

Design of a high-resolution PID temperature controller for use in a low-cost thermoluminescence system

M Mbongo¹ and R O Ocaya²

^{1,2}Department of Physics, University of the free State, P. Bag X13 Phuthaditjhaba 9866

E-mail: mbongom@qwa.ufs.ac.za

Abstract. The operation of an associated low-cost thermoluminescence (TL) system [1] necessitated the design and construction of a precision temperature controller. The temperature controller is presented separately since it is a crucial aspect of the TL system. The overarching design condition was a tightly controllable temperature regime with a resolution of about $\pm 0.5^\circ\text{C}$. The system was designed in such a way that an embedded controller formed around the PIC18f2520 heats up a sample holder to a specified temperature in optimal time while monitoring the temperature. The control algorithm was then written to ramp the temperature through the desired range of temperature between 25 and 700°C . The output of the PID controller was made to drive a resistive heater element or plant, modelled as a low-delay component owing to the small size of the sample holder. A mathematical model of the plant was obtained, simulated within MATLAB and the optimal controller found. The results of the simulation were then used to design an algorithm for the PIC controller. It was initially thought that the demands of controlling the temperature necessitated an additional PIC controller separate from one that would handle USB communications and general control. However, the responses of the temperature controller and optimal design of the overall user interface software and PIC firmware eliminated that need. The performance of the constructed PID controller was verified over the temperature range of 100°C to 400°C . While the PID controller has been designed specifically for usage in the TL system, it can be adapted with minimal adjustments to many other laboratory processes where fine temperature control is required.

1. Introduction

To facilitate their practical studies of thermoluminescence (TL) several independent researchers have offered alternative solutions to commercial instrumentation with the main impetus being low cost, simplicity of usage or suitability for their specific purposes [2, 3, 4, 5, 6, 7]. While TL is simple in principle, in practice there are many technical instrumentation challenges that must be identified and solved. The control of temperature over wide ranges (though typically below 400°C) with good measurement resolution and accuracy for the small dimensioned samples can be difficult, more so if the samples are in powder form. Other issues stem from nonlinearities, output drift, detector correlation errors and so on. The alternatives encountered in the literature have diverse attributes, for example arbitrary, wide range heating, profiled excitation such as logarithmic heating, “automatic” control of heating, and even open-loop “bang-bang” servos. The heating apparatus themselves are just as varied as are the intensity sensing apparatus also. Several of the foregoing designs have used third-party hardware proportional-integral (PI)

or proportional-integral-derivative (PID) control of the heating element. Notwithstanding this detraction from true low-cost, our point of contention in this article is that our own experiences with the open-loop, small heater “plant” have shown that a reported temperature regulation technique often can not have the claimed accuracy, even at the lowest heating rates [1]. For example, in [2], the stated temperature accuracy is erroneously the bit resolution of the analog to digital converter (ADC) itself in open-loop. In this article we report on a design of a temperature controller using a digital PID algorithm implemented as part of the firmware of the PIC18F2520 controller. The output element is a 100 watt resistive soldering iron driven directly by a 2SK3115 power MOSFET using pulse-width modulation (PWM) at 10 kHz, with temperature feedback provided by a k-type thermocouple referenced to ambient temperature. The heater power is derived from a locally built toroidal mains transformer rectified to supply direct current of 0.6 amperes at 180 volts. Varying the duty cycle in the algorithm from 0 to nearly 100% allows a wide range of temperature for the small heater. We report on the considerations of the design, ranging from the identification of the open-loop heater plant to optimization simulations and then to the coding of the digital algorithm. Finally, we present experimental data obtained from actual performance of the heating arrangement for a typical heating run.

2. System identification

2.1. The heater and feedback arrangement

A full description of the overall TL system can be found in [1]. For the purposes of designing the temperature controller and a digital PID algorithm, only a small part of the overall system will suffice. That is, the aluminium sample holder, a type K-thermocouple (Chromel-Alumel) for temperature feedback, and the ambient-compensated temperature conditioning circuit. The K-type thermocouple has an effective Seebeck coefficient of about $41\mu\text{V}$ per degree change in temperature. A system is considered to be open-loop if a control signal sent out simply hopes to achieve a desired action, known as the set point, without any sense of what the instantaneous value of the action actually is. In the present context it can be looked at as the heater simply being turned on in some manner without temperature feedback. It is important to know the various time parameters of the open-loop plant associated with certain types of control input. For example, the times associated with the attainment of a new steady state when a control input is suddenly changed from one value to another. Loosely speaking, these responses convey a sense of the “sluggishness” of the plant and ultimately how best to ply its input. The thermocouple circuit used was built around the low-cost LM324N quad operational amplifier (OPamp) shown Figure 1. External offset trimming and room-temperature compensation using the LM35CZ device were used to improve temperature measurement accuracy. The sample holder is an aluminium block of $2.5 \times 1.7 \times 0.5 \text{ cm}^3$ to which the k-type thermocouple was affixed using a pressing metal plate and screws. A 100W resistive heating source was implemented simply using a commercial pen-type soldering iron with a tip long and narrow enough to be inserted tightly into a compatible hole drilled into the sample holder.

2.2. The software PID temperature controller

In PID temperature control the drive control signal, $u(t)$, to the heating element is derived from the feedback from past and present temperature [9]. The controller first determines the error difference signal $e(t)$ that indicates the difference between the target and the current temperature. It then generates a control signal that is a sum of three quantities, one proportional to $e(t)$, another dependent on the time accumulated (integral) error and another dependent on how fast the error is changing with time i.e. the error derivative. Mathematically,

$$u(t) = K_p e(t) + \frac{K_p}{T_i} \int_0^t e(t) dt + K_p T_d \frac{de(t)}{dt}, \quad (1)$$

with the parameters K (d.c. forward gain), T_d and T_1 as in Figure 3. By direct experimentation

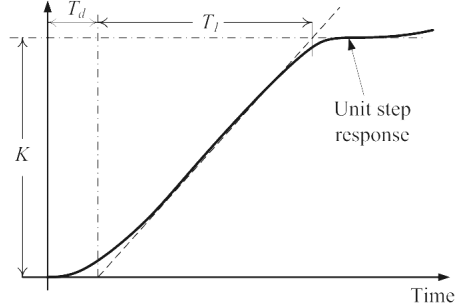


Figure 3. Parameters of interest in Ziegler-Nichols open loop tuning.

the parameters for the heater plant (sample holder and heating arrangement) were estimated graphically to be $T_d=4.0s$, $K=4.4$ and $T_1=184s$. The ZNM method suggests that the parameters of Equation 2 for a starting PID controller for the plant response in Equation 3 are:

$$K_p = \frac{1.2T_1}{KT_d} \approx 1.882, \quad T_I = 2T_d = 150s \quad \text{and} \quad T_D = \frac{1}{2}T_d \approx 6.67s. \quad (4)$$

Substitution of the parameters in Equation 4 into Equation 2 gives a PID controller $C(s)$ that has good transient response.

$$C(s) = 12.55 \left[\frac{s^2 + 0.15s + 0.001}{s} \right]. \quad (5)$$

The MATLAB/Simulink model shown in Figure 5 was obtained from $H(s)=C(s)G(s)$ as shown in Figure 8. The transport delay block models the delay T_d in Equation 3. To implement the

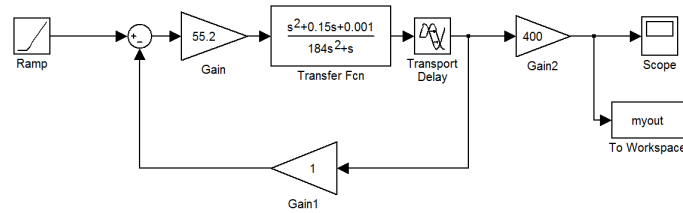


Figure 5. MATLAB/Simulink model of the closed-loop system that gives good transient performance. The input shown is a linear ramp with input duty cycle starting from 0 to 100%.

controller using a digital PID algorithm running on the PIC18f2520 firmware, it was necessary to convert the controller to the sampled time domain. The techniques of the z-transform were readily applied [11], though a full description of the technique is beyond the present scope. The PID controller in Equation 2 has the “velocity” z -transform form in sampled time $t \in 0, T, 2T, \dots$ given by

$$C(z) = K_p \left[1 + \frac{T}{T_I(1 - z^{-1})} + T_D \frac{(1 - z^{-1})}{T} \right] = a + \frac{b}{1 - z^{-1}} + c(1 - z^{-1}), \quad (6)$$

where $a=K_p$, $b=K_pT/T_I$ and $c=K_pT_D/T$. The parameter T is the sampling interval of the converter. It is roughly equal to the firmware looping or polling time. The result is the parallel PID implementation in Figure 6 which can readily be coded into the microcontroller firmware. The controller output $u(kT)$ is the PWM MOSFET gate drive. The sampled PID equations,

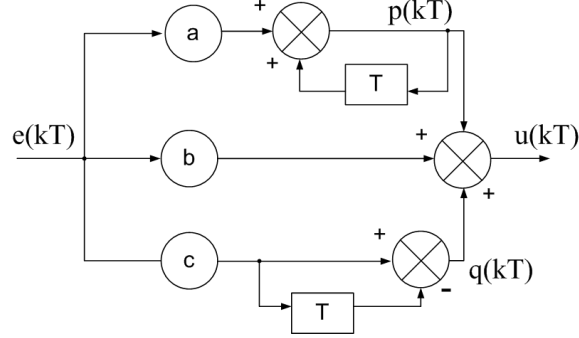


Figure 6. Parallel implementation of the PID TL-system heater controller.

Equations 7, were implemented on the PIC device in mikroC code [12].

$$\begin{aligned} p(kT) &= b e(kT) + p(kT - T) \\ q(kT) &= c e(kT) - c e(kT - T) \\ u(kT) &= p e(kT) + a e(kT) + q(kT) \end{aligned} \quad (7)$$

3. Results

The goal of creating a TL-instrument using common components has been largely met. Figure 7 shows the observed heating open-loop response of the small plant versus the MATLAB simulated function. From this information a good PID controller can then be derived and implemented

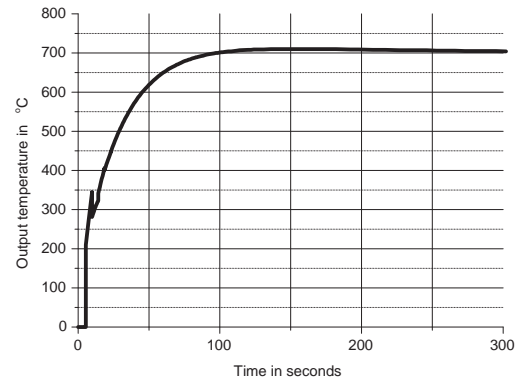
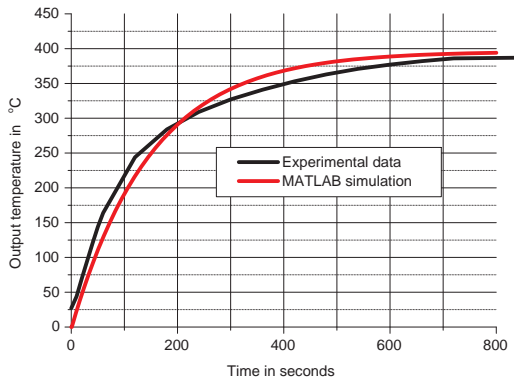


Figure 7. Experimental and simulated open-loop unit step response based on Equation 3. **Figure 8.** Closed-loop unit step response under scaling showing good transient response.

digitally in the microcontroller firmware, with a response typified by Figure 8. Linear heating was possible by ramping the control input from the software through the output range. Heating rate is known to affect observed results [13] and control of the heating rate is therefore needed. Figure 9 shows the typical output of the closed-loop plant in response to ramping duty-cycle input. Simulations show that rates exceeding 20°C/min are possible with the designed controller.

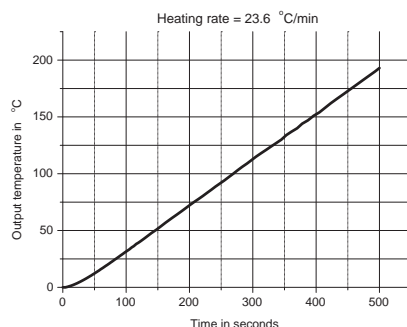


Figure 9. PID response of the system showing linear heating with a ramped duty-cycle input of 0.06 per min with Pearson's coefficient of linearity $R^2=0.999$.

4. Conclusions

We have presented the temperature controller in a low-cost TL-instrument. We show how the transfer function of a physically small heating plant can be determined for fine temperature control. Precise characterizations of the actual heating arrangement are usually not fully described in similar TL instruments in the literature, and many of the comparable TL systems surveyed use open-loop methods at the cost of finer temperature control. We outline the closed-loop PID and heater circuitry, ambient-temperature compensation mechanism and showed how this leads to greater temperature resolution. The digital PID algorithm was then derived and implemented in PIC microcontroller firmware. A linear heating regime with variable heating rates were obtained by ramping the control input from the software through the output range, with attained heating rates exceeding 20°C/min. The use of the digital PID algorithm allowed ease of tuning the controller by allowing minor adjusting the parameters in the firmware. Finally, the present approach to low-cost TL instrument design is significant in many respects and ultimately allow higher accuracy and finesse in glow peak separation on the temperature axis. The scope for future work with respect to temperature control remains to write algorithms for arbitrary heating regimes that can be invoked from the graphical user interface of the control program.

References

- [1] Mbongo M and Ocaya R O 2012, *A low-cost thermoluminescence system for use with .net computing environments. (Submitted to SAIP 2012).*
- [2] Neelamegam P, Padmanabhan K and Selvasekarapandian S 1992 *Meas. Sci. Technol.* **3** 581
- [3] Molina P, Santiago M, Caselli E, Lester M and Spano F 2002 *Meas. Sci. Technol.* **13** N16
- [4] Bhatnagar R, Saxena P, Vora H S, Dubey V K, Sarangpani K K, Shirke N D and Bhattacharjee S K 2002 *Meas. Sci. Technol.* **10** 2017
- [5] Lyamayev V I 2006 *Meas. Sci. Technol.* **17** N75
- [6] Neelamegam P and Rajendranb A 2006 *JINST* **1** T05001
- [7] Quilty J W, Robinson J, Appleby G A and Edgar A 2007 *Rev Sci Instrum.* **78**(8):083905
- [8] Ziegler J G and Nichols N B (1942). *Optimum settings for automatic controllers.* Trans. of the ASME. **64**.
- [9] Ibrahim D, *Microcontroller based temperature monitoring and control*, Newnes 2002, ISBN 978-0750-655569.
- [10] Åström K J and Hägglund Tore, *PID Controllers-Theory, Design, and Tuning*, 2nd edition, ISA, 1995.
- [11] Stroud K A, *Advanced Engineering Mathematics*, 4th ed., Industrial Press, NY, 2003.
- [12] MikroElektronika, *mikroC Pro for PIC Microcontrollers*, *mikroC Pro v3.2*, <http://www.mikroElektronika.com> (last accessed August 2011).
- [13] Kitis G, Spiropulu M, Papadopoulos J and Charalambous S (1993), *Nuclear Instr. & Methods in Physics Research Section B*, **73** (3), pp 367372 DOI: 10.1016/0168-583X(93)95753-R