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Comparative Analyzis of Callibration Performances in a Simpe Interface for Passive Sensors

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Abstract—**A comparative analysis of the calibration performances in a simple sensor to microcontroller interface is presented. Three calibration techniques are analyzed: single point calibration, two point calibration and three signals method. For each calibration technique several comparison aspects are taken into account: accuracy, sensitivity, resolution, speed, complexity, resources and cost. It has being shown that, in particular cases, different calibration technique is more suitable and takes precedence over the others. This paper gives directions of how to recognize and use the advantages of a particular calibration technique.**

Keywords: passive sensor interface, calibration, microcontroller

I. INTRODUCTION

Direct sensor-microcontroller interface is an alternative approach for conditioning of modulating resistive and capacitive sensors without the use of an Analog to Digital (AD) converter. 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.

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 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. 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_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.

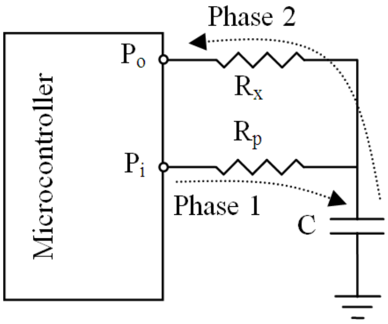

Figure 1. Direct sensor–microcontroller interface based on measurement of discharging time

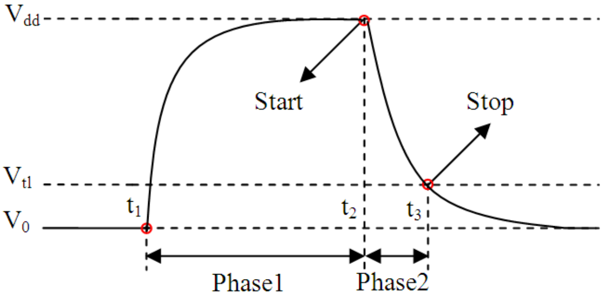

Figure 2. Wave shape of the capacitor voltage in the two measurement phases

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 can be expressed as:

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

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]. Additionally 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], [8], [9], [10] that cancels the contribution of V_0, V_{dd},V_{tl} and C.

II. SINGLE POINT CALIBRATION

The single point is the simplest calibration technique containing only one additional calibration resistor R_c comparing to the basic circuit given in Fig.1. The simplified representation of single point calibration in direct sensor to microcontroller is shown in Fig. 3.

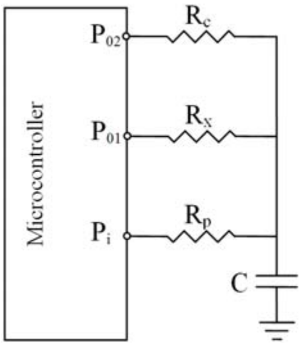

Figure 3. Signgle point callibration technique in direct sensor to microcontroller interface

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:

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

By dividing (1) and (3) we obtain:

$$\frac{t_x}{t_{c1}} = \frac{R_x C \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right)}{R_c C \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right)} = \frac{R_x}{R_{c1}} \tag{4}$$

Finally, from (4) we express the measured sensor resistance as:

$$R_{x1p} = \frac{t_x}{t_c} R_c \tag{5}$$

Comparing the equations (1) and (5) it can be seen that in the second case the sensor resistance depends on the measured time intervals and a stable calibration resistor rather than on the unstable parameters such as C, V_0, V_{dd}, V_{tl}.

III. TWO POINT CALIBRATION

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}. The implementation of the two point calibration is given in Fig. 4.

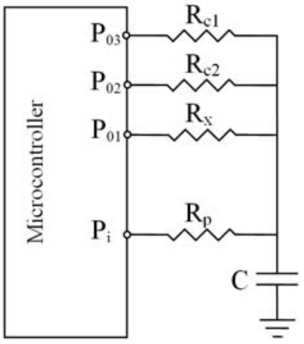

Figure 4. Two point callibration in direct sensor to microcontroller interface

In two point calibration, the sensor resistance is calculated as a two point line fit as follows:

$$\frac{t_x - t_{c2}}{t_{c1} - t_{c2}} = \frac{(R_x - R_{c2}) C \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right)}{(R_{c1} - R_{c2}) C \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right)} = \frac{(R_x - R_{c2})}{(R_{c1} - R_{c2})} \tag{6}$$

Expressing the sensor resistance from (6) results in:

$$R_{x2p} = \frac{t_x - t_{c2}}{t_{c1} - t_{c2}}(R_{c1} - R_{c2}) + R_{c2} \tag{7}$$

As with the single point calibration, the measured sensor resistance (7) 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 (7) rather than one, R_c in (5).

IV. THREE SIGNALS METHOD

Three signals method (fig. 5) is a special case of two point calibration where R_{c2}=0. Hence, the equation (7) becomes:

$$R_{x3sm} = \frac{t_x - t_{c2}}{t_{c1} - t_{c2}} R_{c1} \tag{8}$$

The resistor R_0 in Fig.5 is used to limit the discharge current of the microcontroller port P_{02}.

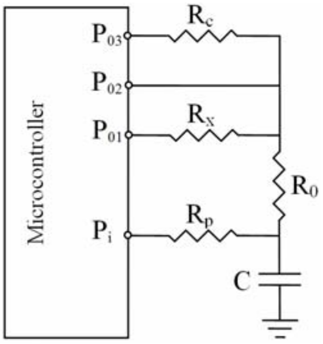

Figure 5. Three signals method in direct sensor to microcontroller interface

V. PERFORMANCE ANALYSIS

A. Accuracy

All calibration techniques described in the previous chapters introduce systematic errors in a form of: gain, offset and nonlinearity [4], [5]. These errors come mainly from the input/output resistances and leakage currents of the microcontroller ports. Moreover, the offset component comes mainly from the output resistances of the microcontroller ports and the gain and nonlinearity errors come mainly from the input resistances and the leakage currents. However, the difference of (5), (7) and (8) lead to different performances of each calibration technique regarding the sources of errors mentioned above.

To evaluate the offset component of each calibration technique we define the output resistances of the digital ports as: R_{0x} for the port P_{01}; R_{0c2} for P_{02}; and R_{0c1} for P_{03}. These output resistances enlarge the discharging measuring intervals t_x, t_{c1} and t_{c2} in (5), (7) and (8) because they appear in a series with the measured resistances R_x, R_{c1} and R_{c2}. Therefore, we can divide the discharging intervals in two parts: part coming from the output resistance and part coming from the resistance being measured. Thus, the equation (5) of the single point calibration becomes:

$$R_{x1p} = \frac{t_{Rx}+t_{R0x}}{t_{Rc1}+t_{R0c1}}\left(R_c+R_{0c2}\right)-R_{0x}, \tag{9}$$

the equation (7) for the two point calibration is:

$$R_{x2p} = \frac{t_{Rx}+t_{R0x}-t_{Rc2}-t_{R0c2}}{t_{Rc1}+t_{R0c1}-t_{Rc2}-t_{R0c2}}\left(R_{c1}-R_{c2}\right)+R_{c2}, \tag{10}$$

and the equation (8) for the three signals method becomes:

$$R_{x3sm} = \frac{t_{Rx}+t_{R0x}-t_{Rc2}-t_{R0c2}}{t_{Rc1}+t_{R0c1}-t_{Rc2}-t_{R0c2}}\left(R_{c1}+R_{0c1}\right)-R_{0x} \tag{11}$$

If we analyze (9), the offset component will be zero only of $R_{x1p}=R_c$, and if the output ports are ideally matched i.e. $R_{0x}=R_{0c2}$. As far as the sensor resistance moves away from the calibration resistance, the offset component increases. Therefore, to achieve minimal overall absolute error of the measurements, the calibration resistance in single point calibration has to be in the middle of the measurement range.

In the two point calibration and the three signals method, the offset component in (10) and (11) is a quotient of the difference between the output port resistances. Therefore, if we have matched ports i.e. $R_{0x}=R_{0c1}= R_{0c2}$, the offset component will be zero regardless of the calibration resistors values. Moreover, even if the microcontroller ports are not ideally matched, the offset component in two point calibration and the three signals method will be by far lower than that of the single point calibration. However, for equal measurement range, the offset component of the single point calibration is greater for low resistance sensors (in the order of hundreds' ohms) and it decreases for sensors in the higher ohmic range (in the order of several tenths' kilo ohms).

The gain and nonlinearity errors of all described calibration techniques depend on the input resistances and leakage currents of the microcontroller ports [4]. This means that, the more microcontroller pins we use, the more gain and nonlinearity errors increase. This reasonably suggests that the single point calibration will have lower gain and nonlinearity errors. However, the offset component in single point calibration is so much higher than the gain and nonlinearity, that apart being better in linearity it will be always less accurate than the two point calibration and the three signals method.

In [6] it is proven that the overall absolute error of a systems with a quadratic response will be minimal if the intersection point with the ideal transfer characteristics is 15% and 85% of the measurement range. Hence, the calibration resistors of the two point calibration will be:

$$R_{c1} = R_{x\min}+0.85\Delta R_x; \qquad R_{c2} = R_{x\min}+0.15\Delta R_x, \tag{12}$$

where R_{xmin} is the minimal sensor resistance and ΔR_x is the measurement range. For the three signals method, we can select R_{c1} as in (12), but R_{c2}=0 as suggested with (8). Therefore, the three signals method disregards the rule for minimal absolute error given in [6] leading to the conclusion that it will have slightly greater gain and nonlinearity errors than the two point calibration.

B. Sensitivity

Sensitivity is a very important parameter of a measuring instrument since it describes the ability to detect small variations of the measuring quantity. In a direct sensor to microcontroller interface, we measure time. Hence, we define sensitivity as variations of time t_x with the sensor resistance R_x:

$$S = \frac{dt_x}{dR_x} \tag{13}$$

The discharging time interval for the single point and two point calibration is:

$$t_{x1p} = t_{x2p} = \left(R_x + R_{0x}\right)C\ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right), \tag{14}$$

and the discharging interval for three signals method is:

$$t_{x3sm} = \left(R_x + R_0 + R_{0x}\right)C\ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right) \tag{15}$$

Applying (13) in (14) and (15) results in:

$$S_{1p} = S_{2p} = S_{3sm} = C\ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right) = k \tag{16}$$

The equation (16) suggests that all calibration techniques have equal performances in terms of sensitivity. Moreover, the sensitivity is constant, and it depends on C, V_0, V_{dd} and V_{tl}.

C. Resolution

The resolution of time to digital conversion depends on the measured time interval (i.e. discharging time t_x) and the time base of the timer. Neither of those parameters depends on the calibration technique being used. Therefore, with respect to resolution, all calibration techniques have equal performances. However, increasing the sensitivity would also increase the resolution of the measurements. Hence, having in mind (16), one possibility to increase the sensitivity and resolution is to increase the capacitor value. The directions for defining optimal time constant that leads to highest effective number of resolution bits (ENOB) is given in [7].

D. Speed

The waveshape of the capacitor voltage in direct sensor to microcontroller interface with two point calibration is given in Fig. 6, whereas the waveshapes of the single point calibration and the three signal method can be seen as a special case of two point calibration.

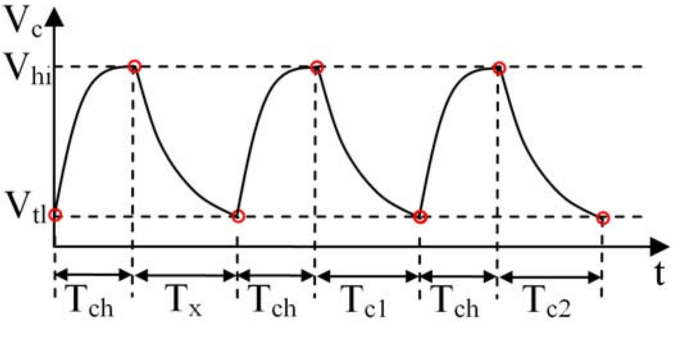

Figure 6. Capacitorr voltage waveshape during two point calibration in direct sensor to microcontroller interface

From Fig.6, the time needed to perform one measurement is:

$$T = 3t_{ch} + t_x + t_{c1} + t_{c2} \tag{17}$$

The charging interval time T_{ch} is:

$$T_{ch} = k_1 R_p C \tag{18}$$

where, usually the constant k_1=7 to 9. For single point calibration, by replacing (1), (3) and (18) in (17), and considering t_{c2}=0, the time needed to perform one measurement is:

$$T_{1pc} = 2k_1 R_p + k(2R_{x\min} + 3\Delta R_x / 2) \tag{19}$$

where, the constant k is equal with the sensitivity coefficient (16). Similarly, the time needed to perform one measurement for two point calibration is:

$$T_{2pc} = 3k_1 R_p + k(3R_{x\min} + 2\Delta R_x) \tag{20}$$

and for the three signals method is:

$$T_{3sm} = 3k_1 R_p + k(2R_{x\min} + 2\Delta R_x + 3R_0) \tag{21}$$

If we compare (19), (20) and (21), it can be seen that the time needed to perform one measurement is shortest for single point calibration. Hence, according [7], for a given time base and given resolution, the single point calibration provides fastest measurements.

E. Complexity, Resources and Cost

We analyze complexity by means of implementing particular calibration technique in a microcontroller. Two criteria can be compared: number of time intervals to be measured and sensor resistance calculation formula.

Considering the first criteria, the single point calibration is implemented by measuring two instead of three measuring intervals comparing to the two point calibration and the three signals method. Hence, we could say that the implementation algorithm is slightly simpler.

Considering the second criteria, the calculating formula for single point calibration (5) contains one division and one multiplication. That is again simpler comparing to the equation (7) and (8), where beside division and multiplication we have also subtraction and addition. However, beside some obvious advantages of the single point calibration technique with respect to both complexity criteria, we don't find it crucial, because all calibration techniques can be easily implemented even in a low performance 8-bit microcontroller.

It is clear that simpler implementation algorithms would use less microcontroller memory and power resources. However, it is more important that single point calibration technique uses less microcontroller pins (three instead of four) to perform the measurements. This can be very important, especially if more than one sensor needs to be measured with the microcontroller.

If we put aside the resources and complexity, the single point calibration and the three signals method take precedence over two point calibration in terms of cost because they use only one calibration resistor. However, the three signals method is by far more accurate than the single point calibration, so we could say that three signals method is the most cost-effective.

VI. CONCLUSIONS

Direct sensor to microcontroller interface allows direct connection of passive modulating sensors to a microcontroller without AD converter or any component in between. The microcontroller measures the discharging time interval of an RC circuit formed by the sensor, one reference component and one or two calibration components. Thus, several known calibration techniques can be applied: single point calibration, two point calibration and the three signals method. Each calibration technique has its own advantages in terms of speed, accuracy, complexity and cost. This paper provides analysis which can help a designer to choose the appropriate calibration technique for particular design.

Two point calibration technique offers the best metrological performances in terms of accuracy because it actually approximates the real transfer characteristics. This calibration technique is the more complex than the others, uses more microcontroller resources and also asks for two stable calibration resistors. Therefore the two point calibration should be used in cases where highest accuracy must be achieved.

Three signals method is a special case of two point calibration with one calibration resistor shortcuted. This calibration technique provides slightly worse accuracy than the two point calibration, but on the other hand reduces the cost. Therefore, this calibration technique should be used in accurate but also cost effective designs.

The single point is the simplest calibration technique using only one calibration resistance. This technique offers highest measurement speed, lowest cost, uses least resources of microcontroller but is also least accurate. 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. One other important advantage of the single point calibration is that it uses less microcontroller pins to perform the measurements.

Considering sensitivity and resolution, all calibration techniques offer equal performances.

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