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Research Article

Toward Smart Tomato Greenhouse: The Fourth Tomato Harvesting Robot Competition

Takayuki Matsuo[1,*], Takashi Sonoda[2], Yasunori Takemura[2], Masanori Sato[3], Kazuo Ishii[4]

[1]*Department of Creative Engineering, National Institute of Technology, Kitakyushu College, 2-20-1 Shii, Kokuraminami, Kitakyushu, Fukuoka 802-0985, Japan*
[2]*Department of Integrated System Engineering, Nishi-Nippon Institute of Technology, 1-11 Aratsu, Kanda, Miyako, Fukuoka 800-0394, Japan*
[3]*Department of Applied Information Technology, Nagasaki Institute of Applied Science, 536 Aba, Nagasaki, Nagasaki 851-0193, Japan*
[4]*Graduate School of Life Science and System Engineering, Kyushu Institute of Technology, 2-4 Hibikino, Wakamatsu, Kitakyushu, Fukuoka 808-0196, Japan*

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ABSTRACT

Agriculture, one of the most important industries for human life, is faced with serious problems, the shortage of workers, the falling birthrate and the aging population, global warming and natural disasters, etc. Tomato is one of the most important fruit vegetables, and most tomatoes in Japan are cultivated in the greenhouses, or large scale farms as the solution for effective production toward smart greenhouses, whereas the high temperature and high humidity, construction and management costs are big problems and technologies such as environmental control system, factory automation technology, AI, robotics are required. We had held Tomato Harvesting Robot competition from 2014 toward realization of smart tomato greenhouse aiming at promote the automated tomato harvesting to reduce the working time of harvesting. In this paper, we report on the tomato harvesting robot competition and the results mainly from the fourth competition.

1. INTRODUCTION

According to the statistical information of the Ministry of Agriculture, Forestry and Fisheries in Japan, Japan's food self-sufficiency rate (calorie base) is about 40%, which is the lowest level among major developed countries. In the agricultural field, the aging and depopulation of producers is progressing, and labor shortage due to lack of successors are serious problems. "Smart agriculture" is proposed as a future agriculture production that solves these problems. One of the key technologies for smart greenhouse is robotics, therefore, agricultural robots are expected to be introduced to the agricultural field as the solution tools.

Tomato is one of the important fruit vegetables and most tomatoes are produced in the greenhouses, or large-scale farms, where the high temperature and humidity, and long harvest age force the farmer heavy works. To develop the tomato harvesting robot, many research issues exist such as manipulator design, end-effector design, collaborative behavior, artificial intelligence, motor control, image processing, target recognition and so on. Kawamura et al. have developed a tomato harvesting robot equipped with a 5-degree-of-freedom (DOF) manipulator on a mobile platform. It shows that the target can be grasped with sufficient accuracy for the commanded position [1]. Tomato recognition is based on the luminance signal and red signal from the camera, and the three-dimensional position estimation of the tomato fruit by stereo vision [2,3]. It points out that the recognition rate declines due to changes in the lighting environment and that it is difficult to recognize stems. As the next step, speeding up tomato harvesting is desired, and research on feed-forward control has been developing. Kondo [4] experimentally investigated the natural frequency of tomato tufts to introduce a model of tomato tufts, and introduced them into manipulator trajectory planning. The harvesting mechanism (end-effector) for harvesting tomatoes is also an important research subject [4,5], and methods such as cutting from stems, breaking, and suction are proposed. Taking advantage of the recent development of computers, real-time image processing technology has also been developed. Tomato fruit gripping experiments are being carried out in an environment where the direction of easy gripping and sunshine conditions change [6]. Xu et al. developed a methodology for automated strawberry grading system based on image processing. Al-Hiary et al. [7] proposed and experimentally evaluate a software solution for automatic detection and classification of plant leaf diseases. Research is actively progressing in recent years. Wang et al. [8] developed a tomato harvesting robot used in greenhouse which consists of a four-wheel independent steering system, a 5-DOF harvesting system, a navigation system and a binocular stereo vision system steering system. Due to the rapid development of image processing technology in recent years, agricultural robots using Deep Learning are attracting attention. Wang Xinshao and Cheng [9] proposed weed seeds classification based on Principal Component Analysis (PCA) Network Deep learning and the PCA Network variant method obtains good classification result and improves the recognition accuracy. And, Jeon et al. [10] developed plant lead recognition system using a Convolution Neural Network (CNN) and proposed a method to classify leaves using the CNN model.

*Corresponding author. Email: matsuo@kct.ac.jp

We have also organized Tomato Harvesting Robot competition from 2014 aiming at smart tomato greenhouse as the tomato harvesting time engages in the whole tomato production [11]. In this paper, we will report on the result of the fourth tomato harvesting robot competition.

2. COMPETITION REGULATIONS

The tomato harvesting robot competition consists of two leagues which are the Senior League and the Junior League. The target competitors for Senior League are supposed to the team with automated and remote-controlled robots, and the Junior League are for high school or junior high school students who build robot using LEGO Mindstorm. In this section, competition regulations of both reargues will be introduced.

2.1. Senior League

The Senior League supposes that teams are not restricted to university nor company, just each team should have own tomato harvesting robot(s). Two kind of competition field are prepared, one is the rail-style area (Figure 1a) and the other is the free-style (Figure 1b). The rail-style area is designed to have the similar environment with the large-scale tomato factory with heat pipes for warming greenhouse. Free-style area is for the robots of open-field culture environment. Tomatoes are hanged on height from 800 to 1200 mm referring to the tomatoes arrangement of Hibikinada Saien Co., Ltd.

The required specification of tomato harvesting robot is shown in Table 1. Regarding the sizes of robot, the projected area of the robot to the ground is within the 800 × 800 mm^2 and no height limitation. For safety reason, the robots should have an emergency stop switch on the easy-to-find position. As the recommendations, the weight of the robot is <50 kg and the electric power of motor is <70 W/each.

The first stage is intended as the inspection of basic functions needed for tomato harvesting, so that single tomatoes are suspended as shown in Figure 2a. The team succeeded to touch the tomato, moves to the second stage. In second stage, some sets of bunches of tomatoes are suspended as shown in Figure 2b. The five high score teams go up to the final stage. The score is calculated based on the number of successfully harvested tomatoes and damages to tomatoes. Also,

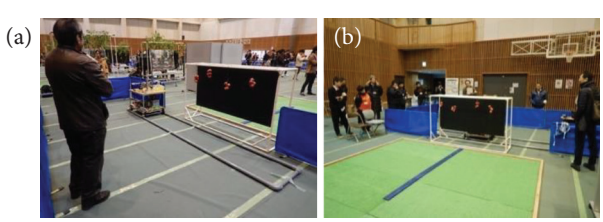

Figure 1 | Competition fields. (a) Rail-style area. (b) Free-style area.

Table 1 | Specifications of a robot

Size	W: 800 mm, D: 800 mm (H: No limitation)
Equipment	Emergency stop switch
Weight	Max. 50 kg (recommend)
Motor power	Max. 70 W (recommend)

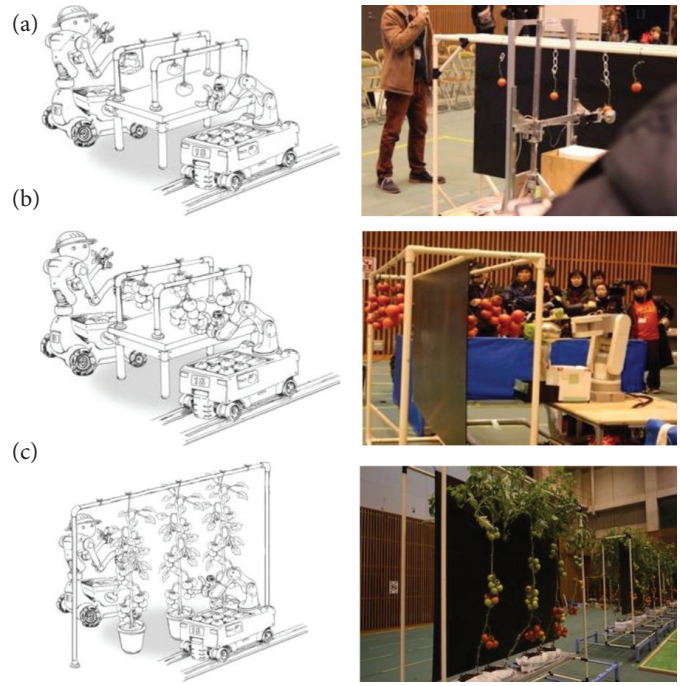

Figure 2 | The missions and stages of the competition. (a) First stage: pick up single tomato. (b) Second stage: pick up tomatoes from bunches. (c) Final stage: pick up tomatoes from plants.

the unripe tomatoes are counted as the damaged tomatoes. Final score of second stage is the score multiplied the basic score and the coefficient decided by a combination of choice between the control method which are remotely and autonomous control and the areas which are the rail area and the free style area. In final stage, the robots harvest tomato from plant body as shown in Figure 2c.

The robots are classified mainly into two types, manual control and autonomous control, and the former robots are classified by whether the operator observes tomato directly or indirectly using cameras mounted on robots, and by robot locomotion whether the robot uses rail or not. Totally, the robots are categorized into six types depending on operation and locomotion method as shown in Table 2. The success points of one-tomato-harvesting change depending on the robot category, e.g., the point of one-tomato-harvesting for T-1 is 2 × 1 = 2 points, and that of category T-6 is 2 × 8 = 16 points.

2.2. Junior League

In Junior League, the subject is to carry small size tomatoes to assigned positions. Students should develop the robot using LEGO Mindstorm with the functions such as line trace, color recognition, end-effector with mechanism design and motors with control, and their programming [11].

In Line Trace Challenge, robots should detect white line in the competition area and move along the line using a color sensor. On the way of the course, the tomato-box-harvesting field (harvest field) exists, where tomato boxes are arranged. The robot must move to the harvest field in order to get the tomato boxes. In Color Identifying Challenge, robots should explore and recognize color signs of the same color of three boxed tomatoes (tomato box) on the course. As guidance to harvest field, red, yellow and blue lines are drawn

Table 2 | Categories of tomato robots

Robot control	**Manual (x1)**				**Autonomous (x8)**	
Operator manipulation	**Direct observation of tomato (x1)**		**Indirect observation of tomato (x2)**		**Start and stop commands**	
Mode of locomotion	Rail-type (x1)	Free-type (x2)	Rail-type (x1)	Free-type (x2)	Rail-type (x1)	Free-type (x2)
Total ratio for one tomato	x1	x2	x2	x4	x8	x16
Category	T-1	T-2	T-3	T-4	T-5	T-6

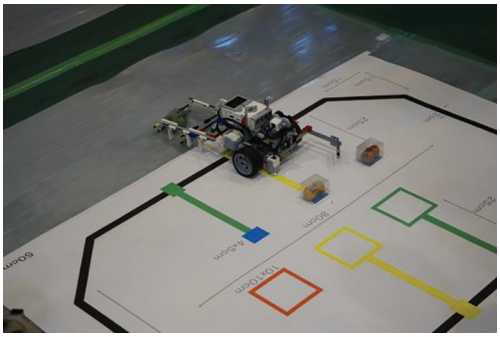

Figure 3 | Overview of Junior League.

Table 3 | The list of finalists

Team	**Affiliation**	**Category**
HAYASHI-LAB	Kyushu Institute of Technology	T-5
Hibikino-Tom's R	Kyushu Institute of Technology	T-5
Nagasaki GANBARANBA	Nagasaki Institute of Applied Science	T-4
KPC2017A	Kyushu Polytechnic college	T-5
KPC2017B	Kyushu Polytechnic college	T-5

in the field. The robots should detect guidance line by color sensor and carry the tomato boxes to the same color positions.

In Mechanism Design and Control Challenge, robot should manipulate a tomato box or boxes using a manipulator and carry to the storage location. To pick up the tomato box, a manipulator equipment should be made by each team. The robot is required to store, transport and relocation depending on tomato box colors. After picking up the box, the robot should return to the course. In Object Detection Challenge, robots should detect a battery charging station and stop there.

The basic specification for robot is that the size of the robot is within 300 × 300 mm^2 on ground. Figure 3 shows overview of Junior League.

3. SUMMARY OF THE FOURTH TOMATO HARVESTING ROBOT COMPETITION

Five finalists are: Hibikino Tom's R (Category T-5, Kyushu Institute of Technology), Nagasaki GANBARANBA (Category T-4, Nagasaki Institute of Applied Science), KPC2017A, KPC2017B (Category T-5, Kyushu Polytechnic college) and HAYASHI-LAB (Category T-5, Kyushu Institute of Technology) as shown in Table 3. Overall winner and Overall runner-up are shown in Table 4. In Junior League, number of the participated teams were 18 teams and the result is Table 5.

Table 4 | Final result of the Senior League

Ranking	**Team**	**Score**
Overall winner	HAYASHI-LAB	120
Overall runner-up	Hibikino-Tom's R	68

Table 5 | Result of Junior League

Ranking	**Team**
1st place	Ohnishi lions (Fukuoka Technical High School)
2nd place	Ooita kogyo C (Oita Technical High School)
3rd place	NiAScience (High school attached Nagasaki Institute of Applied Science)

Table 6 | Results of second stage (Score 1) and score after applying Equation (2) (Score 2)

Team	**Category**	C	α	β	γ	δ	η	**Score 1**	**Score 2**
A	T-5	8	7	2	9	0	0.50	110	31.78
B	T-5	8	4	3	1	0	0.39	86	42.00
C	T-4	4	4	2	1	0	0.57	38	20.86
D	T-5	8	1	1	0	0	0.50	24	12.00
E	T-5	8	1	0	0	0	1.00	16	16.00
F	T-3	2	1	1	0	0	0.50	6	3.00
G	T-1	1	1	0	0	0	1.00	2	2.00

4. DISCUSSION

The score evaluation of the senior league of the fourth tomato harvesting robot competition are shown in Equation (1)

$$P = C(2\alpha + \beta) - 2(\gamma + \delta) - \varepsilon \tag{1}$$

where P is the final score, C: the category coefficient in Table 2, α: the number of obtained tomatoes without damage, β: the number of damaged tomatoes, γ: the number of dropped tomatoes, δ: the number of damaged tomatoes, ε: deducted point when robots damage to tomato plants (the final stage). Table 6 shows the result of the second stage. Score 1 is final score using Equation (1). Team A was the first place in the second stage, which could be 110 score. However, Team A dropped nine tomatoes, the worst number in the seven teams of Table 6. In the case of using Equation (1), Total score P is almost not influenced from γ, δ and ε at selecting high class such as T-5 and T-6. This means that the positive harvesting makes bigger score than the risk of dropping. Therefore, some teams dropped many tomatoes intentionally for the purpose to avoid difficult tomatoes. That is, the tomatoes are not handled carefully. In actual tomato factory, damaged tomatoes and drop tomatoes have no commercial value. Therefore, we considered that concept

of carefully dealing with tomatoes is employed. We proposed new equation as shown in Equation (2).

$$P = \eta C(2\alpha + \beta) - 2(\gamma + \delta) - \varepsilon \tag{2}$$

$$\eta = \frac{\alpha}{\alpha + \beta + \gamma + \delta} \tag{3}$$

Equation (2) used "harvest success rate η" expressed by Equation (2) and if robot damage and drop tomatoes magnification C is decreased. Score 2 of Table 6 shows the result of changing scores after applying Equation (2). Number of dropped tomatoes influences the score and Team A becomes the second place.

5. CONCLUSION

In this paper, tomato harvesting robot competition is introduced toward Smart Tomato Greenhouse. The tomato harvesting robot competition has two leagues which are Senior and Junior League. In Junior League, number of the participated teams were 18 teams. In Senior League, number of participated teams were nine teams. In next competition, concept of carefully dealing with tomatoes will be used and we proposed harvest rate η and if robot damage and drop tomatoes, the score of team will be decreased.

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Authors Introduction

Dr. Takayuki Matsuo

He is an Associate Professor at Department Creative Engineering, National Institute of Technology (KOSEN), Kitakyushu College, Japan. His research area is underwater robots and biomimetic robots.

Dr. Takashi Sonoda

He is an Associate Professor at Department Integrated System Engineering, Nishinippon Institute of Technology, Fukuoka, Japan. His research are underwater robotics and robot manipulator systems.

Dr. Yasunori Takemura

He is an Associate Professor at Department Integrated System Engineering, Nishi-Nippon Institute of Technology, Fukuoka, Japan. His research area is about machine learning, data mining and Robotics.

Dr. Masanori Sato

He is an Associate Professor in the Faculty of Applied Information Technology in Nagasaki Institute of Applied Science, Japan. His main interests are agricultural robots, underwater robots, and life support robots.

Prof. Kazuo Ishii

He is a Professor at Graduate School of Life Science and System Engineering, Kyushu Institute of Technology, Japan. His research area is about field robots and intelligent robot systems.