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Improving the Single Point Calibration Technique in Direct Sensor-to-Microcontroller Interface

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Abstract- An improved single point calibration technique applied on direct sensor-to-microcontroller interface is presented. The improvements are in reducing the systematic errors in a given measurement range by increasing the transfer characteristics nonlinearity. The experimental results showed that this approach reduces the overall systematic errors of the measurements more than twice and considerably increases the measurement speed. In the paper, theoretical and experimental analyses are performed for resistive modulating sensors.

I. Introduction

Direct sensor-to-microcontroller interface is a simple and cost-effective way for signal conditioning of passive modulating sensors e.g. resistive and capacitive. Depending on the type of sensor used, the sensor and one reference element (resistor or capacitor) form RC network which is sequentially charged and discharged by the digital input/output ports of a microcontroller. The built in timer in the microcontroller measures the charging or discharging time of the RC network, which, in general, is proportional to the measured physical quantity. In this way, the sensor is directly connected to the microcontroller without any component between and without Analog to Digital (AD) converter. Those features make this kind of sensor interfaces attractive for low cost and miniature measurement system solutions [1], [2].
Two measurement methods are proposed: a method based on charging or discharging time 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 Smith 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 sink more current than they can source. 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.

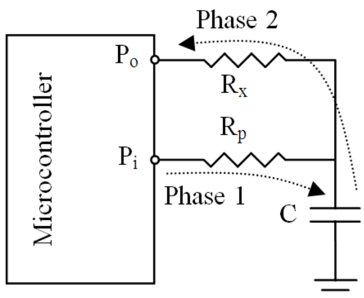

Figure 1. Direct sensor–microcontroller interface based on measurement of discharging time

At the beginning the pin P_i is set as output with logical state “1” and the pin P_0 is set as input (high impedance state). The capacitor charges through R_p to V_{dd} in a period t_1-t_2. In the next step the pin P_0 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:

$$T_x = R_x C \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right) \quad (1)$$

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. The time interval (T_x) is measured with the built in timer in the microcontroller. The result of the time to digital conversion can be expressed as:

$$N = kR_x \qquad (2)$$

where k is constant dependent on V_0, V_{dd}, V_{tl}, C and the time base of the timer. In practice, the constant (k) in (2) is not very stabile. Therefore, usually direct sensor-to-microcontroller interface is realized by using some calibration technique [3], [4], [5] that cancels the contribution of V_0, V_{dd}, V_{tl} and C.

II. Calibration techniques in direct sensor-to-microcontroller interface

Measuring the charging or discharging time interval of RC network with a digital input port is affected by several unstable parameters: the lower V_{tl} or higher V_{th} threshold voltage, the reference capacitor/resistor and the digital output “hi” and “low” voltages. These effects can be reduced by using some calibration technique which yields measurement result which depends on one or two calibration components rather than on the parameters mentioned above. In the literature, three calibration techniques are proposed: single point calibration [4]; two point calibration [4]; and the three signals method [3], [5]. Each of these calibration techniques has its own advantages in terms of simplicity, accuracy, cost and speed. The basic principles of the single point calibration, two point calibration and the three signals method for resistive modulating sensors are given in Fig. 2.a, Fig. 2.b and Fig. 2.c respectively.

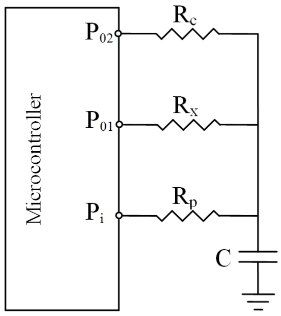

Figure 2.a Single point calibration

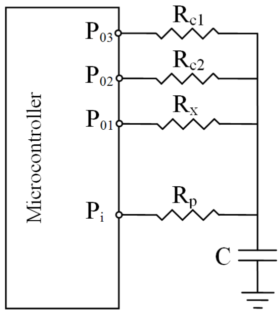

Figure 2.b Two point calibration

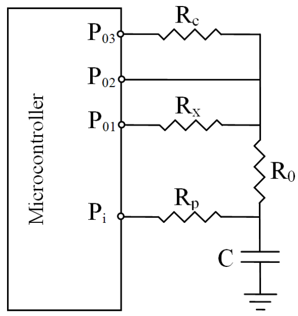

Figure 2.c Three signals method

The single point is the simplest calibration technique containing only one calibration resistor R_c (Fig.2.a). The measurement is performed in two phases: measurement of the sensor resistance R_x, and measurement of the calibration resistance R_c. Each phase contains two sub-phases: charging sub-phase through R_p (protection resistor) and discharging sub-phase trough R_x or R_c. The discharging period through the sensor is given with (1), and the discharging period through the calibration resistance R_c is:

$$T_{c1} = R_c C \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right) \qquad (3)$$

By dividing (1) and (3) we express the measured sensor resistance as:

$$R_{x1p} = \frac{T_x}{T_c} R_c \qquad (4)$$

Comparing the equations (1) and (4) it can be seen that in the second case the sensor resistance depends on the measured time intervals and a stable calibration resistor and not on the parameters such as C, V_0, V_{dd}, V_{tl}. In [4] it is stated that the overall absolute error of the measurements is minimal if R_c is in the middle of the measurement range.

The two point calibration uses two calibration resistors: R_{c1} and R_{c2}. Therefore, the measurement is performed in three phases: measurement of the sensor resistance R_x and measurement of the calibration resistances R_{c1} and R_{c2}. In two point calibration, the sensor resistance is calculated as a two point line fit as follows:

$$R_{x2p} = \frac{T_x - T_{c2}}{T_{c1} - T_{c2}}\left(R_{c1} - R_{c2}\right) + R_{c2} \qquad (5)$$

As with the single point calibration, the measured sensor resistance (5) is not affected by variation of the capacitance value C as well as by variations of the voltages V_0, V_{dd}, V_{tl}. However, this time we have to know the values of two calibration resistors, R_{c1} and R_{c2} in (5) rather than one, R_c in (4).

Three signals method (Fig. 2.c) is a special case of two point calibration where R_{c2}=0. Hence, the equation (5) becomes:

$$R_{x3sm} = \frac{T_x - T_{c2}}{T_{c1} - T_{c2}} R_c \qquad (6)$$

The resistor R_0 in Fig. 2.c is used to limit the discharge current of the microcontroller port P_{02}.

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III. Comparison of the calibration techniques in terms of measuring speed

The waveshape of the capacitor voltage in direct sensor to microcontroller interface with two point calibration is given in Fig. 3, whereas the waveshapes of the single point calibration and the three signal method can be seen as a special case of two point calibration.

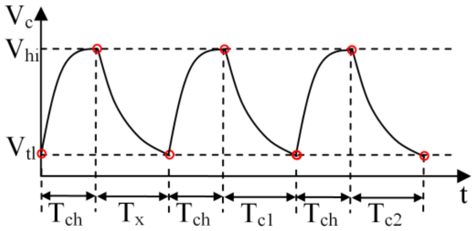

Figure 3. Capacitor voltage waveshape during two point calibration in direct sensor to microcontroller interface

The time needed to perform one measurement is:

$$T = 3T_{ch} + T_x + T_{c1} + T_{c2} \quad (7)$$

The charging interval time T_{ch} is:

$$T_{ch} = k_1 R_p C \quad (8)$$

where, usually the constant k_1=7 to 9. For single point calibration, by replacing (1), (3) and (8) in (7), and considering T_{c2}=0, the time period of one measurement is:

$$T_{1pc} = 2k_1 R_p + k_2 (2R_{x\min} + 3\Delta R_x / 2) \quad (9)$$

where R_{xmin} is the minimal sensor resistance, ΔR_x is the measurement range and the constant k is defined in (2). Similarly, the time needed to perform one measurement for two point calibration is:

$$T_{2pc} = 3k_1 R_p + k(3R_{x\min} + 2\Delta R_x), \quad (10)$$

and for the three signals method is:

$$T_{3sm} = 3k_1 R_p + k(2R_{x\min} + 2\Delta R_x + 3R_0). \quad (11)$$

where R_0 is a shortcut protection resistor. If we compare (9), (10) and (11), it can be seen that the time needed to perform one measurement is shortest for single point calibration. Hence, according [6], for a given time base and given resolution, the single point calibration provides fastest measurements. Therefore, despite the worse performances in terms of accuracy comparing to the two point calibration and the three signals method, the single point calibration can be still useful in a cases where simplicity, cost and speed are of utmost importance.

III. Improved single point calibration

The single point calibration is theoretically and experimentally analyzed in [4] where it is shown that the measurements are affected by offset, gain and nonlinearity errors. Moreover, the output resistances of the microcontroller ports introduce the offset and the input resistances and leakage currents introduce the gain and nonlinearity errors. These errors decrease as the sensor resistance gets closer to the calibration resistance and are minimal for R_x=R_c. Therefore, the overall absolute error of the measurements is minimal if R_c is in the middle of the measurement range. In this paper, we propose selecting calibration resistance R_c at 15% of the measurement range, and artificially increase the nonlinearity of the transfer characteristics so it crosses the ideal transfer characteristics at 0.85% of the measurement range. In this way the single point calibration acts as a two point calibration with increased nonlinearity. The proposed modified single point calibration (MSPC) technique and its theoretical model are given in Fig.4.a and Fig.4.b respectively.

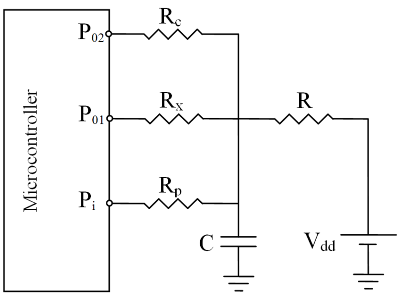

Figure 4.a Improved single point calibration

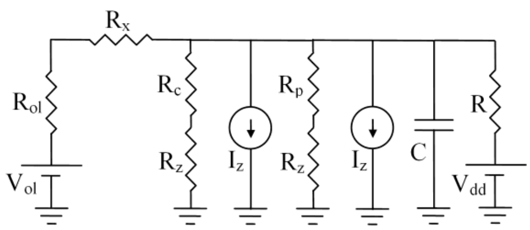

Figure 4.b Theoretical model of the improved single point calibration technique

The task is to determine the value of the resistor R in Fig. 4, at witch, the absolute errors for the minimal and the maximal sensor resistance are equal. According to [7], this will be fulfilled when the second intersection point of the actual and the ideal transfer characteristic is around $0.85\Delta R_x$. When these criteria are met, we expect that the overall absolute error of the modified single point calibration will be lower than that of the single point calibration.

The equivalent circuit model of the modified single point calibration when the capacitor discharges through the sensor R_x is represented similarly as in [4] and is given in Fig. 4.b. The output port P_{01} is represented by a voltage source V_{ol} and a finite output resistance R_{ol}. Since the microcontroller manufacturers doesn't specify the input resistance and leakage current of each microcontroller port separately, the ports P_{02} and P_i are modeled by equal input impedance R_z and leakage current I_z. The solution of the equivalent circuit is performed similarly as in [4]:

$$R_x^{\ *} = \frac{R_{E1}}{R_{E2}} R_c \frac{\ln\left(\dfrac{V_{oh} - V_c^{'}(\infty)}{V_{tl} - V_c^{'}(\infty)}\right)}{\ln\left(\dfrac{V_{oh} - V_c^{''}(\infty)}{V_{tl} - V_c^{''}(\infty)}\right)}, \tag{12}$$

where:

$$R_{E1} = \frac{R(R_x + R_{0l})(R_c + R_z)(R_p + R_z)}{R + R_x + R_{0l} + R_c + R_p + 2R_z}, \tag{13}$$

$$R_{E2} = \frac{R(R_c + R_{0l})(R_x + R_z)(R_p + R_z)}{R + R_x + R_{0l} + R_c + R_p + 2R_z}. \tag{14}$$

To determine the value of R from we have to find the roots of (12) when $R_x^*=R_x$ and to place the highest root at $0.85\Delta R_x$ as suggested by [7]. We propose the algorithm given in Fig. 5.

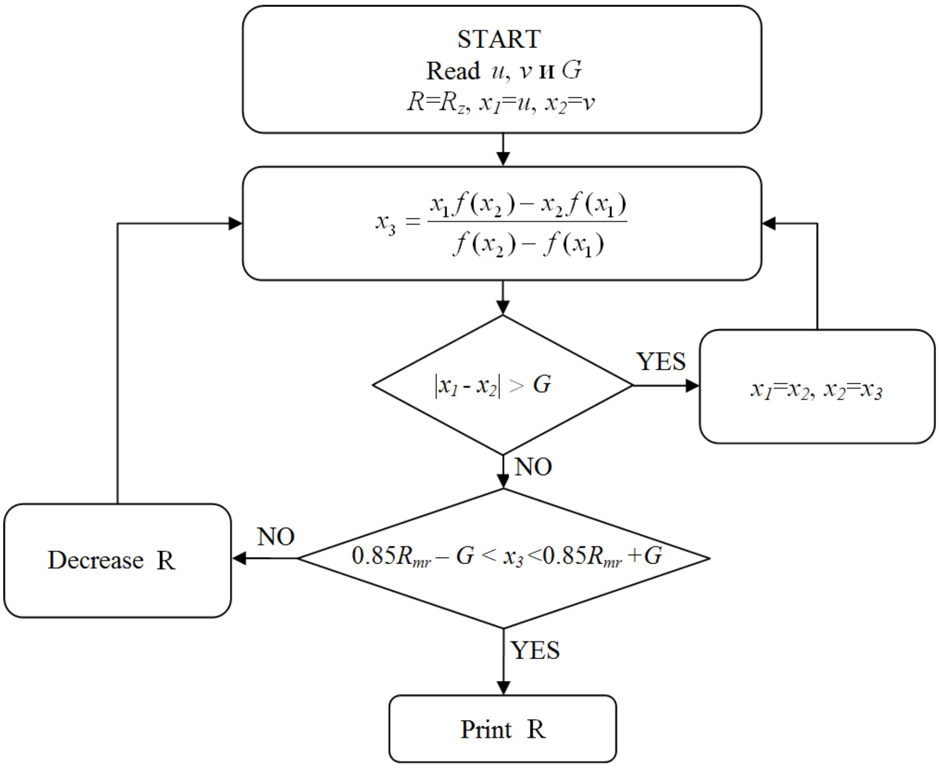

Figure 5. Modified Regula Flasi method for determination of the value of R

We assume that equation (12) is a continuous and monotonous function with root R_{x2} in $[\Delta R_x/2, R_{xmax}]$. The parameters u and v have values near to R_{x2}. However, the second root of (12) doesn't have to be in the interval $[u,v]$. Under these conditions we apply the algorithm given in Fig. 5, which is a modified Regula Falsi method. The maximal deviation G of the calculated root R_{x2}^* can be defined as a fraction of the resolution (in ohms) [6] of the measurements, for example G < 1/2 LSB (Least Significant Bit).

IV. Experimental results

The transfer characteristic of the improved single point calibration was measured in the range typical for PT1000 resistive temperature sensors (R_{xmin}=600 Ω to R_{xmax}=3500 Ω) and was compared to the results reported in [4]. The calibration resistor for MSPC is R_c=1035 Ω, and by rounding to the nearest standard value we have used a resistor with a measured value 996.6 Ω ±0.1 Ω. The calibration resistor for SPC was 1991.3 Ω ±0.2 Ω, which is near the middle of the measurement range. For resolution of 10 bits, the maximal deviation of the calculated root of (12) is G=1,4 Ω. The parameters needed for calculation of (12) were obtained from the microcontroller PIC16F877 datasheets. When these criteria were applied to the algorithm given in Fig. 5, the value of R was 219.1 kΩ. Hence, we have used a resistor from the E24 standard series with nominal value 220 kΩ to implement the MSPC. The measured and the theoretical systematic errors of the SPC and MSPC are given in Fig. 6. The sensor resistance was obtained from Fluke 5500A calibrator with absolute uncertainty ±0.06 Ω.

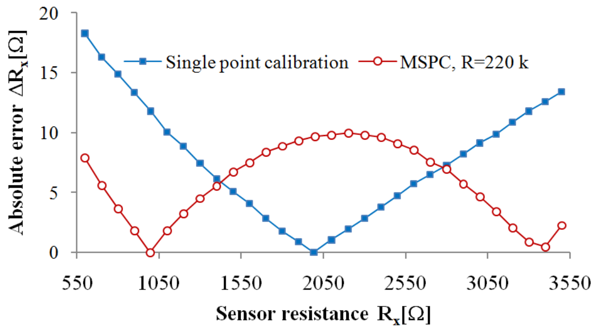

Figure 6. Absolute error for the improved (circles) and standard (squares) single point calibration

As expected, the absolute errors of the single point calibration were minimal near the calibration resistor value. The implementation of the MSPC with R=220 kΩ reduced the absolute errors nearly twice comparing to the SPC and nearly four times comparing to the SPC implementation in [4]. However, the errors at R_{xmin} were higher than those at R_{xmax}. This is due to the high tolerances of the microcontroller parameters. For optimal implementation of the modified single point calibration experimental determination of the microcontroller parameters is necessary. Alternative benefit achieved by MSPC is increasing the measuring speed. The improvements in speed is due to the reduced value of the calibration resistor which decreases the measuring interval given with (9).

V. Conclusions

A direct sensor-to-microcontroller interface with improved accuracy is presented. The sensor interface modifies the single point calibration by adding one more external resistor. In such way reduction of the overall systematic errors is achieved. In the paper an algorithm for determination of the value of the external resistor by iterative numerical calculations is proposed. When analyzing the measurement range typical for PT1000 resistive temperature sensors, MSPC reduced the systematic errors more than twice comparing to the SPC and to the results reported in other work. The experimental results showed that precise determination of the microcontroller parameters is essential for optimal implementation of the MSPC.
Another benefit of using the modified single point calibration is increased measurement speed. Even in cases where measurement speed is not critical, the ability to perform faster measurements can be used to perform averaging and to increase the resolution of the measurements.

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