A Smart and Accurate Interface for Resistive Sensors

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***Abstract*—This paper presents a smart and accurate interface for resistive sensors based on the use of a relaxation oscillator. To obtain high accuracy, good long-term stability and a reduction of the effects of interference and parasitic elements, some classical and new measurement techniques have been applied in the novel sensor interface. Moreover, all multiplicative and additive errors, and the common-mode effect of the interface are eliminated, using a multiple-signal calibration technique. A prototype has been built and was tested. Experimental results show that the interface is able to measure a resistance of 0 to 400 Ω, with a resolution of 7 mΩ and an accuracy of 11 mΩ. The measurement time is about 100 ms.**

***Index Terms*—Auto-calibration, interface, relaxation oscillator, resistive sensor.**

I. INTRODUCTION

RESISTIVE sensors, such as platinum resistors and thermistors, are widely applied for temperature measurements [1], [2]. To perform an accurate temperature measurement using these sensors, one needs a very accurate resistive measurement. For instance, when an accuracy of 0.04 °C for the temperature measurement is required, a platinum resistor (100 Ω) should be measured with an accuracy of 16 mΩ. Some classical and some new measurement techniques, for instance, the chopping technique, four-wire measurement, three-signal calibration and the ac excitation, can be used to get rid of many nonidealities in the resistance measurement [3]. However, the use of an ac square-wave excitation signal in combination with the switched-capacitor sampling technique can cause a significant common-mode effect via the parasitic capacitors.

In this paper, we propose using a multiple-signal calibration technique to reduce the common-mode effect in the resistive-sensor interface. The proposed interface is very suitable for implementation in low-cost CMOS technology.

II. MEASUREMENT CONCEPT

Many classical and new measurement techniques can be applied to obtain a high-performance sensor interface [3], [4]. For instance, the four-wire measurement technique is used to reduce the effect of series impedances caused by the wires and cables used to connect the resistive sensor to the interface circuit. The ac square-wave excitation signal for the sensing element is used to reduce the effect of the low-frequency drift and the influence of parasitic Seebeck voltages. However, the ac square-wave excitation signal can also be used to implement an advanced chopping technique [4]. The use of the chopping technique can significantly reduce the effect of offset, $1/\mathrm{f}$ noise, and low-frequency interference. This enables the use of low-cost CMOS technology for accurate measurement systems. However, the use of the ac square-wave excitation signal, the chopping technique and the switched-capacitor sampling technique will cause a significant common-mode effect via parasitic capacitors. Even when the advanced three-signal auto-calibration technique is used [5], this common-mode effect is not eliminated completely. To reduce the common-mode effect, we propose using a multiple-signal calibration technique, which is described in the following.

As [5], [6] indicates, the three-signal auto-calibration technique is applied to eliminate the multiplicative and offset parameters of the interface. In order to apply this technique, we must measure not only the sensor signal (in our case, resistance) E_x, but also a reference signal E_{ref} and an offset of the total interface in a linear system with output signals M_i

$$M_i = kE_i + M_{off}. \tag{1}$$

After the three-signal auto-calibration technique has been applied, the final measuring result is the ratio

$$M = \frac{M_x - M_{off}}{M_{ref} - M_{off}} = \frac{E_x}{E_{ref}}. \tag{2}$$

In this ratio, the influences of the unknown offset M_{off} and the unknown gain k of the measurement system are eliminated.

According to the experimental results, the common-mode effect affects the offset, but not the gain k in the measurement result M_i. The common-mode voltages are different for the three phases of the measurement. Therefore, instead of a single offset contribution there are two different contributions: M_{offx} and M_{offref} for two measurements M_x and M_{ref}, respectively. A solution for this problem is that two offsets, M_{offx} and M_{offref}, are measured for both measurements of M_x and M_{ref}, respectively. Then, with respect to the common-mode effect, eq. (2) can be rewritten as

$$M = \frac{M_x - M_{offx}}{M_{ref} - M_{offref}} = \frac{E_x}{E_{ref}}. \tag{3}$$

III. DESIGN OF THE INTERFACE

Fig. 1(a) shows a simplified schematic diagram of the interface for resistive sensors. Fig. 1(b) shows some signals of the interface when one of M_{offx}, M_{offref}, M_x, and M_{ref} is measured. The interface mainly consists of a relaxation oscillator, a multiplexer and a logic control circuit. In this figure, R_x denotes the resistive sensor, for instance, a Pt100. The resistor R_{ref} is a well-known reference resistor with a low temperature coefficient and high stability.

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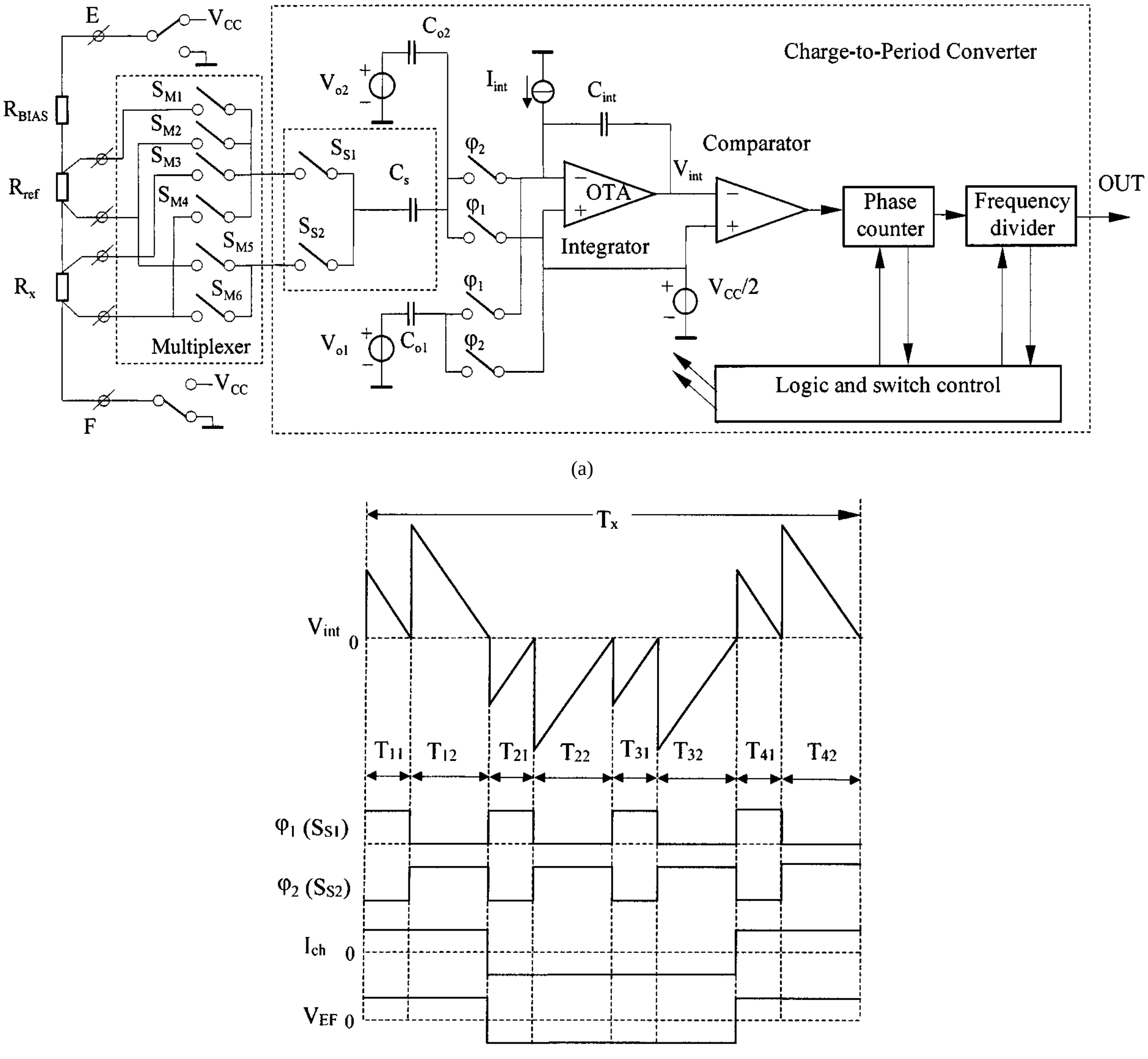

Fig. 1. (a) Schematic diagram and (b) some signals of the interface.

The relaxation oscillator and the switched-capacitor sampler linearly convert the voltage values to period-modulated signals. The multiplexer selects the signal to be measured. Table I lists the situations of switches in the multiplexer when different signals are measured. The control logic will control the situation of all switches. The interface outputs a microcontroller-compatible signal.

In this interface, to apply the chopping technique, two square-wave signals with amplitude of V_{CC} are generated at points E and F to drive the resistor path. These two signals have the same amplitude and a phase shift of 180°. Due to this square-wave driving signal, a large CM ac signal exists. The magnitude of this CM signal is different for R_{ref} and R_x, respectively (see Fig. 2). This causes the problem of unequal offset voltages for both measurements.

TABLE I
SITUATIONS OF SWITCHES IN THE MULTIPLEXER

Meas. Signal	Situation of MUX					
	S_{M1}	S_{M2}	S_{M3}	S_{M4}	S_{M5}	S_{M6}
M_{offref}	0	1	0	0	1	0
M_{ref}	1	0	0	0	1	0
M_{offx}	0	0	0	1	0	1
M_x	0	0	1	0	0	1

IV. NONIDEALITIES

As described in Section II, many nonidealities of the interface are eliminated by means of the multiple-signal calibration technique. However, some effects cannot be eliminated by this technique and should be taken into account during the design of this interface.

A. High-Frequency Pole

The resistors R_x, R_{ref}, and R_{BIAS} and the capacitances associated with these resistors form an RC circuit. For instance,

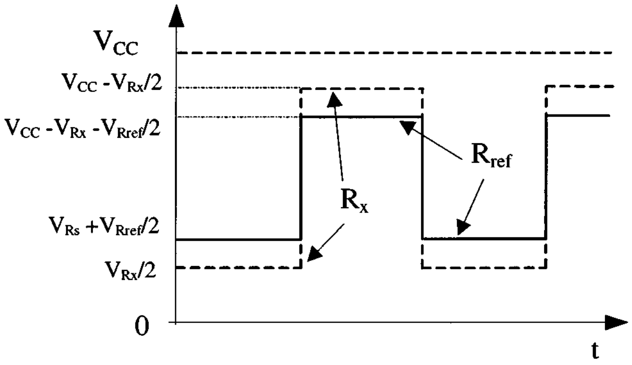

Fig. 2. Averaged common mode signals for the resistors R_{ref} and R_x.

when the resistor R_x is measured and $R_{BIAS} > R_x + R_{ref}$, the time constant of this RC circuit is

$$\tau_i = (R_x // (R_{ref} + R_{BIAS}))(C_s + C_p) \tag{4}$$

where C_s represents the sampling capacitor, C_p is the parasitic capacitor due to, for instance, a long cable wire connecting R_x to the interface. This time constant results in a relative error for the result

$$\varepsilon_{NL} = \exp\left(-\frac{T_p}{\tau_i}\right) \tag{5}$$

where T_p is the time period of the output signal of the oscillator.

Example: When the parasitic capacitance is 2000 pF, $C_S = 28$ pF, $R_{BIAS} = 2.2$ kΩ, $R_{ref} = R_x = 100\ \Omega$ and $T_p = 2\ \mu$s, then, the time constant is about 194 ns. This time constant will result in a nonlinearity of about 33 ppm.

B. Switch Clock Feedthrough

Because the sampling switch S_s consists of two switches that are controlled by opposing clock signals, the effect of switch clock feedthrough can partly be canceled. Moreover, the use of CMOS switches will diminish the effect of switch clock feedthrough because these require opposing clock signals.

C. Noise

Noise in the resistance measurement with the interface shown in Fig. 1 originates mainly from two parts: the oscillator and the period measurement with using the microcontroller. These two noises can be expressed by [7]

$$\varepsilon_{no} = \sqrt{\frac{C_{pin}}{C_s^2}\,\frac{2 f_T C_{int} v_{eq}^2}{V_{cc}^2 N}} \tag{6}$$

$$\varepsilon_{nqt} = \frac{1}{\sqrt{3}}\,\frac{1}{N T_p f_c} \tag{7}$$

where f_T is the bandwidth of OTA, v_{eq} the equivalent input noise (V/$\sqrt{\text{Hz}}$) of OTA, C_{pin} the parasitic capacitance at input of OTA, f_c the sampling frequency of the microcontroller, and N the measured period number.

V. MEASUREMENT RESULTS

The novel method has been tested using the circuit shown in Fig. 1. The interface is implemented with an ASIC, which was presented in ref. [4]. This ASIC has been realized using low-cost CMOS technology. A microcontroller of the type INTEL D87C51AF, which has a 3 MHz counting frequency, is employed to measure the output period of the interface, to process the data and to communicate with the outside digital world. The system is powered by a single 5 V supply voltage.

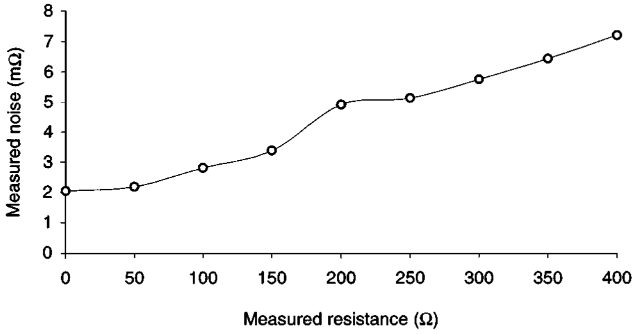

Fig. 3. Measured noise of the interface.

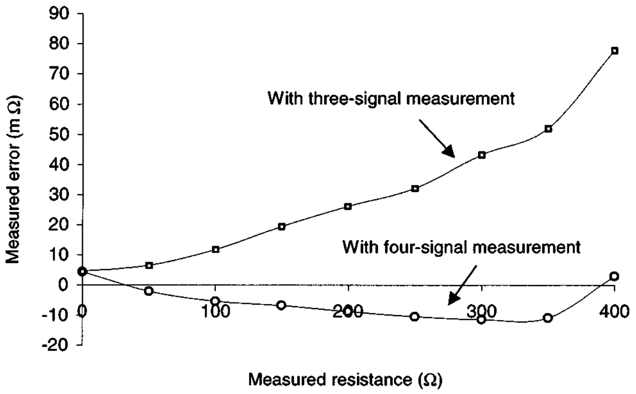

Fig. 4. Measured absolute error of the interface.

The resolution and the accuracy of the interface have been tested for the case that $R_{ref} = 100\ \Omega$ and $R_x = 0\ \Omega$ to 400 Ω with a measurement time of about 100 ms. The measured resolution amounts to 7 mΩ (Fig. 3). Fig. 4 shows the measured error of the interface with the use of the three-signal method and the new method.

It is shown that the interface can measure the resistor of 0 to 400 Ω with an accuracy of 11 mΩ using the new multiple-signal calibration technique. Compared to the measurement results based on the three-signal technique, the accuracy of the interface has been significantly improved.

VI. CONCLUSION

In this paper, it is shown that the accuracy of sensor interfaces with auto-calibration can be considerably improved by performing an extra offset measurement. Applying this technique, a low-cost interface with a high accuracy and good long-term stability has been realized. Experimental results show that the interface can measure the resistor with a resolution of 7 mΩ and an accuracy of 11 mΩ in a measurement time of about 100 ms. The proposed resistive-sensor interface is very suitable for implementation in low-cost CMOS technology.

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