Continual One Point Auto-Calibration Technique in Simple Sensor-Microcontroller Interface

Zivko Kokolanski, Cvetan Gavrovski and Vladimir Dimcev

***Abstract*—The modulating resistive and capacitive sensors can be directly interfaced with a microcontroller. The sensor and one reference element (resistor or a capacitor) form a RC circuit that is exited and measured with the microcontroller. In this way the modulating sensor acts like a quasi-digital and allows direct sensor to microcontroller interface without use of a classical A/D converter. There are several known direct sensor to microcontroller calibration techniques. One of the simplest is the one point calibration technique. This calibration technique has nonlinear transfer characteristics and for wide measurement range several calibration resistors have to be employed. The continual one point auto-calibration technique expands the measurement range without the use of additional calibration resistors and in the same time keeps the simplicity of the measurement. In this paper the continual one point auto calibration technique is presented.**

***Index Terms*—Modulating sensors, Continual one point auto calibration, Microcontroller interface.**

I. INTRODUCTION

DIRECT sensor to microcontroller interface is an alternative approach for conditioning of modulating resistive and capacitive sensors without the use of A/D converter and signal conditioning circuits. The microcontroller uses the built in timer to measure the charging or discharging time of RC circuit formed by the sensor and reference resistor/capacitor. In this way, the microcontroller and the sensor form a relaxation oscillator causing the modulating sensor to act like a quasi-digital sensor. Hence, this approach is attractive to use for a low cost and small size applications.

Two measurement methods are proposed: a method based on charging [1] or discharging time [2] of the RC circuit. The two methods differentiate by the crossing of the upper or the lower threshold voltage (V_{th} or V_{tl}) of the Schmitt Trigger port to create an interrupt. The method based on discharging time gives better measurement results [3] because the lower threshold voltage V_{tl} has better rejection of the power supply interference and because usually the microcontroller ports can drain more current than they can generate. In this paper the analysis are restricted to the interfaces based on measurement of the discharging time but the same methodology can be applied to the interfaces based on measurement of the charging time. The most basic direct sensor-microcontroller interface can be realized by using two microcontroller pins, one output and one input pin (Fig. 1).

The measurement contains two phases: charging phase and discharging phase. The wave shape of the capacitor voltage in the two phases is shown in Fig. 2.

At the beginning the pin P_i is set as output with logical state "1" and the pin P_o is set as input (high impedance state). The capacitor charges through R_p to V_{dd} in an interval $t_1 \div t_2$. In the next step the pin P_o is set as output with logical state "0", the timer starts and the pin P_i is set to high impedance state. This time the capacitor discharges through R_x until the voltage reaches the lower threshold voltage V_{tl}. Crossing of the threshold voltage V_{tl} initiates interrupt that stops the timer. The time needed for the capacitor to discharge from V_{dd} to V_0 is expressed with the equation

$$t_x = (t_3 - t_2) = \tau \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right) \tag{1}$$

where $\tau = R_x C$ is the discharging time constant.

Having in mind that V_0, V_{dd}, V_{tl} and C are constant, from (1) can be seen that the time interval t_x is proportional to the measuring resistance R_x. This time interval (t_x) is measured with the built in timer in the microcontroller. The result of the time to digital conversion in clock cycles is

$$N = kR_x \tag{2}$$

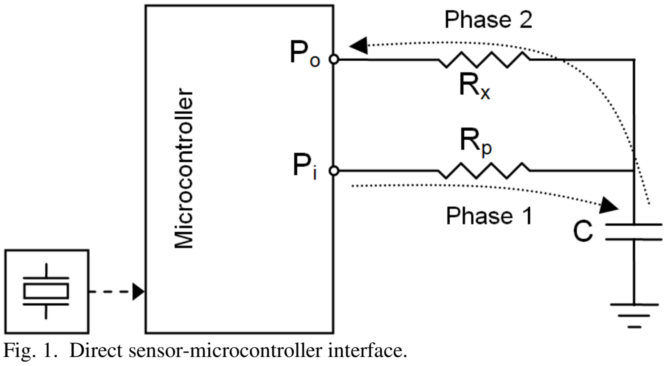

Fig. 1. Direct sensor-microcontroller interface.

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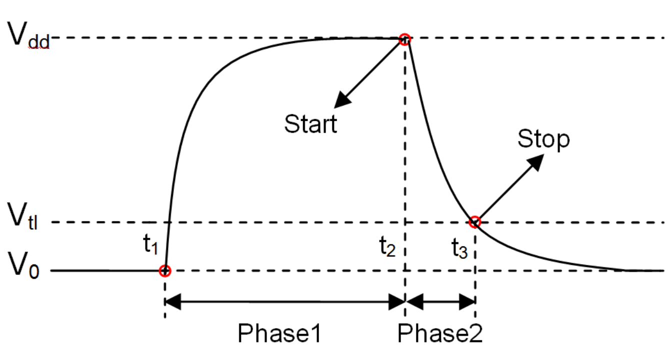

Fig. 2. Wave shape of the capacitor voltage in the two phases.

where k is constant dependent on V_0, V_{dd}, V_{tl}, C and the time base of the timer. In practice the input/output resistances and leakage currents of the microcontroller ports cause gain, offset and nonlinearity errors [4]. Moreover, the constant (k) in the equation (2) is not very stabile. Therefore, usually direct sensor to microcontroller interface is realized by using some calibration technique [5] that cancels the contribution of V_0, V_{dd},V_{tl} and C.

II. SINGLE POINT CALIBRATION TECHNIQUE

The simplified electrical circuit of the direct sensor to microcontroller interface by using single point calibration is shown in Fig. 3.

The measurement contains two phases: measurement of the unknown resistance R_x and measurement of the calibration resistance R_c. The wave shape of the capacitor voltage in the two phases is shown in Fig. 4.

The respective times needed to discharge the capacitor through R_x and R_c, t_x and t_c are

$$t_x = R_x C \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right), \text{ and} \tag{3}$$

$$t_c = R_c C \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right). \tag{4}$$

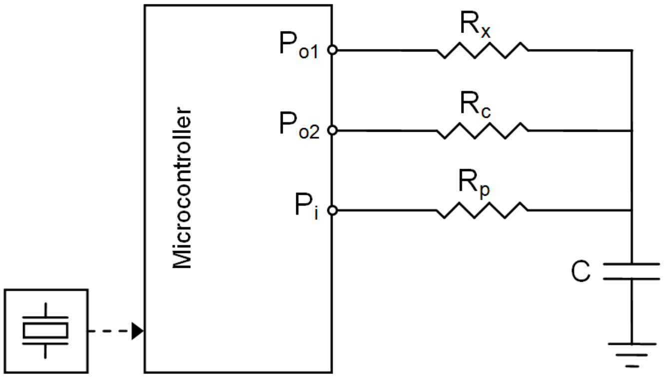

Fig. 3. Electrical circuit of direct sensor to microcontroller interface by using single point calibration.

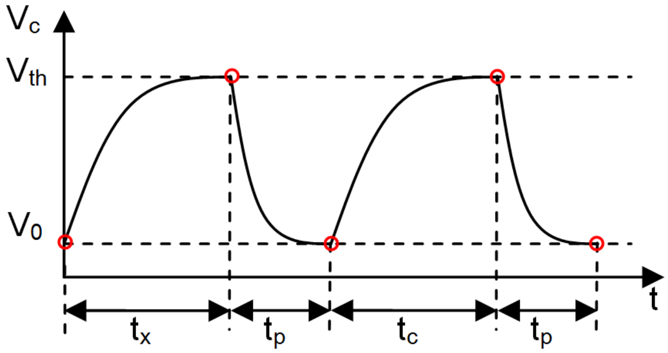

Fig. 4. Electrical circuit of direct sensor to microcontroller interface by using single point calibration.

Since the capacitance C and the parameters V_0, V_{dd} and V_{tl} are the same for both measurements, calculating the ratio of t_x and t_c cancels their contribution. The measurement result is

$$R^*_x = \frac{t_x}{t_c} R_c \cdot \tag{5}$$

The one point calibration technique of this kind is analyzed in [1,2], where a resolution from 6 to 10 bits is achieved. The resolution is limited by the input and output resistances and leakage currents of the microcontroller ports. These limiting factors are considered in [4] and the dependence of the measured value and the estimate of the actual sensor resistance is expressed with

$$R_x^* = (R_{o1} + R_x)k \frac{\ln A}{\ln B}\left[\frac{1}{1 + \dfrac{R_x}{R_{o1} + R_{e1}}}\right] \tag{6}$$

where R_{o1} is the output resistance of the port P_{o1}, and A, B and k are constants dependent on the resistances and the leakage currents of the microcontroller ports. From (6) it can be seen that the input and output resistances and leakage currents cause offset, gain and nonlinearity errors. If the ports P_{o1} and P_{o2} were identical these errors would have being zero for R_x=R_c. This leads to conclusion that the value of the calibration resistor should be chosen to be R_c=R_x in the middle of the measurement range.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experiments were realized by using microcontroller PIC16F877 [6] with clock frequency of 4 MHz, effective instruction cycle speed of 1 MHz and period of 1μs. The falling edge of the input signal was registered with the RB0/INT Smith Trigger pin. This pin initiates interrupt that stops the 16-bit timer - Timer1. To reduce the noise effects affecting the voltage comparison between V_c and V_{tl} several design solutions were applied:

- Decupling capacitor of 100 nF was placed as close as possible to the microcontroller pins as recommended from the manufacturer
- The board ground plane was carefully designed for low electromagnetic interference
- Only the microcontroller was supplied from the power supply to eliminate other interference effects
- The microcontroller didn't execute any other task while waiting for the interrupt.

The measurements were performed by using a variable resistor in the range from 1000 to 3000 ohms. These values are typical for resistive temperature sensors. The resistance of the sensor was measured with measurement instrument with maximal error of ±0.1% + 5. According to (6), for minimal errors the calibration resistance was chosen to be 2000 ohms, which is in the middle of the measurement range. The absolute and the relative errors of the measurements are shown in Fig. 5 and Fig. 6.

From the results reported in Fig. 5 and Fig. 6 it can be seen that the static errors caused by the input and output resistances and leakage currents of the microcontroller ports are minimal in the middle of the measurement range. Having in mind (6) this completely confirms our expectations. However, the errors are maximal for the minimal value of the sensor resistance (≈23Ω or 2.3%). The results suggest that in this case a lower value for the calibration resistance have to be chosen in order to reduce the relative error for the whole measurement range. However, this approach cannot be generalized because according to (6) the errors are nonlinear and grater for lower values of the sensor resistance.

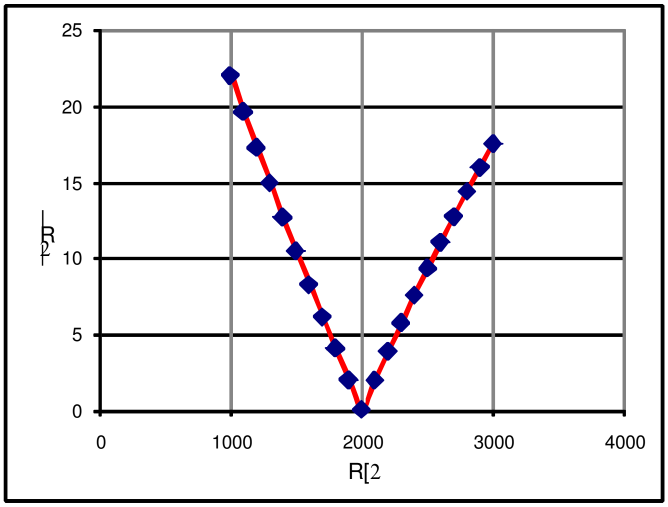

Fig. 5. Absolute errors of the measurements.

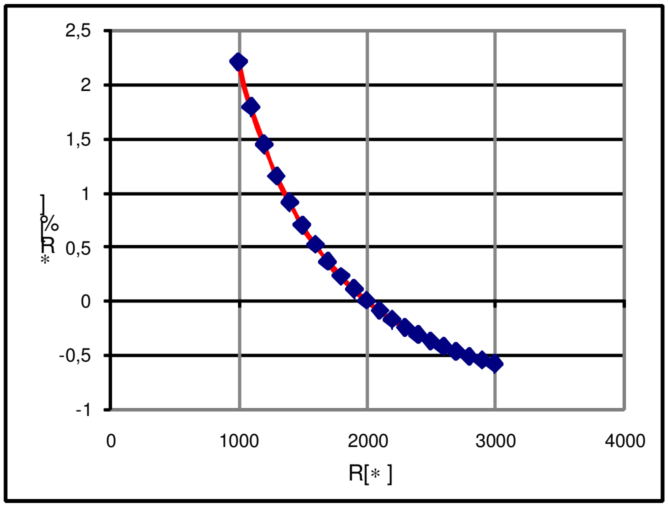

Fig. 6. Relative errors of the measurements.

The dependence of the measured value and the actual sensor resistance was approximated by using the least square method. The approximation with linear function is shown in Fig. 7.

The experimental results for the one point calibration method showed that the measurement range is limited by the maximal error. Therefore, for a given maximal error the measurement range must be divided into appropriate sub ranges. Each sub range must have its own calibration resistance in the middle of the range. This proportionally increases the used microcontroller pins and the number of calibration resistances. Hence, in some cases where the sensor resistance varies over wide dynamic range and where "high" measurement resolution must be achieved this approach tends to lose its economical justification.

IV. CONTINUAL ONE POINT AUTO-CALIBRATION TECHNIQUE

One of the disadvantages of the one point calibration technique applied in direct sensor to microcontroller interface is the limited measurement range. The measurement range is limited by the nonlinear dependence of the measured and the actual sensor resistance when approximated by a linear function. To overcome this problem, the measurement range must be divided into smaller segments and for each segment different calibration resistor have to be used. Consequently, the nonlinearity errors will be smaller than the half of the least significant bit for the desired resolution. Hence, this approach can be used for expanding the measurement range at the cost of additional calibration resistances and additional microcontroller pins.

The same benefit can be achieved when using the continual one point auto calibration technique but using significantly less microcontroller pins. This approach uses digital variable resistor that replaces a lot of calibration resistances and in the same time uses fixed number of microcontroller pins. Today, there are a lot of commercially available digital variable resistors with different characteristics. Most of them are capable to trim the resistance over at least 256 points. Such

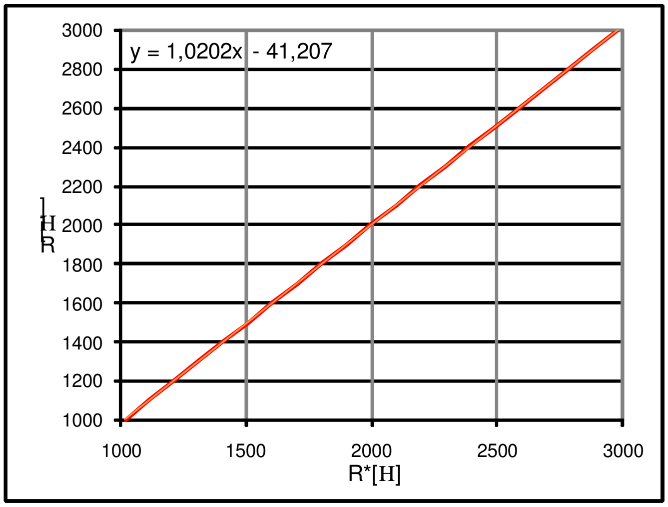

Fig. 7. Approximation by using least square method.

performances are good enough to achieve relatively high measurement resolution and wide measurement range when using the continual one point auto calibration technique. However, the values of the calibration resistances have to be accurate enough to maintain the relative uncertainty, otherwise the calibration resistances have to be measured with precise measurement instrumentation. The measured values are stored in the microcontroller EPROM in a form of lookup table.

The electrical scheme of the continual one point auto calibration technique is shown in Fig. 8.

The digital resistor in Fig. 8 is used as a calibration resistor with variable resistance in 2^n points, where n is the resolution of the digital resistor. Today, there are a lot of available commercial digital variable resistors with different resolutions and different range of values. In most of the cases the communication with the microcontroller is realized by using some serial communication interface such as SPI, RS232, I^2C.

The implementation of the one point auto calibration technique is performed by division of the measurement range into several sub ranges. The nonlinearity error of each sub range must be lower than half of the least significant bit for the desired resolution of the measurements. The condition that must be fulfilled for each sub range (reported in [7]) is

$$\frac{\Delta R_x}{2} < \frac{c - R_o}{1 - 2^{-(n+1)}} - c, R_o - \frac{\Delta R_x}{2} < R_x < R_o + \frac{\Delta R_x}{2} \qquad (7)$$

where the constant c depends of the input and output resistances and leakage currents of the microcontroller ports and the calibration resistance value. The graphical representation of the expanded measurement range by using the continual one point auto calibration technique is shown in Fig. 9.

The continual one point auto calibration technique is preformed in three phases: rough measurement of the unknown resistance, choice of optimal calibration resistance and precise measurement of the sensor resistance.

In the first phase, the value of the calibration resistance is chosen in the middle of the measurement range, that is $R_c=\Delta R_x/2$. In this way a rough measurement of the unknown resistance is preformed, and the optimal sub range is determined. In the second phase the digital resistor is set to a value in the middle of the chosen sub range. In the third phase a precise measurement and calculation of the sensor resistance is preformed.

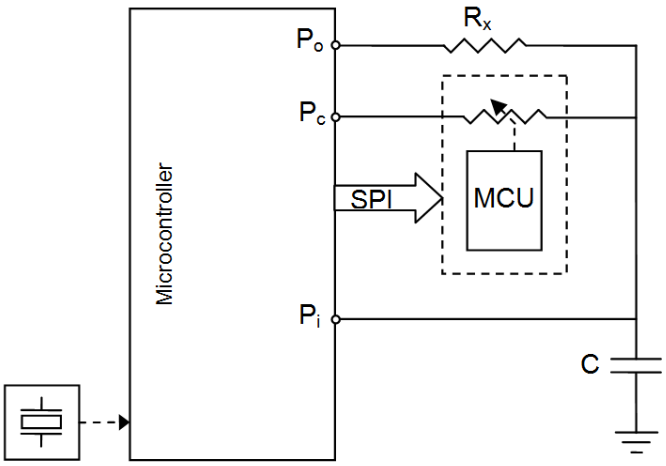

Fig. 8 Continual one point calibration technique.

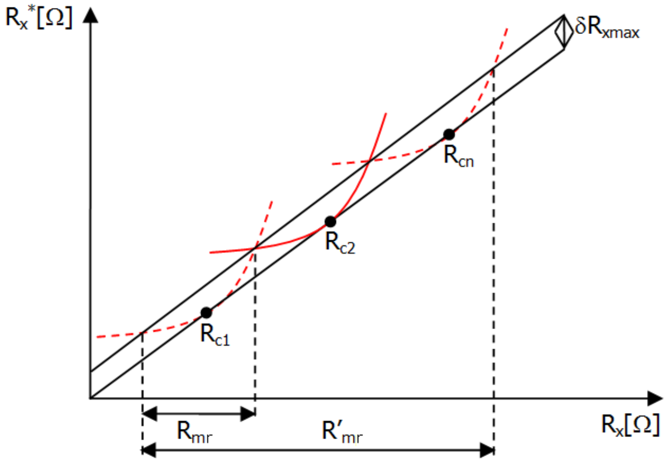

Fig. 9. Continual one point calibration technique.

From the graphic shown in Fig. 9 it can be seen that the measurement range is drastically expanded, and in the same time the maximal nonlinearity error remains within the predefined limits. However, the implementation of this calibration technique requires more complex algorithm compared to the one point calibration. This slightly decreases the speed of the measurements (1/3 slower than the one point calibration technique).

V. IMPLEMENTATION RESULTS AND DISCUSSION

The experiments were realized by using the same microcontroller as in section IV, PIC16F877 with clock frequency of 4 MHz. The falling edge of the input signal was registered with the RB0/INT Smith Trigger pin. The noise effects affecting the voltage comparison between V_c and V_{tl} was reduced by applying the same design solution as in section IV.

The measurements were performed by using a multi-turn variable resistor in the range from 1kΩ to 100kΩ with a step of 1kΩ. The resistance was measured by using the four wire method, with instrument with maximal error of ±0.1% + 5.

Having in mind the equation (6), if we use only one calibration resistor in the middle of the 100kΩ measurement range, according the theoretical calculations the input/output resistances and leakage currents will produce a static errors less than 6% at the beginning and at the end of the measurement range. Hence, if we divide the measurement range, for example on ten sub-ranges then the relative error is expected to be decreased ten times. To test these analyses the one point auto-calibration technique was implemented by using ten calibration resistors. According to (6), for minimal errors the values of the calibration resistances was chosen in the middle of each sub-range.

The calibration resistances were obtained by using a digital variable resistor, type MCP41100 [8]. This device is a 256-position digital potentiometer with maximal value of 100kΩ. The calibration resistances were set as close as possible to the middle of the predefined sub-ranges and were measured with a measuring instrument with maximal error of ±0.1% + 5. The measured values were stored in the microcontroller EPROM forming a lookup table. The ordinal number of the sub-range was used as a pointer in the lookup table.

The MCP41100 communicates with the microcontroller by using the SPI serial interface. The communication was realized through the RC0 microcontroller pin. To reduce the noise effects, the communication between the microcontroller and MCP41100 was disabled during the measurement phases.

The practical experiments were performed twice, when using continual one point auto calibration and when using one point calibration. Each measurement was performed ten times over the whole measurement range of 100kΩ with a step of 1kΩ. The absolute and relative errors of the measurements when using continual one point auto calibration are shown in Fig. 10 and Fig. 11 and when using one point calibration in Fig. 12 and Fig. 13. In Fig. 14 a comparison of the measured and the actual sensor resistance when using the continual one point auto calibration technique (green line) and the one point calibration (red line) is given.

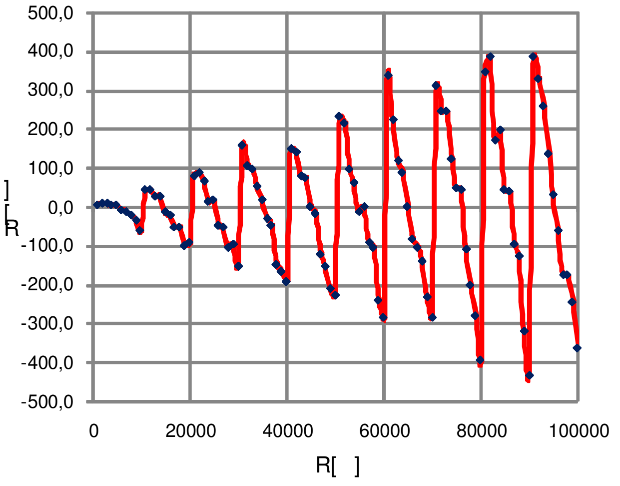

Fig. 10. Absolute errors of the continual one point auto calibration technique.

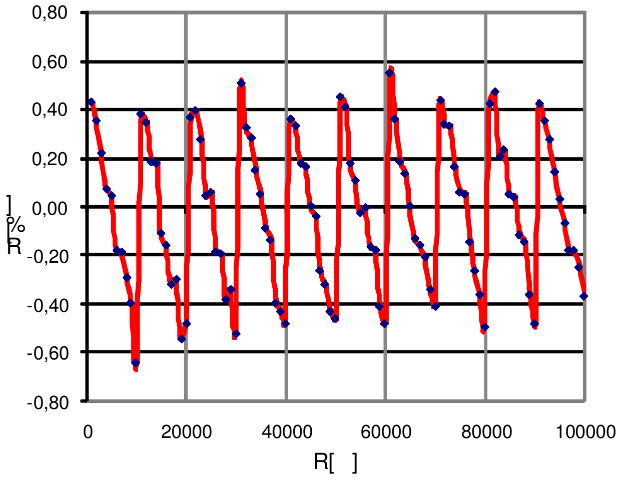

Fig. 11. Relative errors of the continual one point auto calibration technique.

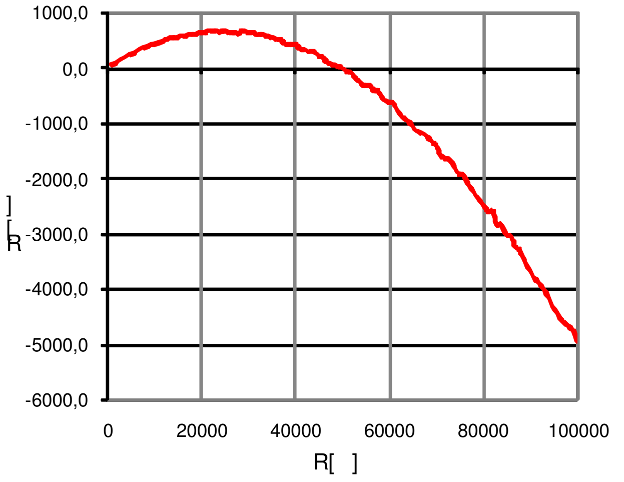

Fig. 12 Absolute errors of the one point calibration technique.

From the results reported in Fig. 10÷Fig. 13 it can be seen that the static errors caused by the input and output resistances and leakage currents of the microcontroller ports are minimal in the middle of the measurement range or sub-range. Having in mind the equation (6) this again confirms our expectations. However, the errors are maximal near the borders of each sub-range and they are less than 1.3% when using the continual one point auto calibration technique. The relative errors when using one point calibration are less than 11%. It can be seen that the continual one point auto calibration technique reduces the static errors nearly ten times comparing to the one point calibration. The relative error reduction factor is proportional to the number of the calibration resistors used. The digital variable resistor MCP41100 can trim the calibration resistance over 256 discreet points. Thus, if all the resistances are used than the relative errors caused by the input and output resistances and leakage currents will be reduced nearly 256 times comparing to the one point calibration technique. However, there is no meaning of using such large number of calibration resistances because in that case the quantization errors and noise interference are much more dominant in the total measurement uncertainty. Moreover, using a large number of calibration resistances complicates the implementation algorithm of this technique and reduces the speed of the measurement. The optimal number of calibration resistances can be calculated by using the relation (7), where the relative errors caused by the input and output resistances and leakage currents should be lower than half of the least significant bit for the desired resolution. For example, if we want to achieve 10 bit resolution over 100kΩ measurement range, then the relative error should be lower than 0.05%. This can be achieved by using 104 calibration resistors. For this particular example, if the microcontroller PIC16F877 is used,

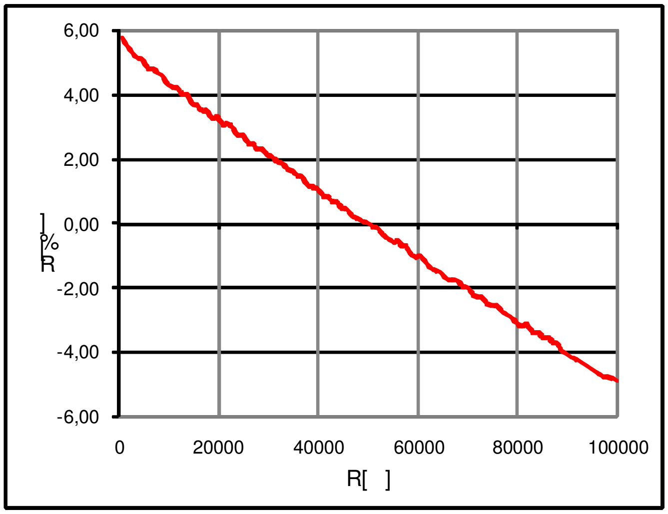

Fig. 13. Relative errors of the one point calibration technique.

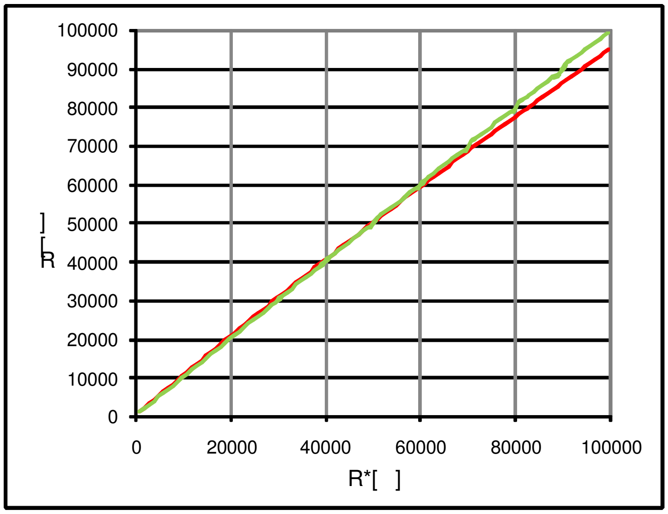

Fig. 14. Comparison of the measurement results.

the value of the constant c in (7) for the second sub-range would be c=2541.

VI. CONCLUSION

The paper is organized in five sections. In the first section a brief introduction of the direct sensor-microcontroller interface is presented. The second section elaborates the one point calibration technique. The implementation of this calibration technique is experimentally verified by using the PIC 16F877 microcontroller and the results are reported in section three. In the next two chapters the continual one point auto-calibration technique and its implementation by using the PIC 16F877 microcontroller and the digital variable resistor MCP41100 is presented.

The one point calibration in direct sensor to microcontroller interface is very simple and effective calibration technique. However, the input and output resistance and leakage currents cause gain, offset and nonlinearity errors. Thus, the measurement range is limited by the maximal nonlinearity error. For a defined maximal error, the measurement range must be divided into several sub ranges. The disadvantage of this approach is that it uses additional calibration resistances and microcontroller pins.

The same benefit can be achieved when using the continual one point auto calibration technique but using significantly less microcontroller pins. This technique is characterized by a very simple implementation and usage of little microcontroller pins. However, the use of digital variable resistor increases the cost of the measurement system and slightly decreases the speed of the measurements (by 1/3) because of more complex implementation algorithms. Therefore, this technique is reasonable to apply in cases where a higher measurement resolution and wider measurement range needs to be achieved.

In this paper a directions and conditions that must be fulfilled for implementation of the continual one point auto calibration technique were presented.

In the paper, practical experiments when using both calibration techniques were performed. The measurements were realized by using a multi-turn variable resistor in the range from 1kΩ to 100kΩ with a step of 1kΩ. For implementation of the continual one point auto calibration technique a digital variable resistor MCP41100 was used.

The measurement errors when using the one point auto calibration technique were maximal near the borders of each sub-range (around 1.3%). When the one point calibration was used, the measurement errors were around 11%. It can be seen that the continual one point auto calibration technique reduced the nonlinearity errors nearly ten times comparing to the one point calibration. The relative error reduction factor was proportional to the number of the calibration resistors used.

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