# A Linear Temperature Measurement System Based on $Cu_{100}$

JIU-QIANG ZHAO, XIAO-FEN LI, ZHI CHENG, GUANG CHEN
College of Computer Science and Technology
Zhejiang University of Technology
Hangzhou, 310023, China
P.R.China
zjq890227@163.com

*Abstract:* - A temperature measurement device is designed for the temperature measurement and control of industrial processes with high accuracy by using $Cu_{100}$ thermal resistor. It consists of AD590M constant current source, resistors, amplifier, A/D converter, data sampling and processing system, digital display, alarming unit, serial output ports, etc. The single comparing method is used to find the thermal resistor value which is mapped to the corresponding temperature by looking into indexing table. Therefore, linearity is implemented, which greatly reduces the impact of temperature-drift and non-linearity in amplifier. Besides, the device implements the measuring of full temperature range of the reference table. The theoretical error of the device is less than 0.1 ℃ and meets the requirements in most of industrial processes.

Key-Words: - linear temperature measurement, $Cu_{100}$ copper resistor, MCU, linear indexing table

## 1 Introduction

Temperature is one of the seven basic physical units in the international system of units (SI), which occupies an important position in all of relevant disciplines [1-6]. At present, there are many methods of measuring temperature in the world, as well as the classification methods of classifying those measuring methods. In general, it is difficult to find an ideal temperature measuring method because of the numerous measuring principles [7-9]. It can be roughly divided into contact measurement and non-contact temperature measurement according to different measurement ways. Contact temperature measurement device which is characterized by a higher measurement precision, simple design, high reliability, wide application range, is carried out according to the principle of heat exchange, such as double metal thermometer, glass thermometer, thermocouple thermometer, hot resistor thermometer and pressure thermometer, etc[10-12]. In order to make the measurement precise, contact temperature measurement method must ensure the device well contacting with the object being measured, and after sufficient heat exchange to get the actual temperature. But contact temperature measurement method can’t be used for too high temperature measurement due to the hysteretic response and the chemical reaction with the object being measured. At present non-contact temperature measurement is mainly the radiant temperature measurement in industry, which keeps a certain distance with the measured object. But it is vulnerable to the object emissivity, and the distance of the object being measured, as well as the media such as steam and smoke. The accuracy of the non-contact temperature measurement can't be guaranteed, which is typically used for high temperature measurement [13-17].

The traditional thermal resistor and thermocouple temperature measurement technology are characterized by simple structure, mature technology and convenient use, etc, which can be widely used in the future [17-19]. With the full development of electronic technology, a small temperature measuring instrument which includes temperature sensing device and the corresponding integrated electronic circuit can be designed, with which we can see voltage, frequency, or directly temperature display. It is not only convenient but also easy to carry.

Micro Controller Unit (MCU) [1-4,20-24] is usually applied to real-time measurement and control, especially to the development of electromechanical integration of intelligent systems and products which is characterized by small volume, low power consumption, cheap and strong control ability, etc. It has very extensive application in the field of measuring temperature because of high automation, intelligence in a system. In this paper, we design a copper resistor ($Cu_{100}$) linear temperature measurement system based on MCU which can meet general industrial temperature measurement occasions [1-4,20,24].

This paper is organized as follows. In Sec.2, we give the theoretical analysis of the thermal resistor temperature measurement. In Sec.3, we provide the hardware design of the system. In Sec.4, we provide the software design of the system. In Sec.5, the error analysis is given. In Sec.6, the conclusion is given.

## 2 The theoretical analysis of the thermal resistor temperature measurement

Thermal resistor temperature measurement device is based on the principle that the value of the metal conductor resistor has linear relation with the measuring temperature[12-17]. The relationship between the metal conductor resistor value and temperature can be expressed as

$$R_t = R_{t_0}[1+\alpha(t-t_0)] \qquad (1)$$

Where $R_t$ and $R_{t_0}$ represent the value of the metal conductor resistance at $t$ (℃) and $t_0$ (℃) respectively; $\alpha$ represents the temperature coefficient of resistor, namely the relative variation of the resistor as the temperature rise per 1 ℃.

Although the general metal material and temperature are not completely linear relationship, it can be approximate to linear relationship in a certain range, the commonly used thermal resistor characteristic curve is shown in figure 1.

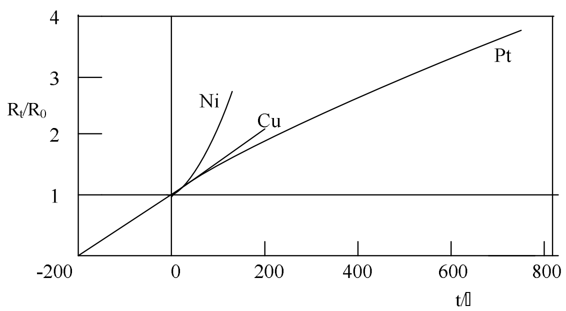


Fig.1 The commonly used thermal resistor characteristic curve

The temperature coefficient of resistor $\alpha$ is defined as

$$\alpha = \frac{R_t - R_{t_0}}{R_{t_0}(t-t_0)} = \frac{1}{R_{t_0}} \cdot \frac{\Delta R}{\Delta t} \qquad (2)$$

It represents the relative variation of the resistor as the temperature rise per 1 ℃ , where $R_t$ and $R_{t_0}$ are the same as ( 1 ) . In fact $\alpha$ is the average in the temperature range of $t_0 \sim t$ , for any $\alpha$

$$\alpha = \lim_{\Delta t \to 0} \frac{1}{R_{t_0}} \times \frac{\Delta R}{\Delta t} = \frac{1}{R} \cdot \frac{dR}{dt} \qquad (3)$$

Formula (3) is the general expression which has a broader significance, but it should be linearized.

Experiments show that the resistor of most metal conductor with a positive temperature coefficient increases 0.36% ~ 0.68% when the temperature raises 1℃. The purer a metal material is, the bigger $\alpha$ is, and vice versa. So the $\alpha$ of alloy is usually smaller than the pure metal. Copper resistor is commonly used in temperature measurement ranged from -50℃ to 150℃, whose resistor is linear with temperature. Its temperature coefficient is relatively big, and its price is cheap, as well as the material is easy purified. But it has low resistivity, and is easily oxidized, so it is reasonable to use copper resistor thermometer if the temperature is not too high and there is no special limit about the size of the temperature measuring element. In this paper, we choose $Cu_{100}$ as the thermal resistor sensor. The relation between the copper thermal resistor and temperature can be expressed as

$$R_t = R_0(1+At+Bt^2+Ct^3) \qquad (4)$$

Where $R_t$ and $R_0$ represent the value of the copper thermal resistor at $t$ (℃) and 0 (℃) respectively; A=4.28899 × $10^{-3}$ /℃ , B= -2.133 × $10^{-7}$ /℃ $^2$ , C=1.233 × $10^{-9}$ /℃ $^3$ . Within a certain range formula (4) can be approximated as formula (5) ignoring B and C.

$$R_t = R_0(1+\alpha t) \qquad (5)$$

Where $\alpha$ =4.28 × $10^{-3}$ /℃, to simplified the calculation, we can set $\alpha$ =4.25 × $10^{-3}$ /℃, because the temperature coefficient of copper thermal resistor is very small and the purity of copper resistor material is not high. After determining the linear relation of copper thermal resistor and temperature, we can measure the value of thermal copper resistor and check the linear indexing table to get temperature.

### 2.1 The current method model for measuring thermal resistor

With the control of the MCU, the thermal resistor adjusting circuit (Fig. 2) completes the signal data acquisition according to logic control table (Table 1).The circuit uses AD590M as constant current source to realize the resistor measurement, which is called "current method".

As shown in table 1 and Fig. 2, the IN0 channel of $M_1$ and $M_2$ multi-channel is open at step 1, and the output current $I$ of AD590M pass through $R_0$ and $R_1$ in calibration circuit forming voltage signal $U_1$ as formula (6)

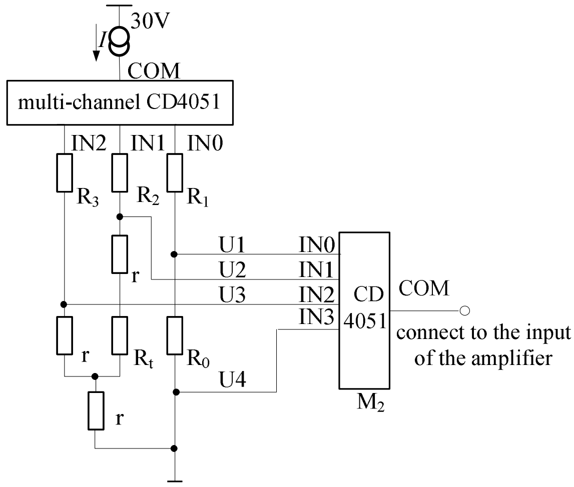


Fig. 2 The signal disposal module of thermal resistor

$$U_1 = I \cdot R_0 \quad (6)$$

Table 1 Logic control function table

| steps | U1 | U2 | P1.0 | P1.1 | P1.2 | P1.3 | collection the signal of |
|---|---|---|---|---|---|---|---|
| 1 | IN0 open | IN0 open | 0 | 0 | 0 | 0 | standard calibration signal $U_1$ |
| 2 | IN1 open | IN1 open | 1 | 0 | 1 | 0 | the measured signal $U_2$ |
| 3 | IN2 open | IN2 open | 0 | 1 | 0 | 1 | the line resistor signal $U_3$ |
| 4 | IN1 open | IN3 open | 1 | 0 | 1 | 1 | zero calibration signal $U_4$ |

To simplify the calculation process, we can assume the zero calibration signal $U_4$ = 0. The calibrating signal sampling value $S_1$ is available after the amplifier, A/D conversion and zero calibration, which can be got as

$$S_1 = K \cdot U_1 = K \cdot I \cdot R_0 \quad (7)$$

The IN1 channel of $M_1$ multi-channel and the IN2 channel of $M_2$ multi-channel are open at step 2, and the output current $I$ of AD590M pass through $R_t$ and $R_2$, as well as the line resistor 2r forms voltage signal $U_2$ as formula (8)

$$U_2 = I \cdot (R_t + 2r) \quad (8)$$

The thermal resistor signal sampling value $S_2$ is available after the amplifier, A/D conversion and zero calibration, which can be expressed as follows

$$S_2 = K \cdot U_2 = K \cdot I \cdot (R_t + 2r) \quad (9)$$

The IN2 channel of $M_1$ and $M_2$ multi-channel are open at step 3, and the output current $I$ of AD590M pass through $R_3$ and the line resistor 2r in correcting circuit forms line correcting voltage signal $U_3$ as formula (10)

$$U_3 = 2r \cdot I \quad (10)$$

The line resistor signal sampling value $S_3$ is available after the amplifier, A/D conversion and zero calibration, which can be expressed as follows

$$S_3 = K \cdot U_3 = K \cdot I \cdot 2r \quad (11)$$

The IN1 channel of $M_1$ multi-channel and the IN3 channel of $M_2$ multi-channel is open at step 4 forming voltage signal $U_4$ and the zero calibrating signal sampling value $S_4^{'}$ is available after the amplifier, A/D conversion and zero calibration

$$S_4^{'} = K \cdot U_4 \quad (12)$$

The value of $U_4$ and $S_4$' is too small to converge to zero and the formula (12) is used to the zero calibration of $S_1$、$S_2$、$S_3$. We can get formula (13) based on formula (9)

$$R_t = \frac{S_2}{K \cdot I} - 2r \quad (13)$$

Formula (14) can be get based on formula (11)

$$2r = \frac{S_3}{K \cdot I} \quad (14)$$

Besides, Formula (15) which is not influenced by the line resistor can be get based on formula (13) and formula (14)

$$R_t = \frac{S_2}{K \cdot I} - \frac{S_3}{K \cdot I} \quad (15)$$

Formula (16) can be get based on formula (7)

$$K \cdot I = \frac{S_1}{R_0} \quad (16)$$

Finally, formula (17) can be get based on formula (15) and formula (16)

$$R_t = \frac{S_2 - S_3}{S_1} \cdot R_0 \quad (17)$$

Formula (17) is the theoretical calculation model of the current method model for measuring thermal resistor. The measurement accuracy error caused by the line resistor can be completely eliminated, which makes the device is not affected by environmental temperature. From formula (17), we can see that $R_t$ is related to $R_0$, $S_1$, $S_2$ and $S_3$ rather than the output current $I$ of AD590M and the amplification factor K of the Amplifier, so this design can ignore the zero drift and nonlinear effects.

## 3. The hardware design of the system

The hardware of the system is designed as the block diagram Fig. 3 shows.

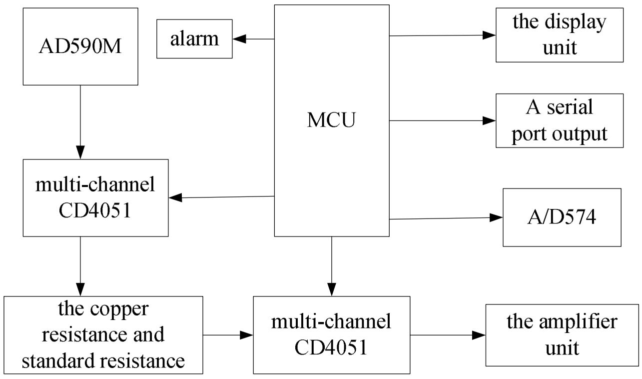


Fig. 3 The hardware block diagram of the system

### 3.1 The temperature signal processing unit

The signal measurement circuit is made up of the copper thermal resistor $R_t$, standard resistor $R_0$(in this paper $R_0$=164.27 Ω ), resistor $R_1$~$R_3$, the multi-channel switch $M_1$ and $M_2$, etc. In addition, $R_1$, $R_2$ and $R_3$ can be calculated according to the standard that the total resistor of each line is nearly equal. In this paper, $R_1$=835.73Ω, $R_2$=868.62Ω, $R_3$=990Ω, r=5Ω. The main functions of this unit are signal acquisition, the calibration of measuring range, zero calibration, the correction line resistor, etc. The hardware parts of the signal measurement circuit are shown as Fig. 4.

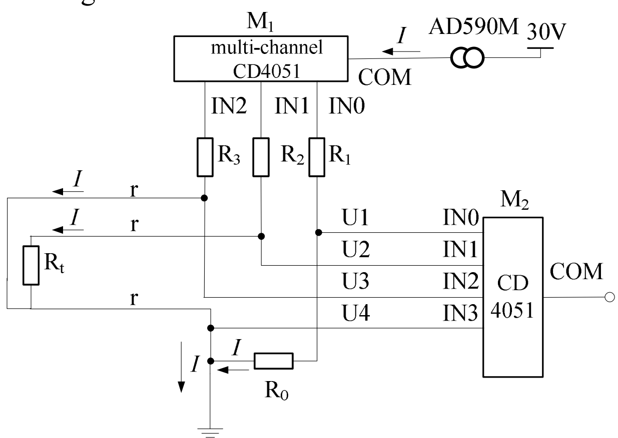


Fig.4 The hardware parts of the signal measurement circuit

### 3.2 The Signal amplification unit

The amplifier unit adopts three-stage amplifier, which is composed of operational amplifiers IC0 ~ IC2, etc. The amplifier unit is designed as Fig.5. Because the input signal is transformed by the current $I$ from AD590M, the input impedance of the amplifier must be designed to be relatively high. The maximum value of $Cu_{100}$ thermal resistor is

164.27 Ω, and the line equivalent resistor 2r is approximate to 10 Ω. The AD converter AD574 adopts 10V input method. The output current of AD590M is 323.2uA when the environment temperature is 50℃. We can get the magnification of the total amplifiers K=10V/[(164.27Ω+10Ω)×323.2 uA]=177.54. The magnification $K_1$、$K_2$、$K_3$ of each amplifier can be calculated as follows

$$K_1 = 1 \tag{18}$$

$$K_2 = \frac{R_6}{R_4} \tag{19}$$

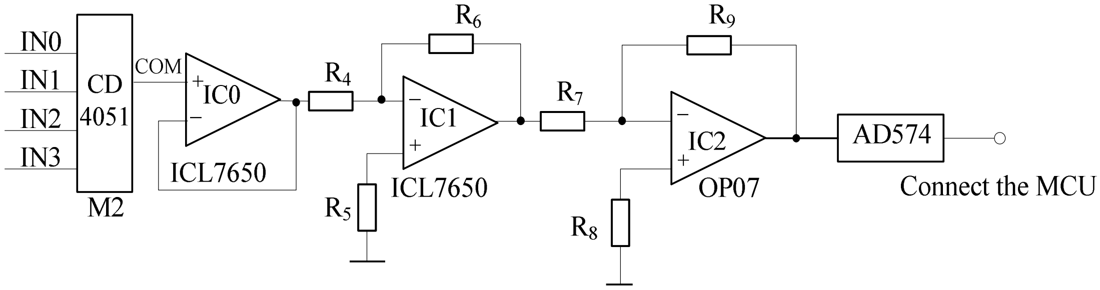


Fig.5 The signal amplification unit

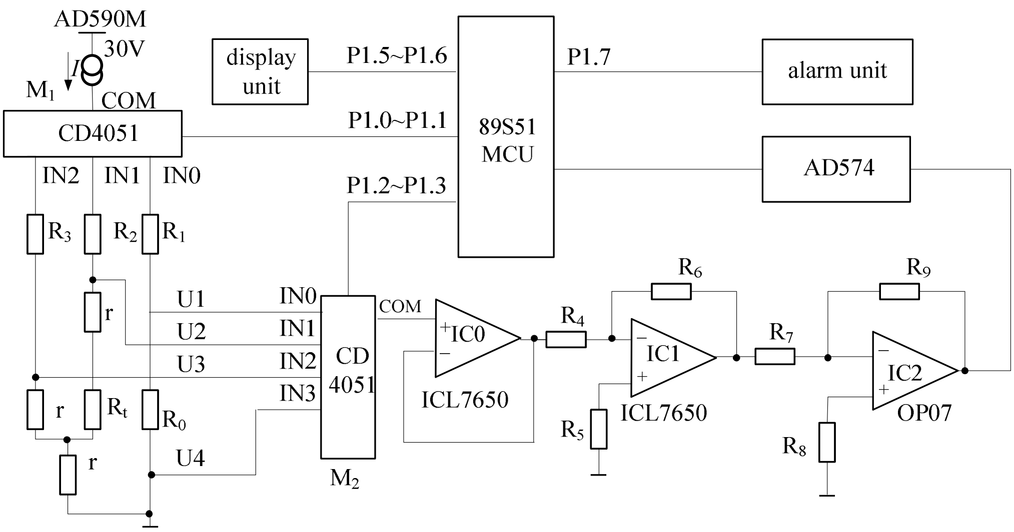


Fig.6 The data acquisition and processing unit

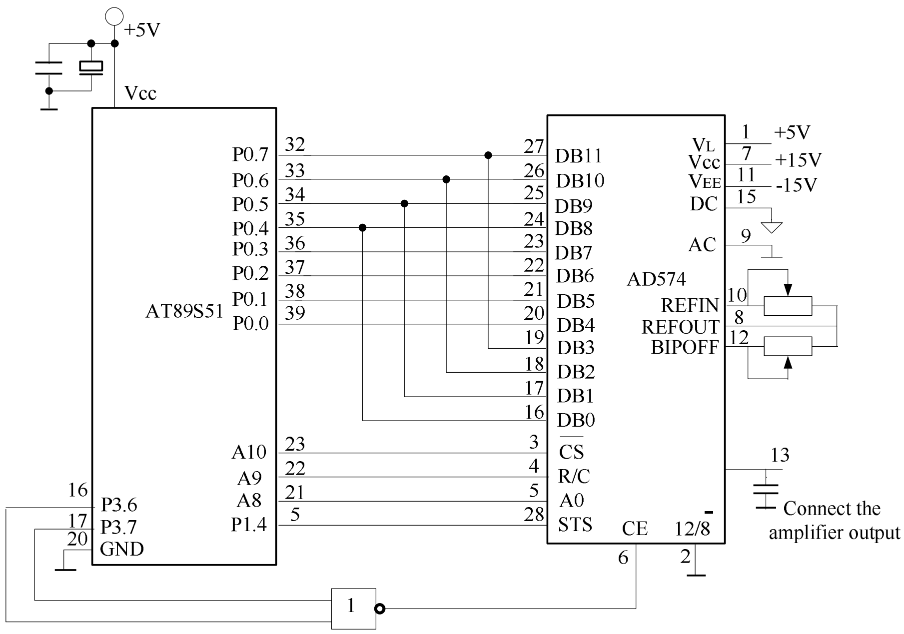


Fig.7 The interface circuit of the MCU and AD574

$$K_3 = \frac{R_9}{R_7} \quad (20)$$

Where $R_4$=2KΩ, $R_6$=51KΩ, $R_7$=1 KΩ, $R_9$=6.8K Ω, $R_5$=$R_4$//$R_6$, $R_8$=$R_7$//$R_9$, the total magnification is

$$K = K_1 \cdot K_2 \cdot K_3 = \frac{R_6}{R_4} \cdot \frac{R_9}{R_7} = 173.4 \quad (21)$$

The actual magnification is slightly less than the calculated value of 177.54, but as a result of using the real-time calibration, the calculation model does not contain the magnification. So the magnification does not affect the accuracy of the results.

### 3.3 Sampling and Data Processing

The data sampling process has been introduced in the current method of measuring thermal resistor model [1-2,24-25]. The MCU samples according to table 1 and Fig. 6. We define the sampling value of $U_1$、$U_2$ 、$U_3$ and $U_4$ to be $S_1'$、$S_2'$ 、$S_3'$ and $S_4'$ respectively. After digital filter, bad data value processing and zero calibration (namely excluding the zero calibration signal $S_4'$), we can get the sampling data $S_1$ 、$S_2$ and $S_3$.

$$S_1 = S_1' - S_4' \quad (22)$$

$$S_2 = S_2' - S_4' \quad (23)$$

$$S_3 = S_3' - S_4' \quad (24)$$

### 3.4 The design of A/D conversion part

This part adopts conversion chip AD574 with single polarity input method [1-4,25], which can convert the voltage ranging from 0V to 10V. After conversion, the eight high numbers is exported from DB11 ~ DB4, while the low numbers is exported from DB3 ~ DB0. Interface circuit is shown in Fig. 7. The conversion process of AD574 can be seen as setting port address to DPTR → starting the transition → tracking the status of the output signal STS → reading the conversion result.

### 3.5 The design of display unit

The interface circuit of the MCU and LED digital tube is shown in Fig. 8.

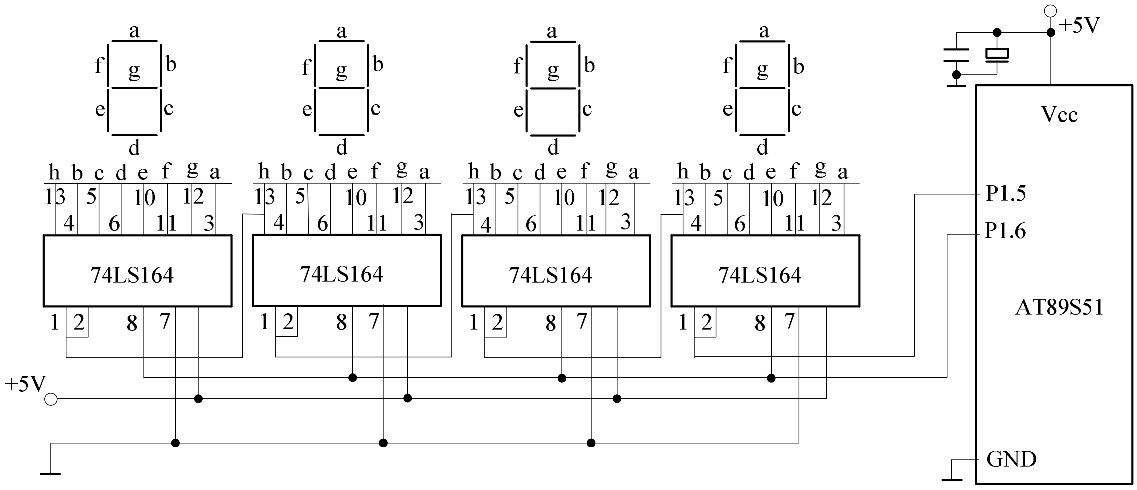


Fig.8 The interface circuit of the MCU and LED digital tube

### 3.6 The design of alarm unit

The temperature measurement range of this device is - 50 ~ + 150 ℃, so the device must give an alarm when the measured temperature is beyond the scope of measurement. The interface circuit of the MCU and alarm unit is shown in Fig. 9.

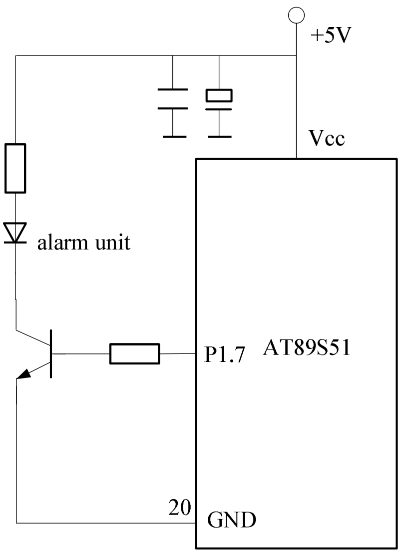


Fig.9 The alarm unit

### 3.7 The design of serial output unit

The serial output port is completed by MAX220. Each data contains 2 bytes and the baud rate is 9600, which can be accurate to 0.1 ℃. The interface circuit of the MCU and the serial output unit is shown in Fig. 10.

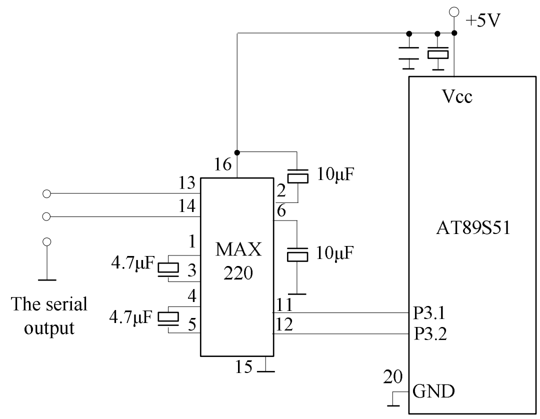


Fig.10 The serial output unit

## 4 The software design of the system

The main function of the system software is to control the multi-channel logic switch completing the data acquisition and accomplish the bad value processing, digital filtering, the copper thermal resistor calculation, the reverse look-up of the indexing table, the calculation of fractional part between two integral temperature points, the warning system and the temperature display part, etc. The software design uses block-based design method in order to facilitate the programming and modification. The block-based design is a set together with a family of subsets (repeated subsets are allowed at times) whose members are chosen to satisfy some set of properties that are deemed useful for a particular application. So we often adopt block-based design to exploit complex systems[1-4,24,27-29].

Through analysis, the software program design of this temperature measuring device can be divided into the program initialization, the bad value processing subprogram, digital filter subprogram, copper thermal resistor calculation subprogram, temperature calculation subprogram, alarm subprogram and display subprogram, etc. Additionally, the block diagram of the software design is presented as Fig. 11.

There are 201 temperature points in the indexing table of $Cu_{100}$ thermal resistor, ranging from -50 ℃ to 150 ℃. The value of the $Cu_{100}$ thermal resistor of each temperature points adopts 10mΩ as the base unit, which exists in two bytes using hexadecimal code. The temperature points were made into indexing table according to the sequence from low temperature to high temperature, which were stored in the memory with the memory address increasing. With the fitting function of Matlab software, we get the temperature characteristic curve of the value of the copper thermal resistor with temperature, where the $R^2 \approx 1$, indicating that the linear relationship is relative good. The scatter diagram and the fitting curve of the $Cu_{100}$ thermal resistor indexing table with the temperature are shown as Fig.12.

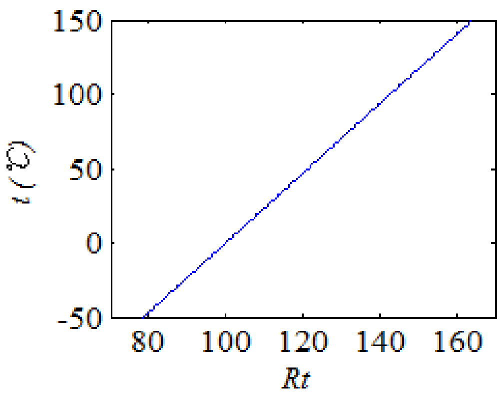


Fig.12 The scatter diagram and the fitting curve of the $Cu_{100}$ thermal resistor indexing table with the temperature

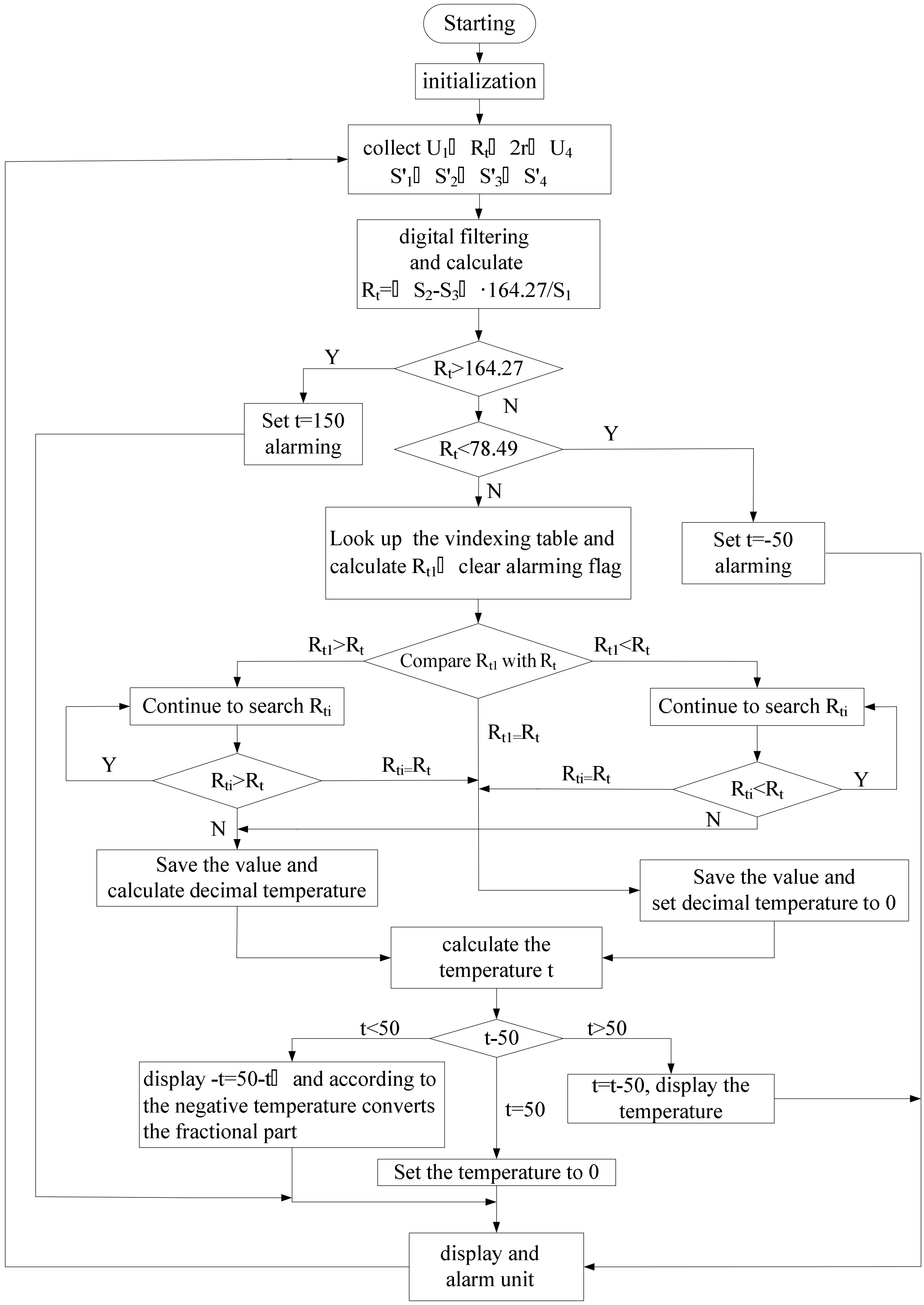


Fig.11 The block diagram of the software design

The formula of the characteristic curve in Fig.12 is shown as

$$t = 2.334 \cdot R_t - 233.34 \qquad (25)$$

Where the unit of $R_t$ and $t$ are $\Omega$ and □ respectively.

The error of the fitting curve and characteristic curve of the copper thermal resistor is relatively small. The maximum temperature error is 0.16 ℃, less than 1 ℃, between the same copper thermal resistor values, so we can find the whole temperature points without missing.

We can get the value of $R_t$ based on the formula (17). If the value of $R_t$ equals to the value in the $Cu_{100}$ thermal resistor indexing table, the temperature value is the corresponding temperature value which is requested. Otherwise, we should calculate the decimal part of the temperature with the linear interpolation method. The decimal part $\Delta t$ can be expressed as formula (26)

$$\Delta t = \frac{R_t - R_t(t_z)}{R(t_z+1) - R_t(t_z)} \times 1\,℃ \qquad (26)$$

where $R_t(t_z)$ is the maximal integer thermal resistor value which is not greater than $R_t$, while $R_t$ ($t_z$ + 1) is the minimum integer thermal resistor value which is not less than $R_t$ , namely, the value of $R_t$ is between $R_t(t_z)$ and $R_t$ ($t_z$ + 1). If the accuracy of $\Delta t$ is 0.1℃, the final temperature value for the measurement can be expressed as formula (27)

$$t = t_z + \Delta t \qquad (27)$$

## 5 The error analysis

From formula (17) we can get the combined standard uncertainty of $R_t$ as formula (28)

$$\begin{aligned} u(R_t) &= [(\frac{\partial R_t}{\partial S_1})^2 u^2(S_1) + (\frac{\partial R_t}{\partial S_2})^2 u^2(S_2) + \\ &(\frac{\partial R_t}{\partial S_3})^2 u^2(S_3) + (\frac{\partial R_t}{\partial R_0})^2 u^2(R_0)]^{\frac{1}{2}} \\ &= [(-\frac{S_2 - S_3}{S_1^{\,2}} \cdot R_0)^2 u^2(S_1) + (\frac{R_0}{S_1})^2 u^2(S_2) + \\ &(-\frac{R_0}{S_1})^2 u^2(S_3) + (\frac{S_2 - S_3}{S_1})^2 u^2(R_0)]^{\frac{1}{2}} \end{aligned} \qquad (28)$$

$S_1$ represents the calibrating signal sampling value with the temperature changing and the minimum value of $S_1$ is $S_1$= ( 273.15/323.2uA ) ×4096=3462 at 0℃. $S_2$ represents the copper thermal resistor signal sampling value and the maximum value of $S_2$ is 4096. $S_2$ represents the line resistor signal sampling value. If we approximate 2r as 10Ω, $S_3$ can be expressed as $S_3$=10Ω×4096/174.27Ω=235.04. $u(S_1)$ 、$u(S_2)$、$u(S_3)$ represent the standard uncertainty of AD574 whose mean value is 1/ ( $2\times 4096\sqrt{3}$ ) =7.04E-5. $u(R_0)$ represent the standard uncertainty of $R_0$ whose value is 164.27Ω(the maximum error is 0.01Ω). By choosing the confidence probability of normal distribution as 0.9973, we can get $u(R_0)$=0.01/3Ω=3.33E$^{-3}$ Ω.

After calculating the minimum value of $S_1$ , the maximum value of $S_2$ ,$S_3$ ,$u(R_0)$, we can get $u(R_t)$ (the combined standard uncertainty of $R_t$). By choosing the confidence probability of normal distribution as 0.9973, we can get the extended combined standard uncertainty of $R_t$, which can be expressed as $U=3\times u(R_t)$=0.011Ω.

From the $Cu_{100}$ thermal resistor indexing table, we can find the minimum difference of thermal resistor value between two integer temperature points is 0.39Ω, which means that the maximum of copper resistor temperature conversion coefficient is 1℃/0.39Ω. The total measuring error is determined by the error of $R_t$ (0.011Ω) and the rounding error of $R_t$ (the maximum rounding error of $Cu_{100}$ is 0.005Ω) when calculating. We convert the resistor error to the limit error of temperature which can be expressed as $\delta_{R_t}$ =0.028℃ , $\delta_b$ =0.013℃ respectively. Finally, the limit temperature error of the device can be expressed as formula (29)

$$\begin{aligned} \delta &= \sqrt{\delta_1^{\,2} + \delta_2^{\,2}} = \sqrt{0.028^2 + 0.013^2} \\ &= 0.031℃ \end{aligned} \qquad (29)$$

Formula (29) is the theoretical limit error of the device, which can meet the general industrial design requirements.

## 6 Conclusion

The purpose of this paper is designing a copper resistance (Cu100) linear temperature measurement device, mainly used for the temperature control of industrial processes. The device is made up of signal acquisition unit, signal amplification unit, A/D converter, digital display unit, serial ports and other sectors, mainly to complete the data acquisition, logic control, bad value processing, digital filtering, the calculation of thermal resistance, look-up table, calculation, warning, serial output and display. The System uses AD590M constant current source instead of the constant current source, providing current. Under the control of the AT89S51 MCU, the standard resistance uses the standard signal to calibrate the system, then conduct signal sampling, calculation of the copper resistance value and the temperature values corresponding to the reverse look-up of the indexing table, thus achieving a true sense of the linearization. The device greatly reduces the temperature drift and nonlinearity of the amplifier in the measurement process, realizing the whole temperature measurement range of the copper resistance. The theoretical error of the device is less than 0.1 □ to meet the requirements in most of industrial processes.

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