Design of PID temperature control system based on STM32

Jianxin Zhang\textsuperscript{1,2,3,4,*}, Hailin Li\textsuperscript{1,3}, Kai Ma\textsuperscript{1,3}, Liang Xue\textsuperscript{1,3}, Bianhua Han\textsuperscript{1,3}, Yuemeng Dong\textsuperscript{2,3}, Yue Tan\textsuperscript{2,3}, Chengru Gu\textsuperscript{2,3}

1 Tianjin Key Laboratory of Optoelectronic Detection Technology and Systems, Tianjin Polytechnic University, Tianjin, China
2 Tianjin Key Laboratory of Advanced Electrical Engineering and Energy Technology, Tianjin Polytechnic University, Tianjin, China
3 Engineering Research Center of High Power Semiconductor Lighting Application System Education Department, Tianjin Polytechnic University, Tianjin, China
4 State Key Laboratory of Hollow Fiber Membrane Materials and Processes, Tianjin Polytechnic University, Tianjin, China

*Corresponding author e-mail: assen_zhjx@126.com

Abstract. A rapid and high-accuracy temperature control system was designed using proportional-integral-derivative (PID) control algorithm with STM32 as microcontroller unit (MCU). The temperature control system can be applied in the fields which have high requirements on the response speed and accuracy of temperature control. The temperature acquisition circuit in system adopted Pt1000 resistance thermometer as temperature sensor. Through this acquisition circuit, the monitoring actual temperature signal could be converted into voltage signal and transmitted into MCU. A TLP521-1 photoelectric coupler was matched with BD237 power transistor to drive the thermoelectric cooler (TEC) in FTA951 module. The effective electric power of TEC was controlled by the pulse width modulation (PWM) signals which generated by MCU. The PWM signal parameters could be adjusted timely by PID algorithm according to the difference between monitoring actual temperature and set temperature. The upper computer was used to input the set temperature and monitor the system running state via serial port. The application experiment results show that the temperature control system is featured by simple structure, rapid response speed, good stability and high temperature control accuracy with the error less than ±0.5°C.

1. Introduction
As an important parameter in industrial manufacture \cite{1} and scientific experiment \cite{2}, temperature needs to be measured and controlled rapidly with high accuracy. Otherwise, the distinct temperature errors will be harmful to the performance and precision of the whole measurement system \cite{3}, especially in the field of modern instrument. For example, it is very important to correctly obtain the accelerated lifetime prediction \cite{4} and photo-electro-thermal properties \cite{5} of LED light source through providing a constant temperature environment with high accuracy and rapid response speed. In another instance, the core parts of fiber optic gyroscope (FOG) is also sensitive to environment temperature \cite{6}, a slight temperature change can cause the zero drift of FOG, so it is necessary to provide accurate temperature control or temperature compensation \cite{7}. Lots of practical applications show that a rapid and high-accuracy temperature control system is worthy of further investigation.
Traditionally, analog circuit is used for temperature control in most cases. In this circuit, electromagnetic relay is usually chosen to control the switchover between heating module and cooling module, as well as controlling the working time and frequency of the two modules, for constant temperature. However, this method has many weaknesses, such as low accuracy of temperature control, great inertia, apparent lag and complex circuit design. In addition, it also has the deficiencies in temperature uniformity, stability and response speed, and so on [8].

In this paper, a thermoelectric cooler (TEC) was adopted to provide a new method of working pattern switchover between heating and cooling. The effective electric power of heating or cooling could be adjusted through regulating the pulse duration ratio of pulse width modulation (PWM) signals about TEC driving voltage. The PWM signals could be automatically controlled by proportional-integral-derivative (PID) algorithm. In order to increase the precision of temperature measurement, the voltage ripple of temperature acquisition circuit was decreased by a passive filter. The STM32 was used as micro-controller unit (MCU) for building a rapid and high-accuracy temperature control system with PID algorithm. Finally, the response speed and stabilization accuracy of temperature control were evaluated by application experiment.

2. Structure design of sample holder and overall design of temperature control system

2.1. Structure design of sample holder

In general, temperature control system need to equip a sample holder with the working patterns of heating, cooling and constant temperature. A FTA951 heating and cooling module, as shown in Figure 1, is selected as the execution unit for temperature control. The TEC in FTA951 module can execute the cooling pattern and rapidly drop the temperature of sample holder when provided with forward direct current. When TEC is driven with reverse current, it can execute the heating pattern and rise the temperature of sample holder in a short time. The TEC has high working reliability because FTA951 module adopts the design of quake-proof and shock-proof. There is a plane sample holder for installing the test sample on one side of TEC. On the other side of TEC, a heat sink with fan is installed to improve the efficiency of heating and cooling [9].

The sample holder needs to be made of copper material with high thermal conductivity capacity. There are two probe-holes in sample holder, through which temperature sensing probes can be send to the central position. One probe-hole is very close to the surface of sample holder and regularly gives the feedback of actual temperature $T_1$. The other one is very close to TEC and collects the referential temperature $T_2$ to judge whether the sample holder is in thermal steady state.

![Figure 1. Structure of FTA951 heating and cooling module.](image)

In order to make the actual temperature $T_1$ of sample holder reach the set temperature $T_0$ quickly without obvious overshoot, the effective power of TEC is high when there is a big difference between $T_1$ and $T_0$; when $T_1$ is approaching to $T_0$, the effective power is declining accordingly; when $T_1$ reaches $T_0$, the effective power is reduced to the level for maintaining slight temperature fluctuation and maintains $T_1$ around $T_0$ for long times. Only when the difference between $T_1$ and $T_2$ is less than ±0.5°C, the temperature of sample holder is deemed to be in thermal steady state.
2.2. Overall design of temperature control system

The overall design frame of temperature control system is shown in Figure 2. The temperature acquisition circuit is designed to convert temperature signal into amplified voltage signal. STM32F103VET6 is used as MCU which can obtain the set temperature $T_0$ given by PC soft through RS232 serial port and regularly monitor the present actual temperature $T_1$ of sample holder through temperature acquisition circuit. After each acquisition of $T_1$, MCU immediately calculates the temperature difference between $T_1$ and $T_0$. According to the plus or minus of temperature difference, MCU can automatically control the pin switch of electromagnetic relay in temperature control execution circuit to adjust the current direction of TEC and execute working pattern switchover between heating and cooling. In addition, according to the absolute value of temperature difference, MCU runs digital PID algorithm to timely adjust the pulse duration ratio of PWM signals which can control the effective power of TEC by temperature control circuit [10]. Finally, the dynamic adjustment of TEC effective power based on the temperature difference can accurately keep the temperature of sample holder around the set temperature $T_0$. During the controlling process, all the temperature data can be timely sent to PC soft through RS232 serial port, and then the present actual temperature values and their variation curve are displayed on the PC soft.

![Figure 2. Frame diagram of overall design for temperature control system.](image)

The temperature control system mainly provides a mandatory stable environment temperature to meet the requirements of LED photo-thermal properties measurement in steady state. The set temperature for measurement should be continuously adjustable and cover the range of 20°C-80°C. When the temperature of sample holder rises from 20°C to 80°C or drops from 80°C to 20°C, the elapsed time for reaching the thermal steady state of target temperature should be less than 140s to ensure a rapid response speed of temperature control. In thermal steady state, the maximum error between actual temperature and set temperature of sample holder should be less than ±0.5°C.

3. Circuit design of temperature control system

3.1. Temperature acquisition circuit

The temperature acquisition circuit is mainly used for the real-time collection and feedback of the actual temperature of sample holder. In the circuit, Pt1000 platinum thermal resistor is used as temperature sensor. The temperature coefficient of resistance (TCR) of Pt1000 is 0.003851 °C⁻¹, and accuracy range is from ±0.05 °C to ±0.5°C. As a temperature sensor, Pt1000 has the advantages of stable electrical performance, vibration endurance, good reliability, high accuracy, sensitivity and long life, etc. Therefore, Pt1000 is qualified for the design of temperature acquisition circuit. The common-mode rejection ratio (CMRR) is usually defined as the ratio of common-mode interference signal acting on the system to the different-mode signal needed by the system to have the same output. Higher CMRR means that the system has stronger ability to resist common interference. AD8221 is a gain-programmable high-performance instrument amplifier and has the remarkable common-mode rejection performance. When the gain is 1, AD8221 can keep the minimum common-mode rejection ratio of 80dB at each level until the frequency reaches 10 kHz, thus it can resist common-mode interference effectively and is very suitable for the sensor interface circuit with differential input. In addition, AD8221 is also featured by low voltage offset, low offset drift, low grain drift and high gain accuracy, so it is a good choice for direct current performance application such as bridge signal
conditioning. Therefore, this circuit uses Pt1000 and AD8221 to enable the collection and amplification of temperature signal respectively.

![Temperature acquisition circuit](image)

**Figure 3.** Temperature acquisition circuit.

The temperature acquisition circuit, as shown in Figure 3, is mainly composed of H-bridge circuit and differential operational amplification circuit with passive filter. In Figure 3, P1 is the terminal for connecting with Pt1000 temperature sensor. When Pt1000 is in ice-water mixture (0°C), the temperature is corrected by adjusting the actual resistance of adjustable resistor RP4 to make the output voltage $V_{out}$ of AD8221 equal to 0 V. The resistance of Pt1000 increases with temperature rising, which changes the divided voltage in H-bridge circuit. As a result, the voltage difference between +IN and -IN of AD8221 also changes accordingly. The differential amplification factor can be obtained through high-accuracy assistance R21. The amplified output voltage $V_{out}$ is input into analog-to-digital converter of MCU and translated into temperature value. In this circuit, a passive filter is used to decline RF energy as much as possible and suppress RF interference before the amplifier. A good RF interference suppression can balance the AC signal between each input and ground, and obtain enough high input impedance in the measuring bandwidth, which can maintain the load capacity of input signal source.

3.2. Temperature control circuit

Temperature control circuit is designed to receive the control signals from MCU and drive the electromagnetic relay or the solid-state relay. The circuit with electromagnetic relay and that with solid-state relay have the same topological structure, as shown in Figure 4, but they have different functions. The former can receive the heating or cooling signals given by MCU to control the conduction pins of electromagnetic relay and adjust the current direction of TEC for working pattern switchover between heating and cooling. The other one, in a constant heating or cooling state, receives the PWM signals calculated by PID algorithm in MCU and control the switching frequency of the solid-state relay for adjustable effective power of TEC and high-accuracy temperature control. In this circuit, TLP521-1 photoelectric coupler is used to transfer control signals, showing a good isolation performance between input and output and high suppression ability about interference. BD237 power transistor has many high working performances of low parasitic capacitance, small on-state voltage drop and easy integration. Therefore, it meets the requirements of circuit design by using the combination of TLP521-1 and BD237 as the main driving devices for relay.

The operating principle of the temperature control circuit is as follow. When the PA2 pin of MCU outputs a high level signal, photoelectric coupler I4 is in off state. Accordingly, the power transistor Q1 cuts off, the relay is in off state and TEC stops working. When the PA2 pin outputs a low level signal, photoelectric coupler I4 is in on state. Accordingly, power transistor Q1 conducts, the relay is in on state and TEC starts working. The negative pole of the diode D2, which is in parallel with relay,
is connected to the positive pole of direct-current source. When the power supply to the coil of relay is cut off, the diode provides a way for current flow in the coil, and the leftover energy is gently consumed in the circuit composed by coil and diode, which can overcome the harmful influence of back EMF on the circuit.

![Figure 4. Temperature control circuit.](image)

3.3. Temperature control execution circuit
As shown in Figure 5, the temperature control execution circuit mainly includes: FTA951 heating and cooling module (with TEC), DC power supply, electromagnetic relay (SL-KE) and solid-state relay (LDG). FTA951 module is the execution device. DC power supply provides electrical energy for TEC and relays. Electromagnetic relay and solid-state relay coordinates with each other to control the heating or cooling pattern and effective power of TEC respectively and accurate temperature control can be realized.

![Figure 5. Temperature control execution circuit.](image)
By receiving the signals from temperature control circuit, the electromagnetic relay controls the working pattern switchover between heating and cooling of TEC. When the coil of electromagnetic relay is energized, the normally closed contact of relay can be opened. Accordingly, TEC is provided with reverse current and executes the heating pattern. When the coil is powered off, its normally closed contact resets. Accordingly, TEC is provided with forward current and executes the cooling pattern. The solid-state relay has the working performance of control voltage 3-32 VDC, load voltage 5-200 VDC and on-off time ≤10 ms, which meets the design requirements of minimum PWM period more than 500 ms, input DC control voltage 12 V and output DC load voltage 12 V. In this system, the pulse duration ratio of PWM signals can be timely adjusted by PID algorithm, which provide a quick on-off control of solid-state relay and control the execution time of heating or cooling pattern, i.e., the effective power of TEC can be adjusted in heating or cooling pattern.

4. Design of software
The flow chart of software control is shown in Figure 6. When the system is powered on, the software first initializes system clock, timer, serial ports and PID parameters, and so on. Next, the user inputs the set temperature $T_0$ in soft for temperature control, and the temperature sensor gives the real-time feedback of present actual temperature $T_1$ of sample holder. In the control process, $T_0$ and $T_1$ are compared in real time. If $T_0 > T_1$, MCU sends out heating signal. Conversely, MCU sends out cooling signal. If $T_0$ approximately equals $T_1$, the previous signal state is maintained. The pulse duration ratio of PWM signals is obtained through calculation of PID algorithm. The greater there is temperature difference between $T_0$ and $T_1$, the greater PWM signal has the pulse duration ratio, and the longer high electrical level lasts in a PWM period, which can rapidly raise or drop the temperature of sample holder. As $T_1$ approaches $T_0$, the pulse duration ratio of PWM declines gradually to avoid a great temperature overshoot. After when $T_1$ reaches $T_0$, the pulse duration ratio of PWM will remain at a small value to keep the temperature of sample holder stabilize at the set temperature.

![Flow chart of system software](image_url)

**Figure 6.** Flow chart of system software.
5. PID algorithm and its parameter adjustment

PID algorithm is a control algorithm with foreseeability. For the controlled object, PID algorithm considers not only its current status values but also its historical status values in past time and its recency status values in the future [11]. The three kinds of value decide collaboratively the present output control signal. The calculation result of PID algorithm is a number which is used to adjust the operation of controlled object, such as different power of the heater, open degree of valve, and so on. Normally, the output is in the form of PWM signal, which meets the design requirements by changing the pulse duration ratio of output control signal as needed.

Figure 7 is PID control schematic diagram. After the set temperature $T_0$ is given by user on PC soft, PID algorithm runs immediately and reads the feedback value of present actual temperature $T_1$ about controlled object in real time. Subsequently, the temperature difference between $T_0$ and $T_1$ is calculated. Accordingly, the historical bias, current bias and recency bias of overall system is obtained. After integral, proportion and differential calculations about the three biases, MCU outputs a PWM signal with variable pulse duration ratio to conduct the next temperature change direction and range. And soon, the present actual temperature $T_1$ of controlled object can rapidly reach the set temperature $T_0$ and be steadily kept to be constant temperature.

![Figure 7. Schematic diagram of PID control algorithm.](image)

The system adopts the positional PID control algorithm:

$$\text{out} = (K_p E_k) + (K_i \sum_{k=0}^{\infty} E_k) + (K_d (E_k - E_{k-1})) + \text{out}_0$$  \hspace{1cm} (1)$$

Let

$$K_i = K_i(t_i/t) \quad K_d = K_d(t_d/t)$$  \hspace{1cm} (2)$$

Thus

$$\text{out} = (K_p E_k) + (K_i (t_i/t) \sum_{k=0}^{\infty} E_k) + (K_d (t_d/t)(E_k - E_{k-1})) + \text{out}_0$$  \hspace{1cm} (3)$$

Where $E_k$ is the sampling deviation of this time, $E_{k-1}$ is the sampling deviation of last time, $K_p$ is scale factor, $t_i$ is integral time constant, $t_d$ is differential time constant, and $t$ is sampling period. And $\text{out}_0$ is set a non-zero constant to ensure the output signal not to be 0 when $E_k$ is 0. Otherwise, when the present actual temperature equals the set temperature, the output signal of PID control algorithm will be 0, and the system will be in uncontrolled status without control signal.

In Eq. (3), $K_p$, $t_i$, $t_d$ and $t$ are main control parameters of PID algorithm, and the determination of the values about these parameters is the key design of temperature control system. Temperature control system is usually a typical lag inertial system, so the trial-and-error method can be employed to
determine the control parameters of PID algorithm. First, let $t_i=\infty$ and $t_d=0$, we can remove the integral terms (terms containing $t_i$) and the differential terms (terms containing $t_d$) out of Eq. (3). The simplified Eq. (3) becomes a pure proportional adjustment of PID and easily determines the scale factor $K_p$. For determining the value of $K_p$, temperature input value is set to be 60%-70% of the highest allowable value (80°C) in system. Gradually, the scale factor $K_p$ increases from 0 until system oscillation occurs. And then, $K_p$ gradually reduces from just value until system oscillation disappears. At this time, the scale factor $K_p$ is 25 and recorded. However, in the practical application of PID, the scale factor $K_p$ should be 60%-70% of above recorded value, i.e. $K_p=15$. After the determination of $K_p$, a big initial value of 5000000 can be set for integral time constant $t_i$. Subsequently, the integral time constant $t_i$ gradually reduces from just value until system oscillation occurs. And then, $t_i$ gradually increases until system oscillation disappears. At this time, integral time constant $t_i$ is 1666667 and recorded. However, in the practical application of PID, integral time constant $t_i$ should be 150%-180% of above recorded value, i.e. $t_i=2500000$. Generally, differential time constant $t_d$ is set to be zero. However, temperature control system as a lag control system, the results of differential adjustment can indicate the change rate of system deviation signal which can predict the tendency of deviation change. Therefore, the deviation can be timely removed by differential adjustment which has the function of proactive control and is necessary parameter for temperature control system. The determination of differential time constant $t_d$ is the same with that of $K_p$ and $t_i$. The final value of $t_d$ should be 30% of recorded value which obtained when system oscillation just disappears, i.e. $t_d=1000$.

PID control program is executed periodically, and the execution period is called sampling period $t$. The shorter the sampling period is, the better the sampling values reflect the real change of analog signal. But too short sampling period will increase the workload of MCU, and two adjacent sampling values will have little difference, which will make the differential parts output by PID controller to be close to zero. Therefore, the sampling period should not be too short. Instead, we just need to guarantee enough sampling points when temperature changes rapidly, so that important information will not be missed due to insufficient sampling points. As a result, the sampling period $t$ is set to 200 ms for the system in this study.

6. Experiment result
Figure 8 shows the control processes of heating from 20°C to 80°C, cooling from 80°C to 20°C and constant temperature beyond the range of temperature changing. As a result of proper adjustment about PID algorithm parameter, a rapid and high-accurate temperature control without overshoot is realized. When temperature rises from 20°C to 80°C, the system need spend about 140 s to finish the process from starting work to a thermal steady state. When temperature drops from 80°C to 20°C, the process of temperature changing need spend about 120 s. The stability accuracy of ±0.5°C can keep constant for a long time with the system runs continuously. Therefore, the application experiment results of temperature changing between 20°C and 80°C show that the working performances meet the design requirement.
Figure 8. Temperature control processes of system between 20°C and 80°C.

Table 1 lists the response time and stabilization accuracy of system in heating and cooling processes aiming at different target temperatures. It can be seen that when the system rises the temperature from 20°C with interval of 10°C, both the response time and stabilization accuracy increase gradually with the highest accuracy of ±0.2°C. When the temperature drops from 80°C with interval of 10°C, similarly, both the response time and stabilization accuracy increase with the highest accuracy of ±0.2°C.

Table 1. Response time and stabilization accuracy of system temperature control aiming at different target temperatures.

| Working patterns | Initial temperature /°C | Target temperature /°C | Response time /s | Stabilization accuracy /°C |
|------------------|--------------------------|------------------------|-----------------|---------------------------|
| Heating pattern  | 20                       | 30                     | 37              | ±0.5                      |
|                  | 30                       | 40                     | 40              | ±0.5                      |
|                  | 40                       | 50                     | 45              | ±0.4                      |
|                  | 50                       | 60                     | 50              | ±0.4                      |
|                  | 60                       | 70                     | 55              | ±0.3                      |
|                  | 70                       | 80                     | 70              | ±0.2                      |
| Cooling pattern  | 80                       | 70                     | 35              | ±0.5                      |
|                  | 70                       | 60                     | 40              | ±0.4                      |
|                  | 60                       | 50                     | 43              | ±0.3                      |
|                  | 50                       | 40                     | 49              | ±0.3                      |
|                  | 40                       | 30                     | 57              | ±0.2                      |
|                  | 30                       | 20                     | 72              | ±0.2                      |

7. Conclusion
A temperature control system based on STM32 was designed using PID control algorithm. In this system, the TEC effective electric power of heating or cooling could be rapidly and accurately adjusted by regulating the pulse duration ratio of PWM signals according to PID algorithm. Furthermore, the voltage ripple of temperature acquisition circuit was decreased by a passive filter. So
the response speed and stabilization accuracy of this system can be effectively improved. The application experiment results of this system show that the largest temperature control range is between 20°C and 80°C with the largest error of ±0.5°C. For the heating from 20°C to 80°C and reaching a thermal steady state, the execution time is about 140 s. And the cooling time from 80°C to 20°C is about 120 s. Therefore, the response speed and stabilization accuracy of designed temperature control system all satisfy the design requirements.

Acknowledgments
This work was financially supported by the Natural Science Foundation of Tianjin, China (Grant No. 15JCQNJC41800); the National Undergraduate Training Programs for Innovation and Entrepreneurship of China (Grant No. 201610058036); the Scientific Innovation Plan for Graduate Students of Tianjin Polytechnic University, China (Grant No. 16118); and the Scientific Research Program of Tianjin Municipal Education Commission, China (NATURAL SCIENCE, Grant No. 2017ZD06).

References
[1] R. Zhang, J. Tao, F. Gao, A new approach of takagi-sugeno fuzzy modeling using an improved Genetic Algorithm optimization for oxygen content in a coke furnace, Ind. Eng. Chem. Res. 55 (2016) 6465-6474.
[2] E. Marti, E. Kaisersberger, E. Füglein, Multicycle differential scanning calorimetry: Thermophysical procedures for research, development, and quality control of substances and materials, J. Therm. Anal. Calor. 101 (2010) 1189-1197.
[3] T. Pardy, T. Rang, I. Tulp, Development of temperature control solutions for non-instrumented nucleic acid amplification tests (NINAAT), Micromachines 8 (2017) Article number: 180.
[4] Y. Zong, J. Hulett, Development of a fully automated LED lifetime test system, Light Eng. 21 (2013) 47-52.
[5] G. Elger, D. Müller, A. Hanß, M. Schmid, E. Liu, U. Karbowski, R. Derix, Transient thermal analysis for accelerated reliability testing of LEDs, Microelectron. Reliab. 64 (2016) 605-609.
[6] X. Chen, C. Shen, Study on temperature error processing technique for fiber optic gyroscope, Optik 124 (2013) 784-792.
[7] J. Nazir, T. Vivek, T. Jaisingh, Temperature stabilization in fibre optic gyroscopes for high altitude aircraft, Optik 127 (2016) 9701-9710.
[8] S. Cao, L. Shi, X. Ze, H. Zhang, “Continuously sintering furnace temperature control system based on intelligent PID adjustment,” in Proceedings of the 2008 International Conference on Computer and Electrical Engineering, Phuket, Thailand, 2008, pp. 190-193.
[9] M. Z. Yilmazoglu, Experimental and numerical investigation of a prototype thermoelectric heating and cooling unit, Energy Build. 113 (2016) 51-60.
[10] H. Huang, S. Fu, P. Zhang, L. Sun, “Design of a Small Temperature Control System Based on TEC”, in 9th International Symposium on Computational Intelligence and Design, Hangzhou, Zhejiang, China, 2016, pp. 193-196.
[11] Y. Wang, Q. Jin, R. Zhang, Improved fuzzy PID controller design using predictive functional control structure, ISA Trans. 71 (2017) 354-363.