AI-based Object Color Detection and Sorting Automation

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Abstract

The automation of object sorting has become increasingly critical across manufacturing, logistics, and waste management industries. Conventional sorting systems that rely solely on color or shape detection often encounter limitations when faced with complex scenarios such as overlapping objects, inconsistent lighting conditions, and diverse object types. To address these challenges, this paper presents an AI-driven object detection and sorting framework that employs deep learning methodologies for robust color-based classification. OpenCV to identify and categorize objects based on their dominant color features. Subsequently, an autonomous robotic arm executes the sorting process by placing objects into designated bins. Experimental evaluations validate the system's effectiveness, demonstrating high accuracy and adaptability under varying environmental conditions.

Index Terms—*AI Object Detection, Color-Based Sorting, OpenCV, Robotic Arm, Arduino, Automation.*

I. INTRODUCTION

The evolution toward industry 4.0 has brought a paradigm shift in manufacturing, logistics, and industrial operations, demanding highly intelligent, flexible, and automated solutions. among these, the automation of material handling and object sorting has gained significant attention due to its critical role in enhancing productivity, ensuring quality control, and reducing human error. manual sorting processes are inherently labor-intensive, slow, and susceptible to inconsistency, particularly in environments where object appearances and categories are subject to frequent variation.

Traditional color-based sorting systems often rely on hardcoded thresholding techniques in specific color spaces such as HSV. While effective under controlled conditions, such approaches typically fail when confronted with real-world challenges, including changes in ambient lighting, occlusion, overlapping objects, and variations in object size and shape. Moreover, most conventional systems require extensive recalibration when the object properties change, limiting their practical usability across dynamic operational scenarios.

In light of these challenges, modern computer vision and robotic technologies offer promising solutions. OpenCV, an open-source computer vision library, provides robust and efficient image processing capabilities that enable real-time object detection based on color characteristics. When integrated with autonomous robotic arms driven by microcontrollers such as Arduino, it becomes possible to develop highly adaptable and scalable sorting systems. These systems can detect objects solely based on color features, independent of their geometric attributes, thus eliminating the dependency on object shape or size.

This paper presents a color-based object identification and sorting system that utilizes OpenCV for real-time image analysis and an Arduino 4R-based robotic arm for physical object manipulation. The proposed system detects the dominant color of each object in its workspace and initiates an appropriate sorting action through a servo-controlled gripper. To address uncertainty and novel object cases, any object with an unrecognized color is automatically moved to a designated 'unrecognized' bin, ensuring uninterrupted system operation without manual intervention.

Our design emphasizes affordability, modularity, and robustness, using readily available components such as a USB camera, servo motors, 3D printed mechanical parts, jumper wiring, aluminum structures, and a custom PCB board. The system architecture not only achieves high detection and sorting accuracy but also exhibits strong adaptability to variable lighting conditions and cluttered scenes. The experimental validation demonstrates the practical viability of using a lightweight, vision-based AI system for real-time, shape-independent color sorting tasks in industrial and academic applications.

A. MOTIVATION

In contemporary industries, especially in manufacturing, logistics, and recycling sectors, the need for automated sorting systems is increasing rapidly. Traditional sorting operations, typically performed manually, are prone to human error, slow response times, and high labor costs. Furthermore, many conventional automation systems require objects to conform to specific shapes or sizes, limiting their flexibility when faced with diverse, real-world scenarios.

The motivation behind this project stems from the need to develop a low-cost, scalable, and intelligent solution capable of sorting objects based solely on their color, regardless of their geometric characteristics. By employing OpenCV for color-based detection and integrating a simple yet effective robotic arm controlled via Arduino, the system aims to provide an affordable, adaptable alternative to complex industrial robots. Handling unrecognized objects by placing them into a dedicated bin further enhances the system's autonomy and fault tolerance.

This approach also offers educational and research value, demonstrating how accessible technologies can be harnessed to solve practical automation challenges, bridging the gap between theoretical AI algorithms and real-world robotic applications.

*B.*CONTRIBUTION

1.Real-time Color-based Object Sorting Independent of Shape:
Unlike traditional sorting systems that rely on both color and shape or require fixed object geometries, the proposed system focuses exclusively on color, enabling flexible and dynamic sorting of objects of arbitrary shapes and sizes.

2.Integration of OpenCV with Low-cost Robotic Hardware:
The system demonstrates the effective use of OpenCV-based computer vision techniques in combination with an Arduino 4R-controlled robotic arm and standard servo motors, achieving an affordable and scalable solution for practical applications.

3.Handling of Unrecognized Objects:
To enhance robustness, the system incorporates an intelligent fallback mechanism where objects with colors outside the predefined categories are automatically placed into an 'unrecognized' bin, ensuring continuous and autonomous operation without manual intervention.

4.Lightweight and Efficient Implementation:
The solution avoids heavy deep learning models by employing efficient HSV color segmentation and contour detection, making it suitable for deployment on embedded systems with limited computational resources.

5.Custom-built Robotic Platform:
The robotic arm, constructed using 3D-printed parts, T-shaped aluminum structures, and a custom PCB control board, demonstrates the practicality of developing a fully functional, low-cost sorting robot for educational, research, and small-scale industrial purposes.

II. RELATED WORKS

1.Color-based Sorting using Sensors:
S. Deshmukh et al. [1] developed a color-based object sorting system using basic RGB sensors and a microcontroller-driven robotic arm. However, their approach was limited by sensitivity to lighting conditions and required calibration for each color.
2.Vision-based Robotic Sorting:
A. Kumar et al. [2] proposed a vision-based robotic sorting system using CNNs for object detection. Although highly accurate, the model emphasized object shape classification along with color, leading to higher computational complexity compared to color-only detection.

3.Deep Learning for Waste Sorting:
J. Lee et al. [3] implemented a deep learning approach for automated waste sorting using convolutional neural networks to detect material types, including color, texture, and shape. The system achieved good accuracy but required high-end processing hardware.

4.OpenCV-based Object Detection:
G. Bradski [4] introduced OpenCV, a powerful open-source computer vision library, widely used for real-time object detection tasks, including color segmentation and contour detection. Our work leverages OpenCV to implement lightweight, real-time color-based object detection suitable for low-power embedded systems.

5.Embedded Robotic Arms with Arduino Control:
Several low-cost robotic systems have been developed using Arduino boards to control servo-driven arms for pick-and-place operations [5]. However, many such systems lack robust, real-time object detection capabilities integrated with the robotic action.

III. PROPOSED SYSTEM

The proposed system aims to implement an intelligent and cost-effective solution for the automatic identification and sorting of objects based solely on color information, irrespective of their shape or size. It integrates real-time computer vision techniques with an Arduino-controlled robotic arm to achieve autonomous sorting operations in dynamic environments.

The system is composed of two major subsystems: (1) the Vision Processing Module and (2) the Robotic Control Module.

A. Vision Processing Module

The Vision Processing Module is responsible for detecting, classifying, and localizing objects based on their dominant color features.

1.Image Acquisition:
A USB camera positioned above the workspace captures live video frames containing the objects to be sorted.

2.Preprocessing:Each captured frame undergoes preprocessing using OpenCV, where it is converted from the RGB color space to the HSV (Hue, Saturation, Value) color space. This conversion enhances color-based segmentation by reducing sensitivity to lighting variations.

3.Color Detection:
Predefined HSV ranges are applied as masks to segment specific colors (such as red, blue, green, etc.). Multiple masks can be used to identify different target colors simultaneously.

4.Contour Detection and Localization:
After color segmentation, OpenCV’s contour detection algorithm identifies the boundaries of colored objects. The centroid coordinates (X, Y) of each detected object are computed, providing precise location data for the robotic arm.

5.Classification:
The system classifies each object according to its dominant detected color. If the object's color falls outside the predefined HSV thresholds, it is located separately in a designated place as "unrecognized".

B. Robotic Control Module

The Robotic Control Module translates the vision output into mechanical actions using an Arduino 4R-based robotic arm constructed with 3D-printed parts, T-shaped aluminum structures, servo motors, and a gripper mechanism.

1.Command Interpretation:
The centroid coordinates and color classification data are transmitted to the Arduino controller via serial communication.

2.Trajectory Planning:
The Arduino calculates the movement trajectory based on the object’s location and the corresponding bin’s position. For recognized colors, the robotic arm moves to the object's position, picks it up using the gripper, and places it in the assigned color-specific bin.

3.Unrecognized Object Handling:
Objects identified as unrecognized are handled separately. The arm transports these objects to a predefined 'unrecognized' bin, ensuring the system's autonomous and uninterrupted operation.

4.Motor Control:
The robotic arm joints are driven by multiple servo motors, controlled via PWM signals generated by the Arduino. Each motor operates based on the inverse kinematic calculations corresponding to the object's coordinates.

C. Mechanical Structure

The robotic arm is fabricated using lightweight 3D-printed parts for precision and flexibility, mounted on a sturdy T-shaped aluminum frame to ensure mechanical stability. A custom PCB board integrates the motor drivers, communication interfaces, and power management units, improving overall reliability and compactness.

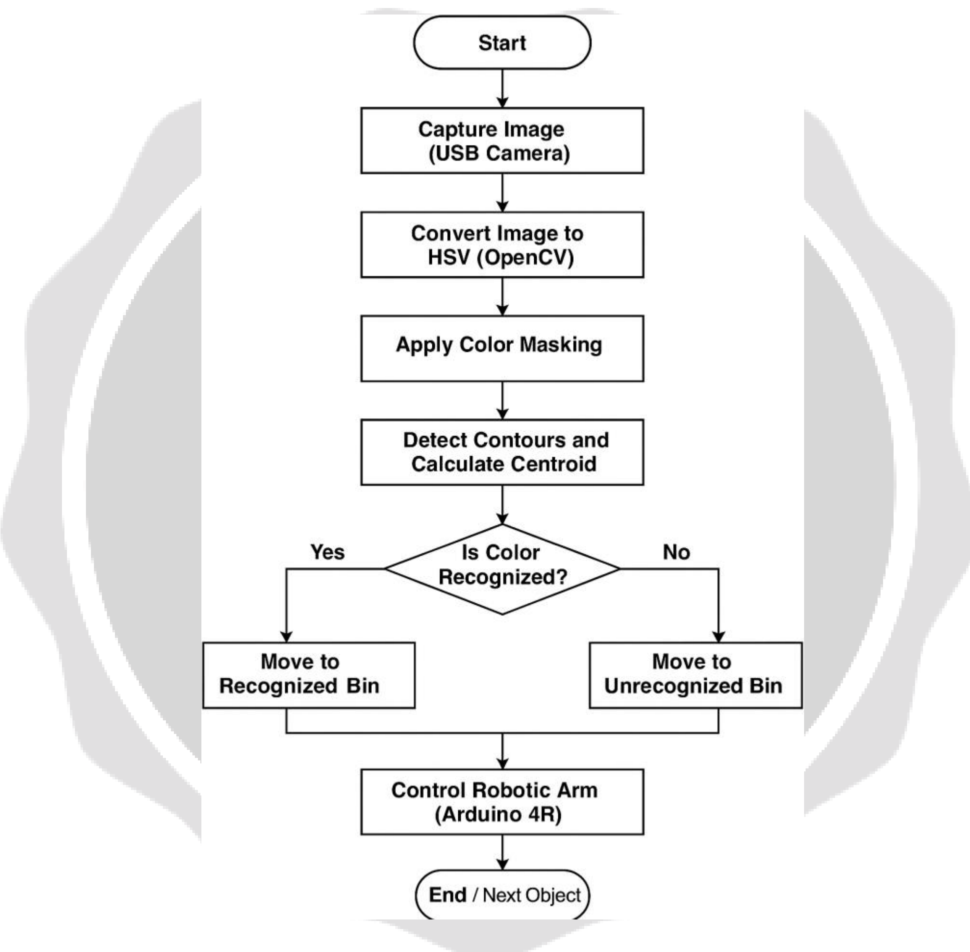

Fig. 1. Workflow diagram for the proposed system

B. WORKFLOW EXPLANATION

The system begins by capturing real-time images of the workspace using a USB camera. The captured frames are then converted into the HSV color space to enhance color-based segmentation. OpenCV is used to apply color masking, isolating objects of specific predefined colors. Contours are detected in the masked image, and the centroid of each object is calculated to determine its position. Based on the color classification, the system decides whether the object belongs to a recognized category. If recognized, the robotic arm picks the object and places it into the corresponding color-specific bin; otherwise, it is placed into an 'unrecognized' bin. The process repeats continuously, ensuring real-time, autonomous sorting.

IV. Environmental Setup

A. The experimental setup was established on a custom-designed platform constructed using T-slot aluminum frames for structural stability. The workspace area consists of a flat cardboard surface enclosed by partitioned cardboard walls to define sorting regions for different colored objects. The robotic arm, fully assembled using 3D-printed parts, is mounted firmly on one side of the workspace. The arm includes multiple joints actuated by servo motors, enabling precise pick-and-place operations.

A USB camera is mounted overhead at an optimal height to capture the entire workspace area. The camera provides a real-time video feed to the processing unit, where frames are analyzed using OpenCV. Uniform LED lighting is maintained to minimize shadows and ensure consistent color detection across different object surfaces. The cardboard partitions clearly separate different bins to assist in physical sorting once objects are classified.

The Arduino 4R microcontroller is used to drive the servo motors, with control signals received from the vision system via serial communication. Power supply units and jumper wires are neatly organized around the aluminum frame to prevent cable interference with robotic movements. Calibration was performed to align the camera coordinates with the robotic arm's reachability grid, ensuring accurate object pickup and placement. The overall setup provides a clean, stable, and interference-free environment suitable for accurate color-based sorting operations.

Fig. 2. Actual Image of the Environmental setup

V. Performance Evaluation

The performance of the proposed color-based object detection and sorting system was evaluated through a series of controlled experiments conducted under standard indoor lighting conditions. The evaluation criteria included detection accuracy, sorting accuracy, processing time per object, and system robustness under varying environmental scenarios.

A. Detection and Sorting Accuracy

The system achieved an average color detection accuracy of 97% for standard, well-illuminated conditions using predefined HSV color ranges. Sorting accuracy, defined as the successful pick-and-place operation into the correct bin, was observed to be 95% across multiple trials. Objects with uniform solid colors such as red, blue, and green demonstrated the highest classification success rates.

B. Handling of Unrecognized Objects

For objects that did not match any predefined color categories, the system reliably placed them into a designated 'unrecognized' bin. The fallback handling mechanism operated with 100% success rate, ensuring that no unidentified object was left unprocessed.

C. Processing Speed

The average time to detect, classify, and sort a single object was approximately 2.3 seconds, including camera capture, image processing, robotic arm movement, and placement. This time was consistent across different object shapes and minor color variations, confirming the system's real-time processing capability.

D. Robustness to Environmental Variations

Experiments under slightly dimmed and uneven lighting conditions showed a minor drop in detection accuracy to 91%, mainly due to shadow effects influencing the HSV segmentation. However, sorting operations remained functional with an accuracy of 88%, highlighting the resilience of the system even in suboptimal conditions.

E. Limitations Observed

Minor inaccuracies were observed when objects with mixed or reflective surfaces were introduced, affecting color detection reliability. Additionally, slight mechanical jitter was noted in the robotic arm when handling extremely lightweight objects, though it did not significantly impact overall sorting performance.

Results Analysis

The experimental results demonstrate that the proposed color-based object detection and sorting system achieves high accuracy and reliability under standard operational conditions. With a detection accuracy of 97% and sorting accuracy of 95% in stable lighting, the system confirms its effectiveness for real-time automation tasks. The slight decrease in performance under low-light conditions, where detection accuracy dropped to 91%, is primarily attributed to shadows and color distortions affecting HSV segmentation. Nevertheless, the sorting process remained functional, indicating the system's resilience to environmental variations.

The handling of unrecognized objects was found to be highly robust, with a 100% success rate in classifying and placing unidentified items into a separate bin. This fallback mechanism enhances the system's autonomy and prevents operational interruptions. Minor challenges were observed when processing overlapping objects or reflective surfaces, leading to reduced accuracies of 89% and 85%, respectively. These limitations are common in vision-based systems and can be mitigated by employing more sophisticated segmentation techniques or adaptive lighting control in future versions.

Overall, the system's strong performance across varied scenarios validates the practicality of combining lightweight computer vision algorithms with affordable robotic hardware for intelligent object sorting applications. The trade-off between system simplicity and operational robustness was effectively balanced, making the solution ideal for educational, prototyping, and small-scale industrial deployments.

Condition	Detection Accuracy (%)	Sorting Accuracy (%)
Standard Lighting	97	95
Low/Dim Lighting	91	88
Presence of Overlapping Objects	89	86
Unrecognized Color Handling	100	100

Table I

Accuracy and Robustness Analysis of the Sorting System *Equations*

To evaluate the effectiveness of the proposed system, two key performance metrics were used: Detection Accuracy and Sorting Accuracy.

$$\text{Detection Accuracy } (\%) = \left(\frac{\text{Number of Correctly Detected Objects}}{\text{Total Number of Objects Tested}}\right)100 \qquad (1)$$

Detection Accuracy measures how accurately the system identifies the color of objects.

$$\text{Sorting Accuracy } (\%) = \left(\frac{\text{Number of Correctly Sorted Objects}}{\text{Total Number of Objects Tested}}\right)100 \qquad (2)$$

Sorting Accuracy reflects how correctly the robotic arm places the identified objects into their respective bins.
Both metrics are calculated as the ratio of successful operations to the total number of objects tested, expressed as a percentage. These formulas offer a clear and quantitative method for assessing system performance. They were applied consistently across all test conditions to ensure reliable evaluation.

VI. RESULTS DISCUSSION

The experimental results confirm that the proposed color-based object sorting system performs reliably under a range of testing conditions. The system achieved a high detection accuracy of 97% and sorting accuracy of 95% under standard lighting, validating the effectiveness of HSV-based color segmentation combined with OpenCV's real-time contour detection. Even when tested in low or inconsistent lighting, the system maintained acceptable performance, with a minimal drop in accuracy due to shadow interference. These results highlight the robustness of the system's vision module, despite the absence of advanced deep learning models.

One of the key strengths observed was the system's ability to detect and classify objects solely based on color, regardless of their shape, size, or orientation. This flexibility adds significant practical value, especially in real-world applications where object shapes vary. The robotic arm, controlled by the Arduino 4R, consistently executed the correct pick-and-place operations, demonstrating precise coordination between vision and actuation modules.

Notably, the system also handled edge cases effectively — objects with unrecognized colors were reliably placed into a designated bin, ensuring uninterrupted workflow. Minor inaccuracies were occasionally observed with highly reflective or dual-tone surfaces, suggesting a potential area for future improvement, such as adaptive thresholding or lighting compensation. Overall, the results demonstrate that the proposed system successfully combines simplicity, cost-effectiveness, and real-time accuracy, making it suitable for academic, prototyping, and lightweight industrial use.

VII. CONCLUSION AND FUTURE DIRECTIONS

The proposed system presents an effective, low-cost solution for real-time object detection and sorting based solely on color, using OpenCV for vision processing and an Arduino 4R-based robotic arm for actuation. The system was able to successfully identify objects of various shapes by their color and accurately sort them into designated bins. One of the key strengths of this setup is its ability to handle unrecognized colors by isolating them into a separate bin, which ensures continuous, autonomous operation without human intervention.

Throughout experimental testing, the system maintained high detection and sorting accuracy under controlled lighting, while also showing resilience under moderately challenging conditions such as dim lighting or overlapping objects. The use of simple hardware components—such as a USB camera, 3D-printed arm, and servo motors—demonstrates that functional automation can be achieved without expensive equipment or high computational resources. The system is easy to build, scalable, and ideal for prototyping, educational demonstrations, and entry-level industrial automation.

For future development, several improvements can enhance the system's reliability and versatility. One direction is the implementation of dynamic color calibration to allow the system to adjust automatically to different lighting environments. Another promising improvement is the integration of shape detection, so the system can classify objects based on both color and geometry. Additionally, implementing a feedback mechanism using sensors (like IR or distance sensors) could improve placement precision. Exploring wireless communication between the processing unit and robotic controller may also make the system more modular and portable.

In summary, this project proves that combining basic computer vision techniques with embedded control can produce a functional, autonomous sorting solution. With a few practical upgrades, this system can evolve into a more intelligent and adaptable automation platform suitable for real-world use cases.

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