Fundamental Research for Intelligent Control in Cultivating and Storage Systems

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INTRODUCTION

It was my greatest honor for me to receive the scientific prize of the Japanese Society of Environment Control in Biology in 2005. I wish to express particular thanks to Prof. Y. Hashimoto for his guidance as a supervisor, Prof. K. Kurata for his suggestions as a chairperson of the nomination committee, and Prof. H. Nishina for his assistance as a recommender.

These studies, which are the results of my research over 26 years from 1979 to 2005, focused on the measurement, the modeling (identification) and the optimization of the physiological responses of plants during cultivation and of fruits during storage, aimed at qualitatively improving the plant and its harvestable products. A system science based on intelligent approaches was applied to each methodology. The concepts of a “speaking plant approach” (SPA) for cultivation and a “speaking fruit approach” (SFA) for storage were also introduced to realize the computer control of a plant production process. SPA and SFA are approaches for controlling environmental factors optimally based on plant responses and yielding higher quality plants. It was found that the results obtained are useful for systematically optimizing plant production processes and yielding higher quality plants (or fruits) under artificial environments, especially plant and storage factories.

START AND PROGRESS OF MY RESEARCH

(1) First stage (Measurement of plant responses and use of system science)

I entered the department of Agricultural Engineering of Ehime University in 1973. At that time, I joined Prof. Hashimoto’s laboratory, feeling that his classes were very interesting. Through his informative lectures I strongly felt the importance and future prospect of Japanese Agriculture.

Prof. T. Nagano (Tokyo Agricultural University), who was an assistant professor at the University of Tokyo in those days, came to our laboratory in 1975 in order to further his experiments. He placed some plants in a growth cabinet which could control the environment exactly and measured leaf temperature using a thermocouple and leaf water potential using a pressure chamber. Especially, the measurement of leaf temperature using a considerably thin thermocouple (0.1 mmφ) impressed me tremendously because he was very skillful in handling and manipulating this instrumentation. Plant responses measured dynamically varied in proportion to the environmental cue. Those experiments created a strong impression throughout my plant research career and reminded me as the seed of inspiration for all my ensuing experiments.
In order to achieve optimized plant growth, it is essential to control the environment optimally, taking the physiological status of the plant into consideration. Measurement of the plant responses and control based on physiological information are major tasks for optimization. Two approaches to achieve this objective are the SPA and the SFA.

From about 1979, the SPA concept was introduced to our laboratory (Morimoto et al., 1995, 1996, 2000b, 2000c and 2003a). SPA is a concept for optimal control of environmental factors based on plant responses during cultivation. The SPA concept, originally proposed by Prof. Gaastra in The Netherlands in 1970, was well suited to our methodology. Consequently, Prof. Hashimoto spread its notion and applicability throughout the world and, at the same time, I applied it to my methodology. The term “speaking plant” (SP) refers to plant responses measured by sensors, allowing us to understand the physiological status of the plant.

A skilled grower is able to deal well with plants based on his intuition and experience, often talking literally with them. It is, however, difficult for people who have no skill or experience in cultivation to grow plants well. The concept of SPA offers them the possibility for better cultivation. H. Murase (Osaka Prefecture University) and S. Shibusawa (Tokyo University of Agriculture and Technology) rapidly followed suit and introduced SPA into their approaches, too.

Third stage (Intelligent approaches)

Most plant responses such as photosynthetic rate or transpiration rate, as affected by environmental factors, are characterized by complexity and uncertainty. It is, therefore, difficult to utilize these complex responses for the optimal control of the cultivation process.

In contrast, intelligent approaches (neural networks, genetic algorithms, and others) have the scientific capacity to deal with even a complicated plant response. They have been widely applied to the control of complex systems to which conventional mathematical approaches are not easily applied. Neural networks have the capability of identifying complex systems with their own high learning abilities. The genetic algorithm can search for an optimal value of a complex objective function by simulating the biological evolutionary process, based on crossover and mutation in genetics.

From these foundational findings, I applied intelligent approaches to the identification and optimization of plant responses after 1990 (Morimoto et al., 1995, 1996, 2000a, 2000b and 2003a, 2003b). The use of intelligent approaches significantly promoted and improved my research findings.

Fourth stage (SFA: speaking fruit approach)

As the next logical step, the SPA concept was expected to be effective in the fruit storage process. This should be a so-called “speaking fruit approach” (SFA). Under the SFA, the storage environment is flexibly and optimally controlled based on fruit responses, although the environment (e.g., temperature) is usually maintained constant at a low level. The concept of SFA was proposed by J. De Baerdemaeker and Y. Hashimoto at the 12th CIGR International Conference in 1994. It was clear that the storage environment could be more controllable than the cultivation environment.

As this research progresses, I have become more closely associated with European researchers, especially J. De Baerdemaeker, who is famous in the field of post-harvest technology. I stayed his laboratory for three months in 1998 and 2003 supported by the Japan Society for the Promotion of Science and collected much valuable scientific data on post-harvest technology in Europe.

The present: total production system, intelligent control techniques, stress responses

I am presently conducting research on the dynamic optimization of environmental factors for accomplishing the qualitative improvement of plants and fruits in a total plant-production process consisting of the cultivating and storage processes using an intelligent control technique fully developed by myself. I am particularly interested in developing a heat stress technique for...
maintaining and improving the quality of fruit during storage. The control input is the temperature and the controlled output is the fruit response representing qualitative factors such as respiration, water loss, sugar and acid content of the fruit. My expectations are that an optimal combination of the maximum (heat stress) and minimum (chilling stress) temperatures would allow for the efficient improvement of fruit quality.

RESULTS OF MY RESEARCH

Plant responses to environmental factors
Fundamental plant responses to environmental factors were measured under a strictly controlled environment using sensors. Non-destructive and continuous measurements of an intact whole plant are useful for real-time control. Plant responses such as net photosynthetic and transpiration rates as affected by environmental changes dynamically varied with time and then reached a steady-state within 2 h. Amplitudes of those responses varied accordingly with gains in those environmental changes. This implies that most physiological and ecological processes can be defined as a “dynamical system”, to which system engineering approaches can be effectively applied for monitored responses.

Modeling (system identification) of plant responses to environmental factors
Most plant physiological and ecological processes can be regarded as a “black-box” characterized by complexity and uncertainty. For model-building of such processes, we should make use of actually measured data. As system identification approach is effective in these cases, I developed a new identification technique using a three layered neural network, which was effective for identifying both linearity and non-linearity between the plant response and the environmental factor, and the identification error was about 2-fold smaller than those by traditional methods such as least-squares and GMDH (group method of data handling). It was found that the neural network was a very effective way to identify complex systems (Morimoto et al., 1995, 1996 and 1997a).

An SPA (or SFA)-based intelligent control system
I have developed an SPA (or SFA)-based intelligent control system for realizing the optimized control of plant responses during cultivation (or of fruit responses during storage) (Morimoto et al., 1995, 1996, 1997a and 1997b). It consists of a decision system and a feedback control system. The decision system, consisting of neural networks and genetic algorithms, determines the optimal set point trajectory of the environmental factors as the control input. Then, the feedback control system controls the environment optimally according to the optimal set points. In the decision system, the plant responses as affected by the environmental factors are first identified using the neural network. Then the optimal l-step set points of the environmental factors that maximize (or minimize) the objective function are searched for through simulation of the identified neural-network model using the genetic algorithm.

It can be found that if these two procedures (identification and the search for an optimal value) are periodically repeated during the cultivation (or storage) process to adapt to the time variation of the physiological status of the plant, then both optimization and adaptation can be fully satisfied.

Application to cultivation processes
The SPA-based intelligent control technique was applied to two optimization problems in hydroponic cultivation. The first was the optimization of the intermittent water supply and drainage which maximizes the net photosynthetic rate of the plant (Morimoto et al., 1995). A slight increase in the net photosynthetic rate was found during the first 5 min after drainage. It decreased later as water stress progressed, implying that optimal drainage and supply times exist. The optimal 4-step drainage and supply operation (4-min drainage; 8-min supply; 4-min drainage; 2-min supply) obtained in this study markedly increased the net photosynthetic rate of tomato plants. The second was the optimization of the nutrient concentration of the solution to promote the reproductive growth of the tomato during the seedling stage (Morimoto et al., 1996). Conventionally,
skilled growers usually increase the nutrient concentration as the plants grow. The optimization problem here is to determine the optimal \( l \)-step set points of the nutrient concentration that optimizes the balance between vegetative and the reproductive growth. The objective function was given by the ratio of total leaf length to stem diameter (TLL/SD) to predict the future balance between the two growths only during the seedling stage. The optimal value (4-step set points of the nutrient concentration) markedly increased the TLL/SD compared to conventional methods. Good seedlings were obtained, giving better future reproductive growth.

Application to storage processes

The SFA-based intelligent control technique was applied to the optimization of temperature during the storage process (Morimoto et al., 1997c and 2003b). The storage temperature is usually maintained at a constant low level. However, there has been much interest in heat treatments that reduce the quality loss of fruit during storage. It is well known that the exposure of living organisms to heat stress produces several types of heat shock proteins (HSPs) in their cells, which acquire transient thermal tolerance. Acquiring thermo tolerance may lead to the reduction of water loss for fruits during storage. In the range of \( 15 \leq T \leq 40^\circ C \) and using the 6-step control process, the optimal set points were determined to be \( \{40, 15, 15, 15, 15, 15^\circ C\} \), which is a combination of the maximum and minimum values (related to heat and chilling stress thresholds, respectively). Controlling temperature so that it first rises to the highest level (40°C) and then drops to the lowest level (15°C) was effective in reducing water loss of the fruit, as compared with 15°C-constant control. A control method that changes flexibly and optimally on the basis of fruit response is useful to maintain fruit quality during storage.

CONCLUSIONS: THE FUTURE

Plant control systems are quite complex and uncertain. I developed an SPA (or SFA)-based intelligent control technique combined with neural networks and genetic algorithms in order to deal well with such complex responses systematically and to realize the optimization of plant production processes. This technique allowed the optimal value (optimal \( l \)-step set points of the environment) to be successfully obtained. An optimal value obtained from this technique was given by the set-point profile (time series) of the environmental factor, and not just by a constant, single one.

The results obtained from the accumulated results of my study are very useful for realizing the optimization of plant production processes and yielding higher quality plants (or fruits) under an artificial environment, especially in plant and storage factories.

I was employed as an Assistant Professor of the Laboratory of Agricultural Environmental Engineering in Ehime University in 1979. These are the cumulative results of my research, spanning 26 years from 1979 to 2005. The laboratory staffs in those days were Prof. S. Funada, Assoc. Prof. Y. Hashimoto, and a technical officer K. Nonaka, to whom I express my heartfelt gratitude for assisting and employing me.

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