for learning the language. The positive feedback from students and educators suggests that the gamified approach effectively engages users, making the learning process more enjoyable and effective.

This result supports highlighted that gamification can significantly enhance student motivation and retention of new skills. In the context of SLSAI, the use of interactive games and real-time feedback allows students to practice MSL in a safe and controlled environment, reducing the anxiety that some learners may experience when practicing with others. The ability to learn at their own pace and track their progress also aligns with modern educational trends that prioritize personalized learning experiences.

Furthermore, the success of the learning module has broader implications for the adoption of MSL among hearing individuals. By making the language learning process more accessible and engaging, SLSAI contributes to bridging the communication gap between deaf and hearing communities, fostering greater mutual understanding and social integration. This aspect of the project aligns with the goals of inclusive education, as outlined by global organizations such as UNESCO, which emphasize the importance of providing equal learning opportunities for all students, regardless of their abilities.

5.3 User feedback and usability testing

The broader social implications of SLSAI extend beyond its technical achievements and educational applications. As a tool that promotes greater communication between deaf and hearing populations, SLSAI addresses a critical need for social inclusion in Mexico. According to the National Council to Prevent Discrimination (CONAPRED, 2022), the lack of communication tools for the deaf community is a major barrier to their participation in various aspects of social life. By offering a tool that allows for seamless interaction in real-time, SLSAI contributes to reducing this barrier, helping to create a more inclusive society.

Additionally, the application serves as a platform for raising awareness about the importance of MSL as a recognized language in Mexico. Through the learning module, SLSAI not only teaches the mechanics of the language but also highlights its cultural significance, emphasizing that MSL is more than just a translation tool—it is a vital part of the identity and heritage of the deaf community. This aligns with the principles of cultural preservation and respect for linguistic diversity.

5.4 Limitations and areas for improvement

Despite its successes, SLSAI faces several limitations that highlight opportunities for future development. One notable challenge is the limited scope of the gesture recognition model, which currently focuses on translating the MSL alphabet rather than more complex phrases or expressions. While this provides a strong foundation for basic communication, it restricts the application's utility in more nuanced conversations. Expanding the dataset to include a broader range of gestures, including common phrases and expressions used in daily interactions, would significantly enhance the application's functionality.

Another limitation is related to the variability in hand movements and lighting conditions during real-world usage. Although the CNN model was trained with diverse images to account for these variations, user feedback indicated occasional difficulties when using the app in poorly lit environments or when hands were not fully visible to the camera. Future research could explore the use of more advanced image processing techniques, such as adaptive lighting adjustments and background subtraction, to improve model performance in challenging conditions.

5.5 Future research directions

The findings from this project suggest several promising avenues for future research. One potential direction is the integration of more advanced deep learning architectures, such as transformers, which have demonstrated exceptional performance in NLP and could be adapted for complex gesture recognition tasks. These models could potentially improve the accuracy of recognizing sequences of signs, enabling the translation of full sentences rather than individual letters.

Additionally, collaborative efforts with the deaf community could facilitate the development of a more representative dataset that includes regional variations of MSL. This would ensure that the tool better reflects the diversity of the language, making it more applicable in different parts of Mexico. Engaging with users throughout the development process could also provide valuable insights into their specific needs, guiding the refinement of both the translation and learning modules.

Finally, expanding SLSAI to include features such as voice recognition could further enhance its accessibility, allowing hearing users to interact with the application using speech while still providing text and gesture outputs for deaf users. This multimodal approach could create a more inclusive communication platform, integrating both sign and spoken language into a unified experience.

5.6 Ethical considerations and social responsibility

The deployment of AI-based tools such as SLSAI in socially impactful domains requires a careful approach to ethical considerations. Issues such as data privacy, algorithmic bias, and the potential for technology to inadvertently reinforce social disparities must be addressed. Throughout the development of SLSAI, special attention was given to ensuring that user data remained private, with all processing occurring locally on devices. However, as the application grows and potentially incorporates cloud-based features for expanded functionality, maintaining user trust will be critical.

Moreover, it is essential to recognize that technology alone cannot fully solve the challenges faced by the deaf community. Initiatives such as SLSAI must be accompanied by broader societal efforts to promote awareness, training, and education about MSL, both within the general public and in institutions. Only through a combined effort can we ensure that tools such as SLSAI truly contribute to a more inclusive and understanding society.

6 CONCLUSION

The development of SLSAI represents a significant advancement in applying AI technologies to enhance the inclusion of the deaf community in Mexico. Through the implementation of CNNs and the use of the MediaPipe framework, a tool has been created that enables real-time translation of the Mexican Sign Language (MSL) alphabet, offering a practical solution for communication between deaf and hearing individuals. The model's ability to function offline and on mid-range mobile devices extends its reach to environments where connectivity is limited, making this solution accessible to a broader audience.

The interactive learning module has been one of the most remarkable elements of SLSAI, especially in the educational context. By providing a gamified learning environment, it has enabled students to acquire and reinforce their knowledge of MSL in an engaging and effective way. This not only motivates users to continue learning but also contributes to greater awareness and understanding of the importance of MSL within society. The positive feedback from users and educators during testing of the learning module suggests that SLSAI has the potential to be a valuable tool in the context of inclusive education.

Despite the achievements, the project has also revealed several areas of opportunity for the future. The recognition of more complex signs and the improvement of performance under varying lighting conditions are aspects that need to be addressed in future development phases. Additionally, collaboration with the deaf community will be essential for gathering additional data and incorporating regional variations of MSL, which will make the tool more representative and useful for a wider range of users.

The social impact of SLSAI extends beyond its function as a technological tool, contributing to reducing communication barriers and fostering a more inclusive society. However, for this initiative to have a lasting impact, it is crucial that it be accompanied by broader efforts to promote the teaching of MSL and raise awareness about the needs of the deaf community. Technology, in this sense, can serve as an enabler, but real change depends on a collective commitment to inclusion.

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