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FPGA-based multi-channel thermocouple temperature measurement system

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Abstract. Aiming at the high and low temperature test requirements of spacecraft before being sent into space, this paper designs and implements a multi-channel thermocouple temperature measurement system based on FPGA. The system adopts thermocouple as temperature sensor, and ADT7310 is used as thermocouple cold junction temperature compensation, which solves the problem of thermocouple cold junction compensation better. The front end adopts AD7193, a 24-bit analog-to-digital converter with low noise, multi-channel and low power consumption, to amplify and A/D convert the signal at measuring junction of thermocouple. The control core is a field programmable logic gate array FPGA, which can better solve the problem of parallel processing of multi-channel temperature signals. At the same time, it uses the transposition method of the thermocouple standard graduation table, the interpolation look-up table algorithm and the cold junction compensation reverse look-up table algorithm, which is effective. The temperature measurement accuracy of each channel is improved. The experimental results show that the system can be connected to 24 K-type or T-type thermocouple sensors, the measurement range can reach $-200^{\circ}\text{C}\sim 220^{\circ}\text{C}$ ($73.15\text{K}\sim 493.15\text{K}$), and the relative error is less than $\pm 0.3\%\text{F.S.}$

1. Introduction

The temperature range of the space environment is quite different from the earth environment, so the spacecraft must undergo high and low temperature resistance tests before being sent into space. With the development of the times, temperature measurement technology is developing towards intelligence, high security, and diverse functions. Thermocouple is the most widely used temperature measuring element in industrial production. It has the advantages of small size, low heat capacity, wide temperature measurement range, fast thermal response speed, no need for excitation power supply and self-heating. It has always been widely used in temperature measurement systems. An ideal temperature sensor to use.

When the thermocouple sensor is measuring, there is a nonlinear relationship between the temperature and the voltage, and the lower the temperature, the more obvious the nonlinearity, which makes the error of the thermocouple difficult to control when measuring the low temperature area. Moreover, the traditional temperature measurement systems at home and abroad mostly use the single-chip microcomputer as the main control chip, but due to the influence of the single-chip processing data speed and instruction cycle, the general system using the single-chip microcomputer as the main control chip cannot meet the needs of multi-channel data processing and A/D. Practical application requirements in terms of conversion. Shi Jingnan et al. designed an embedded piston temperature test system[1]. The system uses a single-chip microcomputer as the core chip and can



only realize the temperature data acquisition of K-type thermocouples with 3 channels. Wenfeng designed a high-precision acquisition module design based on FPGA[2], which can realize the temperature data acquisition of 32-channel K-type or S-type thermocouples.

In order to solve the problem of many measurement channels and large errors of thermocouples in low temperature area, a multi-channel thermocouple temperature measurement system based on FPGA is designed in this paper, which can perform data acquisition, data processing and Data upload and other functions, use Fluke725 process calibrator to calibrate the system, and can accurately measure the temperature range $-200^{\circ}\text{C}\sim 220^{\circ}\text{C}$ online. This paper introduces the temperature measurement principle, cold junction compensation method, system design, data processing and test results of the system.

2. Thermocouple temperature measurement principle and cold junction compensation method

The thermocouple sensor is two different materials of conductors or semiconductors A and B are welded to form two junctions [3], one junction is the working end, that is, the measuring junction, which is placed in the medium to be measured, and the other junction is the reference end. The cold junction, can be at any temperature. When the temperature of the measuring junction and the cold junction are different, an electromotive force will be generated in the two different material loops, and the change of the electromotive force caused by the change of the temperature difference is called the thermoelectric effect, and the electromotive force is also called the thermoelectric power.

The thermocouple ITS-90 international standard comparison table is to place the cold junction of the thermocouple at 0°C , and then obtain the thermoelectric power corresponding to the measurement junction of the thermocouple at different temperatures. However, when the thermocouple sensor is measuring the actual temperature, the cold junction generally cannot be stably at 0°C , which causes the measured thermoelectric power difference to be smaller or larger than the international standard value. The temperature does not match the actual temperature, resulting in an error. Commonly used compensation methods are freezing point trough method, zero point migration method, compensator method and software processing method [4].

The freezing point trough method and the zero-point migration method are to keep the cold junction of the thermocouple in a specific temperature environment to maintain a fixed value, but these two methods have too high requirements on the test environment.

The compensator rule is to use an unbalanced bridge to generate thermoelectric power to compensate for the change in thermoelectric power caused by the temperature change of the cold junction of the thermocouple. However, this method has different current-limiting resistance values for thermocouples of different materials. This method does not apply to the design of many thermocouple sensors.

The software processing method only needs to add a constant corresponding to the cold junction temperature after sampling[5]. This method improves the speed of multi-channel acquisition. Therefore, a thermocouple cold junction compensation circuit is added in the design of this system to obtain the corresponding cold junction temperature. the constant, that is $E_a = E_m(T_1, T_0) + E_c(T_0, 0)$. Among them, E_c is the compensation voltage value of the cold junction of the thermocouple, and E_m is the voltage value of the measuring junction of the thermocouple.

3. Design of multi-channel thermocouple temperature measurement system

3.1. The overall structure of the system

The overall scheme of the multi-channel thermocouple temperature measurement system is shown in Figure 1, which includes a logic control unit, a data acquisition unit, a power supply unit, an MPU and an upper computer.

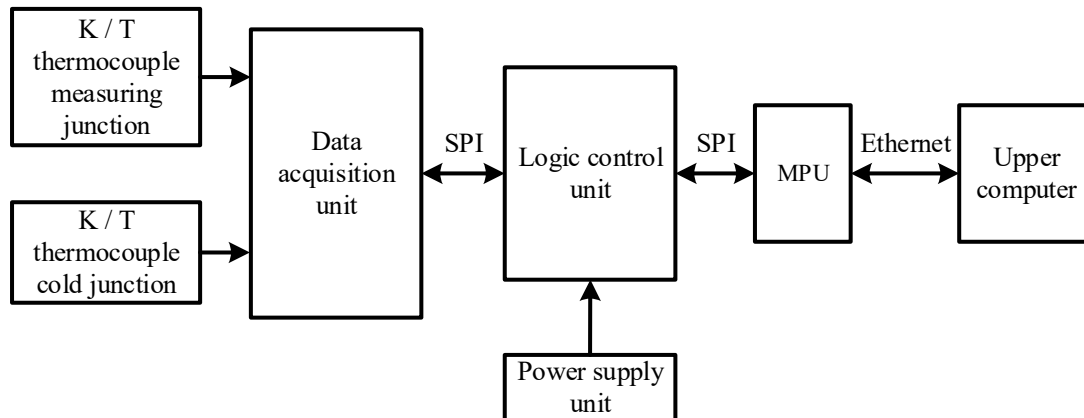


Figure 1. Overall design frame drawing

The logic control unit uses Cyclone III series EP3C25E144I7N to control the whole system. In the data acquisition unit[6], 6 pieces of ADI's 24-bit high-precision analog-to-digital conversion AD7193 chip are used for the temperature signal acquisition of the thermocouple measuring junction, and 1 piece of ADI's ADT7310 is used for the temperature signal acquisition of the cold junction of the thermocouple, which consists of a temperature sensor and a 13 /16-bit analog-to-digital converter, the design of the data acquisition unit is completed around 6 AD7193 chips and 1 ADT7310 chip.

The logic control unit sends control signals to the data acquisition unit through the SPI bus, and accepts the sampling data from the data acquisition unit. The EP3C25E144I7N converts the collected data into corresponding temperature values, stores them in the order of the channels, and sends them to the MPU through the SPI bus. The MPU then uploads the data to the host computer through Ethernet for data display.

3.2. FPGA firmware design overview and process

The FPGA of this system receives the instructions of the host computer software through the SPI bus communication, and completes the data acquisition, processing and uploading operations of each channel according to the instructions[7]. The data acquisition and processing includes 1 channel thermocouple cold junction temperature compensation acquisition, and is converted into the corresponding compensation voltage value through the thermocouple temperature-voltage graduation table and linear interpolation algorithm; 24-channel thermocouple measurement terminal data acquisition, and combined with the compensation voltage value to convert the corresponding temperature value through the thermocouple voltage-temperature scale table and linear interpolation algorithm; The converted temperature value is uploaded to the supporting host computer software through SPI communication. The specific design process of FPGA is shown in Figure 2.

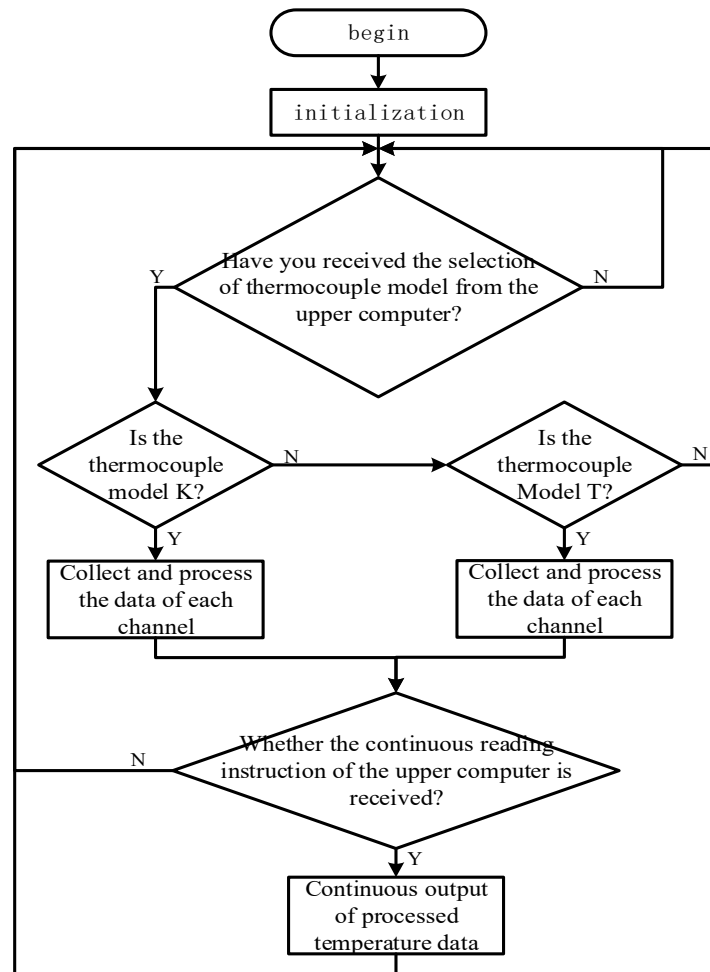


Figure 2. System firmware design flow chart

4. Data processing of multi-channel thermocouple temperature measurement system

4.1. Linear Interpolation Algorithm

The interpolation function of the linear interpolation algorithm is a first-order polynomial[8], and the interpolation error at each interpolation node is 0. Let the values of function $y = f(x)$ on two points x_0 and x_1 be y_0 and y_1 respectively, Find polynomial $y = a_0x + a_1$ to satisfy $f(x_0) = y_0$, $f(x_1) = y_1$, as

$$y = y_0 + \frac{y_1 - y_0}{x_1 - x_0}(x - x_0) \quad (1)$$

For example, the system is divided into appropriate intervals according to the thermocouple LTS-90 international standard (temperature/electromotive force) comparison table, the voltage value at the beginning and end of the section is equivalent to x_0 and x_1 , The temperature value corresponding to the voltage value is equivalent to y_0 and y_1 , the y value in formula (1) is equivalent to converting the voltage value to the temperature value by using the linear interpolation algorithm.

4.2. Compensation voltage value of thermocouple cold junction

ADT7310 is a chip that integrates temperature sensor and analog-to-digital conversion functions. This system uses it for the acquisition of the temperature of the cold junction of the thermocouple, and communicates with the main control chip through SPI. According to the ADT7310 chip data manual, first reset the chip, and then configure the register for the chip. After the configuration is completed, the chip continuously sends the collected digital data of the temperature of the thermocouple cold junction to the main control chip, and then the main control chip performs the processing on it. collection.

The main control chip collects the AD value proportional to the temperature of the cold junction of the thermocouple from the ADT7310 chip, and then looks up the table according to the temperature and voltage scale of the thermocouple, and then calculates the thermocouple corresponding to the temperature value of the cold junction through the linear interpolation algorithm. International standard voltage value. The specific calculation flow chart of the compensation voltage value at the cold junction of the thermocouple is shown in Figure 3.

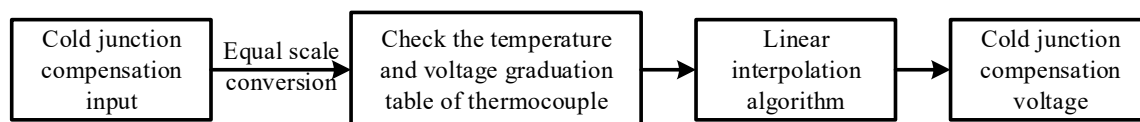


Figure 3. Calculation flow chart of compensation voltage value of thermocouple cold junction

4.3. Thermocouple measurement terminal voltage value

The AD7193 is a low noise complete analog front end with direct input of small signals for high precision measurement applications. It integrates a low-noise, 24-bit sigma-delta analog-to-digital converter, which is used in the system to collect the voltage of the thermocouple measurement terminal, and communicate with the main control chip through SPI. According to the AD7193 chip data manual, first reset the chip, and then configure the register for the chip. After the configuration is completed, the chip continuously sends the collected digital data of the thermocouple measurement terminal voltage to the main control chip, and then the main control chip collects it.

4.4. temperature value measured by thermocouple

The voltage value of the thermocouple measurement terminal is collected from the AD7193 chip by the main control chip, and the cold terminal compensation voltage value is added to the measurement terminal voltage value. The international standard temperature value of the thermocouple corresponding to the actual voltage value is obtained. The specific data calculation flow chart is shown in Figure 4.

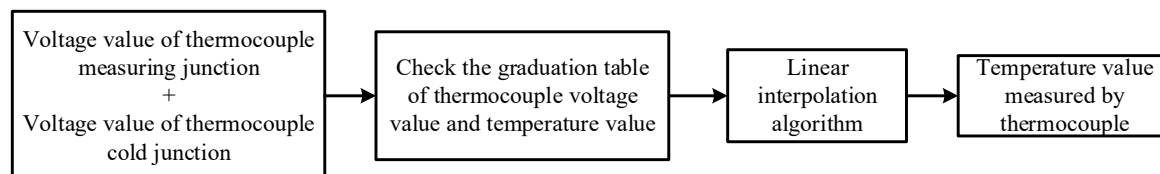


Figure 4. Calculation flow chart of temperature value measured by thermocouple

5. Test results

Using the Fluke725 process calibrator as the standard input, every 10°C in the temperature range of -200°C~220°C is used as a sampling point, using the supporting host computer software to display the actual measured temperature value of the system, and organize the data displayed by channel 0. Calculated with relative error. The following table 1 and table 2 show the actual measured data of the K/T thermocouple sensor in channel 0. Comparing the standard input of the Fluke725 process

calibrator with the actual temperature measured by the system, it can be seen that the relative error of the test is less than 0.3%. The feasibility and accuracy of this design scheme are verified.

Table 1. K-type thermocouple channel 0 whole measured data

Standard input/°C	actual measurement/°C	relative error/%	Standard input/°C	actual measurement/°C	relative error/%
-200	-199.14	0.20	20	19.84	0.04
-190	-189.16	0.20	30	29.88	0.03
-180	-179.37	0.15	40	39.82	0.04
-170	-169.20	0.19	50	49.78	0.05
-160	-159.15	0.20	60	59.77	0.05
-150	-149.32	0.16	70	69.73	0.06
-140	-139.50	0.12	80	79.89	0.03
-130	-129.52	0.12	90	89.86	0.03
-120	-119.44	0.13	100	99.78	0.05
-110	-109.38	0.15	110	109.76	0.06
-100	-99.64	0.09	120	119.83	0.04
-90	-89.55	0.11	130	129.79	0.05
-80	-79.48	0.12	140	139.78	0.05
-70	-69.44	0.13	150	149.80	0.05
-60	-59.45	0.13	160	159.90	0.02
-50	-49.60	0.10	170	169.81	0.05
-40	-39.78	0.06	180	179.94	0.01
-30	-29.72	0.07	190	189.86	0.04
-20	-19.87	0.03	200	199.88	0.03
-10	-9.78	0.05	210	209.90	0.03
0	-0.18	0.04	220	219.76	0.06
10	9.94	0.01			

Table 2. T-type thermocouple channel 0 whole measured data

Standard input/°C	actual measurement/°C	relative error/%	Standard input/°C	actual measurement/°C	relative error/%
-200	-198.77	0.29	20	19.90	0.02
-190	-188.83	0.27	30	29.90	0.02
-180	-179.07	0.22	40	39.92	0.02
-170	-169.01	0.23	50	49.75	0.06
-160	-159.15	0.20	60	59.70	0.07
-150	-149.47	0.12	70	69.73	0.06
-140	-139.32	0.16	80	79.83	0.04
-130	-129.39	0.15	90	89.82	0.04
-120	-119.26	0.18	100	99.87	0.03
-110	-109.48	0.12	110	109.95	0.01
-100	-99.52	0.11	120	119.98	0.00
-90	-89.59	0.09	130	129.96	0.00
-80	-79.70	0.07	140	139.99	0.00
-70	-69.74	0.06	150	149.92	0.02
-60	-59.45	0.13	160	159.84	0.04
-50	-49.51	0.12	170	168.71	0.07
-40	-39.53	0.11	180	179.79	0.05
-30	-29.59	0.10	190	189.77	0.05
-20	-19.66	0.08	200	199.80	0.05
-10	-9.77	0.05	210	209.86	0.03
0	-0.32	0.08	220	219.92	0.02
10	9.83	0.04			

Then randomly select 6 channels from the 24 channels, take the Fluke725 process calibrator as the standard input, and use the temperature range $-200^{\circ}\text{C}\sim 220^{\circ}\text{C}$ as a sampling point every 40°C . The relationship curve between the test temperature of each channel and the standard input can be obtained, Figure 5 and Figure 6 show the relationship between the K-type and T-type standard input and the actual measurement in the random 6 channels.

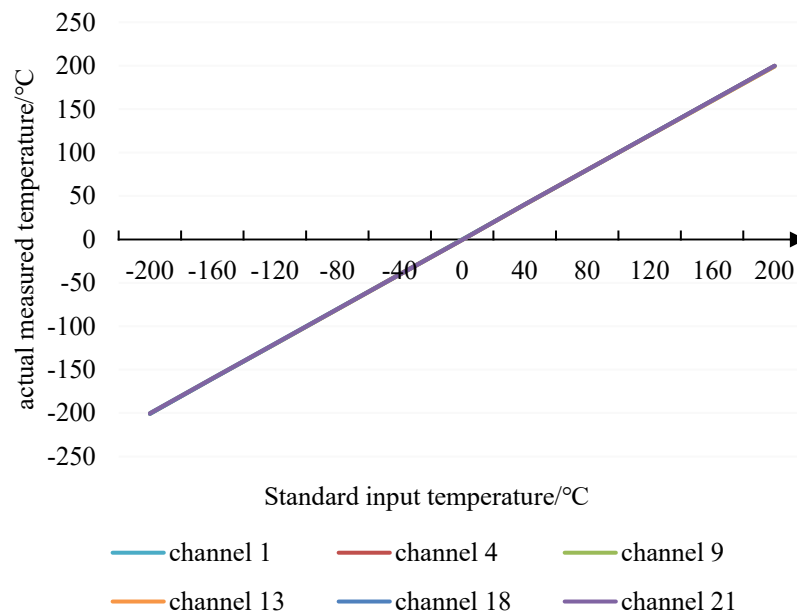


Figure 5. Relationship curve between K-type standard input and actual measurement

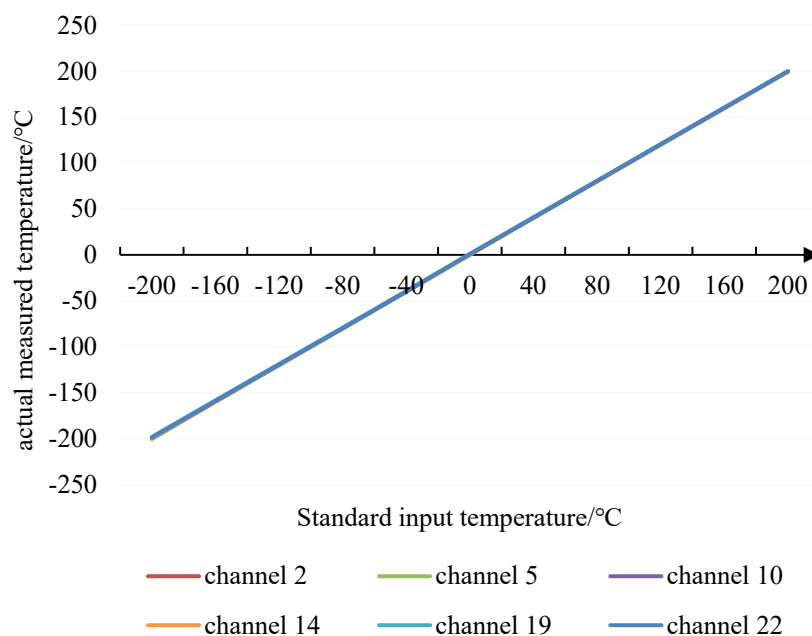


Figure 6. Relationship curve between T-type standard input and actual measurement

The system uses the Fluke725 process calibrator as the standard input and compares the measurement results displayed by the host computer software. The results show that the system is used to measure the temperature range of $-200^{\circ}\text{C}\sim 220^{\circ}\text{C}$, and the relative error can be controlled within

$\pm 0.3\%$ F.S. It makes up for the measurement of the thermocouple sensor at low temperature by the existing temperature measurement system, and further excavates the temperature measurement range of the temperature measurement system for the thermocouple sensor in practical application.

6. Conclusion

This paper introduces the design and implementation of a multi-channel thermocouple temperature measurement system based on FPGA. Six AD7193 analog-to-digital conversion chips and one ADT7310 analog-to-digital conversion chip are used to form the data acquisition unit of this system. The logic control unit uses EP3C25E144I7N to monitor the entire system. The system is controlled, and can be compatible with any device terminal that uses SPI bus communication. And adopt various methods to improve the system accuracy, including thermocouple index table lookup table, thermocouple index table contrast table and linear interpolation algorithm, the final relative error of the system is less than $\pm 0.3\%$ F.S. Moreover, the system is easy to expand the channels and types of thermocouple sensors, and can also expand the scope of the index table look-up table, and expand the temperature measurement range of the system, so as to better adapt to more application scenarios.

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