A Study of the Optimum Growth Control System Using a Microcomputer†

Hiromu NAKAZAWA* and Tsukasa MATSUURA**

In this paper we propose a system which will result in the growth of a plant in the shortest time possible through the control of the plant's environment by the realtime system with the aid of a microcomputer.

The proposed system is to control the condition of the house so that apparent photosynthetic rate of the selected plants in the assimilatory box will be maximized.

The feasibility of the system has been confirmed by the experiments such as the compound control of CO₂ concentration and air temperature.

In this paper, the control method using a model is also considered for an advanced control.

The model which is used here is a growth model of lettuce and the example of planned production, which satisfies the required items, cost, due time of delivery and weight, is explained and finally the optimum illuminance for the plant factory which is planned by the authors is shown by case study.

Key Words: optimal control, growth model, compound control, plant factory, environmental control

1. Preface

Protected cropping in greenhouse has been practised commercially in the North temperate regions of Europe and North America since 1870's.¹⁾ Most famous recent systems are Cristensen Farm in Denmark, Ruthner system in Austria and General Electric, General Mills and General Foods

systems in U.S.A.. In Japan Hitachi has made a lot of contributions in this field.²⁾ Hashimoto has also proposed the concept of computer-aided cultivation.³⁾

Most of them, however, are based on the program control according to the preset conditions. But the optimum condition for plant is not constant and varies time to time depending on its past life, growth period, mutual relation of the environmental factors, and so on.

In this paper, we propose the optimum environmental control system, constantly getting the biological information and making the realtime control, and confirm the efficiency of this system by some experiments, and also for an advanced control system, propose a control method using a growth model.

2. Method of environmental control

The purpose of this system is to force vegetables by giving optimum conditions controlled by a microcomputer. The outline of the system is shown in Fig. 1. In this system, green vegetables are cultivated and the apparent photosynthetic rate (decreasing rate of CO₂) is chosen as the growth index.

Plants are grown in the sealed house and the environmental conditions such as temperature, humidity, CO₂ concentration and illumination are controlled evenly for every plant. A few plants,

Fig. 1 The outline of the optimal control system

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* School of Science and Engineering, Waseda University, Shinjuku-ku, Tokyo

** Laboratory for Materials, Mitsubishi Electric Corp. Amagasaki

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which are arbitrarily chosen, are covered with the assimilatory box, which is covered with a transparent vinyl sheet. The inside condition of the assimilatory box is held to be equal to the outside condition by ventilation. The condition of the house is controlled so that the photosynthetic rate of the selected plants in the assimilatory box will be maximized. Thus in this system a few selected plants represent the whole ones.

3. Preliminary experiments

Preliminary experiments were made in order to know the fundamental relations between environmental factors and photosynthetic rate.

The control system for the experiment is shown in Fig. 2. An assimilatory box covered with a transparent vinyl sheet and equipped with two doors for ventilation is settled in the growth chamber and a few heads of lettuce are cultivated by hydroponics. The condition inside the growth chamber is controlled by the microcomputer.

When the photosynthetic rate is measured, the two doors are closed and the fan rotates slowly to homogenize the air condition, and when not measured, the doors are wide open and the fan runs to ventilate.

3.1 Relation between air temperature and photosynthetic rate

From 10 [deg] to 35 [deg], photosynthetic rate was measured 10 times at each temperature. The result is shown in Fig. 3. The relation shows the

Fig. 2 The optimal control system for the experiment

optimum curve with the maximum point at about 15 [deg].

3.2 Relation between CO₂ concentration and photosynthetic rate

CO₂ concentration was varied from 600 [ppm] to 4600 [ppm] by 400 [ppm] and the photosynthetic rate was measured 5 times at each concentration. As shown in Fig. 4, photosynthetic rate is saturated at about 3000 [ppm] for both temperature, 20 [deg] and 34 [deg].

3.3 Relation between illuminance and photosynthetic rate

Illuminance was changed from 0 [lx] to 50 [klx] and photosynthetic rate was measured 5 times at each setting. It is commonly said that the light saturation point of lettuce is about 25 [klx], but in this experiment as shown in Fig. 5 the curve has an increasing tendency even at 50 [klx]. This

Fig. 3 Relation between air temperature and photosynthetic rate

Fig. 4 Relation between CO₂ concentration and photosynthetic rate

phenomenon may be caused by the leaves which are indirectly or insufficiently illuminated and do not yet reach the light saturation point.

4. Optimal control experiments

4.1 Optimal control of air temperature

As the preliminary experiment shows, there exists an apparent maximum point or the optimum point of the photosynthetic rate to temperature.

The result is shown in Fig. 6. It is determined by the following steps. The search began at 14 [deg], increasing temperature step by step by 6 [deg], measuring the photosynthetic rate at each temperature, and when the photosynthetic rate became lower than former one, decreased the temperature by half interval. The search was repeated until the interval became shorter than 1 [deg]. In this experiment the optimal temperature was 20 [deg].

4.2 Optimal control of CO₂ concentration

Fig. 5 Relation between illuminance and photosynthetic rate

Fig. 6 Optimal control of air temperature

As for CO₂ concentration, the saturation point is regarded as the optimum point. It was obtained by the search starting with the lower concentration, making it higher step by step, examining the statistical significance of photosynthetic rate at adjacent measuring points. When the difference of the photosynthetic rates between two concentrations is not statistically significant, this point is not statistically significant, this point is taken as the saturation point or the optimum point (Fig. 7).

4.3 Compound control of Temperature and CO₂ concentration

In this experiment the Hooke and Jeeves' algorithm⁴⁾ which was modified in order to examine the statistical significance when the search proceeds parallel to the axis of CO₂ concentration was used.

The result is shown in Fig. 8. The optimum

Fig. 7 Optimal control of CO₂ concentration

Fig. 8 Compound control of air temperature and CO₂ concentration

point is at No. 13 with 20 [deg] of temperature and 2600 [ppm] of CO₂ concentration.

5. Optimal control with growth model

The most important purpose of the plant factory is the planned production, in other words, to regard the plants as the manufactured goods and produce them evaluating the required items such as time limit of delivery, cost and quality. In order to realize it, anticipation from the model is indispensable.

In this chapter an example of the planned production using a growth model will be shown.

5.1 Case study

Assume that lettuce is produced and that three required items, biological information and the environmental factor for control are given as follows.

<Required items>

- 1) Weight of one head...100 [g]
- 2) Due date of delivery...Within 35 days
- 3) Cost...Minimum

<Biological information>

Weight

<Environmental factor for control>

Illuminance

From Fig. 5 it is shown that the higher the illuminances becomes, the higher the photosynthetic rate is obtained and the faster the plant grows. Thus growth models depending on illuminance are obtained as shown in Fig. 9(a), and the dates needed for the plant to reach 100 [g] depending upon illuminance is obtained as shown in Fig. 9(b).

The planned production, satisfying two required

items, weight and due date, can be done by giving the plant's weight and controlling illuminance with reference to these figures. Moreover with the consideration of power cost, which is a linear function of illuminance as shown in Fig. 9(c), the production satisfying the three required items will be done.

5.2 Adaption of actual data

The actual data from the experiments are adapted to the case study in order to forecast the optimum condition such as illuminance whose optimum point could not be decided in 3.3.

(1) Growth model

Growth model is formularized as Eque. (1)²⁾.

$$dM/dt = AM^\alpha + BM \quad (1)$$

M : Weight [g]

A : Real photosynthetic rate [ppm/min]

($A > 0$)

B : Respiration speed [ppm/min] ($B < 0$)

α : Constant ($2/3 < \alpha < 1$)

Solution of the above equation is obtained as follows.

$$M = M_\infty [1 - e^{(1-\alpha)Bt}]^{1/(1-\alpha)} \quad (2)$$

M_∞ : Final Weight [g] ($= |A/B|^{1/(1-\alpha)}$)

The actual data at 20 [°C], 3000 [ppm] CO₂, 50 [klx] and 60 [%] humidity are simulated by the equation as follows.

$$M = 400(1 - e^{0.059t})^{10.2} \quad (3)$$

This curve is shown in Fig. 10.

(2) Illuminance and photosynthetic rate

Relation between illuminance and photosynthetic rate is formularized by the equation,

$$P = \frac{bI}{1+aI} - R + cI \quad \text{[ppm/min]} \quad (4)$$

Fig. 9
Typical models for
the example

Fig. 10 The growth curve of lettuce

Fig. 11 Relation between illuminance and photosynthetic rate

P : Real photosynthetic rate [ppm/min]

I : Illuminance [klx]

R : Respiration speed [ppm/min] (<0)

a, b, c : Constants

The real data was simulated by this equation as follows at the same conditions as above,

$$P = \frac{0.02I}{1 + 4.4 \times 10^{-4}I} + 13.74 + 27.5 \quad [\text{ppm/min}] \quad (5)$$

Thus the apparent photosynthetic rate P_a is,

$$P_a = P - 13.74 \quad [\text{ppm/min}] \quad (6)$$

This equation is shown in Fig. 11 with the actual data.

Fig. 12 Plant factory planned

plant	lettuce
cropping amount	11000 pieces/year
weight of plant	100 g
capacity of air conditioner	9000 kcal/h
power of air conditioner	4 kW
lamp	270 W×10
control parameter	temperature, CO ₂ concentration, illumination
computer	personal computer
	RAM 48 kbite
	ROM 6 kbite

(3) Growth model depending on illuminance

Because the variable "A" in the Equ. (1) and "P" in Equ. (5) are both real photosynthetic rates, the growth model with parameter of illuminance is obtained by eliminating these variables from the equations.

(4) Cost and optimum illuminance

Power cost, which varies with facilities and the season, was estimated from the specification of the plant factory we planned, which is shown in Fig. 12.

Power cost consists of that of illumination and air cooling.

(a) Power cost of illumination

Power cost of illumination per day C_i is shown as follows.

$$C_i = 22.0 \times 24 \times W = 528W \quad [\text{Yen}] \quad (7)$$

W : Power of illumination [kW]

In this equation it is supposed that the electric fee is 22.0 [yen/kW.h] and the plant is illuminated for 24 hours a day.

(b) Power cost of air cooling

The cooling ability is 9000 [kcal/h] and the necessary power of the air conditioner is 3.92 [kW].

Fig. 13 Power cost and optimum illuminance

The power cost for air conditioning per day C_c is obtained by the equation,

$$C_c = \frac{Q}{9000} \times 3.92 \times 22.0 = 9.58 \times 10^{-3} Q \text{ [yen]} \quad (8)$$

Q : Cooling load [kcal]

Q is expressed as follows.

$$Q = G \cdot kc \cdot \int_{\text{day}} (T_o - T_e) dt + 24 \times 860 W \text{ [kcal]} \quad (9)$$

where the first term is the load caused by heat conduction and the second term is the load by heat of illumination.

G : Area of the converging ($=22.3 \text{ [m}^2\text{]}$)

kc : Heat conductivity of the converging
($=55.0$)

T_o : Outside temperature

T_e : Setting temperature ($=20.0 \text{ [deg]}$)

Thus C_c becomes as follows.

$$C_c = 198 W + 1.17 \int_{\text{day}} (T_o - 20.0) dt \text{ [Yen]} \quad (10)$$

Thus the power cost per day C_e is obtained by Equ. (11).

$$\begin{aligned} C_e &= C_i + C_c \\ &= 726 W + 1.17 \int_{\text{day}} (T_o - 20.0) dt \text{ [yen]} \end{aligned} \quad (11)$$

On the other hand from the experiment illumi-

nance is expressed by the power of illumination as follows.

$$I = \frac{50.0}{2.70} W = 18.5 W \text{ [klx]} \quad (12)$$

Thus the power cost per day is shown as follows.

$$C_e = 39.2 I + 1.17 \int_{\text{day}} (T_o - 20.0) dt \text{ [Yen]} \quad (13)$$

As the value of $\int_{\text{day}} (T_o - 20.0) dt$ varies with the seasons, it is decided to be 56.4, which is the mean value of 6 months, from May to October.

Then the power cost per day is formularized as follows.

$$C_e = 39.2 I + 66.0 \text{ [Yen]} \quad (14)$$

This curve is shown in Fig. 13.

Finally the total power cost is obtained by (power cost per day) $\times$ (dates needed for plant to be 100 [g]) and is shown in Fig. 13. The required items are weight (100 [g]), due date (within 35 days) and cost (minimum), thus the minimum point of the curve can be regarded as the optimum point. The optimum illuminance is 43 [klx] and the growth date is 35 [days] and power cost is 60.5 [yen].

6. Conclusion

- 1) The feasibility of the proposed system has been confirmed by the experiments.
- 2) The basic planned production, which satisfies the required items such as cost, due date of delivery and weight, has been realized and the optimum illuminance for the plant factory has been shown by the case study.

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