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Research and development of a 3-axis robotic strawberry harvester in a greenhouse using image processing

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Abstract

This research focuses on the development of a robotic strawberry harvester for greenhouse cultivation, aimed at reducing dependence on manual labor and improving harvesting precision. The robotic system features a three-dimensional Cartesian structure with dimensions of 150 × 200 × 140 cm (Width × Length × Height), driven by three stepper motors with a step angle of 1.8°. The system is controlled using a single web camera with a resolution of 1280 × 720 pixels (720p/30fps), which captures images to detect the position and ripeness of strawberries. Image processing is performed using LabVIEW software, which guides the movement along the X, Y, and Z axes to position the gripper precisely at the harvesting location. The gripper is designed to grip and cut the stem of the strawberry, minimizing post-harvest damage to the fruit. Field tests conducted in a greenhouse demonstrated that the robot could accurately classify strawberry ripeness with 100% accuracy. At motor speeds of 1100, 1200, and 1300 rpm corresponding to linear speeds of 0.11, 0.12, and 0.13 m/s the robot achieved target positioning accuracy of 100, 96.66, and 100%, respectively. The average harvesting times per fruit were 53.9, 52.7, and 50.8 s. In addition to its technical performance, an engineering economic analysis showed that the robotic system offers a payback period of 9.6 months and a break-even point at 180.59 h/time/y. These results indicate that the robotic harvesting system is a cost-effective investment for medium- to large-scale greenhouse farming operations.

Keywords: Green house, Harvest, Robot, Strawberry

1. Introduction

Strawberries are an important economic crop in the northern region of Thailand. They are produced for fresh consumption, sent to industrial factories for processing into products, and can also add value in terms of tourism when the strawberry harvest season arrives. Currently, the strawberry cultivation area has been continuously expanding in various provinces in both the North and the Northeast, covering an area of more than 7,000 rai (1,120 ha). Each year, more than 10,000 tons are released to the market [1].

Most strawberry harvesting methods in Thailand still use manual labor, with a harvest capacity of approximately 80-100 kg/person/day. They are harvested in the early morning when the temperature is low, the weather is dry, and the sun is not strong. Strawberry fruits are selected for harvesting when the skin is red, about 3/4 or 75% of the entire fruit is developed, and the fruit is still hard. They can be picked by hand or by using small scissors to cut the strawberry from the stem [2].

Using manual labor to harvest will waste labor and cost money to hire labor. And when it comes to harvesting a large amount of produce, visual inspection of strawberry ripeness can be inaccurate. In addition, there is an increasing shortage of agricultural labor. Currently, robotic technologies have evolved rapidly and play an increasingly important role in various sectors, including industrial, military, medical, and agricultural applications. For instance, De-An, et al. [3] designed and developed a control system for an apple harvesting robot, while Arad, et al. [4] introduced a robot for harvesting sweet peppers. Similarly, Lili, et al. [5] developed a tomato harvesting robot specifically designed for greenhouse environments. Therefore, the researchers have an idea to develop a robot for harvesting strawberries using image processing techniques for harvesting strawberries grown in greenhouses.

2. Materials and methods

2.1 Structural design

The design of the strawberry picking robot structure will choose to use a 3-dimensional straight-line movement type (Cartesian Robot) or a linear robot (Linear) as shown in Figure 1. This type of robot will move in a straight line in all 3 dimensions. The advantages are that the structure is strong, balanced throughout the movement, the operation is not complicated, and the structural components are easy to assemble [6-7]. The robot structure design uses a 30 × 30 mm aluminum profile driven by 3 stepping motors.

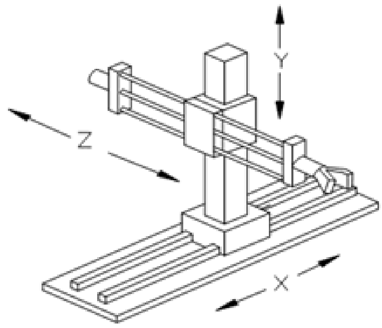

Figure 1 Cartesian Robot

A gripper is a device that enables machines or robots to grasp and hold objects when installed on mechanical systems or robotic arms. In the design of a strawberry-picking robot, an electric gripper was selected due to its superior operating speed compared to other types of grippers. This makes it well-suited for picking up and placing objects into and out of machines. Additionally, it does not require high gripping force, making it ideal for applications that demand light to medium gripping force. The gripper designed for strawberry harvesting is specifically engineered to grip and cut at the stem of the strawberry, in order to minimize potential damage to the fruit during the picking process.

2.2 Design of the maturity measurement program

The maturity measurement method uses the amount of color space that appears on the strawberry photograph that is separated from the background. The color value classification in each pixel is based on the comparison of the similarity between the colors from the photograph and the reference data. The program is divided into 2 steps: the learning step and the color value classification step.

2.2.1) Training Phase

The ripeness levels of strawberries for harvesting are categorized into three color types: white, pink, and red. Sample images were captured from strawberries that had been visually classified by human inspection. These images were then used to record color information in numerical format. The collected data was subsequently utilized to develop a classifier for distinguishing ripeness levels, as illustrated in Figure 2.

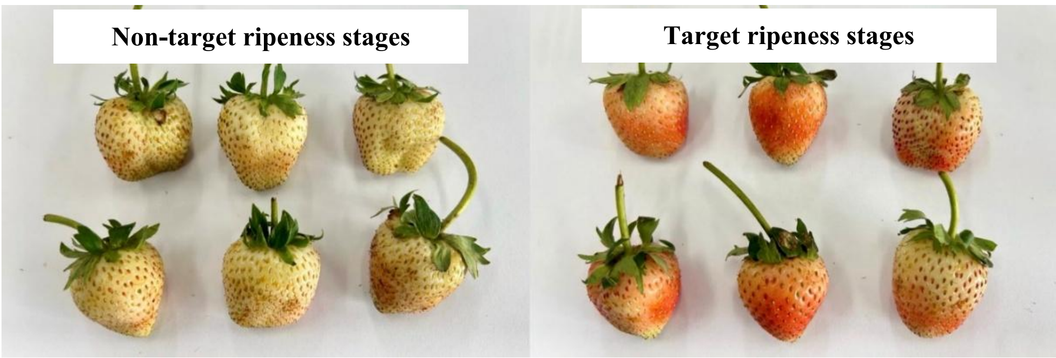

Figure 2 Strawberry samples for ripeness level classification

2.2.2) Color Classification Phase

In this step, the color values from the pixels of the strawberry photographs that need to be collected are compared with the sample color data recorded in the learning step. When the strawberries are classified to the desired level of ripeness (pink and red), the program will order the gripper to move to harvest the strawberries. If the strawberries are still white, the program will order the robot to move to inspect the strawberries in the next location.

2.3 Design of Strawberry Position Detection Program

The image processing position detection program is the management of images by computer by improving or changing the quality of the image to be better for analysis and use in various fields. The image processing position detection program consists of 3 important processes: gray processing, binarization processing, and edge detection. The image will have clear edges and can find the center of the strawberry and control the robot's grip to move to the desired harvesting position. The distance between the gripper and the strawberry on the planting track will be measured using an infrared distance sensor as shown in Figure 3 to control the movement in depth so that the gripper can move to harvest the strawberry correctly.

Figure 3 Infrared distance sensor

2.4 Prototype performance testing method

The performance testing of the strawberry harvesting robot in the greenhouse was performed using image processing techniques to detect the position of the strawberry fruit on the planting track with a width of 40 cm and a height of 100 cm, which is consistent with the strawberry harvesting robot testing method of Han, et al. [8].

The performance testing of the robot (Figure 4) used a rotational speed of 1100, 1200, and 1300 rpm, using 10 test positions, and testing each position 3 times to find the maximum working ability, the accuracy of measuring ripeness, and the accuracy of the strawberry harvesting position. The calculation method is based on the motor speed calculation from Equation 1 and the percentage of accuracy of classifying ripeness and harvesting position is calculated from Equation 2.

Figure 4 Prototype robot testing

The motor speed can be calculated from Equation 1.

$$RPM = \frac{a \times 60 \times fz}{360} \quad (1)$$

where

RPM = revolutions per minute

a = motor rotation angle per step = 1.8°

fz = pulse frequency (hertz)

The percentage of accuracy of ripeness and harvest position measurement can be calculated from Equation 2.

$$\text{Accuracy (\%)} = \frac{\text{Number of fruits harvested}}{\text{Total number of fruits}} \times 100 \quad (2)$$

2.5 Post-harvest damage test

Compare the damage caused by harvesting between robots and human labor by storing strawberries at room temperature and observing the physical changes of strawberries after harvesting every 6 h for a total period of 72 h.

2.6 Engineering Economic Analysis

This section presents an engineering economic analysis of using a prototype robotic strawberry harvester in a greenhouse as a replacement for manual labor. The analysis is based on the straight-line depreciation method, which is used to estimate the cost of equipment usage over time.

3. Results and discussion

3.1 Structural design results

The prototype of the strawberry picking robot in the greenhouse consists of
1. 3D linear moving robotic arm structure (Cartesian Robot) made of 30 × 30 mm aluminum profile, driven by 3 stepping motors
2. Electric gripper driven by 1 stepping motor
3. Control unit

The prototype of the strawberry picking robot in the greenhouse has dimensions of 150 x 200 x 140 cm (width x length x height) as shown in Figure 5 and the installation location of the infrared distance sensor and gripper as shown in Figure 6.

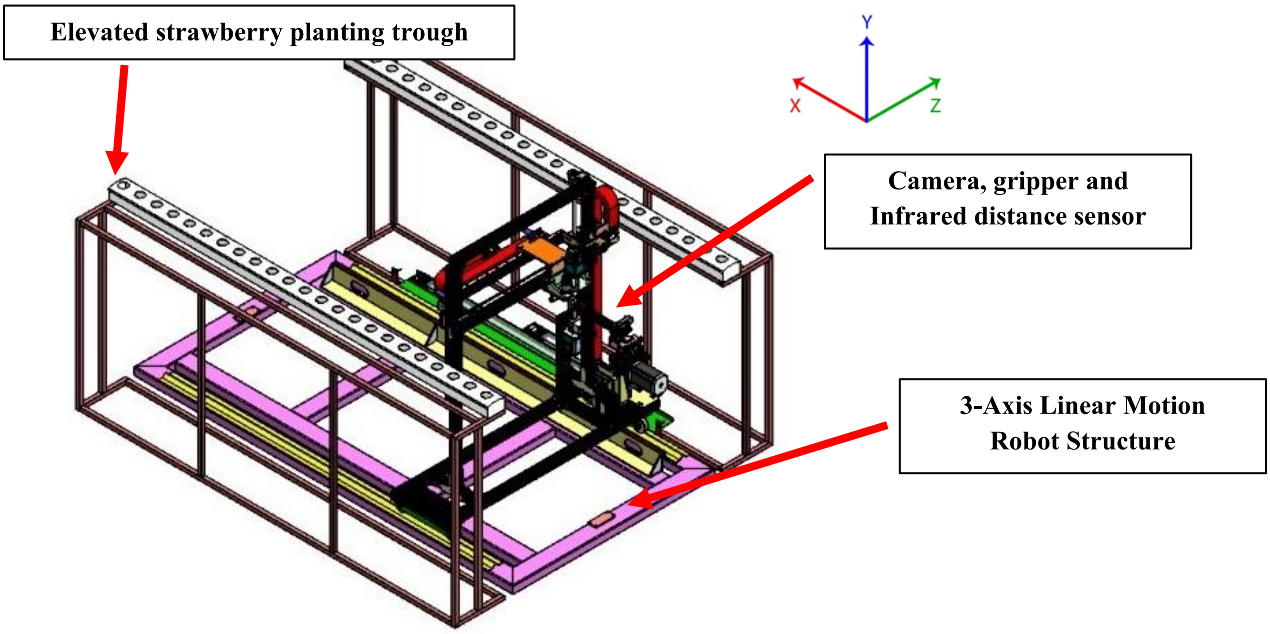

Figure 5 Prototype of a Strawberry Harvesting Robot

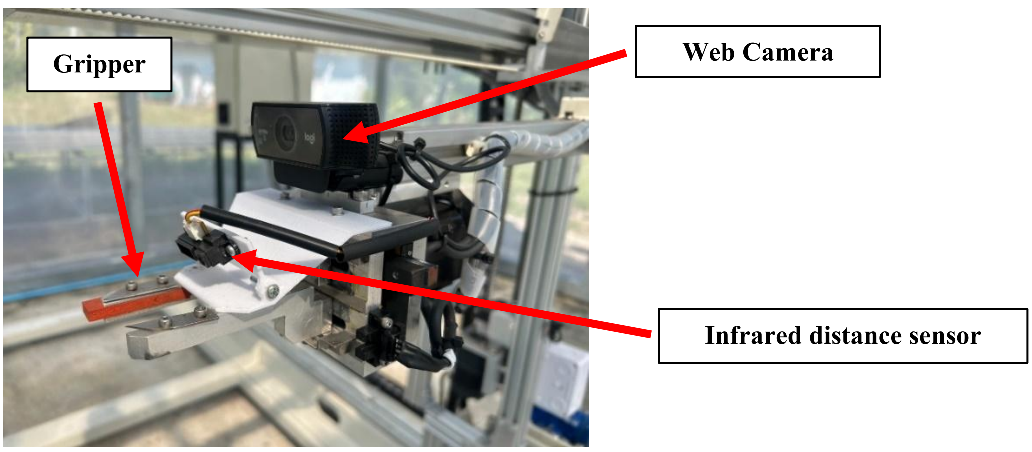

Figure 6 The position of the equipment on the prototype robot

3.2 Results of the design of the ripeness measurement program

The location detection starts with the image import (Vision Acquisition) taken from the Logitech C922 Pro Stream Web camera, taking pictures with a resolution of 1280 x 720 pixels (720p/30fps) with the Labview program to enter the image processing process with the Vision Assistant command to filter the image and cut out unwanted objects in the strawberry fruit, such as the stem, leaves, and green and white strawberry fruits, leaving only the objects that need to be detected, which are pink and red strawberries, to enter the location detection process for harvesting (Figure 7).

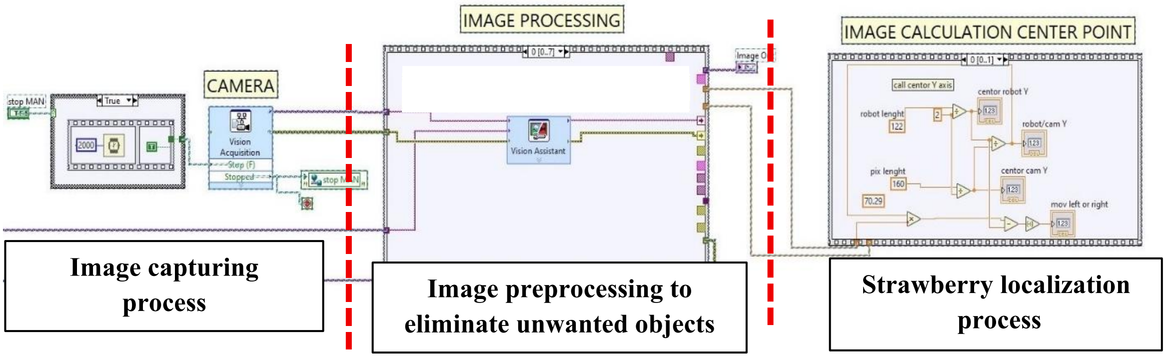

Figure 7 Strawberry position detection program

In the Image Processing process, Vision Assistant command will start to improve the image by adjusting the light and shadow with Brightness command and adjusting the background color to blue to make the red color stand out. In this step, the strawberry that is green and white will be cut out from the image as shown in Figure 8.

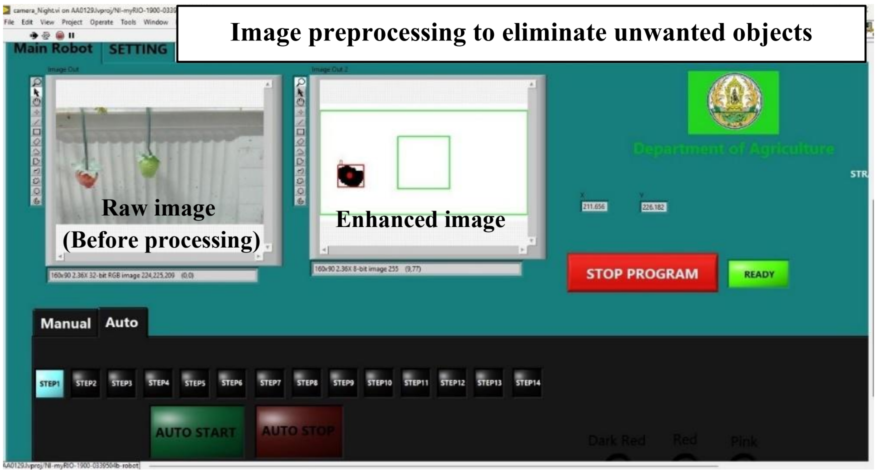

Figure 8 A display interface for strawberry color classification

3.3 Strawberry Position Detection Program Design Results

The Color Plane Extraction command is used to isolate pink and red strawberries from the background, resulting in a grayscale image. This image is then converted into a binary image through a binarization process, followed by edge detection to obtain a clearly defined boundary on the display screen (Figure 9). The detected edges are used to calculate the centroid of the strawberry, and the corresponding coordinates are utilized to control the movement of the robotic arm along the X and Y axes, allowing the gripper to precisely align with the center of the strawberry.

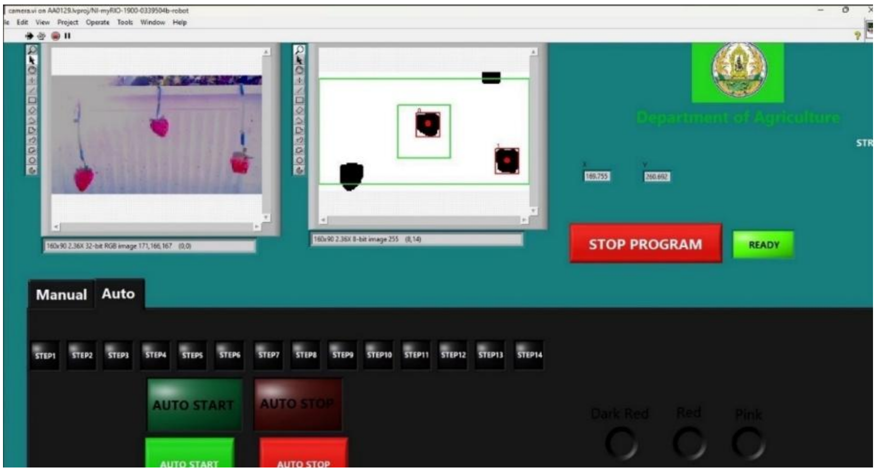

Figure 9 A display interface for strawberry position detection

After the gripper moves to the center position of the strawberry, an infrared distance sensor, mounted at the center and aligned along the same axis as the gripper, measures the distance between the gripper and the strawberry. This measurement is used to calculate the appropriate depth for the gripper's movement, ensuring it reaches the optimal position for harvesting. Once the strawberry reaches the defined harvesting distance, the gripper moves upward along the Y-axis by 5 cm from the fruit's center point to perform the harvesting operation by gripping and cutting the stem of the strawberry.

3.4 Performance Test Results

Table 1 shows the performance test results of the prototype strawberry picking robot in the greenhouse. The experiment involved harvesting strawberries at 10 positions on an elevated planting trough, with 3 repetitions per position (a total of 30 fruits). The motor speed was adjusted to 1100, 1200 and 1300 rpm, corresponding to linear speeds of 0.11, 0.12, and 0.13 m/s, respectively. As the motor speed increased, the average harvesting time per fruit decreased to 53.9, 52.7, and 50.8 s. The harvesting position accuracy was 100% at 1100 and 1300 rpm, but slightly decreased to 96.66% at 1200 rpm, likely due to strawberries being located outside the camera's field of view. Nevertheless, the system achieved 100% accuracy in ripeness classification. Among the tested speeds, 1300 rpm was found to be the most suitable for practical use, as it resulted in the shortest average harvesting time (50.8 s) while maintaining 100% positional accuracy, equivalent to that at the lowest speed. The standard deviation of 1.29 s indicates consistent performance with minimal variability. This is consistent with the field strawberry picking robot developed by Hayashi, et al. [9], which can detect strawberry stems at a rate of 60% and achieve a harvesting accuracy of 41.3%. Additionally, the robot developed by Qingchun, et al. [10] had a harvesting success rate of 86%, with each successful harvesting operation taking an average of 31.3 s.

Table1 Results of the functional testing of the prototype robot

Testing results					
Motor speed (rpm)	Linear speed (m/s)	Average Harvesting Time (seconds/fruit)	SD (s)	Harvesting position accuracy (%)	Accuracy of ripeness measurement (%)
1100	0.11	53.9	1.26	100	100
1200	0.12	52.7	1.84	96.66	100
1300	0.13	50.8	1.29	100	100

3.5 Results of post-harvest damage examination

This study compared the physical damage to strawberries harvested using a robotic system with a 25 cm drop height from the gripper to the receiving basket, which was lined with a foam pad for cushioning, against strawberries harvested manually by human labor. After harvesting, the strawberries from both methods were stored at room temperature, and physical changes on the external surface of the strawberries were observed every 6 h over a total experimental period of 72 h. The results showed no differences in the external appearance or surface deterioration of the strawberries between the two harvesting methods, as illustrated in Figure 10. Changes observed, such as softening of the fruit surface and discoloration, occurred at similar rates in both sample groups. These findings suggest that the robotic harvesting system, with a 25 cm drop height, does not cause greater damage to the strawberries than manual harvesting under room temperature storage conditions.

Immediately post-harvest

Manual harvesting Robotic harvesting

72 hours post-harvest

Manual harvesting Robotic harvesting

Figure 10 Physical changes in strawberries 72 hours post-harvest

3.6 Results of the Engineering Economic Analysis

Based on the engineering economic analysis of implementing a prototype robotic strawberry harvester in a greenhouse to replace manual labor, with the prototype cost set at 200,000 THB, and depreciation calculated using the Straight-Line Method, the annual operating cost of the robot is approximately 56,760 THB/y. Further analysis indicates that the break-even point is reached at 180.59 operating hours/y, and the payback period is approximately 9.6 months. These results demonstrate that the prototype robotic strawberry harvester is a cost-effective alternative to manual labor in greenhouse harvesting operations, particularly in continuous production systems or large-scale planting areas.

4. Conclusions

This study applied image processing techniques in conjunction with a prototype robot for harvesting strawberries in a greenhouse environment. The developed robot features a three-dimensional Cartesian structure with dimensions of 150 × 200 × 140 cm (width × length × height), driven by three stepper motors and controlled by a single webcam for capturing and analyzing images of the fruit. The system is capable of accurately identifying the ripeness levels of strawberries grown on cultivation rails measuring 40 cm in width and 100 cm in height, and it can precisely navigate the robotic arm to the target harvesting positions. Experimental results showed that the robot achieved 100% accuracy in ripeness classification and 100% positional accuracy at a motor speed of 1300 rpm. The robot required an average of 50.8 s/fruit, translating to approximately 70 strawberries/h, or roughly 8 kg/day. However, a major limitation of the current prototype is that it can only harvest strawberries located on the sides of the cultivation rail. It cannot access fruits located above or deep inside the plant, which highlights the need for future development of additional mechanical components to expand its harvesting range. Although the robot's harvesting capacity is still about 10 times slower than that of manual labor (which typically achieves 80 –100 kg/person/day), the study demonstrates that image processing technology can be effectively used to classify strawberry ripeness and precisely control robotic movement without causing physical damage to the fruit. To improve operational efficiency and bring it closer to manual harvesting performance, further enhancements should focus on accelerating image processing algorithms and developing high-speed, precise motion mechanisms to enable faster and more efficient harvesting.

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