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ORIGINAL RESEARCH ARTICLE

Design of a multi-channel high precision wearable temperature collection system based on negative temperature coefficient thermistor

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ABSTRACT

Body temperature is often used to screen infectious diseases and monitor treatment. Through the method of measuring the resistance of constant voltage temperature measuring circuit, a wearable multi-point body temperature monitoring system is researched and designed to determine skin surface temperature. The STM32F103C8T6 chip is used as the core processor, and the negative temperature coefficient thermistor (NTC) as the temperature sensing component. ADS1256 chip is a temperature signal conditioner, Bluetooth module is a wireless transmission unit, and LABVIEW is used to design the host computer interface. The constant voltage bridge circuit composed of thermistor and resistor voltage divider to carry out the acquisition of 8 channels of temperature data, and the 24bits ultra-high-precision analog-to-digital conversion module is configured with differential inputs to amplify, filter and convert analog signals; the converted data is processed and calculated in the single-chip microcomputer; finally, the data is transmitted to the host computer via Bluetooth. The thermistor is linearly compensated using the fourth-order equation of the Stein-hart equation. Reduce the impact of environmental interference and uneven body temperature distribution from software and hardware. The error during the temperature measurement of temperature sensor is analyzed. The experimental results showed that the resolution of measurement system reached 0. 01 ℃, and the temperature measurement accuracy was up to ± 0. 02 ℃. This design scheme has high stability and accuracy; and the circuit is simple in structure, small, and low power consumption which can be used in occasions requiring precise body temperature measurement.

Keywords: 8 channels body temperature measurement; negative temperature coefficient thermistor; high precision; wearable

1. Introduction

Body temperature refers to the temperature inside the human body medically and clinically, which also is the core temperature of human body. The core temperature of human body is defined as the temperature of the internal thoracic cavity, abdominal cavity, and central nervous system of the human body which is one of the four major vital signs

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of human body[1], and an important basis for judging the health status of human body to prevent diseases. Therefore, it is important to effectively monitoring human body temperature. There are temperature measurement by nuclear magnetic, rectal temperature measurement, cochlear temperature measurement, esophageal temperature measurement, pulmonary artery and other direct measurement of human core temperature[1]. Although these methods can measure the core temperature more accurately, there are some disadvantages such as inconvenient measurement which need to invade inside the human body, and unable to measure the dynamic temperature of the human body. A core temperature monitoring system, that can swallow the sensor shaped like pill, is able to read the core temperature in the human body then send the data to a wireless receiver device to monitor the core temperature of the tested person in real time. This method has a high measurement accuracy and can detect the temperature of the human body during exercise, but swallowing sensor lead to poor repeatability and high cost due to hygiene[1]. At present, mercury thermometers and electronic thermometers are mainly used in clinical practice to measure the body temperature directly. The mercury thermometer is simple, accurate and reliable to measure body temperature, the data cannot be automatically transmitted and saved, but it has poor security, and it is hard to achieve continuous monitoring of multi-point measurement. As a result, electronic thermometers have gained popularity[2] in comparison with platinum resistance, thermocouples, and integrated temperature sensors in contact sensors. Negative temperature coefficient thermistors (NTC) are often selected as sensors for electronic thermometers due to their high sensitivity, good stability, rapid response, and low in cost. Yuan et al.[3], used NTC thermistor as the body temperature sensor, using a differential analog digital converter (ADC) chip to convert the analog signal into a digital signal and sent to the microcontroller for analysis and processing, analyzed the source of error and proposed an error calibration scheme, the error is less than ± 0.1 °C which has strong stability and practicality, but it is greatly affected by the ambient temperature, the measurement site also interferes with the accuracy of results in body temperature measurement, and the relationship between the body surface temperature and the core temperature needs to be further studied, so that the body surface temperature of a certain part can better reflect the core temperature. Other than direct measurements, the core temperature can be measured using indirect estimation methods, typical of which are single-channel heat flow models and two-channel heat flow models. These methods are all modeled calculations based on body surface temperature to estimate the core temperature of the human body, and the single-channel heat flow model needs to be calculated in advance to obtain the thermal resistance of the skin and subcutaneous tissue of the corresponding part. Therefore, it is necessary to repeat the calculation for different individuals and different parts of the same individual[4]. Single-channel heat flow technology focuses on measuring a single heat flow through a well-insulated sensor, while dual heat flow measurement is two kinds of heat flow through materials with different thermal resistance or thickness to obtain the core body temperature and the hot plate experiments is used to simulate human skin with materials with similar thermal resistance. Tamura et al.[5] proposed a two-channel heat flow model based on a single-channel heat flow model and conducted a series of simulation experiments and human experiments. An ideal estimation result was obtained, but the experiment was greatly affected by environmental disturbances and the establishment of thermal equilibrium required a long time. Feng et al.[6] from Zhejiang University proposed an improved core body temperature measurement technology that resists ambient temperature disturbances, using an adaptive filter based on the minimum mean square value to reduce the interference caused by ambient temperature fluctuations, and the experiment subjects under various environments such as indoor and outdoor during rest and exercise have obtained the expected. The thermal equilibrium establishment time was shortened by increasing the thermal conductivity of the probe using homogeneous incorporation of calcium carbonate powder in the PDMS (Polvdimethvlsiloxane, PDM) heat transfer block. However, the uneven heat distribution on the warm surface of the skin is still a problem. Atallah et al.[7] developed an ergonomic Y-shaped sensor using 5 cm of composite polyethylene (PE) foam material as a thermal conductive block, using multiple vertical heat flow channels, a curve fitting method to push the skin and thermal resistance of the heat conductive block, avoiding the errors in material parameters, but also introduced the fitting error. The innovative choice of measuring temperature behind ear overcomes the problems of environmental interference and uneven temperature distribution to a certain extent and shortens the time for the establishment of thermal equilibrium to improve the temperature measurement accuracy at the same time. For the above-mentioned direct temperature measurement method, there are problems such as inaccuracy or high in cost, inconvenient temperature measurement, and it is impossible to measure temperature at multiple points, etc. The indirect estimation method has a long thermal equilibrium time and the accuracy in temperature measurement is not high enough, which due to the influence of different individuals of their human tissues, blood perfusion rate, etc. It is difficult to obtain accurate skin thermal resistance, and there is an inevitable error in simulating the skin through the thermal resistance of PDMS materials. Based on the background introduced above, a wearable body temperature measurement system based on NTC thermistor was designed and developed. This paper explains its working principle, introduces the software and hardware design which adopt double-sided compact PCB circuit board and Type-C dual-phase charge and discharge module in small size, solves the endurance problem of wearable device point power, high-precision and resolution of electronic components and improves differential bridge temperature measurement circuit[8]. The fourth-order Stein-hart equation fitted the resistance temperature characteristic curve, greatly improving the accuracy of temperature measurement. The 8-channel temperature measurement combines the selection of the temperature measurement site and the automatic screening and processing of the collected temperature signal by the host computer[9], which can reduce the environmental interference and overcoming the problem of uneven temperature distribution on the skin surface. Performed high-precision linear compensation on NTC thermistor and the source of the error is analyzed. The constant temperature water bath experiment was set up to verify the experiment and test the accuracy of the device.

2. System composition and working principle

The designed body temperature measurement system selected NTC thermistor as temperature sensing component, which has the characteristics of small size, easy to wear, low power consumption, convenient charging, accurate temperature measurement at 8 points, wireless transmission and automatic analysis and processing of data. It is suitable for the field of medical and health temperature monitoring[10]. The body temperature measurement system adopts the method of measuring resistance through constant voltage source, which is composed of NTC thermistor, resistor voltage divider, analog-to-digital converter, main control chip, Bluetooth module, constant voltage source and power supply lithium battery, and adopts the method of differential input, small voltage signal interference, and the accuracy of data acquisition is high. The overall system block diagram is shown in **Figure 1**. This design uses STMicroelectronics' STM32 F103C8T6 as the main control chip, which includes the RISC high-performance core of ARM® Cortex™-M3 32bits, integrated high-speed memory, rich and fast I/O port and port communication interfaces, rich peripheral configuration, which meets the core computing requirements of the temperature acquisition system. The body temperature sensor adopts the MF54 series electronic thermometer thermistor with 30 kΩ produced by Nanjing Huaju Electronics Company, and the error is less than ± 0.01 ℃ when the temperature measurement accuracy is 37 °C, it has some advantages such as high test accuracy, small size, interchangeability, good consistency, rapid reaction speed and able to work stably for a longtime. The calibration resistor adopts Yageo's high-precision 1/10,000 chip resistor with an accuracy of 0.01%, low temperature drift, chip resistor, and a temperature coefficient of ± 0.0005%/℃. The A/D conversion module adopts the ultra-high-precision 24 bits analog-to-digital converter ADS1256 that launched by TI company, the programmable gain amplifier has low noise, providing a gain of 1 to 64 in binary steps, the programmable filter has a noise-free resolution of up to 24 bits, and the data output rate is up to 30 K/s, ± 0.001% low nonlinearity, multiplexing and sensor detection switches provide the flexibility to handle differential and single-ended signals, providing a complete high-resolution measurement solution for the most demanding applications with the communication via SPI-compatible serial port.

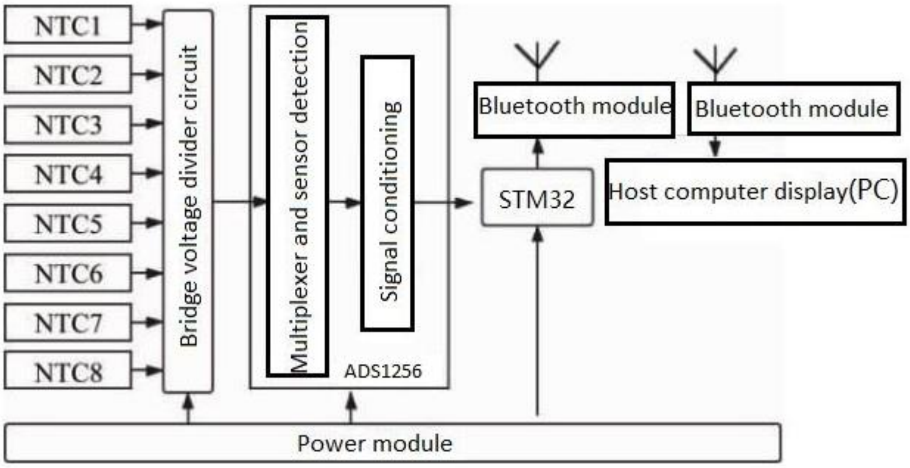

Figure 1. Block diagram of the body temperature measurement system.

The SMD Bluetooth module is used for wireless transmission. The power supply adopts 3.7 V rechargeable polymer lithium battery, high discharge platform, low internal resistance, fast charging, small self-discharge, stable performance and other characteristics. By using the Type-C charging interface, it can be charged with a mobile phone charger which is more convenient. The system hardware block diagram is shown in **Figure 1**. It is mainly composed of a microcontroller, a body temperature acquisition circuit, a signal conditioning circuit, a power supply circuit, a Bluetooth unit, and a host computer receiving unit. The output voltage of the constant voltage power supply source generates a voltage drop across the circuit composed of an NTC thermistor and a resistor voltage divider, the differential input is configured by the analog multiplexer to buffer, amplify, filter and convert the collected analog voltage signal into a digital voltage signal, and the digital signal is processed in the STM32 F103C8T6 and transmitted to the host computer through Bluetooth[11]. This paper will mainly analyze and discuss the body temperature acquisition part of the circuit and analyze the error of each part. The low-level computer software of the system is written in C language and compiled by KEIL software. The upper computer software is written in the graphical language of LABVIEW. The content of the system software includes: Body temperature data acquisition, body temperature data conversion, Bluetooth data transmission, real-time monitoring, analysis, processing and storage of data by the host computer.

The designed PCB circuit board is shown in **Figure 2**. with a size of 33 mm × 33 mm, low power consumption (controllable power switching and BLE technology) which meets the energy efficiency needs of power-constrained wearable systems. Numbers 1, 2, 3 and 4 are microcontrollers, body temperature acquisition modules, Bluetooth units, and power supply module respectively. Moreover, the body temperature measurement system is more compact, with no transmission cables hindering daily activities.

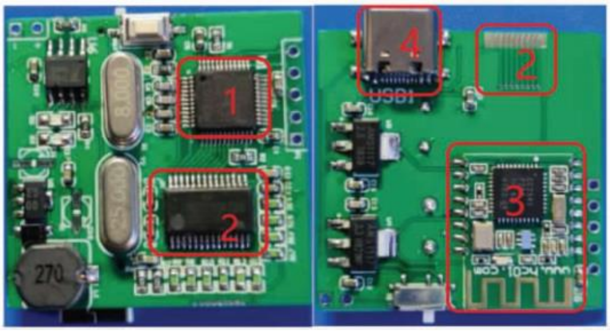

Figure 2. Print circuit board of the temperature measurement system.

3. Part of the system hardware design

3.1. NTC thermistor and temperature acquisition circuit

Combined with the requirements of wearable, high-precision, low-cost, low-power consumption, small size, and good interchangeability of this body temperature measurement system, Nanjing Huaju Electronics MF54 series of temperature measurement NTC thermistors for electronic thermometers were selected as the body temperature sensors[11]. In this design, the encapsulation material for this model, MF54–503E3 949EX-30R, is black epoxy resin in water droplet shape, the lead material is enameled steel wire NTC as the sensing element, and the temperature measurement accuracy is 0. 01℃, and the resistance value accuracy is ±0. 05%. Its dimensions are: 1.4 mm in diameter, 4 mm in length, and 87 mm in lead length, as shown in **Figure 3**.

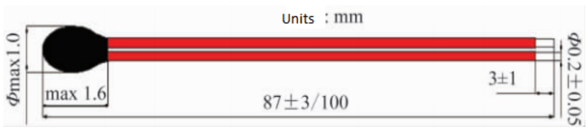

Figure 3. Size of temperature sensor.

Calibrating the thermistor to determine the correspondence between the resistance value *R*and the temperature T is determined by calibrating the thermistor. For NTC thermistor thermometer at 307.15–315.15 K (34–42 °C) using constant temperature water tank to control the temperature, high precision (0.01%), low temperature drift (± 0.0005%/°C) resistor modified resistance meter to measure the resistance value of NTC thermistor with the changes of temperature[12], with a high-precision mercury thermometer with an accuracy of 0. 01 °C is used to measure the actual temperature to obtain data. The resistance of the thermistor with NTC decreases exponentially with the increase of temperature. Based on this, the temperature resistance relationship Table is made, and when the temperature changes caused the resistance change to produce a voltage drop, the temperature value can be determined by calculating the value of voltage[13].

The performance index requirements for GB/T21416–2008 for medical electronic thermometers[14] were shown in **Table 1**.

Table 1. CNS (China National Standards) for electronic thermometers

Temperature range/°C	GB/T21416–2008 Requirements/°C
<35.3	± 0.3
35.3–36.9	± 0.2
37.0–39.0	± 0.1
39.1–41.0	± 0.2
>41	± 0.3

According to the requirements of high-precision, wearable, and multi-point temperature measurement of this temperature measurement system, the constant current, constant pressure, and double integral temperature measurement methods are comprehensively considered, and the constant voltage temperature measurement circuit was selected through the temperature measurement accuracy, system cost, and implementation difficulty. The multi-point temperature measurement circuit is designed according to the principle of the single-point bridge temperature measurement circuit, as shown in **Figure 4(a)**.

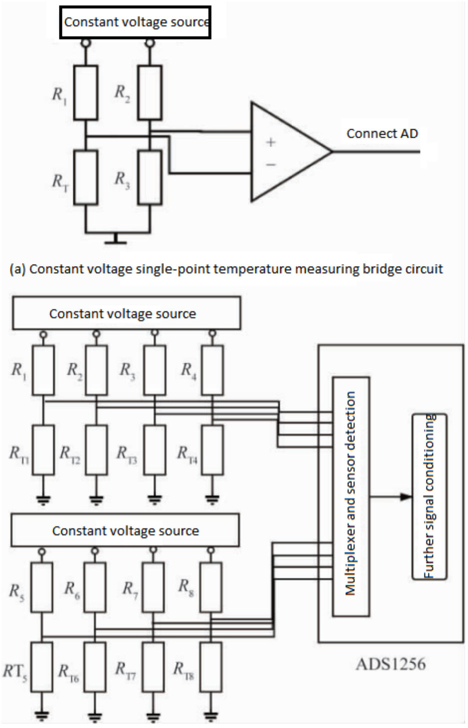

Figure 4. Single channel and multi-channel temperature measuring bridge circuit based on constant voltage.

The principle in temperature measurement of these two methods is similar. Therefore, from **Figure 4(b)**, we know that:

$$V_+ = \frac{R_3}{R_2 + R_3} V_{REF} \quad (1)$$

$$V_- = \frac{R_T}{R_T + R_1} V_{REF} \quad (2)$$

In the equation: V_{REF} is the reference voltage of the circuit; R_T is the NTC thermistor; R_1, R_2, and R_3 are the resistive voltage divider circuit, also known as the Wheatstone bridge. The working principle is: take the difference between the voltage of R_3 and the voltage of R_T, send it to the ADS1256 signal conditioning module for signal amplification, filtering, A/D analog-to-digital conversion, and obtain R_T by the single-chip computer. Use R_1=R_2=R_3=R_T=30 kΩ, equation (1) can be expressed as:

$$V_+ = \frac{R}{R + R} V_{REF} = \frac{1}{2} V_{REF} \quad (3)$$

The voltage difference ΔV is:

$$\Delta V = V_+ - V_- = \frac{1}{2} V_{REF} - \frac{R_T}{R_T + R_1} V_{REF} \quad (4)$$

After amplifying A times (here A = 1), the voltage sent to the A/D converter is:

$$V_{IN} = A\Delta V = \left(\frac{1}{2} - \frac{R_T}{R_T + R}\right) AV_{REF} \quad (5)$$

The digital quantity of the output voltage signal of the A/D converter is:

$$\mathrm{ADC} = 2^N \times \frac{V_{IN} - V_R}{V_{R+} - V_{R-}} 2^N \times \frac{V_{IN}}{V_{REF}} = 2^N \times A\left(\frac{1}{2} - \frac{R_T}{R_T + R}\right) \quad (6)$$

In the equation (6): A is the amplification factor of the voltage signal; N is the number of bits processed by the ADC module, N=24, the value of R_T can be obtained through digital ADC and the resistor voltage divider R_1 from equation (6), and the temperature value is obtained according to the relationship between the NTC thermistor value and the temperature function.

3.2. Master chip

The core of the STM32F103C8T6 microcontroller is the ARM 32bits CortexTM-M3CPU, integrated high-speed memory (128 KByte of flash memory and 20 KByte of SRAM), 72 MHz operating frequency, up to 80 fast I/O ports and 9 communication interfaces, these peripheral configurations make this type of microcontroller well meet the design requirements of the multi-channel body temperature measurement system in this article. It supports three power-saving modes of sleep, shutdown, and standby to provide low power consumption guarantee[15]. The system sets the temperature frequency of 1 Hz, and the main control chip is usually operating under sleep mode when collecting and transmitting data, and the Bluetooth module is only woken up when sending data, which further reducing the power consumption.

4. System software design

The body temperature measurement system is written in C language with low-level computer software and compiled by KEIL software. The low-level computer software includes: body temperature data acquisition, conditioning of body temperature analog signals, and Bluetooth data transmission. The final collected data is displayed to the host computer interface based on LABVIEW graphical programming. Since the collected temperature data is a low-frequency analog signal, and considering that the amplified signal will affect the accuracy of the data, the amplification factor of the programmable gain amplifier (PGA) in the ADS1256 = 1 to keep the original signal, which can provide 25.3 bits effective resolution at this time. Finally, the binary search method and the linear fit of the Steinhart equation are used to calculate the temperature corresponding to the sampling value of the ADC, and the design flowchart is shown in **Figure 5**.

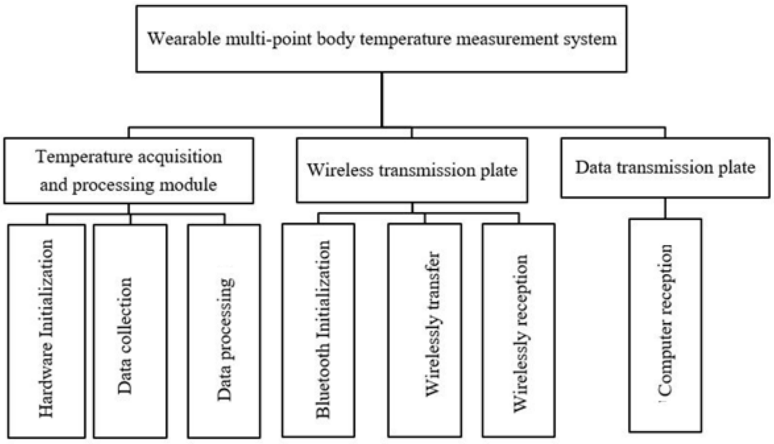

Figure 5. Block diagram of system software design.

4.1. Low-level computer software design

Main program design

The system's main program workflow diagram is shown in **Figure 6**, where the system power-up begins, initializing the firmware (system, ADS1256, Bluetooth) and then entering a low-power mode. When flag = 1 is set in the main program, the temperature conversion is turned on: when the chip selection CS is low, the ADS1256 serial port begins to communicate, then pulls down the RST potential to reset AD converter, and after the reset is completed, it initializes the converter's associated registers and self-calibrates the AD (corrects internal offset and gain errors). After starting the AD conversion, by observing through the DRDY level to determine whether the conversion is completed. When the DRDY is at a high waiting level, ADS1256 began to acquire 8 channels of data, PGA = 1 which the original signal is not amplified, and then through the A/D converter to convert the analog signal into a digital signal. When the DRDY is at low level, the conversion is completed and the on-chip digital filtering is accomplished, and finally the results are output to the main control chip STM32 F103C8T6 through the SPI.

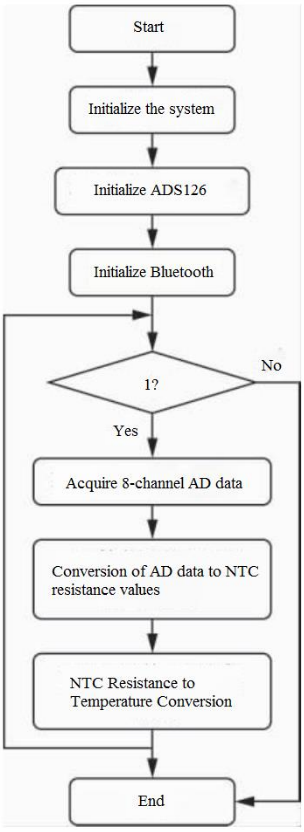

Figure 6. Software flowchart of temperature acquisition and processing module

During the conversion process, the microcontroller and ADS156 exchange the data through the SPI[16]. In the single-chip microcomputer, the digital voltage value is converted into the thermistor resistance value, the temperature data is obtained through the relationship between the fitted resistance value and the temperature function, and finally the 8-channel body temperature data is sent to the host computer through the Bluetooth serial port, then re-enters to the low-power mode.

Compensation of linear thermistor

The temperature measurement range of this temperature measurement system is 34–42°C (depending on the temperature resistance value Table provided in the product specification), and some of the data and the corresponding resistance and temperature accuracy values are shown in **Table 2**.

Table 2. R-T relations

Temperature/℃	35.00	37.00	39.00	41.00
Resistance/kΩ	32.7852	30.1870	27.8200	25.6615
Resistance accuracy/%	± 0.09	± 0.05	± 0.09	± 0.13
Temperature accuracy/%	± 0.02	± 0.01	± 0.02	± 0.03

The MF54-503E 3949 EX-30R type thermistor, which indicates the functional relationship between its resistance value and temperature are shown in **Figure 7**. If it is calculated directly according to the exponential relationship as shown above, the nonlinearity error will be too large.

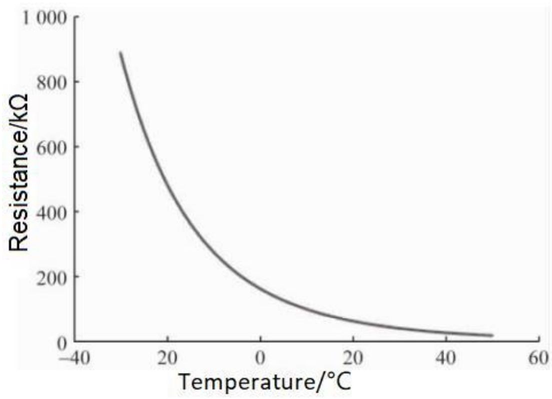

Figure 7. NTC thermistor temperature characteristic curve.

In order to improve the temperature measurement accuracy and eliminate the nonlinearity between the resistance and temperature, the thermistor is usually linearly compensated[17].

The system adopts the constant voltage bridge temperature measurement method as the hardware circuit compensation method. Comparing the three software methods of empirical equation, lookup Table linear interpolation, and polynomial fitting, there is no much difference in the fitting effect, and the first-order fitting error of the least squares method is large, while when the equation is above the third-order, the fitting accuracy is higher[17], considering the fitting accuracy and the performance of the system microcontroller, the software fitting adopts the fourth-order equation of the Stein-hart equation for fitting, as shown in equation (7). **Figure 8** shows the fitting effect, greatly reducing the nonlinear error.

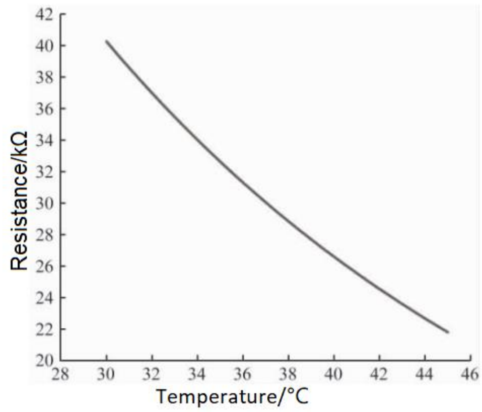

Figure 8. Stein-hart equation fitting effect diagram.

$$T = \frac{1}{\left[A + B\ln\left(\frac{R_T}{R_{ref}}\right) + C\ln^2\left(\frac{R_T}{R_{ref}}\right) + D\ln^3\left(\frac{R_T}{R_{ref}}\right) + E\ln^4\left(\frac{R_T}{R_{ref}}\right)\right]} - 273.15 \qquad (7)$$

In equation (7):

R_{ref} = 30.249 kΩ;

A = 3.224,246,655,096,800,0×10^{-3};

B = 2.532,193,613,303,590,0×10^{-4};

C = 2.809,695,570,637,810,0×10^{-6};

D = −1.002,667,386,689,740,0×10^{-7};

E = −6.843,900,831,606,440,0×10^{-9}.

4.2. PC software design

Using LABVIEW as the host computer programming software to achieve the acquisition of body temperature data, all 8-channel temperature curves are displayed as the waveform chart as shown in **Figure 9**. Since the temperature measurement range of the system is 34–42°C, the curve is maintained at 42°C when the measured temperature exceeds 42°C, and the curve is maintained at 34°C when the temperature is below 34°C, and the data can be stored in the EXCEL Table in real time. At the same time, in order to reduce the interference of the environment on temperature measurement and the estimation of subsequent core body temperature, the data is further processed by programming as shown in **Figure 10**. This ensures that the system measures the body temperature continuously and accurately.

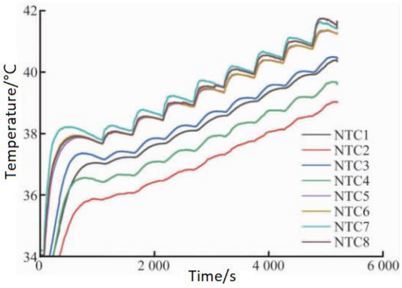

Figure 9. Temperature acquisition.

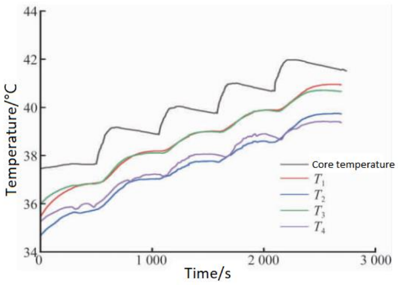

Figure 10. The optimization of the temperature signal.

5. Systematic error analysis

In order to further optimize the temperature measurement system and improve the measurement accuracy, error analysis is very necessary. The measurement system is divided into three parts according to the transmission direction of the signal, the NTC thermistor error, the voltage divider resistance error of the constant voltage source, and the ADC conversion error[18].

5.1. ADC error

The A/D converters uses the micro-power, high accuracy, 8-channel, 24-bits Δ-Σ high performance analog-to-digital converter ADS1256 from TI's Burr-Brown product line, with built-in input analog multiple switches, input buffers, programmable gain amplifiers, and programmable digital filters, 24 bits without data loss, 23 bits with noise-free accuracy, ± 0. 0010% low nonlinearity, 30 K SPS data sampling rate, etc., which is ideal for high-resolution measurements[19]. The digital quantity is 0–167,772,16, according to the above temperature measurement circuit, the voltage data output by the ADC can be expressed as:

$$ADC_{out} = \frac{V_{IN}}{V_{REF}} \times 16777216 = \frac{A\left(\frac{1}{2}V_{REF} - \frac{R_T}{R_T+R}\right)V_{REF}}{V_{REF}} \times 16777216 = 16777216A\left(\frac{1}{2} - \frac{R_T}{R_T+R}\right) \quad (8)$$

Equation (8): ADC_{out} is the digital quantify of the analog signal after A/D conversion; *A* is the amplification factor of PGA. It can be seen from equation (8), ADC_{out} is independent of the reference voltage, so the temperature measurement error caused by the reference power supply of the A/D converter is negligible. The error of the ADS1256 module consists of integral nonlinearity (INL), differentia nonlinearity (DNL), and offset error[20]. The maximum values for integral nonlinearity and differential nonlinearity of the ADS1256 ADC are ± 0.001% and ± 0.0003% LSB (least significant bit) respectively at this point, the PGA = 1, INL refers to the maximum error value between the analog value and real value in all output values of the ADS1256 and DNL refers to the difference between its actual quantization pair level and the theoretical quantization level. When PGA = 1, it can provide an effective resolution of up to 25.3 bits, the ADC uses 1 times oversampling, and according to the INL and DNL definitions, the nonlinearity error is converted to an ADC sampling value of ± 0.001% LSB[20], the temperature error introduced is ± 5.859,220,051,0 × 10^{-10} ℃. Similarly PGA = 1, the maximum ADC intercept error is differential input: ± 0.005% LSB, the temperature error introduced can be calculated to be ± 5.859,220,051 × 10^{-9} ℃.

5.2. Body temperature sensing error

The error of NTC thermistor as a temperature sensing device includes the thermistor error and nonlinearity error which are caused by the product itself. Through calibration experiments, the resistance value of the thermistor and the curve of temperature after fitted and drawn into a temperature resistance characteristic Table, and then build-in into a microcontroller in the form of a program. By using this method, it greatly reducing the nonlinear error to improve the temperature measurement accuracy[21]. According to the data sheet provided by the sensor manufacturer it shows that the temperature measurement accuracy of the MF54-503E 3949 EX-30R type thermistor is 0.01 ℃, and the resistance accuracy ± 0.05%.

5.3. Reference resistance and divider resistance errors

The reference resistor and the voltage divider resistor are selected from the same model with the same resistance value (30kΩ), one-ten-thousandth accuracy, 5 ppm/°C temperature coefficient, so the maximum error value introduced by the reference resistance value is about $\Delta R_f = 6\ \Omega$, by the equation (8) and the resistance temperature Table, it can be known that when the temperature is 37℃, the ADC sampling value is −26,063 LSB, and the ADC sampling value will become −25,224 LSB after the introduction of the resistance error[22]. Obtained from the NTC thermistor R-T relationship Table: When the temperature range is 34.0–42.0 ℃, the NTC resistance range is 34.158–24.647 kΩ, and the corresponding resistance value of the NTC is 34.158 kΩ and 24.647 kΩ, the sample values of the ADC can be obtained by equation (8) as −543,655 LSB and 821,714 LSB respectively, and the ADC sampling value change caused by the average 0.1℃ is calculated as:

$$\frac{26063LSB - 25224LSB}{(42\sim34℃) \times 0.1℃} = 17067LSB \qquad (9)$$

The temperature measurement error caused by the reference resistance Rf can be calculated by equation (9): [(26,063 LSB-25,224 LSB)/17,067 LSB] × 0.1 °C = 0.0049 °C, which is the maximum temperature error introduced by the reference resistor.

6. Experimental results

In order to verify the measurement accuracy of the equipment, and due to the specifications of the MF54-503E 3949 EX-30R model NTV provided by the manufacturer only has a temperature resistance value in the range of 34 to 42 °C from the (R-T) data sheet, the accuracy of the calibrated body temperature device was tested with these 9 temperature points. The test equipment adopts a thermostatic bath. In order to evaluate the error of the thermostatic bath[23], the high-precision mercury thermometer is used as a temperature reference device for measurement[24], and the accuracy of the mercury thermometer is 0.01 °C. Temperature indication (°C)/correction (°C) were: 34 °C/0.000 °C, 35 °C/– 0.001 °C, 36 °C/+ 0.007 °C, 37 °C/+ 0.004 °C, 38 °C/+ 0.001 °C, 39 °C/0.000 °C, 40 °C/+ 0.004 °C, 41 °C/– 0.003 °C, 42 °C/– 0.001 °C. In order to avoid interference, 8 NTC thermistors under test were placed in the tank for accuracy testing. Start to read the number after debugging the temperature measuring device for 5 mins. The measurement data of the measured body temperature are obtained through multiple experiments, as shown in **Table 3**.

The measured body temperature measuring device is at 34–42 °C, and the temperature error distribution curve of the 9 temperature points is shown in **Figure 11**.

As shown in **Table 4**. The measurement results meet the requirements of GB/T21416–2008 for the maximum allowable error of medical electronic thermometers at 34 to 42 °C.

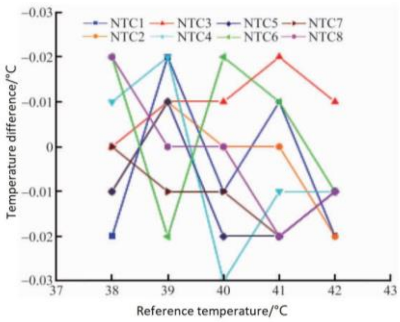

Figure 11. The measurement error of NTC thermistors.

Table 3. Measurement data of measured temperature equipment

NTC thermistor	Set temperature/℃			
	35℃	**37℃**	**39℃**	**41℃**
NTC1	34.98	37.01	39.02	41.01
NTC2	34.98	37.00	39.01	41.00
NTC3	34.99	37.01	39.01	41.02
NTC4	35.00	36.99	39.02	40.99
NTC5	34.98	37.00	39.01	40.98
NTC6	35.01	36.99	38.98	41.01
NTC7	34.98	37.01	38.99	40.981
NTC8	35.00	37.01	39.00	40.98

Table 4. The measurement error of NTC thermistors and data analysis

Temperature scale/℃	GB/T21416–2008/℃	8 NTC experimental results/℃
34	± 0.3	0.00–0.01
35	± 0.1	–0.02–0.01
36	± 0.2	–0.02–0.02
37	± 0.1	–0.01–0.01
38	± 0.1	–0.02–0.02
39	± 0.1	–0.02–0.02
40	± 0.2	–0.03–0.02
41	± 0.2	–0.02–0.02
42	± 0.3	–0.02–0.01

7. Conclusions

Based on the wearable temperature measurement system designed by NTC thermistor for high-precision thermometers, the errors of each part of the circuit are analyzed, and the errors of 34 to 42 °C and 9 temperature points are analyzed through experiments, and the source of temperature measurement errors is analyzed. The temperature measurement unit used high-precision electronic components, and thus the following conclusions can be drawn:

1) The nonlinearity characteristic of the NTC thermistors is corrected by fitting the Stein-Hart equation to greatly improve the accuracy of temperature measurement.

2) The host computer interface based on LABVIEW can wirelessly collects 8 channels of temperature data and processes the temperature signals in real time that able to automatically screen out 4 sets of temperature data with less environmental impact as accurate temperature values and overcome the influence of uneven local body temperature distribution.

3) The use of Wheatstone bridge circuit makes the voltage has less influence on the measurement of body temperature and improves the measurement accuracy, and the application of Type-C charging port and large-capacity lithium battery provides a strong guarantee for the real-time continuous collection of wearable body temperature devices[25].

4) The experimental results of the constant temperature water tank showed that the error of the body temperature measurement system far meets the error requirements of the medical electronic thermometer, indicating that this system fully meets the industry specifications of the medical electronic thermometer.

5) In addition, the accuracy of body temperature measurement results and the corresponding relationship between body surface temperature and core temperature need to be further studied. By estimating the body surface temperature at some point can well reflect the core temperature of the body, which will make the application prospect of body temperature measurement in the field of medical health wider and more meaningful.

Conflict of interest

The authors declare no conflict of interest.

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