Research on the smart measuring system for DC resistance box

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Abstract. Aiming at the shortages existing in the process of measuring DC resistance box’s resistance, this paper proposes a new smart electric bridge. The relationship between the voltage of electric bridge and the value of programmable constant voltage module is discussed using Wheatstone bridge theory. The voltage of electric bridge is obtained by ADC device and the value of programmable constant voltage module is controlled by DAC device. According to the mathematical equation between physical quantities of electric bridge, when the bridge balanced, the system calculates the value of DC resistance box’s resistance. In this study, ratio knob switching circuit is designed to change the value of DC resistance box’s resistance automatically. Experimental results show that the measuring accuracy of the system is 1/10000, Stability reached 5/100000 and the system is easy operating, high working efficiency.

1. Introduction
DC resistance box is widely used in laboratories, industrial workshops and various scientific research occasions. It is an indispensable electronic instrument. However, the DC resistance box will be affected by various factors, so we need to verify the newly, used or repaired resistance boxes to ensure its accuracy. At present, most of the resistance box verification procedures are cumbersome, the workload is large, and the verification efficiency is low, which easily leads to errors in the verification.

To solve the above issues, this paper proposes a new smart electric bridge. It can automatically verify the resistance box and generate verification report, which greatly improves the working efficiency and is more reliable. The system is designed ratio knob switching circuit to automatically change measuring resistance, resistance switching circuit to expand measuring range, Butterworth filter to attenuate high frequency noise, DAC circuit to adjust the balance of Wheatstone bridge and ADC device collects data of bridge. In addition, Using STM32F103 microcontroller and ENC28J60 device allow us can communicate with it via Ethernet, so we can operate verification system complete resistance measurement by control computer.

2. Hardware circuit design
As shown in figure 1, the microcontroller gets the value of \(U_{cd}\) via ADC device, and compared the value with zero, the system can calculate \(\Delta U_{cd}\) and \(d\Delta U_{cd}/dt\). According to the calculation data, the
system will call fuzzy parameter table and change the output of DAC[1], make $U_{odi}=0$, then the system will figure out the value of $R_x$.

$$R_x = \frac{U_{AB}R_1R}{U_{AB}R_2 - UR_1 - UR_2} \quad (1)$$

\[ \text{Figure 1. Smart electric bridge equivalent circuit} \]

2.1. Programmable constant voltage circuit

As shown in figure 2, the pivotal device of programmable constant voltage circuit is DAC (LTC1595BCN8), the stability of measurements depends on DAC’s output, after testing, LTC1595BCN8 meets the design requirements. To achieve the index that precision is 0.01%, means that DAC device has sufficient fineness adjustment, LTC1595BCN8 resolution ratio is $1/(2^{16} - 1) = 0.000015$, it can meet the needs of design[2]. In order to automatic balance bridge, STM32F103 gets the data of ADC collecting all the time, processes the data and calls the correct fuzzy parameter to adjust ADC’s output.

\[ \text{Figure 2. Programmable constant voltage module circuit} \]

2.2. The upper impedance arms design

When using a Wheatstone bridge for resistance measurement, if the measured resistance exceeds the current range, measurement cannot be completed simply by adjusting the variable resistance. In addition, the upper arms at a certain fixed range of resistance values, there is a large measurement error, so that the measured values deviate from their true values, affecting the measurement accuracy. Therefore, whether the bridge was set the appropriate value of the upper arm resistances according to the nominal value of the measured resistance is an important factor for improving the measurement accuracy[3].

As shown in figure 3, in this design, $U_{AB}=2.5V$, $R=1Kohm$, according to the expression (1), we can get:

$$R_x = 1/(\frac{R_2}{R_1} - (1 + \frac{R_2}{R_1}) \frac{U}{2.5}) \; \text{Kohm} \quad (2)$$

Obviously, $U$ is not possible to be negative, so:

$$U \geq 0 \quad (3)$$
Analyzing expression (2) and expression (3), we can draw a conclusion:

\[ R_x \geq \frac{R_1}{R_2} \text{ Kohm} \quad (4) \]

The resistance box of this design is to be tested with a resistance range of 0.1 ohm to 9999.9 ohm. Therefore, the minimum value of R1 is 1Kohm, and the maximum value of R2 is 10Mohm. Based on this, we can set the value of R1 and R2 to meet the measurement requirements, at the same time, we also can improve the measurement accuracy, avoid excessive output of DAC (output voltage close to 2.5V) or too small (output voltage close to 0V), that will make unnecessarily errors. The simulation and experiment show that we can set R1=1Kohm or 1Mohm, and R2=1Kohm, 10Kohm, 100Kohm or 1Mohm. STM32F103 controller will automatically pick the most suitable values of R1 and R2 according to ADC sampling data in conjunction with control rules. This method not only improves the measurement accuracy but also makes the measurement process faster.

![Figure 3. Smart electric bridge circuit](image)

2.3. Voltage sampling circuit

As shown in figure 4, the millivoltmeter sampling circuit uses two operational amplifiers as the input stage, and then the output signal is the input of the third operational amplifier, formed a three-op-amp differential circuit. Theoretically, the sampled voltage is between -2.5V and 2.5V, so the sample voltage may exceed the sampling range of the ADC (the 1.25V reference voltage is superimposed before the ADC input pin). With constantly adjusting, the bridge is getting closer and closer equilibrium and the voltage between the bridges will also decrease, so we need to amplify the voltage between the bridge to enhance its anti-jamming capability. Therefore, the input stage of the sampling circuit must use an inverting amplifier. Suppress common-mode signals and amplify differential-mode signals so that the circuit’s anti-jamming performance will be better. It can change the sampling channel by the relay to generate the appropriate magnification. In order to ensure absolute equal-scale differential amplification of the sampled signal, the resistor network of the sampling circuit must be strictly symmetric, mean that KR5=KR7, KR6=KR8, KR9=KR11, KR10=KR12, KR13=KR15, KR14=KR16. Theoretically, the total gain of the signal through the two differential division is:

\[ A_{ud} = -\frac{KR_9(KR_{10})}{KR_5(KR_6)} \cdot \frac{KR_6}{KR_{15}} \quad (5) \]

The measurement system should also be designed with auto-zero circuit and calibration circuit. By auto-zero circuit, we can eliminate the zero shift of the circuit itself. As long as the sampling port
is shorted during the auto - zero and then read the AD sampling results, the zero-deviation value can be obtained as the compensation value for the subsequent measurement data. By calibration circuit, we can input a number of standard voltages, operate the millivolt meter to collect the voltage, process the ADC sampled voltage data and the standard voltage and we can get the standard curve of least square method[4].

Figure 4. Signal sampling circuit

2.4. Signal conditioning and A/D converter circuit
Because of the measurement error, the sampled signal need to be further processed. As shown in figure 5, according to the amplitude of the signal to enlarge or reduce it for measurement, so the design uses an 8-channel CMOS analog multiplexer MAX308 device to solve this point. Because of some factors of the devices and the circuit itself, there may be some high-frequency noises that interfere with the signal. Therefore, a Butterworth filter circuit is designed to reduce the interference caused by high-frequency noise on the signal[5]. Based on the signal voltage range to be sampled, 2.5V is selected as the reference voltage of the ADC, and the ADS1240E is initialized, AIN1 is used as a sampling channel and a unipolar analog input. However, the sampling voltage may be positive or negative, so the signal of the processed signal is added to the input pin of ADC before it is superimposed with a standard voltage of 1.25V generated by MAX6255 and precision resistor circuit. The median filtering algorithm is used in code to eliminate the errors caused by accidental factors in the sampling process and make the sampling results more accurate and reliable.

Figure 5. Signal processing & converting circuit

2.5. The motor driver circuit
In the general motor control system, the pulse signal required by the motor is generated by the main control chip, and its strength usually cannot directly fit the rated current when the stepping motor is in operation. The stepper motor SS2302A25A selected in this design has a rated voltage of 2.8V and an operating current of up to 2.5A, so we need to design a drive circuit for the stepper motor. As shown in figure 6, L297 and L298 are the commonest driver chips for stepper motors. They only need to
build a simple peripheral circuit to drive the stepper motor. The motor easily generates self-induced electromotive force, so four pairs of diodes are provided on the control signal output port to protect the L298 chip from damaging.

![Motor driver circuit](image)

Figure 6. Motor driver circuit

3. The design of fitting curve

In order to improve the measurement accuracy of the equipment, calibration is an indispensable part of instrument design[6]. A series of standard voltage values is input to the sampling circuit and these voltages will be sampled by ADC device. STM32F103 analyses these data to find an optimal curve to describe the relationship between the external input and the detection value[7].

There is the optimum fitting equation for n points:

\[ Y = k \cdot X + b \]  

(6)

In the expression, Y means the voltage value measured by ADC, X is the standard voltage value, k is the slope of the straight line, b is its intercept.

There is a definition for expression (7):

\[ \phi = \sum_{i=1}^{n} (y_i - k \cdot x_i - b)^2 \]  

(7)

To minimize the value of the squared sum \( \phi \) of the errors, take their partial derivatives of k and b, respectively, let them equal to zero, we can get:

\[
\begin{align}
\frac{\partial \phi}{\partial k} &= \sum_{i=1}^{n} [-2(y_i - k \cdot x_i - b)] = 0 \\
\frac{\partial \phi}{\partial b} &= \sum_{i=1}^{n} [-2x_i(y_i - k \cdot x_i - b)] = 0 
\end{align}
\]  

(8)

There is an expression (8) simplification:

\[
\begin{align}
\sum_{i=1}^{n} y_i &= n \cdot b + k \cdot \sum_{i=1}^{n} x_i \\
\sum_{i=1}^{n} x_i y_i &= b \cdot \sum_{i=1}^{n} x_i + k \cdot \sum_{i=1}^{n} x_i^2 
\end{align}
\]  

(9)

According to expression (9), the microcontroller will figure out the values of k and b and store them in flash.

Since the DC sampling is prone to zero drift, the system will automatically zero every time it is turned on. The new value obtained after zero calibration can cover the previous value of b and eliminate the error caused by zero drift.
4. Experimental findings

In the test, the design uses an Agilent 6612C digital DC power supply as the external standard voltage, the Agilent 34401A digital multimeter as standard instrument and ZX56 high-precision DC resistance box as a device to be tested to complete the test.

Stability test: in the same conditions, measuring a precision resistance ten times, according to the maximum and minimum, we can deduce stability. The results shown in table 1, R_{\text{max}} is maximum, R_{\text{min}} is minimum and R_{\text{avg}} is average value. From table 1, it can be seen that the stability meets the design requirements within 0.005%.

| R_{\text{avg}}/\Omega | R_{\text{min}}/\Omega | R_{\text{max}}/\Omega | stability |
|----------------------|-----------------------|-----------------------|------------|
| 0.99994             | 0.99990               | 0.99994               | 0.0040%    |
| 10.0008             | 10.0005               | 10.0009               | 0.0039%    |
| 100.007             | 100.004               | 100.008               | 0.0039%    |
| 999.988             | 999.976               | 1000.02               | 0.0044%    |
| 9999.89             | 9999.85               | 10000.2               | 0.0035%    |

Accuracy test: in the same conditions, measuring a precision resistance with Agilent 34401A, the measured result as standard value. And then, measuring the resistance with this design, the result as measured value. The results shown in table 2, R_{\text{std}} is standard value and R_{x} is measured value, R_{0} is the indicating value of ZX56. Table 2 shows that the accuracy meets the design requirements within 0.01%.

| R_{0}/\Omega | R_{\text{std}}/\Omega | R_{x}/\Omega | stability |
|-------------|-----------------------|-------------|-----------|
| 1.0         | 0.99998               | 0.99992     | 0.0060%   |
| 10.0        | 10.0002               | 10.0008     | 0.0059%   |
| 100.0       | 100.001               | 100.005     | 0.0039%   |
| 1000.0      | 1000.02               | 999.994     | 0.0026%   |
| 9999.9      | 9999.57               | 10000.1     | 0.0053%   |

5. Conclusion

In this paper, the STM32F103 as the main control core, operation staff can run the UI on computer complete the verification of the DC resistance box. Through the debugging of every modules of the system and testing the whole machine, the expected results are finally achieved: The measurement stability (reproducibility) does not exceed 0.005% and the accuracy is within 0.01%. The design method described in this paper has the characteristics of simple operation, high verification efficiency, and being less prone to errors than most existing verification devices on the market. In the subsequent development, it is also possible to add a small amount of peripheral circuits to achieve the voltage test function based on this design, and further broaden the scope of its use.

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