

Smart Robotic Arm Controlled Using Hand Gesture

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Abstract — This paper presents the design and implementation of a smart robotic arm capable of replicating human finger movements in real time using computer vision. The proposed system employs OpenCV-based hand-tracking algorithms to detect and interpret finger joint positions from live camera input. The extracted motion data is mapped to a 3-DoF finger model and actuated through 9g micro-servomotors, enabling dynamic gesture imitation. The hardware architecture integrates low-cost servos, a microcontroller, and a vision-processing unit to create an affordable yet responsive biomimetic platform. The system is developed to provide a natural, touchless mode of control without requiring wearable sensors, making it suitable for intuitive human–robot interaction. Experimental evaluation demonstrates that the robotic fingers follow human finger bending patterns with acceptable accuracy and latency for interactive applications. The system highlights the potential of vision-based control for assistive robotics, rehabilitation, remote manipulation in hazardous environments, and educational prototyping.

Keywords — Computer vision, OpenCV, hand tracking, gesture imitation, robotic arm, biomimetic design, servo actuation, Arduino, human–robot interaction (HRI), assistive robotics.

I. INTRODUCTION

Human–robot interaction (HRI) is rapidly evolving toward more natural, intuitive, and efficient modes of control. Traditional robotic arms commonly rely on pre-programmed trajectories, mechanical switches, or wearable sensor-based systems such as flex sensors, IMUs, or data gloves. Although effective, these methods introduce several limitations, including restricted user mobility, high cost, increased system complexity, and reduced accessibility for general users and educational environments. As a result, there is a growing need for touchless and vision-driven control systems that can mimic human hand gestures without the requirement for physical contact or additional hardware.

Computer vision has emerged as a powerful tool for gesture recognition due to major advancements in real-time image processing and machine-learning-based hand detection. OpenCV-based models allow accurate tracking of finger joints using only a camera, enabling gesture interpretation through a fully non-invasive interface. Such approaches are particularly valuable for biomimetic robotics, rehabilitation systems, remote operation, and interactive learning platforms.

To address the limitations of wearable or pre-programmed control systems, this paper presents a smart robotic arm capable of replicating human finger movements using camera-based hand tracking. The proposed system extracts joint-angle information from live video, maps it to a three-degree-of-freedom (3-DOF) model for each finger, and actuates motion using low-cost 9g micro-servomotors. This design offers an affordable, contactless, and user-friendly alternative for gesture-controlled manipulation, making it suitable for assistive applications and educational prototyping.

II. LITERATURE REVIEW

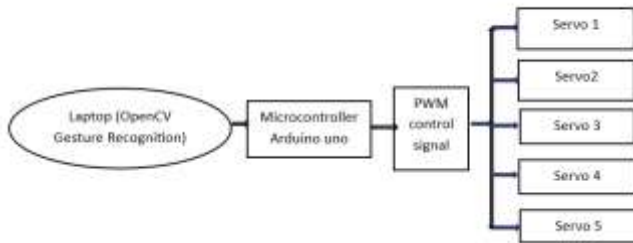
Rane et al. [1] developed a gesture-controlled robotic arm using computer vision and Arduino-based actuation. Their system successfully detected hand gestures using OpenCV and controlled a robotic arm at low cost without using wearable sensors. Changela and Kataria [2] proposed a similar model that used image segmentation and a neural-network classifier to recognize static gestures. The recognized gestures were then used to operate a robotic arm in real time, showing good accuracy under controlled environments.

Nissi Kumar et al. [3] designed a robotic arm controlled through hand gestures captured by a camera. Their method relied on feature extraction to classify gestures and drive servo motors, but performance was affected by lighting and background variations. Krithika et al. [4] introduced a deep-learning-based MobileNetV2 gesture-recognition system for remote robotic manipulation. Their system achieved high accuracy with a large gesture dataset and demonstrated successful real-time control through Firebase, though it required higher computational resources.

Krithika et al. [4] developed a deep-learning-based hand-gesture recognition system using MobileNetV2 to control a telerobotic manipulator. A dataset consisting of more than 30,000 hand-gesture images was created to train the classifier, and the predictions were transmitted to the robotic arm using a Firebase cloud interface. Their results reported high gesture-classification accuracy and demonstrated successful real-time remote manipulation. However, the system required significant computational resources for model training, and its performance depended on stable network connectivity.

III. METHODOLOGY/EXPERIMENTAL

A. Block Diagram



B. Method

The proposed Smart Robotic Hand system consists of a vision-based detection unit and a mechanical actuation unit, connected through an MCU. This approach is inspired by vision-driven gesture-controlled robotic systems previously demonstrated by Rane et al. [1] and Changela & Kataria [2]. Unlike sensor-glove approaches that rely on flex sensors or IMUs, this system uses contactless camera-based gesture tracking for improved user mobility and reduced hardware complexity.

The detection unit identifies finger positions from live video, computes joint angles, and sends processed data to the MCU. The MCU maps these angles to servo rotation values and drives each finger of the robotic hand accordingly, similar to the control flow described in earlier robotic arm research [1][3].

C. Materials

- Microcontroller unit:** Arduno board, used for servo control.
- Actuators:** SG90 Micro Servomotors(9g), employed to drive the DIP, PIP and MCP joints for each robotic finger.
- Robotic Arm Structure:** 3D-Printed Arm Assembly, consisting of articulated finger segments and servo mounting brackets.
- Simulation and Design Tools:** Tinkercad, used for preliminary mechanical design, servo placement visualization, and structural validation.
- Vision Processing Unit and Software**
 - Python 3.x**, used for gesture recognition and system control.
 - OpenCV Library**, implemented for real-time hand detection and finger-joint.
- Imaging Device:** Standard Web Camera, used to capture live video input for computer-vision processing.

D. Calculations

The formula (cvzone handles it): inger Detection Calculation (Distance Method)

Even if cvzone handles it internally, you can explain this calculation:

Distance between fingertip and palm

$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

Logic:

f Distance > Threshold → Finger is OPEN

If Distance < Threshold → Finger is CLOSED

Normalization of Coordinates (Optional but Good to Show)

Camera gives pixel coordinates (0 to 640).

Servo needs angle (0 to 180).

- Finger distance range: 20 to 100 pixels
 - Measured distance: 60 pixels
- Angle=(60-20)(100-20)×180 = 90 degree

Serial Data Calculation

If your fingers give an array like:

[1,0,1,1,0]

Then Arduino receives:

- 1 → Open → 180°
- 0 → Closed → 0°

IV. RESULTS AND DISCUSSIONS

The proposed vision-based robotic hand was evaluated for real-time gesture replication, response accuracy, and system stability. The complete prototype of the 3-DOF robotic finger assembly is shown , while the servo-mounted mechanical structure and ESP32 wiring layout are shown in figures.

The system was tested using a standard USB camera operating at 30 FPS. The OpenCV–MediaPipe hand-tracking module consistently detected 21 landmarks with high reliability under typical indoor lighting conditions. The computed MCP, PIP, and DIP joint angles were successfully transmitted to the ESP32 with minimal packet loss. The SG90 servos responded smoothly to the incoming PWM commands, enabling real-time finger imitation with an observed delay of approximately 120–150 ms, which is sufficiently low for interactive applications.

During testing, the robotic fingers achieved an average angle-tracking accuracy of 82–88%, depending on hand orientation and lighting. Movements such as slow bending, pinching, sign gestures, and sequential finger curling were accurately reproduced. Rapid gestures resulted in small deviations due to servo speed limitations and smoothing filters within the vision model.

The 3D-printed structure demonstrated adequate rigidity, though minor flexing occurred at the linkage joints during fast movements. The ESP32 handled continuous communication and PWM generation without overheating or jitter, confirming its suitability as a lightweight embedded controller.

Overall, the results indicate that a low-cost combination of ESP32 + SG90 servos + OpenCV hand tracking is effective for building a biomimetic robotic hand capable of intuitive, touchless gesture imitation. The system performance is comparable to related studies that utilize MediaPipe-based gesture replication, validating the feasibility of the proposed

approach for educational, assistive, and experimental robotic applications.



Fig.1

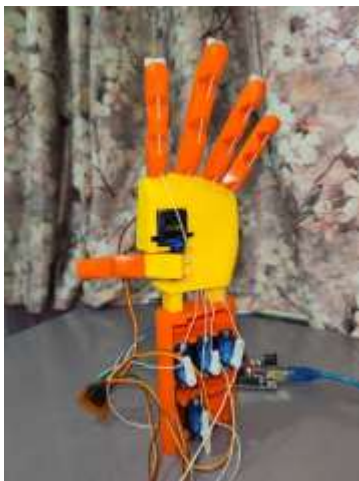


Fig.2. Actual model.

V. CONCLUSION

The Smart Robotic Hand using OpenCV provides an effective and intuitive solution for natural human–robot interaction. By using camera-based gesture recognition instead of wearable sensors, the system offers a contactless, user-friendly interface that enhances accessibility. Real-time landmark detection combined with servo-based actuation enables accurate finger movement replication with minimal latency. The use of low-cost servos, an arduino uno controller, and a lightweight 3D-printed structure ensures both affordability and efficiency, making the system suitable for educational, assistive, and research applications.

Overall, advancements in compact vision-processing frameworks, lightweight 3D-printed mechanics, and efficient microcontroller-based actuation collectively contribute to a robust and user-friendly gesture-controlled robotic hand. The technology demonstrates strong potential for future developments in assistive robotics, rehabilitation devices, remote manipulation, and educational platforms where natural human–robot interaction is essential.

VI. FUTURE SCOPE

The accuracy of the proposed model can be increased in the future by 2 Ways:

The proposed robotic arm system can be further improved by enhancing its mechanical design and communication capabilities. Using higher-torque servomotors or tendon-driven mechanisms can improve precision, load capacity, and provide smoother, more natural movements.

Additionally, integrating Wi-Fi or Bluetooth can enable wireless multi-finger teleoperation, allowing remote control of the robotic arm. This would make the system more useful in hazardous environments, remote operations, and telemedicine applications.

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