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MOTION CONTROL ANALYSIS OF TWO COLLABORATIVE ARM ROBOTS IN FRUIT PACKAGING SYSTEM

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Abstract
As robots' use increases in every sector of human life, the demand for cheap and efficient robots has also enlarged. The use of two or more simple robot is preferable to the use of one sophisticated robot. The agriculture industry can benefit from installing a robot, from seeding to the packaging of the product. A precise analysis is required for the installation of two collaborative robots. This paper discusses the motion control analysis of two collaborative arms robots in the fruit packaging system. The study begins with the relative motion analysis between two robots, starting with kinematics modeling, image processing for object detection, and the Fuzzy Logic Controller's design to show the relationship between the robot inputs and outputs. The analysis is carried out using SCILAB, open-source software for numerical computing engineering. This paper is intended as the initial analysis of the feasibility of the real experimental system.

Keywords:
Agriculture Robot;
Arm Robot Manipulator;
Collaborative Robot;
Relative Motion;

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INTRODUCTION

The first robot to be introduced in human life was a robot arm manipulator used in industries to replace human labor in a dull, dangerous, and dirty working environment [1, 2, 3, 4]. This type of robot has been so well-recognized and well-researched that it creates a perfect worker for industry revolution 4.0 [5]. Automation has penetrated every aspect of human life to support our lifestyle or to spoil us [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15], such as a service robot [6], a worker robot [7], and an agriculture robot [12, 13, 14, 15,16,17].

The new trend in robotics is to take up the concept of community robotics or multi-robots that mimic natural animals' lives like ants, a flock of birds, the swarm of bees, or a fish school. The use of many simple robots is more profitable than using a single robot with high technical specifications. Although most multi-robots found today are mobile robots [7, 8, 9], this idea can also be applied to robot arms [2, 3, 4].

If the arm robot can help people work in repetitive and time-consuming tasks, then using more than one arm robot will increase the task's speed without requiring human intervention [1, 2, 3, 4].

The use of more than one robot or multi-robot in the fruit and goods packaging process will be more beneficial in terms of time and efficiency than using a single robot. One robot can be equipped with a camera to distinguish the colors and shapes of objects or fruits to be packaged. The other robot can only be equipped with a proximity sensor to ensure that the robot's arms' ends do not collide with surrounding objects or objects to be packaged. An example of this robot is position-based visual multi-arm robotic cells using multiple cameras [4]. The problem with numerous cameras, however, is excessive computational time is high.

Image processing is a key point for the visual cue of a robot used in a place where it is necessary to recognize an object, such as an agricultural robot [8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. Image processing is helpful in any agricultural situation, such as seeding [8][9], maintenance [18][19], yield forecast [20][21], harvesting [12], and packaging [17, 22, 23, 24, 25, 26, 27]. The use of robots in agriculture could ease the farmer's work burden and increase the harvest yield [8].

Robot movement is more efficient and smoother by implementing artificial intelligence in the robot arm [29]. The three types of Artificial Intelligence (AI) used in robotics are the Fuzzy Logic Controller, the Neural Network, and the Genetic Algorithm. Each of these AIs can be implemented individually or in combination to have a better impact. However, the robot implementation group's issue is simplicity; therefore, the most used AI is proposed in this study, i.e., Fuzzy Controller Logic [30, 31, 32].

This paper discusses the design and analysis of the motion control of two collaborative arms robots used in the fruit packaging system. Control design and analysis combine the concept of kinematics and relative motion analysis to show how two robots work together to create a collaborative environment between robots. This paper is intended as the initial analysis of the real experimental system's feasibility, where two robots are working collaboratively instead of human and robot co-working. This study also shows image processing, which functions as a visual cue for the robot to pick and place orange objects assigned to it. The robots assigned to this study are robot 1 and robot 2. Robot 1 is equipped with a proximity sensor only, and robot 2 is equipped with a proximity sensor and a camera. The system is connected to a scale system in which a weight sensor is installed [33]. Mathematical analysis, image processing analysis, and Fuzzy Logic Controller design are presented to demonstrate the feasibility of the proposed method. This research is the continuation of our study in [13, 14, 15].

METHOD

The paper analyzes a series of relative motion and visual cues to produce robotic motion resulting from image processing. The motion control analysis of two-arm robot manipulators that work together in a fruit packing system will be discussed. Figure 1 shows the robot arms considered in this study.

Robot Design

The design of robots and their working environment is shown in Figure 1. Robot 1 is equipped with a proximity sensor to sense the distance between the robot's end-effector and the object when picking up the object and to sense the distance between the end-effector and weight scale.

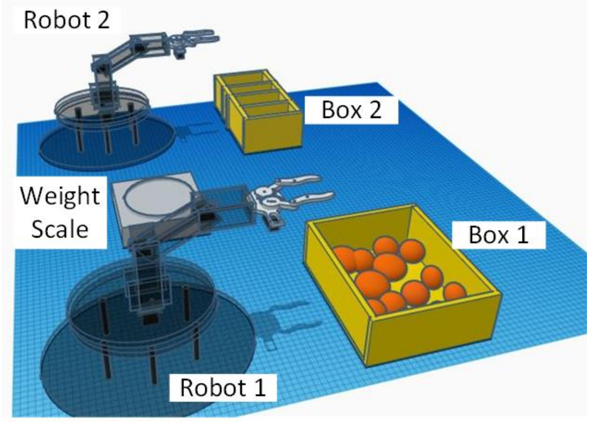


Figure 1. The collaborative arm robots and their workspace

The object considered in this study is orange. Robot 2 picks the orange and place it in the box according to the size of the orange.

The weight system in the weight scale in Figure 1 is connected to the arm robot system. The weight sensor is a sensor for detecting load pressure or weight and is commonly used as the main element of a digital weighing device. The weight sensor works by converting the received forces such as pressure, tension, and compression into the electrical signal.

The concept of weighbridge is used to analyze this system, as shown in Figure 2, where V_{Ex} is the excitation voltage constant, V_0 is the output voltage, R_1 and R_3 are tension strain gauge, and R_2 and R_4 are compression strain gauges. If R_1 to R_4 in Figure 2 are balanced, $\frac{R_1}{R_2} = \frac{R_4}{R_3}$, then V_0 is zero. Hence, changes in R_1 to R_4, results in V_0 changes. The changes in V_0 are measured by using Ohm's Law, $I = \frac{V}{R}$. Therefore, based on the Wheatstone bridge configuration in Figure 2, the voltage output is given by:

$$V_0 = \left(\frac{R_3}{R_3+R_4} - \frac{R_1}{R_1+R_2}\right) V_{Ex}. \qquad (1)$$

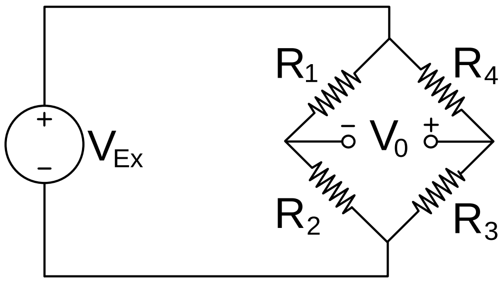


Figure 2. Weighbridge circuit

The electrical design of the arm robot manipulator is presented in Figure 3. The arm robot is equipped with a Pi camera to capture the image and then processed by an image processing method to separate the orange from its background. Hence the coordinate of orange in the coordinate image frame is known by the end-effector. Image processing is conducted in Raspberry Pi, and the output becomes the visual cue for controller ATMega 2560 to move the arms. The robot is also equipped with four servo sensors, one for each joint, and one is on the end-effector to grab the object.

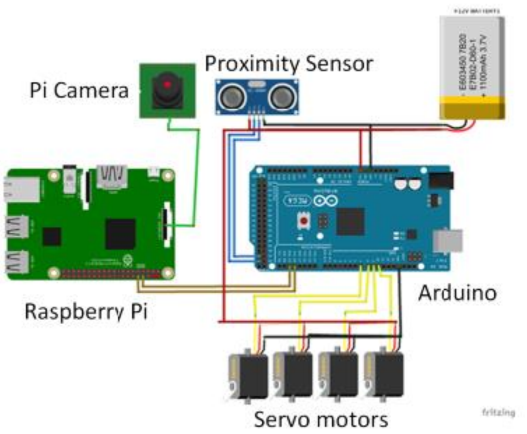


Figure 3. Electrical design of the robot

Relative Motion Analysis

The first analysis is based on a relative motion analysis where each joint is considered to be moving relative to the other joints. The relative motion analysis is undergoing general planar motion, where the robot bodies are translated and rotated simultaneously.

Two arm robots are shown in Figure 1 moving relative to each other and given by

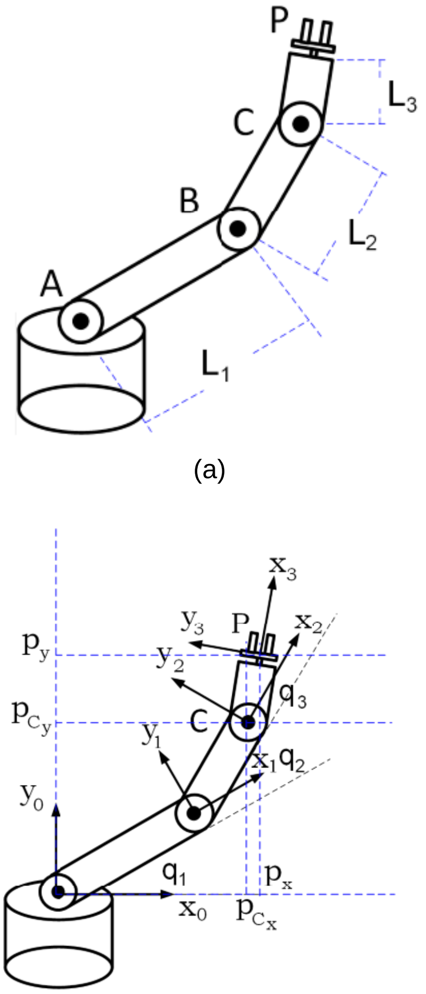
$$V_{R1/R2} = V_{R2} - V_{R1}, \qquad (2)$$

where $V_{R1/R2}$ is the velocity of robot 1 (V_{R1}) relative to robot 2 (V_{R2}).

Two arm robots are identical to each other. Therefore, the relative motion analysis is conducted to one robot. For the sake of simplicity, the robot is considered as a three-link planar arm shown in Figure 4(a), where L_1 is the length from the base (point A) to B, L_2 is from B to C, and L_3 is the length of the third link. The relative motion analysis breaks the robot into four points, A, B, C, and P, where P is the robot's end-effector. Joint A is the only point that is fixed, and the rotations are the motion from A to B then B to C. The end-effector of the robot is on the tip of point P; therefore, the relative velocity of joints of the robot in Figure 1 is

$$V_{P/A} = V_{B/A} + V_{C/B} + V_{P/C}, \qquad (3)$$

where $V_{P/A}$ is the relative motion from point A to point P (end-effector), $V_{B/A}$ is the relative velocity of point B to A, $V_{C/B}$ is the relative velocity of point C to B, and $V_{P/C}$ is from end-effector to point C.



(a)

(b)

Figure 4. Assigned coordinate frames of three-link planar arm

Table 1. DH parameters of arm robot in Figure 4

i	α_i	d_i	a_i	q_i
1	0	0	L_1	q_1
2	0	0	L_2	q_2
3	0	0	L_3	q_3

The velocity of each joint can be analyzed by applying kinematics modeling of the robot in Figure 4(b). The analysis is started by assigning coordinate frames to the robot shown in Figure 1 and finding robot velocity and each joint's velocity.

Consider the three-link planar in Figure 4(a), where all the revolute axes are parallel, and the direction of x_0 is arbitrary. All the parameters of the link offset along the previous z-axis to the common normal (d_i) are null since all the joints are revolute joints. The angles q_i are the angles between the axes a_i. The Denavit-Hartenberg (DH) parameters are presented in Table 1 to analyze the robot's kinematics modeling [34].

Therefore, based on DH parameters in Table 1, the direct kinematics function is given by

$$T_3^0(q) = T_1^0 \cdot T_2^1 \cdot T_3^2$$

$$T_3^0(q) = \begin{bmatrix} c_{123} & -s_{123} & 0 & L_1c_1 + L_2c_{12} + L_3c_{123} \\ s_{123} & c_{123} & 0 & L_1s_1 + L_2s_{12} + L_3s_{123} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \qquad (4)$$

where $q = [q_1 \quad q_2 \quad q_3]^T$, c_1 is $\cos q_1$, s_1 is $\sin q_1$, c_{12} is $\cos(q_1 + q_2)$, s_{12} is $\sin(q_1 + q_2)$, c_{123} is $\cos(q_1 + q_2 + q_3)$, and s_{123} is $\sin(q_1 + q_2 + q_3)$.

It is necessary to find the joint variables q_1, q_2, and q_3, which are corresponding to a given end-effector position and orientation. The robot position and orientation are P_x, P_y, and ϕ, respectively. Therefore,

$$\phi = q_1 + q_2 + q_3. \qquad (5)$$

The position of point C as the origin of Frame 2, which is the origin of angles q_1 and q_2, are

$$p_{Cx} = P_x - a_3c_\phi = a_1c_1 + a_2c_{12}, \qquad (6)$$

and

$$p_{Cy} = P_y - a_3s_\phi = a_1s_1 + a_2s_{12}. \qquad (7)$$

By squaring and summing (6) and (7) yields

$$p_{Cx}^2 + p_{Cy}^2 = a_1^2 + a_2^2 + 2a_1a_2c_2. \qquad (8)$$

Hence,

$$c_2 = \frac{p_{Cx}^2 + p_{Cy}^2 - a_1^2 - a_2^2}{2a_1a_2}. \qquad (9)$$

Then by setting $-1 \le c_2 \le 1$ to ensure the given point is inside the reachable arm workspace, yield

$$s_2 = \pm\sqrt{1 - c_2^2}, \qquad (10)$$

where the positive sign is relative to the elbow-down posture and the negative sign to the elbow-up posture.

Therefore, q_2 is calculated as

$$q_2 = \mathrm{Atan2}(s_2, c_2). \qquad (11)$$

By substituting q_1 and q_2 to (6) and (7), the algebraic equations with unknown s_1 and c_1 as follow.

$$s_1 = \frac{(a_1 + a_2c_2)p_{Cy} - a_2c_2p_{Cx}}{p_{Cx}^2 + p_{Cy}^2}, \qquad (12)$$

$$c_1 = \frac{(a_1 + a_2c_2)p_{Cx} - a_2c_2p_{Cy}}{p_{Cx}^2 + p_{Cy}^2}. \qquad (13)$$

By using the same analogy above; therefore

$$q_1 = \mathrm{Atan2}(s_1, c_1). \qquad (14)$$

If $s_2 = 0$, then $q_2 = 0$, and if the kinematics reach singularity, then $q_2 = \pi$. The angle q_1 can be determined uniquely, except when $L_1 = L_2$, in this case, $p_{Cx} = p_{Cx} = 0$. Hence,

$$q_3 = \phi - q_1 - q_2. \qquad (15)$$

The velocity of center of gravity (CG) of each joint A, B and C obtained from the kinematic analysis is

$$V_A^0 = \begin{bmatrix} -0.5L_1s_1\dot{q}_1 \\ -0.5L_1c_1\dot{q}_1 \\ 0 \end{bmatrix} \qquad (16)$$

$$V_B^0 = \begin{bmatrix} -L_1s_1\dot{q}_1 - 0.5L_2s_{12}(\dot{q}_1 + \dot{q}_2) \\ L_1c_1\dot{q}_1 + 0.5L_2c_{12}(\dot{q}_1 + \dot{q}_2) \\ 0 \end{bmatrix} \qquad (17)$$

$$V_C^0 = \begin{bmatrix} -L_1s_1\dot{q}_1 - 0.5L_2s_{12}(\dot{q}_1 + \dot{q}_2) - 0.5L_3s_{12}(\dot{q}_1 + \dot{q}_2 + \dot{q}_3) \\ L_1c_1\dot{q}_1 + 0.5L_2c_{12}(\dot{q}_1 + \dot{q}_2) + 0.5L_3c_{123}(\dot{q}_1 + \dot{q}_2 + \dot{q}_3) \\ 0 \end{bmatrix} \qquad (18)$$

$$V_D^0 = \begin{bmatrix} -L_1s_1\dot{q}_1 - L_2s_{12}(\dot{q}_1 + \dot{q}_2) - L_3s_{12}(\dot{q}_1 + \dot{q}_2 + \dot{q}_3) \\ L_1c_1\dot{q}_1 + L_2c_{12}(\dot{q}_1 + \dot{q}_2) + L_3c_{123}(\dot{q}_1 + \dot{q}_2 + \dot{q}_3) \\ 0 \end{bmatrix} \qquad (19)$$

By substituting the velocity in (16) to (19) into (3), the relative motion of the considered robot in Figure 4 can be obtained. By obtaining (3), (2) is also achieved, since they are identical robots.

Image Processing

Image processing requires computational time. The more complicated an image processing, the more resources are required. Therefore, the image processing method should be simplified without sacrificing the effectiveness of the method.

The basic image processing operation that is conducted in this study is as follows.

1. Grayscale converting
   The first step of image processing is by converting the image to grayscale, giving the pixels in the image representing the amount of light its carries. This process makes the

information inside the image is limited only on intensity. Therefore, it is easier to proceed to the next image processing steps.

2. Thresholding
   They are conducted by comparing the grey level of each pixel to a threshold. The equal and higher grey level, then the threshold is marked as true, and if the grey level is lower than the threshold, it is considered false. The result of this image processing is called a logical image.
3. Filtering
   Filtering is placing a mask on each pixel to be a new grey or logical value. The object of interest can be emphasized, and an irrelevant object can be removed.
4. Blob analysis
   Blob analysis continues the process by connecting the true pixels. All true pixels are marked by a number greater than zero, while the false mapped is marked as zero. By connecting the true pixels, the characteristic properties such as centroid will be merged.

RESULTS AND DISCUSSION

The proposed method's feasibility is simulated using Scilab, an open-source engineering simulation, to model and simulate mathematical problems in engineering. Simulation results consist of image processing results as a visual cue and a fuzzy logic controller resulting from kinematics analysis.

The Detected Oranges

Image processing is necessary as the visual cue to move the robot. The robot only moves when the camera detects the assigned object. The considered object in this study is oranges. The original image is shown in Figure 5.

Figure 5. The original images of oranges

The raw image of oranges in Figure 5 is processed to make the robot recognized the shape of oranges and taking the most right one as the assigned object to be initially picked and placed by considering the right one is the closest one to the robot. The final detected image is shown in Figure 6, where the boxes show the detected oranges' viewer.

Figure 7 shows step by the steps of the image processing considered in this study. The first step in processing the captured image is to convert the original image to the grayscale image. The grayscale image allows the image to be manipulated and process to detect the assigned object. The thresholding processing is started by inverting the image. The Otsu threshold algorithm is applied to the image to find objects in an image by identifying the significantly brighter or darker pixels than the background.

The next type of image processing is Blob analysis, where the true pixels in the logical image and forming shape and color. The final detected object is shown in Figure 6, and bounding boxes are determined and drawn around the subject as the shape of the assigned objects is detected.

Figure 6. The final detected image

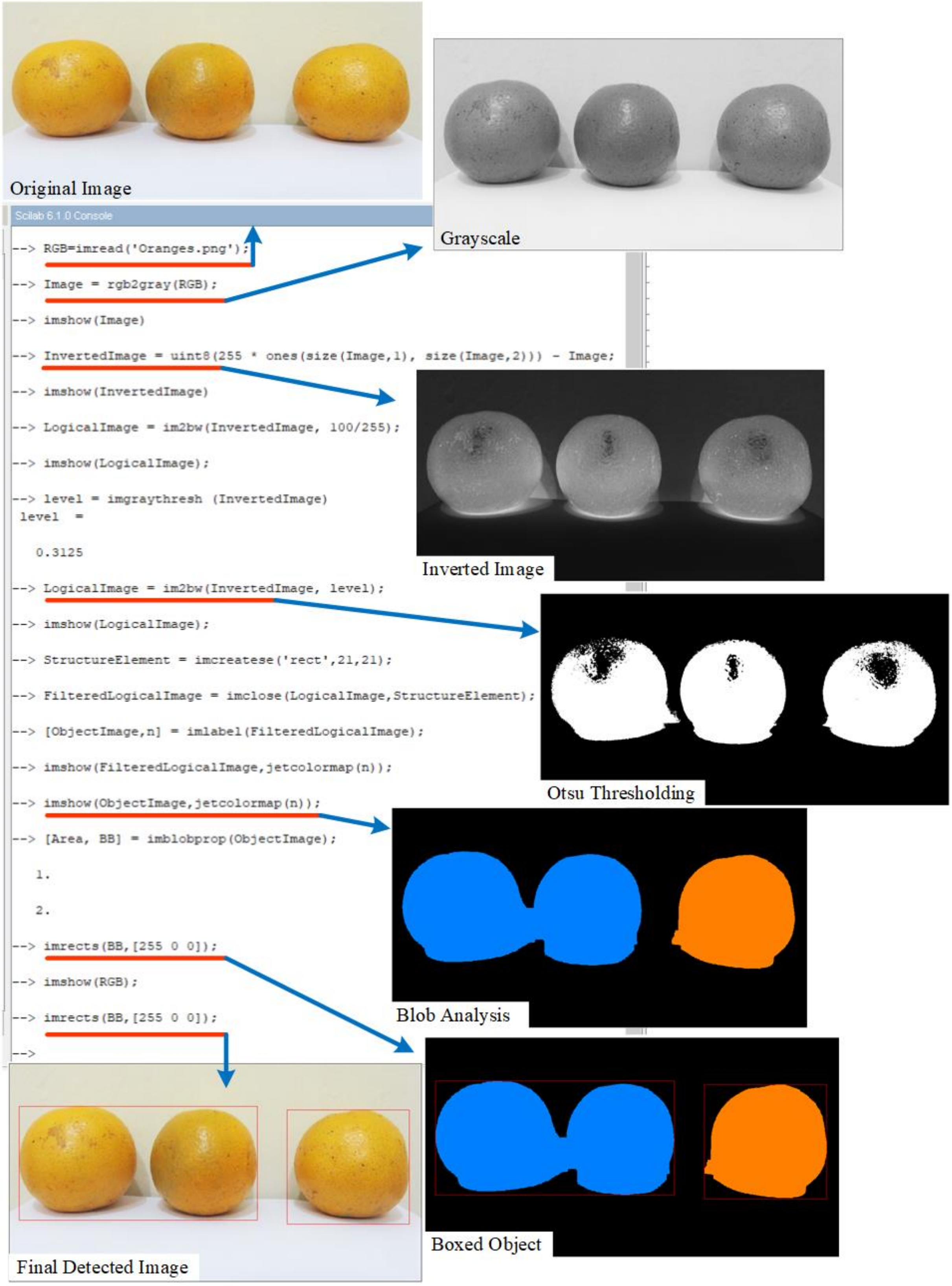


Figure 7. Image processing considered in this study

Fuzzy Logic Controller

Robot 1 takes the input of oranges detection using a camera and proximity sensor to sense the distance between the end-effector and the oranges. Robot 2 takes the weight sensor's input to sort the oranges and place them accordingly in a box. Robot 2 is also received the distance approximation between the end-effector and oranges from the distance sensor. The input membership functions for robots 1 and 2 are shown in Figure 8 and Figure 9.

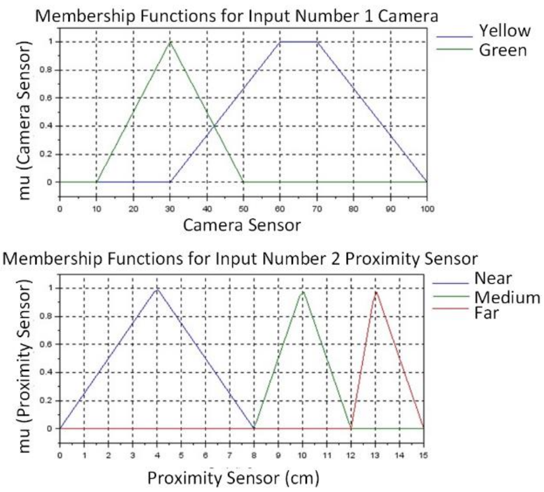


Figure 8. Visual cue and proximity sensor inputs to the system of robot 1

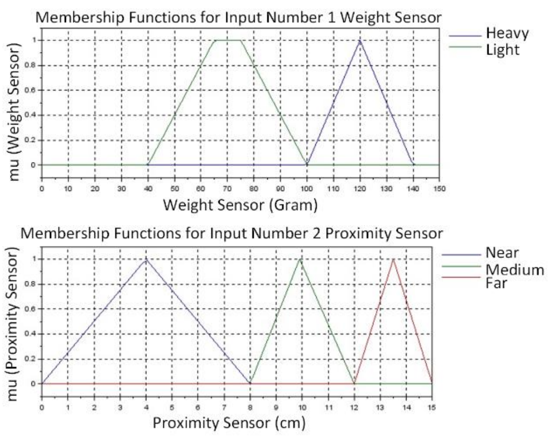


Figure 9. Weight sensor membership function for robot 2

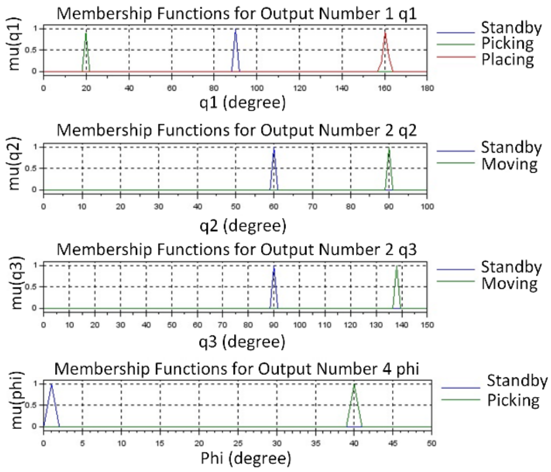


Figure 10. The output membership function as the result of the application of the input membership function

The membership output of robot 1 and 2 are the same, the angles q_1, q_2, q_3, and ϕ, which corresponds with the angles made by the servo motors that move the joints. The membership output is shown in Figure 10.

Figure 11 shows the relationship between camera detection, proximity sensor on end-effector, and phi as the end-effector servo angle as robot 1 picks and places the oranges. Figure 12 shows the base motion (q_1) when the camera detects the orange and moves the robot.

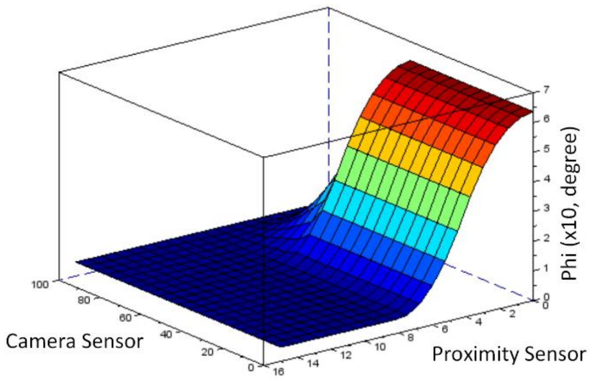


Figure 11. The relation between camera detection, proximity sensor, and ϕ for robot 1

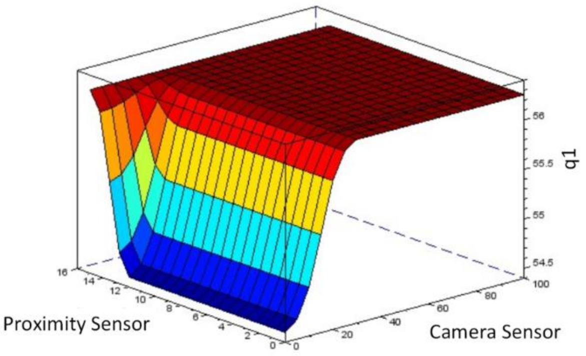


Figure 12. The relation between camera detection, proximity sensor, and q1 for robot 1

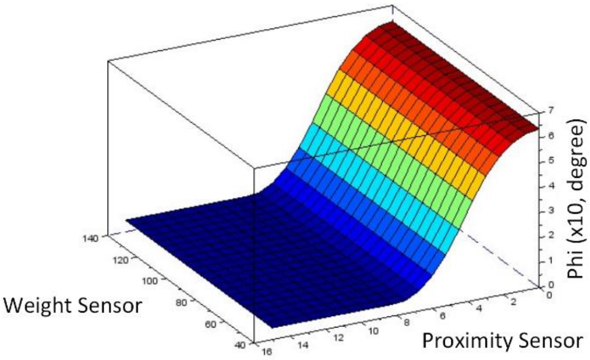


Figure 13. The relation between weight sensor, proximity sensor and, ϕ for robot 2

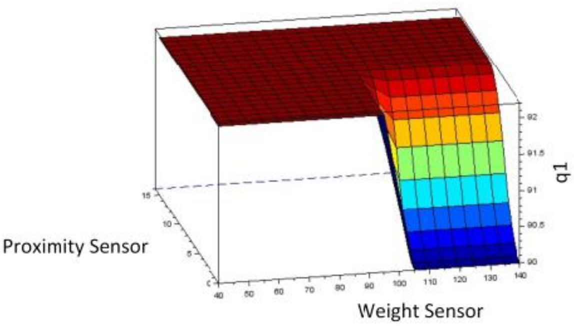


Figure 14. The relation between weight sensor, proximity sensor, and q1 for robot 2

Figure 13 illustrates the relationship between the weight sensor, proximity sensor, and the angles of the end-effector of robot 2 during picking and placing the orange. Figure 14 shows the relationship between the weight sensor, proximity sensor, and the robot-base angle when robot 2 sorts the orange and place it in the box according to the detected weight.

The simulation results show the feasibility of design two collaborative robots in picking and sorting the oranges in an agriculture product packing system.

CONCLUSION

A robot is assigned to replace or assist human beings in many life sectors, such as agriculture, from seed to agricultural products packaging. In doing so, one of the essential factors is image processing, as the robot must be able to recognize the object to be manipulated. Image processing should be simple to accommodate a limited resource without sacrificing the importance of effective detection. Applying more than one robot can increase productivity rather than just one robot; therefore, robots' relative motion must be considered. The kinematics analysis and fuzzy logic controller design show the feasibility of design two collaborative robots applied in an agriculture product packing system.

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