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System Development of Tomato Harvesting Robot Based on Modular Design

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***Abstract*— In this study, we propose a system for designing tomato harvesting robot based on a modular design and describe examples of its implementation. In the agricultural industry, the aging and scarcity workers are becoming serious problems. Smart agriculture, aimed at reducing the need for manual harvesting and management by human workers, by introducing robotic technologies in plant factories, has been attracting much attention in recent years. However, plant factories very diverse in different location of plant factory and different business scales. It is therefore difficult to develop a single tomato harvesting robot optimized for all types of tomato plant factories. We explain hardware and software configurations that adopt modular design, for our proposed robots. Three kinds of tomato harvesting robots based on the proposed development concept are described. Harvesting experiments are then reported. The time to harvest one tomato from the cluster was 29 seconds with a 3-axis manipulator and 43 seconds with a 6-axis manipulator. We then discuss harvesting time and ways to shorten it. Based on the concept of modular design, even if hardware or sensors are changed, it is not necessary to change the entire system, and changing the module can customize the operation according to a specific purpose.**

I. INTRODUCTION

If the continuation of agriculture becomes difficult, farmers are forced to retire. However, there is an attempt to construct an agricultural plant factory, which is an environmental preservation type production system, to provide a stable supply of agricultural products, by utilizing the land that has been abandoned by farmers.

Although large-scale agriculture can provide a stable agricultural products supply, it requires workers for management and harvesting of them. In the case of tomatoes that have high needs, the work ratio of harvesting and management is 60% [1].

We aim to introduce a tomato harvesting robot to a tomato plant factory. Examples of tomato harvesting robots in previous studies are shown in Table I. Kondo et al. developed an End-effector to harvest a cluster of four to six medium-sized tomatoes, which had a harvest success rate of 50% [2]. Yaguchi et al. performed harvesting experiments in a tomato robot competition and a real farm [3]. In terms of harvesting time, their robot took 85 seconds per tomato in the tomato robot competition, and 69 seconds per tomato on the real farm. By improving the harvesting motion for the real farm, the harvesting time fell to 23 seconds. Yoshida et al. proposed a method for recognizing the peduncle of cherry tomatoes [4]. A harvesting experiment was performed on a real farm, and it was reported that the robot succeeded in cutting the tomato peduncles. Ling et al. developed a tomato harvesting robot using a dual-arm manipulator with 3-DOF [5]. In a real farm harvesting experiment, the harvesting time for one tomato was 30 seconds.

A typical tomato harvesting robot mainly consists of four hardware elements: a mobile vehicle, manipulator, End-effector, and a vision sensor. However, the types of hardware differ depending on the target crop's variety and cultivation environment. For example, Yaguchi et al. and Ling et al. developed tomato harvesting robots that harvested single tomatoes at a time, whereas Kondo et al. and Yoshida et al. developed tomato harvesting robots that harvested entire tomato clusters [2-5]. The mobile vehicle also differs depending on the cultivation environment, and there are wheel types and rail types that can move on rails at a plant factory. Regarding the manipulator in the previous studies, there are 4-DOF horizontal articulated types and 6-DOF vertical articulated types, which differ depending on the harvesting motion and operation method in the plant factory.

We worked on the development of a system adopting a modular design. The System, which can cope with diverse plant factories, is proposed by modularizing the elemental technologies that constitute a tomato harvesting robot, such as the mobile vehicle and the manipulator. As shown in Fig.1, the system in this study refers to the whole configuration by modules, which are elemental technologies required for robotic development. As an example of implementation of the proposed system, three types of tomato harvesting robots that targeted medium-sized tomatoes are described. We report the results of the harvesting experiments using different manipulators, and discuss the harvesting times.

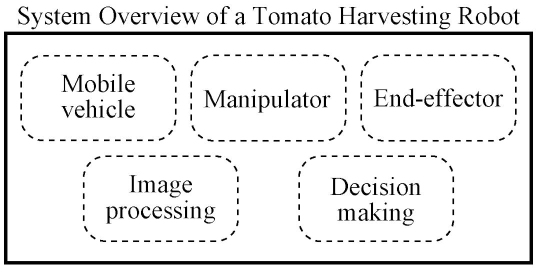


Fig. 1. Overview of the system of the tomato harvesting robot: Modules are surrounded by a dotted line. This system consists of five modules: Mobile vehicle, Manipulator, End-effector, Image processing, and Decision making.

TABLE I. Examples of tomato harvesting robots in previous studies. In this table, "Type of tomatoes," "Harvesting time [s]," "DOF of manipulator," and "Type of mobile vehicle" of each robot are described. Regarding the "Type of mobile vehicle," the rail type is a mobile vehicle that can move on rails at a plant factory.

Authors	Type of tomatoes	Harvesting time [s]	DOF of manipulator	Type of mobile vehicle
N. Kondo et al. [2]	Cluster of medium-sized tomatoes	15	4-DOF (Horizontal articulated robot)	-
H. Yaguchi et al. [3]	Medium-sized tomatoes	85 (Competition) 69 (Real farm) 23 (Improved)	6-DOF (Vertical articulated robot)	Wheel typed
T. Yoshida et al. [4]	Cluster of cherry tomatoes	-	6-DOF (Vertical articulated robot)	Rail type
X. Ling et al. [5]	Medium-sized tomatoes	30	2 mirrored 3-DOF (Horizontal articulated robot)	Rail type

II. DEVELOPMENT CONCEPT

A. Modular design

Modular design is a concept recognized as useful in robotics that requires multiple elemental technologies [6]. It is interdependent within modules, and independent between modules. In Fig. 1, modules, requiring an actuator and a sensor and so on – for example, a manipulator and a mobile vehicle – includes not only hardware, but also software. The system for the tomato harvesting robot consists of five modules, "Mobile vehicle," "Manipulator," "End-effector," "Image processing (including vision sensor)," and "Decision making," as shown in Fig. 1. Since modules are independent, even if a module is recombined due to a change in hardware elements, it is not affected by other modules. Therefore, we think that the tomato harvesting robot, developed based on the concept of modular design, can cope with diverse plant factories.

B. Hardware configuration

Hardware configuration of the tomato harvesting robot in this study is shown in Fig. 2. The tomato harvesting robot consists of four hardware elements: "Mobile vehicle" for moving around in the plant factory, "End-effector" for harvesting the tomatoes, "Manipulator" for approaching the End-effector to the target tomato, and "Vision sensor" for the detection of tomatoes. The micro computer units (MCUs) incorporated in them are connected to a "Main controller." The main controller controls each element and decide the robot movement.

We consider a supplementary artificial light type plant factory as an example of the application of the tomato harvesting robot. In the supplementary artificial light type plant factory, temperature and humidity are controlled to harvest tomatoes for a long period, and equipment for efficient work is introduced. One example of such equipment is a rail installed in the work area. The workers ride on the cart and carry out harvesting, removing leaves and extra tomatoes. They can work smoothly, and the work burden is

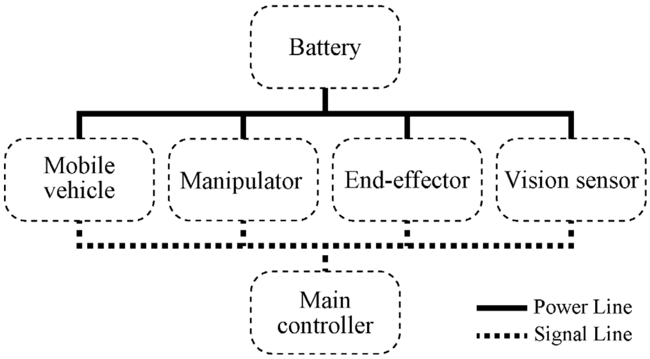


Fig. 2. Hardware configuration of the tomato harvesting robot. The robot consists of four hardware elements; Mobile vehicle, Manipulator, End-effector, Vision sensor. These elements are controlled by the Main controller.

reduced. In addition, the height of grown tomatoes is adjusted so that workers can harvest while sitting on the cart. Furthermore, the leaves are removed to control the growing state, and the expanded leaves do not disturb the harvesting.

On the other hand, there is a supplementary light plant factory which does not use the above-mentioned equipment. The facility scale of the plant factory differs depending on the location of plant factory and the scale of the business. In locations where sunlight is strong, leaves are not removed and may be intentionally left to protect tomatoes from sunlight. There are cases where simple rails are installed using parts that can be purchased at home centers, etc., so that they can be introduced to general farmers.

We develop tomato harvesting robots with different hardware elements, considering cases where rails are installed and not installed at different plant factories, and cases where removing of leaves is done and not done.

C. Software configuration

When a robot is developed by combining multiple elemental technologies – for example, control of a manipulator, image processing, self-localization etc. – in general, a centrally managed system performs all processing. However, depending on the robot, a lot of data needs to be processed at high speeds and continuously, and the one processer may not be able to keep up, which may cause operational delay or a full system stop. In addition, it is very time-consuming and labor-intensive to rearrange the entire system with changes in hardware elements and sensors.

On the other hand, in a distributed system, software is divided into modules. Various modularized processing can be combined according to the purpose. The development speed also can be improved and the cost can be reduced. Therefore, middleware such as the Robot Operating System (ROS) has used for robotic applications [7, 8]. We used ROS and MATLAB/Simulink software to implement the system of our tomato harvesting robot based on the concept of modular design.

The hardware configuration of this robot is mobile vehicle, Manipulator, End-effector, and vision sensor as described above. In order to cope with diverse plant factories, software needs to be modularized for each hardware. In this study, one module consists of hardware, MCU embedded in it, and software. Software for Decision making is also treated as one module. In implementing each software in the main controller, it is necessary to consider the five models: “Mobile vehicle model,” “Manipulator mode,” “End-effector model,” “Image processing model,” and “Decision making model.” The software configuration of this robot is shown in Fig. 3. These models are implemented by Simulink and processed in parallel. The ROS Network is used to share data between each model.

(1) Decision making model

In the Decision making model, the behavior of the tomato harvesting robot is decided. ROS topics in the ROS Network are also logged for debug. The robot behavior is implemented by a toolbox ”Stateflow” for designing a state transition control method.

In “Stateflow of Decision making,” in Fig. 3, the robot behavior is decided based on ROS topics published from each model. This model publishes a ROS topic that represents the state of the robot. The robot state plays the role of a trigger to control each module.

(2) Mobile vehicle model, Manipulator model and End-effector model

The Mobile vehicle model, Manipulator model, and End-effector model send and receive signals with the MCU embedded in each module in the Interface layer. Each module is controlled based on ROS topics and the signals from the MCU in the Processing layer.

The Mobile vehicle model turns the mobile vehicle on or off, controlling the moving direction and calculating the moving distance. The state of the mobile vehicle (moving or stopped), and moving distance, are published to the ROS Network. The Manipulator model controls the manipulator. The state of the manipulator (driving or stopped) is also published to the ROS Network. The End-effector model controls the End-effector. The state of the End-effector (suctioning, cutting or holding) is published to the ROS Network.

(3) Image Processing model

The vision sensor is defined, and images are acquired in the Interface layer. Detection of tomatoes and calculation of the coordinates of target tomatoes are carried out in the Processing layer. A flag as to whether tomato has been detected and its target coordinates are published to the ROS Network.

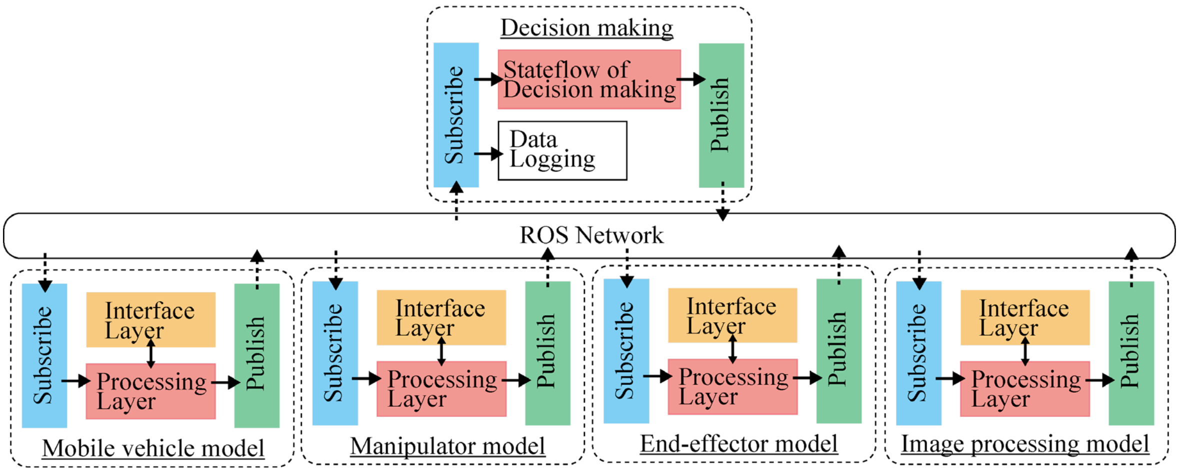


Fig. 3. Software configuration of the tomato harvesting robot. The robot consists of five software models; Decision making model, Mobile vehicle model, Manipulator model, End-effector model, and Image processing model. Robot Operating System (ROS) topics are shared through the ROS Network.

III. THREE TYPE OF TOMATO HARVESTING ROBOTS

The appearances of three types of robots are shown in Fig. 4. The three parts, Fig. 4 (a), (b), and (c), are respectively "Rail movement type equipped with 6-axis manipulator," "Rail movement type equipped with 3-axis manipulator," and "Omnidirectional movement type equipped with 6-axis manipulator." These robots were developed based on the concept described in II. For the vision sensor, a Microsoft Kinect (Kinect), which can acquire RGB and Depth images, was used.

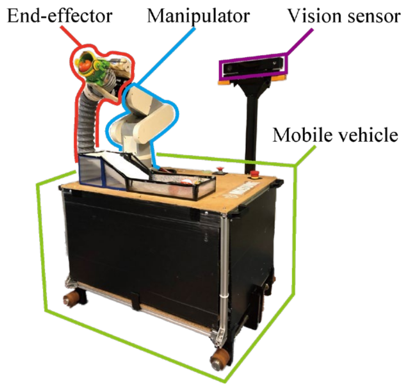
The rail movement types shown in Fig. 4 (a) and (b) were developed by considering operation in a plant factory where rails are installed, and the omnidirectional movement type show in Fig. 4 (c) was developed by considering operation in a plant factory with no rails.

The 6-axis manipulator of Fig. 4 (a) and (c) can approach a target tomato from multiple directions in an environment where removing leaves is not carried out. Although the 3-axis manipulators of Fig. 4 (b) only approach a target tomato from one direction, it is easy to control, and expected that to have a faster harvesting time than the 6-axis manipulator.

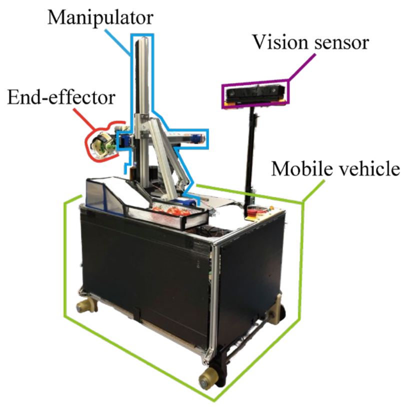
The power line of each type is shown in Fig. 5. One 24 V battery and three 12 V batteries were used. The 24 V battery was used for the mobile vehicle and manipulator, while two of the 12 V batteries were used for End-effector, and the last 12 V battery was used for the Kinect. Regarding the End-effector, it has a DC motor for cutting the tomato peduncle and an electric ducted fan (EDF) for suctioning a tomato, as will be described later. The two 12 V batteries were used for the DC motor and EDF, respectively. The 12 V battery for the DC motor was also used for a circuit that isolate a ground between the main controller and actuators, and for power supply of USB Hub.

In the End-effector, several methods have been discussed in a previous study [9]. Among them, a harvesting mechanism by suctioning and cutting shown in Fig. 6 was adopted in these robots. The end-effector consists of "Fingers" for cutting the tomato peduncles, "DC motor" and "Timing belt" for driving the Fingers, "Cylinder" for holding the harvested tomato, "EDF" and "Duct hose" for suctioning. In terms of the "Fingers", there are upper and lower fingers. A blade for cutting the tomato peduncles is mounted in the upper finger. The lower finger drives, and the target tomato is harvested by closing the upper and lower fingers together. Inside the "Cylinder," there are the line laser and Photoresistor for detecting whether the tomato has entered the Cylinder, and the Stopper so that the harvested tomato does not pass inside the Duct hose. In addition, a blade protecting cover is attached at the upper finger so as not to damage the target tomato and its surrounding area during the harvesting operation. The protecting cover is connected to a pressing spring. When the upper finger and the lower finger are closed, the pressing spring shrinks and the tomato peduncle is cut by the blade.

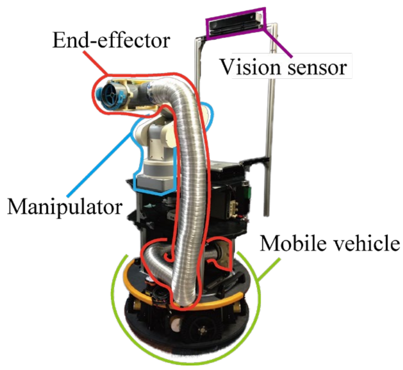
Regarding the software configuration, these robots have followed the configuration of Fig. 3. Since the control method of each module differs depending on the types of hardware, the software of each module also differs. When changing a module, even if the software associated with the hardware to be changed is changed, the other modules are not affected. For example, although Fig. 4 (a) and (b) are different manipulators, only the software that depends on the manipulators is different, and the other software, Mobile vehicle model, End-effector model, and Image processing model, are the same. However, for the Decision making model, the action strategy changes based on the hardware configuration, so it needs to be changed.



(a) Rail movement type equipped with 6-axis manipulator



(b) Rail movement type equipped with 3-axis manipulator



(c) Omnidirectional movement type equipped with 6-axis manipulator

Fig. 4. Photographs of Tomato Harvesting Robot. These types all consist of four hardware elements: Mobile vehicle, Manipulator, End-effector, and Vision sensor.

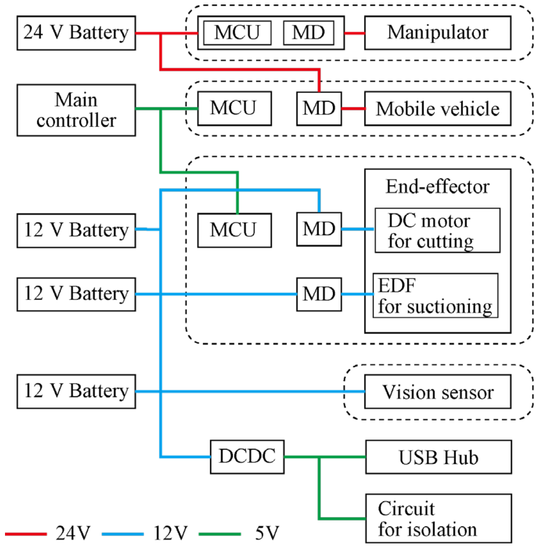


Fig.5. This schematic indicates the power lines of the tomato harvesting robot. “MCU” is a micro computer unit for controlling each actuator. “MD” is a motor driver, and “EDF” is an electric ducted fan. “DCDC” is a convertor for converting voltage. Each Module is surrounded by a dotted line.

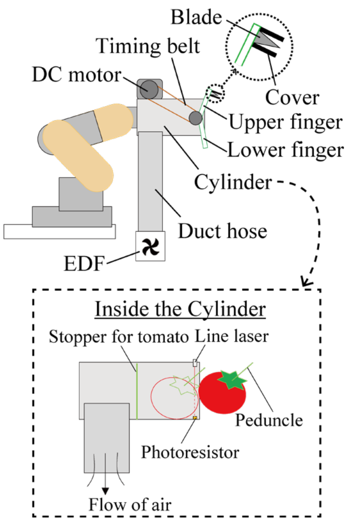
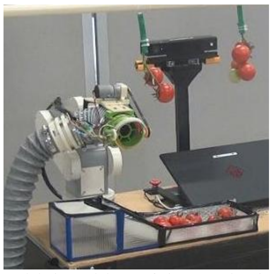


Fig. 6 This is an End-effector mechanism of the suction and cutting type. By engaging the EDF, the target tomato enters the Cylinder. When the line laser is blocked by the suctioned tomato, the lower finger drives. The tomato peduncle is cut by closing the upper finger and lower finger together.

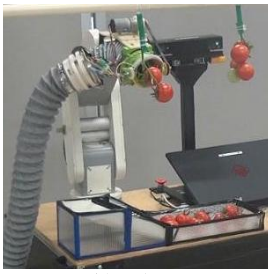
IV. Harvesting Experiment

A. Experiments and Results

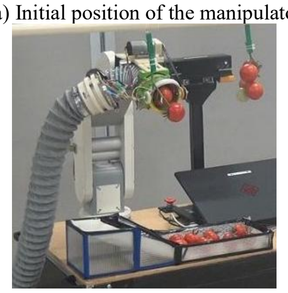
In order to evaluate tomato harvesting robots with different manipulators (Fig.4 (a) and (b)), we demonstrated a harvesting experiment under a second stage environment of a tomato robot competition [10]. Clusters of medium-sized tomatoes were used for harvesting experiments. The harvesting motion of the “Rail movement type equipped with 6-axis manipulator” is shown in Fig.7. This shows the process from the approach to the target tomato, to the dropping of the harvested tomato into the harvest box.



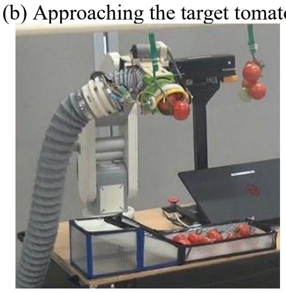
(a) Initial position of the manipulator



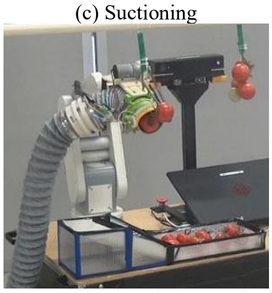
(b) Approaching the target tomato



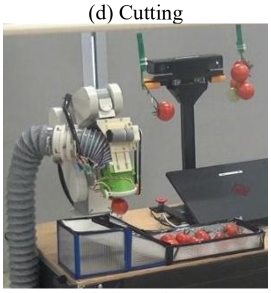
(c) Suctioning



(d) Cutting



(e) Approaching the harvest box



(f) Dropping

Fig. 7 Harvesting motion, from the initial position of the manipulator to the dropping of tomatoes into the harvest box, after detecting the target tomato.

TABLE II Harvesting time in the case of the rail movement type equipped with 6-axis and 3-axis manipulators (Fig.4 (a) and (b)). Item is a sequence of the harvesting motion.

Item	Manipulator type[s]	
	6-axis.	3-axis
Decision of a target tomato’s position	5.5	1.7
Approaching the tomato (Fig.7(b))	9.5	5.7
Suctioning and cutting (Fig.7(c) and (d))	6.0	6.7
Approaching the harvest box (Fig.7(e))	11.5	6.4
Dropping the harvested tomato (Fig.7(f))	6.0	6.7
Controlling to the initial position	4.8	1.4
Total	43.3	28.6

Table II shows the harvesting times when tomatoes are harvested from the cluster. Regarding “Decision of a target tomato position” of the rail movement type equipped with the 6-axis manipulator, the mobile vehicle adjusts the stop position so that the tomato is positioned on the entire surface of the manipulator, in consideration of the limitation of the workspace of the manipulator. “Dropping the harvested tomato” is a process of guiding the harvested tomato into a harvest box. “Controlling to the initial position” moves the manipulator to the initial position for the next harvesting motion.

B. Discussion

The harvesting time of the 3-axis manipulator was found to be shorter than that of the 6-axis manipulator. This is likely because the arrival time to the target position of the 6-axis manipulator was slower than that of the 3-axis manipulator. By increasing the operating speed of the 6-axis manipulator, it is possible to shorten the total harvesting time.

The limitation of the workspace of the 6-axis manipulator caused time loss in the "Decision of a target tomato position" step. This time can also be shortened by detecting the tomato in consideration of the geometrical positional relationship between the vision sensor and the manipulator.

Regarding the "Cutting the tomato" step, this time was affected by the rotational speed of the DC motor used in the End-effector. The DC motor had a rated speed of 154 rpm (the rated torque was 2 kgf · cm). By increasing the rotation speed, the time of "Cutting the tomato" can be shortened.

The time from "Approaching to the harvest box" to "Dropping the harvested tomato" took the longest time for both manipulator types. The harvest box was fixed, so it was necessary to approach the harvested tomato to the harvest box in order to drop it. After the target tomato was harvested, the upper and lower fingers were closed. As a result, it was necessary to return the lower finger to its original position to drop the harvested tomato into the harvest box, which took time. In the current harvesting motion, the harvested tomato is "dropped" into the harvest box. "Dropping" the tomatoes, however, can damage them, and render them unsaleable.

We need to consider how to shorten the harvest time and put the tomatoes into the harvest box more carefully. One possible method for this might use an actuator attached to the harvest box itself, wherein the harvest box harvests the tomato directly. Another possibility is to have an induction hose attached to the manipulator, wherein the harvested tomato would be passively conducted through the induction hose into the harvest box. It is possible to shorten the harvest time by eliminating "Approaching the harvest box" and "Dropping the harvested tomato" step entirely.

V. Conclusion

We proposed a system for a tomato harvesting robot that can cope with diverse plant factory. Three tomato harvesting robots with different hardware elements were developed, and the harvesting experiments carried out to evaluate their performance were reported. This system is based on a modular design. It is therefore possible to construct different types of tomato harvesting robots by changing the modules. However, the system still needs to be refined and optimized. In the future works, we will discuss the design rules of the robot, with attention how to set the communication standard, how to better connect the software and hardware, and how to unify power supply (e.g., use only one 24 V battery).

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