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

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**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 $\pm 0.5^{\circ}$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 $41\mu$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 $2.5\times1.7\times0.5$ 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,

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

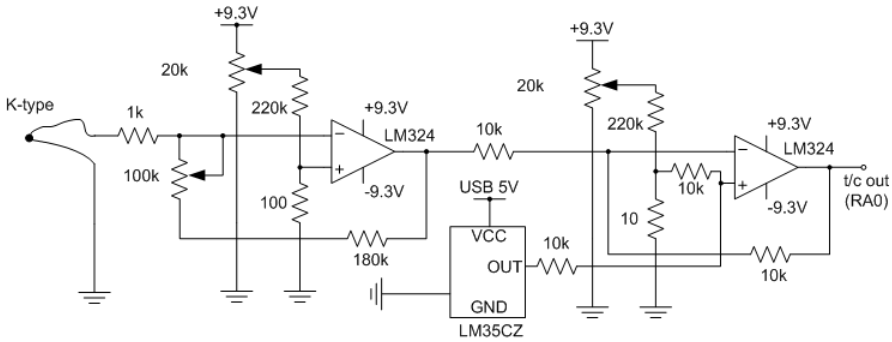


**Figure 1.** The temperature measurement circuit based on a K-type thermocouple.

where $K_p$ is the proportional gain, $T_i$ and $T_d$ are the integral and derivative time constants respectively. Tranforming Equation 1 and defining a common forward gain $K_p$ in Laplace transform space gives the PID controller:

$$C(s) = K_p\Big[1 + \frac{1}{T_I} + T_D s\Big] \tag{2}$$

Figure 2 shows the PWM actuator used. The gate of the MOSFET was driven at a software generated 10 kHz, forming the input of the controlled plant. Therefore, an input is subsequently any fixed amplitude (i.e. 5V), 10 kHz gate input distinguishable from other inputs by its duty-cycle only. A true "unit step" input was then a duty-cycle change from 0 to 100%. In practice a smaller step range can also be used to characterize the plant. To implement Equation 1, the time constants $T_i$ and $T_d$ were determined using the Ziegler and Nichols tuning method (ZNM) [8, 10] on the open-loop plant. Converting the system to z-transform space allowed digital implementation on the PIC18f2520 micro-controller.

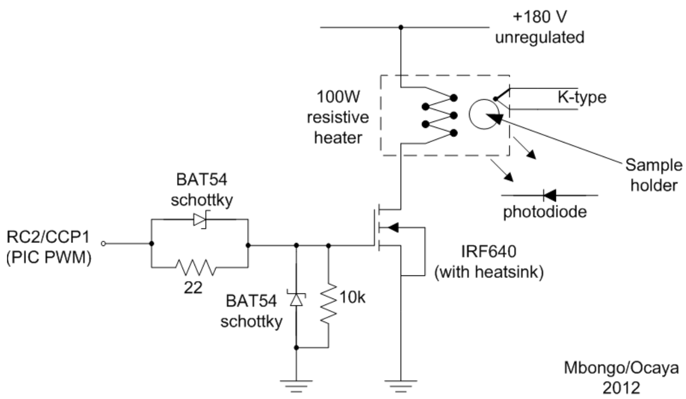


**Figure 2.** Diagram of the PWM heater driver.

*2.3. Realization of a discrete PID controller*

The Ziegler-Nichols method can be used in both open and closed loop configurations to ascertain the parameters of a plant thereby enabling a reasonable controller to be defined. In the present work the response to a step input on the open-loop plant was found to be sufficient. According to ZNM the open-loop unit step response, $G(s)$, can be approximated by the Laplace transform

$$G(s) = \frac{K\ e^{-sT_d}}{sT_1 + 1} \tag{3}$$

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

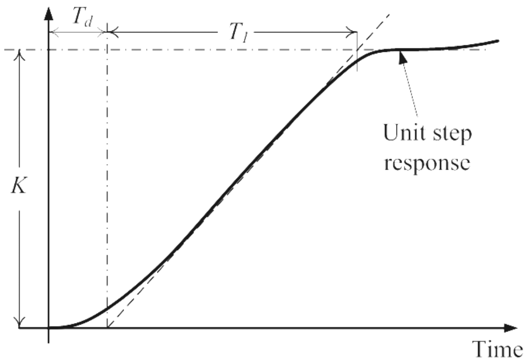


**Figure 3.** Parameters of interest in Ziegler-Nichols open loop tuning.

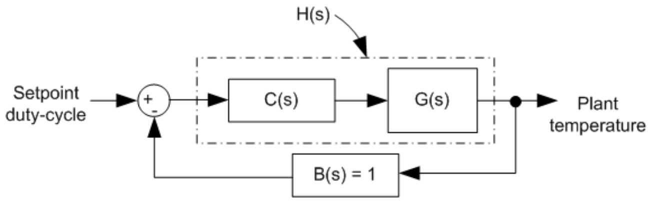


**Figure 4.** Block diagram of the implemented temperature controller. The closed-loop function can be written as $H(s)$=$C(s)G(s)$.

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:

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

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

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

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

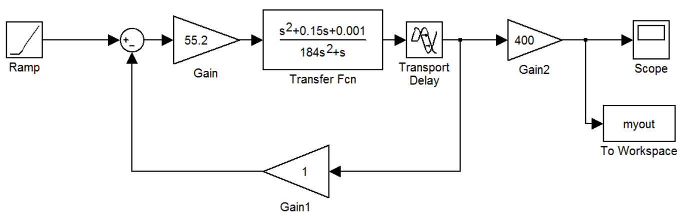


**Figure 5.** MATLAB/Simulink model of the closed-loop system that gives good transient performance. The input shown is a linear ramp with input duty cycle starting from 0 to 100%.

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 $t \in 0, T, 2T, \ldots$ given by

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

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,

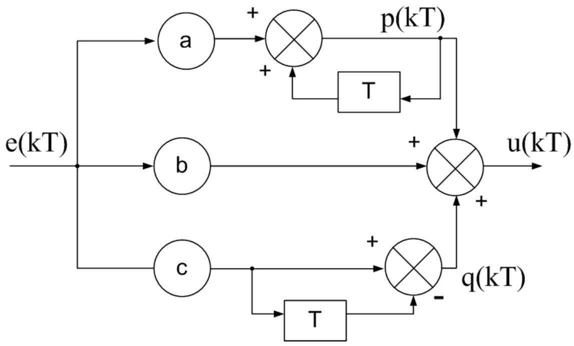


**Figure 6.** Parallel implementation of the PID TL-system heater controller.

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

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

## 3. Results and Conclusions

The goal of creating a TL-instrument using common components has been largely met. This article addresses the temperature controller of the TL instrument that is presented in [1]. We show that the physically small plant has a transfer function that needs to be known precisely if controlled heating of samples is to occur, as in Figure 7. Precise characterizations of the actual heating arrangement are conspicuously absent from almost all the proffered TL instruments in the literature. The article outlines the ambient-temperature compensated sample-temperature feedback and heater circuitry, showing that the time responses of the arrangement must be properly quantified for accurate temperature measurement. From this information a good PID controller can then be derived and implemented 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], but simulations show that rates exceeding 20°C/min are possible with the designed controller. Figure 9 shows the simulated output of the closed-loop plant in response to ramping duty-cycle input. The innovative use of the digital PID algorithm allows 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.

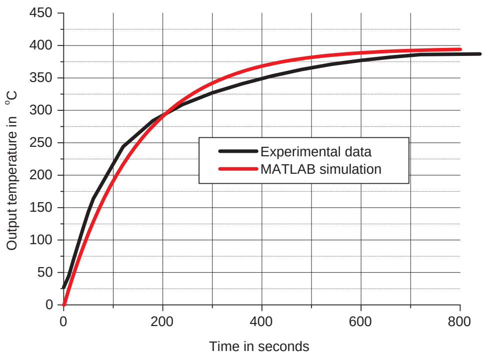


**Figure 7.** Experimental and simulated open-loop unit step response based on Equation 3.

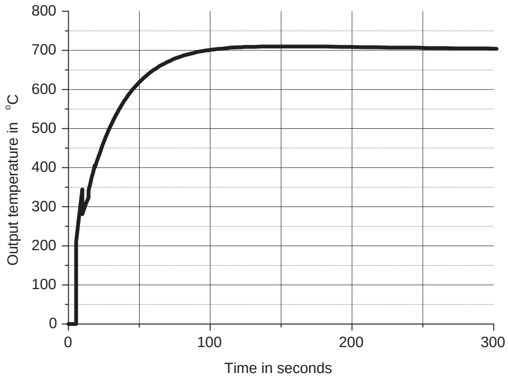


**Figure 8.** Simulated closed-loop unit step response under scaling showing good transient response.

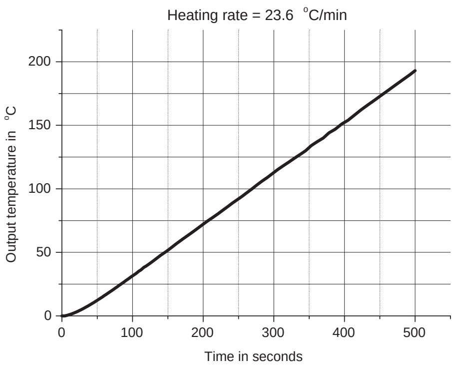


**Figure 9.** Simulation showing linear heating with a ramped duty-cycle input of 0.06 per min with Pearson's coefficient of linearity $R^2$=0.999.

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