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Design and Development of a 4-DOF Robotic Sorting System Utilizing an Efficient Image Processing Technique

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ABSTRACT: *This study describes the findings associated with the design and development of a 4-degree-of-freedom robotic arm model. The Arduino Mega 2560 serves as the control unit for the robotic arm. The system operates as follows: upon entering the conveyor belt, cargo boxes are detected by a camera via QR codes affixed to them. Following QR code detection, the camera transmits a signal to the computer, which utilizes the Visual Studio C# platform for data processing. Subsequently, the computer transmits commands to the Arduino, which in turn transmits control signals to the robotic arm, directing its movements. Testing has demonstrated the system's operational stability and its ability to achieve a high degree of accuracy in item picking and sorting.*
Keywords:*4-DOF robot arm, Arduino Mega processor, Image processing, QR code,Visual studio C#.*

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I. INTRODUCTION

The Fourth Industrial Revolution (Industry 4.0) is marked by a relentless improvement in production tools. Legacy machinery, characterized by limited productivity and quality, is progressively replaced by advanced systems offering superior accuracy, increased efficiency, and the ability to manufacture high-precision goods. This transition towards automation also minimizes human involvement in industrial activities, particularly on assembly lines and in hazardous environments rife with dust, chemicals, radiation, and similar threats.

Consequently, the development and deployment of robotic arms within the industrial sector have become a focal point due to their versatility and aptitude for executing repetitive tasks with exceptional consistency. However, the automation of production processes, specifically in product sorting and arrangement, presents substantial challenges. The burgeoning diversity in product colors and the growing reliance on QR codes for product information tracking are increasingly critical factors. These factors often necessitate human intervention, thereby incurring increased costs and potentially introducing errors.As a result, many factories continue to depend heavily on manual labor for product sorting and arrangement, leading to potential delays and inaccuracies.

Additionally, the application of image processing to robotic arms has been attracting significant attention both domestically and internationally for various purposes [1]. The field of robotics has also achieved notable advancements in several areas such as dynamics, machine vision, and object manipulation [2]. In 2015, researchers conducted a study on a robotic arm designed to classify the shape of products using digital image processing techniques based on the object's perimeter [3]. Similarly, another robotic arm equipped with four fingers utilizes digital image processing to classify products based on color, operating in real-time with a webcam for image capture and analysis [4]. Moreover, research and development have been conducted on a robot deployed in practical settings to identify objects through image processing from cameras [5]. The ongoing development of more complex and flexible types of robots will undoubtedly enhance production efficiency and accuracy [6]. As robot technology continues to evolve, it is predicted that research on robots will increasingly explore the possibility of automating various industries [7].

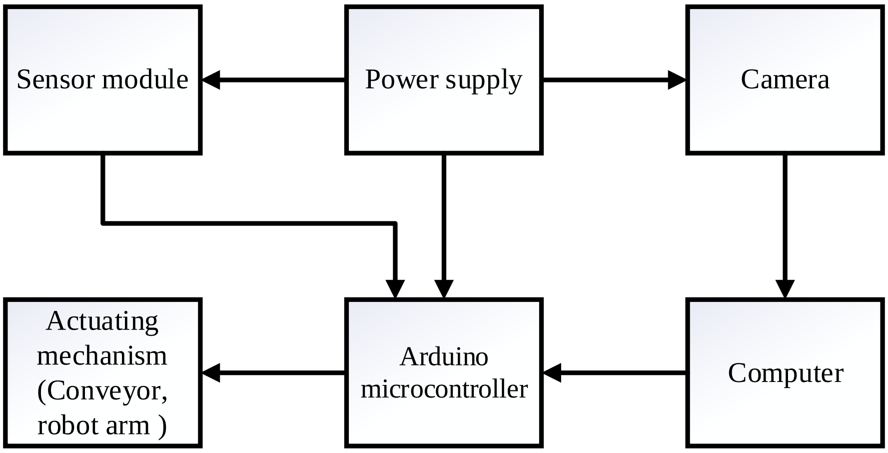
This study presents the design and construction methodology of a sophisticated product classification system that integrates a robotic arm with advanced image processing techniques. The primary objective is to engineer a system that is both adaptable and precise. This system aims to alleviate the burden on human labor while simultaneously streamlining production workflows and enhancing product information management through QR code utilization. By meticulously exploring the system's architecture, algorithmic complexities, and operational dynamics, this research seeks to offer insights into the intricate interplay between robotic automation and image-based classification methodologies within the industrial domain. By elucidating the design rationale and implementation intricacies, this study aims to contribute to the growing field of research on automation technologies, offering pragmatic solutions to contemporary challenges in industrial production and management.

II. DESIGN METHOD

2.1. Overview

For image processing tasks using QR codes, there are various powerful tools available, such as the OpenCV library with Python, C#, LabVIEW, Visual Studio's Image Toolbox, etc. Figure 1 illustrates the block diagram of a whole system aiming to classify products based on image processing technique.

Figure 1.Block diagram describing the proposed system.



The system consists of two main parts:

- Control mechanism part includes: Arduino Mega 2560, Esp32-CAM, RAMPS1.6, Step Module A4988, Infrared sensor and BTS7960 Driver.
- Executive mechanism unit involves: A 4-degree-of-freedom robotic arm and a conveyor belt system.

Following this block diagram, a control system can be built for the classification aim.

2.2. Kinematic analysis and design of robotic arm

The kinematics section delves into the mathematical description of the robotic arm's motion within a predefined reference frame. This reference frame, often referred to as a coordinate system, serves as a fixed point of reference for analyzing the arm's movement without considering the forces or torques that generate that motion. Kinematic analysis encompasses two fundamental problems: forward kinematics and inverse kinematics.

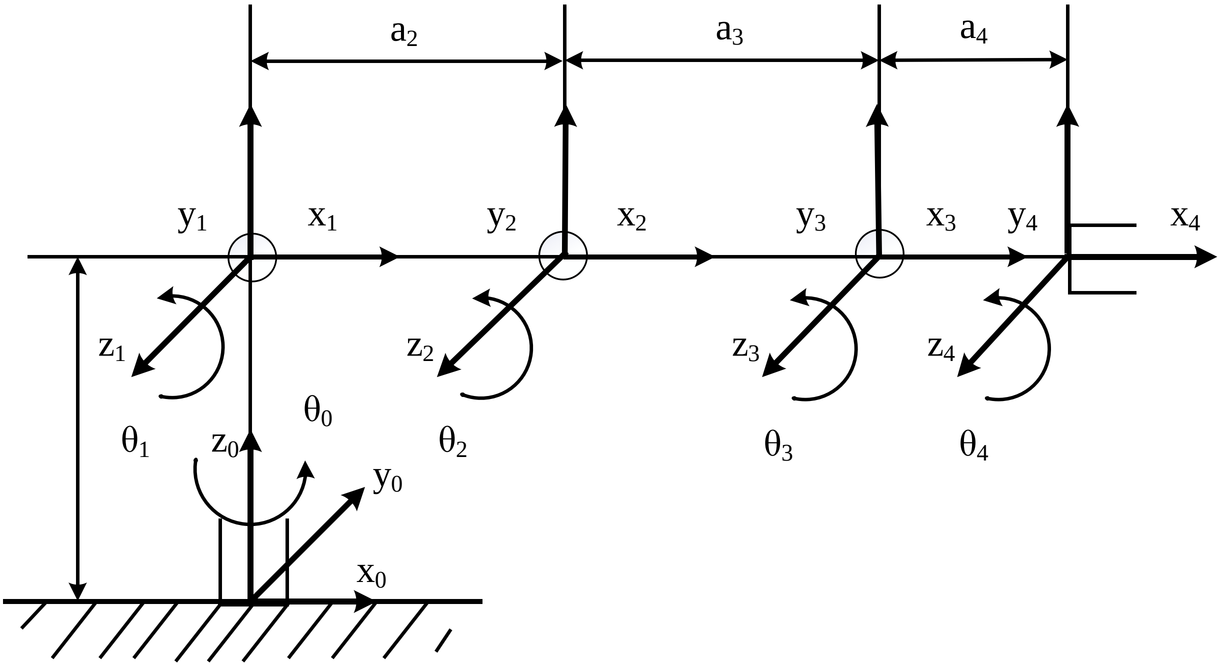
- ✓ Forward kinematics addresses the problem of calculating the position and orientation (pose) of the robotic arm's end-effector (the gripper or tool at the tip) in the reference frame, given the joint angles (configuration) of the arm's links. This essentially translates the internal joint positions into the external spatial coordinates of the end-effector.
- ✓ Inverse kinematics, conversely, seeks to determine the required joint angles (configuration) of the robotic arm for the end-effector to reach a desired position and orientation in the reference frame. This problem often involves complex mathematical calculations, especially for robots with multiple degrees of freedom.

The forward kinematics problem uses the principle to determine the position of the end-effector based on the robot's joint variables in the Cartesian coordinate system.Meanwhile, the inverse kinematics problem uses the principle to determine the joint angles when the position of the end-effector of the robot is known.

Forward kinematics calculation

Figure 2 describes the coordinate diagram for the 4-DOF robot which is typical in industry.

Figure 2. Coordinate diagram of the 4-DOF robot.



The forward kinematics problem for a serial configuration can be solved using the Denavit-Hartenberg (**D-H**) method.[10]

A table representing the Denavit-Hartenberg parameters is shown in Table 1.

Table 1: The Denavit-Hartenberg parameters table of the 4-DOF robot.

Link i	θ_i	α_i	a_i	d_i
1	θ_1	90	0	d_1
2	θ_2	0	a_2	0
3	θ_3	0	a_3	0
4	θ_4	0	a_4	0

Based on the Denavit-Hartenberg table, it is necessary to establish the state matrices as given in (1) – (6) below.

$$A_1 = \begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$A_2 = \begin{bmatrix} C_2 & -S_2 & 0 & a_2C_2 \\ S_2 & C_2 & 0 & a_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$A_3 = \begin{bmatrix} C_3 & -S_3 & 0 & a_3C_3 \\ S_3 & C_3 & 0 & a_3S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$A_4 = \begin{bmatrix} C_4 & -S_4 & 0 & a_4C_4 \\ S_4 & C_4 & 0 & a_4S_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

The end-effector matrix for this robot can be obtained below:

$$T_4 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = A_1.A_2.A_3.A_4 \quad (5)$$

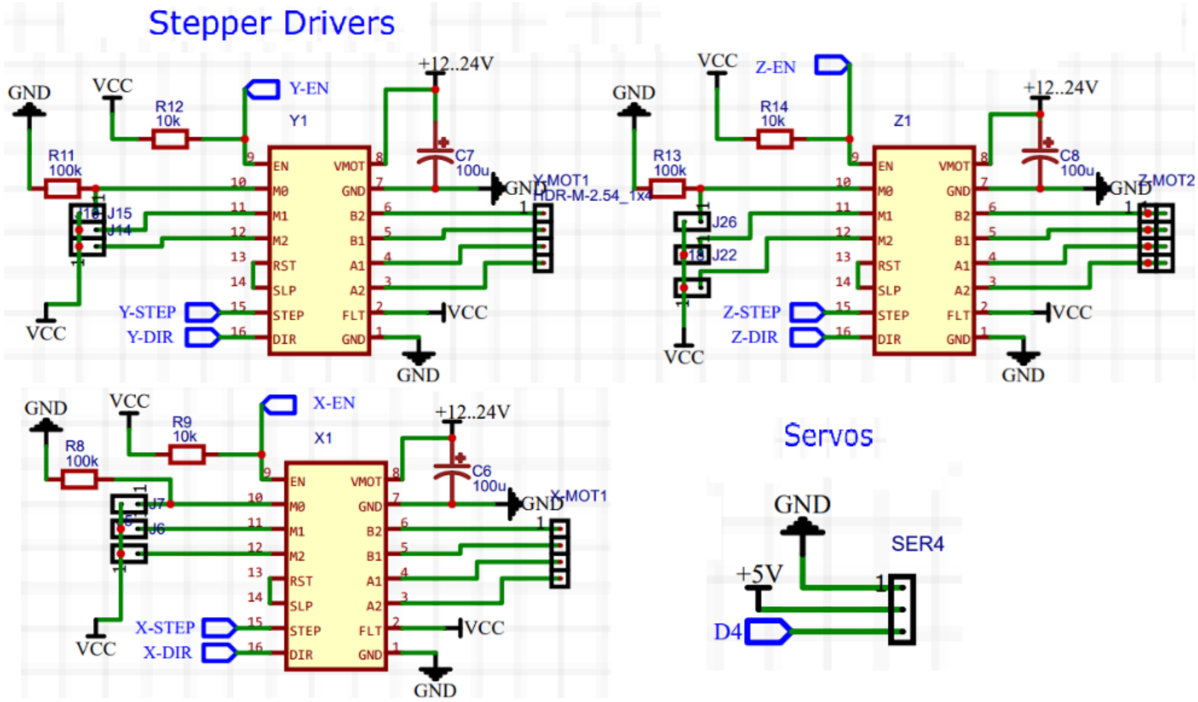
Inverse kinematics calculation

The condition for the system of equations to have a solution is:

$$\begin{cases} \dfrac{o_y}{o_x} = -\dfrac{a_x}{a_y} = \dfrac{p_y}{p_x} \\ \dfrac{n_z}{o_z} = -\dfrac{o_x}{n_x} = -\dfrac{o_y}{n_y} \\ a_z = 0 \end{cases} \quad (6)$$

Solving the inverse kinematics equation by multiplying the inverse matrix of A_i with the matrix T_4 successively, the final values of rotational angles can be obtained. These are used to model and control the entire robot system.The robot arm model is controlled by three stepper motors and one servo motor to control the gripper arm for grasping objects. The motors will be controlled through drivers and connected to an Arduino Mega 2560. Figure 3 presents the connection of Arduino Mega 2560 to the motor drivers. This is the hardware design for the current study.

Figure 3:Connect Arduino Mega 2560 to the motor drivers.



III. DESIGN OF CONTROL AND PROCESSING UNITS

3.1. Components in the system

The system consists of the following blocks:

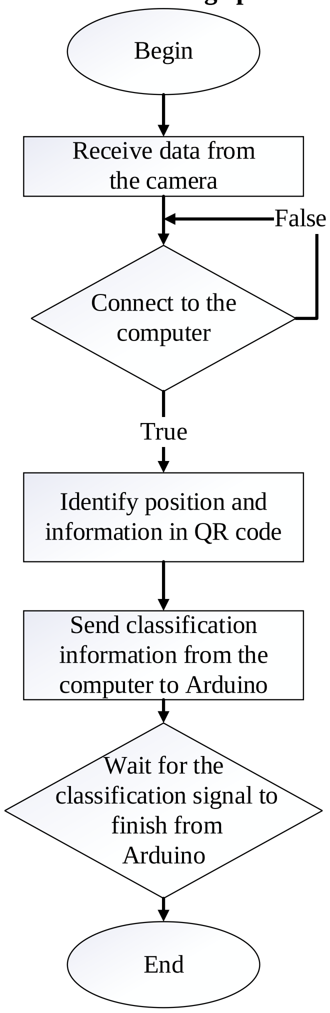
- **Control block:** Utilizing the Arduino Mega 2560 microcontroller [11], it receives information from the Esp32 and processes it before sending signals to the driver to control the actuator.

- **Central processing block:** The central processing block, which is the Arduino Mega 2560 , is responsible for receiving data from the camera and transmitting it to the control block.
- **Camera block:** Incorporating a camera integrated with the Esp32 [12] -[13], its function is to capture images from the surroundings and transmit the data back to the Arduino.
- **Actuator block:** Comprising a 4-degree-of-freedom robotic arm [14] and a conveyor belt [15]. The robotic arm's task is to reach different positions to grip the cargo boxes on the conveyor belt as per the control.
- **Power block:** Utilizing a 12VDC-10A power supply block to provide power to the system.

3.2. QR code processing

QR codes can contain many different types of information: Contact information, Calendar event, Phone number, E-mail address and URL.Initially, the system will identify the position of the QR code on the surface of the package, then proceed to recognize and decode the information provided by the QR code such as the type of goods, manufacturing date, etc. Figure 4 illustrates the flowchart for image processing algorithm applied in this study. After the data retrieval step from the QR code is completed, the data will be transmitted back to the computer for processing. Subsequently, the computer will send signals to the microcontroller to proceed with the sorting process.

Figure 4: A flowchart of image processing algorithm.



3.3. Object classification

The principle of the classification is presented as follows.

Upon receiving a control signal from the host computer, the Arduino microcontroller executes the pre-programmed sorting algorithm based on the embedded instructions. This algorithm utilizes the received data to determine the appropriate sorting action. Subsequently, the Arduino transmits control signals to the stepper motor driver, which in turn generates pulse width modulation (PWM) signals to govern the movement of the robotic arm. These precise movements manipulate the goods, ultimately placing them in their designated locations.

In the event that the system fails to receive a control signal within a predefined time frame, a fail-safe mechanism is triggered. This mechanism instructs the robotic arm to return to its initial position, effectively resetting the system and ensuring it remains prepared to receive the next sorting command from the host computer.

IV. EXPERIMENTAL RESULTS

The core component of this project is the robotic arm model, meticulously constructed using high-precision 3D printing technology. This technology allows for the creation of intricate parts with exceptional dimensional accuracy from a readily available material - PLA plastic. A visual representation of the completed robotic arm model is provided in Figure 5. As showcased in the figure, the model effectively maneuvers cargo boxes, precisely positioning them according to pre-defined parameters. This operational accuracy underscores the model's ability to meet the established system requirements with a high degree of success.

The control program governing the robotic arm is designed with simplicity and user-friendliness in mind. This user-centric approach facilitates straightforward operation and reduces the learning curve associated with system utilization. This focus on user experience complements the model's core functionality.

The classification results achieved by the robotic arm system are particularly noteworthy. The system exhibits an almost perfect accuracy rate, demonstrating its exceptional capability to correctly categorize and sort cargo boxes. This near-flawless performance signifies the effectiveness of the design and implementation strategies employed in the project.

Furthermore, the model, having undergone meticulous calculations and design optimizations, delivers classifying times that are detailed in Table 2. It is crucial to emphasize that these classifying times are not only deemed acceptable within the context of the controlled experimental environment, but are also projected to translate seamlessly into practical industrial applications. This successful translation from a controlled setting to a real-world industrial environment highlights the model's robust functionality and its potential for practical use cases.

Figure 5. An illustration of the actual model.

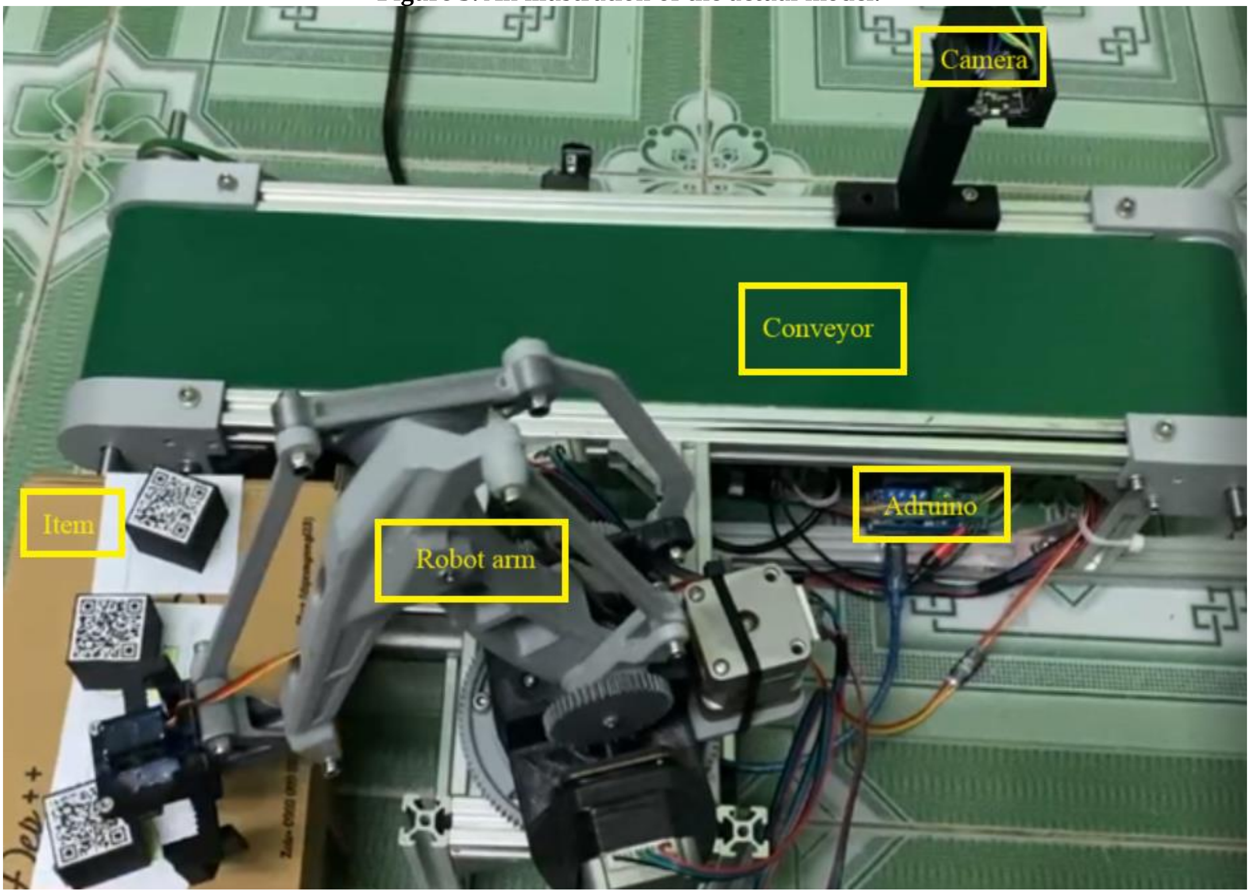


Table 2. Classification times obtained from the system built in this study

Test	Type	Time	Results	Average time
1	Type 1	14.5s	✓	14.6s
2	Type 3	14.2s	✓	
3	Type 1	14.5s	✓	
4	Type 3	15.3s	✓	
5	Type 2	14.5s	✓	

V. CONCLUSION AND FUTURE WORK

The current study has represented the initial design and fabrication of a 4-DOF robotic arm prototype for product classification using QR codes. This prototype serves as a foundational development, fulfilling a preliminary set of functionalities outlined in the introduction. Further refinements are necessary to ensure industrial-grade durability and production line-level accuracy. Nevertheless, the system demonstrates potential as a valuable educational tool for engineering students to acquire knowledge of robotic arm principles.

This research establishes a groundwork for the development of more sophisticated and versatile robotic control methods, potentially leading to significant advancements in industrial automation. Furthermore, it advocates for a transition from "human-machine" to "human-robot-machine" production structures, thereby contributing to the progress of the domestic robotics industry. This shift has the potential to mitigate worker exposure to hazardous and physically demanding tasks, consequently reducing workplace accidents.

Future endeavors will focus on expanding the system's capabilitiesa to include tasks such as color-based product sorting and packaging. This will culminate in the establishment of a more comprehensive and accurate production line. Achieving these objectives necessitates the development and integration of robust hardware components, crafted from high-strength materials such as steel or alloys, to minimize vibrations and oscillations.

REFERENCES

[1] A. R. A. Tahtawi, M. Agni và T. D. Hendrawati, "Design of a 5 Degree of Freedom Robotic Arm for Pick and Place Mission based on Inverse Kinematics", Pages 87–92, 2020.

[2] F. Maulana, Kurniawan và Setyawan, "Implementation of a 3 DOF Robotic Arm for Material Transfer using Inverse Kinematics Method.", Jurnal Pengembangan Teknologi Informasi Dan Ilmu Komputer , 2018.

[3] V.B.Raskar, N. Hargude, S. Vishwanath và K. Chavan, “Practical applications of robotic hand using image,” International Journal of Advanced Research in , Vol. 4 Issue 3, 2015.

[4] B. Basule1 và Shubhangi Borkar, “Robotic Four Finger ARM Controlling using Image,” International Journal of Engineering Science , Vol. 7, No.7, 2017.

[5] M. Dragusu, A. Mihalache và R. Solea, “Practical applications for robotic arms using image processing,” 16th International Conference on System Theory, Control and Computing, 2012.

[6] W. Garcia, "Color Recognition for Robotic Arm Object Manipulation using Deep Learning", Proceedings of the International Conference on Robotics and Automation, 678-685, 2020.

[7] B. Turner, "Vision-Based Object Sorting and Picking using a 4-DOF Robotic Arm", Journal of Automation and Robotics, 223-237, 2021.

[8] A. Gupta, A Geometric Approach to Inverse Kinematics, International Journal for Research in Applied Science & Engineering Tech, Vol.6, Issue. 1, pp. 352-357., 2018.

[9] T. T. Pham, “Controlling the Path of a 4 DOF Robot”, The University of Danang - Journal of Science and Technology, Da Nang, 2015.

[10] B. S. G. B. Carlos Canudas Wit, Theory of Robot Control, Springer Science & Business Media, 2012.

[11] Joy-it, MEGA2560 Microcontroller Learning - Kit, SIMAC Electronics GmbH, 2020.

[12] Espressif, ESP32 Series datasheet, Espressif Systems (Shanghai) Co., Ltd, 2024.

[13] Espressif, ESP32 Technical Reference Manual, Espressif Systems (Shanghai) Co., Ltd, 2024.

[14] A. Y. Ahmed, A. M. Ahmed và M. A. Hussein, Design and Control of 4-DOF Robotic-Arm Simultaneously using Matlab and Arduino, Abdelrady Okasha Elnady, 2020.

[15] Portable Modular Conveyor Belt Speed Control by Arduino, Available at https://www.talentedsky.com.

[16] A. S. Narayanan, "QR Codes and Security Solutions," International Journal of Computer Science and Telecommunications , Sultanate of Oman, 2012.