Temperature Control System of Medical Instrument Based on Dual Threshold Hysteresis Comparison Circuit

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Abstract. The paper presents a design method of temperature control system of medical instrument based on dual threshold hysteresis comparison circuit. The system adopts a negative temperature coefficient thermistor as the temperature sensor and a thermoelectric cooler as the control object. By means of this method, the working temperature in the medical instrument ranges from two degrees centigrade to four degrees centigrade accurately. According to the test results the design scheme is optimized and improved. The design method is scientific, effective and economic by experiments.

1. Introduction
The precise control and regulation of temperature, which may affect the accuracy of the measurement results, the quality of the samples to be tested[1], the effect of the treatment[2] and many other factors, is a critical problem for medical equipment. Therefore, in many circumstances, it is necessary to control the internal working temperature of the medical equipment rapidly and accurately[3].

In this paper, a method of adjusting and controlling the working temperature of the internal structure of medical instrument is proposed, which takes thermistor as the temperature sensor and thermoelectric cooler as the control object. The temperature could be kept in the range of 2°C to 4°C through the regulation strategy[4]. The experimental results show that the temperature control method is scientific, effective and economic.

2. Design idea and scheme
As the expected temperature regulation range is 2°C ~ 4°C, which is lower than the general room temperature range (about 20°C), the thermistor with negative temperature coefficient[5] is considered as the temperature sensor. According to the corresponding relationship between the resistance value of the temperature sensor and the temperature, the R-T characteristic curve is shown in the figure below. At 25°C, the resistance is about 5 kohm.
Figure 1. R-T curve of NTC temperature sensor (-40°C~120°C)

The acquisition circuit of the temperature sensor consists of NTC temperature sensor, constant current source, low-pass filter, voltage follower and ADC preprocessing circuit. The specific circuit structure is shown in the figure below[6]. The detection accuracy can reach at least ±0.5°C.

Figure 2. Temperature acquisition circuit

The refrigeration control circuit of the thermoelectric cooler which is connected between the drain electrode Q1_D of the Metal Oxide Semiconductor Field Effect Transistor(MOSFET) Q1 and FLAT_1 is shown in the figure below. The working current I_M_1 of the thermoelectric cooler is monitored and controlled in real time by the subsequent microcontroller[7].

Figure 3. The refrigeration control circuit of the thermoelectric cooler
The control circuit adopts dual threshold hysteresis comparison circuit\textsuperscript{[8]} and TI’s double differential comparator LM393A\textsuperscript{[9]} is selected here. The circuit diagram is shown in the figure below. The comparator’s comparative voltage is obtained from the reference voltage source of 2.5V(AD1582) through a resistor divider. The temperature sensor converts the current temperature to be adjusted into a voltage signal through the AD1582\textsuperscript{[10]} as an input of the comparator. The dual threshold comparator sets the comparison reference voltage by a resistor divider. When the temperature to be regulated reaches 4°C, the output signal of one comparator turns over and the thermoelectric cooler starts refrigeration with the red indicator light on as an alarm. When the temperature to be regulated reaches 2°C, the output signal of the other comparator turns over and the thermoelectric cooler stops refrigeration with the yellow indicator light on as an alarm. When the temperature to be regulated is in the range of 2°C to 4°C, the temperature indicator light is green, indicating normal.

![Figure 4. Schematic diagram of dual threshold hysteresis comparison circuit](image)

In the figure above, $V_{\text{CONL}}$ at TP3 is the high temperature threshold ($T_H$) comparison voltage to start the thermoelectric cooler and $V_{\text{CONH}}$ at TP2 is the low temperature threshold ($T_L$) comparison voltage to stop the thermoelectric cooler\textsuperscript{[11]}.

The operation principle of the temperature control circuit is illustrated by a period of temperature change.

1. Assuming that the initial temperature tested ($T_0$) by the sensor is below $T_L$ and the corresponding input voltage is $V_{\text{TEMP}}$. At this time we can get the following relationships:
   \[ T_H > T_L > T_0 \]  \[ V_{\text{CONL}} < V_{\text{CONH}} < V_{\text{TEMP}} \]
   Thus the output of $U_{6,1}$ is low level and so is $U_{6,7}$. Therefore the state of the MOSFET Q1 is cut-off and the thermoelectric cooler does not start the refrigeration.

2. With the rise of the temperature to be regulated, the temperature sensor detects that the temperature change is within the range of $T_L$ to $T_H$, which decreases with the rise of the temperature. At this time we can get the following relationship:
   \[ T_H > T_0 > T_L \]
   \[ V_{\text{CONL}} < V_{\text{TEMP}} < V_{\text{CONH}} \]
   Thus the output of $U_{6,1}$ is still low level and the output of $U_{6,7}$ is high level. However, since the output of LM393A is an open-collector gate\textsuperscript{[12]}, the state of the MOSFET Q1 is still cut-off and the thermoelectric cooler still does not start the refrigeration.

3. The temperature to be regulated continues to rise until the temperature sensor detects that the temperature is higher than $T_H$, at this time we can get the following relationships:
\[ T_0 > T_H > T_L \]  \hspace{1cm} (5)
\[ V_{\text{TEMP}} < V_{\text{CONL}} < V_{\text{CONH}} \]  \hspace{1cm} (6)

Thus the output of \(U_{6.1}\) is high level and so is \(U_{6.7}\). Therefore the state of the MOSFET Q1 is saturated and the thermoelectric cooler starts the refrigeration.

④As the thermoelectric cooler starts the refrigeration, the temperature to be regulated begins to decrease until the temperature sensor detects that the temperature is lower than \(T_H\).

At this moment, since the output of \(U_{6.1}\) in the previous step is high level, the voltage of \(U_{6.5}\) is no longer equal to \(V_{\text{CONL}}\), but changes to a new value. If the new threshold is assumed to be greater than (or equal to) \(V_{\text{CONH}}\), then we have the following relationships:
\[ T_H > T_0 > T_L \]  \hspace{1cm} (7)
\[ V_{\text{TEMP}} < V_{\text{CONH}} < U_{6.5} \]  \hspace{1cm} (8)

Therefore, when the temperature is lower than \(T_H\), the comparator will not turn over.

⑤With the continuous refrigeration of the thermoelectric cooler, the temperature sensor detects that the temperature drops below \(T_L\). Then we have the following relationships:
\[ T_H > T_L > T_0 \]  \hspace{1cm} (9)
\[ V_{\text{CONH}} < V_{\text{TEMP}} < U_{6.5} \]  \hspace{1cm} (10)

Therefore the comparator will turn over and the state of the MOSFET Q1 is cut-off again, which causes the thermoelectric cooler to stop refrigeration and the voltage of \(U_{6.5}\) to return to \(V_{\text{CONL}}\). Now it’s back to the first state, one cycle complete.

Through the analysis above, we can see that the circuit realizes dual threshold control.

3. Discussion on design defects

In the experiment, it was found that when the temperature detected by the temperature sensor was equal to 2°C, the thermoelectric cooler stopped refrigeration. But when the temperature gradually rose to 4°C, the thermoelectric cooler did not start refrigeration until it rose to about 6°C.

The reason is that the resistance parameters in the circuit have not been calculated completely, so the circuit can not work as expected. The experimental results are not in accordance with the expectations, which may be caused by two reasons: ①The temperature to start the thermoelectric cooler is greater than the set threshold; ②The thermoelectric cooler stops soon after it starts refrigeration. In view of these two situations, we will analyze them separately[13].

According to the characteristics of the NTC temperature sensor mentioned above, The temperature to start the thermoelectric cooler is 4°C and the corresponding voltage threshold is 1.838V; The temperature to stop the thermoelectric cooler is 2°C and the corresponding voltage threshold is 1.881V.

3.1. The temperature to start the thermoelectric cooler is greater than the set threshold

Causes of the design defect:
①The influence of comparator feedback on calibration voltage is not considered; ②Unscientific location selection of calibration test point.

According to the previous description, the voltage values at TP3 and TP2 are respectively calibrated as:
\[ V_{\text{CONL}} = 1.838V \]  \hspace{1cm} (11)
\[ V_{\text{CONH}} = 1.881V \]  \hspace{1cm} (12)

Meanwhile the temperature sensor is not connected to the circuit board, so the voltage value at TEMP equals to 2.5V. It is easy to get:
\[ V_{\text{CONL}} < V_{\text{TEMP}} \]  \hspace{1cm} (13)
\[ V_{\text{CONH}} < V_{\text{TEMP}} \]  \hspace{1cm} (14)

According to the characteristics of LM393A, the output of \(U_{6.7}\) is low level. Right now there exists current on the current path TP3\(\rightarrow\)R22\(\rightarrow\)R19\(\rightarrow\)R42\(\rightarrow\)U6.7. Therefore in fact, the low voltage threshold of the comparator should be \(U_{6.5}\). The voltage of \(U_{6.5}\) can be expressed as:
Querying the R-T curve of NTC temperature sensor (-40 ℃ ~120 ℃), this voltage value corresponding to the temperature value of the temperature sensor is 5.1 ℃.

Considering that R22, R19 and R42 are all resistances with accuracy of ±1%, taking the extreme value of U6.5, the accuracy of R22 is assumed as +1%, meanwhile, the accuracy of R19 and R42 is assumed as -1%:

\[ V_{U6.5} = V_{\text{CONL}} \times \frac{R19 + R42}{R22 + R19 + R42} = 1.814V \]  \hspace{1cm} (15)

Obviously, the difference is not big. Therefore, the location selection of calibration test point is not scientific, resulting in the high temperature to start the thermoelectric cooler greater than the set threshold.

3.2. The thermoelectric cooler stops soon after it starts refrigeration
The root cause of the design defect lies in the problem of calibration of the low temperature to stop the thermoelectric cooler of circuit. There are two possible reasons for this:

①After the thermoelectric cooler starting refrigeration,

\[ V_{U6.5} < V_{\text{CONH}} \]  \hspace{1cm} (17)

The voltage threshold of the low temperature to stop the thermoelectric cooler is \( V_{U6.5} \), not \( V_{\text{CONH}} \).

②There are some problems in the calibration of the low temperature to stop the thermoelectric cooler of the circuit. The voltage at TP2 is below \( V_{\text{CONH}} \).

According to point ④ of the operating principle of the temperature control circuit, when the thermoelectric cooler starts refrigeration, the voltage of \( U_{6.5} \) changes to a new value, which is greater than \( V_{\text{CONH}} \). When the circuit actually works:

\[ V_{U6.5} = V_{\text{CONL}} \times \frac{9V - V_{\text{DIO}}}{R43 + R22 + R19 + R42 + R16} \times (R43 + R22) = 1.903V \]  \hspace{1cm} (18)

Namely \( V_{U6.5} \) is greater than \( V_{\text{CONH}} \). So the reason of the design defect should be the second case.

4. Improvement and conclusion
In order to improve the design, the following measures can be taken.

①Move the test point of TP3 to U6.5, so that the voltage at TP3 is the same as the voltage at U6.5.

②Ensure that the voltage at TP3 is not less than the voltage at TP2 when the output of U6.7 is high level.

③Ensure that the high-level output of U6.7 is lower than 5V to ensure that the level value meets the subsequent requirements of 74LS07 on the input level.

After the design improvement, according to the actual results of experimental measurement, the circuit can work as expected, with a temperature of 2 ℃ to 4 ℃.

5. Expectation
If the temperature control range can be adjusted as required, assume that the adjustable range is 0 ℃ to 10 ℃. At this time, 10 ℃ is the high temperature (the corresponding voltage threshold is 1.70v) and 0 ℃ is the low temperature (the corresponding voltage threshold is 1.922v). The high temperature threshold (Tii) to start the thermoelectric cooler and the low temperature threshold (Til) to stop the thermoelectric cooler should meet the following two expressions in the range (R22=0Ω):

\[ 1.7 + \frac{(9V - V_{\text{DIO}}) \times R43}{(R19 + R42) + R43 + R16} \geq 1.922V \]  \hspace{1cm} (19)

\[ V_{\text{DIO}} + \frac{(9V - V_{\text{DIO}}) \times R16}{(R19 + R42) + R43 + R16} \geq (9V - 5V) \]  \hspace{1cm} (20)
According to the experimental results, the voltage drop of the diode D10 is about 0.3V when D10 is on. Take $R_{43} = 9.09\, \Omega$ into the above two expressions to get:

$$5^*R_{16} - 3.7*(R_{19} + R_{42}) \geq 33.6\, \Omega$$  \hspace{1cm} (22)

Here, we take $R_{19} = 80.6\, \Omega$, $R_{42} = 95.3\, \Omega$, $R_{16} = 150\, \Omega$ to meet the above requirements.

Acknowledgments

This work was financially supported by Scientific and technological innovation projects of colleges and universities in Shanxi Province (Grant No. 2020L0621) fund: Person Re-identification Based on Local Feature Attention Model, and Changzhi university scientific research project fund: Person Re-identification Based on deep learning.

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