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System Integration of an Automatic Citrus unshiu Harvesting Robot and a Method for Their Fruits Recognition

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Abstract— **In recent years, the number of farm households in Japan has been decreasing due to the aging of farmers and the shift away of young labors, thus automation and labor saving are required as a solution. In this study, we propose an automatic harvesting robot for the purpose of automating harvesting, one of the tasks in Citrus unshiu cultivation. Previously, we proposed an end-effector consisting of a suction pad and scissors for automatic harvesting, one of the tasks in Citrus unshiu cultivation. In this paper, we report a system integration of a crawler-type mobile manipulator that mount an arm robot with the EE and automatically travel on slopes and uneven terrain in the field, also a method for recognizing Citrus unshiu using the Watershed algorithm that can separate and recognize the adjacent area of the target. This system is expected to enable night harvesting, which is expected to contribute to the sustainable development of agriculture.**

I. INTRODUCTION

In recent years, Japan has been facing a serious shortage of agricultural workers due to the declining birthrate, aging population, and the younger generation's disengagement from farming[1]. As further labor shortages are anticipated in the future, there is an urgent need for automation and labor-saving measures in agricultural operations. The authors' research group is developing an automated Citrus unshiu harvesting robot by mounting a collaborative robot (Universal Robot, UR5e) on a crawler-type vehicle (Sanko Seiki Co., Ltd., Rakuraku-go).

In the United States, specifically in Florida, orange harvesting is conducted using a large tractor-towed harvesting machine known as a "canopy shaker[2]." The canopy shaker is equipped with vibrating claws that periodically impact the trees, causing the fruit to fall, enabling efficient orange harvesting. Most of the oranges targeted by this method are for processing, so minor damage is acceptable. However, the Citrus unshiu targeted in this study are intended for consumption by consumers, so any damage that could reduce their market value or cause spoilage is unacceptable, making this harvesting method unsuitable.

Similar to this study, many studies have been reported on automatic harvesting robots for fruits and vegetables using mobile robots and collaborative robots. In the apple harvesting robot developed by Onishi et al[3]., the robot grips apples with a hand composed of three claws and mimics manual harvesting methods by rotating the shaft multiple times. Additionally, to facilitate robotic operations, the study targets apple trees pruned into a V-shape, conducting reserch in an environment adapted for robotic automation.

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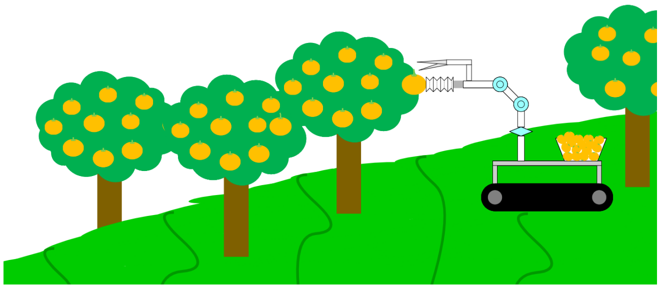


Fig. 1: Grand Design of the Study

In Saito et al[4].'s suspended pepper harvesting robot, the system grips the stem with a roller, cuts it with scissors, and harvests it. The robot's movement utilizes a system that moves along wires installed inside a greenhouse, enabling harvesting unaffected by ground conditions. Additionally, in the tomato harvesting robot developed by Yaguchi et al[5]., comparative experiments were conducted between picking-type hands and scissor-type hands, clearly identifying the advantages and challenges of each, and concluding that selecting the appropriate EE(end-effector) based on the situation is desirable.

Based on the above prior research, it was considered that designing EEs capable of mimicking human harvesting motions using robots would be useful. Furthermore, many prior studies assume an environment prepared to facilitate robot operation. On the other hand, in Citrus unshiu cultivation, a V-shaped cultivation system has been developed, and its usefulness has been confirmed in mechanical adaptability tests using an autonomous mobile platform. However, its adoption in fields remains limited, and the current mainstream cultivation method is the traditional open-canopy natural shape. Furthermore, Citrus unshiu have a relatively tall tree height of 2 – 3 m and dense branches and leaves, making robotic operations challenging. Furthermore, since they are generally cultivated on sloped terrain, conventional carts cannot navigate such environments.

Therefore, this study aims to achieve competitive 24 hours full automation of Citrus unshiu harvesting by constructing an autonomous system capable of detecting and picking target fruits even in environments with dense branches and leaves, and by implementing a manipulator armed mobile crawler cart capable of autonomous navigation on uneven

Fig. 2: Proposed Citrus unshiu Harvest Robot System

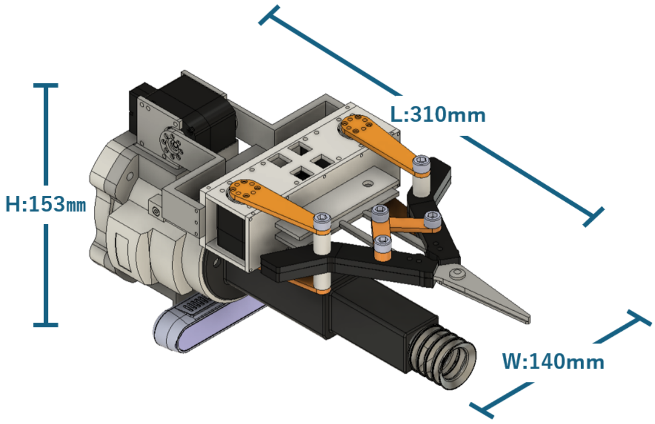


Fig. 3: Developed End Effecter[7][8]

terrain and slopes. Fig.1 illustrates the grand design of the study. In this paper, we report a system integration of the mobile manipulator and a method for recognizing Citrus unshiu.

II. PROPOSED METHOD

We propose a robot system that automatically harvests Citrus unshiu detected by a camera, equipped with a collaborative robot mounted on a crawler vehicle and an EE consisting of a small suction pad and scissors(Fig.2). In this chapter, we describe the structure and functions of the EE for automatic harvesting that we have developed, followed by an explanation of the robot system configuration. We also discuss the method for detecting fruits using a RGB-D camera.

A. Harvesting End-effector

First, we will briefly describe the structure and functions of the EE for automatic harvesting that we developed previously[7][8]. Traditionally, when harvesting Citrus unshiu, workers hold the fruit in their hands and cut it with scissors, leaving a few centimeters of the stem attached. They then cut the remaining stem again so that it is parallel to the fruit. This process is performed to prevent the cut surface from damaging other fruits when they come into contact after harvesting, and is referred to as "double cutting." However, reproducing this double cutting process with a single-arm robot is challenging.

Therefore, in this study, we propose an EE that combines an adhesive pad and scissors mechanism to enable harvesting with a single cut. One advantage of the adhesive pad is that it is less likely to damage surrounding fruits or branches and leaves. Additionally, by adjusting the pad diameter according to the size of the harvest target, flexible adaptation is possible.

As a prior study on harvesting using suction pads, Saiki et al[6]. developed the "Trun corn pad," a suction-type harvesting hand designed for spherical crops. This suction hand was developed to enable suction with minimal pressure on crops that are difficult to generate counterforce, and it has been shown to be effective for suctioning crops with various shapes, including those with irregularities. However, since the pad diameter is relatively large at 50 mm in outer diameter and wraps around the target object, it is unsuitable for adhering to fruits with dense branches and leaves, such as Citrus unshiu.

To address these limitations, we developed a harvesting EE, as shown in Fig.3. The dimensions of the EE—height (H), width (W), and length (L)—are also indicated in the figure. The proposed mechanism consists of a suction unit and a cutting unit. In this study, a 30mm bellows-type pad suitable for securely adhering to spherical objects was adopted. The vacuum pressure required for appropriate adhesion using the 30 mm diameter pad was derived from Eq.1[9], and it has been experimentally confirmed that the fruit can be harvested without damage.

After suction is completed, the fruit is detached from the branch by the cutting unit, as described below. The cutting unit consists of a pair of harvesting scissors, which is commonly used for Citrus unshiu harvesting. They are driven by three motors. They are opened and closed by giving opposite rotational commands to the two side motors. Another motor is also installed at the base of the cutting mechanism, enabling pitch motion to adjust the cutting angle with respect to the fruit.

$$W = P \times S \times 0.1 \times \frac{1}{t} \tag{1}$$

W:Lifting force[N], P:Vaccum Pressure[KPa],
S:Pad area[cm^2], t:Safety Factor

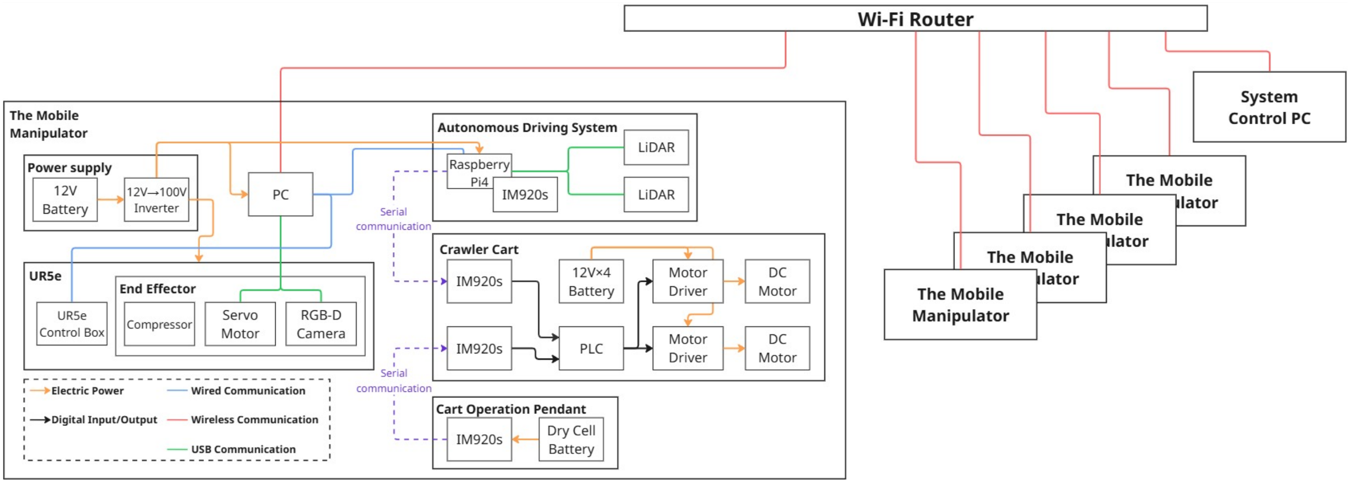


Fig. 4: Robot System

B. Robot System

In this study, a crawler vehicle (Sanko Seiki Co., Ltd, RakURaku-go) is equipped with a collaborative robot (Universal Robots, UR5e). This enables operation even in Citrus unshiu orchards that include slopes and uneven terrain. An RGB-D camera (Intel, Realsense D415) is attached to the robot's hand as a visual sensor. The crawler vehicle is equipped with two 2D LiDAR sensors (YDLIDAR, X4-PRO) to explore the surrounding area. The EE described in the previous section is attached to the robot's EE to perform Citrus unshiu harvesting.

To enable suction with the EE, a 12V-driven compressor is installed to supply compressed air. Being vehicle-mounted, the system automatically replenishes pressure when it drops, ensuring stable suction. Python is used for system development, and the control of the EE is also implemented in the Python file that controls the UR robot. The UR RTDE library is used for motion control of the UR5e robot, enabling remote control. By enabling operation of the cart from both the PC and the controller,the system allows switching between autonomous driving and manual operation, enabling flexible response on-site.

In this robot system, two types of lead-acid batteries are installed—one for the mobile platform and one for the UR robot. For the mobile platform, a high-output sealed lead-acid battery is used to ensure stable driving performance and to provide the instantaneous current required when traveling on slopes or uneven terrain. For the UR robot, a semi-deep-cycle lead-acid battery is employed in combination with a 700 W high-efficiency sine wave inverter, providing sufficient output while suppressing unnecessary standby power consumption associated with large-capacity inverters. This not only improves the reliability of the platform's return to the base but also extends the operating time per session due to the increased battery capacity, thereby reducing the effort needed for battery replacement and charging.

The network configuration connects the robot-mounted PC to the base station router via wireless communication, using the PC as a router, while the UR robot is linked via a bridged Ethernet cable. This eliminates the need to mount a separate router on each robot, reducing weight and power consumption, simplifying management, and improving both the reliability and maintainability of the system. Furthermore, when implementing swarm control in the future, identical robot systems can be duplicated, enabling simultaneous operation of multiple units, thereby improving work efficiency. Fig.4 shows the robot system configuration, Fig.5 depicts the robot's motion trajectory, and Fig.6 illustrating the overall process as a flowchart.

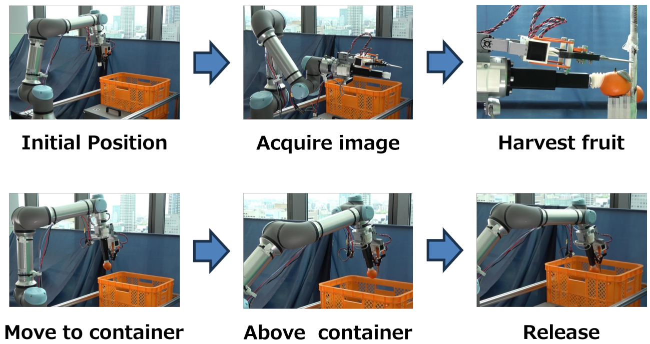


Fig. 5: Robot Motion Trajectory

C. Fruits Detection

In this study, we use RGB images and depth images obtained by an RGB-D camera attached to the robot's hand to recognize Citrus unshiu. While object recognition using deep learning such as YOLO is mainstream in many harvesting robots, we adopted a recognition method that combines conventional image processing. To recognize fruits with dense branches and leaves using deep learning, a large amount of training data from various situations is required, which necessitates significant time for annotation work. However, conventional image processing has the advantage of being able to flexibly adapt to on-site conditions by adjusting parameters without requiring pre-training or labeled

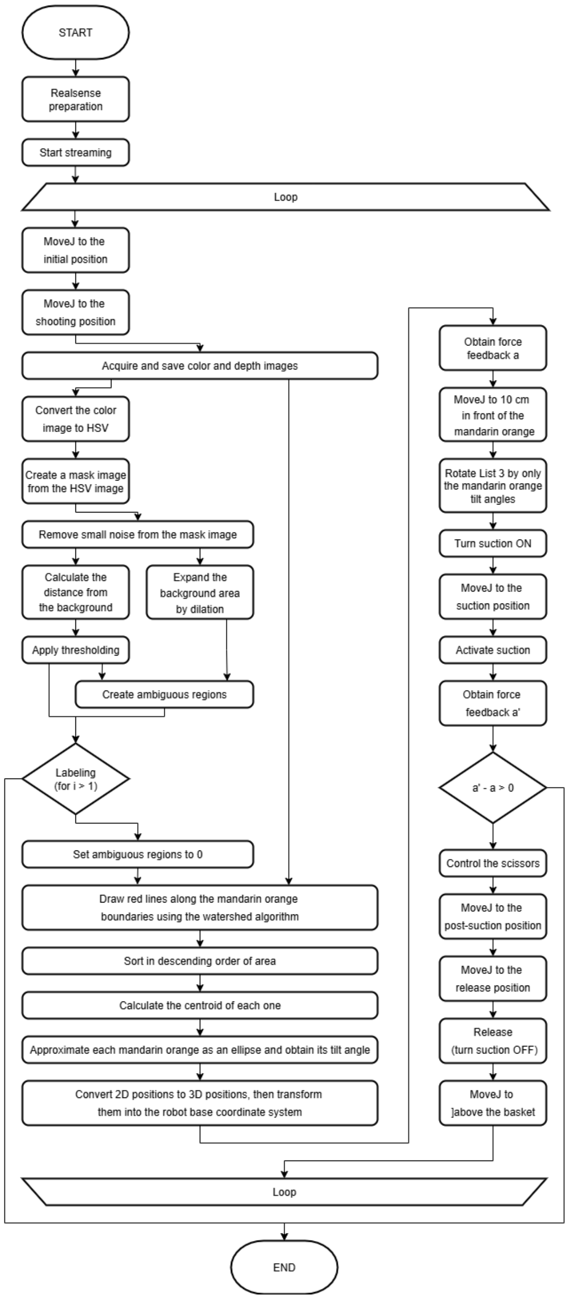


Fig. 6: Robot System Flowchart

data.Furthermore, a dataset of Citrus unshiu under various conditions does not currently exist.

In this study, we created a mask image where the orange-colored areas in the initially acquired RGB images were set to white in the HSV color space. Furthermore, Otsu's binarization was applied to the grayscale images to create binary images with dark areas as white. By performing a logical AND operation on these two images, we extracted potential fruits regions based on both color and brightness to recognize them. However, as shown in the Fig.7 when fruits were adjacent, multiple of their regions in binary image and were recognized as a single fruits.

Therefore, in this study, we decided to use the Watershed

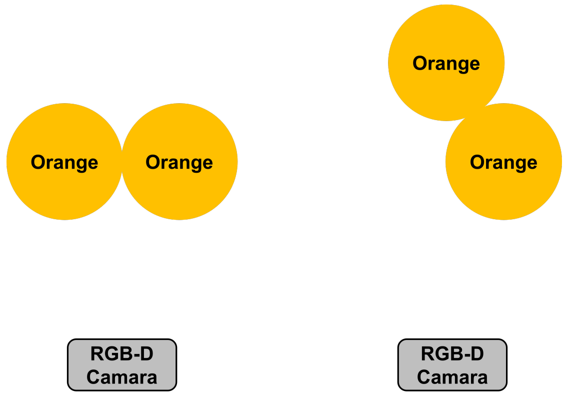


Fig. 7: Arrangement of fruits

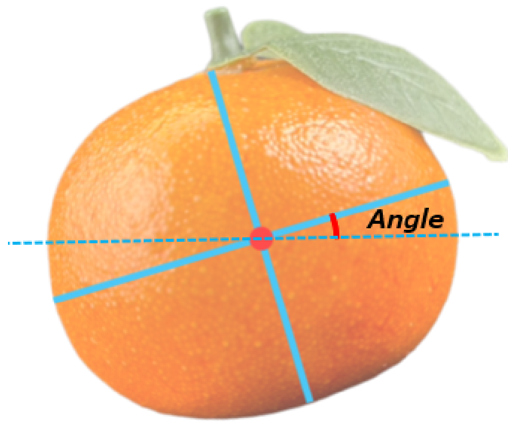


Fig. 8: Tilt of fruits

algorithm to divide the areas. The Watershed algorithm is a method used to extract the boundaries of objects, enabling the recognition of overlapping oranges as individual objects. For the labeled image obtained by the Watershed algorithm, we created a binary image with the target label area as white (255) and the rest as black (0). The area and center of gravity of each region are calculated for this image. Regions with an area of 0 are excluded, and the regions are sorted in order of area, labeled, and harvested in order.

In addition, the contours of the target regions are extracted, and if there are five or more contour points, an elliptical approximation is performed. The OpenCV fitEllipse function is used for the approximation process to obtain the center point, major axis, minor axis, and slope of the ellipse. The tilt of the fruits is derived from the angle between the horizontal line and the major axis, as shown in the Fig8. This tilt is applied to the UR5e robot's wrist rotation axis (List 3), and by rotating it by the angle, it enables horizontal cutting relative to the stem during Citrus unshiu harvesting. An example of the harvesting posture is shown in the Fig.9.

III. Harvest Experiment

A. Experimantal Procedure

This experiment was conducted in a simulated indoor environment for the purpose of verifying the operation of the constructed robot system and testing the performance of the recognition method. Plastic simulated oranges (mass: 12 g, dimensions: 6.8 × 7.5 cm) were used in the experiment, and multiple oranges were randomly placed within the range of motion of the robot arm, taking into consideration the orientation and tilt of the fruit.

Previous studies have shown that when suction is successful, cutting with scissors is also successful. Therefore, in this experiment, we evaluated the actions of recognizing the fruits, suctioning them, and storing them in a basket. The arrangement of the fruits is shown in Fig.7, with the left side showing them arranged side by side without gaps and the right side showing them arranged so that they overlap when viewed from the camera.

Since the experiment was conducted indoors, lighting was used to maintain consistent lighting conditions. The experiment was conducted 10 times for each case. In Experiment II, where the oranges were stacked, the lighting conditions were changed, so the experiment was conducted 5 times each for the left, right, and center positions. In Experiment I, the time required for the entire sequence of actions from start to finish was measured.

Robot arm speed and acceleration settings
(1) Normal operation: Speed was set considering safety and efficiency.
(2) Movement toward the suction target position within 10 cm: Set to a slower speed to avoid contact with other fruits.
(3) Storage movement into the basket: Set to the highest possible speed to minimize suction time.

Under these conditions, experiments were conducted in two cases.
(A) Multiple fruits arranged side by side without overlapping.
(B) Multiple fruits in an overlapping state.

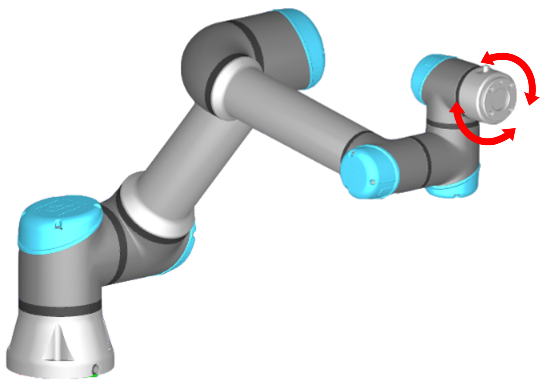


Fig. 9: Examples of Harvesting Postures

TABLE I: Experimental results for one fruit

	Recognition	Adsorption
Without leaves	9/10	8/9
With leaves	6/10	3/6

TABLE II: Experimental results for two fruits

Position	Lighting Position	Recognition	Adsorption
Parallel	Right	8/10	8/8
Overlap	Left	0/5	-
Overlap	Center	2/5	2/2
Overlap	Right	2/5	2/2

IV. Harvest Results

A. *Experiment* Ⅰ：*In the case of one fruit*

One fruits was placed, and experiments were conducted comparing cases where there were leaves on the camera side and cases where there were no leaves.

The experimental results are shown in Table I. In cases where there were no leaves, a 90% recognition success rate was achieved, but in cases where there were leaves in front, there were cases where recognition failed because the outline extraction did not work properly due to the absence of part of the orange color.

Additionally, the total time required for the sequence of actions from detecting the fruit to storing it was approximately 40 seconds. However, since this experiment did not include cutting with scissors, the actual harvesting process would require additional time for the cutting operation in addition to the current time.

B. *Experiment* Ⅱ：*In the case of two fruits*

In Experiment I, it was found that the recognition success rate varied depending on the presence or absence of leaves. In this experiment, the focus was on recognizing adjacent fruits. Therefore, in subsequent experiments, the experiments were conducted on the assumption that the leaves of the fruits were not on the camera side.

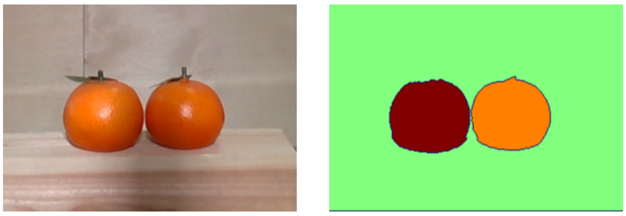
When arranged side by side, recognition was successful 80% of the time(Fig.10). In cases where the fruits overlapped, the recognition success rate dropped significantly.

When the lighting was on the right side or in the center, the shadow of the fruit in the foreground hit the one in the background, allowing the boundary to be recognized. However, when the lighting was on the left side, it was found that in all cases, the fruits were mistakenly recognized as a single fruit.(Fig.11).The experimental results are shown in Table II.

V. Discussion

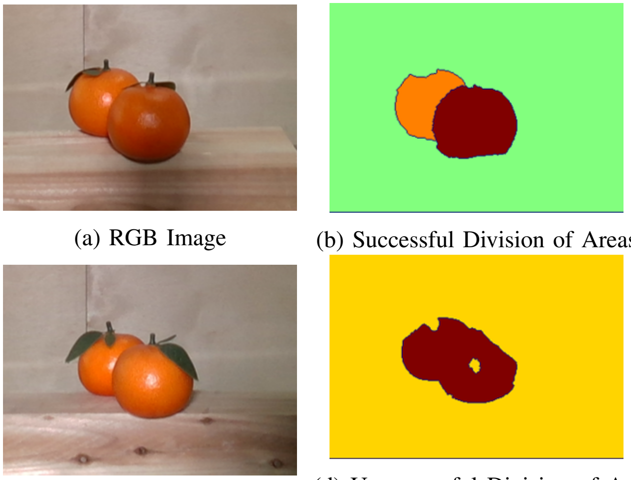
The experimental results confirmed the usefulness of the Citrus unshiu recognition method proposed in this paper. Depending on the lighting conditions, the method failed to separate the boundaries when some parts overlapped.

We believe that recognition is possible by creating a mask image from the depth image and the binary image after applying the Watershed algorithm, and then extracting only the fruits in the foreground. Furthermore, by using Gaussian



(a) RGB Image (b) Successful Division of Areas

Fig. 10: Experimental Results with fruits Placed Side by Side



(a) RGB Image (b) Successful Division of Areas

(c) RGB Image (d) Unsuccessful Division of Areas

Fig. 11: Experimental Results with Some of the fruits Overlapping Each Other

splatting, a neural rendering technique, to create a 3D model from images taken from multiple viewpoints, we believe it is possible to identify the shape and position of fruits even when they are hidden by branches or leaves.

In this experiment, we used replicas of oranges with the same shape, but in actual fruits, there are variations in size, and if the fruit in the background is larger than the one in the foreground, there is a possibility that the one in the background will be harvested first. Therefore, we assigned weights to the "pixel count" and "depth" of each fruits, calculated a normalized score using Eq. 2, and determined the harvesting order based on the score to encourage harvesting from the front, aiming for efficient and reliable harvesting. The weight for pixel count is denoted as X, and the weight for depth is denoted as Y.

$$Score_i = X \times norm\_size_i - Y \times norm\_depth_i \tag{2}$$

$$norm\_size_i = \frac{size_i - min(size)}{max(size) - min(size)}$$

$$norm\_depth_i = \frac{depth_i - min(depth)}{max(depth) - min(depth)}$$

VI. CONCLUSIONS

In this paper, we proposed a mobile manipulator with a 6-axis arm robot and a method for recognizing fruits of Citrus unshiu for automatic harvesting and the arm robot is equipped with an EE which was previously proposed. The recognition method aim to accurately recognize between adjacent fruits, which was previously impossible.

To confirm the usefulness of the proposed recognition method, we conducted an experiment in which multiple fruits were placed, recognized, sucked up, and stored in a basket. As a result, recognition was successful in 80% of cases, and all recognized fruits were successfully adsorbed and stored in the basket.

However, when some fruits were overlapping from the camera's perspective, the experimental success rate varied significantly depending on lighting conditions. Recognizing fruits that are overlapping or partially obscured by branches and leaves remains a challenge for the future. We will work to improve recognition accuracy by employing not only OpenCV but also techniques such as Gaussian splatting, a type of neural rendering method.

Going forward, we plan to conduct harvesting experiments in actual Citrus unshiu orchards. For experiments in actual orchards, improvements to the EE and enhancements to the recognition system's accuracy will be necessary, also autonomous mobility.

ACKNOWLEDGMENT

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