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Article

Optomechatronic system for robotic arm using neural networks for educational inclusion

Sistema optomecatronico para brazo robótico con el uso de redes neuronales para la inclusión educativa

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Abstract

The artificial vision system is crucial in technological advancements, offering innovative solutions for assisting people with disabilities. This study presents an optomechatronic system designed to control a robotic hand prosthesis using artificial vision to interpret hand movements and translate sign language into voice commands. The prosthesis operates through artificial vision-based control that maps hand positions to prosthetic fingers. This technology aids in direct communication between people with hearing impairments and others, enhancing inclusivity. The project emphasizes the use of low-cost and open-source software, making it accessible to a broader audience.

Optomechatronic System for Robotic Arm Using Neural Networks for Educational Inclusion

Objective

The main objective of this project is to design and develop an optomechatronic system for controlling a robotic hand prosthesis using artificial vision and neural networks. The system aims to enhance educational inclusion for individuals with auditory and physical disabilities by translating sign language gestures into voice commands, facilitating both communication and physical control of the prosthesis.

Methodology

The project follows a structured methodology across four phases:
•**Hardware Development**: The prosthesis was designed using 3D printing technology and equipped with servomotors controlled by an Arduino UNO board.
•**Software Development**:
- Use of **Python** and computer vision libraries like OpenCV for image processing and gesture recognition.
- **MediaPipe** implementation to extract key hand points and map them to specific prosthetic movements.
- A control algorithm that processes binary signals to move the prosthetic fingers.

•**Testing and Calibration**: The system was tested under various lighting conditions to evaluate the accuracy of the vision system and the responsiveness of the servomotors.
•**Optimization**: Adjustments in the control algorithm and integration of a text-to-speech engine to improve gesture translation.

Contribution

This work makes a significant contribution to educational inclusion by:
•**Facilitating Communication**: The system allows real-time translation of sign language gestures, enhancing interaction between people with hearing impairments and their environment.
•**Improving Accessibility**: The use of low-cost components and open-source software makes the project accessible and scalable to a broader audience.
•**Precision in Control**: The servomotors accurately replicate finger movements, enabling the prosthesis to perform complex tasks.
•**Future Applications**: Plans include optimizing the detection of complex gestures and improving functionality in low-light conditions, increasing the system's potential for real-world adoption.

Artificial vision, Prosthesis control, Sign language

Resumen

Los sistemas de visión artificial son fundamentales en los avances tecnológicos, ofreciendo soluciones innovadoras para personas con diferentes discapacidades. Este estudio se centra en un sistema optomecatrónico diseñado para controlar una prótesis de mano robótica mediante visión artificial, que interpreta movimientos de la mano y traduce el lenguaje de señas en comandos de voz. La prótesis opera a través de un control basado en visión artificial que mapea posiciones de la mano a los dedos protésicos. Esta tecnología facilita la comunicación directa entre personas con discapacidad auditiva y otras, promoviendo la inclusión. El proyecto destaca el uso de software libre de bajo costo, haciéndolo accesible a una audiencia más amplia y a un costo bajo.

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Objetivos

El objetivo principal de este proyecto es diseñar y desarrollar un sistema optomecatrónico para el control de una prótesis robótica de mano, utilizando visión artificial y redes neuronales, con el fin de mejorar la inclusión educativa de personas con discapacidades auditivas y físicas. El sistema traduce los gestos del lenguaje de señas en comandos de voz, facilitando la comunicación y el control físico de la prótesis.

Metodología

El proyecto sigue una metodología estructurada en cuatro fases:
•**Desarrollo de Hardware**: La prótesis fue diseñada con tecnología de impresión 3D y equipada con servomotores controlados por una placa Arduino UNO.
•**Desarrollo de Software**:
- Uso de **Python** y bibliotecas de visión artificial como OpenCV para procesar imágenes y reconocer gestos.
- Implementación de **MediaPipe** para extraer puntos clave de la mano y mapearlos a movimientos específicos de la prótesis.
- Algoritmo de control basado en el procesamiento de señales binarias para el movimiento de los dedos.

•**Pruebas y Calibración**: Se realizaron pruebas bajo distintas condiciones de luz para evaluar la precisión del sistema de visión y la capacidad de respuesta de los servomotores.
•**Optimización**: Ajustes en el algoritmo de control y la integración del motor de conversión de texto a voz para mejorar la traducción de gestos.

Contribución

Este trabajo aporta un avance significativo en el campo de la inclusión educativa al:
•**Facilitar la comunicación**: El sistema permite la traducción de gestos del lenguaje de señas en tiempo real, mejorando la interacción entre personas con discapacidad auditiva y su entorno.
•**Mejorar la accesibilidad**: Al utilizar componentes de bajo costo y software libre, el proyecto es accesible y escalable para un público más amplio.
•**Precisión en el control**: Los servomotores logran replicar con precisión los movimientos de los dedos, permitiendo que la prótesis realice tareas complejas.
•**Aplicaciones futuras**: Se plantea la optimización de la detección de gestos complejos y la mejora de la funcionalidad bajo condiciones de baja iluminación, lo que incrementa su potencial de adopción en escenarios reales.

Visión artificial, Control de prótesis, Lenguaje de señas

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Introduction

Optomechatronic systems, which combine mechanical, electronic and optical elements, have transformed the field of prosthetics, offering innovative solutions for people with disabilities.

With the help of artificial vision systems, designed to interpret visual data and execute precise mechanical responses, it has enabled the development of robotic prostheses capable of performing complex tasks, such as replicating human hand movements and translating sign language.

The importance of this project lies in its ability to improve communication for people with hearing and physical disabilities, particularly those who require hand prostheses. Traditional methods, such as Braille or tactile communication, have limitations, while a system based on artificial vision offers a more dynamic and real-time interaction.

This study presents a novel machine vision system designed to control a robotic prosthetic hand. Unlike other methods that rely exclusively on manual inputs or expensive hardware, our system uses low-cost components and free software, making it an accessible and scalable solution.

The central hypothesis is that a real-time machine vision system can effectively control a prosthetic hand while simultaneously translating sign language into voice commands, providing dual functionality for communication and physical movement.

The first section of this paper explains the mathematical basis of the elements of the project.

The second section describes all the elements that make up the project, both sensors and actuators, as well as their technical specifications and the development process for the generation of the final prototype.

In the next section, the results obtained with the prototype are presented, as well as the graphical user interface created for the control of the vision systems and modes of operation.

In the discussion section, reference is made to future work, as well as the areas of opportunity to be developed in the prototype for a better implementation in a real working environment.

Finally, the conclusion section describes the lessons learned from this research work, as well as its potential large-scale implementation.

1. Theoretical Framework

The development of machine vision controlled robotic prostheses involves a combination of several disciplines such as biomechanics, robotics, and artificial intelligence (AI), specifically in areas such as image processing. In the following, the theoretical background and mathematical basis of the main areas involved in this project are described.

1.1 Biomechanics of Human Motion

Biomechanics studies the movements of the human body and how forces act on joints.

In this case, the movements of the human hand, such as flexion and extension of the fingers, can be modelled using equations that describe the relationships between the applied forces and the resulting movements.

The movement of a finger can be modelled as a system of levers, where tendons, muscles and joints act as force application points and pivots. To model these motions, the torsional moment equations are used:

Formula [1]

Where:

τ is the torsional moment (N-m), F is the applied force (N), d is the distance from the pivot point to the force application point (m).

This equation is fundamental to the design of servo motors in prosthetics, as the torque required to move each finger must be considered, especially in conditions of resistance or when performing tasks that require force.

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1.2 Prosthetic Robotics

The control of robotic prostheses involves concepts of inverse kinematics, where, given a desired position of the end of an articulated system (in this case, the fingers of the hand), the angles to be adopted by the joints are calculated. In a robotic arm or hand, inverse kinematics allows the angles of the joints to be calculated to obtain an end position of the finger. The general equation for solving the inverse kinematics of a manipulator system with n degrees of freedom is:

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

Where:

$\vec{q} = [q_1, q_2, q_3, \dots, q_n]$ are the joint angles of each joint, x is the desired end position (in this case, the position of the fingertip), and x is the desired end position (in this case, the position of the fingertip). f^{-1} is the inverse function relating the end position to the joint angles.

Numerical methods such as the Newton-Raphson algorithm or geometric solutions in simpler cases can be used to solve this system of equations. Accuracy in inverse kinematics is key for the prosthesis to perform precise and controlled movements.

1.3 Image Processing and Machine Vision

The implemented machine vision system uses image processing techniques to detect and track hand movements. In this context, feature detection is crucial.

To detect key points on the hand (fingers), a method based on edge detection algorithms, such as the Sobel or Canny filter, which calculates the intensity gradient of the images, is used.

The gradient of a two-dimensional image can be calculated as:

$$\nabla I = \left(\frac{\partial I}{\partial x}, \frac{\partial I}{\partial y}\right) \quad [3]$$

Where:

- $\frac{\partial I}{\partial x}$ is the derivative of the image in the direction of x,
- $\frac{\partial I}{\partial y}$ is the derivative of the image in the direction y.

These gradients allow for the detection of edges or intensity changes in the image, which are indicative of the contours of fingers and other key objects.

In addition, for hand detection, an algorithm based on the recognition of specific hand features is implemented, using techniques such as the active deformation algorithm and landmark tracking. The MediaPipe library is key in this process, which allows 21 key points (joints) of the hand to be extracted using a convolutional neural network (CNN). These points are used to map hand gestures to specific commands in the control of the prosthesis.

1.4 Servomotor Control

The control of the servomotors, which allow the movement of the fingers in the prosthesis, is based on the control of the angular position.

The position of each servomotor is adjusted by means of the pulse width control (PWM) signal, which can be described by the following equation:

$$\theta(t) = \frac{T_{on}}{T_{periodo}} \cdot 180° \quad [4]$$

Where:

- $\theta(t)$ is the angle of rotation of the servomotor as a function of time,
- T_{on} is the period during which the signal is high (in milliseconds).
- $T_{periodo}$ is the total period of the PWM signal (in milliseconds).

Precise control of the angular position allows the prosthetic fingers to move precisely and in accordance with the movements detected by the machine vision system.

1.5 Artificial Intelligence in Gesture Recognition

To improve the interaction between the user and the prosthesis, supervised learning techniques are employed to recognise specific gestures that correspond to hand movements.

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The gesture recognition system is trained using a labelled gesture dataset, where the neural network learns to classify new gestures based on features extracted from key points on the hand. The back propagation algorithm is commonly used to train neural networks by adjusting the weights w of the network based on the error E between the desired output and the actual output:

$$\Delta w = -\eta \frac{\partial E}{\partial w} \quad [5]$$

Where:

- η is the learning rate,
- $\frac{\partial E}{\partial w}$ is the gradient of the error with respect to the weights.

This model is implemented in the neural network to improve the accuracy of gesture detection and to optimise the control of the prosthesis.

2. Methodology

The methodology used in this project is divided into four main phases: hardware development, software development, system testing and optimisation.

2.1 Hardware development

The hardware of the hand prosthesis was designed using 3D printed materials and accessible electronic components. The main components include:

- **Prosthetic structure:** The prosthesis was 3D printed using *PLA* filament, selected for its durability and ease of use. Each finger of the prosthesis was designed to move independently by servo motors, providing flexibility and functionality, see Figure 1.

Box 1

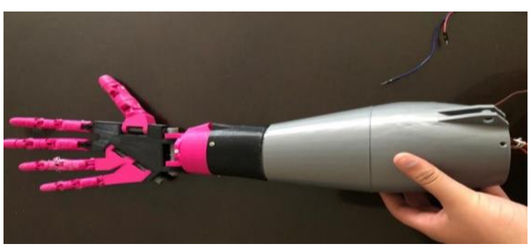

Figure 1
Prototype robotic right hand prosthesis

- **Servomotors (MG995):** Each of the five servomotors was assigned to a finger. These servomotors allow precise control of the movement and maintain a constant torque, which is essential for replicating the grip and release movements of the human hand, see table 1.

Box 2

Table 1
MG995 Servo Motor Specifications

Property	Value
Weight	55 g
Dimensions	40.7 x 19.7 x 42.9 mm
Torque	8.5 kgf·cm (4.8V), 10 kgf·cm (6V)
Operating Speed	0.2 s/60º (4.8V), 0.16 s/60º (6V)
Operating voltage range	4.8V a 7.2V

Source: Electrónicos Caldas, 2022

- **Arduino UNO:** The Arduino UNO board served as the central control unit, managing the inputs of the machine vision system and translating those signals into specific actions of the prosthetic motors.

- **Sensor Shield:** An auxiliary board that facilitated the connection of the servomotors to the Arduino board and regulated the power required for their operation.

2.2 Software Development

- Software development included the implementation of algorithms for machine vision and servo motor control. The Python programming language was selected due to its simplicity and compatibility with open source libraries such as OpenCV and CV Zone.

- **Machine Vision System:** A camera was used to capture hand movements, and the software used the OpenCV library for image processing and object recognition, see Figure 2. The system identified specific hand gestures, such as the number of fingers raised, and mapped them onto corresponding prosthetic movements.

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Box 3

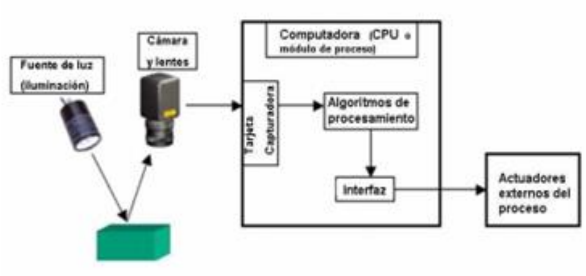

Figure 2
Schematic diagram of machine vision system
Source: *Researchgate, 2022*

- **Control Algorithm:** The control algorithm for the servomotors was designed to move each finger of the prosthesis in response to the detected gestures. The algorithm interprets binary inputs (1 for 'open' and 0 for 'closed') and sends these signals to the corresponding servomotor.
- **Sign Language Translation:** The system was also designed to interpret hand gestures corresponding to sign language, and translate them into voice commands using a text-to-speech conversion engine. This feature was implemented using the MediaPipe library for hand tracking and the Google API for speech synthesis.

2.3 Testing and Calibration

Several tests were performed to ensure the accuracy and responsiveness of the system. The prosthesis was tested under different light conditions and distances to evaluate the robustness of the machine vision system. The capture rate of the camera and the sensitivity of the servo motors were adjusted to minimise the delay between gesture detection and prosthesis response, see Figure 3 and 4.

Box 4

Figure 3
Detection of manual gestures and translation into prosthetic movements

Box 5

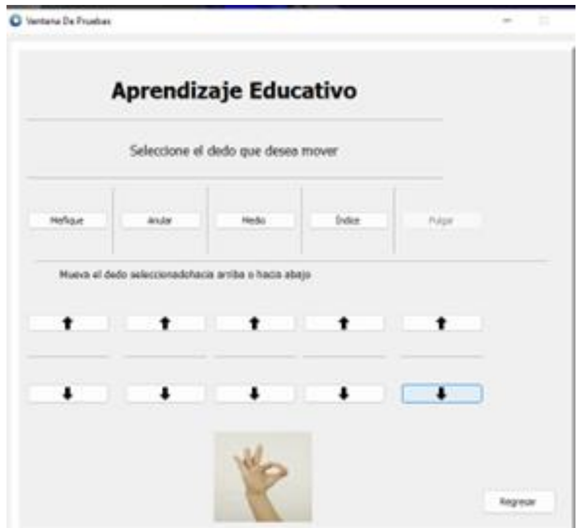

Figure 4
Learning interface

3. Results

3.1 Gesture detection and machine vision

The machine vision system was able to detect hand gestures with 95% accuracy in optimal lighting conditions. Figure 5 shows an example of real-time detection of hand gestures and their corresponding movements on the prosthesis.

Box 6

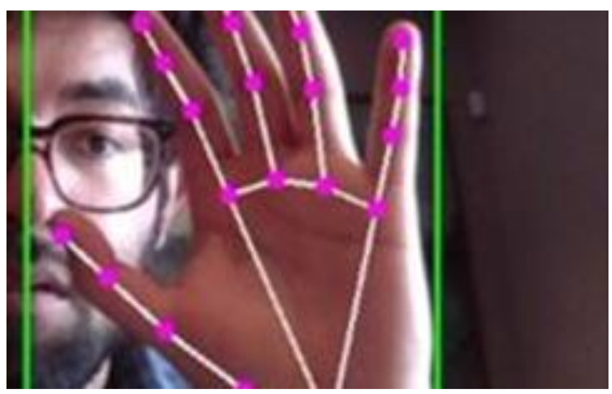

Figure 5
Detection of manual gestures and translation into prosthetic movements

However, in low light conditions, the accuracy decreased by 10%, highlighting the importance of constant light conditions for optimal system performance.

3.2 Servo Motor Response

The servomotors demonstrated high accuracy in replicating human hand movements.

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Each motor correctly performed its assigned tasks, which included opening and closing the prosthetic fingers. During stress testing, the servo motors exhibited a small delay (less than 0.5 seconds) when multiple fingers moved simultaneously. This delay was mitigated by adjusting the algorithm to process signals in parallel, see table 2.

Box 7

Table 2

Response times and accuracy in different conditions

Test Condition	Response Time [s]	Accuracy [%]
Normal lighting	0.2	95
Low illumination	0.35	85
Multi-finger movement	0.5	90

3.3 Sign Language Translation

The sign language translation function was able to interpret basic gestures, translating them into voice commands with a 90% recognition rate. The system was tested with a set of 20 common Mexican Sign Language (LSM) gestures, see Figure 6 and 7.

Box 8

Figure 6

Detection of manual gestures and translation into prosthetic movements

Box 9

Figure 7

System start interface for operation selection

However, more complex gestures involving simultaneous movements of both hands were not recognised by the current system, an example of the serial communication of the servomotors is shown below, see Table 3.

Box 10

Table 3

Example of serial communication of servomotors

Posture	Meñique	Cancel	Medium	Index	Pulgar
Cero	0	0	0	0	0
Uno	0	0	0	1	0
Dos	0	0	1	1	0
Tres	0	1	1	1	0
Cuatro	1	1	1	1	0
Cinco	1	1	1	1	1

Source: Murtaza's Workshop, 2021

4. Discussion

The machine vision-based prosthesis control system has shown great potential for assisting people with hearing and physical disabilities.

The use of open source software libraries such as OpenCV and Python enabled the creation of a functional and accessible system. However, the system's performance in low light conditions and its limited ability to recognise complex gestures present areas for improvement.

Future iterations of the project should focus on:

- **Improving low-light performance:**

Integration of infrared sensors or improvements in image processing algorithms could optimise performance in sub-optimal lighting conditions.

- **Extending gesture recognition capabilities:**

Incorporating machine learning techniques would allow the system to handle a wider range of gestures, including those involving simultaneous movements of both hands.

- **Reduced delay:** Optimisation of the control algorithm could further reduce the response time between gesture detection and prosthesis movement.

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Conclusions

This study has successfully demonstrated the potential of a machine vision system for the control of a robotic hand prosthesis. By using low-cost hardware and free software, this project offers an accessible solution for people with disabilities, particularly those who rely on sign language for communication.

The current prototype translates hand gestures into prosthetic movements and interprets basic sign language gestures. While there are areas for improvement, such as reducing response delay and extending gesture recognition, the core functionality of the system has been validated.

With further development, this technology has the potential to be adopted on a large scale, improving the quality of life for people with physical and hearing disabilities.

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

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

García-Cervantes, Heraclio: Contributed with the research methodology, design and prototype development.

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

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

ANN	Artificial Neural Network
API	Application Programming Interface
IA	Artificial Intelligence
CNN	Convolutional Neural Network
LSM	Mexican Sign Language
PLA	Polylactic Acid
PWM	Pulse Width Modulation

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