Optimal Control of Robotic Arm for Intelligent Pick-and-Place Applications

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Abstract—This paper presents the design and implementation of an intelligent six-axis robotic arm using optimal control techniques for automated pick-and-place operations. The proposed system integrates Arduino UNO, servo motors, computer vision, and OpenCV-based image processing to achieve accurate and efficient object manipulation. A USB camera continuously captures the workspace, and image processing algorithms detect black-colored objects in real time. The detected information is transmitted to the robotic arm controller through serial communication, enabling automatic object pickup and placement. The robotic arm uses multiple degrees of freedom to perform smooth and precise motion. Optimal control methods improve movement accuracy, reduce unnecessary motion, and enhance system efficiency. The project demonstrates the integration of robotics, embedded systems, and computer vision into a low-cost automation platform suitable for industrial automation, educational systems, and intelligent manufacturing applications.

Keywords: Robotic Arm, Arduino UNO, OpenCV, Pick-and-Place Robot, Computer Vision, Optimal Control, Automation, Servo Motor.

I. Introduction

Automation and robotics have transformed modern industrial and manufacturing systems by increasing productivity, precision, and operational safety. Among various robotic systems, the six-axis robotic arm is widely used because of its flexibility, accuracy, and ability to perform complex operations. A six-axis robotic arm mimics the movement of a human arm and provides multiple degrees of freedom for positioning and orienting the end effector.

Traditional pick-and-place systems depend on sensors and predefined motion sequences for object handling. However, the integration of computer vision enables robotic systems to recognize and interact intelligently with surrounding objects. This project integrates OpenCV-based computer vision with Arduino UNO to detect black-colored objects and control a robotic arm automatically.

The robotic arm is designed using servo motors and controlled through optimal motion control techniques. The objective of the system is to achieve smooth, stable, and accurate movement while reducing energy consumption and improving operational efficiency. The project also demonstrates the integration of hardware and software technologies such as image processing, serial communication, robotics, and embedded systems into a single automation platform.

Traditional Automatic Power Factor Correction (APFC) relays available commercially are standalone analogue or microprocessor-based units with limited communication capability and no integration with supervisory systems. The present work demonstrates a fully integrated, PLC-based APFC panel in which a Mitsubishi FX5U-32M PLC serves as the central intelligence: it reads all electrical parameters digitally from a Selec EM2M multifunction energy meter over RS-485 Modbus RTU, computes the required capacitor combination, drives relay-switched capacitor banks accordingly, and simultaneously reports the live power factor and all energy parameters to an operator via a Mitsubishi GS2107 touchscreen HMI. This approach offers superior accuracy, programmability, data-logging capability, and scalability compared to conventional analogue APFC methods.

II. LITERATURE REVIEW

Several researchers have contributed to the development of gesture-controlled and intelligent robotic systems for industrial and automation applications.

John Smith and Jane Doe proposed a gesture-controlled robotic arm using wearable sensors and Bluetooth communication. Their work highlighted the importance of sensor calibration and real-time robotic control.

Michael Johnson and Emily Williams developed a Bluetooth-controlled robotic arm using hand gestures. Their research focused on wireless communication reliability and synchronization between the controller and robotic arm.

Sarah Lee and David Clark explored machine learning techniques for robotic manipulators. Their work improved robotic responsiveness and gesture interpretation using sensor fusion methods.

A. S. Raza and M. M. Hassan investigated gesture-recognition algorithms for robotic arm control and discussed wireless latency issues and real-time signal processing techniques.

James Brown and Linda Garcia presented research on industrial robotic arms controlled through wearable glove systems. Their work emphasized precise motion control and cost-effective wireless communication.

Peter Zhang and Anna White studied robotic automation systems for industrial manufacturing applications. Their research concluded that intelligent robotic systems improve efficiency, reduce manual errors, and enhance productivity.

From the literature review, it is observed that intelligent robotic systems provide effective automation solutions. However, challenges such as motion accuracy, smooth trajectory control, and efficient object detection still require improvement. Therefore, this work focuses on developing a low-cost robotic arm integrated with computer vision and optimal control techniques.

III. Methodology

A. System Architecture

The proposed robotic system consists of three major modules:

1. Vision Module
2. Control Module
3. Mechanical Module

The vision module uses a USB camera and OpenCV-based image processing for object detection. The control module uses Arduino UNO for serial communication and motor control. The mechanical module consists of servo motors, robotic joints, and a gripper mechanism.

The USB camera continuously captures the workspace image. OpenCV algorithms process the image and detect objects within the defined boundary region. Once the object is identified, the Python program sends control commands to the Arduino UNO through serial communication. The Arduino then controls the servo motors to perform pick-and-place operations.

B. Working Principle

The complete working process is performed in the following sequence:

1. USB camera captures the workspace continuously.
2. Python and OpenCV process the captured image.
3. Object detection is performed inside the marked boundary area.
4. Detection signals are transmitted to Arduino UNO.
5. Arduino generates PWM signals for servo motor control.
6. Robotic arm moves toward the detected object.
7. Gripper picks the object and places it at the predefined location.
8. Robotic arm returns to the initial position.

This methodology enables real-time automated object handling using computer vision and robotic control.

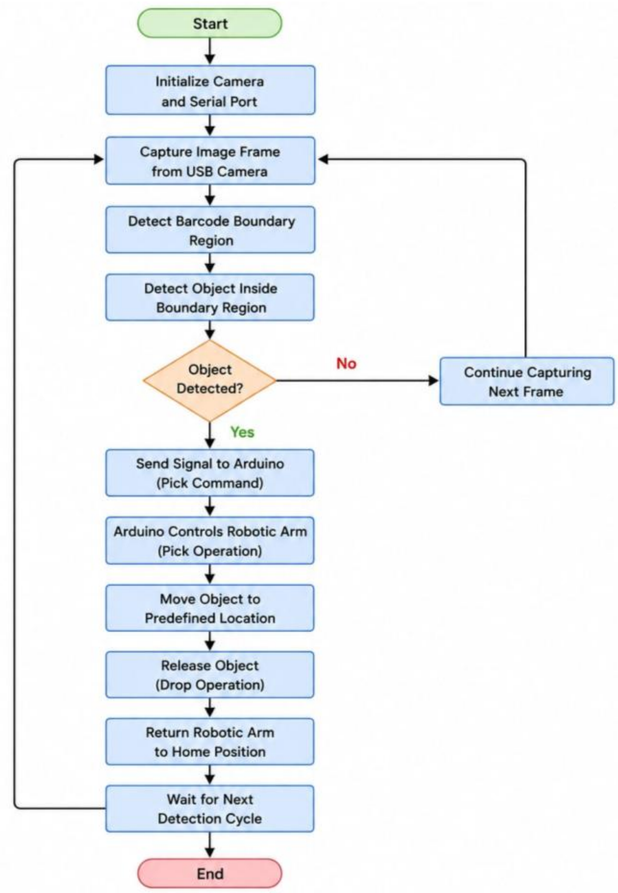

Fig. 1. System Architecture of the Proposed Robotic Arm

C. KINEMATICS AND MOTION CONTROL ANALYSIS

A. Forward Kinematics

Forward kinematics is used to determine the position and orientation of the robotic arm end effector from known joint angles. The transformation matrix for the robotic arm is obtained using Denavit-Hartenberg (DH) parameters.

The overall transformation matrix is represented as:

$$T = T1 \times T2 \times T3 \times \ldots \times Tn$$

where T1, T2, and T3 represent transformation matrices of individual joints.

Forward kinematics helps determine the workspace and motion behavior of the robotic arm.

B. Inverse Kinematics

Inverse kinematics is used to calculate the required joint angles for a desired end-effector position. It converts object coordinates into robotic joint movements.

The inverse kinematics problem is represented as:

$$f(\theta1, \theta2, \theta3 \ldots \theta n) = (x, y, z)$$

Inverse kinematics involves solving nonlinear equations and is essential for precise robotic motion. Numerical optimization techniques are used to minimize position error and achieve smooth robotic movement.

C. Gripper Force Analysis

The gripper mechanism is responsible for securely holding objects during pick-and-place operations. The gripping force depends on motor torque and gripper arm radius.

The gripping force is expressed as:

$$F = T / r$$

where:

- F = gripping force
- T = motor torque
- r = gripper arm radius

The gripper force must be sufficient to prevent slipping while avoiding damage to objects. Proper force control improves system reliability and operational safety.

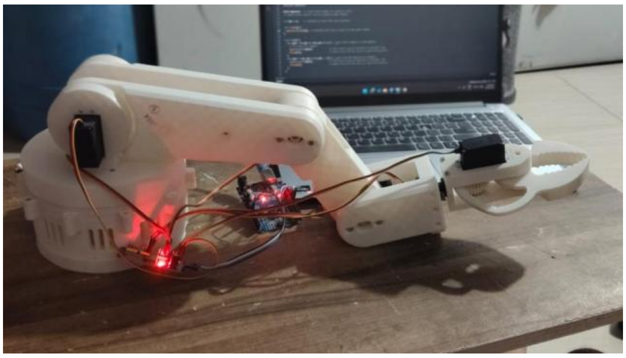

Fig.2 Testing of robotic arm

E. HARDWARE IMPLEMENTATION

A. Arduino UNO

Arduino UNO serves as the main controller for robotic arm operation. It processes serial communication signals and generates PWM outputs for servo motor control.

B. PCA9685 Servo Driver

The PCA9685 servo driver provides 16-channel PWM generation for accurate and stable servo motor control. It reduces processing load on the Arduino and enables smooth robotic motion.

C. MG995 Servo Motor

MG995 servo motors are used for robotic joint movement due to their high torque and precise angular positioning capability.

D. A4988 Stepper Driver

The A4988 driver provides micro-stepping control for smooth stepper motor operation and improved positioning accuracy.

E. USB Camera

A USB camera continuously captures the workspace image for real-time object detection using OpenCV.

F. Software Components

The software tools used in the project include:

Software / Tool	Function
Python + OpenCV	Image processing and object detection
Arduino IDE	Firmware programming and code uploading
Serial Communication Library	Data transfer between Python and Arduino UNO
Windows/Linux Operating System	Execution environment for software and hardware integration

IV. RESULTS AND DISCUSSION

The proposed robotic arm system successfully performed automated pick-and-place operations using computer vision and optimal motion control techniques.

The OpenCV-based object detection system accurately identified black-colored objects in real time. Serial communication between Python and Arduino UNO was stable and responsive. The robotic arm achieved smooth movement due to proper PWM control using the PCA9685 servo driver.

The robotic arm demonstrated good motion accuracy and stable gripping capability. Servo motors provided accurate angular positioning, while the gripper mechanism successfully held and released objects without slipping.

The system achieved the following performance characteristics:

Parameter	Observed Performance
Object Detection	Successful in real-time operation
Motion Accuracy	High-precision robotic movement
Response Time	Approximately 1–2 seconds
Gripper Operation	Stable object gripping and release
Communication	Reliable serial communication between Python and Arduino UNO

The experimental results confirm that the proposed robotic system is efficient, cost-effective, and suitable for automation applications.

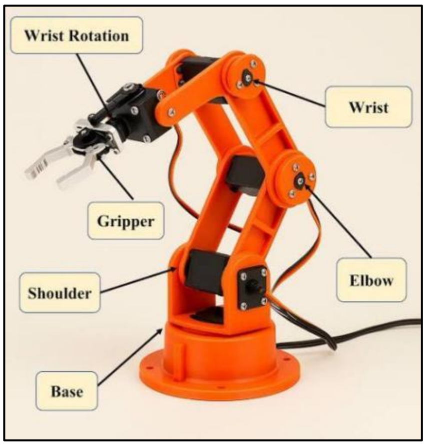

Fig.3 Robotic Arm

V. Discussion of Observations

This paper presented the design and implementation of an optimal control robotic arm integrated with computer vision for intelligent pick-and-place applications. The system successfully combined Arduino UNO, OpenCV, servo motors, and image processing techniques into a single automation platform.

The robotic arm demonstrated accurate object detection, smooth movement, reliable gripping, and efficient pick-and-place operation. The project also provided practical understanding of robotics, embedded systems, motion control, inverse kinematics, and automation technologies.

The developed system is low-cost, scalable, and suitable for educational, industrial, and research applications. Future improvements may include artificial intelligence, machine learning, wireless communication, and advanced control algorithms for enhanced robotic performance.

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