

Paper:

A Control Method for a Swarm of Plant Pot Robots that Uses Artificial Potential Fields for Effective Utilization of Sunlight

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Plant production factories and agricultural robots are being studied and developed these days. In these cultivation systems, however, it has been difficult to manage the state of each individual plant. We propose a cultivation system that uses a swarm of plant pot robots to automatically move each plant to an optimal environment, based on the plant's sensory information and surroundings. In this paper, we propose a control method for the swarm of plant pot robots that uses artificial potential fields for effective temporal and spatial utilization of sunlight, and we show its effectiveness through simulation and experimentation.

Keywords: plant pot robots system, agricultural robotics, artificial potential fields, swarm robotics

1. Introduction

Plant production factories and agricultural robots have recently been studied and developed to improve plant productivity and reduce agricultural labor cost [1–5]. In earlier cultivation systems, plants were fixed in the ground, and the environment, including the temperature, humidity, and carbon dioxide concentrations, were controlled by air conditioners or other means. However, it has been difficult for such systems to control the state of each individual plant. We propose a cultivation system that uses a swarm of plant pot robots that automatically move to an optimal environment based on sensory information from each plant and the surrounding environment, and we aim to realize a system capable of maximum utilization of sunlight.

Kawakami et al. [6] developed a mobile robot that supported a potted plant. This robot, called PotPet, automatically moved to communicate with people like a pet. Our research envisions a swarm of these plant pot robots to create an efficient cultivation system. In this paper, we propose control methods for the swarm and present trials studying the effects of crowding on successful mobility. We have adopted an artificial potential field method to control individual plant pot robots. The method, proposed in the 1980s [7], has been widely used in various applications of swarm robots, and there have been many investigations and improvements, including clarifying lim-

itations mathematically [8] and avoiding local minimum problems [9, 10]. The main focus of the paper is not the potential field method; our proposed application is very different from previous applications of the method in several points. In our proposed application, the goal of each robot is not a point but an area, and obstacles are also moving, so we basically don't have to worry about local minimum or deadlock problems.

2. Effective Temporal and Spatial Utilization of Sunlight

In order to maintain the high photosynthetic capability of plants, or, to make plants grow, the following important factors for effective temporal and spatial utilization of sunlight can be considered.

- High-density placement of plants in the sun
- Location changes of the plants between the sun and the shade

Regarding the high-density placement of plants in the sun, we seek to increase the photosynthetic capability of plants effectively in spatially limited areas by locating plants densely in sunny places. However, when the temperature of the leaf surface gets too high due to continuous strong sunlight, the photosynthetic capability of plants declines [11, 12]. Our proposal also targets a system in which plants under the above conditions are moved to the shade, while plants in the shade are moved into the sun. Ultimately, we seek a system in which plants can be alternately repositioned between sun and shade as needed, based on their individual requirements.

Using these methods, we can optimize the photosynthetic capability of the plants per unit time per unit area. This in turn will promote the growth of the plants, increase their yields, and increase the amount of carbon absorbed.

3. The Proposed System of a Swarm of Plant Pot Robots

A schematic illustration of the “swarm of plant pot robots system” is shown in **Fig. 1**. The system consists



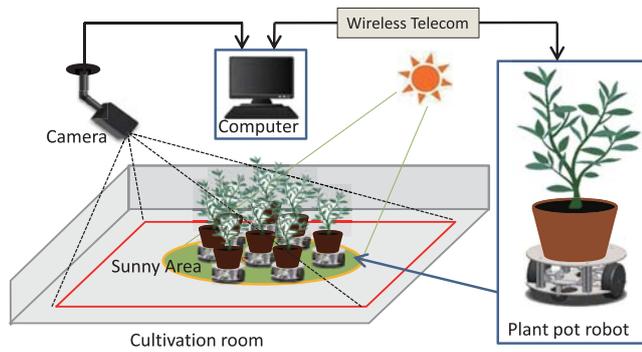


Fig. 1. Proposed cultivation system using swarm of plant pot robots.

of a camera fixed on the external environment, the control computer, and the swarm of plant pot robots. The control computer calculates the location and shape of the sunny place, obstacles, and plant pot robots based on the visual information from the camera. In addition, various sensors, such as soil moisture sensors, illuminometers, thermometers, and others, are installed on the plant pot robot to observe the conditions of each plant. Information from the sensors is transmitted to the control computer. The control computer calculates control commands for the plant pot robots based on the sensory information and transmits the commands to the robots.

4. Control of the Swarm of Plant Pot Robots Using Potential Fields

In this paper, we propose a movement control method using a potential field method for the swarm of plant pot robots. Potential field methods for robotic applications were first described by [7] and have frequently been used with mobile robots for tasks such as navigation and obstacle avoidance. Potential field methods generate artificial potential fields, such as mountains and valleys, based on environmental information, such as the positions and shapes of obstacles as well as robots. In the method, a robot is navigated to the target position using virtual forces, such as attraction and repulsion, based on the slope of the artificial potential fields. In this case, artificial potentials are described as follows:

- Attractive potential to navigate the robot to a target position
- Repulsive potential to avoid collisions with obstacles

To utilize sunlight effectively using the two methods written in Section 2, we design the attractive potential based on the sunny place and the repulsive potential to avoid collisions of the robot with the other robots and obstacles.

Our goal is to achieve effective sunlight utilization through high-density plant pot placement in sun or shade as needed. The potential field method is employed for this goal by identifying sunlight with an attractive potential

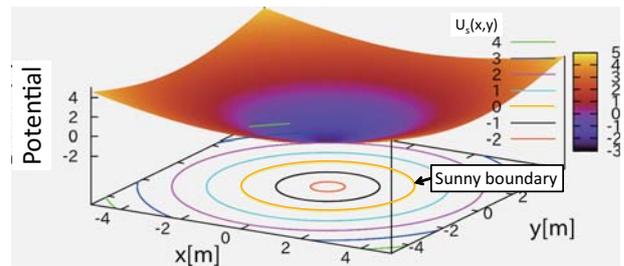


Fig. 2. The sunny potential field is designed to attract plants to sunny places.

and identifying the proximity of neighbors and obstacles with a repulsive potential to avoid collisions.

4.1. Designing the Sunny Potential Field

The sunny potential field U_s (an attractive potential) is designed to be able to get a mobile robot to move to a sunny place (Fig. 2). In this paper, we assume that the robot moves in a two-dimensional (2-D) workspace. Its position in the workspace is denoted by $\mathbf{q} = [x \ y]^T$.

Different attractive potential functions have been proposed in the literature. The most commonly used attractive potential takes the form [7–15], described below.

$$U_{att}(\mathbf{q}) = \frac{1}{2} \xi \rho(\mathbf{q}, \mathbf{q}_{goal})^m \dots \dots \dots (1)$$

where ξ is a positive scaling factor, $\rho(\mathbf{q}, \mathbf{q}_{goal}) = \|\mathbf{q}_{goal} - \mathbf{q}\|$ is the minimal distance between the robot \mathbf{q} and the goal \mathbf{q}_{goal} , $m = 1$ or 2 . For $m = 1$, the attractive potential field is conical in shape. For $m = 2$, the attractive potential field is parabolic in shape. Although the purpose of the previous attractive potential fields was to navigate the robot to a target position, the sunny potential that we propose aims to navigate the robot to the sunny place. The major difference is whether the target is a point or an area. We design the sunny potential field based on any shape of boundary between the sun and shade. The sunny place is denoted by Ω . We define the sunny potential U_s as follows:

$$U_s(\mathbf{q}) = \begin{cases} -\rho_{min}(\mathbf{q}) & (\mathbf{q} \in \Omega) \\ \rho_{min}(\mathbf{q}) & (\mathbf{q} \notin \Omega) \end{cases} \dots \dots \dots (2)$$

where $\rho_{min}(\mathbf{q})$ is the minimal distance between the robot \mathbf{q} and the boundary between the sun and shadow. Accordingly, the sunny potential field U_s is 0 on the boundary, and its gradient is 1 in the normal direction of the boundary curve.

4.2. Designing the Potential Field Between Robots

We install a potted plant on the mobile robot. It is assumed that there are plants of various sizes, so the repulsive potential field between the robots should be designed to keep the robots carrying plants of different sizes from colliding. In this paper, we assume that the shape of each plant pot robot viewed from above is a circle, and we design the repulsive potential field in consideration of each

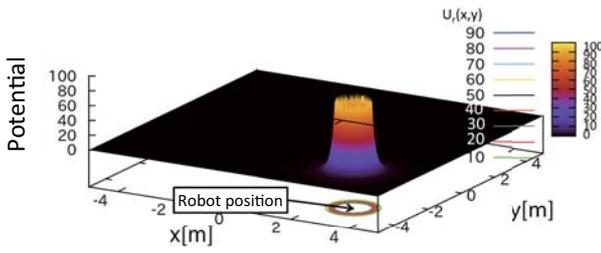


Fig. 3. The robot potential field is designed to avoid collisions and is adjusted to match the plant radius.

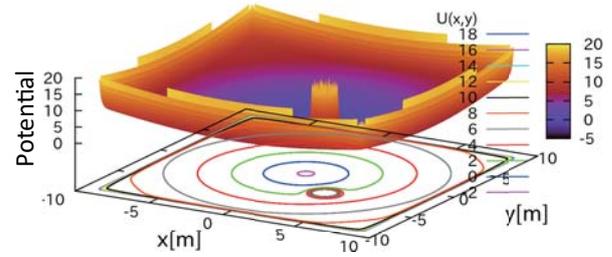


Fig. 5. The total potential field.

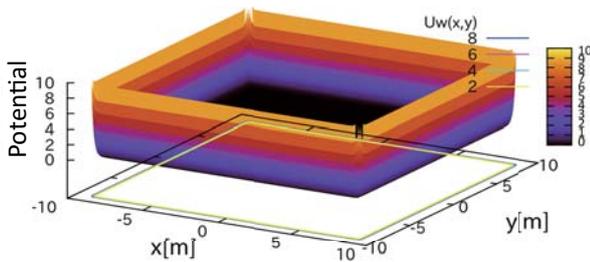


Fig. 4. The wall potential is a repulsion designed to avoid collisions of the robot with the walls.

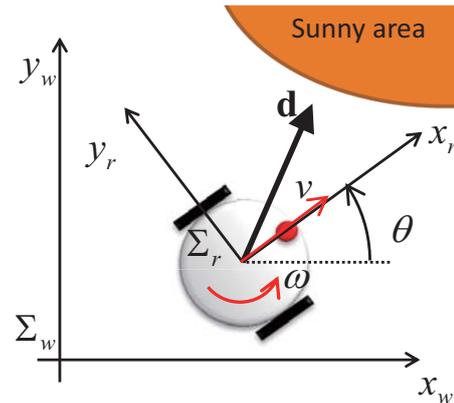


Fig. 6. Relations of coordinate systems between robot and world coordinate.

diameter. We define the repulsive potential field ${}^jU_{ri}$ as follows:

$${}^jU_{ri} = \frac{a(d_i \cdot d_j)^b}{\rho(\mathbf{q}_i, \mathbf{q}_j)^c} \dots \dots \dots (3)$$

where $\rho(\mathbf{q}_i, \mathbf{q}_j) = \|\mathbf{q}_j - \mathbf{q}_i\|$ is the distance between the robot \mathbf{q}_i and the robot \mathbf{q}_j . d_i and d_j correspond to each diameter of the robots. Based on the simulation results of the following section, we determined $a = 3.0$, $b = 3.0$, and $c = 6.0$ to be suitable choices. Assuming that d_i and $d_j = 1$, $\mathbf{q}_j = [3 \ -3]^T$, **Fig. 3** shows that the repulsive potential field ${}^jU_{ri}$, generated by the robot \mathbf{q}_j , affects the robot \mathbf{q}_i . By making its gradient steep near the robot \mathbf{q}_j , we design the field so that the robots can be placed very closely together but still without colliding.

4.3. Designing the Wall Potential Field

The wall potential field is designed to avoid collisions of the robots with the walls. We define the repulsive potential field $U_{wk}(\mathbf{q})$ as follows:

$$U_{wk} = \frac{1}{\{\rho_k(\mathbf{q})\}^d} \dots \dots \dots (4)$$

where $\rho_k(\mathbf{q})$ is the distance between the robot \mathbf{q} and the wall k . Assuming that $d = 12$, **Fig. 4** shows that the repulsive potential field $U_{wk}(\mathbf{q})$ generated by $x_1 = 10, x_2 = -10, y_1 = 10$ and $y_2 = -10$ affects the robot \mathbf{q} .

The total potential field U_i that finally affects the robot \mathbf{q}_i is given by:

$$U_i = U_s + \sum_{j \neq i} {}^jU_{ri} + \sum_k U_{wk} \dots \dots \dots (5)$$

Adding up the potential fields of **Figs. 2, 3,** and **4** gives the total potential field U_i which is shown in **Fig. 5**.

4.4. Velocity Control of the Robot Based on an Artificial Potential Field

Potential field methods determine the speed reference given to the robot by using the steepest descent direction of potential fields. In this section, we assume that the robot is a differential two-wheeled robot, and we determine its speed reference based on the potential fields. The schematic illustration of relations of coordinate systems is shown in **Fig. 6**.

The steepest descent direction \mathbf{d}_{wi} of the robot i in world coordinates Σ_w is given by

$$\mathbf{d}_{wi} = -\nabla U_i = - \begin{bmatrix} \frac{\partial U_i}{\partial x_{wi}} \\ \frac{\partial U_i}{\partial y_{wi}} \end{bmatrix} \dots \dots \dots (6)$$

Accordingly, the steepest descent direction \mathbf{d}_i in the robot i coordinates Σ_i is given by

$$\mathbf{d}_i = {}^i\mathbf{R}_w \mathbf{d}_{wi} = - \begin{bmatrix} \frac{\partial U_i}{\partial x_i} \\ \frac{\partial U_i}{\partial y_i} \end{bmatrix} \dots \dots \dots (7)$$

where ${}^i\mathbf{R}_w$ is the rotating matrix to transform Σ_w into Σ_i .

The speed reference $\mathbf{V}_i = (v_i \ \omega_i)^T$ for the robot i based on \mathbf{d}_i is given by

$$\mathbf{V}_i = \mathbf{K} \mathbf{d}_i \dots \dots \dots (8)$$

$$\mathbf{K} = \begin{bmatrix} k_v & 0 \\ 0 & k_\omega \end{bmatrix}$$

where k_v and k_ω are constant parameters for adjusting the translation velocity and turning angular velocity. According to Eq. (8), the velocity control of the differential two-wheeled robot can be done onboard by a simple algorithm that adjusts wheel speeds based on the theta angle and total potential gradient.

4.5. Possible Problems of the Potential Field Method

Although the potential field method has the problem of local minima, it would not be a serious problem in the case of realizing high-density placement of plants in the sun. Because the boundary shape between the sun and shade always changes, trap situations due to local minima are temporary, and we can expect a kind of simulated annealing effect. In addition, since the goal for each robot is not a point but just an area, the probability that every robot can reach the goal without being trapped by local minima is comparatively high.

Yet another difference we should note is that in most previous applications of the potential field method, the obstacles did not move. In our application, obstacles are also plant pot robots and are also affected by all other agents. The behavior of the swarm is similar to that of a gas which consists of numerous particles (gaseous molecules). Therefore, we do not need to be so careful about problems such as local minima or deadlock.

5. Simulation of the Swarm of Plant Pot Robots

In this section, we simulate moving the swarm of plant pot robots by using artificial potential fields designed in the previous section, and we demonstrate an effective utilization of sunlight.

In the following simulations, we assume that each plant pot robot has separately driven two wheels and that its location can be accurately observed. The workspace is 20 m × 20 m, and the diameter of each plant ranges from 0.5 m to 1 m. For simplicity, we draw only the robot without the plant and assume that the robot size is equal to the plant size.

5.1. Simulation of High-Density Placement in a Sunny Place

In order to utilize the sunlight effectively, we succeed in putting the plant pot robots in a spatially limited sunny area. The results of the high-density placement simulation of plant pot robots in the sun is shown in Fig. 7. The initial position of each robot is scattered around the workspace. By moving to the sun by using the potential fields, as written in the previous section, every robot

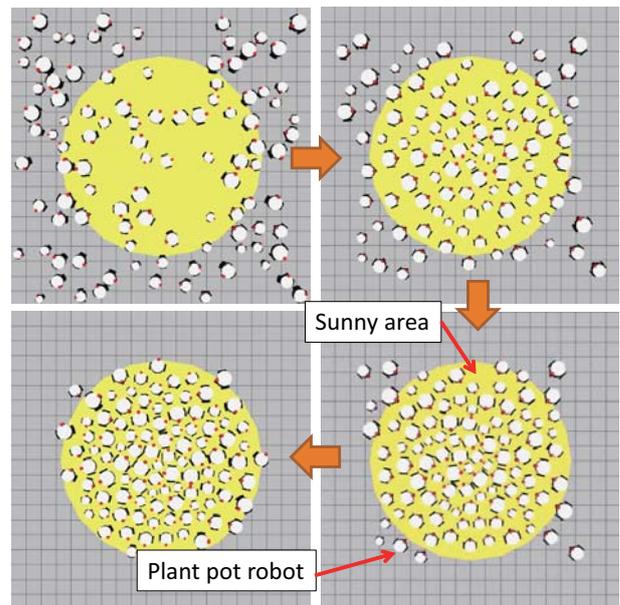


Fig. 7. High-density placement simulation of plant pot robots in a sunny place.

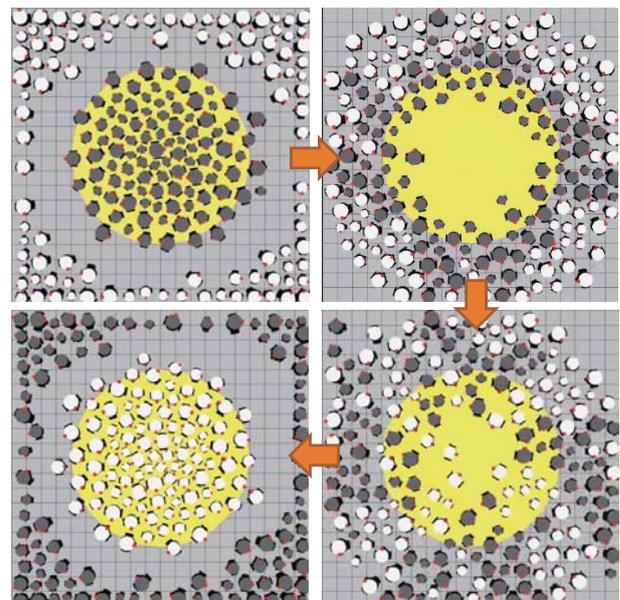


Fig. 8. Simulation of changing places of plant pot robots between the sun and shade.

can finally be placed in close proximity in the sunny area without colliding with the other robots.

5.2. Simulation of Changing Places of Plant Pot Robots Between the Sun and Shade

When the temperature of the leaf surface gets too high (e.g., when sunlight is strong and continuous), the photosynthetic capability of plants declines. Accordingly, plants under the above conditions should be moved to the shade, while plants in the shade should be moved into the sun. The results of the simulation of changing places is shown in Fig. 8. Every white plant pot robot, whose plant

is capable of photosynthesis, moves to the sunny place, while every black plant pot robot, whose plant is incapable of photosynthesis, moves to the shade. Moving to the shade can be realized by inverting the sign of the sunny potential. The simulation results show that changing the places of plant pot robots is feasible in a high-density workspace.

5.3. Simulation of Changing Places Based on the Model of Photosynthetic Capability

In order to maintain the high photosynthetic capability of plants, plants should be alternately repositioned between sun and shade based on their individual requirements. In this section, we design a model of photosynthetic capability of plants and propose a control method based on the model. Finally, we show its effectiveness through a simulation involving changing places.

5.3.1. Modeling of Photosynthetic Capability

Photosynthetic capability dependent on leaf temperature is described in detail in [12], which defines a photosynthetic model. Although the photosynthetic model is related to various parameters, we assume for simplicity that the model is only related to leaf temperature and is a quadratic function. We define the model relating photosynthetic capability P_c to leaf temperature T as follows:

$$P_c(T) = -\frac{P_{\max}}{(T_{\text{sat}} - T_{\text{opt}})^2}(T - T_{\text{opt}})^2 + P_{\max} \quad \dots (9)$$

where P_{\max} is maximum photosynthetic capability, and T_{sat} and T_{opt} are high and optimal leaf temperature, respectively. When the leaf temperature T rises to T_{sat} , photosynthetic capability P_c becomes zero. When the leaf temperature T is equal to T_{opt} , photosynthetic capability P_c becomes maximum capability P_{\max} .

In order to maintain the high photosynthetic capability of plants, every plant pot robot that is low in temperature should be given priority to move into the sun, while every robot which is high in temperature should get out of the sun. In order to realize such conditions, we introduce a parameter K_{grad} adjusting the gradient of the sunny potential ∇U_s , and we replace ∇U_s by $K_{\text{grad}(i)}\nabla U_s$ for each robot (i). We define K_{grad} as follows:

$$K_{\text{grad}}(T_i) = -\frac{T_i - (T_{\text{opt}} + T_k)}{T_{\text{sat}} - (T_{\text{opt}} + T_k)} \quad \dots \dots \dots (10)$$

where T_i is the average temperature of the leaves of each robot i , and T_k is a temperature offset. If T_i is less than $(T_{\text{opt}} + T_k)$, the plant pot robot i will move into the sun. If T_k is set to a greater value, robots will have more desire to move into the sun. By suitably determining T_k , plants with high photosynthetic capability will want to go inside the sunny area.

5.3.2. Simulation Results

In this simulation, we assume that every leaf temperature changes according to a constant temperature chang-

ing ratio $K_{\text{tmp}} = dT_i/dt$ [$^{\circ}\text{C}/\text{s}$] (differentiation of temperature by time) in the sun or shade. We define K_{tmp} as follows:

$$K_{\text{tmp}} = \begin{cases} \frac{T_{\text{sun}} - T_{\text{shade}}}{\tau} & (T_{\text{shade}} < T_i < T_{\text{sun}}) \\ 0 & (T_i \leq T_{\text{shade}} \text{ or } T_{\text{sun}} \leq T_i) \end{cases} \quad (11)$$

where τ is a parameter representing leaf temperature changes, T_{sun} is the maximum leaf temperature in the sun, and T_{shade} is the minimum leaf temperature (i.e., room temperature). In the sun, the leaf temperature rises linearly to T_{sun} according to K_{tmp} with time. In the shade, the leaf temperature falls to T_{shade} also. By using this K_{tmp} as the gradient coefficient $K_{\text{grad}}(T_i)$, the gradient based on the sunny potential for each robot i becomes $K_{\text{grad}}(T_i)\nabla U_s$.

The results of the simulation of changing places based on the model of photosynthetic capability are shown in **Fig. 9** and **10**. The photosynthetic capability of each robot is indicated by its color: black is lowest and white is highest. The color of the head of the robot indicates leaf temperature, which is generally higher in the sun and lower in the shade. We chose $P_{\max} = 1.0$, $T_{\text{opt}} = 30^{\circ}\text{C}$, $T_{\text{sat}} = 50^{\circ}\text{C}$, $T_{\text{shade}} = 20^{\circ}\text{C}$, $T_{\text{sun}} = 45^{\circ}\text{C}$, $T_k = 7^{\circ}\text{C}$, $\tau = 300$ s, and $k_v = k_{\omega} = 0.8$. The sun is 12 m in diameter, and there are 250 robots. The initial leaf temperature for every robot is T_{min} .

Figure 9 shows two simulations. One (lower row) is changing places of plant pot robots based on the photosynthetic model by using Eqs. (9) and (10), and the other (upper row) is changing places not based on the model. For non-model-based place changes, plant pot robots are divided into two groups and change places every 300 seconds, as mentioned in Section 5.2. The photosynthetic capability and the leaf temperature of the plant is represented by the color of the robots in the simulation. At $t = 100$ s to 150 s, the leaf temperature of the plants in the sun rises to T_{opt} . For model-based place changes, robots with rising leaf temperatures gradually move out of the sun. As a result, it is possible to maintain the high-density placement of high photosynthetic capability plants in the sun.

Figure 10 shows the average of the photosynthetic amount per unit time in the simulation (**Fig. 9**). We define a photosynthetic amount as the integral of photosynthetic capability P_c over the time the robot is in the sun. It shows that changing places by using the model can maintain the highest photosynthetic amount.

5.4. Simulation of High-Density Placement Based on Sunny Place Detection by Image Processing

We performed an experiment using a real camera and virtual plant pot robots, as shown in **Fig. 11**. We sought to move the plant pot robots to a sunny area of any shape based on images from a camera fixed on the ceiling. We got images from the camera fixed on the ceiling and detected the boundary between the sun and the shade based on image processing by using OpenCV, an image pro-

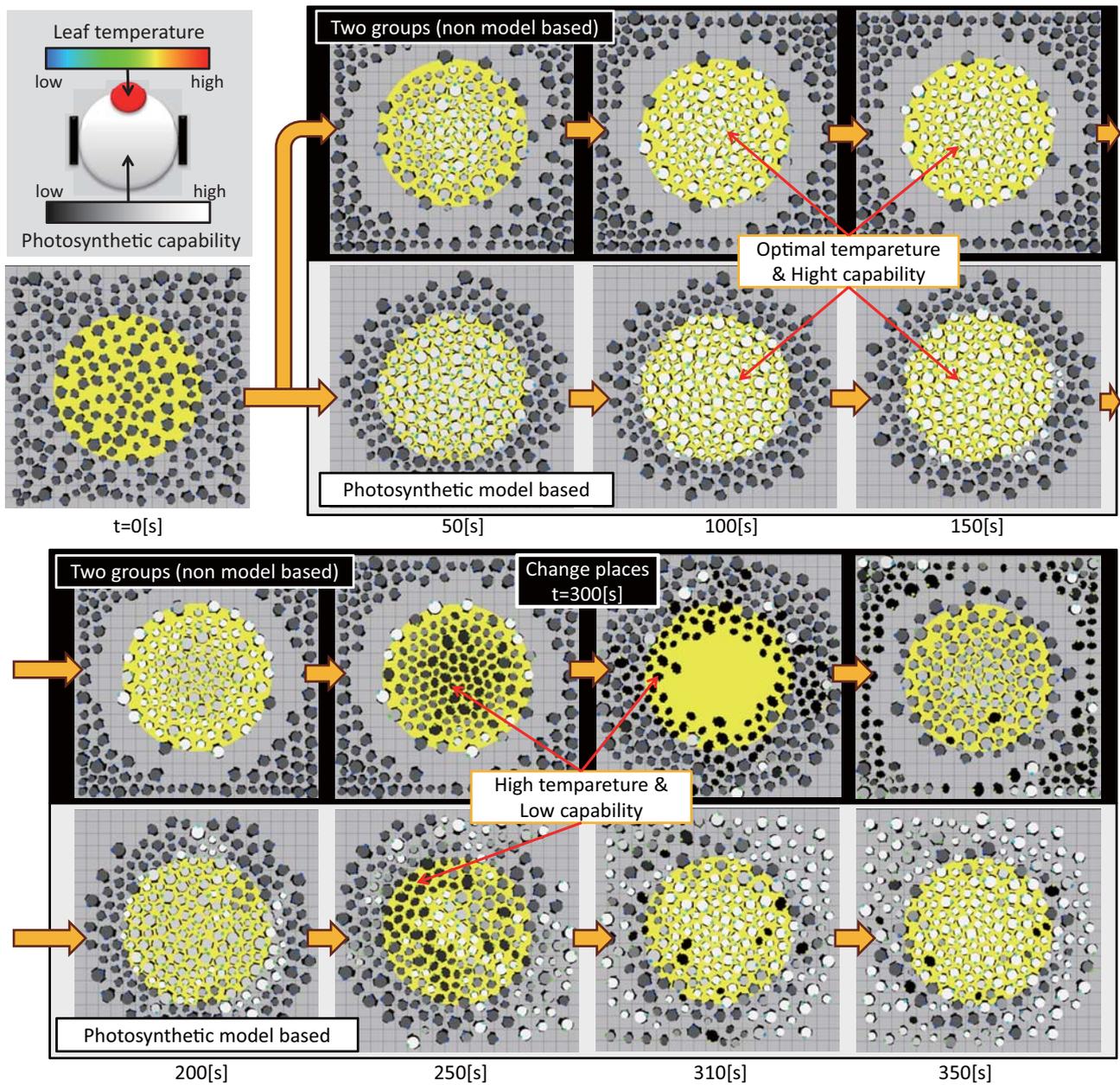


Fig. 9. Simulation of changing places of plant pot robots based on a photosynthetic model.

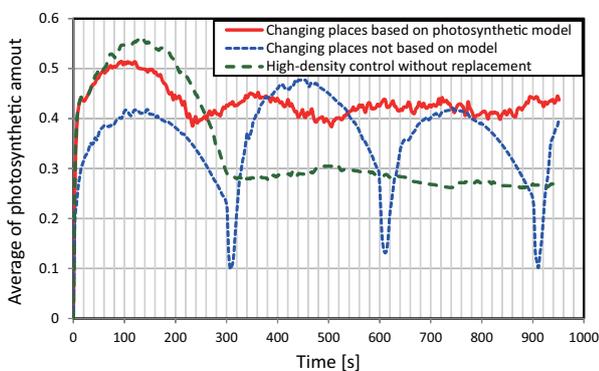


Fig. 10. Average photosynthetic amount per unit time.

cessing library. We generated a perspective-transformed image which was viewed from above, and we detected sunny places based on their brightness. The sunny potential field was generated using the sunny place boundary. The results of the experiment showed the capability of high-density placement in sunny places of any shape by using a real camera.

In a real workspace, there might be plural sunny area of different sizes, and a robot might go to a smaller sunny place crowded with other robots. In such a case, however, it would be easy to determine where the robot should go, because we could calculate the size and state of congestion of every sunny area by using the ceiling camera.

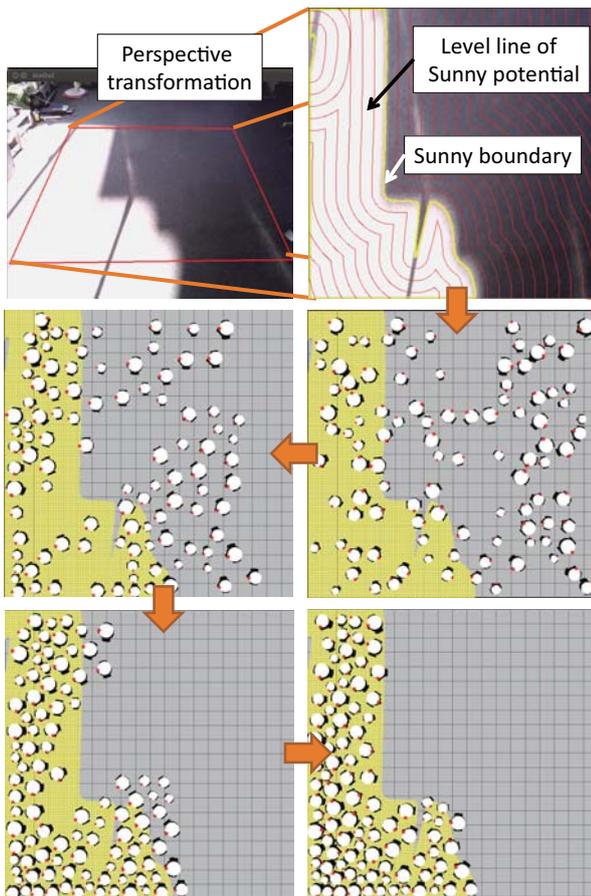


Fig. 11. Simulation of high-density placement based on image processing to detect sunny place.

6. Experimental Evaluation of the Control Method

Finally, we performed a preliminary experiment involving high-density placement in the sunny area and using real mobile robots in a real workspace. We manufactured mini plant pot robots to experimentally evaluate the control method. **Fig. 12** shows the setup of the experiment and one of the plant pot robots. The experiment consisted of four mini plant pot robots, the ceiling camera, and a control computer. Each plant pot robot communicated with the control computer via the XBee module incorporating the ZigBee networking protocol. As red and blue markers installed on each robot were detected by the ceiling camera, visual information was used to localize each robot. The control computer calculated control commands for the robots based on the visual information and transmitted the commands to each robot. The workspace was $900 \text{ mm} \times 670 \text{ mm}$, and we assumed that the diameter of every robot was 120 mm . To simplify the robot localization, we didn't install a real plant on each robot.

Figure 13 shows the experiment of the high-density placement in the sunny area. The results show the capability of the robot to move to the sunny area while avoiding collisions with other robots in the same way as in the simulation.

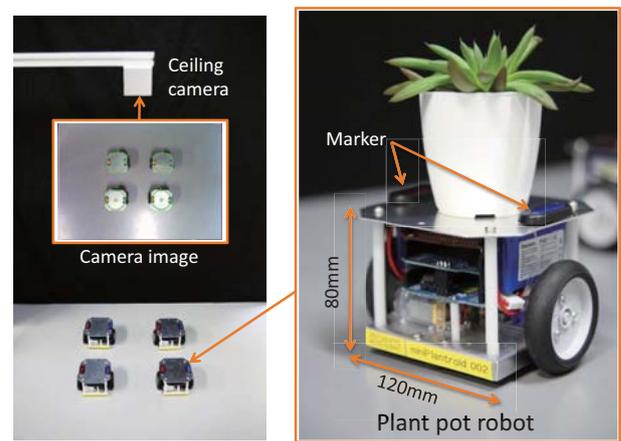


Fig. 12. Experimental setup consisting of the ceiling camera and mini plant pot robots.

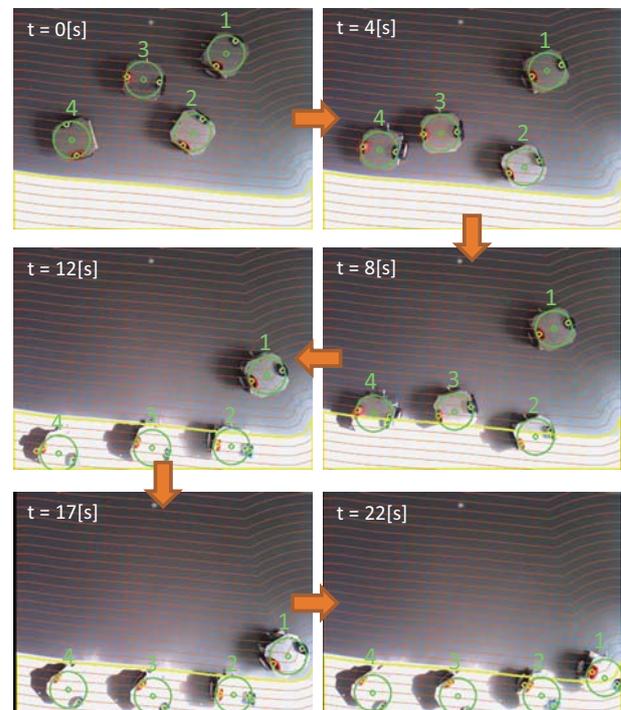


Fig. 13. A preliminary experiment of high-density placement by using real mobile robots.

7. Conclusion

In this paper, we proposed a method for controlling a swarm of plant pot robots by using artificial potential fields to realize a cultivation system that utilizes sunlight efficiently. For effective temporal and spatial utilization of sunlight, we designed the sunny potential field to navigate each robot to the sunny place based on the distance from the robot to the boundary between the sun and shadow. The simulation showed that it was possible to realize densification in the sunny area and change the placement of robots if potentials were appropriately designed. We proposed the control method based on the photosynthetic model and conducted a simulation of

changing places based on the model to show that it was possible to maintain high photosynthetic capability. We manufactured mini plant pot robots and verified the control method in a preliminary experiment involving concentrating robots in a sunny area detected by a real camera.

Energy efficiency is one of the most important factors in our research. In general, this paper has discussed how to increase the utilization of a given light source (sun or artificial light) for photosynthesis. Using plant pot robots requires more energy than not using them. The important question is whether the increase in the storing of light energy (to photosynthesize is to store light energy as carbon compounds) is greater than the increase in the energy consumption by the robots or not. We have not yet confirmed it, but we believe the answer may very possibly be yes. One of our future works will include verifying the effectiveness of the proposed method through practical experiments using plant pot robots on which real plants and various sensors are installed. Marker occlusions and overly bright sunlight will also be issues. In the future, it would be better for the robots to also consider other environmental conditions, such as the CO₂ density gradient.

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Main Works:

- M. Yuasa and I. Mizuuchi, "A Control Method of a Swarm of Plant Pot Robots for Utilization of Sunlight Based on Photosynthetic Property and Preliminary Experiment by Using Real Robots," in *Proc. of the 2013 JSME Conf. on Robotics and Mechatronics*, 2P1-F03, 2013.
- M. Yuasa, S. Nishiki, and I. Mizuuchi, "Development of Autonomous Movable Fruit Growing Plantroid," in *Proc. of the 2013 JSME Conf. on Robotics and Mechatronics*, 1A1-Q05, 2013.

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