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Design for a Small High-efficiency and High-precision Simulated Blackbody Controller

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Abstract. This paper explains the urgent need for, and technological bottleneck of, current portable general-use infrared detectors, and several proposals have been put forward and carried out. Specifically, the TEC semiconductor cooler was adopted to achieve the positive and negative temperature difference required by the infrared detector based on the Peltier effect; a fuzzy-PID control algorithm was employed to achieve high-precision control over the output temperature difference; and the high stability AD acquisition circuit and Newton's iteration algorithm were adopted to realize a design method for high-resolution and high-accuracy temperature indication, thus to achieve real-time and automated control of the blackbody.

Introduction

Infrared thermal imaging equipment is popular and widely applied in battlefields as well as equipment and civilian fields in various countries, owing to its numerous advantages, such as easy concealment, all-weather operation, resistance to electromagnetic interference and effectiveness under harsh light. In practice, infrared thermal imaging equipment comes in numerous distinct models and complex classifications, with precise structures and delicate components, so it is a difficult task to develop and supply the portable general infrared detector systems that are urgently needed. The most critical step will be the design and development of a simulated blackbody controller.

The design was mainly carried out from three aspects presented in this paper. Specifically, the TEC semiconductor cooler was adopted to achieve the positive and negative temperature difference required by the infrared detector based on the Peltier effect; a fuzzy-PID control algorithm was employed to achieve high precision control over the output temperature difference; and the high stability AD acquisition circuit and Newton's iteration algorithm were adopted to realize the high resolution and high accuracy of temperature.

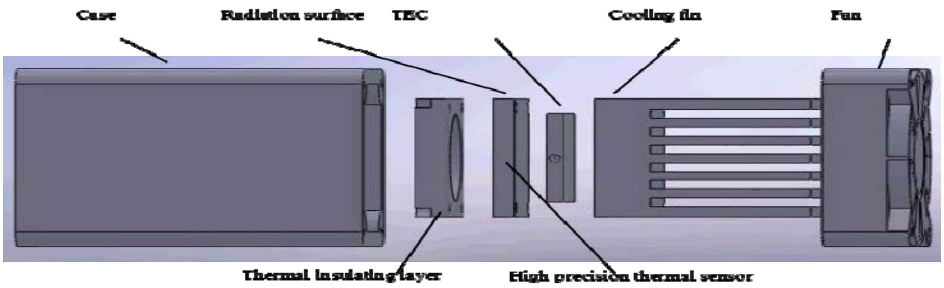

Figure 1. Diagram of Simulated Blackbody

Structural Schematic

The thermoelectric cooler (TEC) was employed as the heating and cooling drive source, of which, one side was coated with an aluminum hot layer and the other side was installed with a radiator and a fan. It is used to dissipate the heat generated from the heating surface when the blackbody is cooling, thus to increase the blackbody's installed temperature range. The TEC and hot aluminum layer were installed between the insulation layer and the radiator, and the two cross sections of the TEC were applied with thermally conductive silicone grease to enhance the heat transmission efficiency. A high precision thermal sensor was installed in the centre of the aluminum thermal layer to accurately sample the temperature of the radiation surface, as shown in Figure1.

Hardware Design

Design of Thermal Resistance Acquisition and Conversion Unit

The design includes two elements, namely, the acquisition circuit hardware design and the resistance-temperature software conversion algorithm. For the hardware and circuit element, it was used mainly to acquire the real-time resistance of PT100 platinum thermistor from the temperature sensor, and for the other element, it was to achieve a real time temperature display through the resistance - temperature conversion algorithm.

The precision constant current source was adopted to directly drive the PT100 circuit, and see the schematic diagram of precision current source circuit in Fig.2. Resistances including R1, R2, R3 and R4 and operational amplifier U1 constitute the differential amplifier circuit, and U2 is adopted to constitute a feedback circuit. The current flowing through the Rload can be calculated by the following formula:

$$I_0 = V_{ref} \frac{R_2/R_4 + R_3/R_1 \bullet R_2/R_4}{R_5(1+R_2/R_4) + R_{load}(R_2/R_4 - R_3/R_1)} \tag{1}$$

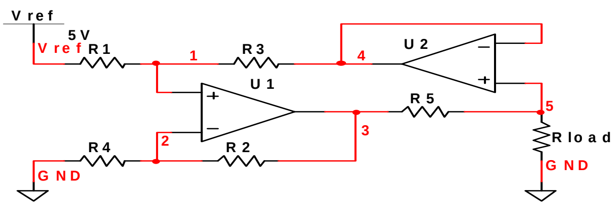

Figure 2. Schematic Diagram of Precision Current Source Circuit

In practice, the difference amplifier AD8276, characterized by low offset voltage, low offset voltage drift, low gain error and low gain drift, was used to replace the discrete differential circuit, which not only ensures the conformity of the equipment performance and enhances reliability, but also reduces the noise jamming caused by discrete devices. The feedback buffer was employed with the low-offset current amplifier AD8606, eliminating the current drift caused by load changes. See details of specific circuit in Figure 3.

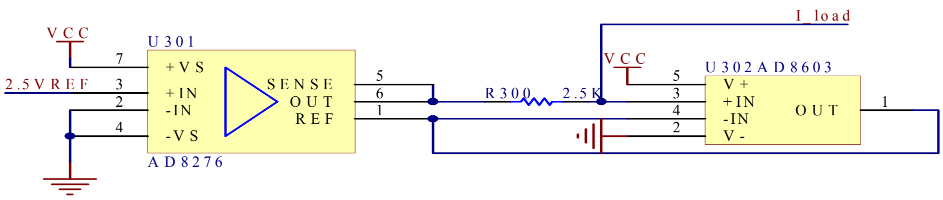

Figure 3. PT100 Drive Circuit Diagram

As the current flowing through PT100 exceeds 2mA, the accuracy of the measurement results will be affected by the thermal accumulation of PT100 under long-term usage. Therefore, the output of the precision current source was reduced to 1mA, not only decreasing the thermal effect of PT100, but also facilitating the revaluation of data by AD acquisition.

Design of AD Acquisition Circuit

The 16-bit Σ-ΔA/D converter AD7705 was adopted for the AD acquisition circuit. This device is characterized by high resolution, wide dynamic range, self-calibration, strong anti-noise performance, low voltage and low power consumption. It is equipped with 3-wire serial interface and two full-differential input channels, enabling it to achieve 0.003% nonlinearity and 16-bit error-free data output. Its gain and data output update rate can also be programmed, and the selective input is available to analog buffer and between self-calibration and system calibration.

According to the formula $lsb = V_{ref} / ((2^n - 1) \bullet PGA)$, the sampling precision of AD7705 acquisition circuit can reach 2.4mΩ and the corresponding changes are within a 0.01 ℃ temperature range, on the premise of PGA in 16-bit.

The schematic diagram of AD acquisition circuit is as shown in Figure4. Wherein, E represents the radiation source temperature and T represents the environmental target temperature. The adoption of AD differential pair input pattern can effectively suppress the common-mode noise on the PT100 lead and improve the sampling stability. The reference voltage of AD7705 and precision current source are the same, so the effect of the reference voltage drift on the sampling accuracy can be reduced.

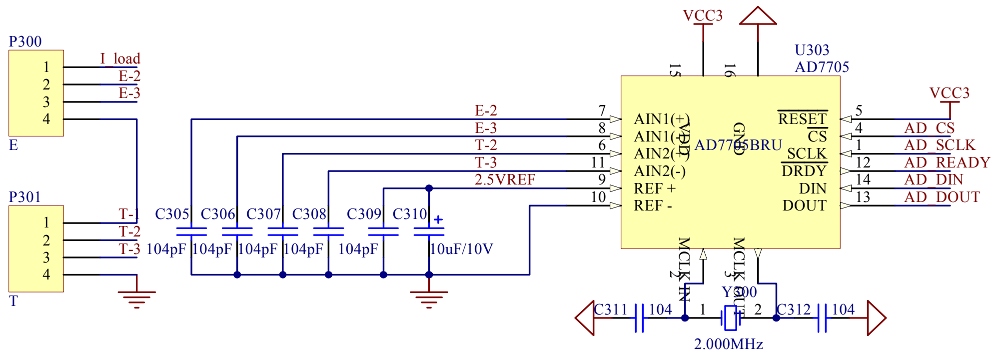

Figure 4. Schematic Diagram of AD Acquisition Circuit

Design of EC Drive and Temperature Accuracy Control Unit

TEC is established based on the principle of the Peltier effect, in which, there is a galvanic couple connected by an N-type semiconductor and a P-type semiconductor. The switch between heating and cooling can be achieved by changing the direction of the current in the thermoelectric reactor. The current can determine the heating and cooling capacity to regulate the temperature of the blackbody radiant panel. Hence, the power drive was adopted with H-bridge amplifier, which is composed of an IR2104S driver, 3 NMOS tubes and 1 PMOS. The circuit connection is shown in Figure 5.

During heating, Q203 and Q201 are open, and Q200 and Q204 are closed, with current flowing from left to right in a thermopile; during cooling, Q200 and Q204 are open, and Q201 and Q203 are closed, with current flowing from right to left. CH and HC are used as enable signals for heating or cooling. During heating, HC=H and CH=L; during cooling, CH=H and HC=L. Heating and cooling thus are controlled by input PWM signal.

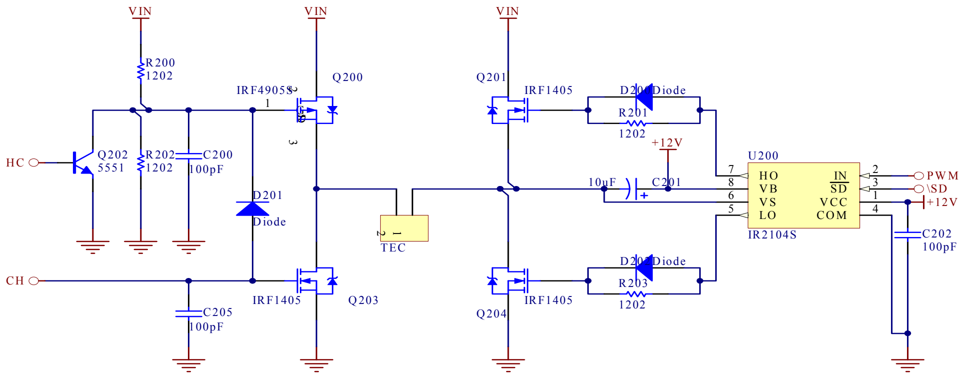

Figure 5. TEC Drive Circuit Diagram

The heating and cooling capacity of TEC is determined by the average current flowing through the TEC. However, the pulse width of the PWM wave changes, thus changing the average current of the TEC. The pulse width modulation (PWM) can be used to obtain the normalized control quantity and the input frequency value, and then generate PWM waves according to the PID output calculation module.

Software Design

The system software is mainly employed with single-chip C language programming. The software design is required not only to complete the AD acquisition function according to the time sequence, but to accurately display the temperature value at the same time.

Design of AD Acquisition Software

Since the system is required to collect two temperature signals, and the AD7705 can only collect the data of one channel at a time, attention shall be paid to the initialization and interval settings after switching between different channels. The AD7705 communicates with the host through the SPI interface, by which, the DRDY pin status can be determined by the querying algorithm to decide whether or not to carry out data transmission, and the relevant information can be read through the external interrupt mode. The initialization process and data reading process of AD7705 are shown in Figure 6.

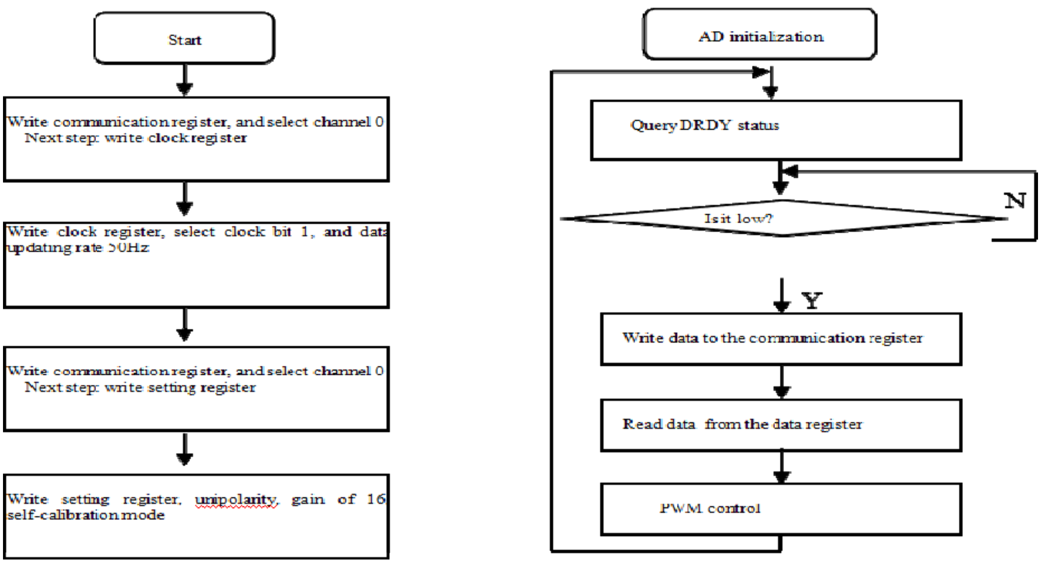

Figure 6. AD7705 Channel Initialization and Reading Process

Resistance - Temperature Conversion Software Design

There is a non-linear relationship between thermal resistance and the temperature of platinum resistance, so nonlinear correction of the measured data is an indispensable part of high precision temperature measurement. Since the value of thermal resistance from AD acquisition is the scaling table and scaling function R(t) of thermal resistance for temperature, but during actual calibration, the real need is the reverse function t(R), that is, to calculate the corresponding temperature according to the thermal resistance. Considering the specific hardware resource configurations, Newton's iteration was adopted to achieve the accurate temperature display.

Newton's iteration method achieves the nonlinear correction based on the existing scaling function, and the correction can be very accurate, as long as the scaling function is precise. According to the scaling function, assume that:

$$P(t) = R(t) - R(0)\left[1 + At + Bt^2 + Ct^3 + Dt^4 + Et^5\right] \tag{2}$$

The nonlinear correction is to solve "t" for the above algebraic equation, and Newton's iteration method is an effective method for solving algebraic equations and transcendental equations. The equation of Newton's iteration is:

$$t_{n+1} = t_n + \frac{p(t_n)}{dp(t_n)/dt} \tag{3}$$

$$t_{n+1} = t_n + \frac{R - 100\times(1 + At + Bt^2 + Ct^3 + Dt^4 + Et^5)}{100\times(A + Bt + Ct^2 + Dt^3 + Et^4)} \tag{4}$$

Wherein, t_n represents the temperature achieved after n-time iteration. In order to reduce the operation times, the initial value shall be input with suitable data, like assuming that pure linear relation exists between R and t, and an initial value can be obtained.

$$t_0 = (R/100 - 1)/A \tag{5}$$

According to the scaling table of PT100, when the accuracy is set as 0.01, the result of the MATLAB simulation is the same whether A and B parameters or all five parameters are retained. In order to speed up the calculation, when Newton's iteration method is applied, only A and B parameters are retained and the last three items are treated with 0, wherein A=3.910030×10-3℃-1 and B=-6.120761×10-7℃-2.

Temperature Control Software Design

The purpose is to convert the error obtained from AD acquisition into the controlled variable of TEC, thus to achieve the stability of the temperature of black body radiation source.

(1) PID Algorithm

The PID algorithm has been widely used in temperature control, flow control, etc. The input parameters of PID controller are the process variable and the set point, wherein, the process variable is the actual temperature value, and the set point is the setting temperature value. According to preset parameters of P, I and D, the PID controller can use the PID algorithm to calculate a controlled variable. After the controlled variable is applied in the system, the controller can approximate the actual temperature value to the set value and finally stabilize it around the set temperature value. The PID algorithm can be expressed as:

$$u(t) = K_c(e + \frac{1}{T_i}\int_0^t edt + T_d\frac{de}{dt}) \tag{6}$$

Wherein, $e = SP - PV$, SP is the set point and PV is a process variable; K_c is control gain, indicating the proportional control; T_i is integral time, indicating the integral regulation; and T_d is derivation time, indicating the derivation regulation.

(2) Fuzzy PID Algorithm

The algorithm is usually characterized by large delay, time variation and non-linearity when being applied in temperature control system. On such a basis, some parameters are unknown or change slowly, some are lagging or experience random disturbances, and others cannot achieve a precise mathematical model. Fuzzy control is used to determine the controlled variable according to the control decision table, rather than mastering the accurate mathematical model of the controlled object. The combination of fuzzy control and PID control combines the advantages of high flexibility and adaptivity of fuzzy control and high accuracy of PID control. Generally, fuzzy control is used in large error ranges, and PID control is used in small error ranges. PID control is adopted with an incremental algorithm, and the sampling period T is controlled by the program. As long as deviation is obtained from the measurement value after three repeated measurements, the control increment $\Delta u(k)$ can be obtained when the proportionality coefficient Kp, integral time constant Ti and differentiating time constant To are determined.

A 2D fuzzy controller is used as the temperature fuzzy controller, in which the error E of the actual temperature to the set temperature and the change Ec of the error are taken as the input fuzzy variables of the fuzzy control system, while U is the output fuzzy variables of the fuzzy control system. The fuzzy set for describing the status of E, Ec and U can be defined as {negative big, negative middle, negative small, zero, positive small, positive middle, positive big} or {NB, NM, NS, 0, PS, PM, PB}, and their domains of discourse are set as {-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6}. Suppose the subordinate functions of E, Ec and U are all gaussian membership functions, and the parameter σ=0.8493. 21 fuzzy condition statements are the basis of judgment for the fuzzy control rule of fuzzy control, for example:

If (E=NB or NM) and (Ec=NB or NM) then U=PB, The output control variables of established fuzzy variables and fuzzy control rules are determined by fuzzy inference decision. The fuzzy rule is "Ai and Bi→Ci ("i" is the i(th) fuzzy conditional statement)", so the inference result $c_i^{'}$ is:

$$u_{C_i^{'}}(z) = u_{A_i}(x_0) \wedge u_{B_i}(y_0) \wedge u_{C_i}(z) \tag{7}$$

Wherein, ^ represents min, x0 and y0 are the values of input variables in the discourse domain, and the final conclusion c_i is the result of comprehensive inference:

$$u_{C^{'}}(z) = u_{C_1^{'}}(z) \wedge u_{C_2^{'}}(z) \ldots \wedge u_{C_n^{'}}(z) \tag{8}$$

Wherein, ˅ represents max. The output inference result is output as an accurate output result through defuzzification, and by MIN-MAX-gravity methods, namely the Mamdani method, the gravity of fuzzy set $c^{'}$ can be calculated as follows:

$$z_0 = \sum_{i=1}^{n} u_{C^{'}}(z_i) z_i \Big/ \sum_{i=1}^{n} u_{C^{'}}(z_i) \tag{9}$$

All values corresponding to the domain of discourse of E and Ec can be obtained through corresponding E and Ec values of all input variables according to the above process, and the corresponding output accurate U value can be calculated. In this way, an accurate value table of the corresponding input E, Ec and output U values can be obtained through defuzzification. This table is stored in the program as a constant table. The fuzzy values of E and Ec can be obtained by judging the temperature measurement value during the operation of the program. According to this table, the control output value U can be obtained immediately to achieve rapid system response.

Summary

Characterized by a new structure and a wide and controllable temperature range, the simulated blackbody temperature controller can not only demonstrate accurate control over temperature differences (less than 0.05°) and display real-time temperature through various algorithms (resolution smaller than 0.01°), but also achieve real-time and automated blackbody control and provide core technical support for the infrared detector through a wide application range, multiple detection objects and high-accuracy, fast detection.

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