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Voice-controlled didactic robotic system for the representation of Mexican Sign Language

Sistema robótico didáctico controlado por voz para la representación del lenguaje de señas mexicano

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Abstract: This paper presents the development of a voice-controlled didactic robotic system designed to reproduce letters of the Mexican Sign Language (LSM). The prototype integrates eight independent servomotors, a Raspberry Pi 3-based architecture, and a PCA9685 module for coordinated motion control. A mobile application built in MIT App Inventor enables operation through Spanish voice commands or manual control, enhancing user interaction. The results show that 60% of the letters were correctly executed, 33% with minor mechanical limitations, and 7% not achieved, validating the system's mechanical stability, gesture accuracy, and educational potential. This project fosters technological inclusion and promotes the use of robotics as a tool for social and educational learning.

Palabras clave: educational robotics, Mexican Sign Language, voice recognition, Raspberry Pi, technological inclusion.

Resumen: El presente trabajo describe el desarrollo de un sistema robótico didáctico controlado por voz diseñado para representar letras del Lenguaje de Señas Mexicano (LSM). El prototipo integra ocho servomotores independientes, una arquitectura basada en Raspberry Pi 3 y un módulo PCA9685 para el control simultáneo de movimientos. La aplicación móvil desarrollada en MIT App Inventor permite operar el sistema mediante comandos de voz en español o control manual, facilitando la interacción con el usuario. Los resultados muestran una ejecución correcta del 60 % de las letras, un 33 % con leves dificultades y un 7 % no logradas, validando la estabilidad mecánica, la precisión gestual y el potencial educativo del sistema. Este proyecto promueve la inclusión tecnológica y el aprendizaje de la robótica aplicada a contextos sociales y educativos.

Keywords: robótica educativa, Lenguaje de Señas Mexicano, reconocimiento de voz, Raspberry Pi, inclusión tecnológica.

1. INTRODUCTION

In recent years, educational robotics has become a key tool to strengthen engineering education, foster active learning, and promote social inclusion. In particular, its application to the learning of Mexican Sign Language (LSM) represents an opportunity to link technology with communicative accessibility. In Mexico, hearing impairment affects more than five million people, while more than two million present difficulties in oral communication [1]. This highlights the urgency of incorporating inclusive strategies into educational processes.

The development of robotic systems oriented towards teaching and inclusion has gained relevance by enabling the convergence of mechatronics, artificial intelligence, and assistive technologies. In [2], a low-cost robotic hand was proposed for technological education, emphasizing its potential in resource-limited environments. Similarly, [3] developed a robotic assistant for sign language learning in children with hearing disabilities, highlighting its social impact. In [4], the effectiveness of using Raspberry Pi and Python in the programming of an educational robotic hand was demonstrated, while [5] emphasized the importance of ergonomic design in soft-robotics-based prostheses, proposing a user-centered approach.

From an educational and social perspective, [6] addressed the integration of virtual voice assistants into academic environments, and [7] explored the incorporation of auditory interfaces to enhance attention and comprehension, showing that the interaction between users and technology strengthens inclusion and interdisciplinarity. Likewise, [8] and [9] highlighted that educational robotics projects promote creativity, collaborative work, and problem-solving skills in engineering students, establishing a valuable formative precedent for the development of this project.

In the technical domain, [10] presented a computer-controlled sign language translator, and [11] achieved greater gestural fidelity by using fifteen servomotors, although with higher cost and complexity. In [12] and [13], low-cost 3D-printed versions were developed, although with limitations in finger independence and without voice control. In [14], computer vision was incorporated to synchronize sensors and actuators, while [15] applied local materials in accessible prototypes. Finally, [16] introduced the use of Raspberry Pi-based PLCs and Node-RED in IoT systems, and [17] confirmed the efficiency of 3D printing in the fabrication of precision mechanisms.

Moreover, [18] explored the application of language models in robotic manipulation, demonstrating the potential of machine learning to optimize movement accuracy and the adaptability of mechatronic systems.

Based on this review, a technological gap was identified: most previous developments focus either on sign translation or rehabilitation, but not on an educational approach adapted to the Mexican context nor with Spanish voice control. Therefore, this project proposes a didactic and articulated robotic system capable of representing LSM letters through voice commands, integrating mechanical, electronic, and programming subsystems into an accessible and replicable architecture.

The main objective of this work is to design and develop a didactic robotic system controlled by voice that performs LSM configurations through a mechatronic architecture of eight independent servomotors and a Raspberry Pi interface, to strengthen LSM teaching and promote educational inclusion. To achieve this, specific objectives were proposed to guide the analysis of mechanical, electronic, and control requirements; the implementation of local Spanish voice recognition; coordinated servomotor programming; and the evaluation of the prototype's performance and educational value.

In summary, this project links engineering, social inclusion, and education through a low-cost, modular, and replicable technological solution. The main contributions of the work are as follows:

- Development of a mechatronic architecture based on Raspberry Pi 3 and PCA9685, with independent control of eight servomotors.
- Implementation of a Spanish voice recognition system to perform gestures of the Mexican manual alphabet.
- Integration of a mobile application in MIT App Inventor that enables manual or voice control of the robotic arm.
- Design of a didactic and replicable prototype, adaptable to educational contexts in STEM fields.
- Contribution to strengthening STEM competencies and awareness toward the Deaf community through educational robotics.

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2. MATERIALS AND METHODS

The development of the voice-controlled didactic robotic system was carried out under a comprehensive mechatronic approach, in which the mechanical, electrical, electronic, and control components converged. The objective was to obtain a functional, stable, and replicable prototype capable of representing the configurations of Mexican Sign Language (LSM) based on voice commands.

The methodological process was structured into consecutive phases that enabled the progression from conceptual design to the experimental validation of the system, prioritizing accessibility, low cost, and ease of implementation in educational contexts. The stages were carried out following principles of iteration and continuous improvement, ensuring coherence among modeling, fabrication, and control.

2.1 General system architecture

The development process followed an iterative methodology composed of four main phases: design, printing and assembly, electronic integration, and functional validation.

- *Design and simulation:* adaptation of the 3D model and planning of internal wiring.
- *Fabrication:* printing of the components, assembly tests, and tendon adjustment.
- *Hardware and software integration:* connection of the servomotors, installation of the operating system on the Raspberry Pi 3, and configuration of voice control through the PCA9685 module.
- *Functional tests:* verification of mechanical response and motor calibration.

These stages enabled the consolidation of a modular workflow in which each phase provided information to optimize prototype performance and guarantee its replicability in future academic or research environments.

2.2 Mechanical design

The mechanical design of the robotic arm was based on the three-dimensional model in [19], selected for its modular structure and adaptability to educational environments (see Fig. 1).

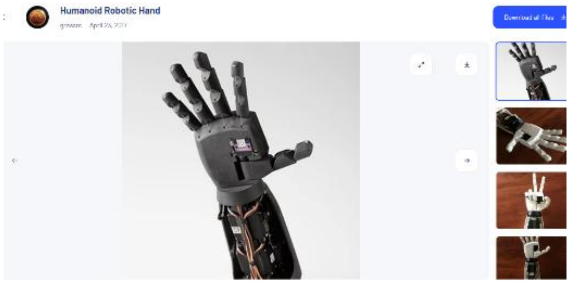

***Fig. 1**. Screenshot of the official GrossRC project page.*
***Source:** [19].*

The screenshot shows the original design used as a base, which was modified to improve stability, servomotor coupling, and internal cable routing. Each component was printed in PLA filament with a layer height of 0.2 mm and 25% infill, optimizing resistance while reducing total weight.

The hand design was based on human anatomy to preserve proportionality and joint mobility, as illustrated in (see Fig. 2), which shows the layout of phalanges and rotation axes. The final structure integrates six SG90 servomotors for the fingers, an additional servo for index crossing, and an MG995 for the wrist, providing eight degrees of freedom. This configuration enabled the correct reproduction of complex LSM letters, such as “R”, while maintaining a lightweight, stable, and easily replicable structure.

***Fig. 2** Human hand anatomy image.*
***Source:** [20].*

During the construction phase, modifications were made to the base design, incorporating a new support structure and 3D-printed tensioning discs to improve cable tension and system stability (see Fig. 3). These adjustments were necessary to enable the effective integration of all eight servomotors and ensure coordinated actuator operation.

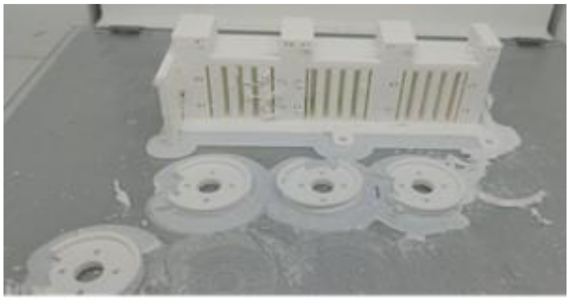

Fig. 3. Printed tensioning discs and modified base.
***Source:** own elaboration.*

2.3 Electrical and electronic design

The electrical system was initially designed with a configuration based on an Arduino Nano and a PCA9685 board, responsible for distributing PWM signals to the servomotors. This setup enabled the first movement and calibration tests for the fingers, ensuring the stability of the 5 V supply.

Subsequently, the Arduino was replaced by a Raspberry Pi 3, which integrates the control functions, Spanish voice recognition, and user interface communication. This transition enabled a more stable, scalable, and autonomous system by eliminating dependence on the microcontroller and centralizing processing on a single platform.

Connections were made using male-female Dupont wires and a 5 V/3 A power supply, sufficient to power the eight servomotors controlled by the PCA9685. Table 1 summarizes the movements assigned to each channel and its angular calibration range, while Fig. 4 shows the final electrical diagram with the I²C communication between the Raspberry Pi 3 and the PCA9685.

***Table 1:** Servomotors. Movements and calibration ranges*

Channel (PCA9685)	Controlled movement	Approx. range
1	Thumb rotation (SG90)	120° to 0°
2	Thumb flexion	0° to 180°
3	Index	180° to 0°
4	Middle	0° to 180°
5	Ring	0° to 180°
6	Pinky	0° to 180°
7	Finger crossing (index)	180° to 0°
8	Arm rotation (MG995)	180° to 0°

***Source:** own elaboration*

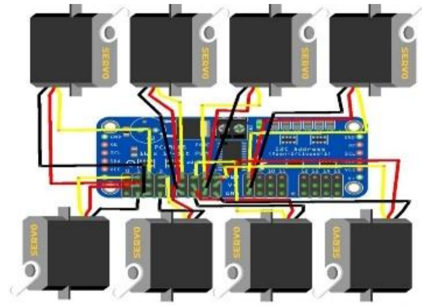

*Fig. 4. Final electrical diagram of the system based on Raspberry Pi. **Source:** own elaboration*

2.4 Control system design

The control system was developed on the Raspberry Pi 3 platform using Python to manage the PWM signals sent to the PCA9685 module. This module enabled the coordination of the eight servomotors, assigning each one an independent channel to ensure precision in the execution of LSM letters.

The control flow begins with the reception of Spanish voice commands through the mobile application developed in MIT App Inventor. These commands are transmitted via Bluetooth to the Raspberry Pi, where a local script processes the instructions and executes the predefined motion sequences.

The main algorithm implements calibration and synchronization routines to avoid interference between adjacent servos, as well as safety parameters that limit maximum displacement angles. In this way, a stable and fluid response was achieved, with an average latency imperceptible to the user.

3. RESULTS

The results obtained demonstrate the integral functionality of the voice-controlled didactic robotic system, validating both its mechanical and electronic performance as well as its pedagogical usefulness. The prototype successfully executed the configurations of the LSM manual alphabet in a stable manner, showing the correct integration between the control, mechanical, and mobile application subsystems.

3.1 Robotic system performance

The final assembly of the robotic arm demonstrated adequate structural stability and smooth response in finger articulation (as shown in Fig. 5), where the execution of the letter "R" in Mexican Sign Language is presented.

***Fig. 5**. Execution of the letter "R" in Mexican Sign Language.*
***Source:** own elaboration*

The PLA-printed parts maintained their rigidity after multiple operating cycles, and the optimized design allowed the integration of eight servomotors without interference between adjacent axes. One of the main improvements implemented with respect to the base model consisted of incorporating an additional servo for index-finger crossing, which enables the diagonal motion characteristic of the letter "R" in LSM. This modification represents a significant advance in terms of gestural realism and kinematic precision, as it reproduces a gesture that was not achievable with conventional six-servo configurations.

The execution of the letter "R" constitutes one of the most representative results of the project, as it demonstrates correct synchronization between the eight servos and the kinematic improvement achieved through the new diagonal index coupling. This configuration proved reproducible, stable, and precise, consolidating the technical contribution of the prototype in the context of LSM.

3.2 Validation of LSM configurations

To validate system performance, execution tests of the letters of the Mexican Sign Language manual alphabet (LSM) were carried out. The procedure consisted of entering voice commands corresponding to each letter and recording the accuracy of the resulting gesture, considering its stability, shape, and synchronization.

During the tests, most letters were correctly reproduced, including A, B, C, D, E, F, I, J, K, L, O, R, U, V, W, and Y, which showed stable and fully achieved gestures. Other letters, such as G, H, M, N, P, Q, S, X, and Z, were executed with slight difficulty due to mechanical limitations in the flexion and crossing of some fingers. Finally, the letters Ñ and T could not be adequately represented due to geometric constraints in the printed structure.

The results were classified into three categories: correctly executed, executed with difficulty, and not executed. Table 2 shows a summary of the evaluated configurations along with the percentage of effectiveness obtained in each case.

***Table 2:** Validation results of LSM letters through voice commands*

Category	Percentage (%)	Brief description
Correctly executed	60	Letters reproduced in a complete and stable manner.
Executed with difficulty	33	Letters with correct gestures but slight mechanical limitations.
Not executed	7	Letters that could not be adequately reproduced.

***Source:** own elaboration*

The analysis showed that 93% of the letters were executed correctly or with slight limitations, demonstrating the stability and precision of the system. Variations were mainly associated with cable tension and geometric differences between printed fingers.

The system maintained high repeatability during the tests, with smooth control response and an average execution time per gesture of less than two seconds. These characteristics demonstrate the reliability of the design and its potential for use as a didactic resource for teaching LSM.

3.3 Functional evaluation and system integration

The integration of the mechanical, electrical, and control subsystems enabled the validation of the complete operation of the prototype. During the final tests, the system responded correctly to Spanish voice commands, executing the gestures associated with each letter of Mexican Sign Language (LSM) in a precise manner. Communication between the mobile application and the Raspberry Pi was established via Bluetooth, ensuring a stable and low-latency connection.

Fig. 6 shows the final version of the application developed in MIT App Inventor, which allows the user to select between manual or voice control. Each command activates a preprogrammed routine that

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sends PWM signals to the PCA9685 module, generating the corresponding movement in the servomotors. The interface design prioritizes visual simplicity so that students can easily interact with the system during didactic activities or demonstrations.

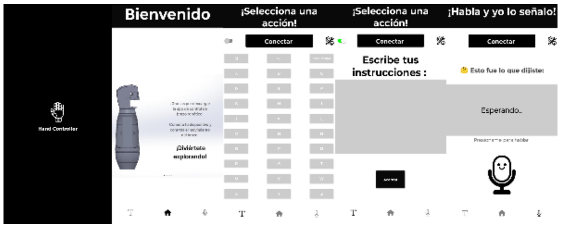

Fig. 6. *Final version of the application developed in MIT App Inventor.* ***Source:*** *authors' own elaboration*

The overall performance of the system confirmed its reliability in educational environments. The executed letters showed mechanical stability, immediate response to voice recognition, and gestural coherence with the Mexican manual alphabet. This result demonstrates that the proposed architecture, based on local control, modularity, and low-cost materials, can be replicated in academic contexts as a tool for teaching robotics and raising awareness of the Deaf community.

4. CONCLUSIONS

The development of the voice-controlled didactic robotic system made it possible to effectively integrate the principles of mechatronic engineering with a social and educational purpose. The architecture based on Raspberry Pi 3 and the PCA9685 module proved to be a functional and adaptable platform for the independent control of eight servomotors, achieving precise and reproducible movements of the letters of the Mexican Sign Language manual alphabet (LSM).

The implementation of Spanish voice recognition facilitated natural interaction between the user and the system, eliminating linguistic barriers and reinforcing technological accessibility. Likewise, the mobile application developed in MIT App Inventor enabled simple and flexible operation in both manual and voice-command modes, promoting interactive learning.

The resulting prototype represents a replicable didactic tool that can be easily integrated into school contexts, favoring the teaching of robotics and STEM competencies through an inclusive approach. Furthermore, the project contributes to raising awareness of the Deaf community and fostering a technological culture with a human perspective.

Overall, the results validate the technical and educational feasibility of the proposal, consolidating it as a solid foundation for the development of new solutions in inclusive robotics.

As part of future developments, efforts will focus on strengthening the mechanical design of the robotic arm to incorporate movements that allow the representation of letters that have not yet been accurately reproduced and to improve those executed with difficulty. In addition, plans include updating the mobile application that functions as the control interface, with the aim of making it public and available for download so that other users can operate the robotic system and replicate its functionality. Finally, the intention is to share the project repository with the design and control files, together with the implemented improvements, in order to promote adoption in educational environments, encourage academic collaboration, and contribute to the development of inclusive technologies with social impact.

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