A MULTIPLE-PURPOSE SENSOR INTERFACE AND ITS APPLICATION IN RESISTIVE AND CAPACITIVE TRANSDUCERS

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Abstract: This paper discusses and demonstrates the concepts and features of a novel sensor interface which has recently been developed at the Delft University of Technology. The sensor interface supports resistive sensing elements, such as Pt 100 and Pt 1000 temperature sensors, thermistors, resistive bridges and potentiometers and capacitive sensing elements such as elements for humidity sensors and displacement transducers. Capacitors in the 2 pF range are measured with a resolution of 50 aF and a linearity of 14 bits. In the resistive bridge application a 7 microvolts resolution is obtained. The interface output signal is a complex period-modulated square wave voltage, which can easily be decoded by a microcontroller or a computer without using any additional hardware. The paper will show that the accuracy and log-term stability of the interface properties are obtained by the applied concepts, such a auto-calibration, 4-wire measurements of resistors and two-port measurement of capacitors, dynamic element matching of feedback resistors in amplifiers and suppression of interference effects of advanced chopping and dithering. The interface properties, including some drawbacks, will be discussed and demonstrated in two applications for weighing equipment and humidity sensors, respectively.

I. INTRODUCTION

A main problem with sensor systems nowadays is the electronic part that interfaces between the sensor element and digital modifier, especially when the sensor element is not integrated on the same substrate as the interface. The missing link in the sensor system is a low-cost sensor interface which can be read out by a microcontroller and which can offer a high reliability, a high accuracy and which is easy-to-use. Such an interface ~~would enable the use of~~ sensor systems in a lot of new applications in both consumer electronics (coffee makers, washing machines etc., etc.), and more sophisticated (industrial) markets.

Recently, some interesting sensor interfaces have been developed. Interface ICs from Crystal Semiconductor Corporation [1] are able to read-out resistive bridge transducers and RTDs. They contain Delta-Sigma converters, digital filters and serial interfaces to communicate with a microcontroller. Interface ICs from Analog Devices [2] (for instance, the AD7710, AD7711 and the AD7712) are capable to readout resistive sensor elements and voltage-generating sensors. The setup of the interfaces of both companies show some similarity. Another interesting project [JAMIE, 3] resulted in interface IC named USIC. It is capable in performing many different types of measurements such as the measurement of voltage, resistance, current, capacitance and frequency. Of course this is hardly a complete list of interfaces.

However none of these interfaces supports the important class of capacitive sensors. Capacitive sensor elements can be applied in many applications to measure many different types of physical signals, and therefore it would be a great advantage to support them. Another drawback of many of the present interfaces is the need for additional components and circuits to process part of the sensor signals. The production costs of interface chips is strongly related to the amount of chips which can be sold in a year. Since the sensor market can not (yet) be considered as a high-volume market, a good method to keep the production cost at a low level is to realize a general-purpose interface. Such an interface is described in this article. The following sensor elements are supported:

- capacitive sensors in a wide variety of ranges
- platinum resistors
- thermistors
- resistive bridges with various bridge impedances output voltages and drive modes
- potentiometers

Some general specifications of the system are: a measurement time of 1-100ms, an accuracy of 14 bit, a resolution of 16 bit. Only a single power supply of 3.3-5.5V is required. There is suppression for 50/60 Hz interference.

II. CONCEPTS

The system design is based on a consequent use of classical and novel concepts which guarantee a good long-term stability and a high precision without using calibration of the electronics. These concepts include continuous autocalibration, two-port measurement techniques, piece-wise measurement and advanced synchronous detection. Moreover, the sensor signals are converted to the time domain to enable an easy detection by the microcontroller. An overview of the applied concepts is presented now.

a) Continuous autocalibration: The applied continuous autocalibration technique is referred to as the three-signal technique [4, 5]. Besides the measurement of the sensor signal E_x, a reference signal E_{ref} and the offset E_{off} of the total interface are measured in an identical way, using the same system. This results in three measurement results M_x, M_{ref} and M_{off}. It requires time multiplexing of the three input signals at the input of the modulator. The reference signal is taken from a reference element. The relation between input signal E (E equals E_x+E_{off}, $E_{ref}+E_{off}$ or E_{off}) and measurement result M is given by $M = a + bE$. The final measurement result is now given by M_{final}:

$$M_{final} = \frac{M_x - M_{off}}{M_{ref} - M_{off}} = \frac{E_x}{E_{ref}} \qquad (1)$$

The additive term (a) and the multiplicative parameter (b) of the interface do not affect M and performing the measurements continuously will also strongly reduce low-frequency 1/f-noise. The microcontroller offers the required memory and calculation facilities for this technique.

b) Two-port measurement: The application of the two-port measurement technique reduces the effect of parasitic impedances of the connecting cables. Two practical cases are displayed in

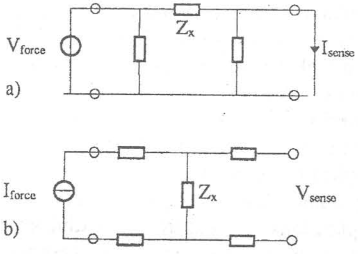


Figure 1. Two cases of the two-port measurement technique.

Figure 1. When the parasitics and the sensing element Z_x can be modeled as a π-network (a), a voltage V_{force} must be forced and the short-circuit current I_{sense} must be measured. The ratio V_{force}/I_{sense} depends only on Z_x and not on the parasitics. This technique will be applied in the interface to measure capacitances. The dual case is shown in (b): A current I_{force} is forced and

the open-circuit voltage V_{sense} sensed. The ratio I_{force}/V_{sense} depends only on Z_x. This technique is applied in the measurement of resistors and resistive bridges.

c) Piece-wise measurement: This technique has been introduced in an interface for resistive bridges [6]. Here, the drive voltage across the bridge is used as a reference signal to perform the autocalibration technique. The reference signal is divided into nearly equal pieces and sampled, resulting into charge packages. These charge packages fall within the same range as those resulting from the sampling of the output voltage of the bridge, thereby using the full dynamic range of the A/D converter. The ratio of the charge packages from the bridge output voltage and the average charge from the voltage across the bridge is a very accurate measure of the bridge imbalance. This technique will be applied to realize an on-chip accurate calibration-free voltage divider. The PWM technique can be considered as a modification of the dynamic element matching (DEM) technique. In our interface chip we will use the DEM technique to realize a voltage amplifier with an accurate gain [7]. Also in this case, calibration is not required and the gain is accurately known over a large temperature range.

d) Advanced synchronous detection: As will be explained in the next section, the sensor signals are used to modulate the period of a first-order relaxation modulator. This period can simply be detected by the microcontroller. The oscillator is adapted to suppress interfering signals at the input of the sensing element. These are suppressed by a high-pass filter (HPF), as shown in Figure 2.

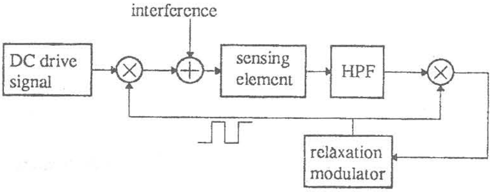


Figure 2. Synchronous detection to suppress interference.

The HPF is based on a switched-capacitor (SC) filter. The sampling sequence results in a filter operation which is applied to the interference. The filter is given in the *z*-domain by:

$$1 - z^{-1} - z^{-2} + z^{-3} \qquad (2)$$

We obtain a second-order frequency behavior for low freqencies of the interference. This advanced chopping has earlier been presented for use in a capacitive sensor interface [8].

e) Dithering techniques: As will be described, the A/D conversion is based on a first-order signal-dependent oscillator whose period is measured by a microcontroller. The presence of this microcontroller introduces high-frequency interfering signals, which can cause undesired locking of the oscillator to the interfering signal. This can be avoided by shielding and keeping analog bandwidths as low as possible (filtering). In addition to this in the interface circuit dither techniques will be applied to eliminate the locking effect. The dither technique is based on random sampling of the high-frequency interfering signal [13, 8].

III. DESIGN

The type of Analog-to-Digital (A/D) conversion is based on indirect conversion, which has been introduced in previous sensor systems [9, 10, 11, 12]. The indirect conversion in our interface is implemented by using a first-order relaxation modulator, whose period depends on the value of the sensor element The period of the modulator is measured by a microcontroller.

The three measurement phases, as discussed above, are selected by the interface itself. This requires a phase counter, as shown in Figure 3.

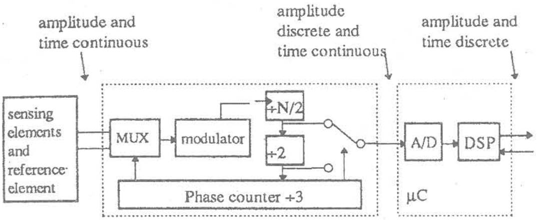


Figure 3. Setup of the sensor system

The modulator is followed by an N-counter which triggers the phase counter to select the next measurement phase. Every measurement phase therefore consists of N periods. The frequency of the output signal of the interface during the offset measurement phase is doubled to enable the microcontroller to synchronize with the phase counter. The output signal of the interface [13] is displayed in Figure 5.

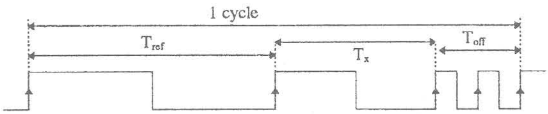


Figure 4. Output signal of the interface when one complete measurement takes three phases.

We will discuss now the complete modulator for the readout of capacitive sensors:The circuit shown in Figure 5 is used to determine the value of C_x with respect to C_{ref}. These capacitors have one common electrode, thereby requiring three IC pins to connect the capacitors to the interface chip. Other setups are used to process up to 4 capacitors and 1 reference capacitor (with one common electrode), thereby requiring 6 pins. These pins are denoted with A, B, C, D, E and F. These pins are also used in other sensor applications and have, therefore, different functions for the different applications.

We will now explain the working principle of the setup in Figure 5:The capacitor C_s samples output voltage of capacitance-to-voltage (C-V) converter. Charge is dumped into the integrator. The current I_{int} is periodically integrated and this results in periodic signals. The three-signal technique has been implemented: the capacitor C_x is selected during the signal measurement phase, the capacitor C_{ref} during the reference phase and none of these two during the offset phase. The capacitors are measured according to the two-port technique: the transmitting electrode is driven from a voltage source and the receiving electrode is connected to a virtual ground. The period of the modulator is rather insensitive to 1/f noise. This is caused by the fact that all relevant signals are represented by frequencies and not by DC signals. Therefore, it is possible to apply chopping techniques to eliminate the effect of 1/f noise. This enables the use of low-cost CMOS processes. The current I_{int} is an AC square wave current. It is very important that the positive and negative levels of this current are equal to achieve a good low-frequency suppression. The common part for all applications is the charge-to-period converter, consisting of an integrator, a current source, a comparator and some extra circuits. For the measurement of other types of sensor elements, the circuitry is slightly modified, as will be discussed now. The interface adapted for the measurement of resistive

IV. APPLICATIONS

All specific parts which are discussed in the previous paragraph have been combined to form a single general purpose sensor interface. This results in 16 different modes which are listed in Table I. This table also displays the number of measurement phases within one complete measurement cycle. The accuracy has been measured for various modes or applications and is listed below. The temperature range for these measurements amounts to -20ºC to 80ºC. Figure 7(a) shows a photograph of a weighting scale. In this application the measurement affects

Table 1. All modes of the interface and the number of measurement phases in one complete measurement cycle.

Mode	Function	# phases
1	5 capacitors, 0-2pF	5
2	3 capacitors, 0-2pf	3
3	5 capacitors, 0-12pF	5
4	capacitors, ext. MUX, 0-2pF/0-12pF	-
5	3 capacitors, var. range up to 300pF	3
6	platinum resistor	4
7	thermistor	4
8	2 or 3 platinum resistors	5
9	2 or 3 thermistors	5
10	resistive U-bridge, 200mV range	3
11	resistive U-bridge, 12.5mV range	3
12	resistive I-bridge, 200mV range	3
13	resistive I-bridge, 12.5mV range	3
14	Res. bridge and two resistors, 200mV range	5
15	Res. bridge and two resistors, 12.5mV range	5
16	3 potentiometers	5

Table 2. Measurement results.

Application	Resolution Slow mode	Accuracy
Capacitors 0-2pF	50aF	14 bit
Capacitors 0-12pF	0.3fF	14 bit
Platinum res.	7µV (9mK)	15 bit
Thermistors	7µV (1mK)	15 bit
R-bridg. 200mV	7µV	11 bit
R-bridg. 12mV	700nV	10 bit

strain in a piezo-resistive bridge which is assembled at a load cell (Fig. 7(b)). The accuracy of the weighting scale is about 4g over a range of 5000g. The noise is about 0.5g (standard deviation with a settling time of 2s. The inaccuracy is found to be mainly due to the mechanical imperfections in the system. Figure 8 shows a photograph of a capacitive sensing element for the measurement of humidity. The value of the sensing element changes linearly with 0.7 pF/% over a relative humidity (RH) range of 5% to 95%. At a RH of 5% the value amounts to 300 pF. The changes of this element are measured using the interface in mode 5 (Table I). The inaccuracy of the present system is mainly due to that of the sensitive element.

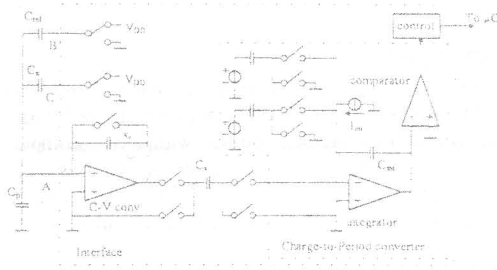


Figure 5. Two capacitors are connected to the interface.

bridges is displayed in Figure 6. The resistive bridge consists of four resistors R_b of which minimally one is sensitive to a physical signal, resulting in a relative resistive change Δ. When the maximum value of the bridge output voltage V_x is below a certain level, V_x is amplified 15 times by an amplifier based on dynamic element matching techniques, before sampling by four capacitors $C_s/4$ in parallel. This amplifier has a very accurate gain which needs no calibration [7]. During the reference measurement phase, the voltage V_{ref} across the bridge is divided into 8 almost equal parts (piece-wise measurement), which are sampled by one capacitor $C_s/4$. The realized on-chip voltage divider, therefore, divides V_{ref} effectively by 32. This division ratio is very accurate while calibration is not required.

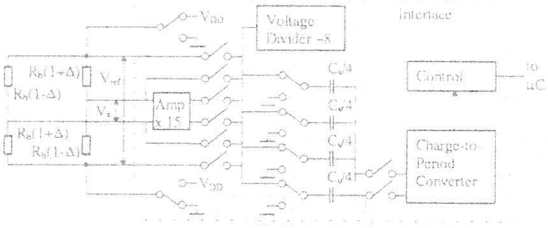
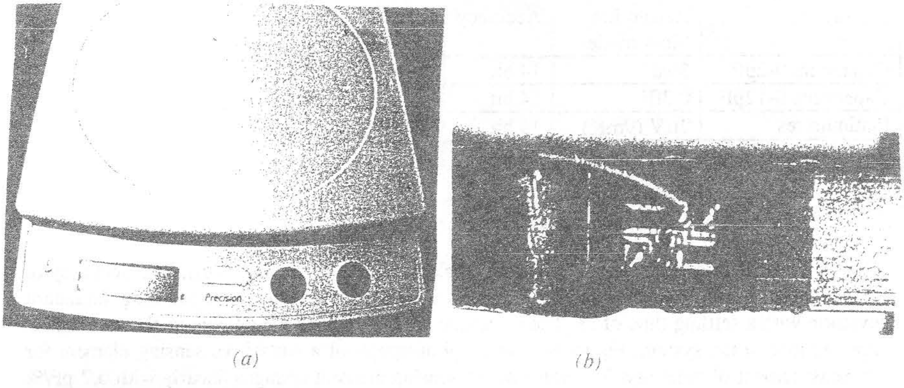


Figure 6. Setup of the interface to measure the imbalance of a resistive bridge.



(a) (b)

Fig 7 a) A photograph of a weighting scale with b) a resistive bridge fixed on a load cell

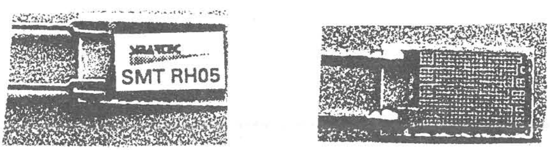


Fig. 8 A capacitive humidity-sensing element

VII. CONCLUSIONS

A general-purpose sensor interface for capacitors, platinum resistors, thermistors, resistive bridges and potentiometers has been designed and fabricated. This interface is readout by a microcontroller. Classical concepts for accurate measurement have been implemented in a single integrated circuit. Amongst these concepts are: the three-signal technique (continuous autocalibration of offset and gain), indirect A/D conversion based on a first-order oscillator, dynamic element matching and two-port measurement of sensor elements. The application of an advanced chopping technique and synchronous detection enabled the use of a 0.7μm CMOS process, without having problems with the typical nonidealities of CMOS, such as the effects of 1/f noise and offset voltages. The main test results are an accuracy of 10-15 bits and a resolution of 16 bits. The measurement time is in the range 1-100ms. These results are achieved over the temperature range of -20ºC to 80ºC. Calibration of the electronic part is not required. The number of external components is kept to its minimum.

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