A Digitally Programmable Temperature Controller Based on a Phase-Locked Loop

OSAMA I. MOHAMED, STUDENT MEMBER, IEEE, SERGIO SHOJI, AND KENZO WATANABE, SENIOR MEMBER, IEEE

Abstract—**A digitally programmable temperature controller is developed based on a phase-locked loop (PLL). Temperature under control is converted to frequency form and then compared, in a phase detector, with the reference frequency which corresponds to the target temperature. The detected phase drives the actuator. The frequency difference is also detected by a one-chip microcomputer which changes the reference frequency according to a proportional-integral-derivative operation. A prototype controller achieved 0.1°C stability in the temperature control of a water bath.**

I. Introduction

CHEMICAL and physical reactions are highly sensitive to temperature and thus temperature control is indispensable for industrial processes. To that aim, several controllers have been developed which use computers as the central unit [1]–[4]. By virtue of their powerful computing engines these controllers feature high accuracy, programmability, and adaptability. The temperature sensors used in these systems, however, provide their outputs in current or voltage form. Therefore, a high precision analog-to-digital converter is required for interfacing the sensor with the central unit. In addition, some controllers require digital-to-analog converters to drive the actuator according to the control algorithm.

Intensive effort is now devoted to the development of an intelligent sensor that provides the sensed variable in digital form [5]. A variety of output formats are possible, but frequency encoding requires only a simple interface and provides the best method of transmitting data. In view of this trend, a temperature control method compatible with such an intelligent sensor has been developed.

Section II describes the principles of operation and the architecture. To prevent an oscillatory response due to the slow heat transfer process, a proportional-integral-derivative (PID) control is essential. Its algorithm is also given. An integral part of the architecture is the temperature-to-frequency (T/F) converter. Section III describes a prototype controller using a newly developed T/F converter. Experimental results are presented which confirm the control principles. The paper concludes (Section IV) with a description of the potential applications and future works.

Manuscript received April 20, 1988. This work was supported by the Kurabe Industrial Company, Kamimura, Japan.

The authors are with the Research Institute of Electronics, Shizuoka University, Hamamatsu, 432 Japan.

IEEE Log Number 8823504.

II. Architecture

A. Hardware

The block diagram of the temperature controller is shown in Fig. 1. It can be divided into two main blocks: a one-chip microcomputer as the central unit, and the phase-locked loop (PLL) consisting of the T/F converter, frequency divider, phase detector, and power stage.

The T/F converter corresponds to a voltage-controlled oscillator in a conventional PLL. For simplicity, its output frequency f_T is assumed to be proportional to the temperature T under control,

$$f_T = f_o + S_c T \tag{1}$$

where f_o is the offset frequency and S_c is the conversion sensitivity. Comparing the two frequencies, f_T and f_r/D, where f_r is the oscillation frequency of the stable clock generator and D is the divisor set to the frequency divider, the phase detector produces the error signal to drive the power stage. The transfer function of the PLL is expressed as

$$H_p(s) = \frac{\omega_n^2}{S^2 + 2\zeta\omega_n S + \omega_n^2} \tag{2}$$

where the damping factor ζ and the natural frequency ω_n are given, respectively, by

$$\zeta = \frac{1}{2R}\sqrt{\frac{1}{CS_cS_dG}} \tag{3}$$

$$\omega_n = \sqrt{\frac{S_cS_dG}{C}} \tag{4}$$

where S_d is the sensitivity of the phase detector, G is the transfer gain of the power stage, C is the thermal capacity of the liquid under temperature control, and R is the thermal resistance to heat flow through the tank surface. It is clear from (2) that if D, given by

$$D = \frac{f_r}{f_o + S_c T_s} \tag{5}$$

where T_s is the target temperature, is set to the frequency divider, then the PLL controls temperature T to track T_s.

The damping factor is usually less than 1 and thus the overshoot and undershoot appear in the step response of

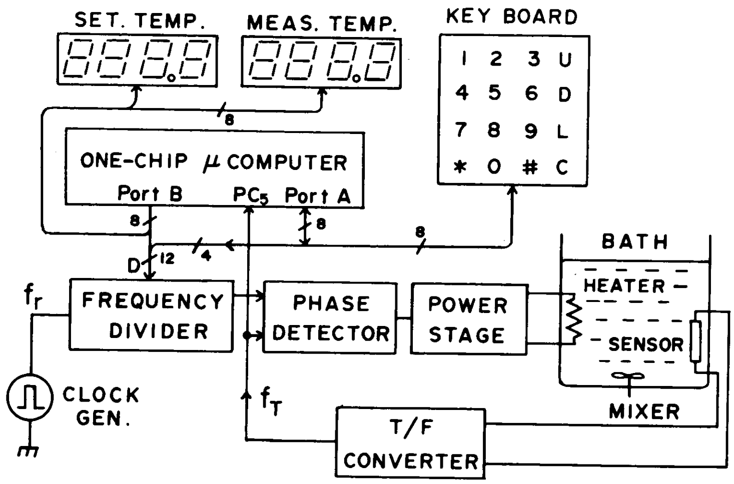

Fig. 1. The block diagram of the temperature controller.

PLL. For avoiding such an oscillation, and obtaining quick and stable response, the PID control is indispensable. To this aim, a one-chip microcomputer measures f_T and compares it with f_s to calculate the divisor D appropriate for the PID control. Its details are described below.

B. Software

The control software assumes an 8-bit, one-chip microcomputer μPD-7811 which accommodates, besides CPU, ROM, and RAM, three parallel I/O ports, two 8-bit timers, and a 16-bit event counter. The I/O port assignment is as follows: Port A is assigned to the keyboard for inputting the target temperature. Port B and the upper half of port A are used for setting the divisor D for the 12-bit frequency divider. Port B is also used for dynamic display of the target temperature T_s and temperature T under control, which is found by counting the output of the T/F converter applied to the fifth bit PC_5 of port C. The other bits of port C are used to issue timing scales to latch and display dynamically, T_s and T, and to set the divisor D for the frequency divider.

One of the two timers, timer A, is used for generating an interrupt request signal every $1/(30 \times 8)$ s to scan the dynamic display and the keyboard sequentially. The other timer, timer B, is connected in parallel with timer A to produce a gate signal every 0.5 s during which the event counter counts the output of the T/F converter to measure f_T.

Fig. 2 shows the flowchart of the main program developed with the above-mentioned hardware architecture in mind. The program first initializes all registers, timers, and the event counter, and then waits for the interrupt signals from the timers. Upon receiving the interrupt request from timer A, the program scans the keyboard to input the target temperature and also issues the scanning signal for the dynamic display of T_s and T. The interrupt request from timer B, on the other hand, commands the event counter to measure f_T. Using f_T thus measured and the target temperature equivalent frequency f_s, the program executes the PID algorithm according to the flowchart shown in Fig. 3.

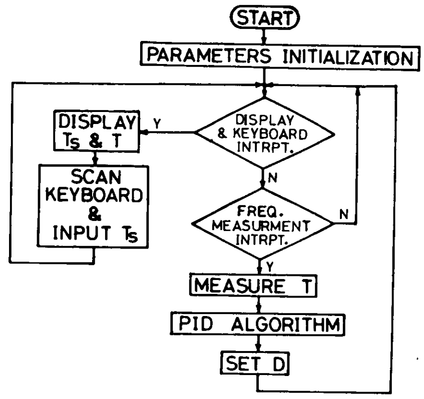

Fig. 2. The flowchart of the main program.

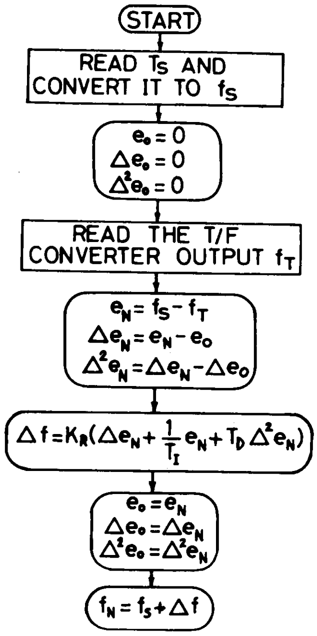

Fig. 3. The flowchart of the PID algorithm.

The PID algorithm can be expressed as

$$f(t) = K_R \left\{ e(t) + \frac{1}{T_i} \int e(t)\, dt + T_d \frac{de(t)}{dt} \right\} \tag{6}$$

where $f(t)$ is the control parameter, $e(t)$ is the difference between f_T and f_s, K_R is the gain, and T_i and T_d are the integration and derivation constants, respectively.

Expressing (6) in the difference equation form, we have

$$\Delta f = K_R \left(\Delta e_n + \frac{1}{T_i} e_n + T_d \Delta^2 e_n \right) \tag{7}$$

where e_n is the error between f_T and f_s, and Δe_n is the difference between the new and old errors. The PID program calculates Δf and recognizes that the frequency f_n with which f_T is compared in the phase detector is $f_s + \Delta f$. Updating D depending on this operation, the program waits again for an interrupt signal.

III. Experimental Results

To confirm the principles of operation, a prototype controller was built using off-the-shelf components except the T/F converter. The clock generator used is a 12-MHz

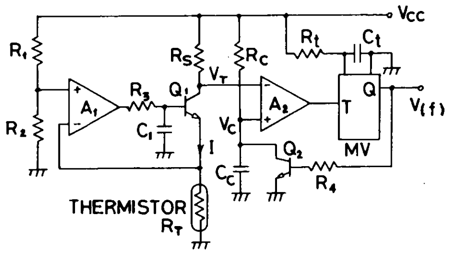

Fig. 4. The circuit diagram of the T/F converter.

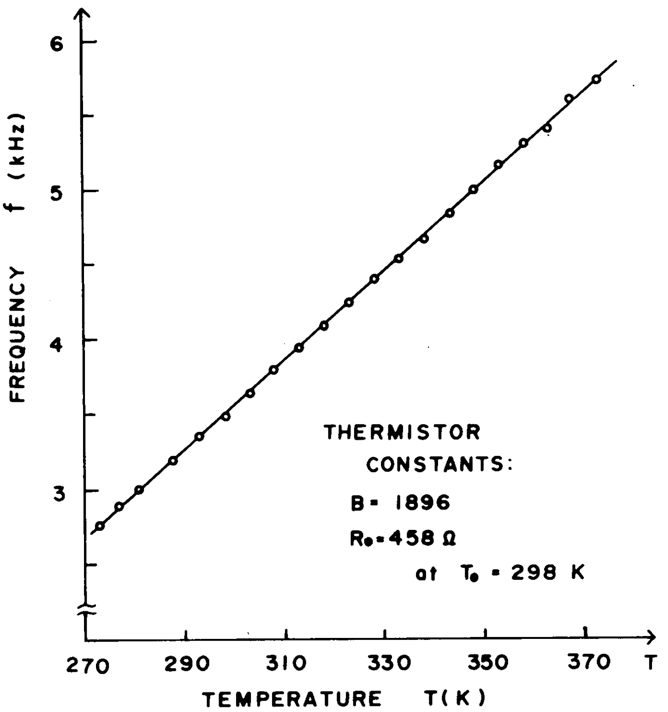

Fig. 5. The oscillation frequency f versus temperature T measured by a prototype T/F converter.

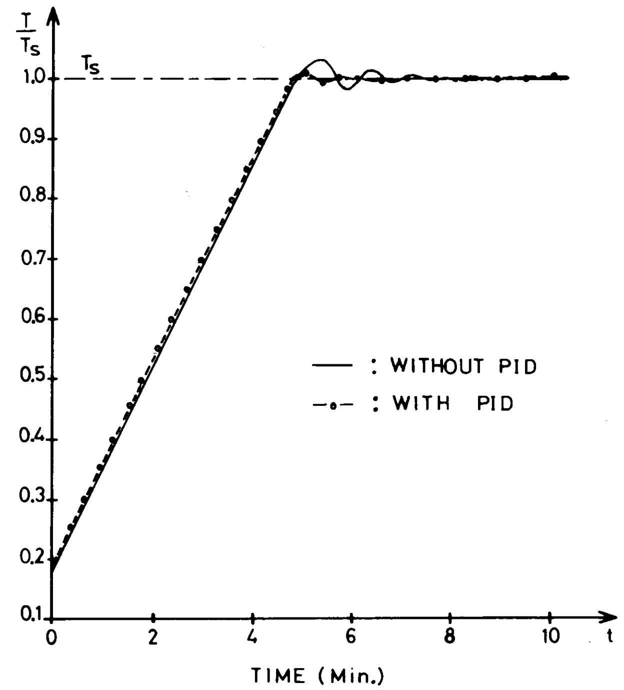

Fig. 6. The controller response to step change in the target temperature with and without the PID algorithm.

crystal oscillator. The power stage is the solid-state relay of zero-crossing detection which switches 100-V ac on and off depending on the output of the CMOS phase detector.

For temperature control up to 100°C, a T/F converter using a thermistor is developed [6]. Its circuit diagram is shown in Fig. 4. Op-amp A_1 and transistor Q_1 form the thermistor-controlled current source, producing the temperature-dependent voltage V_T at the controller of Q_1. A low-pass filter $R_3 C_1$ is incorporated to prevent the current source from oscillating. Voltage V_T is then compared with the exponentially increasing voltage V_c across C_c by the comparator A_2. This comparison converts the linear change in V_T into the exponential change over time. V_T changes exponentially with $1/T$, and the time required for V_c to reach V_T is inversely proportional to T. Therefore, repeating this comparison process by discharging C, one can obtain a linear relation between the oscillation frequency f and temperature T.

The oscillation frequency of the T/F converter using a thermistor with the material constant $B = 1896$ and $R_0 = 458\ \Omega$ at $T_0 = 298$ K is plotted in Fig. 5. From this plot, the offset frequency f_o and the conversion sensitivity S_c of the present T/F converter are found to be 2695 Hz and 30 Hz/°C, respectively. These values are stored in the control program to convert the target temperature into the frequency.

This prototype controller was applied to the temperature control of a water bath. Fig. 6 shows the controller response with and without the PID algorithm. Because of the small damping factor of the PLL, the step response without the PID control (solid line) oscillates around the target temperature. The PID algorithm for suppressing the oscillation is executed using the sampled data and thus the PID parameters should be determined from the PLL response in the z domain [7]. In this system, however, the discrete response was approximated by a continuous one because the thermal time constant CR of the water bath is much larger than the sampling period, and the conventional approach using the step response [8] was adopted to find the optimum PID parameters $K_R = 17.73$, $K_I = 8.16$, and $K_D = 0.231$. Experimental data in Fig. 6 demonstrate the performance of the controller using the PID algorithm. Temperature of the water bath tracks to the target temperature closely and the overshoot and undershoot are greatly reduced. The error in the steady-state is within 0.1°C.

IV. Conclusions

A new technique for temperature control based on the PLL has been proposed and confirmed experimentally by the prototype controller. The principles of control are compatible with intelligent sensors now being developed and are applicable to the control of other quantities such as humidity, pressure, and flow.

The prototype controller presented here features low cost, high precision, and programmability, but its range is limited to 100°C by the T/F converter. To expand the control range, a T/F converter using a platinum resistance thermometer is now under development.

References

[1] *Constant temperature baths and circulators.* Neslab Instruments, Inc., Portsmouth, NH, 1980.

[2] M. Kaucsar, "Digitally programmable temperature programmer," *Elec. Eng.*, Mar. 1980.

[3] R. J. Muha, S. M. Gates, and J. T. Yates, Jr., "Digital temperature programmer for isothermal and thermal desorption measurements," *Rev. Sci. Instr.*, vol. 56, pp. 613-614, 1985.

[4] Jeng-Renyang and Juht Zeng Lue, "A microcomputer-based programmable temperature controller," *IEEE Trans. Instrum. Meas.*, vol. IM-36, pp. 87-91, Mar. 1987.

[5] S. Middelhoek, P. J. French, J. H. Huijising, and W. J. Lian, "Sensors with digital or frequency output," in *Proc. Transducers '87*, pp. 17-24, 1987.

[6] Osama I. Mohamed, Toshifumi Takaoka, and K. Watanabe, "A simple linear temperature-to-frequency converter using a thermistor," *Trans. IEICE*, vol. E-70, Aug. 1987.

[7] C. L. Phillips and H. T. Nagle, Jr, *Digital Control System Analysis and Design.* Englewood Cliffs, NJ: Prentice-Hall, 1984.

[8] J. K. Astrom, "Adaptive feedback control," in *Proc. IEEE*, vol. 75, pp. 185-217, Feb. 1987.