Plant Factory System Construction: Cultivation Environment Profile Optimization

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A multi-functioned small scale plant production system was constructed using the speaking plant approach (SPA) as a basis. The optimal plant cultivation environmental conditions have been studied by many researchers, however this report details the experiment and results taken from an automated self-optimizing control system. Unlike the systems used in standard high yield plant factories, this system was designed to determine optimal environmental parameters. Criteria such as air composition, nutrient solution concentration, and lighting conditions were measured and optimized for numerous plant breeds. Through the use of color webcams and sensor data, statistics for many plants were obtained. The measured data was then turned into a profile intended to be used for controlling future growth. Profiling gave the system the unique ability to predetermine the most suitable environmental conditions for each plant. Large scale plant factory running costs are expected to reduce with the use of this profile, scheduling, real time environmental data, and plant growth images. This system also supplied and stored the obtained environmental parameters to a database on a CLOUD server. From the CLOUD server, that information could be offered, in real time, to business associates and other end users.

Keywords : ECHONET, environmental control, environmental profile, multi-sensor, plant factory

INTRODUCTION

For this research, an automated plant cultivation environmental control system (SEED-N) was developed. The purpose of the system was to supply agricultural produce on demand. To achieve this, production stability, planning, and year round unchanging production costs are required. Since these plant breeds produced in the factory must be safe for consumption it is important to also establish a traceability plan that can guarantee the quality.

This developed SEED-N system utilizes the basic concepts of speaking plant approach (SPA) (Hashimoto, 1989; Hashimoto, 2013; Takayama, 2013). Many researchers have proposed optimizing environmental conditions for plant cultivation (Takatsuji, 1997; Ikeda, 2009; Takatsuji, 2010; Okada et al., 2011). Unemura et al. (2013) conducted the initial SEED-N prototype validation. The system used in this paper is a modified version of the original prototype. It was a small, lightweight system developed to create and utilize optimized profiles of environmental conditions to enhance plant growth. The system could create individual profiles for each plant by continuously monitoring distinct parameters such as cultivation state, nutrient solution concentration, air composition, and lighting settings.

In particular, this system had a special nutrient solution management sub system. The sub system measured the many different ion sensors and saved the data to the environmental profile. From the profile, the ion concentration could be modified to best suit plant growth.

This environmental profile was optimized by correlating recorded images from a web camera (webcam) to measured environmental data. All the profile parameters could also be modified and executed at any time during system operation. The profile data was intended to be used to streamline product management in a plant factory by predetermining the most suitable environmental adjustments. For companies with high yield cultivation sites, this system could ultimately reduce production costs.

The SEED-N system also had the unique characteristic that all sensors and actuators could communicate via a wireless network. As a result, necessary wiring was substantially reduced and the control hardware needed to run a complete plant factory required minimal space, especially for factories simultaneously growing different plant breeds. From the PC, the complete system operation could be handled remotely with a standard remote virtual private network connection. The optimal environmental control parameters could easily be selected or modified through the CLOUD database simply by providing a user with a network connection.

MATERIALS AND METHODS

System construction

Figure 1(a) shows an overview of the SEED-N plant cultivation environmental system, while Fig. 1(b) shows the actual system implementation. The room dimensions for the SEED-N system is 5.6 m (width), 2.0 m (depth), and 3.0 m (height). The system sits on a purpose built rack of

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the following dimensions: 1,700 mm (width), 800 mm (depth), and 2,100 mm (height). The overall weight is roughly 140 kg. Casters are attached to the bottom of the rack for easy mobility. The system consists of four cultivation bed rows. Each row holds 11 separate cultivation pots, each 75 mm in diameter. Within each pot a 15 mm square of rock wool is inserted. Using the rock wool allows each plant to grow continuously in the same pot. This is accomplished by placing a black cover over the pot during germination to block light until the seed sprouted. After sprouting, the plant can remain in the same location until harvest time.

The morphogenesis of different plants grown in close

(a) SEED-N system details.

(b) SEED-N system actual implementation.

Fig. 1 SEED-N system overview. (a) SEED-N system details. (b) SEED-N system actual implementation.

proximity can cause interfere with each other. However, this system is not intended for mass cultivation in a plant factory, so different plants were grown in the same row. The lanes were designed so that the spacing between the pots could be adjusted to accommodate varied plant growth.

To evaluate plant growth, the system is equipped with three webcams. The webcams monitors plant morphogenesis and allows for remote viewing of the plant biometrics. The user can manually optimize the profile parameters, either during or after the cultivation period, through correlating the webcam images with the measured environmental data. Then the profile parameters can be modified to optimize plant growth for any part of the growth stage. The future plan is to develop an algorithm that can correlate the plant leaf area and chromaticity component information from the webcam image data to the environmental data from the multi-sensor and bioelectric potential signals. Then use that information as a biofeedback controller to automatically optimize the environmental conditions and nutrient solution concentration within profile.

The SEED-N system differs from conventional cultivation systems. Conventional systems discretely manage each parameter individually. The SEED-N system combines all measured environmental data. Then, the developed algorithm controls the environment. For example, while applying light stimulation the algorithm will also realize effects on air temperature due to radiated heat from the lights, and will pre-emptively control the air conditioner if necessary. As all actuator control comes from the same source, complex parameters such as water temperature, air temperature, and light timing are continuously calculated and the various actuator conditions are decided simultaneously in order to yield optimal environmental control. The basic system operation is as follows: First, the measured sensor data was compared to the environmental profile. Then the actuators are manipulated in response to the comparison results. The actuators operated instruments such as the air conditioners and LED lights that are responsible for maintaining the optimal cultivation environment.

Hardware architecture

Figure 2 shows the verification system structure, while

Fig. 2 System structure.

Fig. 3 shows an outline of the system architecture. The wireless block, nutrient control block, and the four color independent light source block are all accessed through middleware (software) on the computer. The collected environmental data and profile are compared and all the information is sent to the CLOUD server. The program construction in Fig. 4 shows the separated control process and user interface. The CLOUD server is used to share the information between the two. The built in system characteristics are then verified by the devices listed below.

Wireless network

The network system is a flexible wireless module installation, compliant with the IEEE802.15.4 protocol. This low power protocol was selected because it has a maximum power rating of 50 mW during normal operation, and a 5 μ W rating during sleep mode. This module con-

Fig. 3 System architecture. The environmental profile was compared to the growth evaluation algorithm and the resulting information was fed back into the profile. The actuator conditions were decided from the newly adjusted environmental profile. The measured parameter data was saved to a database and the growth conditions were analyzed for links between the image data and environmental conditions.

Fig. 4 System control process and user interface.

sumed the least amount of energy in the 2.4 GHz communication band and is suitable for battery based applications. Furthermore, the maximum transfer rate of 667 kbps is sufficient for most sensor networks. The transfer standard called ECHONET (Energy Conservation and Homecare Network), was made for home networking and HEMS (Home Energy Management Systems). ECHONET was selected because it offers standards for many different sensor and actuators, while allowing the user to easily define standards for unsupported sensors. ECHONET was also based on open standards, which reduced overall development costs.

Multi-sensor and actuators

Figure 5 shows the compact, low energy consumption multi-sensor (PLML-S-101 SAKATECHONO science. Co., LTD., Japan). This sensor combines four environmental parameters (temperature, humidity, CO₂ concentration, and light intensity) into one unit. This multi-sensor offers the benefits of reduced installation costs, reduced overall size and weight, and increased ease of maintenance. The sensor is also compatible with the wireless network, which reduces the required installation area and wiring. The multi-sensor dimensions were 65 mm (width), 135 mm (length), and 38 mm (height). The small size can keep the sensor out of the way of growing plants within small plant factories, even if more than one sensor is installed.

Actuators

Based on the environmental data measured from the multi-sensors, the environmental conditions are controlled via actuators. To adjust the air conditions, actuators operate the air conditioner, humidifier, de-humidifier, air circulation fans, and CO₂ solenoid valve. The actuators used in this system (Prototype SAKATECHONO science. Co., LTD., Japan) are an original design developed to work with consumer grade equipment, thus reducing installation and customization costs.

The air temperature is managed through a consumer grade air conditioner (MS2-GY402S-W Mitsubishi). The SEED-N system automatically controls the air conditioner with an actuator module in place of the standard manually operated controller. The air conditioner actuator module is a specifically designed IR (infra-red) type controller (Prototype SAKATECHONO science. Co., LTD., Japan). The module only requires power and direct-line of sight to the air conditioner. The internal air temperature, humidity, and nutrient solution temperature within the cultivation

Fig. 5 Wireless multi-sensor. (Temperature, Humidity, Light Intensity, CO₂).

rows, are all factored into the air conditioner settings when the command is sent to the IR actuator module.

The humidifier (JH-750 TEKNOS), de-humidifier (VS-502 Versos), and air circulation fans (HFT-2114 CCP) are also consumer grade equipment. All are attached to separate actuators. Operations for these three units are controlled by sending the monitored air humidity and temperature data to the algorithm. The results from the algorithm are then sent through a software based switch node. As a result, the wireless actuator modules are manipulated to maintain the desired environmental parameters.

The CO₂ concentration is measured by the multi-sensor and the resulting data is used to wirelessly control the CO₂ cylinder solenoid valve (PLCOC-101 SAKATECHONO science. Co., LTD., Japan). The CO₂ concentration is set at a range between 800 ppm to 1000 ppm during photosynthesis, when the lights are on. Otherwise the CO₂ concentration is reduced. However, during dark conditions, the CO₂ tends to remain around 600 ppm to 700 ppm because the system is well sealed from external air conditions and CO₂ cannot easily escape.

Nutrient solution management block

The SEED-N's nutrient solution control system (Prototype SAKATECHONO science. Co., LTD., Japan) maintains the total concentration of ions (EC), dissolved oxygen, and the optimal pH range for ion absorption by plant roots. It is possible to further optimize the nutrient solution by discretely measuring each individual ion in the solution. Continuously measuring separate nutrient solution components with off-the-shelf sensors pose maintenance and conditioning problems for the sensors. When the sensor probe remains immersed in the nutrient solution, the internal base compound deteriorates over time. Sensor chip deterioration is also a concern with this type of system because the expensive sensor chip would have to be replaced every few weeks to remain in the nutrient solution. To help keep the sensors properly conditioned, the system was designed so that each sensor remains in its appropriate preservation fluid until it is used to take measurements. When the measurements are taken, the sensors are moved into the nutrient solution for only the necessary amount of time. The sensor probes are washed with purified water before and after the measurements are taken, to prevent the preservation fluid and nutrient solution from becoming contaminated.

One focus of the SEED-N system was to automate the entire measurement process for each sensor. In order to automatically take measurements, clean the probes, and store them in preservation fluid, motion control hardware and software was required. Figure 6 shows the automated sensor measurement system. Using a nutrient measurement system increases the development cost. However, due to the greatly extended sensor life, the overall running cost should ultimately be reduced. Although the SEED-N system uses various ion sensors to create a profile, simplified profile management can be obtained by using only EC sensors within an actual plant factory. In order to automatically modify the solution's composition and concentration, the SEED-N system uses pumps and controllers which

Fig. 6 Nutrient solution sensor measurement system. The automated solution measurement system extended sensor life by keeping the sensors in their respective preservation fluid when not taking measurements.

Table 1 Four-color LED lighting parameters.

Characteristic	Value
Colors	Red, Blue, Green, White
Dominant wavelengths	White 400~750 nm Blue 455~465 nm Green 518~535 nm Red 618~632 nm
Pulse cycle	1.2 μ s~10 Sec (72Step)
Pulse duty	0~100%
PPFD (measured 10 cm from the light source)	White 30 μ mol m ⁻² s ⁻¹ Blue 62 μ mol m ⁻² s ⁻¹ Green 23 μ mol m ⁻² s ⁻¹ Red 24 μ mol m ⁻² s ⁻¹

allows for 10 different nutrients to be individually introduced into the system as required.

Four-color independently controlled cultivation lamps

Various types of research exists on chlorophyll fluorescent lights and growth control diagnostic technology (Omasa et al., 2001; Takayama, 2010). In addition to the photosynthetic reaction to chlorophyll, high speed pulsed lighting has shown higher growth efficiency over continuous lighting. Studies have shown that high speed ON/OFF lighting pulses have increased plant growth over the conventional continuous lighting. The pulse lighting also requires less input energy from the power source. Implementing the correct equipment will not only decrease the running costs, but will also increase the plant's growth efficiency.

Red light affects the electron transportation system required for photosynthesis, causing germination and leaf expansion. Blue light affects the plant's morphogenesis, which reduces inter-node elongation (Takatsuji, 1997). Table 1 shows the characteristics of the developed four-color independently controlled LED lamp (SAKATECHONO science. Co., LTD., Japan hand crafted). This lamp can independently change light intensity and emission parameters, whereas conventional lighting cannot. It is possible for these LED lamps to meet the optimal growth promotion pulse period of 10 to 400 μ sec.

Growth monitoring images

Maintaining a record of the morphogenesis growth

process is essential in order to assess the optimal environmental conditions for cultivation. Figure 7 shows the resulting images from a webcam (CS-WMVO4N Planex Communication, BB-HCM581 Panasonic Co., LTD., Japan) as a fixed-point observation tool. By utilizing specific viewing angles and magnifications of the cultivation

Fig. 7 Morphogenesis evaluation images from the observation webcam.

bed, a color webcam can take detailed and repeatable pictures. The resulting images provide vital plant morphogenesis information. Each image taken is also coupled with a time stamp. Alterations of the control parameters could be performed by observing the synchronized morphogenesis and measured environmental data. The future plan is to use an image processing program to obtain biometrics such as plant height, chlorophyll concentration, and root development.

CLOUD server

Initially, after obtaining the combined environmental and control data a standard server was designed to send the information to a local database. However, after considering the burden to the local system and the required administrative tasks for upkeep, implementing a CLOUD server instead posed expense reduction benefits. By using a CLOUD service, data access and management can easily be executed anywhere, anytime by anyone with access. The CLOUD server also enables modifications to the system features to be executed in real time, such as the environmental profile, or nutrient solution concentration.

Figure 8 shows “Visualization” (a monitoring screen example), while Fig. 9 shows the “Graphic Analysis

Fig. 8 Visualization: Growth status observation screen from the CLOUD server.

Fig. 9 Graphic analysis service screen: system measured data example.

Fig. 10 Morphogenesis results from the color webcam. With these cameras, scheduled image capturing and remote operation was possible. The images from the fixed point camera could be zoomed and panned either from the pre-set profile or by remote control. (a) Fixed point camera growth record (morphogenesis). (left: leafy daikon (*Raphanus sativus*), center: bok choy (*Brassica rapa*), right: red leaf lettuce (*Lactuca sativa*)). (b) Example of the plants grown with a specific environmental control profile. (Leafy daikon, bok choy).

Service” screen. Screens like these can be provided by the CLOUD service anywhere and anytime there is internet access. With these sensors, parameters can always be viewed, such as the current system status and the environmental control history.

RESULTS AND DISCUSSION

In 2012, a small room was prepared to begin testing the prototype SEED-N system. This initial build had a window installed to utilize natural sunlight. The sunlight based growth chamber was the first experiment to use the SEED-N system. In June 2013, the system was rebuilt in another small room. This time artificial lighting was used. The same tests were repeatedly verified in the newer fully enclosed growth chamber.

Figure 10 (a) and (b) show morphogenesis images captured from the webcam. Figure 10(a) displays sample morphogenesis growth records of leafy daikon, bok choy, and red leaf lettuce from the first three weeks after germination. The preliminary environmental profile results show that these plants had similar morphogenesis to plants grown in standard plant factories. In addition to the fixed point

observations, the cameras offered the ability to take images on demand. Furthermore, camera pan and zoom could be executed at pre-set times in the environmental profile. Figure 10 (b) shows the same daikon, bok choy, and lettuce plant morphogenesis at germination, mid-growth and at harvest time.

The future goal is to have the system determine optimal environmental parameters for a variety of plants and to save that information into a profile. The profile would be used to set current environmental conditions and to forecast future changes necessary to maintain optimal plant growth. The system would check the profile and continuously optimize the plant’s environmental conditions from seed to harvest. In order to further improve this system, the effect of auxiliary blue lights, on morphogenesis in addition to the typical growth lighting, needs to be examined for possible increases in growth efficiency. Although the SEED-N closed system (artificial lighting) findings are not shown in these results, four 23 W LEDs, with two supplementary LED tube lamps, provided sufficient illumination for red leaf lettuce, bok-choy, and various other types of lettuce. From these preliminary results, it is possible to achieve the following with the implementation and improvement of the

SEED-N system.

Shortening of the growth cycle and profile

The SEED-N system's optimal environmental parameters for the best growth promotion effects have not yet been decided. Currently, these profile parameters are manually modified by the user. However, by alternatively using the fixed point observation data with the measured environmental parameters, profile automation is possible. The future plan is to incorporate a control algorithm for modifying the nutrient solution and environmental control parameters through analysis of the image data. The resulting profile from this automation method should reduce the plant's cultivation growth cycle compared to the currently established profiles.

Bioelectric potential (Leaf area potential) feedback characterization data and environmental control integration

Hirama et al. (1997), Utamaru et al. (2000), Morita et al. (2002), Hirama (2013) have reported strong primitive and inhibitive links between leaf bioelectric potential responses and various environmental changes. The research showed that the greater responses from the growth diagnosis coincided with healthy growth and morphogenesis, while weaker responses coincided with poor growth and morphogenesis. These measured responses will be used as a biofeedback sensor to help diagnose the health of the cultivated plants. By using the combined bioelectric potential feedback and image data, the environmental profile can be validated, or modified to increase system efficiency.

Relationship between system power consumption and measured variables

By measuring overall power consumption and by introducing a data analysis system to correctly assess general running costs, it is possible to expand energy savings.

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