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AUTOMATIC BODY TEMPERATURE CONTROL SYSTEM FOR SMALL ANIMAL STUDIES USING DUAL MODE PI CONTROL

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Abstract- Body temperature regulation of the experimental animal is important because anesthesia reduces the body temperature to deteriorate the physiological condition of the animal. We have developed an automatic body temperature control system based on a microcontroller (80C196KC) with a dual mode proportional integral (PI) control algorithm where two different sets of PI gain coefficients were used depending on the response state. The developed system also provides user interface through an LCD display and two push button inputs and PC interface through RS-232 serial communication protocol. Through *in-vitro* and *in-vivo* tests, we were able to maintain the temperature of the target object within the range ± 0.3 ℃ of the set point temperature.

Keywords: Automatic body temperature control, PI control, thermometry, dual mode PI control

INTRODUCTION

Animal model is one of the most important research methodologies because it can be performed under various conditions that cannot be directly applied to human bodies. For this reason, animal experiments have been widely used in both basic and clinical research of medical science. In most cases of the animal experiments, the animal is anaesthetized, which reduces the body temperature and alters the physiological condition of the animal. Although the body temperature can be maintained manually by changing heating and cooling levels of the thermal devices, this is labor-intensive and not highly reliable. Especially in small sized animals, even very short hypo- or hyper-thermal period could cause irreversible deterioration of animal condition from the intended condition. One example is the experiment of measuring the size of cerebral infarction or cerebral hemorrhage due to ischemic brain damage [1]. Besides this, in experiments finding the correlation between hypothermia and ischemic brain damage, a device is necessary to maintain the body temperature at a desired set point temperature. For these reasons, unless the brain temperature is maintained within the range of ± 0.5 ℃ from the set point, the experimental results are worthless.

Several investigators have used automated control systems to heat or cool the experimental animal [2]. However, such previously reported systems are not compatible with the constraints of using heating device only with narrow temperature variation limit. In order to achieve greater performance and ease of application, we have developed a microcontroller-based automated body temperature control system. Compensation algorithm of the feedback control loop is basically the conventional PI control law [3]. Since the characteristics of the total system are nonlinear and partially unknown, dual mode tuning of the PI coefficients was attempted. We have also developed a PC-based monitoring system to evaluate the characteristics of the developed system. The performance of the developed system was evaluated during *in-vivo* studies in rats.

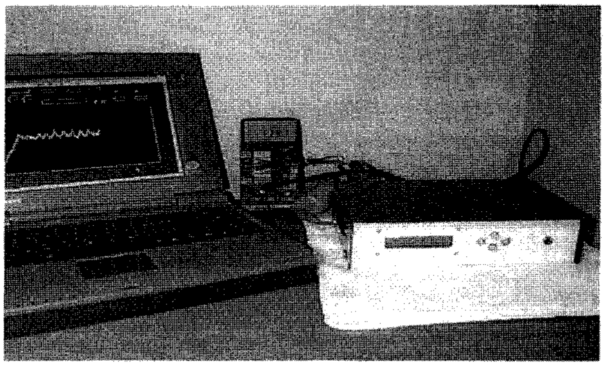

Fig. 1. Photograph of the total system composed of a PC for monitoring, a thermometer, the developed controller and a heating pad.

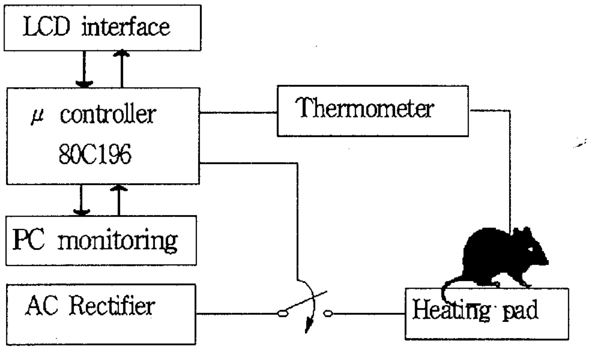

Fig. 2. Block diagram of the automatic body temperature control system.

METHODS

A. Structure of the Automatic Body Temperature Control System

The developed system consists of a thermometer (TM1300K, Heung Chang, Korea), microcontroller (80C196KC, INTEL, USA)-based digital circuit with RS-232 protocol PC interface for monitoring, LCD (HC 16202, Hyundai Electronics Industries Co.,Ltd) module (1x16 character type), 110/220V AC rectifying circuit with switching circuit at 10Hz and heating pad (Model M-15, Dae Sin, Korea). The operating principle of each unit is as follows.

Thermometer gives an output voltage proportional to the body temperature sensed by a hypodermic needle type thermocouple (K-type) probe inserted into the body of the animal. The microcontroller converts the amplified analog output voltage from the thermometer to a digital signal to be used in control algorithm. Then the control loop generates a 10 Hz PWM (pulse width modulation) signal based on the PI control law. Tuning of the PI coefficients is performed separately in transient and steady state phase. Based on the magnitude of the temperature difference between the target and measured values as well as the slope of the measured temperature change, empirically determined different PI coefficient set was employed. This PWM control signal switches the rectified 110/220V DC voltage applied to the heating pad meaning that the heating pad is continuously turned on and off at the same frequency.

B. Data Acquisition and Dual Mode PI Control Algorithm

The output signal resolution of the thermometer is 1 mV/℃ and the signal was amplified at a gain of 50 before A/D conversion (150Hz sampling rate). In this procedure, noisy signals were also mixed into the analog output voltage. To smooth out this high frequency noise, we low pass filtered the signal by averaging 150 data samples.

The recursive digital PI control formula is given as follows using the bilinear transformation [4];

$$U[n] = U[n-1] + K_P(E[n] - E[n-1]) + K_I(E[n] + E[n-1]) \tag{1}$$

where $U[n]$: PWM output,
$E[n]$: $T_s[n]$-$T_C[n]$
$T_C[n]$: set point temperature
$T_s[n]$: current measured temperature,
K_P : proportional gain and
K_I : integral gain.

The calculation rate of the PI control loop was 1 Hz and the result was used to update the PWM output at every 1 second. The empirically determined coefficient sets were provided from the PC based monitoring system. Basically, relatively larger K_P is used in transient phase and larger K_I in steady state. The two criteria used in selecting PI coefficient set were the peak-to-peak temperature variation and rising time. Relatively low PWM frequency, 10 Hz, was chosen to minimize the noise originated from the heating pad to avoid interfering with the thermometer output.

C. User Interface

The developed automatic body temperature control system has two kinds of user interface. For portable use, LCD display panels with two push button switches are attached on the front panel of the controller. The set temperature and measured temperature are displayed on the LCD with a resolution of 0.1℃. The user can change the set temperature manually by pressing the input switches.

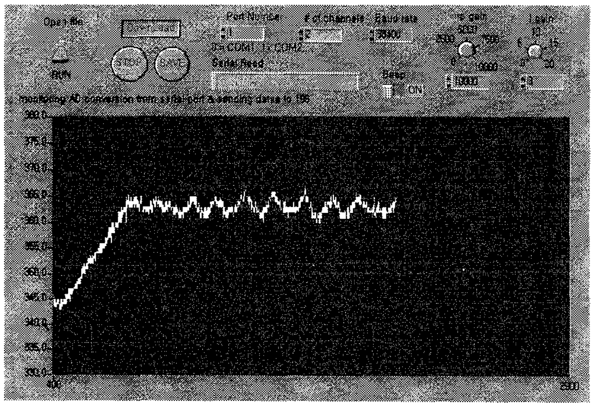

Fig. 3. User interface screen for both monitoring of the body temperature of the animal and tuning PI gain coefficients.

We could monitor the change of the body temperature and save temperature data with the PC monitoring program as shown in Fig. 3. The monitoring program was developed using Labview 4.02 (National Instruments, USA) and communicates with the microcontroller through an RS-232 communication line.

D. In-Vivo Test Evaluating the Performance of the System

In neurological animal experiments to test the effects of medicinal compounds on the size of cerebral infarction and cerebral hemorrhage, the size of lesion is very sensitive to the brain temperature. Experiments using rats were performed for both short term (<1 hour) and long term (>15 hours) cases. The body temperature was measured with a hypodermic needle type thermocouple inserted into the temporal muscle of the animal.

RESULTS

Fig. 4 shows a typical result of the *in-vivo* test with a 270g rat when the set point temperature was 36.5℃. The body temperature that had fallen down to 34.5 ℃ due to anesthesia was recovered to the set point. The rising time was about 13 minutes and overshoot was less than 0.3℃. The results were also satisfactory for rats in various size (30g-300g), which means that the dual mode PI control algorithm successfully control the system with different inertia of heat.

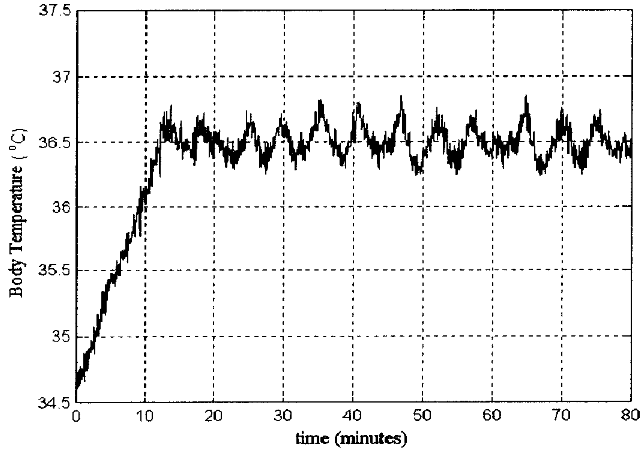

Fig. 4. Body temperature of an animal during *in-vivo* test with small overshoot (< 0.3 °C) and short rising time (< 15 minutes)

DISCUSSION

Finding the two coefficient values of K_P and K_I that satisfy the overshoot and rising time requirements over the wide range of operating condition is the main issue in PI control theory. Using dual gain sets of K_P and K_I for transient and steady state separately, it was effective to control the body temperature of small animals. The criteria used to determinate the border of the two phases were current temperature error and slope of the temperature curve. This type of process is necessary because of two conflicting requirements of short rising time and little overshoot. The former restriction requires relatively large K_P in comparison to K_I, and the latter requires the opposite case, that is, relatively large K_I in comparison to K_P. Further studies will be made on the use of more intelligent control algorithm such as adaptive fuzzy logic control algorithm for better performance.

CONCLUSIONS

The developed automated control system allowed us to more quickly warm the animal to a target temperature (<15min) while avoiding significant temperature overshoot with minimal subsequent deviations about the set point. Such control is especially important for the small animal experiments. This fast heating and maintaining narrow temperature variation window was achieved by using dual sets of PI gain coefficients determined through trial and error. Since the developed system requires a heating pad only and no additional device, it can easily be applied to almost any other animal model in any experimental setup.

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