

IOT Enabled Vision-Guided Robotic Arm System for Automated Color-Based Object Segregation

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Abstract: The rapid advancement of Industry 4.0 technologies has increased the demand for intelligent and automated industrial sorting systems capable of performing accurate object segregation with minimal human intervention. Traditional sorting mechanisms often rely on expensive industrial robotic platforms and conventional sensor-based approaches that suffer from limited adaptability, high maintenance costs, and sensitivity to environmental variations. To address these challenges, this research presents the design and implementation of a vision-guided intelligent robotic arm for automated color-based object segregation using IoT and cloud computing technologies.

The proposed system utilizes a decentralized architecture that separates computational perception from mechanical actuation to improve processing efficiency and operational reliability. A high-definition optical sensor integrated with a Python-based OpenCV engine performs real-time image acquisition, HSV color masking, contour detection, and centroid calculation for identifying colored objects. The processed data is transmitted through the lightweight MQTT communication protocol using the HiveMQ cloud broker, enabling low-latency communication and real-time cloud monitoring. An ESP32 dual-core microcontroller receives the transmitted commands and controls multiple servo motors to perform precise pick-and-place operations.

The robotic arm is fabricated using lightweight PVC materials to achieve a low-cost and sustainable mechanical structure while maintaining adequate stability for industrial sorting applications. Experimental analysis demonstrates that the proposed system achieves high sorting accuracy, efficient cloud synchronization, and reliable object detection under varying lighting conditions. The integration of computer vision, IoT communication, and embedded control makes the system suitable for smart manufacturing, warehouse automation, educational robotics, and small-scale industrial applications. The proposed framework provides a scalable and cost-effective alternative to conventional industrial

robotic systems and contributes toward the development of affordable Industry 4.0 automation solutions.

Keywords: Vision-Guided Robotic Arm, Computer Vision, OpenCV, ESP32, MQTT, HiveMQ, IoT, Automated Object Segregation, Industrial Automation, Industry 4.0, Cloud Computing, HSV Color Detection.

I. INTRODUCTION

The rapid growth of Industry 4.0 technologies has increased the demand for intelligent and automated industrial systems capable of performing accurate object sorting with minimal human intervention. Conventional manual sorting methods are time-consuming, less efficient, and prone to operational errors, especially in industries such as logistics, pharmaceuticals, manufacturing, and recycling. Traditional industrial robotic systems are often expensive, complex, and difficult to implement for small-scale industries and educational applications.

Recent advancements in Computer Vision, Embedded Systems, and Internet of Things (IoT) technologies have enabled the development of affordable and intelligent automation systems. Computer Vision techniques using OpenCV allow robotic systems to identify and track objects in real-time through image processing methods such as color masking, contour detection, and centroid calculation. Similarly, modern microcontrollers such as the ESP32 provide integrated Wi-Fi connectivity and efficient motor control capabilities suitable for IoT-based robotic applications.

This research presents the design and implementation of a Vision-Guided Intelligent Robotic Arm for Automated Color-Based Object Segregation using IoT and Cloud Computing. The proposed system utilizes a high-definition camera and a Python-based OpenCV engine for real-time color detection in the HSV color space. The detected object information is transmitted through the MQTT protocol using the HiveMQ cloud broker, while an ESP32 microcontroller controls

multiple servo motors to perform automated pick-and-place operations.

The robotic arm is fabricated using lightweight PVC materials to achieve a low-cost and sustainable mechanical structure. The proposed system offers advantages such as real-time monitoring, low-latency communication, high sorting accuracy, and reduced implementation cost compared to conventional industrial robotic systems. The developed framework can be further applied in smart manufacturing, warehouse automation, agricultural grading, recycling systems, and educational robotics applications.

II. LITERATURE REVIEW

Recent developments in Computer Vision and IoT technologies have enabled the growth of intelligent robotic systems for automated object segregation. OpenCV-based image processing techniques such as HSV color masking and contour detection are commonly used for real-time object identification and tracking.

Several researchers have developed robotic sorting systems using embedded controllers like Arduino and ESP32 along with MQTT-based communication for remote monitoring and automation. These systems provide better flexibility and accuracy compared to conventional sensor-based sorting methods.

However, many existing systems suffer from high implementation cost, limited scalability, and sensitivity to environmental conditions. The proposed system overcomes these limitations by combining OpenCV, ESP32, MQTT, and cloud integration into a low-cost and efficient robotic automation framework.

Author / Year	Technology Used	Key Features	Limitations
Bradski et al. (2008)	OpenCV Vision System	Real-time image processing	No IoT integration
Lakshmanan et al. (2018)	OpenCV + Arduino	Color-based object sorting	Limited scalability
Chinchansure et al. (2020)	IoT-Based Robotic Arm	Remote monitoring support	High response delay
Sharma et al. (2020)	Vision-Based Automation	Improved sorting accuracy	Sensitive to lighting conditions
Proposed System	OpenCV + ESP32 + MQTT	Cloud-integrated, low-cost, real-time sorting	Limited payload capacity

Table 1: Comparison of Existing Robotic Sorting Systems

III. METHODOLOGY

1. Image Acquisition

A high-definition USB webcam is used to capture real-time video frames of the workspace. The camera continuously monitors the objects placed in the operational area. The captured images are transferred to the Python-based processing system.

2. Image Processing

The captured frames are processed using OpenCV techniques. The system converts the images from BGR to HSV color space for better color detection accuracy. Gaussian blur and color masking are applied to reduce noise and isolate target objects.

3. Object Detection

The system detects colored objects using contour detection algorithms. After identifying the object boundaries, centroid coordinates are calculated using image moments. These coordinates help determine the exact position of the object.

4. MQTT Communication

The processed object data is transmitted using the MQTT protocol through the HiveMQ cloud broker. The Python vision engine acts as the publisher, while the ESP32 acts as the subscriber. This enables low-latency communication and cloud-based monitoring.

5. Robotic Arm Actuation

The ESP32 receives the command data and controls the servo motors using PWM signals. MG996R servos are used for base movement, while SG90 servos control the gripper mechanism. The robotic arm performs automated pick-and-place operations based on object color.

6. Sorting Operation

The robotic arm picks the detected object and moves it toward the predefined sorting location. Different bins are assigned for different object colors. After releasing the object, the arm returns to its home position.

7. System Feedback and Monitoring

The system continuously monitors the sorting process and operational status. After completing each cycle, the ESP32 sends feedback signals through the cloud platform. This ensures synchronization between the vision system and robotic arm operation.

IV. HARDWARE COMPONENTS

1. ESP32 NodeMCU

The ESP32 NodeMCU is used as the main controller of the robotic system. It provides dual-core processing, built-in Wi-Fi connectivity, and PWM signal generation for servo motor control. The ESP32 also manages MQTT communication through the HiveMQ cloud broker.

2. MG996R Servo Motor

The MG996R metal gear servo motor is used for the base and shoulder movement of the robotic arm. It provides high torque and stable rotational control for handling object movement. The servo operates using PWM signals generated by the ESP32.

3. SG90 Micro Servo Motor

The SG90 micro servo motor is used for the elbow and gripper mechanism of the robotic arm. It offers lightweight operation and precise angular movement for pick-and-place tasks. The compact size of the servo improves overall mechanical flexibility.

4. USB HD Webcam

A high-definition USB webcam is used as the vision sensor of the system. The camera captures real-time video frames for object detection and tracking. It provides visual input to the OpenCV-based image processing engine.

5. PVC Structural Frame

The robotic arm structure is fabricated using lightweight PVC materials. The PVC frame provides mechanical stability while reducing the overall system cost and weight. It also allows easy modification and assembly of the robotic structure.

6. Power Supply Unit

A 5V regulated DC power supply is used to provide stable power to the ESP32 and servo motors. The power supply ensures smooth robotic movement during continuous operation. Proper voltage regulation prevents system instability and voltage drops.

7. Connecting Wires and Mechanical Components

Various jumper wires, connectors, screws, and mounting components are used for hardware integration. These components provide electrical connections and mechanical support for the robotic arm assembly. Proper wiring improves operational reliability and safety.

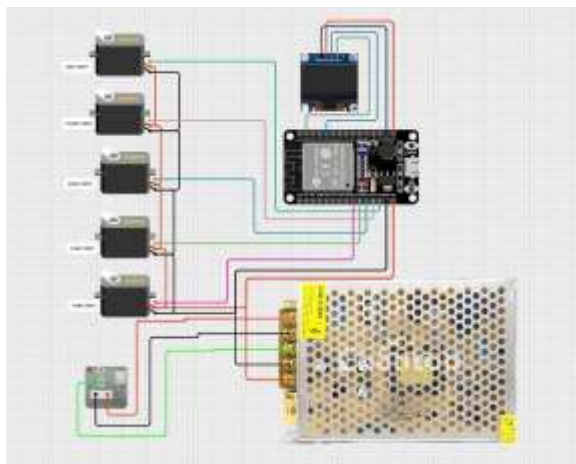


Fig. 1: ESP32 Robotic Arm Hardware Connection Diagram

V. SOFTWARE TOOLS

1. Python Programming Language

Python is used for implementing the Computer Vision and image processing operations of the system. It provides simple integration with OpenCV libraries for real-time object detection and tracking. Python also handles MQTT communication and data transmission.

2. OpenCV Library

OpenCV is used for image processing and color-based object detection. It performs operations such as HSV color masking, contour detection, centroid calculation, and object tracking. The library enables accurate real-time visual processing.

3. Arduino IDE

Arduino IDE is used for programming and uploading code to the ESP32 microcontroller. It provides support for ESP32

board configuration and embedded C/C++ programming. The IDE also helps in serial monitoring and debugging.

4. MQTT Protocol

MQTT is used as the communication protocol between the vision system and the ESP32 controller. It enables lightweight and low-latency data transmission through the HiveMQ cloud broker. MQTT ensures reliable real-time communication.

5. HiveMQ Cloud Broker

HiveMQ Cloud Broker is used for cloud-based communication and remote monitoring. It acts as an intermediary between the publisher and subscriber devices. The broker allows real-time transmission of robotic control commands.

6. ESP32 Servo Control Libraries

ESP32 servo control libraries are used for generating PWM signals for robotic arm movement. These libraries provide accurate servo positioning and smooth motor control. They simplify the implementation of pick-and-place operations.

7. Operating System and Dashboard

The system operates on a workstation environment for running the Python vision engine. A monitoring dashboard is used for displaying detected objects and operational status. This improves system monitoring and user interaction.

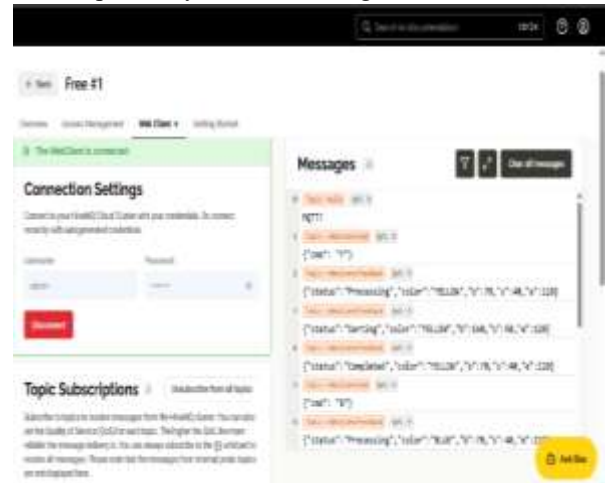


Fig.2: HiveMQ MQTT Communication Interface

VI. RESULTS AND DISCUSSION

1. Object Detection Performance

The proposed system successfully detected colored objects in real-time using OpenCV and HSV color masking techniques. The vision system accurately identified object boundaries and centroid positions under different lighting conditions. Experimental observations showed reliable detection for red, green, blue, and yellow colored objects.

2. Robotic Arm Operation

The ESP32-controlled robotic arm successfully performed automated pick-and-place operations based on the detected object color. The servo motors provided smooth movement and accurate positioning during sorting operations. The robotic arm was able to place objects into their respective bins with stable mechanical performance.

3. MQTT Communication Efficiency

The MQTT communication framework using the HiveMQ cloud broker provided low-latency and reliable data transmission between the vision system and the ESP32 controller. Real-time command transfer and feedback monitoring were achieved successfully. The cloud-based communication improved synchronization between software processing and robotic actuation.

4. System Accuracy and Reliability

The overall system demonstrated high sorting accuracy and stable performance during continuous testing. The use of HSV color space improved robustness against lighting variations compared to traditional RGB-based detection methods. The proposed architecture provided a low-cost, scalable, and efficient solution for automated industrial object segregation applications.



Fig. 3: Color-Based Object Segregation Using Vision-Guided Robotic Arm System

VII. ADVANTAGES

1. Low-Cost Implementation

The proposed system utilizes affordable components such as ESP32, PVC materials, and open-source software, reducing the overall implementation cost compared to conventional industrial robotic systems.

2. Real-Time Object Detection

The integration of OpenCV and Computer Vision techniques enables accurate real-time color detection and object tracking for automated sorting operations.

3. IoT and Cloud Connectivity

The use of MQTT and HiveMQ cloud integration provides low-latency communication, remote monitoring, and efficient synchronization between the vision system and robotic arm.

4. High Sorting Accuracy

The system achieves reliable object segregation using HSV color masking techniques, which improve detection performance under varying lighting conditions.

5. Lightweight and Flexible Structure

The PVC-based robotic arm structure is lightweight, easy to assemble, and suitable for educational as well as small-scale industrial applications.

6. Reduced Human Effort

The automated pick-and-place mechanism minimizes manual labor and reduces operational errors during repetitive industrial sorting tasks.

7. Scalable and Upgradable System

The proposed framework can be further upgraded with Artificial Intelligence, Machine Learning, and advanced object recognition techniques for future smart automation applications.

VIII. APPLICATIONS

1. Industrial Automation

The proposed robotic arm system can be used in industries for automated color-based sorting and material handling operations. It improves productivity and reduces manual labor in manufacturing environments.

2. Warehouse and Logistics Management

The system can be implemented in warehouses for automated parcel and package segregation based on color labels or identification markers. This increases operational efficiency and sorting accuracy.

3. Recycling and Waste Management

The robotic arm can be used for automated segregation of recyclable materials and electronic waste. Vision-based sorting helps improve recycling efficiency and reduces human exposure to hazardous materials.

4. Pharmaceutical Industries

The system can assist in sorting medicine packages, capsules, and laboratory samples based on color identification. This reduces human errors and improves safety in pharmaceutical operations.

5. Agricultural Product Sorting

The proposed system can be used for grading fruits and vegetables according to color and ripeness. Automated sorting improves quality control and processing speed in agricultural industries.

6. Educational and Research Applications

The project can be used in robotics laboratories and educational institutions for studying Computer Vision, IoT, embedded systems, and industrial automation technologies.

7. Smart Manufacturing Systems

The integration of IoT and cloud communication makes the system suitable for Industry 4.0 and smart factory applications requiring intelligent automated sorting mechanisms.

IX. FUTURE SCOPE

1. Artificial Intelligence Integration

The proposed system can be enhanced using Artificial Intelligence and Machine Learning algorithms for advanced object recognition and intelligent decision-making operations.

2. Deep Learning Based Detection

Future systems can implement Deep Learning models such as YOLO and CNN for detecting objects based on shape, texture, and size instead of only color detection.

3. Edge AI and Faster Processing

The system can be upgraded with advanced processors and Edge-AI modules to improve real-time processing speed and reduce dependency on external workstations.

4. Multi-Object Sorting Capability

Future improvements can enable the robotic arm to detect and sort multiple objects simultaneously for higher industrial productivity and efficiency.

5. Mobile and Wireless Automation

The robotic arm can be integrated with mobile robotic platforms and wireless monitoring systems for autonomous industrial and warehouse automation applications.

6. Smart Factory Integration

The proposed framework can be integrated into Industry 4.0 smart factory environments with cloud-based monitoring, data analytics, and predictive maintenance systems.

7. Improved Mechanical Design

Future versions of the robotic arm can use advanced materials and stronger actuators to increase payload capacity, stability, and industrial durability.

X. CONCLUSION

The proposed Vision-Guided Intelligent Robotic Arm System successfully demonstrates the integration of Computer Vision, IoT, and embedded automation technologies for automated color-based object segregation. The system utilizes OpenCV-based image processing, MQTT cloud communication, and ESP32-based robotic control to perform efficient real-time pick-and-place operations.

The implementation of HSV color detection and cloud-integrated communication improves sorting accuracy, operational reliability, and real-time monitoring capabilities.

The lightweight PVC structure and low-cost hardware components make the system suitable for educational, research, and small-scale industrial applications.

The developed framework provides a scalable, cost-effective, and intelligent automation solution for Industry 4.0 environments. The proposed system can be further enhanced using Artificial Intelligence and advanced object recognition techniques for future smart manufacturing and robotic automation applications.

The proposed system provides a scalable and cost-effective solution for next-generation smart industrial automation applications.

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