Implementation and analysis of different discrete PI controller algorithms on single board heater system

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Abstract: *A single board heater system (SBHS) has been developed at IIT Bombay to provide a hands on capability to control system students. In this paper, different discrete PI controller algorithms are implemented and analyze on SBHS using LabVIEW. The PD controller gives faster response, but fails to reject the offset error generated due to load change. The PI controllers are widely used in industries to provide better tracking response. Different discrete PI controller algorithms are described and implemented on SBHS. The analysis of the obtained results is useful to select proper discrete PI controller algorithm.*

Key words: *single board heater system, PI controller, offset, tracking response.*

1. Introduction

In the process industries, 95% of the control loops are of PID type (Astrom & Hagglund, 1995; Yu, 1999) and only a small percent of control loop works efficiently [1-3]. It means that PID controller is widely used, but poorly understood. Poor understanding leads to poor quality of product, excessive controller action and increase in cost. Derivative action used to provide faster response, but it fails to reject the disturbance changes [1]. In order to reject the disturbance and setpoint changes the integral action is used. In most of the process industries PI controller is widely used [4]. Different discretizing methods given in [5] can be used to develop the discrete PI controller.

In this paper, different discrete PI controller algorithms are implemented on a single board heater system (SBHS). The SBHS setup designed and developed at IIT Bombay [6]. The SBHS consist of a heater assembly which has the small time constant and dead time. We have used LabVIEW for data acquisition, controller implementation and monitoring. On the SBHS different describe PI controller algorithms are implemented along with disturbance rejection.

This paper has been organized as follows: Section 2 describes different discrete PI controller algorithms. Section 3 provides details of the SBHS. In section 4, discrete PI controller implementation results are shown using LabVIEW. Finally, Section 5 summarizes the contributions of this paper and possible future research work.

2. Discrete PI controller algorithms

The PI controller in continuous time is given by

$$u(t) = K_p\left\{e(t) + \frac{1}{\tau_i}\int_0^t e(t)dt\right\} \tag{1}$$

where, $u(t)$ =controller output, $e(t) = r(t) - c(t)$ =error signal, K_p =proportional gain, and τ_i =integral time. By taking the Laplace transforms of (1), we obtain

$$U(s) = K_p\left\{1 + \frac{1}{\tau_i s}\right\} E(s) \tag{2}$$

Using different discretizing methods given in [5], PI controller algorithms are as follows.

A. Trapezoidal approximation

Trapezoidal approximation of Laplace transform is

$$\frac{1}{s} = \frac{T_s}{2}\frac{Z+1}{Z-1} \tag{3}$$

where T_s =sampling period. By discretizing the PI controller given in (2) using trapezoidal approximation given by:

$$u(n) = K_p\left\{1 + \frac{T_s}{2\tau_i}\frac{Z+1}{Z-1}\right\} e(n) \tag{4}$$

Rewriting the (4) as

$$(Z-1)u(n) = K_p\left\{(Z-1) + \frac{T_s}{2\tau_i}(Z+1)\right\} e(n) \tag{5}$$

Using shifting theorem and inverse z-transform

$$u(n)-u(n-1)=K_p\{e(n)-e(n-1)+\frac{T_s}{2\tau_i}e(n)+\frac{T_s}{2\tau_i}e(n-1)\} \quad (6)$$

The PI controller in recursive form is usually written as

$$u(n)=\ u(n-1)+\ c_0e(n)+c_1\ e(n-1) \quad (7)$$

where,

$$c_0=K_p\left(1+\frac{T_s}{2\tau_i}\right)$$
$$c_1=K_p\left(-1+\frac{T_s}{2\tau_i}\right)$$

B. Backward difference approximation

Backward difference approximation of Laplace transform is

$$\frac{1}{s}=\frac{T_s Z}{Z-1} \quad (8)$$

By discretizing the PI controller given in (2) using backward difference approximation given by:

$$u(n)=K_p\left\{1+\frac{T_s}{\tau_i}\frac{Z}{Z-1}\right\}e(n) \quad (9)$$

Rewriting (9) as

$$(Z-1)u(n)=K_p\left\{(Z-1)+\frac{T_s}{\tau_i}(Z)\right\}e(n) \quad (10)$$

Using shifting theorem and inverse z-transform

$$u(n)-u(n-1)=K_p\left\{e(n)-e(n-1)+\frac{T_s}{\tau_i}e(n)\right\} \quad (11)$$

The PI controller in recursive form is usually written as

$$u(n)=\ u(n-1)+\ c_0e(n)+c_1\ e(n-1) \quad (12)$$

where,

$$c_0=K_p\left(1+\frac{T_s}{\tau_i}\right)$$
$$c_1=-K_p$$

C. Forward difference approximation

Forward difference approximation of Laplace transform is

$$\frac{1}{s}=\frac{T_s}{z-1} \quad (13)$$

where T_s =sampling period. By discretizing the PI controller given in (2) using trapezoidal approximation given by:

$$u(n)=K_p\left\{1+\frac{T_s}{\tau_i}\frac{1}{Z-1}\right\}e(n) \quad (14)$$

Rewriting the (14) as

$$(Z-1)u(n)=K_p\left\{(Z-1)+\frac{T_s}{\tau_i}\right\}e(n) \quad (15)$$

Using shifting theorem and inverse z-transform

$$u(n)-u(n-1)=K_p\left\{e(n)-e(n-1)+\frac{T_s}{\tau_i}e(n-1)\right\} \quad (16)$$

The PI controller in recursive form is usually written as

$$u(n)=\ u(n-1)+\ c_0e(n)+c_1\ e(n-1) \quad (17)$$

where,

$$c_0=K_p$$
$$c_1=K_p\left(-1+\frac{T_s}{\tau_i}\right)$$

3. Single Board Heater System (SBHS)

A single board heater system, shown in Fig. 1, is a lab-in-a-box setup developed by IIT Bombay [6]. The setup mimics a process in which temperature control problems are involved. The SBHS comprises of a coil, metal plate, fan and temperature sensor. It also consists of an 8-bit ATmega16L microcontroller, LCD, instrumentation amplifier and associated circuitry. A stainless steel plate of size 5cm × 2cm is used as the main process. The controlled problem is to maintain the temperature of the plate at the desired point. Nichrome wire wound with 20 equally spaced helical turns to form a coil of 5mm × 11mm having 0.7mm diameter. The coil is placed at a distance of 3.5mm from the metal plate, which is acting as the heating element. AD590, a monolithic integrated circuit, is used as a temperature transducer, is soldered beneath the metal plate. The temperature of the metal plate is change according to the current passing through the coil. A fan is placed near to the heating metal plate which acts as a disturbance to the heating system.

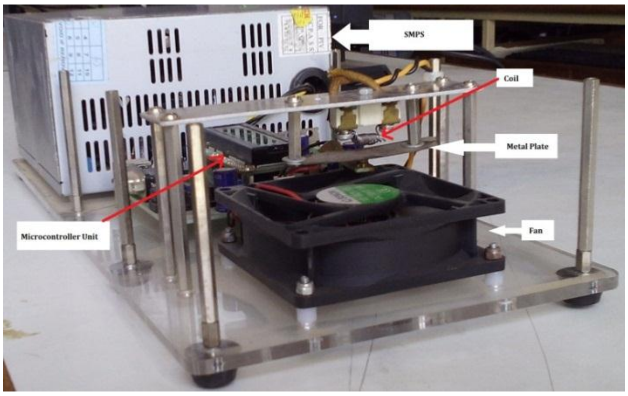

Fig. 1. Single Board Heater System (SBHS)

The ATmega16L AVR microcontroller is the heart of this single board heater setup. It converts analog signal of metal plate temperature to digital signal, serially communicates with the computer, facilitates display of temperature on LCD and generates PWM signals for the heating coil and fan. It has on-chip programmable Flash, 4 PWM channels, 8-channel 10-bit ADC, programmable serial Universal Asynchronous Receiver and Transmitter (UART) and 32 general purpose input and output lines make it suitable for this application [6]. The heater setup requires one channel of ADC for the metal plate temperature measurement and 2 PWM channels for heating coil and fan. An LCD is mounted above the microcontroller, used to display the temperature of metal plate, fan and heating coil input and also the set point value from the serial port.

Timer1 of the ATmega16L is used to generate 8-bit PWM signal with a frequency of 488 Hz, which is given to heating coil and fan. The ATmega16L has been programmed to control the heater coil current and fan speed and also to display and communicate measured values of metal plate temperature.

LabVIEW is software which is used for monitoring and numerical computations [7]. The SBHS setup is programmed to communicate with 8 bit data at 9600 baud rate, no parity and no protocol. As the SBHS supports serial and USB communication port, one can work with a laptop or computer. The block diagram of interfacing SBHS and LabVIEW is shown in Fig. 2.

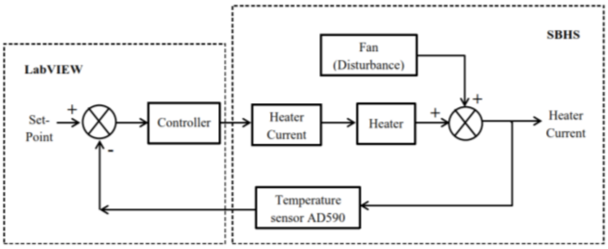

Fig. 2. Block diagram of the SBHS

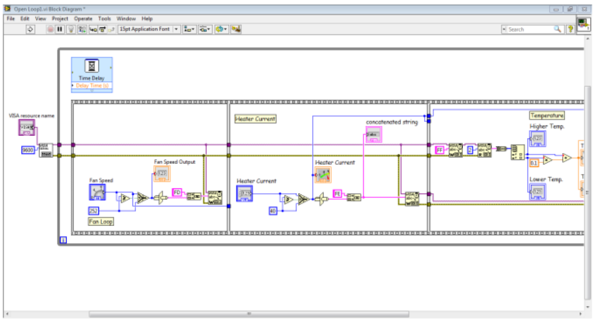

Fig. 3. Block diagram in LabVIEW

To communicate with SBHS VISA block of LabVIEW is used. The numbers 253,254 and 255 are reserved as fan speed, coil current and plate temperature respectively. Fan speed and coil current are inputs, while plate temperature is the output of SBHS. The discrete PI controller is designed in LabVIEW, which will send a byte following 254 to manipulate coil current in order to achieve a set point. The block diagram of LabVIEW for SBHS data communication is shown in Fig. 3.

Sampling time of 1 sec is used for performing experiments on the SBHS. Interfacing of computing device with the SBHS is shown in Fig. 4.

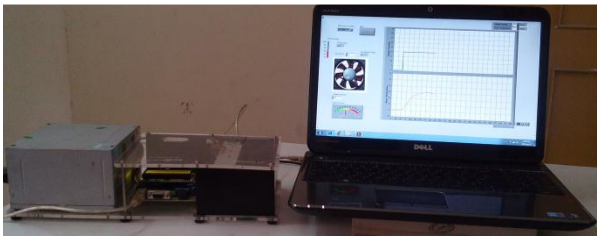

Fig. 4. Interfacing of the SBHS

4. Experimental Results

The SBHS operates as a single input single output system with sampling time one second and fan speed as a disturbance. The fan speed is maintained at a zero at the start of the experiment. In order to identify the model the SBHS open loop step response is obtained. A step change of 20 PWM units is given to the coil, which results rise in the temperature of the coil as shown in Fig. 5. The first order plus dead time model obtained from the Fig. 5 is explained in [8,9]

$$\frac{1.38e^{-10s}}{92s+1}$$

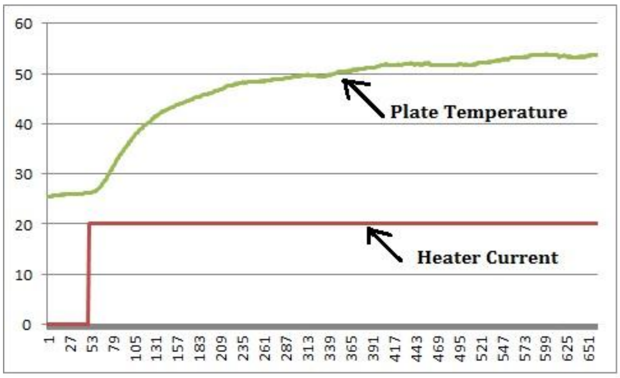

Fig. 5. Open loop response of the SBHS

Using the Ziegler-Nichols tuning rules PI controller parameter $K_p = 3$ and $\tau_i = 33\ sec$. The parameters of the discrete PI controller can be derive by used of methods proposed in [10,11]. Now, implement discrete PI controller algorithms discussed in section II using the LabVIEW environment as shown in Fig. 6.

In Fig. 7, 8 and 9 the close loop results of discrete PI controller using trapezoidal, backward and forward difference approximation, respectively. The step change in setpoint is given at 20 sec. for each of the results shown in Fig. 7, 8 and 9. The fan speed of 100 PWM units is given as disturbance at 375 sec. in each of the experiments.

From the experimental results for the setpoint tracking forward and backward difference approximation based discrete PI controller give less overshoot than the trapezoidal approximation. However, the trapezoidal approximation based discrete PI controller provide faster response with less oscillation in the temperature. The forward difference approximation based discrete PI controller provide an inverse response in coil current, initially as shown in Fig. 9. The forward difference rejects the disturbance effect faster as compared to other two approximations.

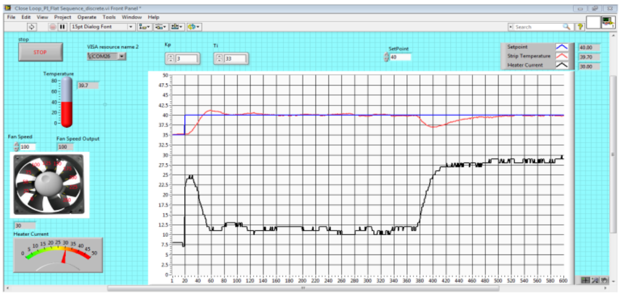

Fig. 6. LabVIEW implementation of the SBHS

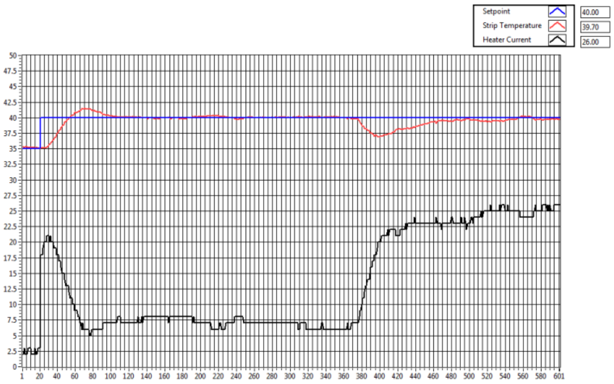

Fig. 7. PI controller closed loop response using trapezoidal approximation

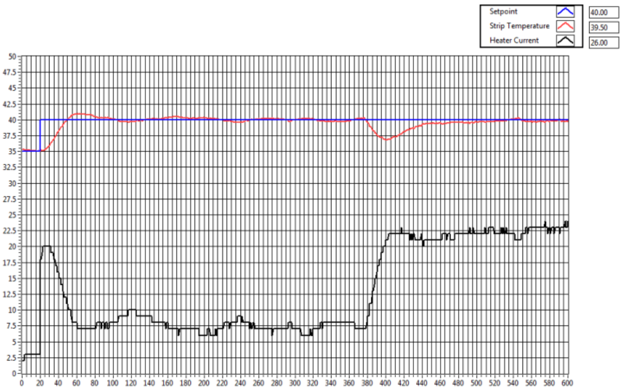

Fig. 8. PI controller closed loop response using backward difference

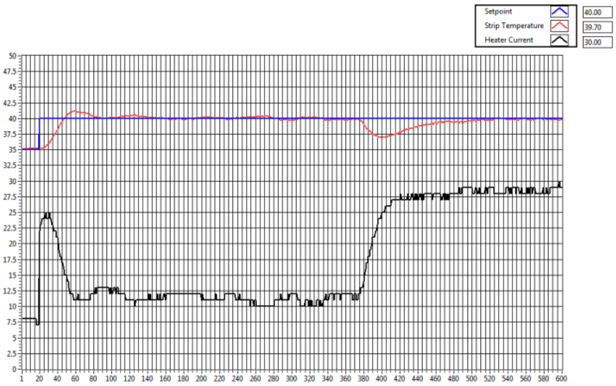

Fig. 9. PI controller closed loop response using forward difference

5. Conclusion

As the growing number of applications of discrete PI controller demands an accurate and efficient method for implementing it. In this paper, different discretizing methods of PI controller are given along implementation on the SBHS. The PI controller closed loop results given in Fig. 7, 8 and 9 shows that the trapezoidal approximation provides more overshoot than of backward and forward difference method. However, the trapezoidal approximation provides less oscillation as compared to backward and forward difference method in setpoint tracking response. The forward difference PI controller gives faster disturbance rejection as compared to the other two methods but it provides an inverse response in the heater current. This analysis is useful to implement discrete PI controllers for industrial applications.

Interesting issues related the PID controllers and SBHS to provide good parameter tuning algorithms and implement advanced control algorithms are still open.

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