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Research Article

Toward Smart Tomato Greenhouse: The 6th Tomato-Harvesting-Robot Competition and Regulation Changes Aiming at Practical Application

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ABSTRACT

Agriculture is one of the most important primary industries, however the agricultural workforce in Japan has been decreasing due to the aging, shortage of successors and their heavy work. Smart agriculture and farms, which aim to automate farm work, have been attracting attention for the future sustainable society. We have been organizing the Tomato-Harvesting-Robot Competitions since 2014 to introduce robotic technology and AI into agriculture and promote agricultural technology. The competition consists of a Junior League for young students and a Senior League for general competitors. In this paper, we report the results of the 6th Tomato-Harvesting-Robot Competition and the regulation changes toward practical applications..

1. Introduction

According to statistical information by the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) [1], the agricultural workforce in 2020 is 1.4 million workers, which is 22.5%, 400 thousand less compared to those of 2015 in spite of world population increase. In addition, the rate of older workers (over 65 years old) increased 4.9% to 69.8%. The decrease of the number of agricultural workers and their aging have become one of the social problems in Japan, whose reasons are heavy work, knowledge transfer from experts to younger workers, the large initial investment when starting farming, and a small income compared to the investment, etc. Recently smart agriculture using AI, IoT, big data and robot technologies has been attracting attention, and it is expected to improve the agricultural works in efficiency and contribute to labor-saving by automated operations, parameterization and visualization of expert farmers and sharing. In the automation of agricultural work, research on agricultural harvesting robots has been actively carried out, e.g., Hayashi et al. developed a

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strawberry harvesting robot with obstacle avoidance control algorithm to approach the target fruit without damaging the neighboring fruits [2], Henten et al. developed an autonomous robot for removing unwanted cucumber leaves [3] and Lehnert et al. realized autonomous harvesting of sweet pepper using mobile robot with 6-DOF robot arm, end-effector and RGB-D camera[4].

We have been organizing the Tomato Harvesting Robot Competition since 2014 with the aim of developing Agri-robots, arousing the interests of young researchers of robotics in agriculture, and giving back the developed technology to the agricultural field [5]. The competition is divided into two leagues, Junior league for outreach activities to junior and senior high school students and Senior league for actual harvesting demonstrations. In the junior league, each team develops a robot that harvested small tomatoes using LEGO Mindstorm. In the senior league, competitors demonstrate the harvesting performances of their developed robot(s) using tomato plants for commercial production. Yaguchi et al. developed an end-effector that grasped a fruit using grippers and plucked it from the separation layer in the peduncle using the results of the competitions. They described the results of harvesting experiments conducted on an actual farm, demonstrating that the harvesting time was shortened by improving the harvesting motion [6]. In addition, they developed tomato harvesting robots and carried out evaluation experiments on three robot systems with different end-effectors for cutting and an end-effector or birdview stereo cameras [7]. Fujinaga et al. also report the mosaic image of tomato plants using IR and RGB-D images for estimation of maturity of tomato fruits, which are also developed through the competitions [8][9].

In this paper, we report the results of the 6th Tomato-Harvesting-Robot Competition and discuss the regulation changes toward actual applications. Chapter 2 provides an overview of the junior and senior leagues of the Tomato Harvesting-Robot Competition. Chapter 3 describes the history of the rule revision in the senior league. Chapter 4 presents the results of the 6th Tomato Robot Competition. Section 5 concludes.

2. Tomato-Harvesting-Robot Competition

The Tomato-Harvesting-Robot competition started in 2014 and the 6th competition was held in the winter of 2019, which consists of two leagues, the Senior League and the Junior League. The target competitors in Senior League are supposed to have and automated and self-contained robots, and the Junior League are for young students, where they make teams with 2 to 4 students and make a robot with LEGO Mindstorms.

2.1 *Senior League*

In the Senior League, each team developed one or two robots that harvest medium tomatoes (approximately 60 to 120 grams) provided by Hibikinada green farm Ltd.. In the first stage, there are tomatoes hanging one by one in line, and the basic robot performances, such as mobility, tomato handling and recognition are evaluated. In the second stage, bunches of tomatoes are hung in a cage, and each team competes the number of harvested tomatoes and total performance as a system is evaluated. In the final round, each team harvests tomato fruits from plants which are the same as commercial ones.

Each team chooses one of two areas depending on moving the method, the rail-style area (Fig. 1(a)) assuming the operation in the greenhouse with rails or the free-style area (Fig. 1(b)) assuming the outdoor cultivation. In particular, the rail style area reproduces the rails installed in the Dutch-light greenhouse as shown in Fig.2. The rails of the Dutch-light greenhouse are about ϕ50 mm, and the distance between the centers of the rails is 600 mm. All greenhouses use rails with almost the same specifications. From the second round, the harvesting point is calculated based on the number of tomatoes harvested multiplied by robot class coefficient C by degree of automation and working area shown in Tables 1 and 2. In Table 1, "Directly" means that the operator controls the tomato by directly looking at the spot, and "Indirectly" means that the operator controls the robot remotely and manually using visual information and others.

(a) (b)

Fig.1 Working fields of senior league
(a)Free-style area (b)Rail-style area

Fig. 2 Dutch-light greenhouse

Table 1 The class number and coefficient C at choose remote control

Method of View	Directly		Indirectly	
Area	Rail	Free	Rail	Free
Class number	T1	T2	T3	T4
Coefficient C	1	2	2	4

Table 2 The class number and coefficient C at choose autonomous control

Area	Rail	Free
Class number	T5	T6
Coefficient C	8	16

2.2 *Junior League*

The competition field of Junior League is illustrated in Fig. 3. We set the subjects to make a tomato harvesting system of an autonomous transport such as the transportation and sorting of harvested tomatoes. Competition subjects are shown as following [10].

(1) Line Trace

The robot moves along the black course line using the color sensor, which is designed to guide to tomatoes and other landmarks.

(2) Color Identification

The robot explores the working field and recognizes color signs along the course line, and finds three sets of tomatoes in the boxes (tomato-box). In the harvest field, there are red, green and yellow Tomato-squares. The tomato-boxes are arranged in the corresponding squares so as to find them if a robot moves along the line.

(3) Mechanism Design and Control

Participants are expected to design and make a robot arm to get a tomato-box for picking up the tomato-boxes. The robot is required to store, transport and relocate the boxes to the assigned storage area. After picking up the box, the robot is to return to the course line. Then, the robot carries the box to the specific storage location.

(4) Object detection

The robot should return to the course line after putting the tomato-boxes. Then, the robot is to go to the charging station which is put at a certain distance away from the course line. The robot has to stop by the distance measuring sensor.

Each team consists of 3 or 4 students and makes a robot using LEGO Mindstorms. The sizes of the robot are within 300 x 300 [mm] as the basic specification for the robot. The robot can have structural change after starting, so that the initial robot structure is judged as the robot size.

Until the 4th Tomato-Harvesting-Robot Competition, the tomatoes were stored in a transparent box "Tomato-Box", from the 5th competition, the tomatoes themselves were placed without boxes. Therefore, more careful handling of tomatoes is needed when the robot manipulates and transports them. For participants not to forget tomatoes food products, and if they are handled improperly in this competition, they will not be scored for storage points.

Criteria for improper handling of tomatoes are:

1. The liquid inside the tomato is released to the outside or not.

2. The tomato inside is visible or not

3. The tomato is clearly dented from their pre-race condition or not.

4. The tomato is transported in contact with the floor or not.

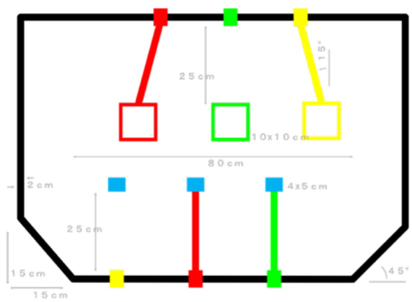


Fig.3 Robot Jr. League competition Field

3. Regulations Changes in the Senior League

The regulation of the competition is changed by evaluating the achievement of teams toward actual greenhouse toward smart agriculture. Table 3 shows the history of regulation changes. The first competition was held in 2014 with the Senior League only. From the second competition, Junior League started as the outreach activity of agricultural robotics. From the third competition, a bump was put on the free-style field to motivate the improvement of mobility for rough terrain. From the fifth competition, the black board shown in Fig.4, which was placed in the image processing easy, was removed and the robots were asked to find tomatoes in various colored environments.

(1) Mobility: Working field

The Senior league of Tomato-Harvesting-Robot competition consists of mainly two classes depending on working fields, the rail-style and the free-style fields. The rail style field is designed assuming the Dutch-light greenhouse where a pair of rails is laid for temperature control and carts transferring tomato maintenance, and the free-style field is assuming an open-field culture field and currently the flat ground covered with artificial grass instead of soil. In order to give the robots incline to the ground, 10mm or 16mm height bumps are put on the field and currently slope is arranged near tomato plants to imitate ridges of open-field culture (see Fig.5).

(2) Automation and Image Processing

The black board was placed behind the tomato plants in the first competition to reduce the computational cost of image processing for harvesting tomatoes autonomously. To make the competition close to the actual harvesting gradually, teams select tomato printed background (x2 point/tomato) or black boards in the third competition. Most teams for automated harvesting classes utilized RGB-D cameras like Intel Realsense device to obtain RGB image and depth information, and no background board from the 5th competition.

(3) Scoring for gentle manipulation as products

The damages to tomato fruits and the planets are crucial evaluation as commercial products, and the degree of maturity is directly connected to the shipping time. The harvesting robots should take the proper color tomatoes without any damage to fruits and plants. Until the third competition, the score P was calculated mainly depending on the color and damage conditions of the harvested tomatoes as shown in Eq. 1.

$$P = C(2\alpha + \beta) - \varepsilon \qquad (1)$$

where C is the coefficient of robot class, α is the number of successful tomatoes, β is that of damaged ones, and ε is the plant damage. When harvesting the target tomatoes, some teams dropped neighboring tomatoes as the tomato grows up as a cluster and turns red from upper fruits, moreover, some teams intentionally dropped immature tomatoes to harvest the target tomatoes. Therefore, Eq. 2 was employed from the fourth competition, and two points were deducted for each dropped tomato. Tomatoes remained in the plant and damaged without being harvested were also counted.

$$P = C(2\alpha + \beta) - 2(\gamma + \delta) - \varepsilon \qquad (2)$$

γ is the number of dropped tomatoes and δ is the number of damaged tomatoes without being harvested. The current evaluation function is modified to Eq. 3 for consideration of the inequality point per successful harvesting between manual operation and autonomous operation. The autonomous harvesting team got higher points and less effect of point reduction due to dropping tomatoes. Therefore, the harvest rate η as shown in Eq. 4 was adopted from the fifth competition. As a result, the more tomatoes the robot dropped, regardless of its class, the less points it received for each tomato it harvested. The robots should deal with tomatoes gently as commercial products.

$$P = \eta C(2\alpha + \beta) - 2(\gamma + \delta) - \varepsilon \qquad (3)$$

$$\eta = \frac{\alpha}{\alpha + \beta + \gamma + \delta} \qquad (4)$$

At the beginning of the competition, only the number of tomatoes harvested was reflected in the score (Eq. 1). However, in order to improve the robot's harvesting technique, we added a section that deducted points based on the number of dropped and damaged tomatoes (Eq. 2). This was done to reduce the number of unsalable tomatoes. Finally, to improve the harvesting accuracy, we introduced the concept of harvest rate (Eq. 3 and 4).

Table 3 History of regulation changes

N-th	Year	Rule & Changes
1	2014	Senior League started with 6 categories from T1 (manual operation) to T6 (autonomous) and 2 kinds of working fields (rail and artificial grass)in indoor field (Gymnastium). The black boards are set behind tomato plants.
2	2015	Senior: No rule change. Junior: Junior League started. Lego mindstorm is used for basic platform.
3	2016	Senior: Bump is placed in the center of grass field. Junior: No rule chage.
4	2017	No rule change.
5	2018	Senior: Slope is placed instead of Bump in the grass field. The black boards are removed. In scoring, success rate is added. Junior: Original arm made of stationery is allowed. Tomato box removed.
6	2019	No rule change.
7	2020	Senior: Video evaluation instaed of 1st and 2nd rounds. The cometition field is changed to the ourdoor experimental green house. The grass field is changed to the soil field. Junior: Online cometition in each school.

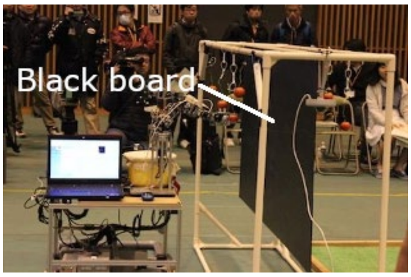
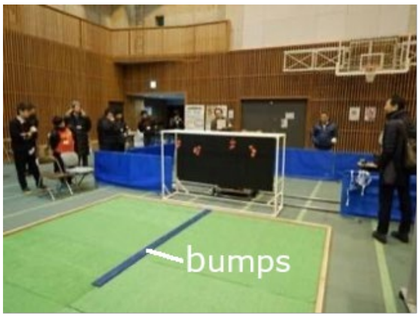


Fig.4 A black board set up behind the tomatoes.



(a)


(b)

Fig.5 (a) A bumps set up in the freestyle area. (b) A slope set up in the freestyle area

4. Result of 6th Tomato-Harvesting-Robot Competition

The Senior League regulation was revised in the 5th competition, including changes to the scoring equation and the slopes of the free-style area. Equation 4 introduces the concept of harvest rate, where dropping tomatoes and scratching tomatoes have a significant effect on the score. In actual use, the robot needs to harvest more tomatoes within a certain time, therefore, it is desirable for the robot to work for the entire competition (10 min). However, many teams quit the competition before 10 min not to make the harvest rate worse. As for the free-style slope, some robots become inclined and difficult to control the robot by sliding down the slope or collisions as intended. The results of the Senior League are shown in Table 4 and the winner the robot of Hibikino-Tom's is shown in Fig.6, second place robot of Sugar-lab is in Fig.7.

The winning robot had succeeded in harvesting five tomatoes with no damage and two damaged tomatoes remaining in the plant in the first trial, and then five tomatoes succeeded and four dropped, two ones remained in the plant in the 2nd trial. It takes 2 min per one harvesting, which is almost 10 times slower than human harvesting.

For Junior League, this competition was the second one after the regulation changes to require the teams to handle fresh tomatoes. Although some teams damaged tomatoes in the previous competition, in this competition, most teams were able to instill an awareness of the importance of handling raw plants through their crafts with ingenuity in handling the tomatoes with care and few damages to tomatoes. Overall, the competition scores improved from the previous year, and one team had succeeded in making a system to harvest and transport all the tomatoes in one week. Basically, we will not change the basic rules, however, some additional subjects for the next competition should be considered.

Some comments from students are related to the difficulties from tomato size variation, which often happens in natural environments. That encourages ingenuity in the devices and algorithms due to the inconsistent environment of handling natural objects.


Fig.6 The winner robot Kyushu Institute of Technology team.

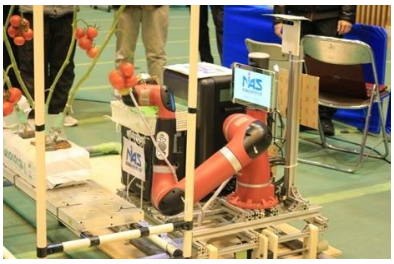


Fig.7 Second place robot of Nagasaki Institute of Applied Science team

Table 4 Result of Senior League

Team	Trial	Class No.	C	α	β	γ	δ	ε	η	Score
Syuga-Lab (Nagasaki Inst. of Appied Science)	1st	T5	8	2	0	0	0	0	1	**32**
	2nd	T5	8	0	0	1	0	-5	0	-7
HSRL (Osaka Electro-Communivation Univ.)	1st	T3	2	0	0	2	0	0	0	-4
	2nd	T3	2	0	0	0	1	0	0	-2
HAYASHI-LAB (Kyushu Inst. of Tech)	1st	T5	8	0	0	0	0	0	0	0
	2nd	T5	8	0	1	6	1	0	0	-14
OLUS (Kyushu Polytechnic College)	1st	T5	8	0	0	0	2	0	0	-4
	2nd	T5	8	1	1	1	3	0	0.167	-4
Habikino-Toms (Kyushu Inst. of Tech.)	1st	T5	8	5	0	0	2	0	0.714	**53.143**
	2nd	T5	8	5	0	4	2	-5	0.455	19.364

5. Conclusions

In this paper, we report on the 6th Tomato Robot Competition, which aimed at the social synthesis of robots. In the Junior League, 24 teams participated, and in the Senior League, 9 teams. We also summarized the changes in the rules of the Senior League since the first competition. The operating environment was modified to be similar to that of a real farm, and the calculation method of the score was modified to aim at harvesting "sellable tomatoes".

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Appendix

Results of the 6th Tomato Harvesting Robot Competition are as follows. Both teams competed with a T5 class robot that operates in a rail-style area and harvests tomatoes autonomously. Table 5 shows the result of the senior league. Table 6 shows the result of the junior league.

Table 5 Result of Senior League

Ranking	Team
Winner	Hibikino-Toms (Kyushu Inst. Of Tech.)
2nd Place	Syuga-Lab (Nagasaki Inst. Of Applied Science

Table 6 Result of Junior League

Rankin	Team
1st Place	Tangokinasu (Fukuoka Joto High School)
2nd Place	Double Lycopin (Fukuoka Joto High School)
3rd Place	NiASience Ver.2 (Nagasaki Sogo Fuzoku High School)
Special Award	
Best Presentation Award	G-Advance (Fukuoka Joto Highschool)
Perfect Award	Tangokinasu (Fukuoka Joto High School)
Special Judges Award	Kako Tomato Curry (Kashii Technical High school)
Idea Award	Revolutionary (Fukuoka Joto High School)
Challenge Award	SyokugyoMochi (National institute of Technology, Kitakyushu college)

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