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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

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学位論文題目：
Title of Dissertation

Modeling and optimal controls of plant responses of tomato plants to environmental factors in hydroponics

(水耕トマトの環境要因に対する植物応答のモデル化と最適制御)

学位論文要約：
Dissertation Summary

Hydroponic crop production has significantly increased in recent years worldwide and the culture techniques have become a center of attraction in green plant factories because technical ease of flexible control of the root-zone environment. The studied control variables have been applied to root-environmental factors to optimize the greenhouse environmental variables. However, it is difficult to realize optimal control of plants because interactions between plant responses and environmental factors are difficult to understand as a result of the complexity of physical and physiological processes. Moreover, the mathematical model technique is not suitable for solving the problem such as cultivation system that has real complex properties, non-linearity and time variation. Furthermore, intelligent control approaches such as neural networks and genetic algorithms make the treatment of complex systems easier. Neural network has capability to identify non-linier systems with their own learning ability. Meanwhile, genetic algorithm is combinatorial optimization techniques, which search for optimal value of a complex objective function depending on many independent variables using genetic operations, such as crossover and mutation.

A new intelligent control technique for optimization of plant growth was developed by Morimoto in 2000 (Fig. 1). It consists of a decision system and a feedback control system. The decision system determines the optimal set point of environmental factors which optimize plant responses using neural networks and genetic algorithms. In the system, neural networks are used for identifying (learning) plant responses to environmental factors and dynamic models are built. Then, genetic algorithms are used for searching for optimal set points of environmental factors which optimize the plant responses through simulation of the identified neural-network models. Finally, the optimal set points are applied to the set point of the feedback control system.

In this study, an intelligent control technique was applied to two optimization problems. One optimization was meant to promote initial plant growth of tomatoes in hydroponics, by controlling solution nutrient concentration, and the other is optimization to maximize the leaf water content of tomatoes by controlling water temperature.

1) Dynamic optimization of solution nutrient concentration to promote the initial growth of tomato plants in hydroponics.

The aim for dynamic optimization in this study was to maximize plant growth (growth rate of plant height) of tomatoes during the initial growth stage by controlling nutrient concentration. The manipulating factor (control input) is solution nutrient concentration and controlled output is the growth rate of plant height in tomato cultivation.

In this method, plant responses, affected by environmental factors in the root-zone, are first identified using neural networks (Fig. 2), and then the optimal environmental set-points are determined through simulating the identified neural-network model using genetic algorithms (Fig. 3).

The estimated responses obtained from model simulation showed that the growth rate of plant height increased with nutrient concentration. However, the growth rate of plant height decreases with nutrient concentrations in the range above 0.9 dSm^{-1} (Fig 4). This means that the growth rate of plant height was significantly suppressed by high nutrient concentration. It was found that the relationship between nutrient concentration and plant height growth rate had a strong nonlinearity. These results suggest that a reliable computational model could be obtained to predict the behavior of plant growth under any combination of the 6-step set points of nutrient concentration.

The optimal 6-step set points of nutrient concentration was 1.0 for 1^{st} step, 0.5 for the 2^{nd} step, 0.8 for the 3^{rd} step, 0.9 for the 4^{th} step, 1.1 for the 5^{th} step, and 1.2 dSm^{-1} for the 6^{th} step during the initial growth stage. In optimal control performance of plant growth, the growth rate of plant height was about 1.12 times higher with optimal control than with conventional control, and the fresh weight was also about 1.15 times larger with optimal control than with conventional control. Afterwards, there was a significant reduction (0.5 dSm^{-1}) in nutrient concentration in the second step and this significant reduction corresponds to nutrient stress. The significant reduction in nutrient concentration in this step means a kind of nutrient stress was applied to the plant. We surmise that plant growth became active after removing the nutrient stress, while it decreased when applying nutrient stress to the plant. This means that applying nutrient stress to the plant optimally accelerated the physiological responses and promoted plant growth.

Finally, the optimal value (6 step set points) of nutrient concentration was applied to the actual cultivation of tomato plants (Fig. 5). Under optimal control and conventional control of nutrient concentration, the plant growth is larger in the optimal control than in the conventional control. Plant height was about 1.12 times higher with optimal control than with conventional control. The fresh weight was also about 1.15 times larger with optimal control than with conventional control. These results were confirmed at the 5% level of significance.

2) Dynamic optimization of water temperature for maximizing leaf water content of tomatoes in hydroponics using an intelligent control technique

The other optimization problem was to maximize the leaf water content of tomatoes by controlling water temperature. In the root-zone environment in hydroponics, water temperature is also one of the major manipulating factors for controlling plant growth and development. The manipulating factor in this study is water temperature and the controlled factor is the leaf water content of the tomato in hydroponics. It is, however, difficult to directly and continuously measure the dynamic change in leaf water content of an intact whole plant, without damaging the plant. Therefore, the leaf water content was estimated from leaf thickness. An eddy current-type displacement sensor allows the leaf thickness to be measured in a continuous and non-destructive manner.

The estimated responses obtained from model simulation showed that the leaf water content increased until the water temperature reached approximately 35°C, and then decreased with increasing water temperature. The identification results shows a three-layer neural network with time-delay operator for identifying this system. Furthermore, the results suggest that a reliable computational model (neural-network model) could be obtained to predict the behave or of leaf water content under any combination of the 5-step set points of water temperature (Fig. 6).

The optimal value (5-step set points) obtained was 40°C for the 1st step, 15°C for the 2nd step, 40°C for the 3rd step, 22°C for the 4th step and 30°C for the 5th step when water temperature was constrained to 10–40°C. The final water temperature at the 5-step was fixed to 30°C because it maximized leaf water content. A combination of the sudden rise to 40°C and drops it to 15°C had showed a tendency to increase the leaf water content of the plant, compared to when the water temperature was maintained at the suitable level (30°C) over the control process. Figure 7 shows the actual optimal control performance of leaf water content (bold black line). One step was 60 minutes. The grey line is the step response of leaf water content to the step input of water temperature from 10 to 30°C, which is used for comparison. The optimal value (40→15→40→22→30°C manipulation) looks like a combination of the high and low water temperatures. That is, under the constraint of water temperature from 10 to 40°C, an intelligent optimization technique recommends repeating the manipulation that raises the water temperature to the high level (40°C) and then drops it to the low level (15°C) to maximize the leaf water content of the tomato plants. The average value of leaf water content under optimal manipulation gradually increases with applying the maximum and minimum water temperatures to the tomato seedlings, compared with the step response. It is, therefore, suggested that applying a suitable (or optimal) environmental stress such as heat stress to plants is effective in promoting root water uptake which then increases leaf water content of plants during the short-term management of water temperature in hydroponics.

It is, therefore, significant rise and drop for both input control (nutrient concentration and water temperature) during the control process looks like a kind of stress application to the plant and seems to be unsuitable for plant growth. However, applying environmental stress such as moderate nutrient stress and water temperature stress to the plant successfully accelerated the physiological responses and promoted plant growth.

Finally from this work we accomplish that a control technique based on plant responses representing the physiological status is essential for optimization of plant growth. Furthermore, the intelligent control technique combined with a neural network and genetic algorithms is suitable for optimizing such complex system as the plant responses to environmental factors in a hydroponics system.

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Figures

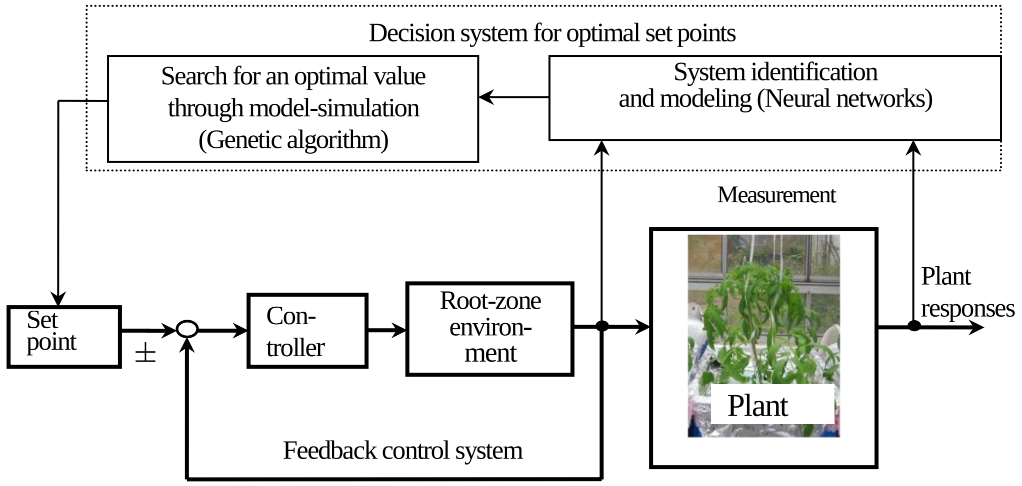
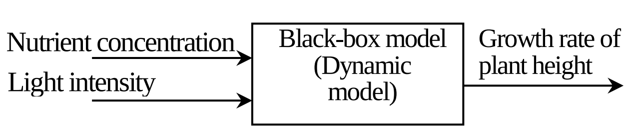
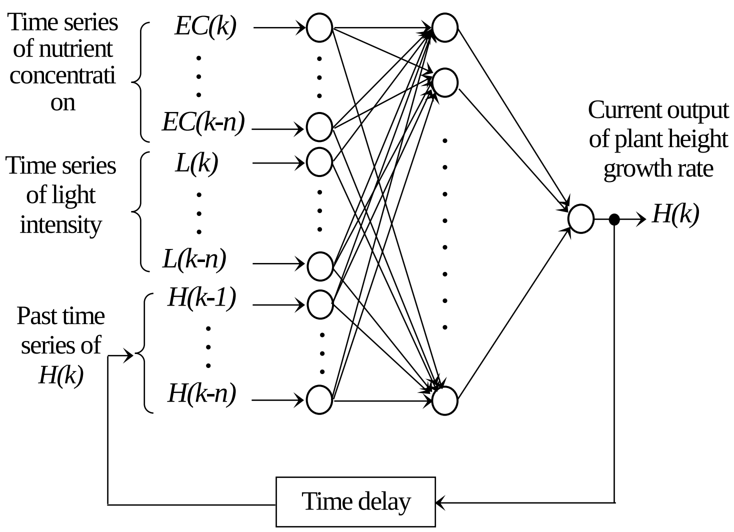


Fig. 1 Block diagram of a speaking plant-based optimal control system for hydroponic cultivation.



(a) A dynamic model with two inputs and one output



(b) A three layered neural network for identifying a dynamic system

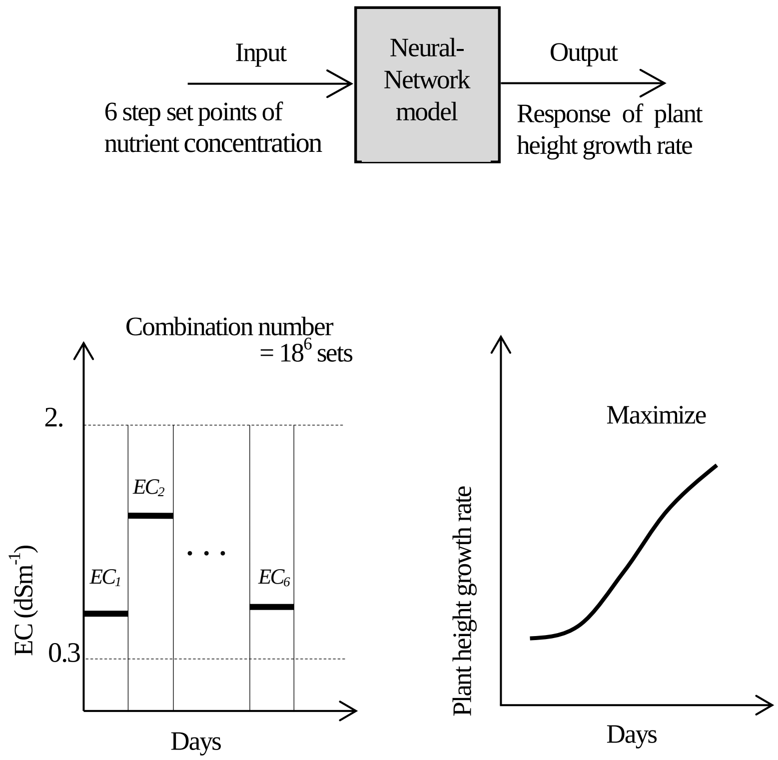


Fig. 2 A method for finding an optimal value (combination of the 6-step set points) of nutrient concentration that maximizes the integration of plant height growth rate (objective function) through simulation.

Fig. 3 A method for finding an optimal value (combination of the 6-step set points) of nutrient concentration that maximizes the integration of plant height growth rate (objective function) through simulation.

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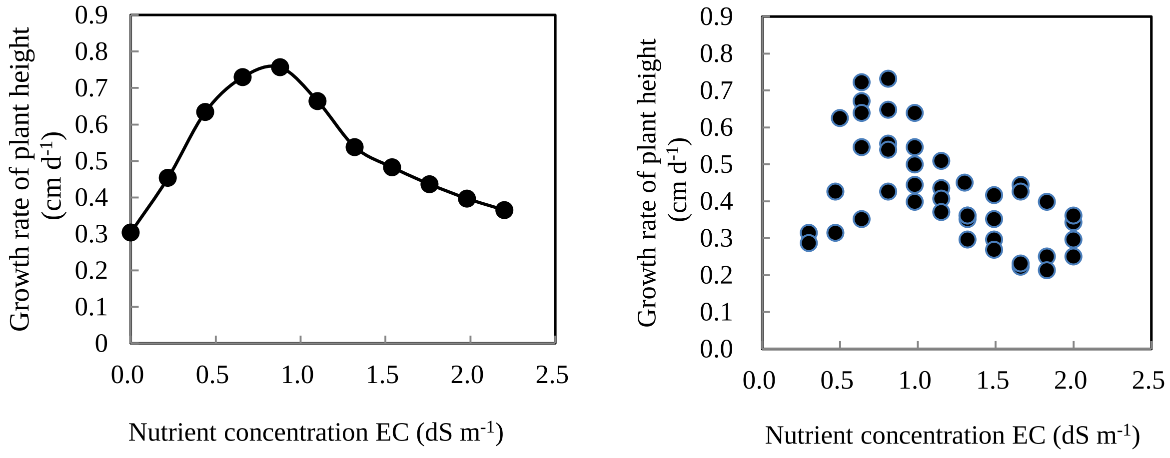

(a) Estimated relationship (b) Observed relationship

Fig.4 Comparison of estimated and observed static relationships between nutrient concentration and plant height growth rate

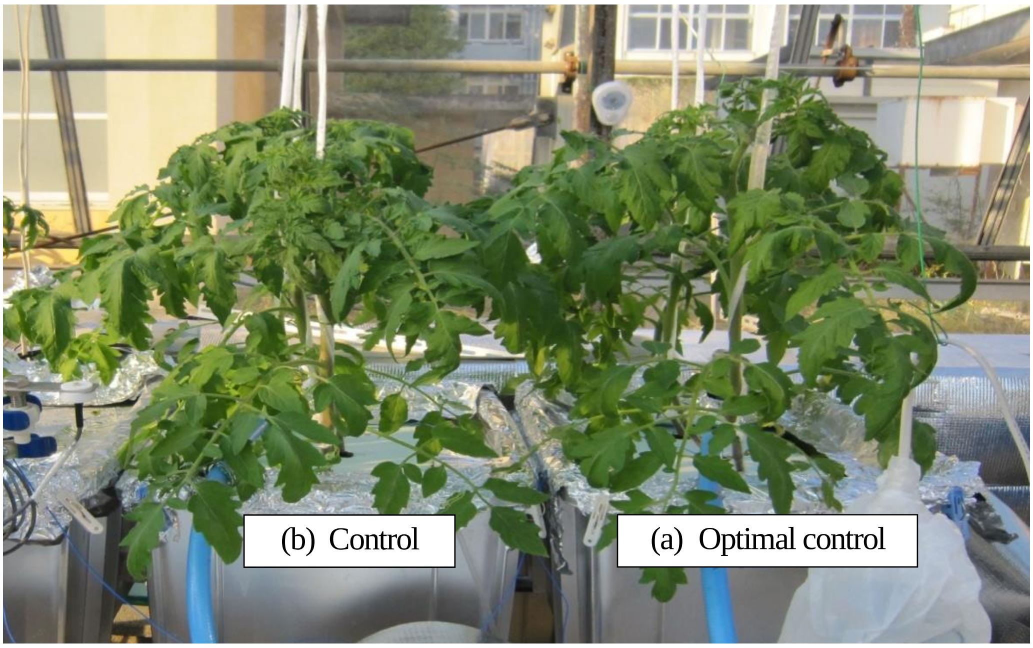

Fig. 5 Plant growth of tomatoes at the final stage (45 d after transplanting) under optimal control and conventional control of nutrient concentration

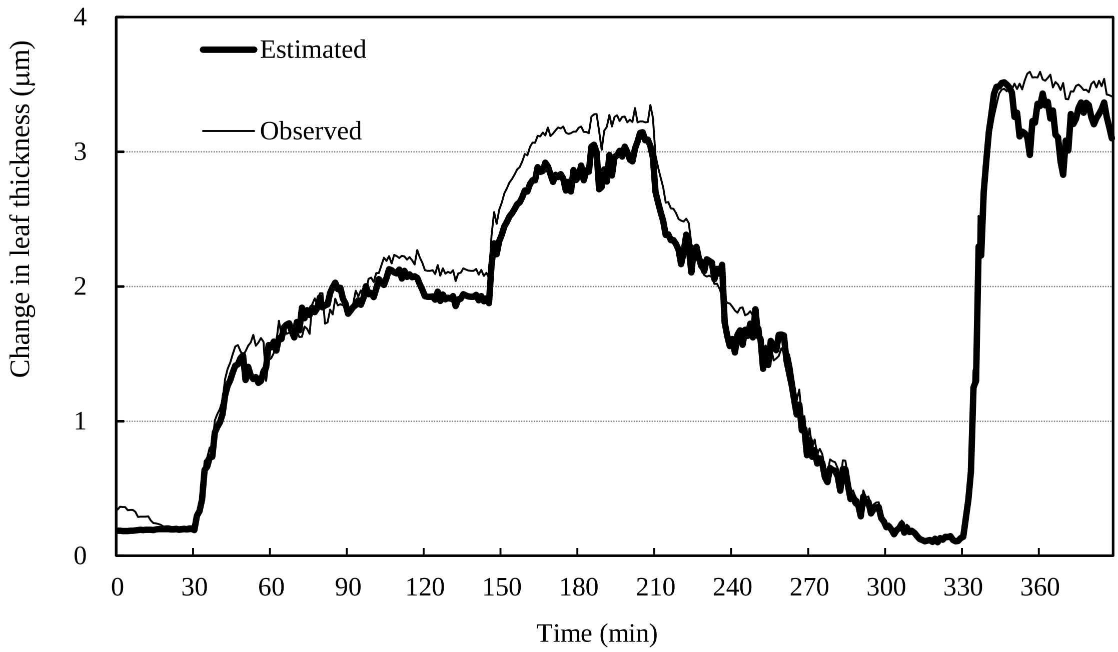

Fig. 6 Comparison of the estimated response, calculated from the neural network model, and the observed response for leaf water content.

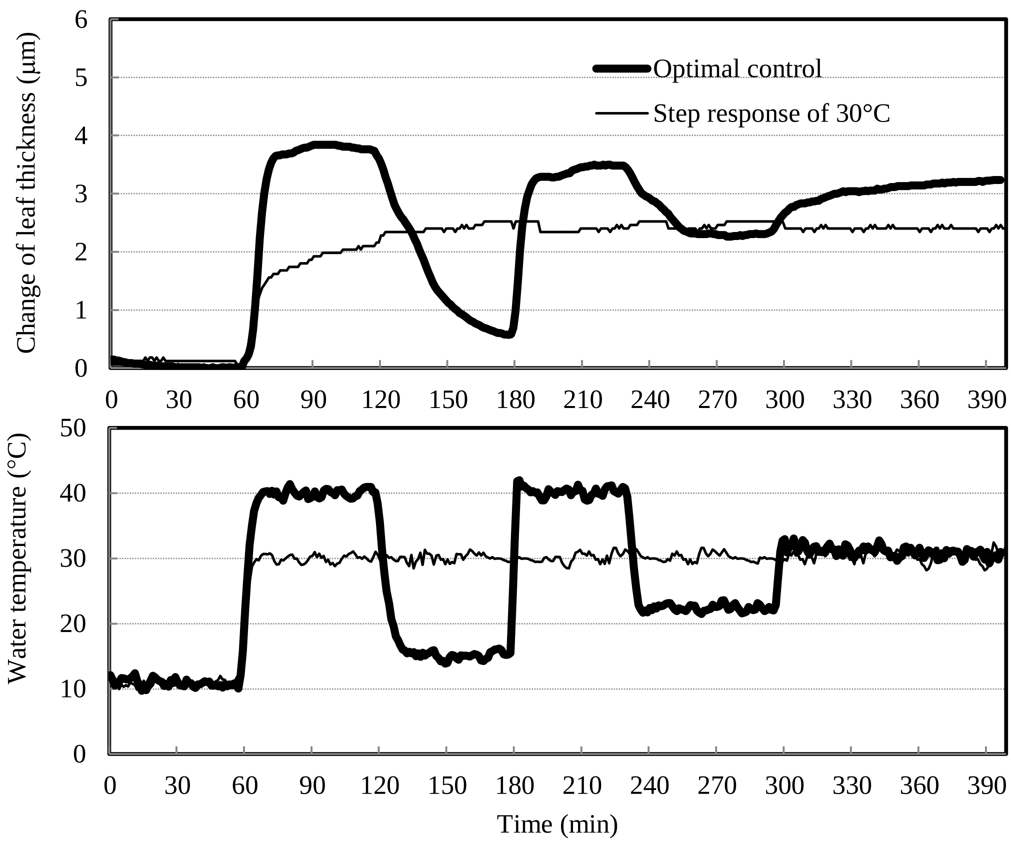

Fig. 7 Actual optimal control performance of water temperature that maximizes leaf water content of the tomato plants at the final step. The division number of the control process m is equal to 5 steps.