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Four-DOF Robotic Arm System for Goods Transport

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Abstract:

Paper presents the design, development, and implementation of a Four-Degree-of-Freedom (Four-DOF) Robotic Arm System tailored for the purpose of efficient goods transport. The increasing demand for automation in logistics and industrial sectors has prompted the need for versatile robotic solutions capable of manipulating objects in various environments. The proposed robotic arm system addresses this need by offering four independent degrees of freedom, enabling it to perform intricate tasks involved in goods transport. The system's mechanical design incorporates four joints, each contributing to a specific movement: lifting, lowering, rotating, and extending. These movements provide the necessary flexibility to manoeuvre in complex spaces, making it suitable for applications within warehouses, factories, and distribution canters. The design process involved careful consideration of structural integrity, weight distribution, and motion optimization to ensure safe and precise operation. In conjunction with the mechanical design, the robotic arm is equipped with advanced sensing and control mechanisms. Sensor arrays, including proximity sensors and cameras, enable the arm to perceive its environment and detect objects, ensuring accurate object detection and collision avoidance. The control system, driven by a combination of microcontrollers and software algorithms, orchestrates the movement of each joint to achieve seamless coordination and efficient goods transport.

Real-world implementation of the Four-DOF Robotic Arm System showcases its ability to streamline goods transport operations. By automating tasks that previously required manual intervention, the system enhances operational efficiency, reduces labour costs, and minimizes the risk of human error. Furthermore, its adaptability to diverse environments underscores its potential to revolutionize the logistics industry.

Keywords:- Robotic Arm, Inverse Kinematics, Image Processing.

INTRODUCTION

The increasing use of robotic arms in the industrial sector can be attributed to their ability to perform tasks with high accuracy and repeatability. Among these applications, the transportation and grouping of goods are prominently featured. To achieve successful implementation, meticulous design is essential to ensure precise arm movements. Therefore, this research aims to design a 4-degree-of-freedom (4-DOF) robotic arm capable of autonomously moving rectangular-shaped objects to designated storage locations based on their colors.

The field of robotics has made remarkable progress in various areas, including kinematics, computer vision, and object manipulation. Researchers have explored designs of robotic arms with multiple degrees of freedom, employing inverse kinematics principles for efficient pick and place operations. Internationally, SCARA (Selective Compliance Assembly Robot Arm) serpent robots have gained attention, with studies focused on their kinematics and interface. Humanoid robotic arms have also been investigated as alternatives for handling specialized tasks, such as handling chemical glassware. Additionally, advanced techniques for object recognition and detection, such as the Hough Transform, have been developed using cameras.

Integrating computer vision technology for object sorting by robotic arms has been a subject of significant interest. Furthermore, prototypes for object color classification using 4-DOF robotic arms have been designed and developed.

The experimental results demonstrate the system's capability to detect objects of red, blue, and green colors accurately, achieving a 100% success rate. The robotic arm successfully transports objects to storage locations based on colors, attaining a 100% success rate for red objects, 60% for blue objects, and 100% for green objects. The time required from object detection to the robotic arm's return to its ready position is 25.771 seconds for red objects, 27.727 seconds for blue objects, and 27.063 seconds for green objects.

The development of more sophisticated and versatile robotic arms will undoubtedly revolutionize industrial automation and expand their applications across various industries, paving the way for more efficient and precise manufacturing processes. As robotic technology continues to advance, further exploration in areas such as advanced computer vision algorithms, multi-robot coordination, and adaptive control systems is expected to enhance the capabilities of robotic arms in industrial environments.

In conclusion, this study presents a comprehensive design of a 4-DOF robotic arm integrated with computer vision technology for efficient object manipulation based on color recognition. The successful implementation of the proposed system demonstrates the potential for robotic arms to revolutionize industrial automation and bring about significant improvements in manufacturing processes. As technology continues to advance, it is anticipated that further innovations and research in robotics will open new possibilities for automation in various industries.

METHODS AND RELATED WORKS

Previously, research was carried out related to the robotic arm for moving goods with the title "Controlling the Robotic Arm Sorting Objects Based on Shape Using Computer Vision Technology". This study uses five degrees of freedom robotic arm. The arm robot is controlled using a Raspberry Pi with an endoscope camera sensor. The inverse kinematic method is applied to the arm robot. The use of computer vision technology with the shape detection method is applied to the camera sensor to identify the shape of the object to be moved. From the results of the shape detection research, there was an error of 2 times in the triangular shape out of a total of 15 tests. The inverse kinematic method on the arm robot has an error of 0.6 cm to 5.3 cm. The camera sensor works well at a light intensity of 59 lux with Hue, Saturation, and Value (HSV) segmentation with values ranging from low-HSV(0,103,120) to high-HSV(180,255,255).

Based on the problems and previous research, the authors created a 4 Degree of Freedom (DOF) arm robot that is capable of carrying out the task of moving objects from one position to another by grouping them based on color and shape of objects using the open CV image processor. Each joint is driven by a servo motor which is controlled by an arduino-uno and a camera sensor which functions as an object detection tool based on color. The working principle of this system, the input is in the form of a cube-shaped object in the form of red, yellow and green which is placed above the work area measuring 15 cm x 30 cm. Objects will be left randomly on the work area. The process of taking the colors and shapes using the camera is processed in the open CV program. The results of the image processing program are the coordinates of the X and Z axes and the color of the objects, then the data is sent using serial communication to Arduino Uno and the coordinates are processed using the reverse kinematics method to get the angular degrees for the joint base, shoulder, elbow, wrist and gripper. The angle degree value will be sent to each servo on the joint robot so that the end-effector robot arm can go to the target point and the gripper on the robot arm can reach the intended object and place the object in the container according to the color detected by the camera.

THEORITCS AND EXPERIMENTAL PROCESS

Robots Arm and gripper robots are one of the tools in the industrial field. There are certain conditions in the industry that are impossible to handle by humans such as the need for high accuracy, large power and high risk. These conditions can be overcome with robots, one of which is a robot with a type of arm or robotic arm. Gripper is an effector that functions to grip and hold objects. There are 3 types of grippers known as mechanical grippers, vacuum grippers and magnetic grippers. The mechanical gripper is designed to grip and hold objects by providing contact with them. Usually using mechanical fingers called jaws. This finger can be removed and installed so it is very flexible in use. The power source provided to this gripper can be pneumatic, hydraulic, and electric. The movement of the robot's wrist must be designed so that the end-effector can do its job. Movements from the wrist include roll movements, pitch movements and yaw movements.

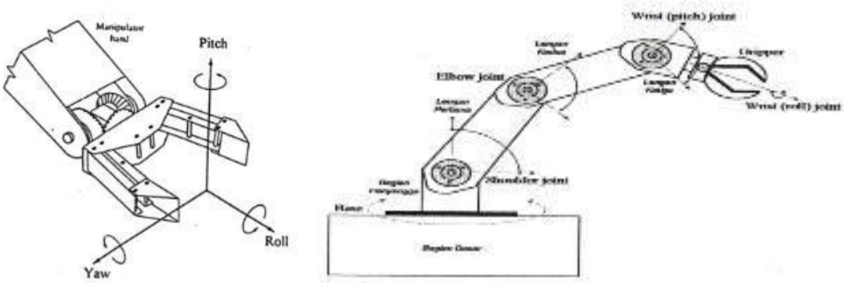

Figure 1: Physical construction of robotic arms

Reverse kinematics is a calculation to find the variable angle (joint) of the robot in determining the position and orientation of the end-effector. This reverse kinematics solution can be solved using the Pythagorean law and the cosine rule. (MAYUB et al., 2020) The kinematics solution must be solved by looking at two sides, namely the top view and side view of the robotic arm structure. The top face is used to find the angular degrees (theta1) of the joint base. The lateral side is used to find the degree angle theta 2 of the shoulder joint, elbow joint and wrist joint. The return kinematics equation for the top and side can be seen in Figure 2.

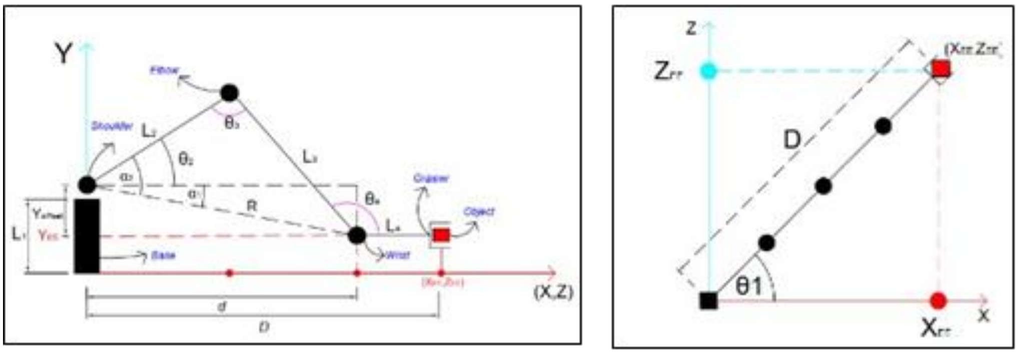

Figure 2: Side and 8 top Robotic Arms

SYSTEM DESIGN AND ASSEMBLY PROCESS OF ROBOT

This study aims to design and manufacture a 4 Degree of Freedom (DOF) arm robot capable of carrying out the task of moving objects from one position to another by grouping them by colour using the open CV image processor. Each joint is driven by a servo motor controlled by an arduino-uno and a camera sensor which functions as a colour-based object detector. The working principle of this system, the input is in the form of a cube-shaped object in the form of red, yellow and green which is placed above the work area measuring 15 cm x 30 cm. Objects will be left randomly on the work area. The process of taking the colours and shapes using the camera is processed in the open CV program. The results of the image processing program are the coordinates of the X and Z axes and the colour of the objects, then the data is sent using serial communication to Arduino Uno and the coordinates are processed using the reverse kinematics method to get the angular degrees for the joint base, shoulder, elbow, wrist and gripper. The angular degree value will be sent to each servo on the robot joint so that the end-effector robot arm can go to the target point and the gripper on the robot arm can reach the intended object and place the object in the container according to the colour detected by the camera.

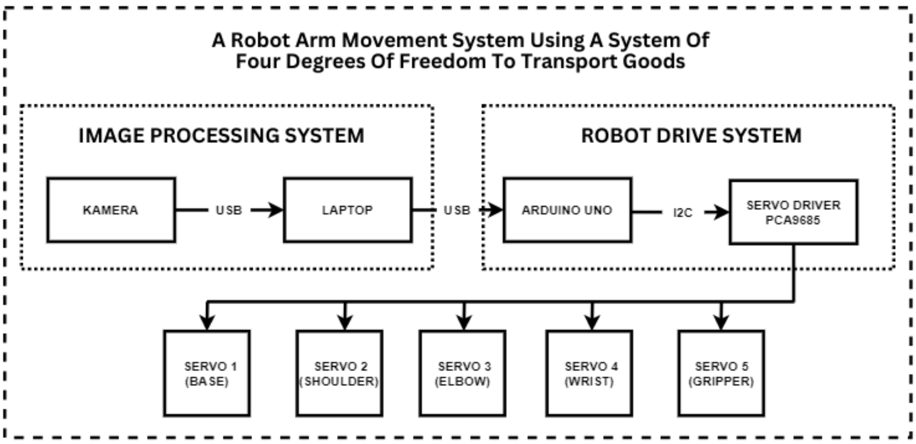

Figure 3: System Block Diagram

Based on the block diagram in Figure 3, it can be explained that this system consists of two parts: an image processing system and a robot drive system. In the image processing system section there is a camera that is used to get pictures or videos, then the images are processed using a computer. Data processing carried out by the computer will produce coordinates of the x-axis and z- axis and the color of the objects which are then sent using serial communication to Arduino to process the coordinates of these objects with reverse kinematics calculations so as to obtain the value of the angles of the base,

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shoulder, elbow, wrist and gripper angles. The angular degree value will be sent to each servo on the joint robot so that the end-effector robot arm can go to the target point and the gripper on the robot arm can reach the intended object.

Robot Arm Mechanical Design

In the mechanical design of the robot which including designing in its size of robot. The robot arm consists of five parts, namely base, shoulder, elbow, wrist and gripper. There are several major parts to the hardware design of an automated robotic arm. Each piece of hardware, its uses and specifications will be explained in more detail in the following sections. The robot used in this final project is a robot that has 4 degrees of freedom equipped with a gripper on the end effector. The robot is designed to have 5 types of rotating joints (revolute), each of which is the base, shoulder, elbow, wrist and gripper.

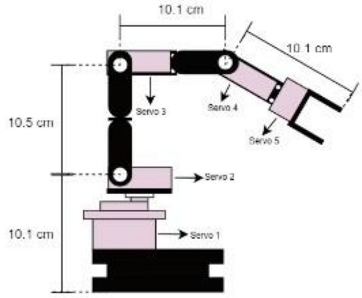

Figure 4: Arm Robot

The movement of the robot arm joints uses five servo motors as shown in Figure 4. This design uses 3 MG996R servo motors which are applied to the elbow, wrist and gripper and then 2 5521MG servo motors which are applied to the base and shoulder. For each joint on the robotic arm is designed with a range of angles respectively. For joint 1 ($\theta 1$) of 180°, joint 2 ($\theta 2$) of 180°, joint 3 ($\theta 3$) of 180°, joint 4($\theta 4$) of 180°. For joint 5 as an end effector, the change in angle will be converted into a change in position from open to closed.

Design of Image and Colour Processing for identification of robot objects

The object used in this study was a cube measuring 3cm x 3cm x 3cm weighing 200 grams made of wood, each cube having a colour of red, blue and green as shown in Figure 5 and 6.

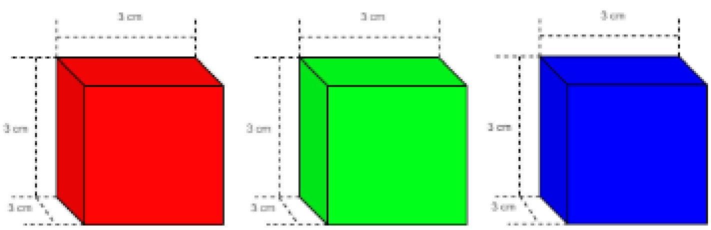

Figure 5: Colored Cube

The object base is the place where the colored objects are placed. The base is made of rectangular plywood with a size of 45 cm x 30 cm. With the work area measuring 15 cm x 30 cm.

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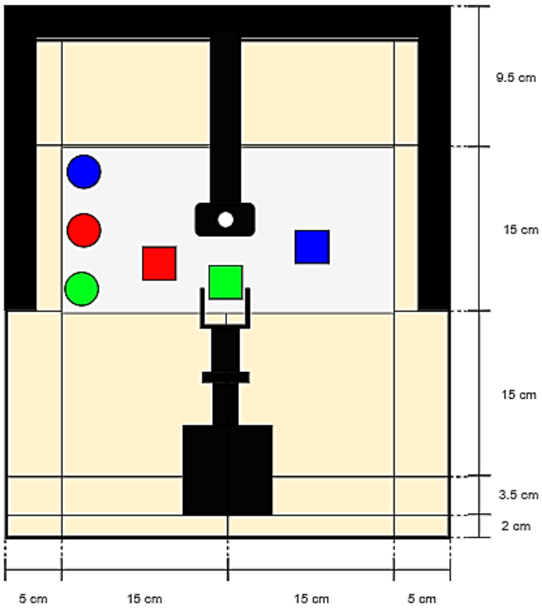

Figure 6: Object Foundation

Hardware design of the robot system

The overall electrical circuit is a wiring diagram of all electrical components consisting of cameras, laptops, Arduino UNO, PCA9685, power supplies and servo motors. The overall electrical circuit can be seen in the Figure 7.

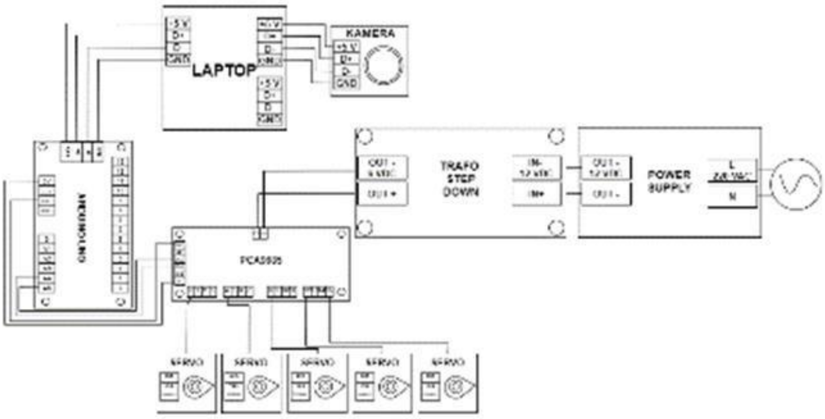

Figure 7: Overall Series of Arm Robots

In this four DOF arm robot system, a power supply is needed to provide voltage to the MG99R and 5521MG servo motors. In the servo motor datasheet, it is attached that the maximum input voltage to supply the servo motor so that it has a maximum torque is 6 volts. Therefore a 6 Volt power supply is needed. To get a voltage value of 6VDC, a 12VDC power supply is used, then the voltage is lowered using the LM2596 module so that you get a voltage value of 6VDC, which then the output of the LM2596 module is connected to the PCA9685 module. The camera sensor used in this design is the Logitech C270h series to retrieve data in the form of video. This camera plugs into a Universal Serial Bus (USB) port on a laptop. This camera can work according to the Open CV program commands using the python language. The camera position is above the object placement area with a distance of 45 cm.

So that the scale of the webcam and the area where the object is placed are the same, the pixel size of the image captured by the webcam is 640 x 480 pixels.

Software design of the robot system

The software in this study is divided into two parts or process units and shown in Figure 8 below. The first processing unit is an image processing system using Open CV. Image processing is performed to detect objects in the form of colored cubes and obtain the position of the object. The object position data will be used to determine the angular position of the servo. When an object is detected, the computer will send data to Arduino using UART serial communication. The second process unit is a robot propulsion system using Arduino-uno. Arduino is used as a servo controller. Arduino will give commands to move the servo according to the position on the object. Based on the reverse kinematics formula, a program for the reverse kinematics formula was created using the C language and library <math.h> in the Arduino IDE software with the final results to be used, namely Theta_1 for joint base, Theta_2 for joint shoulder, Theta_3 for joint elbow, and Theta_4 for joint wrist.

```
else if (X_End_Effector >=165.00 && X_End_Effector <250.00)
{
  D = sqrt(pow(X_End_Effector,2) + pow(Z_End_Effector,2));
  Theta_1 = (atan(Z_End_Effector/X_End_Effector))*(180.00/Pi); //theta 1
  d = D - L4;
  Yoffset = L1-Y_End_Effector;
  R = sqrt(pow(d,2) + pow(Yoffset,2));
  alpha1 = (atan(d/R))*(180.00/Pi);
  alpha2 = (acos((pow(L2,2) + pow(R,2) - pow(L3,2))/(2*L2*R)))*(180.00/Pi);
  Theta_2 = (alpha2 - alpha1+5); //theta 2
  Theta_3 = ((acos((pow(L2,2) + pow(L3,2) - pow(R,2))/(2*L2*L3)))*(180.00/Pi)); //theta 3
  Theta_4 = 180.00 - ((180.00 - (alpha2 + Theta_3)) + alpha1); //theta 4
  Serial.println("x2");
}
```

Figure 8: Reverse Kinematics Calculation Program on Arduino

RESULTS AND DISCUSSIONS

The results of the tool design apply the existing theory to produce a system. Following are the results of the design of the Arduino- Uno-based four-degrees of freedom robotic arm system tool

Figure 9: Results of Arm Robot

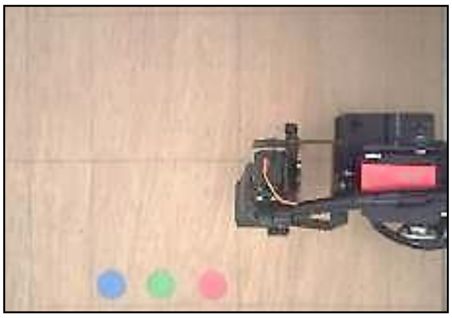

Figure 10: Control Panel

Figure 11: Colored Objects

Figure 12: Object Foundation

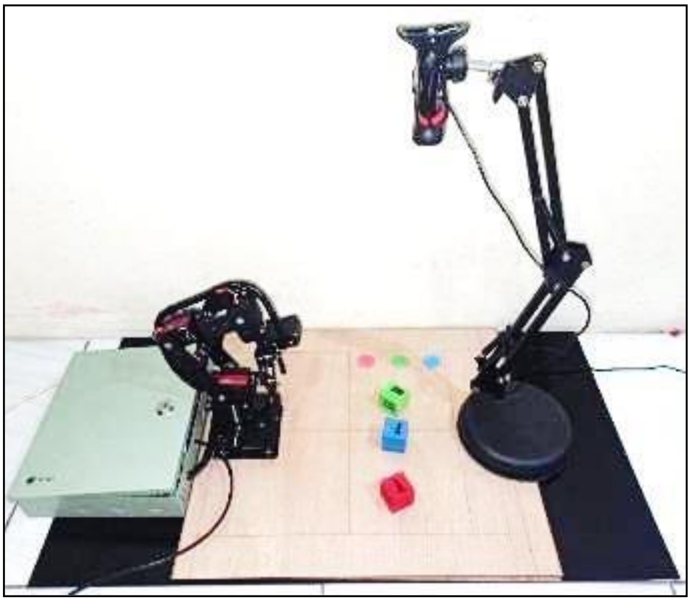

Figure 13: The Final Results of Tool Design

On the hardware side, there is Figure 9 which is a robot arm with four degrees of freedom. In Figure 10 there is a control box containing a power supply, PCA9685 module, step down transformer module and Arduino Uno. Furthermore, in Figure 11 there are red, green and blue cubes. In Figure 12 there is a foundation for the foundation object made of rectangular plywood with a size of 45 cm x 30 cm. with a work area measuring 15 cm x 30 cm.

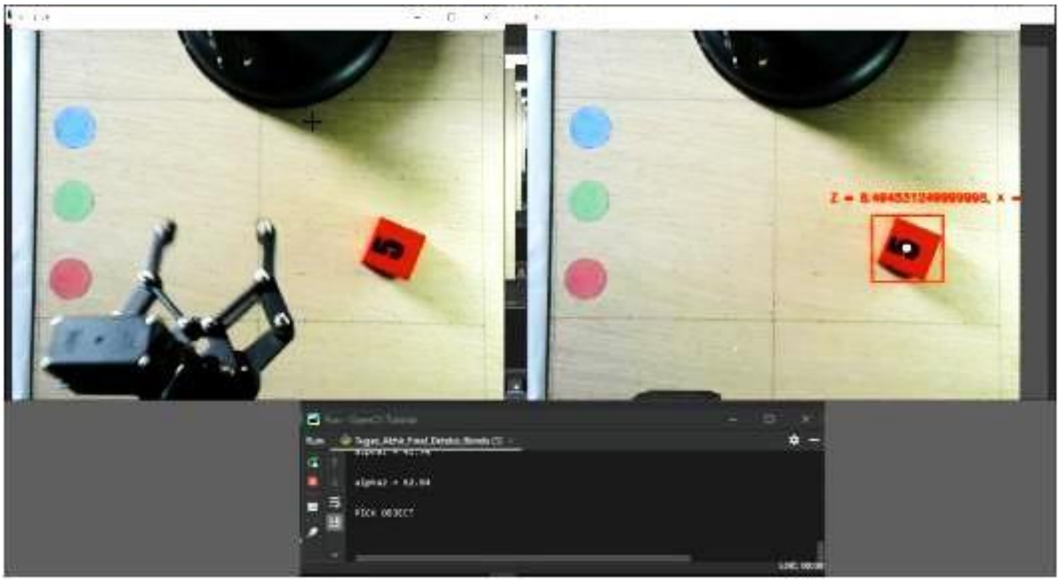

Figure 14: Program Screen Display

On the software side, there is a display of the pycharm program shown in Figure 14, the LIVE window title functions to display movements in the object base area directly or in real time. The Color Tracking window title functions to display objects that will be detected by the user which contains information on the coordinates (X, Z) and the color of the object. Furthermore, there is a log window that contains information on coordinate point values, object colors, joint angles, kinematic calculation results, and the stages of each robot movement process.

Image processing design results

Testing of the image processing system is enabled to detect the color and position of objects. The camera position is above the height of the baseboard as high as 40 cm and does not move. The object detection uses the HSV color segmentation method with a range of values for red with a lower limit (0,50,50) to an upper limit (10,255,255), for green with a lower limit (44,86,56) to an upper limit (96,177,255), and blue with a lower limit (98,80,2) to an upper limit (120,255,255). The results of object detection can be seen in Table 1.

The test was carried out 15 times with each color 5 times and placed in different positions. From table 1 it can be explained that the red, blue and green cubes were successfully detected five times each at the coordinate positions listed in Table 1. From the test results it can be concluded that the image processing system can detect objects at a 100% success rate.

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Table 1 Image Processing System Test Results

TEST	COLOR	COORDINATES		RESULTS
		Z	X	
1	RED	0.821	21.75	✓
2		-7.56	27.09	✓
3		6.440	23.52	✓
4		0.001	15.07	✓
5		-11.44	17.55	✓
6	BLUE	6.11	25.42	✓
7		5.49	22.32	✓
TEST	COLOR	COORDINATES		RESULTS
		Z	X	
8	BLUE	-7.51	23.80	✓
9		-0.044	15.03	✓
10		-11.63	27.08	✓
11	GREEN	-5.13	18.99	✓
12		-7.08	18.85	✓
13		0.488	17.80	✓
14		0.001	15.077	✓
15		11.86	22.32	✓
Description : ✓ (Successful), X (Unsuccessful)				

Testing the Overall Robotic Arm System

Testing of the entire robot arm system is carried out after testing the image processing system, end effector testing and robot drive system testing has been carried out. Overall system testing was carried out 15 times with each color 5 times and placed in different positions. The system is said to be successful if it can detect, pick up and place objects at predetermined storage points based on color.

Each test will measure the length of time it takes from object detection until the robot arm returns to the standby position.

In designing the program for the rotation angle of the servo, placing objects is divided into three parts based on the color of the object, namely red, yellow and blue. To determine the rotation angle of each placement of the object color, you can use the coordinates of each point where the object is placed. The coordinate points of each color can be seen in table 2.

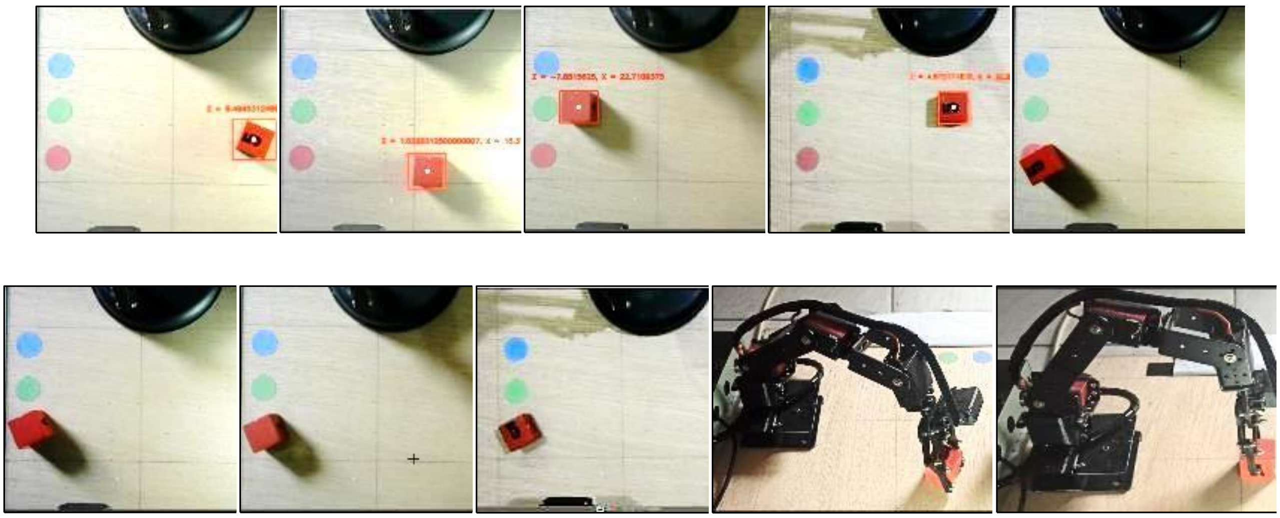
Table 2 Coordinate point

Color	Coordinate Point (cm)	
	X	**With**
Red	22.281	-10.6875
Green	26.875	-10.734
Blue	17.828	-10.781

Table 1 Robot Arm Angle

Joint	**θ (degree)**		
	Red	**Green**	**Blue**
Base	-31.16	-21.77	-25.63
Shoulder	29.72	-0.72	15.38
Elbow	55.30	104.41	75.07
Wrist	80.02	83.69	85.45

The test for moving red cubes is done by placing red cubes measuring 3x3x3 cm in the object base area. The position of the object or the coordinate point of the object is placed differently in each test. The coordinates of the objects can be seen in Table 2. Then the user will press the "R" button on the laptop to select a red object to be detected.



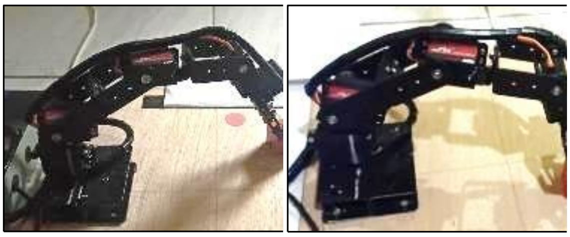


Figure 18: Red Color Object Testing

Table 4 Red Test Results

Test	Color	Coordinates		Value Angle of object capture				Results	Time
		z	x	Joint 1	Joint 2	Joint 3	Joint 4		
1	Red	84.95	196.61	23.37	26,10	44.74	57.58	✓	25.783
2		16.32	163.73	5.69	47.93	22.44	71.35	✓	24.161
3		-76.61	228.06	-18.57	18.35	60.07	64.12	✓	26.465
4		46.75	228.36	11.57	20.58	55.54	69.03	✓	26.461
5		-118.22	173.68	-34.24	27.30	42.35	71.20	✓	25.989
Average Time									25.771

From the test results that can be seen in Figure18 that the robotic arm system can detect and generate coordinate points so that the robotic arm can pick up red objects whose angular values of each joint can be seen in Table 4 and store objects at red storage points with a 100% success rate. From five attempts, the average length of time it took from object detection until the robotic arm returned to standby position was 25,771 seconds.

CONCLUSIONS

Paper based on the conducted testing and analysis, research findings lead to the following conclusions. The system demonstrates proficiency in object detection using the HSV color segmentation method. It accurately identifies the colors red, blue and green, providing precise coordinates for the object's positions in the workspace.

The robotic arm successfully moves colored cube objects from various positions to predetermined points based on their colors. Notably, it achieves a remarkable success rate of 100% for red objects, 60% for blue objects, and 100% for green objects. The time required for the robotic arm to complete the entire process, from object detection to returning to its ready position, varies for different colors. Specifically, it takes approximately 25.771 seconds for red objects, 27.727 seconds for blue objects, and 27.063 seconds for green objects.

These results demonstrate the effectiveness and efficiency of the developed robotic arm system, integrated with computer vision technology for object manipulation based on color recognition. Such capabilities hold significant promise for practical applications in various industrial settings. As technology advances, particularly in robotics and computer vision, the potential for automation and enhanced manufacturing processes is expected to expand further. This research paves the way for more sophisticated and versatile robotic systems, promising substantial improvements in industrial automation.

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