Design and Development of a Constant Temperature Reservoir for a Database-Driven Smart Cultivation System

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Abstract

Decreasing the number of agricultural working population is serious problem. Production of agricultural products in plant factories is as one of the solutions to the above problems. However, it is not easy to set optimal environment conditions for many kinds of plants in food factories. This research aims for realization of a smart cultivation system that uses a database-driven (DD) technique. In this work, a pilot scale constant temperature reservoir is developed, and a DD nonlinear temperature control is performed.

Keywords: Cultivation System, Temperature control, Data-driven control, Nonlinear control.

1. Introduction

Recently interests and requirements to domestic production and pesticide-free production of agricultural products have been increasing in Japan. However, it has not putting the brake on the decreasing of agricultural workforce. Because of this situation, a plant factory, that can make many production processes of agricultural products automate and is able to produce them safely and stably, has been gotten much attention. A plant factory can be said as one form of protected horticulture that can control production schedule by manipulating its environment conditions such as temperature, humidity, CO2 concentration. Techniques for such environments controls have been actively studied in process control, and they can be applied to the system easily. Although, actual controlled variables that should be manipulated in plant factories are growth speed, taste, nutrition etc. of plants, and the environment control system must be designed to maximize a criterion including the above variables, a uniform method that can deal with many kinds of plants has not been established.

A plant can be regarded as a controlled object which has strong nonlinearity from a point of view of control engineering. Thus, it is difficult to manipulate them by a linear controller with fixed control parameters. Moreover, it may difficult to maintain ideal environment conditions of a plant factory by the controller due to the changing environment around the factory and aged deterioration of equipment. For such systems, a database-driven (DD)

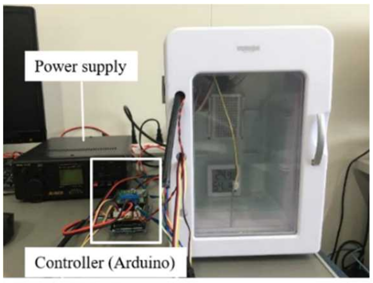

Fig. 1. Appearance of constant temperature reservoir.

control method[1], that adaptively tunes control parameters corresponding to environment conditions by utilizing a database which is stored a lot of previous operation data, is expected to achieve high control performance. Moreover, as related researches of the DD control technique, design methods of nonlinear modeling[2], soft-sensor, expert controller[3] (that can imitate several experts' control action) based on a database have been proposed. From these circumstances, it can consider to be able to realize a smart cultivation system that utilizes DD methods as core technique.

In this research, a pilot scale constant temperature reservoir is developed as a first step. In this system, a Peltier device which is one of thermoelectric conversion devices is implemented to control temperature. In the Peltier device, by supplying current to the device, one side exhausts the heat, and the other side absorptions the heat corresponding to the amount of the current. Moreover, the exhaust and absorption face of the heat can be switched by changing the direction of the current. However, the amount of generated Joule heat follows the square of the amount of the current, thus a linear controller with fixed control parameters does not maintain a good control performance due to the nonlinearity. Therefore, in this paper, the DD temperature controller is designed and applied to the system to track the actual temperature to wide range temperature references. However, it spends much time to evaluate the effectiveness of the system due to the large time constant of the system. In order to perform debug and performance evaluation of an algorithm the DD controller rapidly, a nonlinear simulator is first constructed based on a principal of the heat balance.

This paper is organized as follows. In Section 2, the pilot scale constant temperature and its nonlinear modeling is explained. In Section 3, control results of a fixed PID controller and the DD controller is shown. Finally, Section 4 summarizes the research findings.

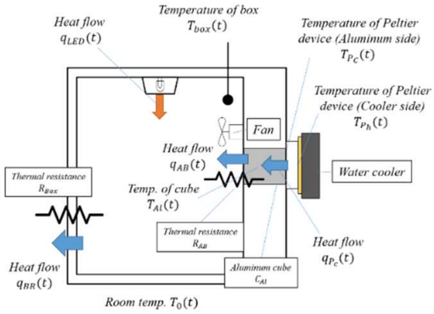

Fig. 2. Schematic of constant temperature reservoir.

Table 1. System parameters.

Variable name	Explanation	Value
R_P	Resistance of Peltier device	3.85
λ_P	Thermal conductivity of Peltier device	10.0
π_P	Peltier coefficient	1.00
α_P	Proportionality constant for T_{P_h}	5.00
R_{AB}	Thermal resistance	0.83
C_{Al}	Thermal capacity	5.00
R_{Box}	Thermal resistance	39211
C_{Box}	Thermal capacity	994.6

2. Constant Temperature Reservoir Design

Appearance of the constant temperature reservoir is shown in Fig. 1. The schematic and system parameters are shown in Fig. 2 and Table 1. Specific values of system parameters are identified by the genetic algorithm.

2.1. *Constant Temperature Reservoir*

A Peltier device is implemented on the back of the system, and temperature sensor and humidity sensor are putted on the inside wall. Moreover, full color LEDs for growing plants is putted on the ceiling. The Arduino is utilized as a controller, and it can manipulate the amount of current from the power supply by changing a duty ratio of PWM output voltage of the controller.

2.2. *Modeling*

In this section, the following couple of heat balance relationships are derived:

(1) Peltier device – Aluminum block.

(2) Aluminum block – Space of constant temperature reservoir.

A simulator based on these heat balance models is constructed by using MATLAB/Simulink.

2.2.1. Heat balance between Peltier device and aluminum block

A derivative equation related into the time variation of $T_{Al}(t)$ is given as follows:

$$C_{Al}\frac{dT_{Al}(t)}{dt} = q_{Pc}(t) - q_{AB}(t). \quad (1)$$

Where the maximum voltage of the power supply $V_{P_{max}}$ is set to 15 V, and the range of the manipulated value $u_P(t)$ is set between $-100\% \leq u_p(t) \leq 100\%$, the amount of the current in the Peltier device can be given as follows:

$$i(t) = \frac{V_{P_{max}}}{R_P}\frac{u_P(t)}{100}. \quad (2)$$

$q_{Pc}(t)$ that is generated by the above current in the Peltier device is described as follows:

$$q_{Pc}(t) = \pi_P\, i(t) + \lambda_P \Delta T_P(t) + \frac{1}{2}R_P i(t)^2, \quad (3)$$

$$\Delta T_P(t) = T_{Ph}(t) - T_{Pc}(t). \quad (4)$$

Note that the exhaust heat face of the Peltier device touches a water-cooling face, and it is assumed that the temperature of the contact face is given the following equation:

$$T_{Ph}(t) = \alpha_P i(t). \quad (5)$$

The $q_{AB}(t)$ is given as follows:

$$q_{AB}(t) = \frac{1}{R_{AB}}\{T_{Al}(t) - T_{Box}(t)\}. \quad (6)$$

2.2.2. *Heat balance between aluminum block and Space of constant temperature reservoir*

A derivative equation related into the time variation of $T_{Box}(t)$ is given as follows:

$$C_{Box}\frac{dT_{Box}(t)}{dt} = q_{AB}(t) - q_{BR}(t) + q_{LED}(t). \quad (7)$$

Where $q_{BR}(t)$ is given as follows:

$$q_{BR}(t) = \frac{1}{R_{BR}}\{T_{Box}(t) - T_0(t)\}. \quad (8)$$

The $q_{LED}(t)$ is the heat flow from the full color LEDs. Thus, the $q_{LED}(t)$ is given as follows by introducing the maximum heat discharge of each color LED (red, green, blue) $q_{R_{max}}, q_{G_{max}}, q_{B_{max}}$ and command signals to each LED u_R, u_G, u_B ($0\ \% \leq u_{R,G,B} \leq 100\ \%$):

$$q_{LED}(t) = q_{R_{max}}\frac{u_R(t)}{100} + q_{G_{max}}\frac{u_G(t)}{100} + q_{B_{max}}\frac{u_B(t)}{100}. \quad (9)$$

The static property between $u_p(t)$ and $T_{Box}(t)$ of the obtained simulation model is shown in Fig. 3. The figure shows that the system has nonlinearity.

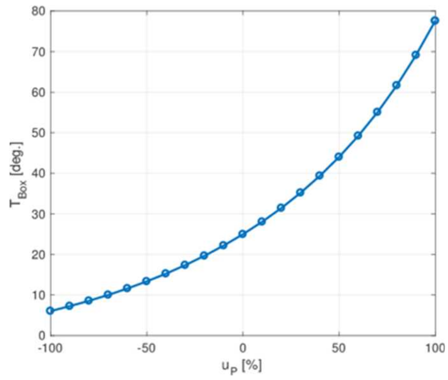

Fig. 3. Static property of simulation model.

3. Application of DD Control Technique

Temperature of the constant temperature reservoir must be controlled properly in order to produce many kinds of plants. In this work, the DD control technique is applied to control the temperature. In the DD controller design scheme, the initial database is required. Thus, in order to generate an initial database, a fixed PID controller is applied to the system, and its operation data is stored into a database.

3.1. *Control result by Fixed PID controller*

Initial PID parameters are obtained based on a model munching. Firstly, it is assumed that the controlled object can be approximated as the following first order system with time delay around an equilibrium point:

$$G(s) = \frac{K}{1+Ts}e^{-Ls}. \quad (9)$$

Where, $T, K,$ and L is the time constant, the system gain, and the time-delay. By using the least squares method, the system parameters around $T_{Box} = 20$ are obtained as $T = 934, K = 0.282,$ and $L = 60$, respectively. The following approximated model can be obtained by applying first order approximation to the time-delay:

$$G(s) \cong \frac{K}{1+Ts}\frac{1}{1+Ls}. \quad (10)$$

Secondly, the following I-PD control law is introduced:

$$u(t) = k_c\left\{\frac{1}{T_I}e(t) - \frac{dy(t)}{dt} - T_D\frac{d^2y(t)}{dt^2}\right\}, \quad (11)$$

$$e(t) = r(t) - y(t). \quad (12)$$

Where, $u(t)$ and $y(t)$ are the controller output and the system output, respectively. In this simulation, $u(t) = u\_P(t)$ and $y(t) = T_{Box}(t)$. $r(t)$ is the reference temperature. The following transfer function is introduced as a reference model:

$$G_r(s) = \frac{1}{1+\left(\frac{\sigma}{2}s\right)^2}. \quad (13)$$

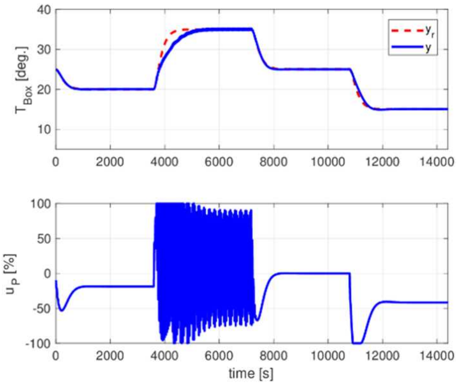

Fig. 4. Control result obtained by fixed PID controller.

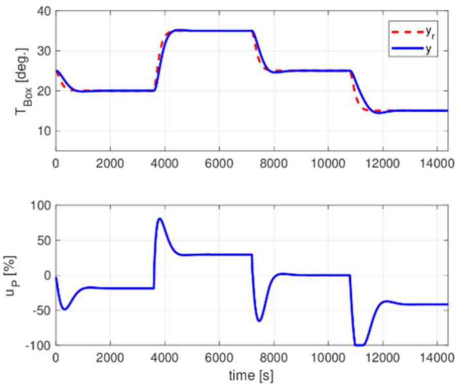

Fig. 5. Control result obtained by DD-PID controller.

σ is the required rise-time of the closed loop system, which is arbitrarily set by a user. The following relationship can be obtained by comparing the transfer function of the closed loop system, constructed by (10) and (11), and the reference model (13):

$$kc = c_1,\ \ T_I = \frac{c_1}{c_0},\ \ T_D = \frac{c_2}{c_1} \tag{14}$$

$$c_0 = \frac{27(T+L)}{K\sigma^3},\ c_1 = \frac{27(T+L)-\sigma^2}{K\sigma^2},\ c_2 = \frac{9(T+L)-\sigma TL}{K\sigma} \tag{15}$$

The control result by fixed the I-PD controller is shown in Fig. 4. In this simulation, the rise time is set to $\sigma = 500$, and the discrete I-PD controller whose sampling time $T_s = 10$ is applied. Moreover, the reference temperature is given as follows:

$$r(t) = \begin{cases} 20 & (0 \le t < 3600) \\ 35 & (3600 \le t < 7200) \\ 25 & (7200 \le t < 10800) \\ 15 & (10800 \le t < 14400) \end{cases}. \tag{16}$$

From Fig. 4, the controller output around $y(t) = 35$ oscillates due to the nonlinearity of the system, and the tracking property is deteriorating.

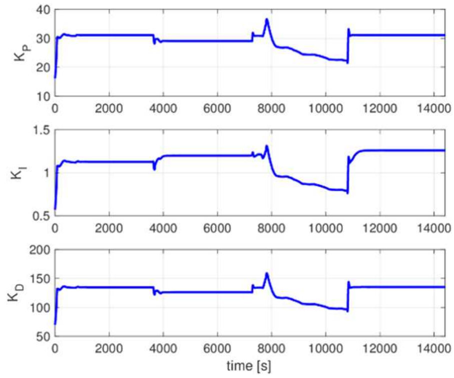

Fig. 6. Trajectories of PID gains corresponding to Fig. 5.

3.2. *Control result by DD-PID controller*

The control result in Fig. 4 and PID gains are stored into a database, and a DD controller is designed according to the reference[1]. The control result using the DD controller is shown in Fig. 5. And trajectories of PID gains are shown in Fig. 6. In this simulation, the rise time is set to $\sigma = 210$, that is faster than the fixed I-PD controller design. These results show that a good control performance is obtained by adaptively tuning PID gains based on the DD control technique.

4. Conclusions

In this work, a constant temperature reservoir that can manipulate several environmental variables was developed to establish a smart cultivation system based on the DD technique. The mathematical model based on a principal of the heat balance was derived and a simulator is constructed by MATLAB/Simulink. The DD controller was also designed, and the effectiveness of the controller was verified by using the simulation model. The implementation of the control system to the real system and designing the structure of smart cultivation system are future works.

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