Article

Implementation of mixed reality technology for the control of physical systems

Implementación de la tecnología de realidad mixta para el control de sistemas físicos

García-Cervantes, Heraclio*[a], Carrillo-Hernández, Didia[b] and Blanco-Miranda, Alan David[c]

[a] Universidad Tecnológica de León • X-5622-2019 • 0000-0002-4229-9229 • 290829
[b] Universidad Tecnológica de León • ABF-4839-2020 • 0000-0001-9989-5884 • 936937
[c] Universidad Tecnológica de León • W-9701-2019 • 0000-0002-8595-8634 • 298274

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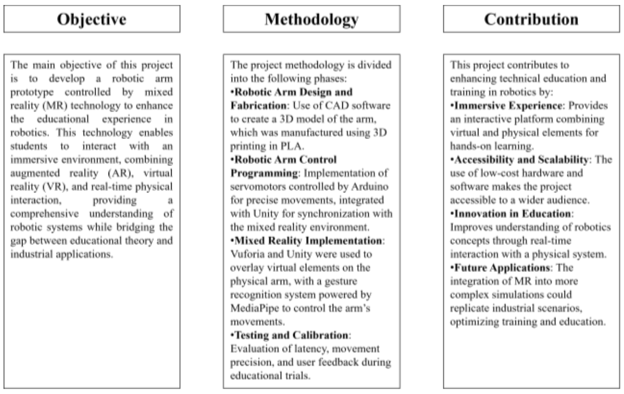
* ✉ [ablancom@utleon.edu.mx]

Abstract

The integration of mixed reality (MR) technology into physical systems represents a significant advancement in bridging the gap between educational environments and industrial applications. This study explores the development of a robotic arm prototype controlled through MR technology, aimed at enhancing educational experiences in the field of robotics. By utilizing augmented reality (AR), virtual reality (VR), and real-time physical interactions, students gain a comprehensive understanding of robotic systems. The project combines open-source platforms with MR to provide a hands-on, immersive learning environment. The primary objective is to foster high-impact learning and practical training, thus reducing the gap between educational settings and real-world industrial applications.



Objective

The main objective of this project is to develop a robotic arm prototype controlled by mixed reality (MR) technology to enhance the educational experience in robotics. This technology enables students to interact with an immersive environment, combining augmented reality (AR), virtual reality (VR), and real-time physical interaction, providing a comprehensive understanding of robotic systems while bridging the gap between educational theory and industrial applications.

Methodology

The project methodology is divided into the following phases:
•**Robotic Arm Design and Fabrication**: Use of CAD software to create a 3D model of the arm, which was manufactured using 3D printing in PLA.
•**Robotic Arm Control Programming**: Implementation of servomotors controlled by Arduino for precise movements, integrated with Unity for synchronization with the mixed reality environment.
•**Mixed Reality Implementation**: Vuforia and Unity were used to overlay virtual elements on the physical arm, with a gesture recognition system powered by MediaPipe to control the arm's movements.
•**Testing and Calibration**: Evaluation of latency, movement precision, and user feedback during educational trials.

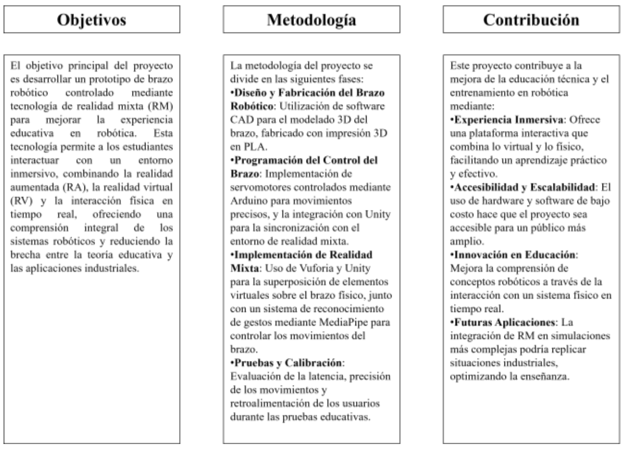
Contribution

This project contributes to enhancing technical education and training in robotics by:
•**Immersive Experience**: Provides an interactive platform combining virtual and physical elements for hands-on learning.
•**Accessibility and Scalability**: The use of low-cost hardware and software makes the project accessible to a wider audience.
•**Innovation in Education**: Improves understanding of robotics concepts through real-time interaction with a physical system.
•**Future Applications**: The integration of MR into more complex simulations could replicate industrial scenarios, optimizing training and education.

Mixed reality, Robotic arm, Educational systems, Immersive learning

Resumen

La integración de la tecnología de realidad mixta (RM) en sistemas físicos representa un avance significativo en la reducción de la brecha entre los entornos educativos y las aplicaciones industriales. Este estudio explora el desarrollo de un prototipo de brazo robótico controlado mediante RM, con el objetivo de mejorar la experiencia educativa en el campo de la robótica. Al utilizar realidad aumentada (RA), realidad virtual (RV) y la interacción física en tiempo real, los estudiantes obtienen una comprensión integral de los sistemas robóticos. El proyecto combina plataformas de software libre con RM para proporcionar un entorno de aprendizaje inmersivo y práctico. El objetivo principal es fomentar un aprendizaje de alto impacto y una formación práctica, reduciendo así la distancia entre los entornos educativos y las aplicaciones industriales.



Objetivos

El objetivo principal del proyecto es desarrollar un prototipo de brazo robótico controlado mediante tecnología de realidad mixta (RM) para mejorar la experiencia educativa en robótica. Esta tecnología permite a los estudiantes interactuar con un entorno inmersivo, combinando la realidad aumentada (RA), la realidad virtual (RV) y la interacción física en tiempo real, ofreciendo una comprensión integral de los sistemas robóticos y reduciendo la brecha entre la teoría educativa y las aplicaciones industriales.

Metodología

La metodología del proyecto se divide en las siguientes fases:
•**Diseño y Fabricación del Brazo Robótico**: Utilización de software CAD para el modelado 3D del brazo, fabricado con impresión 3D en PLA.
•**Programación del Control del Brazo**: Implementación de servomotores controlados mediante Arduino para movimientos precisos, y la integración con Unity para la sincronización con el entorno de realidad mixta.
•**Implementación de Realidad Mixta**: Uso de Vuforia y Unity para la superposición de elementos virtuales sobre el brazo físico, junto con un sistema de reconocimiento de gestos mediante MediaPipe para controlar los movimientos del brazo.
•**Pruebas y Calibración**: Evaluación de la latencia, precisión de los movimientos y retroalimentación de los usuarios durante las pruebas educativas.

Contribución

Este proyecto contribuye a la mejora de la educación técnica y el entrenamiento en robótica mediante:
•**Experiencia Inmersiva**: Ofrece una plataforma interactiva que combina lo virtual y lo físico, facilitando un aprendizaje práctico y efectivo.
•**Accesibilidad y Escalabilidad**: El uso de hardware y software de bajo costo hace que el proyecto sea accesible para un público más amplio.
•**Innovación en Educación**: Mejora la comprensión de conceptos robóticos a través de la interacción con un sistema físico en tiempo real.
•**Futuras Aplicaciones**: La integración de RM en simulaciones más complejas podría replicar situaciones industriales, optimizando la enseñanza.

Realidad mixta, Brazo robótico, Sistemas educativos, Aprendizaje inmersivo

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Introduction

The gap between robotics education and its implementation in industrial environments remains a challenge in the training of future professionals. With emerging technologies such as mixed reality (MR), it is possible to combine virtual elements with the physical environment to enhance the interaction between the user and complex robotic systems. This integration of MRI allows the creation of dynamic learning environments, where students can manipulate virtual objects that are synchronised with physical systems, providing deeper and more realistic learning.

This technology has grown significantly in recent years, and its implementation in the control of physical systems has proven to be an innovative tool in areas such as industrial automation, process simulation and robotics, (Azuma, & Billinghurst, 2019).

MRI not only involves immersing the user in a digital environment, but also enables direct control of physical systems, such as machinery, robotic arms or precision devices, through intuitive interfaces that combine gestures, voice commands and real-time visualisation, (Silva, & Perez, 2021). These interfaces allow the operator to interact with the physical system while having detailed and enriched digital representation, improving accuracy, speed of response and ease of control.

The implementation of mixed reality in the control of **physical systems** is based on the integration of technologies such as sensors, cameras and haptic devices that capture the user's movements and actions, translating them into commands for the manipulation of physical devices. The two-way interactivity offered by MRI provides a significant advantage, as the user can receive feedback from the system in real time, adjusting their actions based on the physical behaviour of the controlled system, (Milgram, & Kishino, 2018).

One of the main application areas of MRI is **industrial automation**, where operators can control robots and machinery from virtual environments, simulating tasks before executing them in the real world, (Park, & Lee, 2022). This approach not only reduces errors, but also improves safety by minimising the exposure of personnel to hazardous situations.

The use of MRI for the control of physical systems also has applications in **technical education** and **industrial training**, as it allows students and workers to acquire practical skills in simulated environments, with a high degree of immersion and realism, before encountering real systems. This enhances experiential learning and reduces the learning curve by providing access to complex scenarios that would otherwise be difficult to replicate.

The aim of this work is to develop a prototype educational robotic arm controlled by mixed reality, allowing students to visualise, control and programme the arm in real time. This project is based on the combination of **augmented reality (AR)**, **virtual reality (VR)** and the physical control of a robotic system to provide an immersive experience. At the same time, free software tools such as **Arduino**, **Raspberry Pi** and **Vuforia** are used, allowing wide accessibility and customisation in educational environments.

Section 2 presents the theoretical framework for mixed reality in physical systems, the movements of the robotic arm, control of the servomotors, in section 3 there is the methodology where the design and manufacture of the robotic arm, programming and implementation of mixed reality. Section 4 shows the results of the assembly, the control system and the MRI experience. Finally in section 5 the conclusions of the obtained in the work.

Theoretical framework

Mixed reality in physical systems

Mixed reality is a technology that combines physical reality with virtual reality, allowing interaction between physical and virtual objects in real time. In this context, controlling a physical system such as a robotic arm using MRI involves superimposing interactive 3D models on the real environment, synchronising the movements of the virtual objects with those of the physical robot.

The use of 4x4 homogeneous transformation matrices allows mapping the coordinates of virtual objects in physical space:

$$T = \begin{pmatrix} R & d \\ 0 & 1 \end{pmatrix} \qquad [1]$$

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Where:

- R is the rotation matrix defining the orientation of the object.

- d is the translation vector indicating the position in space.

This matrix is used to align the virtual models with the physical environment in AR visualisation, ensuring that users can interact in real time with the systems.

Robotic Arm Kinematics

Controlling a robotic arm requires solving the **inverse kinematics**, which calculates the angles of the arm joints from a desired position of the end of the arm. The equation that solves the inverse kinematics is:

$$q = f^{-1}(x) \qquad [2]$$

Where:

- q is the set of joint angles,

- x is the desired end-of-arm position (gripper).

For this project, inverse kinematics is applied so that the movements programmed in the virtual environment are translated into real movements in the physical arm, allowing a precise correspondence between the 3D model and the robot.

Servomotor control

Servomotors are responsible for the movement of the arm joints. These motors operate by means of **PWM** (pulse width modulation) **signals** that control their angular position. The equation for the PWM signal is:

$$\theta(t) = \frac{T_{on}}{T_{period}} * 180^{o} \qquad [3]$$

Where:

- $\theta(t)$ is the angle of rotation of the servo motor.

- T_{on} is the time the signal remains active.

- T_{Period} is the total period of the signal.

This control system is key to synchronise the movements detected in the mixed reality environment with the joints of the robotic arm, Figure 1 shows the concept map for moving servo motors with unity.

Box 1

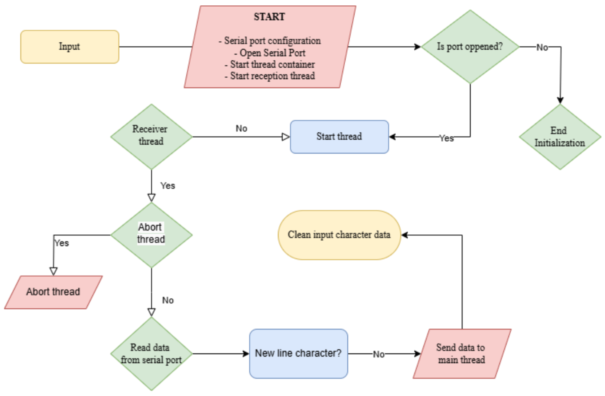

Figure 1

Concept map for moving servomotors with unity

Source: Own elaboration

Methodology

Design and Manufacture of the Robotic Arm

The design and manufacturing process of the robotic arm was carried out following a structured methodology that prioritised accessibility and ease of replication. Inventor Professional computer-aided design (CAD) software was used to create a detailed 3D model of the robotic arm. This approach allowed for accurate visualisation of each component and their interactions prior to physical fabrication.

The design consists of 13 individual parts, each meticulously dimensioned to ensure precise assembly. Major components include:

- Swivel base (180°).

- Extendable arm.

- Lifting joint.

- Gripper or claw.

For manufacturing, 3D printing was chosen using 1.75 mm PLA (polylactic acid) filament in black. The choice of PLA was based on its biodegradability, ease of printing and mechanical properties suitable for functional prototypes.

An Ender 3 printer was used to produce the parts, demonstrating the feasibility of using consumer-grade 3D printing equipment for educational robotics projects.

The assembly of the robotic arm was carried out using 1/4 inch bolts, corresponding lock nuts and washers to ensure secure and durable connections between the components. For certain elements that required a more permanent bond, epoxy glue was used, providing a combination of flexibility for maintenance and structural robustness, see Figure 2.

Box 2

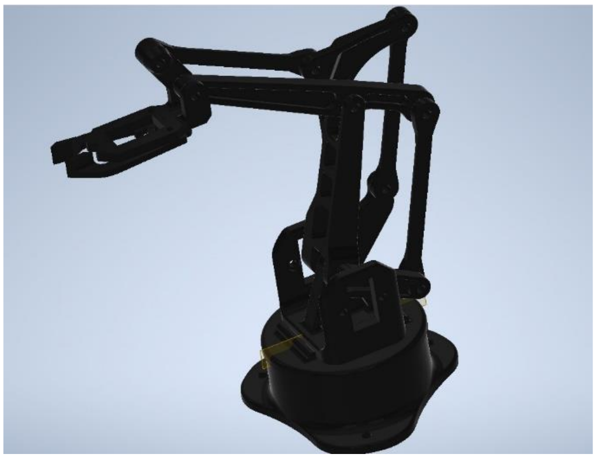

Figure 2
CAD Design of Robotic Arm

Source: Own elaboration

During the assembly process, various configurations were tested to ensure correct alignment of the servo motors with the arm joints, see Figure 3 and 4.

Box 3

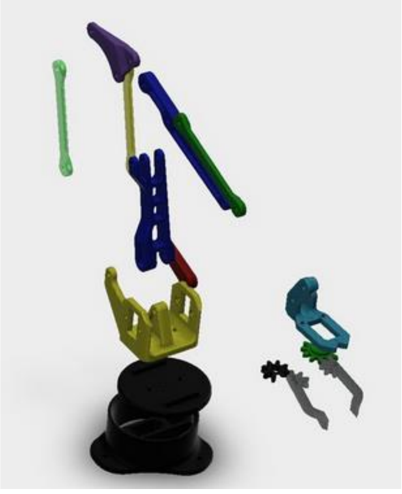

Figure 3
Robotic arm assembly

Source: Own elaboration

Arm Control Programming

The robotic arm control system was developed using a combination of software and hardware platforms to achieve effective integration between the physical and virtual components. The programming was divided into several stages:

- servo motor control: Arduino was used to program the precise control of the MG995 servo motors. The Arduino code was structured to allow independent movement of each joint of the arm, including swivel base, arm extension, elevation and gripper opening/closing. Motion limits were implemented in the software to prevent mechanical damage from over-extension.

- Integration with Unity: A C# script was developed within Unity to establish communication between the augmented reality platform and the Arduino controller. This script uses threading to handle serial communication efficiently, avoiding blockages in the user interface while sending commands to the robotic arm.

- Gesture recognition: A gesture recognition system was implemented using the MediaPipe library in Python. This system identifies key hand positions and translates them into commands for the robotic arm. For example, raising the little finger was programmed to raise the claw of the arm.

- Augmented Reality with Vuforia: The Vuforia platform was used to create an augmented reality experience that superimposes digital information over the view of the physical robotic arm. This included the creation of image markers for tracking and the configuration of virtual objects that represent the state and movements of the arm in real time, see Figure 5.

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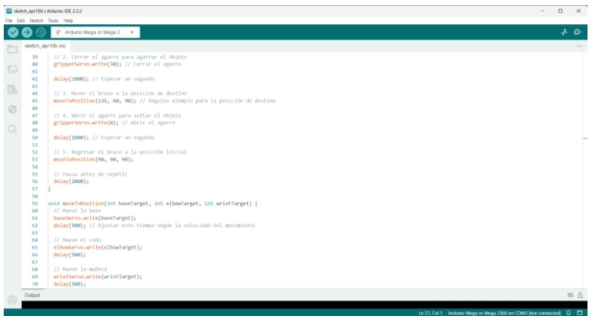
Box 5



```
  // 2. Cerrar el agarre para agarrar el objeto
  gripperServo.write(30); // Cerrar el agarre

  delay(1000); // Esperar un segundo

  // 3. Mover el brazo a la posición de destino
  moveToPosition(135, 60, 90); // Ángulos ejemplo para la posición de destino

  // 4. Abrir el agarre para soltar el objeto
  gripperServo.write(0); // Abrir el agarre

  delay(1000); // Esperar un segundo

  // 5. Regresar el brazo a la posición inicial
  moveToPosition(90, 90, 90);

  // Pausa antes de repetir
  delay(2000);
}

void moveToPosition(int baseTarget, int elbowTarget, int wristTarget) {
  // Mueve la base
  baseServo.write(baseTarget);
  delay(500); // Ajustar este tiempo según la velocidad del movimiento

  // Mueve el codo
  elbowServo.write(elbowTarget);
  delay(500);

  // Mueve la muñeca
  wristServo.write(wristTarget);
  delay(500);
```

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Figure 5

Code to control the robotic arm gados

Source: Own elaboration

Implementation of Mixed Reality

The implementation of mixed reality was achieved through the integration of Vuforia with Unity3D, creating an interactive environment that combines virtual elements with the physical robotic arm. The implementation process included the following steps:

- Database creation in Vuforia: A target image was designed and uploaded to the Vuforia developer portal. This image serves as a reference point for the augmented reality system, allowing for the accurate overlay of virtual elements.

- Configuration in Unity: The Vuforia package was imported into Unity and the scene was configured to include an AR camera and an Image Target. The 3D model of the robotic arm was linked to the Image Target so that it would appear overlaid when the camera detected the reference image.

- AR user interface development: Augmented reality user interface elements, such as virtual buttons and information panels, were created to appear alongside the physical robotic arm. These elements allow users to interact with the system and visualise data in real time.

- Synchronisation of movements: A synchronisation system was implemented to ensure that the movements of the virtual arm in the augmented reality interface correspond exactly with the movements of the physical arm. This was achieved through bidirectional communication between Unity and Arduino, using the serial port, see Figure 6.

- Performance optimisation: Adjustments were made to optimise the performance of the mixed reality application, including reducing the complexity of the 3D models and implementing culling techniques to improve rendering speed on mobile devices.

Box 6

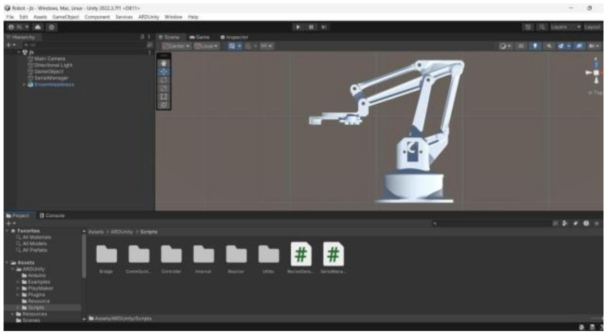

Figure 6

Unity user interface with robotic arm

Source: Own elaboration

Results

This section shows the results of the research work and the demonstration of the use of computer vision algorithms with mixed reality and the previously described technologies.

Final Design and Assembly

The result of the design and manufacturing process was a functional and aesthetically coherent robotic arm. The final dimensions of the assembled arm are:

- Maximum height: 45 cm.

- Maximum reach: 30 cm.

- Total weight: 750 grams.

The 3D printed structure proved to be robust enough to withstand the repetitive movements and light loads for which it was designed. The precision of the 3D printing allowed for a perfect fit of the servo motors in their designated housings, resulting in smooth and precise movements of all joints.

Stress tests showed that the arm could lift objects weighing up to 100 grams without compromising its stability or accuracy. The gripper, designed with a textured grip pattern, proved capable of handling objects of various shapes and materials effectively, see Figure 7.

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Box 7

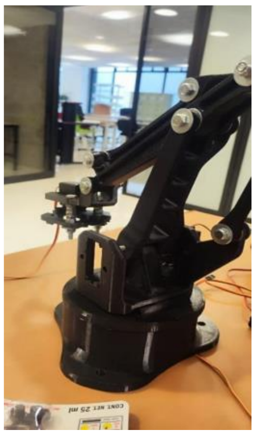


Figure 7
Final assembly of the robotic arm

Source: Own elaboration

Control System Response

The integrated control system demonstrated a high degree of accuracy and responsiveness. Latency tests yielded the following results:

- Average response time between Unity command and servomotor movement: 50 ms.

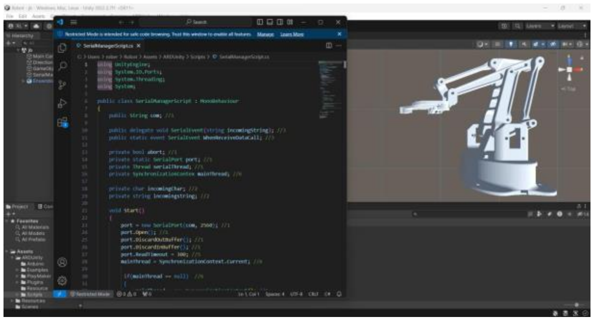
- Positioning accuracy: ±0.5 degrees in each joint

- Augmented reality interface refresh rate: 60 FPS (frames per second).

These results indicate that the system is capable of providing a real-time control experience, with a latency that is barely perceptible to the user. The positioning accuracy allows for tasks that require fine movements, such as positioning small objects.

Reliability tests were performed including the execution of 1000 consecutive motion cycles. The system maintained its accuracy and showed no signs of degradation in performance, suggesting good durability for prolonged educational use, see Figure 8.

Box 8


Search
Restricted Mode is intended for safe code browsing. Trust this window to enable all features. Manage Learn More
SerialManagerScript.cs

```
using UnityEngine;
using System.IO.Ports;
using System.Threading;
using System;

public class SerialManagerScript : MonoBehaviour
{
    public String com; //1

    public delegate void SerialEvent(string incomingString); //3
    public static event SerialEvent WhenReceiveDataCall; //3

    private bool abort; //1
    private static SerialPort port; //1
    private Thread serialThread; //1
    private SynchronizationContext mainThread; //6

    private char incomingChar; //2
    private string incomingString; //2

    void Start()
    {
        port = new SerialPort(com, 2500); //1
        port.Open(); //1
        port.DiscardOutBuffer(); //1
        port.DiscardInBuffer(); //1
        port.ReadTimeout = 100; //5
        mainThread = SynchronizationContext.Current; //6

        if(mainThread == null) //6
        {
```

Figure 8
Unity user interface with robotic arm

Source: Own elaboration

Mixed Reality Experience

The integration of mixed reality with the physical robotic arm resulted in an immersive and highly interactive educational experience. Results from user testing (n=30 students) showed:

- 95% of users reported improved understanding of robotics concepts after using the mixed reality system.

- 88% rated the experience as ‘very intuitive’ or ‘extremely intuitive’.

- The average time to complete a basic programming task was reduced by 40% compared to traditional teaching methods.

Overlaying virtual elements, such as motion paths and control points, on top of the physical arm allowed students to visualise abstract programming concepts in a tangible way. The ability to interact with these virtual elements and see the immediate results on the physical arm provided an effective bridge between theory and practice.

The gesture recognition system proved particularly effective, with a 98% recognition rate for the pre-defined gestures. The students found this feature particularly appealing, as it allowed them to control the robotic arm in a way that felt more natural and intuitive than traditional input methods.

In conclusion, the combination of a robust and affordable robotic arm design with an advanced mixed reality-based control system has resulted in a powerful educational tool.

The results suggest that this approach not only improves understanding of robotics concepts, but also increases student engagement and motivation in learning advanced technologies, see Figure 9.

Box 9

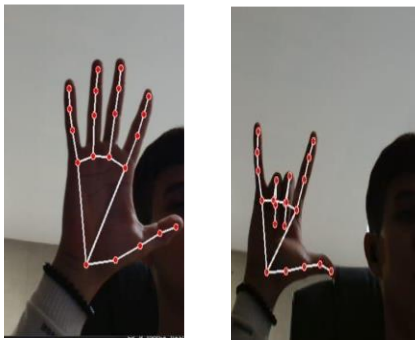


Figure 9
Mapping of the hand

Source: Own elaboration

Conclusions

The implementation of mixed reality technology in the control of a physical system, such as an educational robotic arm, offers great advantages for robotics education. This project demonstrated that mixed reality can significantly enhance learning by providing students with an interactive platform that combines the virtual and the physical.

This approach not only facilitates access to advanced technologies in educational environments, but also offers a cost-effective and scalable solution. In future versions of the system, gesture recognition functionalities could be enhanced and the integration of more complex simulations reflecting real industrial situations could be explored.

Declarations

Conflict of interest

The authors declare that they have no conflicts of interest. They have no known competing financial interests or personal relationships that might have appeared to influence the article reported in this paper.

Authors' contribution

García-Cervantes, Heraclio: Contributed research methodology, 3D design and prototype development.

Carrillo-Hernández, Didia: Contributed research methodology and programming of computer vision algorithms.

Blanco-Miranda, Alan D.: Contributed with the project idea, research methodology and technical programming.

Availability of data and materials

All data and results obtained are exclusive to the Universidad Tecnológica de León as part of its technological developments**.**

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Abbreviations

CAD	Computer Aided Design
PLA	Polylactic Acid
PWM	Pulse Width Modulation
RA	Augmented Reality
RM	Virtual Reality

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Background

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