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Paper:

Effect for a Paddy Weeding Robot in Wet Rice Culture

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In recent years, wet rice farming that does not use chemical herbicides has come in demand owing to the diversified consumer needs, preference for pesticide-free produce, and need to reduce the environmental load. In this paper, we propose a "weeding robot" that can navigate autonomously while weeding a paddy field. The weeding robot removes the weeds by churning up the soil and inhibits the growth of the weeds by blocking-off sunlight. It has two wheels, whose rotational speed is controlled by pulse width modulation (PWM) signals. Moreover, it has capacitive touch sensors to detect the rice plants and an azimuth sensor used when turning. To demonstrate its effect in wet rice culture, we conduct a navigation experiment using the proposed weeding robot in two types of paddy field: conventional and sparse planting. The experiment results demonstrate that the proposed weeding robot is effective in its herbicidal effect, promoting the rice seedling growth and increasing the crop yield.

Keywords: autonomous mobile robot, weeding, wet rice culture, paddy field, agricultural machines

1. Introduction

In recent years, many types of agricultural equipment have been introduced into farming to drastically improve the efficiency in agricultural work. However, there are high expectations from the use of robots because of aging, the decreasing number of agricultural producers, and the increasing demand for food [1–3]. Various agricultural robots have been developed, some employing sensing systems that allow them to autonomously navigate by accurately monitoring their self-positions [4, 5].

Chemical removal using herbicides is the main method used today to weed wet rice paddies, because it is labor-saving and effective. However, recently, wet rice farming that does not use chemical herbicides is being demanded owing to the diversified consumer needs, preference for pesticide-free produce, and need to reduce the environmental load. Weeding without herbicides can be achieved by mechanical methods including walking-type weeding machines, physical methods such as sheet mulching, and biological methods such as rice duck farming. However, mechanical weeding requires a worker to operate the device in the rice paddy, involving heavy labor, whereas rice duck farming requires an operator to grow and care for the ducks, which is costly. Thus, a method of weeding that reduces herbicide use, does not require human care or labor, and reduces the economic burden is crucial.

Our group has proposed a paddy weeding robot (hereafter referred as weeding robot) to address such problems. Until now, weeding robots have been developed and tested by other research institutions [6–8]. The weeding robot proposed in reference [6] employs a camera-based sensing system, and it can turn around at the end of a row of rice seedlings via image processing to sense the end of the row. This method requires cameras at the front and rear of the robot as well as a high-performance computer to process the images, and consequently, it is costly.

The proposed robot was developed to satisfy four attributes: (a) operational simplicity, (b) capability of navigating in the inter- and intra-row spaces, (c) compactness and light weight, and (d) low cost. To develop a weeding robot that meets these requirements and is appropriate for use on ordinary family farms, the following four technical issues must be overcome:

1. development of a chassis capable of navigating stably on uneven ground,
2. development of a sensor system and navigation algorithm to achieve autonomous navigation and turning,
3. verification of the effects of the weeding robot on rice paddy weeding and rice plant growth and yield, and
4. introduction of information and communication technology (ICT), allowing a remote worker to monitor the working conditions of the robot.

Until now, we have developed a sensor to detect rice seedlings and a chassis capable of navigating stably on uneven ground to resolve issues 1 and 2. Consequently, the developed weeding robot was found capable of navigating stably on the muddy ground in rice paddies and detecting rice seedlings to allow it to navigate without damaging them [9–11]. However, the weeding robot was not

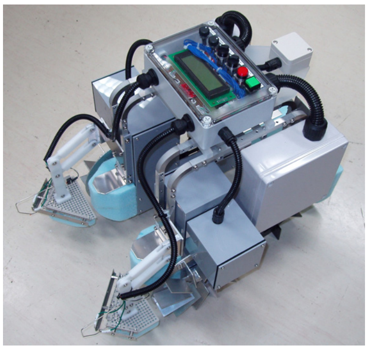


Fig. 1. Weeding robot.

Table 1. Specifications of the weeding robot.

Size (Width × Length × Height)	428 mm × 558 mm × 465 mm
Weight	7500 g
Maximum Speed	20 m/min
Power Source	Li-Po 7.4 V 4000 mAh × 2
Continuous Running Time	3 h

sufficiently tested in rice paddies with actual transplanted seedlings to verify its effect on the weeding or growth of the rice plants and rice yield.

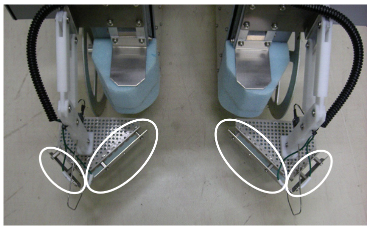
In this paper, we report on an experiment in which the weeding robot was operated in two types of rice paddy: conventionally-spaced paddy, in which the intra-row distance (i.e., between the clusters) was 150 mm, and sparsely-spaced paddy, in which it was 300 mm. We allow the weeding robot to navigate in these experimental paddies to verify the weeding effect and effect on the rice plant growth and yield, which constitute issue 3 mentioned above.

2. Weeding Robot

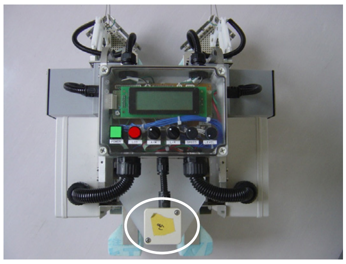
2.1. Hardware Specifications

Mechanical weeding is often adopted as the main alternative to the use of herbicides or rice duck farming. However, it usually entails a large rider-operated machine, which is costly, and thus, can be purchased only by large-scale farmers. Therefore, the aim of the authors was to develop a weeding robot that can be purchased by individual family farms, can be operated stably, and can cover all the inter- and intra-row spaces in rice paddies.

Figure 1 shows a photo of the weeding robot, and **Table 1** presents its dimensions and specifications. The robot has DC motors in the left and right drive units, and it employs PWM control as the basic navigation control. The weeding robot can move at a speed of 20 m/min, although this may differ depending on the quality and condition of the rice paddy soil; further, the robot can operate for 3 h with a single charging to cover an area of approximately 1–1.5 are.



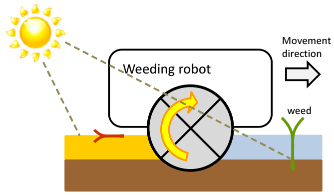
(a) Capacitive touch sensor



(b) Azimuth sensor

Fig. 2. Mounting positions of the sensors.

(a) Movement method



(b) Weeding method

Fig. 3. Movement and weeding method of the weeding robot.

2.2. Sensor System

The weeding robot is equipped with capacitive touch sensors to detect rice seedlings, and an azimuth sensor to measure the movement direction. **Fig. 2** shows the positions of the sensors. Four capacitive touch sensors are installed at the front of the robot. When a sensor plate contacts a rice seedling, the sensor capacitance changes, which is output as a voltage value. The azimuth sensor is installed on the top of the robot toward its rear end. It outputs the movement direction of the robot as an azimuth angle between 0°–360°.

2.3. Weeding Method

As shown in **Fig. 3(a)**, the weeding robot weeds by running while straddling a row of rice seedlings. As shown in **Fig. 3(b)**, the robot uproots the weeds by churning up the soil and, stirring up the water to prevent sunlight from reaching them, which kills the weeds by obstructing photosynthesis. In addition, as the wheels churn the mud, extra gases are released.

3. Navigation Algorithm

It is difficult for the weeding robot to navigate while straddling the rice seedlings because its wheels can slip,

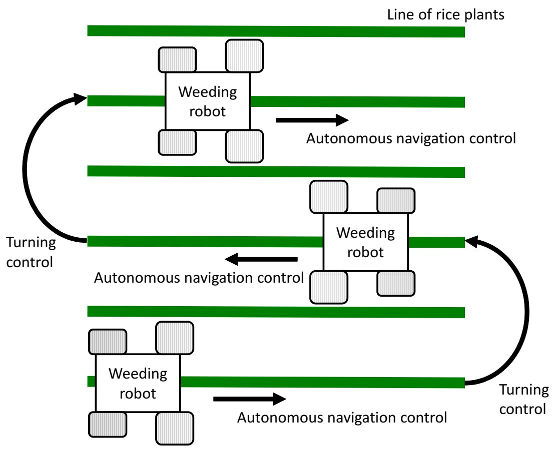


Fig. 4. Navigation route in paddy field.

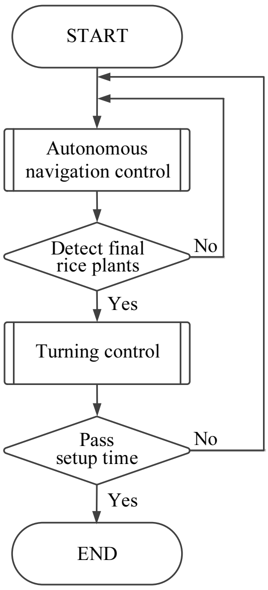


Fig. 5. Navigation algorithm.

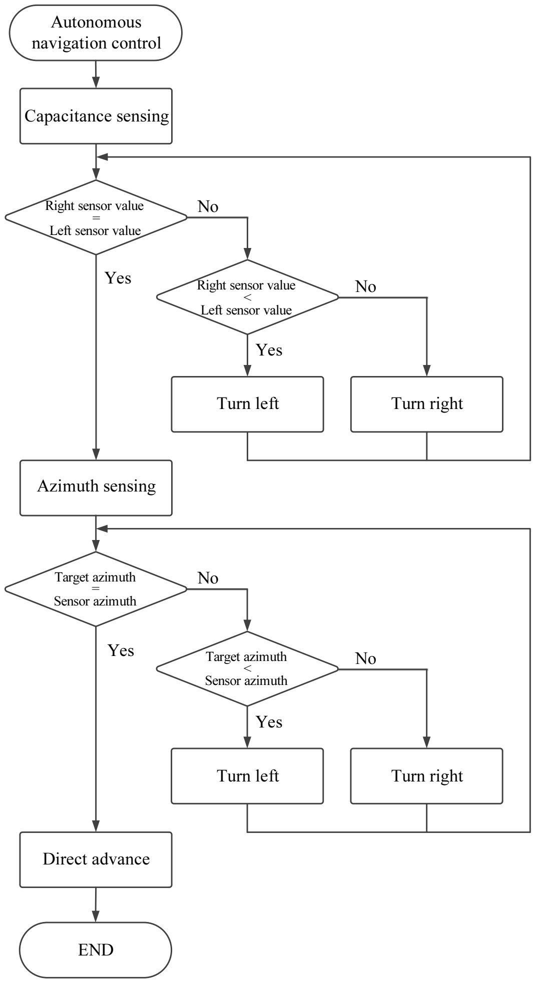


Fig. 6. Autonomous navigation control algorithm.

the ground is uneven, and the rows of rice seedlings are not always straight, as is the case in terraced paddies.

In this study, the weeding robot is controlled to navigate autonomously by employing the four capacitive touch sensors mounted right and left on the front to detect the rice seedlings, whereas a microcomputer controls the duty ratio of the left and right DC motors to adjust the rotating speeds of the wheels in order to avoid the rice seedlings. Furthermore, a turning control is implemented by using the capacitive touch sensors to detect the final rice seedling in a row, so that the robot, on reaching the end of a row, can turn using the azimuth sensor and enter a different row. Because a user only needs to press the start-up switch, after which the weeding robot will autonomously cover the entire rice paddy, an ordinary farmer without any mechanical expertise can operate it with ease.

The navigation route taken by the weeding robot in a rice paddy is displayed in **Fig. 4**. The navigation algorithm is presented in **Fig. 5**.

3.1. Autonomous Navigation Control

The weeding robot must be capable of recognizing rice seedlings so that it can autonomously navigate over a row of rice seedlings. Although previous studies have proposed the use of image processing to detect a row of rice seedlings, they are unable to respond adequately to the environmental changes in a rice paddy. This study achieves autonomous navigation control by employing capacitive touch sensors to directly detect the rice seedlings and an azimuth sensor. **Fig. 6** presents the algorithm for the autonomous navigation control.

When the weeding robot is aligned with a row of rice seedlings and the start-up switch is pressed, it measures the azimuth angle at that point and stores it in the memory as the target azimuth angle. Once it is running, the signals from the right and left capacitive touch sensors are read to identify the presence of rice seedlings.

As shown in **Fig. 7**, when a rice seedling is detected by a reduced sensor value, the duty ratio of the DC motors is controlled to change the direction of the robot and avoid the rice seedling. When the sensor readings of the right and left capacitive touch sensors are equal, the sensor value of the azimuth sensor is read and compared with the target azimuth to adjust path of the robot. The capaci-

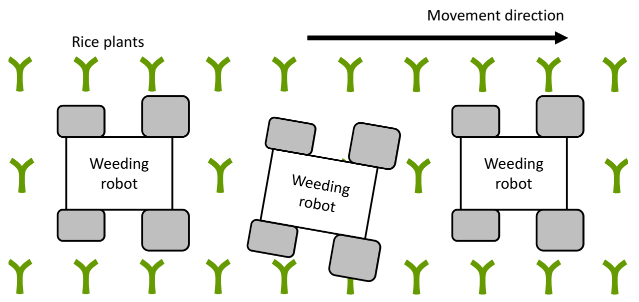


Fig. 7. Autonomous navigation control.

Fig. 8. Autonomous navigation control experiment.

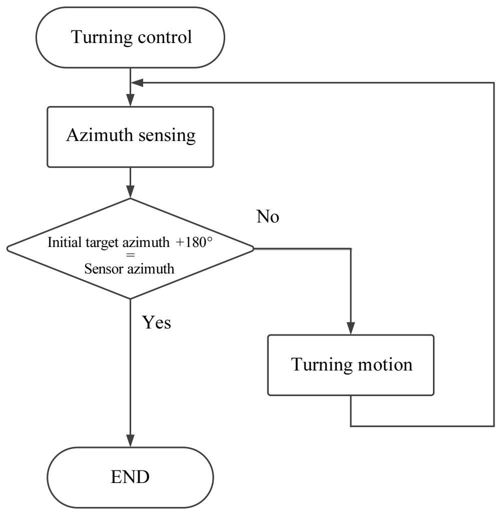


Fig. 9. Turning control algorithm.

tive touch sensors are positioned to retain a certain height above the water surface so that they are not affected by the changes in the attitude of the robot because of moving on uneven ground. **Fig. 8** shows the weeding robot as it runs autonomously. It can be seen that the robot moves without trampling the rice seedlings.

3.2. Turning Control

As shown in **Fig. 4**, to conduct the weeding efficiently and stably, when the weeding robot reaches the end of the row it has been moving along, it follows a curved path to turn and enter a row that is two rows further. **Fig. 9** presents the turning control algorithm.

When no rice seedling is detected by the right and left capacitive touch sensors on the front for a certain period, the robot determines that it has reached the end of a row, and starts the turning motion. At this time, the azimuth sensor detects the azimuth angle when the robot starts to turn, and stores it as the initial azimuth angle. Next, by rotating the right and left wheels at different speeds, the robot continues to turn until the current azimuth angle is larger by 180° than the initial azimuth angle. **Fig. 10** shows the weeding robot executing the turn. Note that to secure sufficient space for the robot to turn, it is necessary to ensure a distance of 1200 mm between the end of the rice rows and ridge bordering the rice paddy.

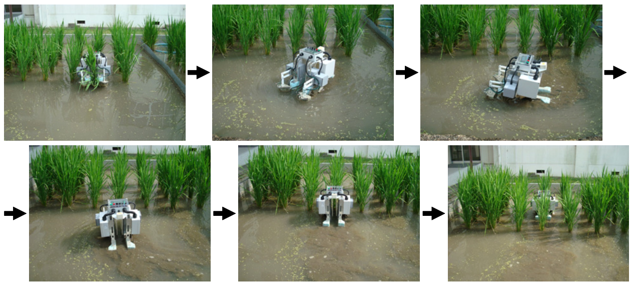


Fig. 10. Turning control experiment.

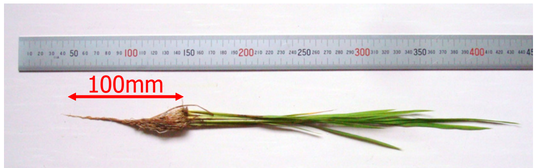


Fig. 11. Transplanted rice seedlings.

4. Weeding Experiment

To verify the effect of the weeding robot on wet rice culture, an experimental field was prepared in which two types of plantings were introduced: conventional and sparse planting.

In both the methods, a single cluster or hill consists of three rice seedlings. **Fig. 11** shows a cluster of rice seedlings prepared for transplanting. The experimental field was divided into two areas: with and without weeding. The weeding robot was run through the weeded area once a week, whereas no weeding was performed in the unweeded area.

4.1. Experiment Results for Conventional Planting

Conventional planting is the method of rice cultivation commonly used in Japan, in which the rice seedlings are transplanted in rows spaced 300 mm apart, at distances of 150 mm between each cluster (hill). This is equivalent to 22.2 clusters/m^2, or 72 clusters/tsubo (approximately 33 m^2). The experimental field with conventional planting is depicted in **Fig. 12**.

4.1.1. Weeding Effect on Growth

After the rice seedlings were transplanted, the weeding robot was run along the rows of rice in the weeded area

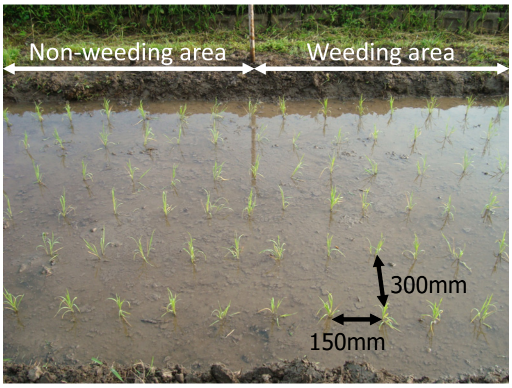


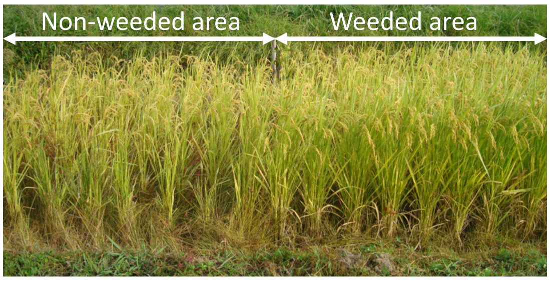
Fig. 12. Conventional planting culture.

(a) Weeded area

(b) Non-weeded area

Fig. 13. Herbicidal effect of each area (conventional planting culture).

Fig. 14. Growth of the rice seedlings (conventional planting culture).



(a) Before rice harvesting

(b) Height of the rice plant

Fig. 15. Crop yield effect of each area (conventional planting culture).

once a week. **Fig. 13** shows the weeding status of the two areas five weeks after transplanting. **Fig. 13(a)** shows the condition in the weeded area and **Fig. 13(b)** that in the unweeded area. It can be seen that there are no weeds growing in the weeded area, in which the weeding robot is operated.

Figure 14 displays the growth of the rice seedlings in the two areas four weeks after transplanting. It shows that the roots, stems, and leaves of the rice plants in the weeded area display a larger growth compared with those in the unweeded area.

4.1.2. Effect on Yield

Figure 15(a) shows the growth of the rice plants in the two areas at the time of harvest (three months after transplanting). **Fig. 15(b)** displays the harvested rice: the height of the rice plants is 920 mm in the weeded area and 760 mm in the unweeded area. Comparison of the number of stems (tillers) of rice revealed that a single cluster contains an average of 19.8 stems in the weeded area, and 11.8 stems in the unweeded area. From the comparison of the weight of the unhulled rice an average of 46.5 g/cluster was found in the weeded area and 9.5 g/cluster in the unweeded area.

4.2. Experiment Results in Sparse Planting

Sparse planting is a labor-saving, low-cost method that allows reduction in the working time and production costs. The rice seedlings are transplanted in rows spaced 300 mm apart, at intervals of 300 mm (between the clusters). This is equivalent to 11.1 clusters/m^2, or 37 clusters/tsubo. Thus, the number of rice seedlings in sparse planting is approximately half of that in conventional planting. The experimental field with sparse planting is depicted in **Fig. 16**.

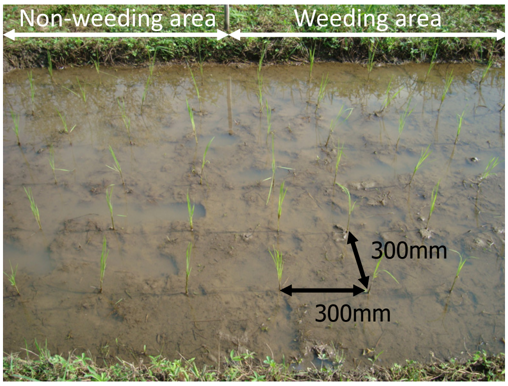


Fig. 16. Sparse planting culture.

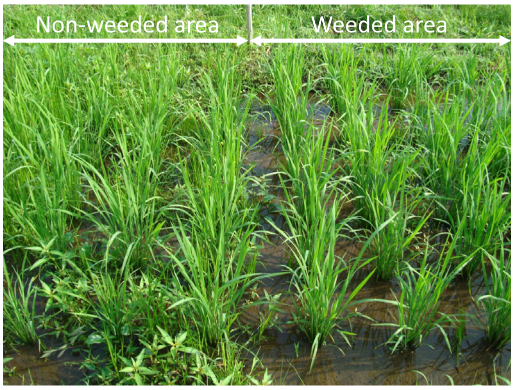


Fig. 17. Herbicidal effect in each area (sparse planting culture).

Fig. 18. Growth of the rice seedlings (sparse planting culture).

4.2.1. Weeding Effect on Growth

As in conventional planting, after transplanting, the weeding robot was operated along the rows once a week in the weeded area. **Fig. 17** shows the weed status in the two areas five weeks after transplanting. It can be seen that there are no weeds growing in the weeded area, in which the weeding robot is operated.

Figure 18 displays the growth of the rice plants in the two areas four weeks after transplanting. It shows that even in sparse planting, the roots, stems, and leaves of the rice plants in the weeded area display a larger growth compared with those in the unweeded area.

4.2.2. Effect on Yield

Figure 19(a) shows the growth of the rice plants in the two areas at the time of harvest (three months after transplanting). **Fig. 19(b)** displays the harvested rice: the height of the rice plants is 930 mm in the weeded area and 750 mm in the unweeded area. Comparison of the number of stems of rice revealed that a single cluster contained an average of 27.6 stems in the weeded area, and 16.2 stems in the unweeded area. From the comparison of the weight of the unhulled rice, an average of 52.0 g/cluster was found in the weeded area and 28.0 g/cluster in the unweeded area.

(a) Before rice harvesting

(b) Height of the rice plant

Fig. 19. Crop yield effect in each area (sparse planting culture).

4.3. Comparison of Effects on Growth and Yield

Table 2 presents the growth and yield when the weeding robot was not used, case (a) and (c), and when it was used, case (b) and (d), for the conventional and sparse plantings, respectively. In addition, the growth and yield when the weeding robot was operated along both the inter- and intra-row spaces for the sparse planting are presented in case (e).

It can be seen that the rice plants for case (b), (d), and (e), i.e., when weeding was conducted, display a larger growth and higher yield when compared with those in case of (a) and (c) conditions. This demonstrates that the weeding robot had a positive effect on rice growth and yield in both the planting cultures. Furthermore, we can see that the weight of the unhulled rice per square meter is nearly the same in cases (b) and (e), both with weeding. This shows that when the weeding robot is used in sparse planting, one can expect a similar yield to that in conventional planting or sparse planting as it is generally practiced.

5. Conclusion

In this paper, we reported the effects on weeding and rice growth and yield, i.e., technical issue 3 stated earlier, when the weeding robot was operated along the rows of

Table 2. Comparison of the growth and crop yield.

	Weeding method	Number of rice seedlings per square meter	Height of rice plant [mm]	Number of stems per rice plant	Weight of unhulled rice per rice plant [g]	Weight of unhulled rice per square meter [g]
Conventional planting culture	(a) Non-weeding	22.2	760	11.8	9.5	2489
	(b) Weeding (inter-row spacing)	22.2	920	19.8	46.5	20440
Sparse planting culture	(c) Non-weeding	11.1	750	16.2	28.0	5035
	(d) Weeding (inter-row spacing)	11.1	930	27.6	52.0	15931
	(e) Weeding (inter- and intra-row spacing)	11.1	970	28.8	60.0	19181

rice in two fields: conventional and sparse planting. The two experimental fields were each divided into two areas, with and without weeding. In the former, the weeding robot was operated once a week.

The experiment results showed that there was no weed growth in the weeded area, in which the weeding robot was operated. Furthermore, the rice plants in the weeded area displayed a larger growth in the roots, stems, and leaves compared with those in the unweeded area. Furthermore, after harvesting, the height of the rice plant, number of stems, and weight of the unhulled rice from the weeded area displayed substantially larger values compared with those for the unweeded area.

To follow up this study, we plan to incorporate ICT, to enable a remote worker to monitor the operating status of the weeding robot, which constitutes the fourth technical issue mentioned earlier, and will make it possible to introduce the proposed weeding robot into ordinary family farms. Specifically, we are considering mounting the robot with a low-cost GPS, including a device and network environment, that will allow real-time monitoring of the weeding conditions based on the GPS position data.

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