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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.

Keywords: 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.

Palabras clave: robótica educativa, lenguaje de señas mexicano, reconocimiento de voz, Raspberry Pi, inclusión tecnológica.

INTRODUCTION

In recent years, educational robotics has established itself as a key tool to strengthen engineering education, promote 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 disability affects more than five million people, while over two million have difficulties communicating orally[1], which highlights the urgency of incorporating inclusive strategies into educational processes.

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

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

In the technical field, in [10] a computer-controlled sign language translator was introduced, and in [11] greater gesture fidelity was achieved through fifteen servomotors, although at higher cost and complexity. In [12] and [13] low-cost versions were developed using 3D printing, although with limitations in finger independence and no voice control. In [14] computer vision was incorporated to synchronize sensors and actuators, while in [15] local materials were applied in accessible prototypes. Finally, in [16] the use of Raspberry Pi and Node-RED based PLCs was introduced in IoT systems, and in [17] the efficiency of 3D printing in manufacturing precision mechanisms was confirmed.

For its part, in[18]the application of language models in robotic manipulation was explored, showing the potential of machine learning to optimize the precision of movements and the adaptability of mechatronic systems.

This review identified a technological gap: most previous developments focus on sign translation or rehabilitation, but not on an educational approach adapted to the Mexican context or with voice control in Spanish. In response, this project proposes an articulated didactic robotic system capable of representing LSM letters through voice commands, integrating mechanical, electronic and programming subsystems in an accessible and replicable architecture.

The general objective of this work is to design and develop a voice-controlled didactic robotic system that executes LSM configurations through a mechatronic architecture of eight independent servomotors and a Raspberry Pi interface, in order to strengthen LSM teaching and foster educational inclusion. To achieve this, specific objectives were set aimed at analyzing the mechanical, electronic and control requirements; implementing local voice recognition in Spanish; programming the servos in a coordinated manner; and evaluating the performance and didactic value of the prototype.

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

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

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 purpose was to obtain a functional, stable and replicable prototype capable of representing the configurations of Mexican Sign Language (LSM) from voice commands.

The methodological process was structured in consecutive phases that allowed progress from conceptual design to experimental validation of the system, prioritizing accessibility, low cost and ease of implementation in educational contexts. The stages were developed following principles of iteration and continuous improvement, ensuring coherence between modeling,

manufacturing and control.

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 the internal wiring.
- Manufacturing: printing of the parts, assembly tests, and adjustment of the tendons.
- Hardware and software integration: connecting the servomotors, installing the operating system on the Raspberry Pi 3, and configuring voice control through the PCA9685 module.
- Functional tests: verification of the mechanical response and calibration of the motors.

These stages made it possible to consolidate a modular workflow in which each phase contributed information to optimize the prototype's performance and ensure its replicability in future academic or research environments.

Mechanical design

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

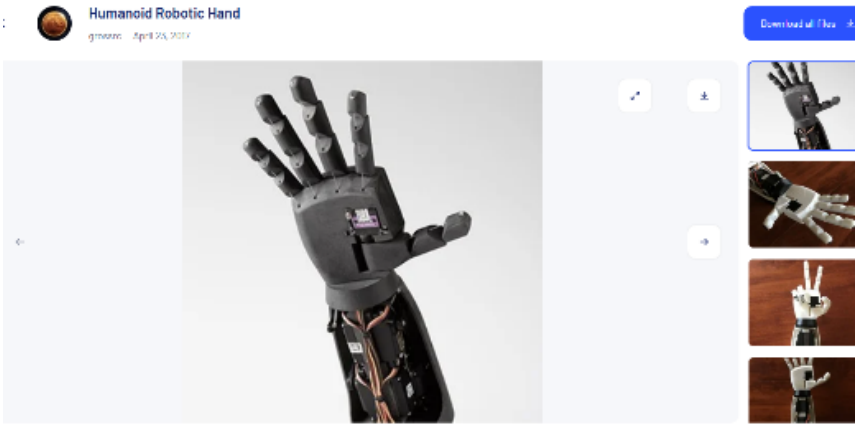

Fig. 1. *Screenshot of the official GrossRC project page.*
Source: [19].

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

The design of the hand took human anatomy as a reference in order to preserve proportionality and joint mobility, as observed in (see Fig. 2), which illustrates the arrangement of phalanges and rotation axes. The final structure integrates six SG90 servomotors for the fingers, an additional servo for crossing the index finger, and an MG995 for the wrist, giving eight degrees of freedom. This configuration made it possible to correctly reproduce complex LSM letters, such as "R", while keeping the structure lightweight, stable, and easily replicable.

During the construction stage, modifications were made to the base design, incorporating a new support structure and 3D-printed tensioner discs to improve cable tension and system stability (see Fig. 3). These adjustments were necessary to allow the effective integration of the eight servomotors and to guarantee coordinated operation of the actuators.

Electrical and electronic design

The electrical system was initially designed with a configuration based on an Arduino Nano and a PCA9685 board, which distributed the PWM signals to the servomotors. This setup allowed the first motion and finger calibration tests to be performed, verifying the stability of the 5 V supply.

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

The connections were made using male-to-female Dupont cables and a 5 V 3 A power supply, sufficient to power the eight servomotors controlled from the PCA9685. Table 1 summarizes the movements assigned to each channel and their angular operating range, while Fig. 4 shows the final electrical diagram with the I²C communication between the Raspberry Pi 3 and

the PCA9685.

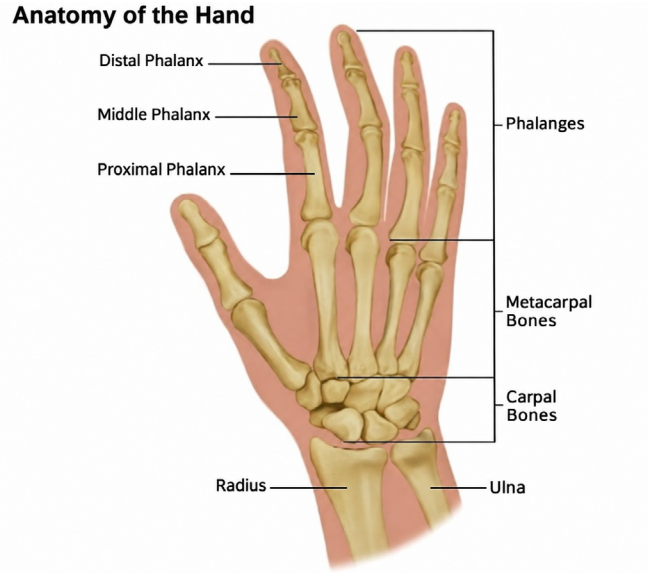

Fig. 2 Image of hand anatomy.
Source: [20].

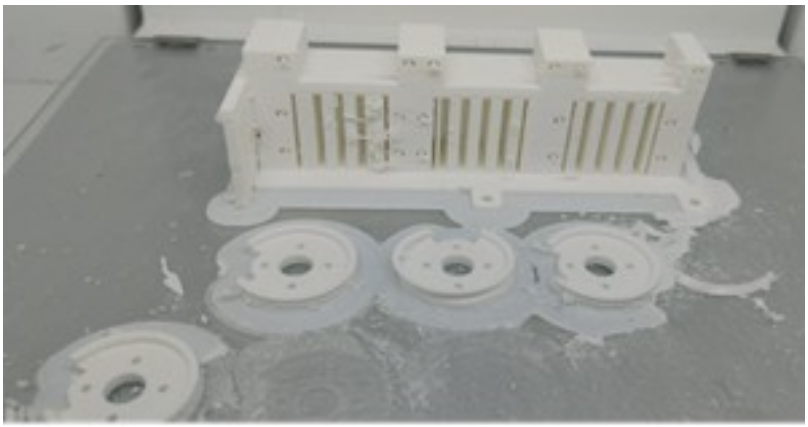

Fig. 3. *Printing of tensioner discs and modified base.*
Source: own elaboration.

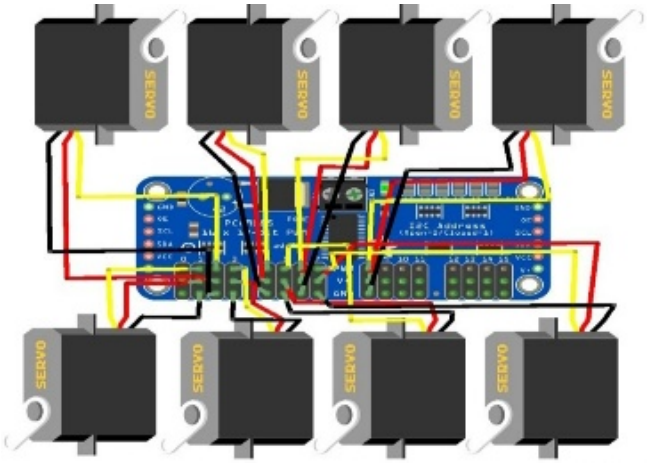

Fig. 4. *Electrical diagram of the final Raspberry Pi-based system.*
Source: own elaboration.

Table 1: Servomotors. Movements and calibration ranges

Channel (PCA9685)	Controlled motion	Approximate range
1	Thumb rotation (SG90)	120° to 0°
2	Thumb flexion	0° to 180°
3	Index finger	180° to 0°
4	Middle	0° to 180°
5	Ring	0° to 180°
6	Little finger	0° to 180°
7	Finger crossing (index)	180° to 0°
8	Arm rotation (MG995)	180° to 0°

Source: own elaboration

Control system design

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

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

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

RESULTS

The results obtained demonstrate the comprehensive functionality of the voice-controlled didactic robotic system, validating both its mechanical and electronic performance and its pedagogical usefulness. The prototype was able to stably execute the configurations of the LSM manual alphabet, showing the correct integration between the control, mechanical and mobile application subsystems.

Performance of the robotic system

The final assembly of the robotic arm showed adequate structural stability and a fluid response in the articulation of the fingers (as observed in Fig. 5), where the execution of the letter “R” of Mexican Sign Language is presented.



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

The parts printed in PLA maintained their rigidity after multiple operating cycles, and the optimized design allowed housing the eight servomotors without interference between adjacent axes. One of the main improvements implemented with respect to the base model consisted of the incorporation of an additional servo for crossing the index finger, 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, by reproducing 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 shows the correct synchronization between the eight servos and the kinematic improvement achieved through the new diagonal coupling of the index finger. This configuration proved to be reproducible, stable and precise, consolidating the technical contribution of the prototype in the context of LSM.

Validation of LSM configurations

To validate the performance of the system, tests were carried out on the execution of the letters of the manual alphabet of Mexican Sign Language (LSM). 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 it was observed that most of the letters were correctly reproduced, among them 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 restrictions in the printed structure.

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

Table 2: Validation results of LSM letters using voice commands

Category	Percentage (%)	Brief description
Correctly executed	60	Letters reproduced completely and stably.
Executed with difficulty	33	Letters with correct gestures, but with slight mechanical limitations.
Not executed	7	Letters whose shape could not be reproduced adequately.

Source: own elaboration

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

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

Functional evaluation and integration of the system

The integration of the mechanical, electrical, and control subsystems made it possible to validate the complete operation of the prototype. During the final tests, the system responded correctly to the voice commands issued in Spanish, precisely executing the gestures associated with each letter of Mexican Sign Language (LSM). Communication between the mobile application and the Raspberry Pi was established via Bluetooth, ensuring a stable, 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 control and voice control. Each command activates a preprogrammed routine that sends PWM signals to the PCA9685 module, generating the corresponding motion in the servomotors. The interface design prioritizes visual simplicity, so that students can easily interact with the system during didactic activities or demonstrations.

The overall performance of the system confirmed its reliability in educational environments. The letters executed showed mechanical stability, immediate response to voice recognition, and gestural coherence with the Mexican manual alphabet. This result shows 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.

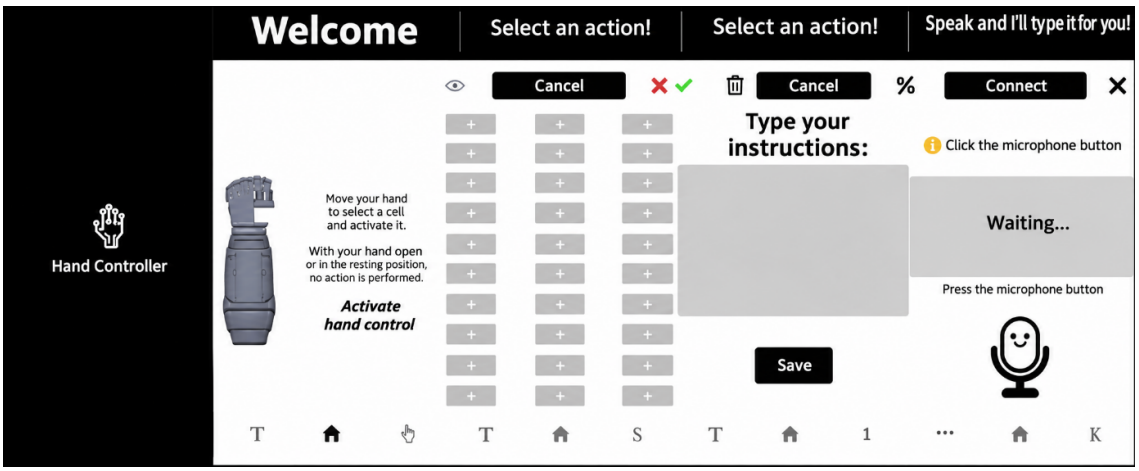

Fig. 6. *Final version of the application developed in MIT App Inventor.*
Source: own elaboration.

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 manual alphabet of Mexican Sign Language (LSM).

Implementing voice recognition in Spanish facilitated natural interaction between the user and the system, eliminating language barriers and reinforcing technological accessibility. Likewise, the mobile application developed in MIT App Inventor enabled simple and flexible operation, both in manual mode and by voice commands, promoting interactive learning.

The prototype obtained represents a replicable didactic tool that is easy to integrate into school contexts, favoring the teaching of robotics and STEM competencies through an inclusive approach. In addition, the project contributes to raising awareness of the deaf community and to fostering a technological culture with a human sense.

Taken together, the results achieved validate the technical and educational viability of the proposal, consolidating it as a solid basis for the development of new solutions in inclusive robotics.

As part of the project's future advances, we plan to strengthen the mechanical design of the robotic arm to incorporate motions that allow representing the letters that have not yet been achieved with precision and to improve those that were executed with difficulty. Likewise, we plan to update the mobile application that serves 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 operation. Finally, we plan to share the project repository with the design and control files, together with the improvements made, in order to foster its adoption in educational settings, promote academic collaboration, and contribute to the development of inclusive technologies with social impact.

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CONFLICT OF INTEREST

None

AUTHORSHIP CONTRIBUTIONS

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