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Automation of Resistance Bridge Calibrator

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Abstract The article addresses the automation of the resistance bridge calibrator (RBC). The automation of the RBC is performed in order to facilitate the operation of the RBC, improve the reliability, and enable several additional possibilities compared to the tedious manual operation, thereby making the RBC a more practical device for routine use. The RBC is used to calibrate AC and DC resistance bridges, which are mainly used in a primary thermometry laboratory. It consists of a resistor network made up from four main resistors from which 35 different resistance values can be realized using toggle switches. Literature shows that the resistors' non-zero temperature coefficient can influence the measurements, causing difficulties when calibrating resistance bridges with low uncertainty. Placing the RBC in a thermally stable environment can reduce this, but it does not solve the problem of the time-consuming manual selection of the resistance values. To solve this, an automated means to manipulate the switches, while the device is placed within a thermally stable environment, was created. Computer operation completely substitutes for any manual operation during which an operator would normally have to be present. The computer also acquires measurements from the bridge. In this way, repeated and reproducible calibration measurements inside a temperature-stable environment can be carried out with no active involvement of personnel. The automation process itself was divided into several stages. They included the construction of a servo-manipulator to move the switches, the design of a dedicated electronic controller that also provides a serial interface (RS-232) to the computer, and the development of custom computer software to configure the servo-manipulator and control the calibration process. Measurements show that automation does not affect the long-term stability and mechanical

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repeatability of the RBC. The repeatability and reproducibility of bridge calibration ratios were also demonstrated by making consecutive measurements.

Keywords Automation · Resistance bridge · Resistance bridge calibrator (RBC)

1 Introduction

Standard platinum resistance thermometers (SPRTs) are used by national measurement institutes (NMIs) to measure temperature at the defining fixed points of the International Temperature Scale of 1990 (ITS-90). The SPRT resistance is directly proportional to the temperature being measured; thus, the quality of the temperature measurement is dictated by the quality of the resistance measurement. To measure resistance, AC and DC resistance-ratio bridges are used. They operate by comparing the unknown resistance to a standard resistor, giving a result that is a ratio of one to the other. The uncertainty of resistance bridges can be as low as a few tens of parts per billion (ppb). In terms of temperature, this means that measurements with uncertainties down to 5 μK can be achieved.

Resistance-ratio bridges have to be calibrated periodically to ensure that temperature measurements are made with the lowest possible uncertainty. It is known from the experience of the NMIs that only approximately two out of five resistance bridges are within their specification. The major sources of uncertainty for the resistance bridges are frequency dependence, ratio error, repeatability of measurements, and non-linearity. The largest uncertainty contribution is usually the non-linearity of the bridge. As described in [1,2], several methods exist for the verification of resistance bridges:

- Verification using a ratio turns unit (RTU by ASL). The RTU is an inductive voltage divider that produces 14 distinct ratio values to determine the non-linearity of a resistance bridge. Due to its inductive nature, it is only applicable to AC resistance bridges.
- A complements check method is used to verify the ratio error. Two reference resistors are compared by measuring the normal and reciprocal resistance ratios. The ratio error is then determined from the equation:

$$\delta(10^6) = \frac{[1 - (R_1/R_2)(R_2/R_1)] \cdot 10^6}{2} \tag{1}$$

- In the case of AC resistance bridges, AC quadrature effects/frequency dependence of an AC bridge is estimated from the difference between the low-frequency and high-frequency measurements of both the SPRT and the reference resistor.
- Measurement repeatability is determined by making two similar measurements using the resistance bridge. This is usually done by measuring a thermally controlled reference resistor over at least 10 h.
- Verification using the resistance bridge calibrator (RBC). The RBC is a four-resistor network able to provide resistance ratios to determine the non-linearity of a resistance bridge.

All of the stated methods for calibration/verification usually involve manual operations, meaning that a thorough examination of a resistance bridge may require a great amount of time during which an operator has to be present. Of the methods listed above, the one most frequently applied and also widely available is the use of a RBC. This method, however, has several practical drawbacks that can be minimized by automation, as shown in this article.

2 Resistance Bridge Calibrator

The RBC is a resistor network that was purposely developed for the calibration of resistance bridges [3], although it can also be used to test other instruments used for resistance measurements. The commercially available RBC 25, 100, and 400 were originally designed and built by D. R. White of the Measurement Standards Laboratory of New Zealand [4]. The schematic for the RBC is shown in [5, p. 14]. The RBC has four base resistors (R1 to R4) that can be connected in series or in parallel using switches. The base resistors are connected to a low-resistance common point at one end and to the switch matrix at the other end. There are also four potential-sharing resistors that are wired in series to the base resistors to compensate parasitic resistances in the network, making sure that the voltage is measured correctly. It is important that four-wire connections are used. In this way, the influence of connection-wire resistances is cancelled. Thirty-five different resistances can be obtained by switching the eight toggle switches on the control panel to certain positions.

For the purpose of the experiment, an Aeonz RBC 100 was used. With it, resistance values in the range from 16.8 Ω to 129.9 Ω can be obtained by series and parallel connections of the base resistors. By comparing the calculated values of these combinations to the measured values, the linearity of the bridge is determined. The results can be analyzed in several ways. The simplest is to use the measured values for the ratios of the base resistors to calculate the expected readings of the other ratios. A more accurate assessment is made by using a least-squares fit to find the best values of the base-resistor ratios. The difference of a measured ratio (Nimeas) from the calculated ratio (Nicalc) is the error due to non-linearity for that particular combination. The combined non-linearity of the measured resistance bridge is expressed as its associated standard deviation (δ). This is calculated by using Eq. 2, where n is the number of measured combinations of the RBC (up to 35).

$$\delta = \sqrt{\frac{\sum_{i=1}^{n} (Nimeas - Nicalc)^2}{n-1}} \tag{2}$$

When the standard resistor and RBC connections to the bridge are interchanged, up to 35 additional combinations can be obtained, thus creating 70 combinations. This makes it possible to use the ratio complements check method to quantify the ratio error of the measured bridge as well.

The values of the resistors used in the RBC 100 are presented in Table 1. The base resistors have values such that their series and parallel combinations have equally

Table 1 RBC 100 resistor values

	Base resistor (Ω)	Potential sharing resistor (Ω)
1	81.8186	2.6327
2	48.1768	1.5495
3	36.5153	1.1749
4	31.2419	1.0049

spaced values throughout the measuring range. The potential-sharing resistors are of low resistance and are proportional to the base resistor values.

3 Automation

In principle, the RBC presents a simple approach to resistance bridge calibration. The construction of the resistance network is simple and, in principle, easy to employ. When the RBC under investigation is used on secondary laboratory resistance bridges (with uncertainty down to 1 ppm, e.g., ASL F700), a complete calibration can be completed in less than 1 h with repeatable results. However, when the unit is applied to calibrate a low-uncertainty resistance bridge (e.g., ASL F900, MI 6010T), several problems present themselves, making the calibration of such a resistance bridge with the RBC impractical. The two major reasons for the RBC to be automated are described below.

The first reason comes from the measurement technique itself. During the calibration, an operator has to be present to switch between different combinations. For the calibration to be successful, a set of 35 measurements has to be obtained consecutively. When the calibration is carried out with a low-uncertainty resistance bridge, taking up to 15 min or more to correctly measure a single resistance combination, the operator has to be present for over 9 h. This is a tedious and mentally demanding job for the operator and usually means that, in most cases, only one measurement set can be obtained per day. An automated RBC would be able to make repeated measurement sets over longer periods of time.

The second reason for automating the RBC comes from the largest source of uncertainty. The resistors used in the RBC have temperature coefficients specified within $\pm 0.6 \times 10^{-6}/°\mathrm{C}$ at temperatures in the range from 20 °C to 23 °C. This means that a laboratory with temperature control to within 1 °C will have a maximum variation of resistances of about 0.3 ppm, leading to an uncertainty of about 0.1 ppm. This makes the RBC unusable for low uncertainty resistance bridges, since most of them have a stated uncertainty below 0.1 ppm, and even as low as 0.02 ppm (ASL F900). This implies that careful attention has to be paid to ambient temperatures. A thermally more stable environment can be achieved by isolating the RBC within an insulated enclosure, making measurements with uncertainties of 0.01 ppm possible. To make sure that no thermal influence from outside is present, this enclosure must be sealed and the RBC operated from within the enclosure. Some attempts [1] to reduce the influence of the temperature dependence of the device have already been made; however, none of them included automating the system, leaving the process of calibration still rather impractical.

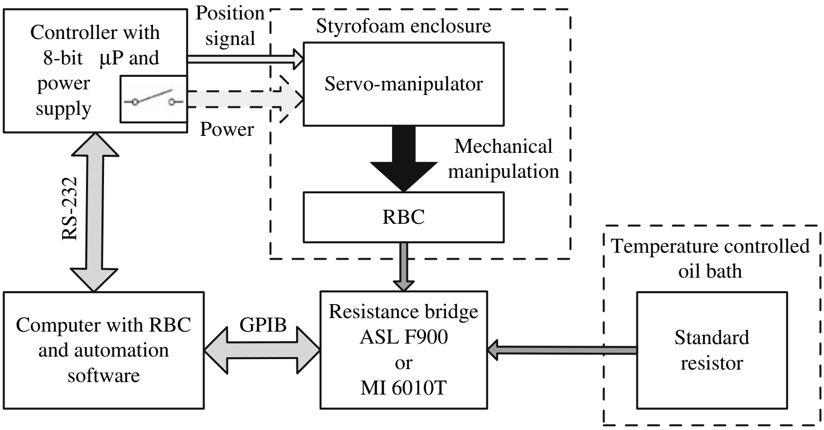


Fig. 1 Block diagram of automation process

For the automation to be successful, additional requirements have to be met. The automated system should be universal (i.e., it should be attachable to any RBC unit) and only the positions of the switches should have to be calibrated within the software. All measurements have to be saved to a file for later analysis by the RBC software. The automated manipulation of the RBC must not in any way affect measurements taken by the RBC, nor harm it in any way.

The automation process was divided into three stages (Fig. 1). First, a servo manipulator for the RBC was built to actuate the RBC switches. The second task was the construction of an electronic controller to provide power and control signals to the servo manipulator. The controller receives instructions from the computer. Finally, the computer software was created to control the automatic switching and to acquire measurements from the bridge.

3.1 Servo Manipulator

The servo manipulator required every switch to be separately actuated and brought to any of the three positions. The force of the manipulator would have to be low so that the switches would not be mechanically harmed. During the measurements, no force should be present on the switches.

The servo manipulator was constructed on a $(50 \times 50)\,\text{mm}^2$ L-shaped aluminum bar (Fig. 2). This was fixed on top of the RBC and provided a sturdy base for the servomotors. Eight small servomotors (one for each switch) were used. These can provide a maximum torque of $0.09\,\text{N}\cdot\text{m}$, enough to actuate the switches, but low enough not to harm them. The servomotors were fixed to the aluminum bar and connected to the switches using semi-rigid connecting links. The non-rigidity of the links provided an added safety measure. If the motor exerted extra force on the switch in its final position, the link would bend, protecting the switch from damage. Although the connector links provided flexibility, they did not have backlash in their joints. The repeatability of a movement was measured to be about 0.2 mm. The switch-arm

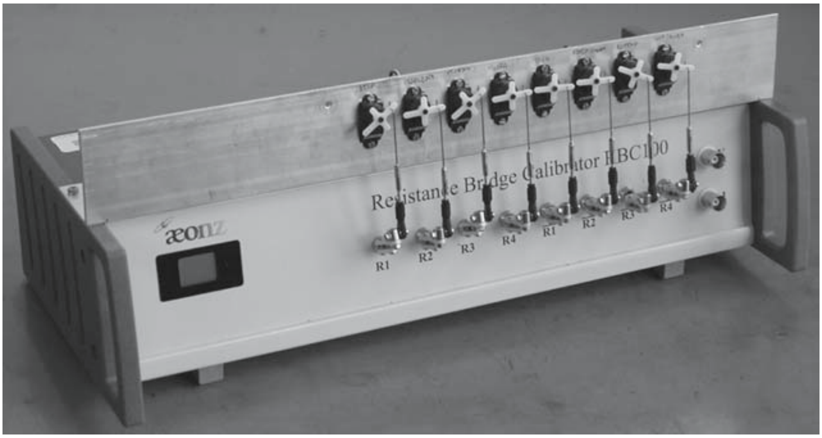


Fig. 2 Servo-manipulator on top of RBC

attachments were purpose-made and could be removed at any time to make the RBC manually operable again. The power and control signals were brought to the manipulator via a 2 m cable. This meant that only the manipulator would be present along the RBC inside the enclosure. The use of servomotors meant that power could be cut off during measurements. This is due to the fact that servomotors remain stable and do not exert force on the switches when power is cut off.

3.2 Electronic Controller

The main task of the electronic controller was the interpretation of control instructions received from the computer. These would be translated into control signals that would move the servomotors on the manipulator. A means of disconnecting power to the servomotors needed to be incorporated into the controller. In this way, no electric signals would be present from the servomotors during measurements.

The functional block diagram of the controller is shown in Fig. 3. The controller was designed around an 8-bit microcontroller. An Atmel mega8535 running at 8 MHz was used for this task. It provided enough I/O ports for the servo and power signals and computer interfacing. The microcontroller was interfaced to the computer using a RS-232 (COM) interface. Eight servo-control signals were generated by the microcontroller and buffered at the output stage. This made the signals more resistant to interference, which could be picked up on the 2 m cable to the manipulator. Power to the controller was provided from a dual-output 5 V power supply. One output provided up to 5 A of current to satisfy the power needs of the servomotors (these servomotors can draw currents of 0.5 A each during movement). The second, less powerful output provided power for the microcontroller, ensuring that the power drain from the servomotors would not interfere with the microcontroller. A separate control signal from the microcontroller controlled a power relay to switch the power to the servomotors.

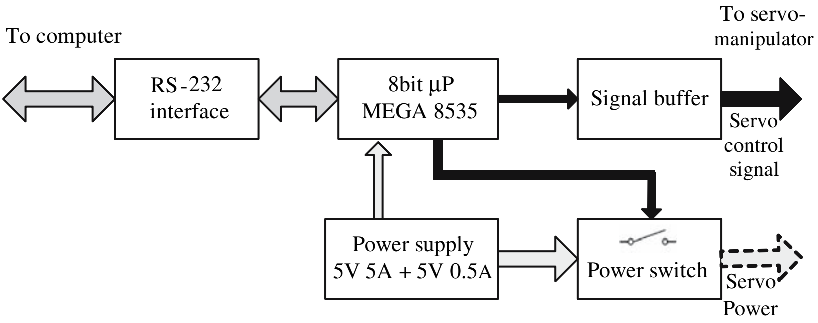


Fig. 3 Block diagram of electronic controller

For ease of assembly and repair, the controller was built on three printed circuit boards. These were the microcontroller board including the RS-232 interface, the power supply board, and the output board (this incorporated a signal buffer and the relay for the switching of manipulator power).

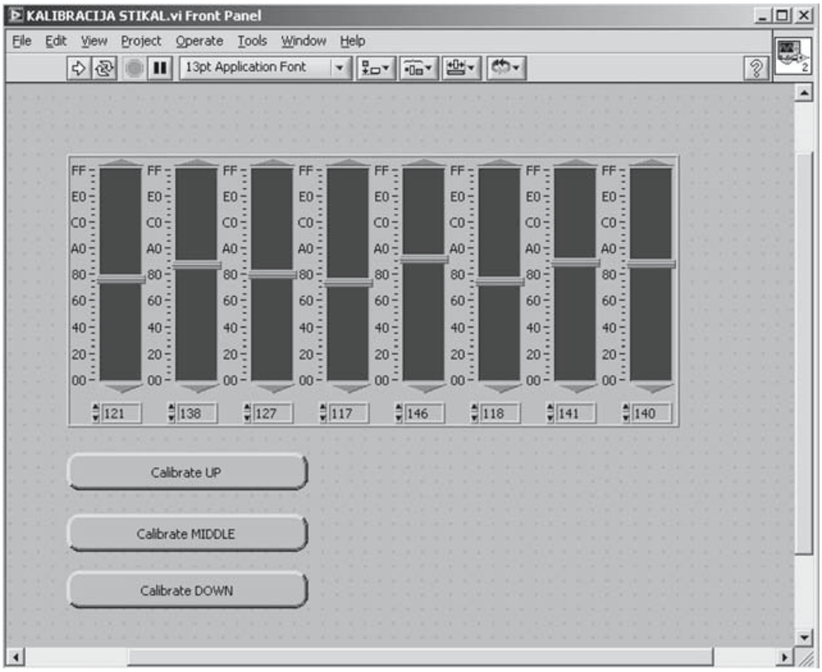
An important part of the controller was the control program running inside the microcontroller. The end positions of the servomotors were stored in the EEPROM memory of the microcontroller. The control program enabled these to be adjusted by instructions received from the computer. The servo signals were generated when control instructions were received from the computer. The control program enabled different levels of movement to be selected using various instructions. This means that a single servomotor could be moved, or several servomotors together, or even all motors could be moved to a particular combination of positions stored inside the microcontroller.

3.3 Computer Software

The automated RBC was designed to be controlled from a personal computer. This was done using purpose-specific software. The requirements for the software were that it must be able to control the automated RBC, acquire measurements from the resistance bridge, and save them to a file for later processing.

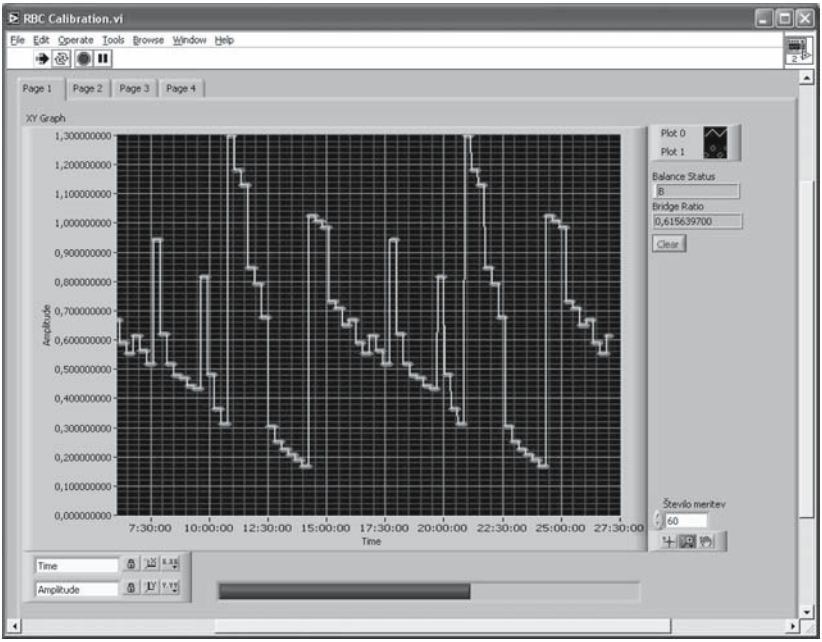
The software was created using LabVIEW. It consists of two modules, each accessible from its own user interface. The first part of the software controls the positions of the servomotors using scroll bars (Fig. 4). By moving the scroll bars, the servomotors on the manipulator are moved and move, in turn, the toggle switches on the RBC control panel. The RBC switches are moved to their upper, middle, and lower positions where they are set by pressing the "calibrate" buttons on the interface panel. The end positions are sent to the controller where they are stored in the EEPROM. This procedure configures the end positions of the RBC switches. The configuration of the switch positions needs to be done only when mounting the manipulator on the RBC.

After the configuration procedure is completed, measurements can be acquired using the second module of the software. The user interface is shown in Fig. 5. The user interface consists of four different screens that show the progress of the measure-



121 138 127 117 146 118 141 140

Fig. 4 User interface for configuration of servo-manipulator



Balance Status: B

Bridge Ratio: 0,615639700

Število meritev: 60

Fig. 5 User interface for control and data acquisition ments, including the measured values over time, as well as the mean values and the standard deviation of a particular measured combination. Readings are acquired from the resistance bridge via the GP-IB (IEEE-488) interface. The number of readings and the period between readings can be set. From the acquired readings, the first-half readings are discarded to avoid any effect from the settling time of the bridge. From the remaining readings, the mean value and standard deviation for a particular combination are calculated. These are shown in the console graphs and stored to a .txt file to be processed by the RBC software. Several measurement sets can be acquired successively.

4 Measurements

For the purpose of testing the automated RBC, several measurement sets were performed. These were carried out under different thermal conditions with manual or automatic operation. The effects of automating the RBC were tested, as were the improvements, if any, that could be gained by placing the RBC in a thermally isolated Styrofoam enclosure.

For the purpose of the experiment, the automated RBC was used to test ASL F900 and MI 6010T resistance bridges. Several measurements sets were taken with each of these bridges. The current in both cases was set to 2 mA, making the measurements comparable. For each measurement set, all 35 resistance ratios (combinations) were measured. For each of these combinations, 60 readings were taken. Readings were taken at 15 s intervals for the ASL F900 and 10 s intervals for the MI 6010T. This meant that a measurement set took 9 h for the ASL F900 and 6 h for the MI 6010T. From these readings, the software discarded the first 30 readings to avoid any transition effects on the bridge reading. From the remaining 30 readings, the mean value and standard deviation of a single RBC setting were calculated. These results were used by the resistance bridge calibrator software (v1.51 [6]) to calculate the non-linearity and associated standard deviation of the bridge and the recommended offset.

Measurements were performed under different thermal conditions. The first sets were switched manually and performed in normal laboratory conditions at a temperature of 23 °C and stability of ±1 °C. Later sets were performed with automatic switching of the RBC inside a Styrofoam enclosure. This environment provided a temperature stability of ±0.1 °C. The measurements were made by measuring the RBC against 100 Ω and 25 Ω standard resistors connected to the ASL F900 and MI 6010T, respectively. The standard resistors were in a temperature-controlled oil bath with a stability of ±0.002 °C.

The measurements are shown in Table 2. The first sets of measurements were made by manually switching the RBC under normal laboratory conditions. Later, the automated RBC was tested with the ASL F900 using a measuring current of 1 mA. The measurements performed in this manner show that automatic manipulation of the RBC does not affect the measurements. The subsequent measurements were all done using automatic manipulation of the RBC inside the Styrofoam enclosure. By comparing the measurements done with the RBC inside the enclosure to the ones done under normal laboratory conditions, it is clear that the standard deviation of the bridge is

Table 2 Results of measurements done with the ASL F900 and MI 6010T

Measurement setup Measurement set #	Calculated deviation (ppm)
Automatic, ASL F900, 1 mA, laboratory	
1	0.053
2	0.032
Manual, ASL F900, 2 mA, laboratory	
1	0.062
2	0.033
3	0.045
Automatic, ASL F900, 2 mA, Styrofoam enclosure	
1	0.025
2	0.024
3	0.030
4	0.025
Manual, MI 6010T, 2 mA, laboratory	
1	0.128
2	0.176
3	0.143
Automatic, MI 6010T, 2 mA, Styrofoam enclosure	
1	0.047
2	0.049
3	0.046
4	0.046
5	0.047
6	0.052

lower with the insulated enclosure. For the ASL bridge, this is below 0.03 ppm and is about 0.05 ppm for the MI bridge. Both of these values fall within the specifications of the respective bridges. It must be added that the combination with the value of 129.9 Ω is at the limit of the measuring range of the ASL bridge, and therefore is measured with higher uncertainty. By excluding this value, the standard deviation of the ASL bridge becomes approximately 0.02 ppm.

In previous experiments, little attention was paid to the reproducibility of results obtained with the RBC. This is mostly due to the time-consuming manual operation of the RBC. By looking at the first three measurement sets described in Table 2, it becomes clear that temperature stability plays a major role. When the RBC is placed in a thermally more stable environment, the associated standard deviations of the bridge became similar. With both bridges, only small differences were observed. This showed the reproducibility of the method and added credibility to the results.

5 Conclusion

The goal of this article was to present the improvements that can be made to an RBC in order to make it more practical when calibrating low-uncertainty resistance bridges. By automating the device and enclosing it in a thermally more stable environment, the temperature dependence has been minimized. Automation also means that an operator need not be present during the calibration process. This has made it possible for several measurement sets to be performed consecutively, enabling us to estimate repeatability and reproducibility of the bridge performance in a more practical way.

Further improvement could be made by constructing a thermally stabilized enclosure for the RBC. This could be done by heating the existing enclosure to several °C above the surrounding temperature. With careful attention paid to the control of this temperature, the stability of the enclosure could approach ±0.01 °C. However, the question remains whether any benefit would be gained, since the RBC performance is already at the design limit (uncertainty of several parts in 10^8).

Future work on the RBC would involve the construction of a fully automated unit. This could be done by using latching relays instead of toggle switches. However, new problems may arise since latching relays possess higher contact resistance than toggle switches.

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