INTRODUCTION

Japanese agriculture is beginning to decline, and it is not easy to reverse this trend. If our agricultural sector was a growing industry, we would not have the problem of land use changing from agriculture to other purposes. The main problem is that landowners get much more profit by using farmland for other purposes rather than for agriculture. We believe that several operation styles of “profitable agriculture” are needed to resolve this situation. One of the most effective actions that can be taken is to establish plant factories, which will provide efficiency through automation and the use of robots for each and every operation.

To quickly enhance the productivity of intelligent greenhouses, quality control is needed at agricultural production sites, along with a speaking plant approach to monitor the growth conditions of plants and avoid diseased and underdeveloped plants. We are developing a multi-operation robot equipped with units that contain functions to solve the problem of the instability of environmental factors and subsequent crop yield. Growth-information, pest-detection, and pest-control units were developed for the multi-operation robot and effectively linked to report their actions in order to construct a suitable integrated pest management technology for intelligent greenhouses. The information gathering and various operations were automated by designing each unit to operate autonomously. The system was designed to detect abnormalities by mapping the information provided by the growth-information and pest-detection units. It can then determine the invasion diffusion course of the pest, which makes it easy to take appropriate prophylaxes. Furthermore, the system makes safer working conditions possible because it enables the natural dispersal of ozonated water as a preventive measure. We can expect a further reduction in pesticide consumption by adding a function to disperse a pesticide locally when pests are detected.

Keywords: automation, greenhouse, growth-information, integrated pest management, robot, speaking plant approach
research related to these.

MULTI-OPERATION ROBOT

We are developing a multi-operation robot to solve the problem of the instability of environmental factors and subsequent crop yield. This robot consists of the following units: growth information, pest detection, pest control, harvesting, and running units. The robot gathers and effectively links together information on the cultivation environment, growth diagnosis, cultivation management, fruit quality, and harvesting.

Mounting various sensors and devices on the running unit makes it possible to collect information about the cultivation environment and growth diagnosis and automate each task.

Autonomous running unit

1. Operation part

The running unit runs automatically on the heating pipes that are installed in an intelligent greenhouse between the rows of plants. It is able to recognize its own position. A picture of the running unit is shown in Fig. 1, and its dimensions are shown in Fig. 2 (a. top view and b. side view). The running unit consists of wheels for moving along the pipe rail, wheels for moving across the headland, a DC driving motor, sensors of running controller, guide rollers for correcting the track position (when moving onto the pipe rail), and the control unit for all of these. The wheels for moving across the headland are large and positioned in the middle of the body. The wheels for driving on the pipe rails are small and positioned at the front of the body. The small wheels at the back are driven wheels for running on the pipe rails.

2. Control unit

Figure 3 shows a layout of the home position and guide board. Figure 4 shows a block diagram of the controls for the running unit. The distance sensor (Keyence/GV-H 1000), photoelectric sensor (Keyence/LV-S62), ultrasonic sensor (Keyence/FW-H07), and rotary encoder (TRD-J-RZ) are used to control the running unit. Each sensor sends a signal to the CPU, and a control method is selected. The right and left motor rotations are controlled by the speed controllers (Tokushudenso/ TD12763-24FL16). The distance sensor is used for line tracing to sense the distance to the guide board. The photoelectric sensor is used to recognize the turning position when entering and exiting a lane. The ultrasonic sensor is used to recognize obstructions. The encoder detects the rotation frequency of the wheels and determines its own position in the intelligent greenhouse. Remote operation is possible by using a wireless local area network (station: NE-W11 and access point: NE-W01).

3. Movement procedure

The running control procedure is as follows. After recognizing the home position,

(i) While moving straight ahead, the distance sensor...
DEVELOPMENT OF A MULTI-OPERATION ROBOT

determines the distance to the guide board.

(ii) When the side photoelectric sensor detects the reflector mounted on the guide sensor, the unit turns 90°.

(iii) It moves forward toward the pipe rails.

(iv) It runs on the pipe rails while recognizing its own position using the encoder set on a back wheel.

(v) If the limit switch at front body touches the stopper on the edge of the pipe or if it runs the same distance as the length of the cultivation bed, it takes reverse direction.

(vi) After reaching the end of a lane, the photoelectric sensor recognizes the turning position on the headland by detecting the reflector and makes a 90° right turn.

(vii) It then repeats the above procedure for the other lanes.

4. Operating test

A straight movement test was recorded using a video camera mounted on the front of the body. The detection distance setting of the distance sensor was changed and a line tracing test was performed. Then the difference between the movement of the center of the operating unit and the ideal motion track was analyzed in an image analysis (Fig. 5). The tolerance of the approaching angle of the ideal track was also measured. As a result, considering that the headland was 2.33 m in width and the tolerance of the approaching angle was approximately 20°, the optimum detection distance for accurate operation of the running unit was found to be 4 cm on the right and left.

Growth-information measuring unit

The growth-information measuring unit (Fig. 6) has an optical sensor, chlorophyll-fluorescence measuring instrument (Keyence/CV-3500), digital camera (Keyence/CVS035MH), and radiation temperature sensor. It collects information on the cultivation environment (temperature, humidity, and light intensity), and simultaneously monitors the photosynthesis and transpiration using image processing (chlorophyll fluorescence imaging in the case of photosynthesis). It also collects important information at different growth stages of the plants.

The technology for the early detection of disease damage by measuring the intensity of the chlorophyll fluorescence in the growth-information unit has already been established (Takayama and Nonami, 2010). A reduction in pesticide consumption is expected by performing suitable control at an early stage based on this information.

1. Monitoring photosynthesis

(1) Induction curve

An induction curve is a curved line plotted on a logarithmic temporal axis based on the changes in the intensity of the chlorophyll fluorescence shown by a plant body under light and dark conditions (Fig. 7). A numerical evaluation is performed by using the peak values P, S, and M, which are found from the induction curve. A photosynthesis function diagnosis is performed by using the ratio of the chlorophyll fluorescence intensities from S and M and the intensity of chlorophyll fluorescence P (Takayama et al., 2008). However, the detection of the peak value is needed to automate the diagnosis because there are individual differences in the onset times for P, M, and S. To measure this automatically, the minimum and maximum widths of an expression period were found using a basic experiment.

(2) Photosynthesis-function-diagnosis unit

The photosynthesis-function-diagnosis unit was constructed using a monochromatic camera with a long-path filter on the lens, eight blue light-emitting diode (LED) panels, and an image processor to capture only the chloro-
phyll fluorescence (red light) (Fig. 6). The image input was performed at night (dark environment), and the luminance value was calculated. The shutter speed was 0.1 s.

(3) Material and method

It was tested in a solar-powered intelligent greenhouse at the Research Center for High-technology Greenhouse Plant Production of Ehime University. The measurements started at the northwest corner of the greenhouse, and the procedure outlined below was followed.

(i) After the growth-information measuring unit approached the pipe rail, it stopped at points 1, 4, 7, 10, 13, 16, and 19 m from the northern boundary.

(ii) Irradiation by the blue LED panel allowed images to be captured at the measurement times for P, S, and M.

(iii) The unit then moved to the next stopping position.

(iv) After reaching the approach distance limit, it moved to the next lane.

(v) Each value was mapped.

The obtained data were saved as a csv file and mapped using a macro function on Excel.

(4) Results and discussion

As a result of the test, it was possible to map the growth information in the intelligent greenhouse by using the intensity values of the chlorophyll fluorescence. Figure 8 shows a growth diagnosis information map (the data were obtained from 8:00 pm to 10:00 pm on December 19, 2013, when it was cloudy and the temperature was 7.2°C). The point where a photosynthesis dysfunction becomes clear by showing it on the map. The type of disease can then be determined using visual observation and destructive measuring, and it can be treated topically and early at the detection point. Furthermore, the source and conditions for a disease can be identified using regular measurements.

Pest-detection unit

1. Early attraction of pests using adhesive sheets for pattern processing

Many flowers are considered to have characteristic patterns that effectively attract insects. The use of adhesive sheets for capturing pests is a one-dimensional pest control method that uses a range of colors. A more effective two-dimensional pest control technology was constructed by introducing patterns. Fifteen round stickers (φ8 mm) of the following colours: blue, red, gold, green, silver and black, were attached to adhesive sheets in a 3 × 5 pattern. A seventh adhesive sheet contained holes (φ6-mm) arranged in the same pattern (Fig. 9). Then, the number of insects captured each week was measured. After a three-week period, the sheet containing the holes was found to have captured more insects than the other six sheets. In the first week, the number of insects captured by the control sheet (that had no pattern) was 62 and 44 in the second week. The figure for the sheet containing holes was 128 in the first week and 78 in the second. As can be seen, the sheet containing holes captured approximately twice as many insects in this period. However, in the third week, the difference was not as large: 24 for the control and 29 for the sheet containing holes (Fig. 10). Therefore, putting patterns on the adhesive sheets had a fast-acting effect in attracting insects.

2. Effect of pest monitoring

Progress is being made in the development of early detection technology. The adhesive sheets discussed in the previous step were set in the intelligent greenhouse, and pictures were regularly taken with a digital camera to evaluate the pests captured (the kind and number). The time of pest detection and the erosion change situation were clarified by mapping.

(1) Material and method

Yellow adhesive sheets (100 mm × 257 mm) made by Arysta LifeScience were used for the test, and the higher attraction for pests was confirmed by the previous test. The φ6-mm holes were made at equal distances in a 3 × 5 pattern. These yellow sheets were placed in Ehime University’s solar-powered intelligent greenhouse (1,300 mm²). They were placed at intervals of 2 m and hung down 10-30

---

**Fig. 8** Photosynthetic function diagnostic map.

**Fig. 9** Adhesive sheet designs.

**Fig. 10** Change of the number of insects captured.
cm above the bases of tomato plants. The testing period was from July 27 to December 12, 2012, and pictures were taken twice a week with a digital camera (SONY, 18.2 mega-pixel). They were changed twice, in the beginning of September and the middle of December.

Various harmful insects were caught by these adhesive sheets (Sciaridae and Aleyrodidae) and counted. The number captured and killed in every two-week period was mapped using an Excel macro function.

(2) Results and discussion

The number of Aleyrodidae captured and killed in every two-week period was mapped and is shown in Fig. 11. Many Aleyrodidae appeared from the end of August to the end of September, and most appeared at the end of September. A large number of Sciaridae appeared at the end of August to the beginning of November, with a peak period at the end of August. Many pests appeared around the northern end of the greenhouse. The entrances for the workers and for moving equipment in and out are found in this area, and it is believed that pests entered the greenhouse with people. A countermeasure can be devised for the flow of the workers.

Counting the number of pests caught on the adhesive sheets took a long time and required many images. Therefore, an image data processing method for automating this pest counting process is being developed.

This system is newly installed as a pest-detection unit. By continuously collecting and analyzing data for the pest map, growth diagnosis map, and cultivation environment, the mechanism for a pest outbreak can be clarified, and early and suitable pest control is expected.

Counting the number of pests caught on the adhesive sheets took a long time and required many images. Therefore, an image data processing method for automating this pest counting process is being developed.

Pest-control unit

Recently, ozone water, which has a strong sterilizing power against microbes, has attracted attention in the agricultural sector. It is used to sterilize the nourishing solution for the plants and the greenhouse itself after cultivation (Matsuo, 1993). According to a report on pest control, applying ozone water directly to crops is highly effective in preventing some diseases (Kusakari, 2008).

It has been reported that spraying ozone water is important for prevention (Matsuo and Takahashi, 1994). From this point of view, it is effective to spray ozone water and chemical pesticides to reduce the excessive use of chemical pesticides in solar-power intelligent greenhouses.

A massive reduction in the use of chemical pesticides can be expected by spraying ozone water for prevention and chemical pesticides directly on the area where pests are located, as determined through early detection using the growth-diagnosis unit and pest-detecting unit.

Ozone is a very unstable substance. Thus, when it is sprayed using the type of power sprayer in general use, the problem of a remarkably low ozone water density is seen. In this study, progress was made in the development of a pest-control unit for ozone water spraying, and the spray performance was tested.

1. Ozone water density target

The effective ozone water density for pest control was investigated based on the result of an existing study. It was found that the application of ozone water to the fungus Cladosporium at a density of 0.5 ppm was highly effective (Matsuo and Takahashi, 1994). It used a hand operated power sprayer and found that an ozone-water density of 0.5 ppm was as effective as pesticides on cucumber powdery mildew (Kusakari, 2008).

The intelligent greenhouses that were used in this study have a 1–1.2 m space between rows of plants, and the pest control robot moved between the rows. The ozone water needed to be applied using a method that maintained a density of 0.5 ppm and a spraying distance of at least 60 cm (from the spraying nozzle to the point of application).

2. Ozone water application devices and nozzles

1. Material and method

Ozone water was produced using an ozone water production device made by the Hamanetsu Corporation (How-2-S). A water tank was filled with the ozone water, which was sprayed from a nozzle using an application pump. The initial density of the ozone water was 0.5 ppm. The spraying pump used was a tube pump. This tube pump was op-
erated by a stepping motor, which could control the speed (rpm). The tube pump discharged at a rate of 2.86 ml rev⁻¹, and the discharge pressure was below 0.3 MPa. To investigate the effect of the application pressure and droplet diameter on the ozone water density, four different kinds of application nozzles were tested. The minimum application pressure needed to maintain the application pattern was 0.07 MPa, and this was increased by 0.01 and 0.02 MPa. The ozone water density was measured at 60 cm from the application nozzle. When the ozone water was discharged from the application nozzle, the density of the dissolved ozone decreased as a result of exposure to the air. Approximately 100 mL of ozone water was collected at a distance of 60 cm from the nozzle during spraying, and the dissolved ozone density was measured using an ozonometer (Kasahara Chemical Instrument, 03-3F). Measurements were made at the time of collection (0 min) and 2 min, 5 min, 10 min, and 30 min after collection.

(2) Results and discussion

Figure 12 shows the relationship between the spraying pressure and ozone water density using the four different kinds of spraying nozzles. For each spraying nozzle, a higher spraying pressure resulted in a lower ozone density. This was because when the spraying pressure was low, the droplet particle collision inside the nozzle and discharge port was low and there was less contact with the air. Therefore, to control the decrease in the ozone water density, it is effective to spray with as low a pressure as possible. On the other hand, each nozzle showed a different decrease in the density, and nozzle D was found to maintain the highest ozone water density in the range of pressures used in this test.

Figure 13 shows the relationship between the droplet diameter and ozone water density. For each application nozzle, a larger droplet diameter resulted in a smaller decrease in density. It was found that the density could be kept above 1.0 ppm when the droplet diameter was larger than 200 μm.

Figure 14 shows the relationship between the elapsed time after the ozone water collection and the dissolved ozone density. The density decreases with the elapsed time in each case. The targeted ozone water density of 0.5 ppm was obtained at 4 and 9 min after application with nozzles A and D, respectively. In this experiment, ozone water was collected in a plastic container, but under practical conditions, the density of the ozone water that was sprayed and adhered as dispersed droplets was significantly different. Therefore, the time that the ozone water could exist as droplets was calculated by measuring the average droplet diameter $d$ (μm). The existence time $t$ (s) for an applied particle of a pesticide is calculated as follows. $\Delta T$ is the difference between the dry-bulb and wet-bulb temperatures (Matthews, 2000).

$$ t = \frac{d^2}{80\Delta T} \quad (1) $$

The relative humidity was 80%, dry-bulb temperature was 30°C, wet-bulb temperature was 27°C, and $\Delta T = 3°C$. The lengths of time (t) that droplets sprayed from nozzles A, C and D could exist as particles were 2.2, 5.5 min and 13.6 min, respectively. It was clear that it is necessary to apply ozone water for 5 min at a density of 0.5 ppm to sterilize Fulviafulva (Matsuo and Takahashi, 1994).

Therefore, the nozzle C and D can keep the density of 0.5 ppm for over five min when a mist droplet could exist as a particle of 5.5 for 13 min and it can be expected as a high sterilized effect as chemical pesticide.

3. Specification of pest-control unit

The specifications of the tested prototype are listed in

Table 1

| Spraying pump | Tube pump |
|---------------|-----------|
| Number of nozzles | 5 on one side (10 on both sides) |
| Interval of nozzle | 40 cm |
| Angle of nozzle | 20° |

Fig. 12 Relationship between spraying pressure and ozone water density.

Fig. 13 Relationship between the droplet diameter and ozone water density.

Fig. 14 Relationship between the elapsed time after ozone water collection and dissolved ozone density.
DEVELOPMENT OF A MULTI OPERATION ROBOT

Table 1. The nozzles C and D that met the aimed ozone water density as mentioned before were used.

The running speed of the prototype was 0.3 m s$^{-1}$, and the adhesion rate on actual plants was measured. The positional relation of the prototype and plants is shown in Fig. 15. Water sensitive paper was set on both sides of the leaflets (i.e., small leaves) of the upper, middle, and lower parts of the plant bodies in area 1 to area 2, whereas in area 4, the water sensitive paper was set only on the backs of the leaflets. After spraying, the pieces of paper that had changed color were collected, read by a scanner (Canoscan LiDE 700F), and measured using the original adhesion measuring software.

Figure 16 shows the adhesion rate of the plant body. The adhesion rates of the front of area 1, the back of area 2, and the front of area 3 were better than the back of area 4 (Fig. 16(a), (b)). The causes for this difference include the fact that the scattering of the droplets that arrived at area 4 was disturbed by many leaves.

The adhesion rates of the backs of the leaflets in area 1, surfaces of the leaflets in area 2, and backs of the leaflets in area 3 were poor. However, the spraying in the intelligent greenhouse took place one lane at a time, which meant that the plant bodies were sprayed from both sides. Therefore, estimation results that take this into consideration are shown in Fig. 16 (c), (d). The average adhesion rate was estimated to be 38.6% in the middle of the plant using nozzle C. The worst adhesion rate was found at the backs of the leaflets in areas 1 and 4, for leaves closest to the nozzle. The actual effect of pest control at an average adhesion rate of 38.6% needs to be confirmed using a pest control test. In addition, a method for improving the adhesion rate on the backs of the leaflets closest to the nozzle needs to be examined.

CONCLUSIONS

The growth-information, pest-detection, and pest-control units for a multi-operation robot were developed and effectively linked for the construction of an IPM technology suitable for intelligent greenhouses.

Automated information gathering and various functions were enabled by mounting each unit on an autonomous running unit. Abnormalities could be discovered by mapping the information provided by the growth-information and pest-detection units. This also made it possible to determine the invasion diffusion course of a pest, which made it easy to use an appropriate prophylaxis. Furthermore, a safe environment could be created for workers because the possibility was shown of spraying ozone water as a preventive measure. We can also expect a further reduction in pesticide consumption by adding a function to perform pesticide dispersion locally when pests are detected.

REFERENCES

Kusakari, S. 2008. Control of plant disease by ozonated water-research and development of ozonated water in hydroponics and agriculture (in Japanese). Agric. Technol. 63: 337-344.

Matsuo, M. 1993. Ozone sterilizing for the plant pathogenic fungi in the solution of soilless culture -the case of microconidia of fusarium oxysporum cucumerinum-. J. Jpn. Soc. Agric. Machinery 55: 105-111.

Matsuo, M., Takahashi, R. 1994. Control of tomato cladosporium fungus by ozone water spraying. J. Jpn. Soc. Agric. Machinery 56: 95-99.

Matthews, G. A. 2000. Pesticide Application Methods. Third Edition, Blackwell Science Ltd., London, p 83-87.

Takayama, K., Nishina, H. 2008. Chlorophyll fluorescence
imaging as a plant diagnosis tool in protected horticulture, plant engineering environment. J. SHITA 20: 143–151.
Takayama, K., Nonami, H. 2010. New development of intelligent solar plant factory -New development and measurement of physiological organism-. Agric. Hortic. 5: 563–570.