Multi-electrode capacitive sensors

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Summary

This paper deals with a systematic approach to the design of reliable, high-performance, low-cost capacitive sensors. It discusses the relation between the measurand and the capacitance, the effects of shielding and guarding electrodes, the effects of pollution, condensation and shunting conductances. The importance of selectivity is explained with respect to desired and undesired parameters as well as desired and undesired electrical signals. Electronic processing circuits are presented. The examples given concern position detection, liquid-level gauges and personnel detectors.

1. Introduction

Capacitive sensor elements offer the advantages of a simple and light construction, low-power dissipation, and high accuracy. In the past the measurement of small capacitor values posed some problems. But nowadays these problems have been solved. Smart capacitive sensors measure physical or chemical quantities by transducing the measurands into capacitive quantities first and then transducing this quantity into an electrical signal which is read-out by a micro-controller [1,2] or a DSP. In the first step the non-electrical quantity is transduced in a change of a capacitive quantity . We can distinguish three ways of doing this:

- The non-electrical quantity changes the properties of the dielectric. This method is applied in sensors which can measure humidity, liquid-levels, properties of chemical substances, etc.
- The non-electrical quantity changes the electrode distance. This method is applied in sensors which can measure quantities such as force, pressure, acceleration, levels and distances.
- The non-electrical quantity changes the electrode area or shields a part of the transmitted electrical field. This method is applied in sensors which can measure, for instance, speed, position, level, etc.

Capacitive sensor elements can be made in micro-machined silicon technology as well as in conventional non-silicon technology. When compared with other types of sensor elements, the capacitive elements offer some attractive features: the energy consumption is rather low, the mechanical construction is simple and can be made in low-cost technology. In the past the use of capacitive sensors was limited to a quite moderate number of applications, mainly due to the relatively high costs of the processing equipment and the rather slow signal processing. In this paper it will be shown that these drawbacks are overcome when using the concepts presented in this paper. Table I gives an overview of a number of capacitive sensors.

Table I, *overview of capacitive sensors.*

Name	Input Signal	Physical Principle
Angular encoder	mechanical rotation	Change of an effective electrode area
Position sensor	mech. displacement	
Force sensor	mechanical force	Change of electrode distance
Pressure sensor	pressure	
Humidity sensor	humidity	Change of dielectric constant
Accelerometer	acceleration	Change of electrode distance
Level gauge	liquid level	Change of dielectric constant, shielding
Movement detector	movement of objects or persons	Change of dielectric constant, shielding
Property sensor	material properties	Change of dielectric constant

The design of problems of capacitive sensor systems can be distinguished in the following groups:
physical problems, including the problem in finding an optimal multi-electrode structure with regard to field-bending effects, cross-talk, parasitic effects, problems related to the design of an accurate measurement system with selective detection of the measurand and problems related to the data processing.

This paper presents a systematic approach to solve these problems and shows how to realise low-cost high-performance capacitive sensor elements.

2. Physical problems; the design of multi-electrode configurations.

For easy understanding of the basic problems of capacitive sensors we consider a simple structure with two parallel-plate electrodes (Fig.1(a)). The capacitance between the two electrodes with surface area S, separated by a distance d and a dielectric with dielectric permitivity ε, is given by

$$C_o = \varepsilon \frac{S}{d} \tag{1}$$

In this equation the effects of field bending and non-homogeneity of the dielectric are neglected.
The capacitance can be measured by applying an (ac) voltage V_m and measuring the resulting currents i_1 or i_2. (Fig.1(a)). The signals to be measured are very small: Capacitances are measured by measuring the charge displacement $\Delta Q = \Delta(CU)$. For a supply voltage of 5V and a desired resolution of 10aF (= 10^{-17} F), the charge displacement amounts to 5 x 10^{-17} C, which equals the modulus of only 312 times the charge of a single electron. A reliable detection of these small capacitance changes requires integration over a number of these small charge displacement.
Interfering voltage sources V_{int} can easily spoil the accuracy. Therefore the sensitive structure has to be electrically shielded, (Fig1(b)).

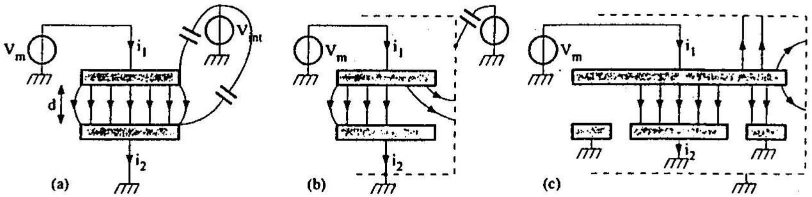


Fig.1(a) *Measurement principle and the effect of an interfering voltage source $V_{int.}$* **(b)** *Shielding to eliminate the effect of interface.* **(c)** *The application of guard electrodes to eliminate field-bending effect.*

The next problem which arises is that due to field bending the presence of shielding electrodes effects the field which represents the measurand (Fig.1(b)). In this way a displacement of the shielding electrodes would affect the measurement result. This problem is solved by applying guard electrodes (Fig.1(c)).
The bottom electrode is surrounded by grounded guard electrodes. Note that now the current i_2 is not influenced by the presence of the shielding, but the current i_1 still is. Therefore, it is important to have access to all of the electrodes. However, for practical reasons, sometimes only one electrode is accessible, while the other one is connected to ground (Fig.2). In that case, as an alternative, active guarding or shielding can be applied. In this technique a voltage follower is applied to connect the shielding. Because there is no voltage over the parasitic capacitance C_p, no current drain through C_p will appear. This technique can also be applied to eliminate the effects of parasitic resistors to ground or to surrounding electrodes.

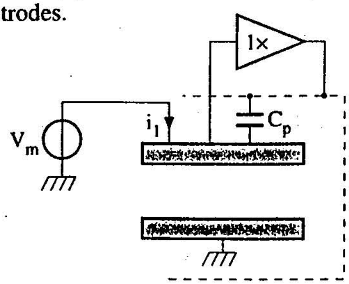
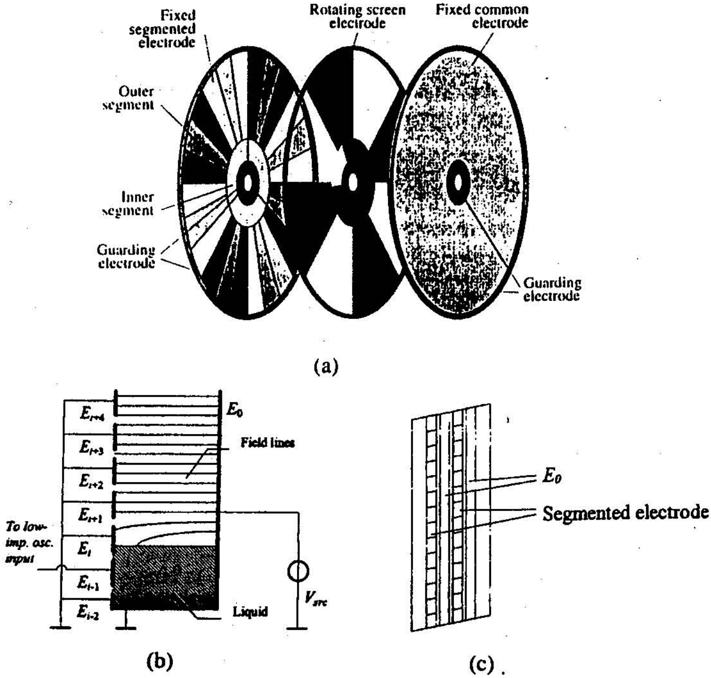


Fig.2. *Active shielding*

In a well-designed electrode structure always guarding and shielding electrodes are applied to eliminate field-bending effects and electro-magnetic interface, respectively. Figure 3 shows as an example some multi-electrode structures for an angular encoder [3] and liquid-level gauges [4] respectively.

In al of these sensors a large number of capacitances is measured and the measurand is accurately calculated by interpolation.



(a)

(b)

(c).

Fig.3. *Electrode structures for (a) angular-position sensors,* (b) *liquid-level gauges,* (c) *planar version of the liquid level gauges.*

In case of the liquid level gauge (Fig.1.(b)) there are two vertical electrodes. One of them is segmented. After measuring all of the capacitances between the segments and the right-hand electrode with a coarse signal processing the segment is found in which region the air-liquid interface exists. Then, using interpolation with a fine signal-processing, algorithm, the level position is accurately calculated . Recently, a planar version of such an electrode structure has been presented [4]. As compared to the structure of Fig.1.(b), the structure of Fig. 1.(c) offers the advantage of a much simpler, low-cost production process. For all of the capacitive sensors, but especially for the planar multi-electrode ones, a major drawback is the sensitivity to pollution and condensation. Pollution and condensation can cause the occurrence of parasitic conductive layers between the electrodes. The parasitic conductances shunt the sensor capacitance C_x and can case serious problems for the accuracy and reliability. To limit this effect the signal frequency should be as high as possible. For a reliable detection the physical conditions should be well defined. However, in practical situations this is not always so easy to realise. Notorious examples of undefined conditions are those due to the occurrence of pollution and condensation. Pollution and condensation can form conductive layers which can be considered as being electrodes. Sometimes these undesired electrodes are grounded and can attenuate the electrical field of the sensor capacitors. It is also possible that the undesired electrodes enlarge the area of the transmitting electrodes so that the field of the sensor capacitor increases. It will be clear that the occurrence of undefined conductive layers is not acceptable. Therefore the use of capacitive sensors is limited to those applications where a clean or dry environment can be guaranteed. It is also possible to fill the sensor housing with oil or another dielectric non-hygroscopic liquid. As a second example Fig.4 shows an electrode structure which has been designed to detect the presence and movement of persons, animals and objects [5].

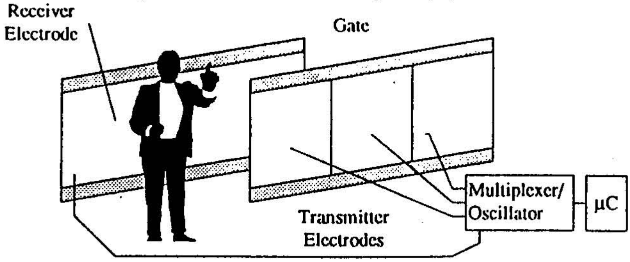


Fig.4. *A personnel detector*

Although the idea is nice and the system has been successfully demonstrated in a laboratory environment, there is still a major reliability problem to be solved: The person is an electrode itself; but it is not defined whether or not he is a floating or a grounded electrode, when the person is grounded this effect is opposite to the effect of a floating person. In practical situation the condition of the floor or bottom is very important. Even when the floor is covered with a additional electrode, to define the physical environment, the thickness of the soles of his shoes is of importance for the reliability of the detection.

3. Selectivity.

The measured system has to be designed and implemented in such a way the information carrying parameters are measured in an accurate and reliable way. Selectivity is an important feature of such a system and concerns two types of undesired signals: the effects of parameters which do not represent the measurand, the effects of interfering signals and noise. In this section it is discussed how the desired selectivity is obtained.

3.1 Selective detection of a selected parameter.

In a well-designed electrode configuration the use of floating electrodes has to be avoided. In that case the electrical equivalent network can be modelled as shown in Fig.5. Here C_x represents the selected part of the multi-electrode structure. The capacitances C_{p1} and C_{p2} represent the sum of all capacitances from each side of C_x to ground, including the parasitic capacitance's of wiring and connectors. Parasitic capacitance C_{p3} results from imperfect shielding and forms an offset capacitance. When the transducer capacitance C_x is connected to an AC voltage source and the current through the electrode is measured with an amplifier with a low input impedance, the effect of C_{p1} and C_{p2} is eliminated. The effect of capacitor C_{p3} can be eliminated by performing an offset measurement.

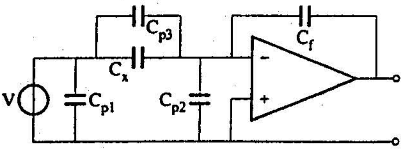


Fig.5. *Elimination of parasitic capacitances*

The current through $C_x + C_{p3}$ is measured by the amplifier with shunt feedback, which is designed to have a low input impedance. To obtain the required linearity, the unity-gain bandwidth f_T of the amplifier has to satisfy the following condition:

$$f_T > \frac{12}{\pi T \dfrac{C_f}{C_f + C_{p2}}} \qquad (2)$$

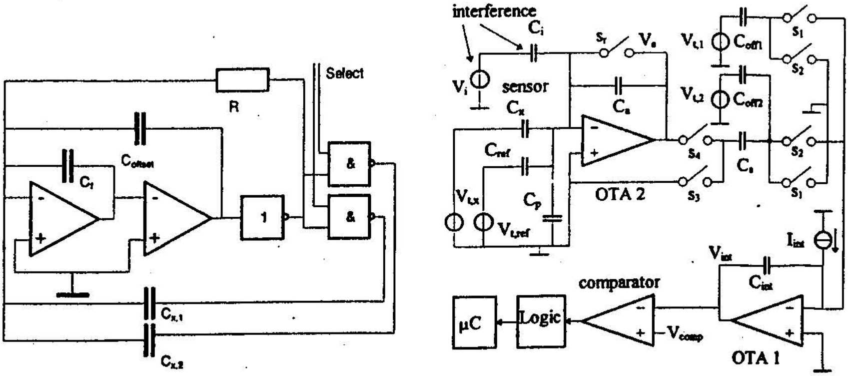
where T is the period of the input signal. Since C_{p2} consists of cable capacitances and the input capacitance of the opamp, it may indeed be larger than C_f and can not be neglected. In some application, in parallel to C_x, a conductive shunting effect can occur. A simple way to reduce this effect is to choose the signal frequency as high as possible. This technique requires amplifiers and IC technology which allows HF designs.

3.2. Selective detection of band-limited frequencies.

The effect of interference and noise can be decreased by selective detection of the information carrying signals by using harmonic oscillators and synchroneous detection. However the required electronic circuitry is rather complicated and difficult to implement in low-cost single-chip integrated circuits. Relaxation oscillators are easy-to-realise, but require special attention to obtain selectivity. In [6] and [7] it is shown that, when using relaxation oscillators , good suppression of low-frequency (LF) interfering signals and noise can be obtained by applying an advanced chopping technique. By sampling the sensor signal in a +,-,-,+ order a second-order behaviour of the LF filtering properties is obtained. The suppression of high-frequency (HF) interfering signals and noise is obtained by limiting the bandwidth of the applied amplifiers [6].

These guidelines for selectivity concern the suppression of disturbing signal with a small or medium amplitude. In the case of a very strong interference, the injected current can be so large that their size exceeds that of the biasing currents of the amplifiers and other active components. For such a strong interference any type of active signal processing will fail. Therefore, by shielding and passive filtering at the input, the size of interfering signals has to be limited.

As an example Fig. 6 (a) shows the principle of the electronic processing circuit for multi-electrode capacitive sensors described in [8]. The described circuit is based on the use of a simple low-cost relaxation oscillator.



(a) (b)

Fig. 6(a) *Principle of a capacitance-controlled oscillator (CAPCO) for multi-electrode capacitive sensors* ***(b)*** *An alternative setup for an CAPCO in which the switched-capacitor(SC)principles and an advanced chopping technique are applied.*

Figure 6(b) shows the principle of an alternative design [6] which uses the principle of advanced chopping and switched capacitors.
In both oscillator circuits the changes of the capacitor values are linearily converted into the time domain.

4. The microcontroller system

The relaxation oscillators of Fig. 6(a) and Fig. 6(b) linearily convert capacitance values into periods. Therefore they are sometimes called "Capacitance-Controlled Oscillators" (CAPCOs). The period-modulated signals can easily be read-out in a low-cost way by a microcontroller. Such a microcontroller can also control the multiplexers to select the various capacitive sensing element. Figure 7 shows a complete schematic [8] of such a circuit.

The circuit of Fig. 7 is based on the use of an Intel 87C51FA microcontroller. Recently, similar versions have been developed based on the use of Texas Instrument's TMS370 and Microchip's PIC16C73 microcontrollers [9].
The measured nonlinearity of the system of Figs. 7 less than 100 ppm for a full-scale value of 2pF. The resolution can be improved by averaging of the measurement results over a longer time. For a total measurement time of 100 ms the standard deviation for a relative measurement of C_x/C_{ref} amounts to about 80 ppm [7].

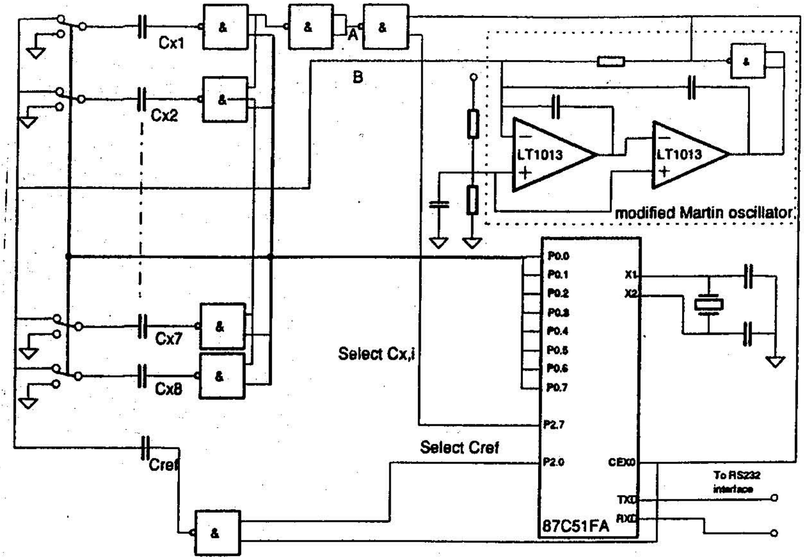


Fig. 7 *A complete schematic of a measurement circuit for a multi-electrode capacitive sensor system.*

5. Conclusions

A systematic design of multi-electrode sensor systems starts with the design of an optimized electrode structure. The sensing elements have to represent the physical measurand as good as possible. Shielding electrodes reduce the effects of electromagnetic interference,while guarding electrodes provide that the information carrying electric fields exceeds the borders of a well protected space, and in addition to this, help to create homogeneous fields. In this way a well-defined relation between the physical measurand and the sensor capacitance will exist.

The occurance of floating electrodes and unpredictable existance of conductive layers, due to, for instance condensation and pollution, should be avoided, which limits the range of possible applications.

The electronic circuitry can be designed in such a way that the system selectively detects the desired selected parameters and signals. The use of microcontrollers completes the low-cost system design by the introduction of memory, control and calculation capabilities.

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