High Performance Capacitive Sensor Electronic Interfaces for Displacement Measurement in Industrial Applications

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I. Introduction

Capacitive sensors are popular in industry because they have a simple construction and they perform well. As the name of the sensor suggests, the electrical model of the capacitive sensor is capacitance, the value of which is related to the value of the input variable. Naturally, the main function of the capacitive-sensor electronic interface is to measure capacitance. This can be done in a number of ways by using different excitation signals, as is shown in Figure 1.

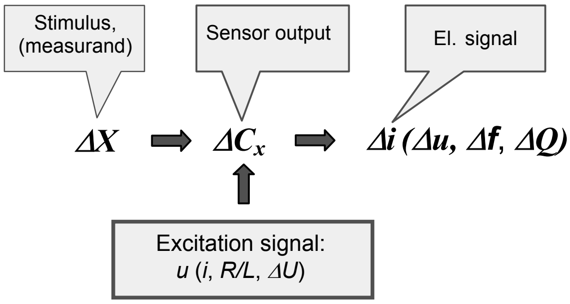

Figure 1. Interfacing capacitive sensors with different reference excitation signals.

With harmonic excitation signals (*u* or *i*), the reactance of the unknown capacitance can be measured. By knowing the frequency, the excitation, and the measured signal values, the value of the unknown capacitance can be found. Another way to measure capacitance is to make it part of the frequency-defining circuit of an oscillator, together with another passive component. For a first-order (relaxation) oscillator this is usually a resistor, whereas for a second-order (harmonic) oscillator this can be an inductor. In this particular case the information carrier of the measured capacitance value is the frequency/period of the generated signal [1-5]. Alternatively, the sensor capacitance C_x can be extracted by measuring the charge $Q_x=C_x.U_{ref}$, which is stored in it. Here U_{ref} is a reference voltage used to (re)charge the sensor capacitance [5].

There are three main performance parameters used to evaluate the level of performance of capacitive-sensor electronic interface: (1) resolution; (2) measurement time (i.e., the time from the moment we want to know the value of the measurand and the moment when the result is available); and (3) stability. Additionally, in some applications, other parameters are also important, such as power consumption, linearity, and dynamic range. The required accuracy is achieved by calibration with an accurate reference.

This paper addresses the high-end industrial applications of capacitive sensors for measuring very small displacements in the nanometer and the sub-nanometer range, for which very high performance is required with respect to resolution, measurement speed, and drift. First, the general features and challenges of a typical industrial working environment are briefly discussed. Then, the basic limitations of the capacitive-sensor and the interface electronics are addressed. Lastly, methods for improving the long-term stability, resolution, and immunity to interference are presented.

II. Industrial application challenges for capacitive sensors

The main differences between applications of capacitive sensors in an industrial environment and, for example, in experimental laboratories, is the freedom available in choosing optimal operating conditions. In industry, capacitive sensors form part of complex equipment and machines, where the optimization of

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the machine performance leads to design restrictions and leaves very little space for optimization of the capacitive sensor system. Typical restrictions are:

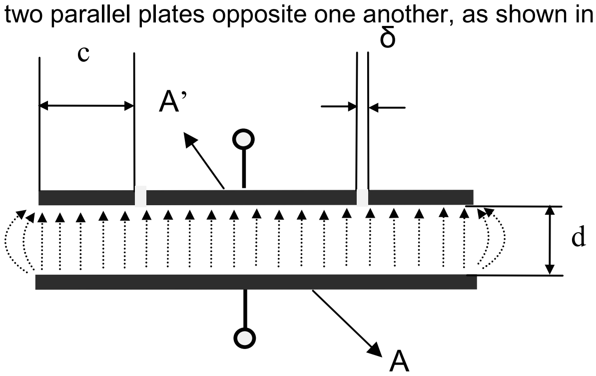
- limited volume and limited mounting freedom of the sensor head;
- significant mounting tolerance of the sensing electrode with respect to the target electrode;
- the location of the electronic interface in a rack far away from the sensor head, meaning that long cables have to be used;
- the need for low-power electronics due to heat generation restrictions if the electronics are allowed to be located in the sensor head;
- different routing of the two sensor-electrode cables and the need to create loops with large enclosed areas that are sensitive to EMI (electro-magnetic interference);
- sources of electromagnetic interference present in the neighborhood;
- limited or completely absent conditions for initial calibration after mounting and/or periodic re-calibration during operation.

These restrictions lead to deterioration of the sensor performance. Therefore, a clever design approach has to be used and application-specific design solutions need to be found in order to achieve the best possible performance of the capacitive sensor in such a “hostile” environment. To do so, it is essential to know the main factors that influence both the performance and the performance limitations of the capacitive sensor, in particular the interface electronics. This is the topic of the next section.

III. Capacitive-sensor performance limitations

a) Sensor head

Let us consider the most popular construction of capacitive sensor for measuring small displacements: two parallel plates opposite one another, as shown in Figure 2.



$$C = \frac{\varepsilon_r \varepsilon_o A'}{d} \quad (1)$$

$$\eta_{guard} < e^{-\pi(c/d)} \quad (2)$$

$$\eta_{gap} < e^{-\pi(d/\delta)} \quad (3)$$

Figure 2. Capacitive sensor with two parallel plates, with a guard ring around one of them to eliminate the fringe effect of the electric field on the transfer characteristic.

The transfer characteristic is indicated by equation (1), provided that the electric field has ideally parallel lines, i.e. the ring electrode around electrode A’ with a width of c completely eliminates the fringe effect of the electric field. Unfortunately, this is only true when there is a very large ratio between the width of the ring electrode c and the distance between the plates d, in addition to a very large ratio between the distance between the plates d and the gap δ between the ring electrode and electrode A’. Otherwise the relative errors η_{guard} and η_{gap} should be taken into account, as represented by equations (2) and (3) in Figure 2 [6]. These two equations contain the measurand value d, which introduces non-linearity to the transfer characteristic. Another source of non-linearity is the tilt (non-parallelism) between the two electrodes, and the roughness and flatness of the surface of the electrodes [7, 8].
In general, the ideal relation between C and d in equation (1) suggests the function Y=f($1/x$), which can easily be linearized. In practice, the high-order non-linear behaviour of the sensor must be taken into account in high-end applications, especially when severe design constraints of the sensor head are imposed..

b) Electronic interface

In the introduction of this paper, we classified the capacitive sensor electronic interfaces with respect to how capacitance is measured. The capacitance measurement principle has an impact on performance parameters such as conversion speed, circuit complexity, linearity, etc.

Another way to classify the electronic interface is with respect to how the capacitive sensor is connected to the electronic circuit. There are two basic configurations called “one-port” or “two-port” [1, 9]. A very important design target for both configurations is to eliminate the negative effect of the inevitable parasitic capacitance around the capacitive sensor, which is mainly the effect of the cable capacitance. By means of two simplified circuits, Figure 3 shows the principle of operation of the one-port (left) and the two-port (right) solutions.

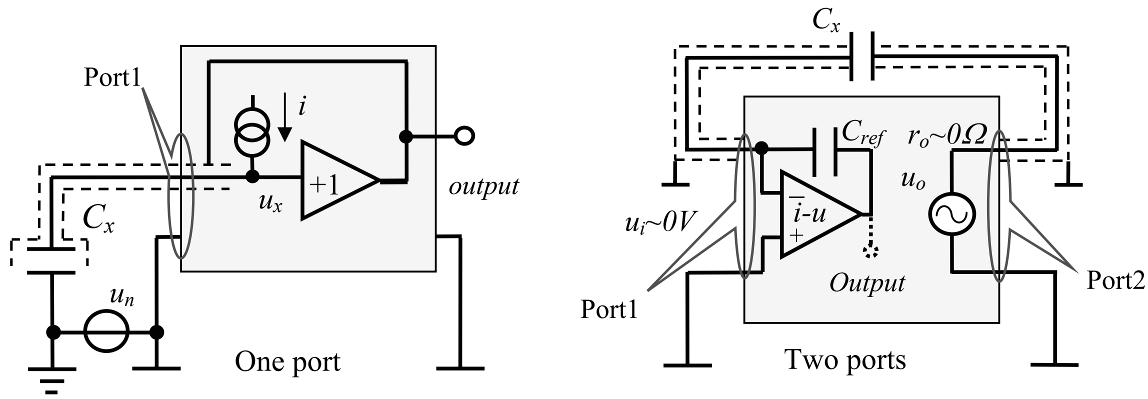


Figure 3. One-port (left) and two-ports (right) electronic interfaces of capacitive sensors.

An advantage of the one-port interface is that the excitation and the read-out signals are applied to one of the sensor electrodes, which is called an “active” electrode. The other electrode is “passive” and can be grounded. Normally this is the target electrode, which can be connected to the already available (machine) ground, i.e. no special cable is needed. In this configuration the sensor capacitance appears parallel to the input capacitance of the electronic circuit and the cable capacitance (i.e. the capacitance between the signal wire and the cable shield, which is represented by the dashed line in Figure 3). For longer cables, the cable capacitance may have a much higher value than the sensor capacitance and will therefore take the major part of the excitation current *i*, which will cause reduced sensitivity, increased non-linearity, and drift. The main solution to this problem is called “bootstrapping”. The potential of the cable shield is kept equal to the potential of the “active” electrode, namely the signal wire, by means of positive feedback. Once this has been accomplished there will be no current running through the cable capacitance and the cable capacitance will not influence the measurement result. Unfortunately, bootstrapping can never be 100% efficient. The positive feedback has to be close to 1, but it cannot be equal to 1. Otherwise the input circuit will start oscillating. This means that some residual effect of the cable capacitance will always be present. Other sources of drift and non-linearity are the finite output impedance of the excitation current source *i* and the finite input impedance of the input follower “+1”. They both have to be extremely high not to affect the linearity and the stability of the sensor interface.

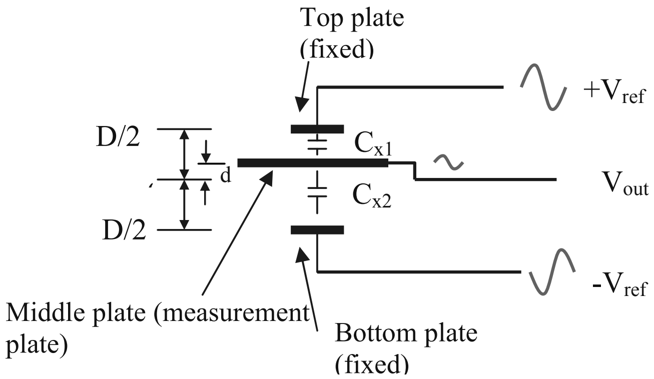
When switched-capacitor technique is used to realize the “one-port” interface, instead of “bootstrapping” a ”feed forward” method is applied to reduce the effect of the cable capacitance [10]. The advantage of this method is the open-loop configuration, which is intrinsically stable. The price to pay here are a few additional large-size analog switches at the input, which could be sources of extra noise and drift. To improve the accuracy, the conversion period, i.e. the response time, has to be increased [10].

Additional disadvantages of the one-port interface are: (1) increased noise when using machine ground, because of unpredictable high currents running through it; and (2) parasitic current leakage paths from the high-ohmic input of the electronic interface to ground, which bring extra drift and non-linearity.

The one-port approach is a real design challenge when: high stability is required; long cables have to be used; the electronic interface is not placed in a well-controlled temperature environment; and the power dissipation is limited. To achieve better performance from such an interface, initial calibration after mounting the sensor and periodic calibrations during operation are recommended.

The “two-port” sensor interface demonstrates better performance with respect to linearity and stability, but it is also not completely immune to the effect of long cables and high parasitic capacitance at the input of the interface electronics. With the two-port approach, neither of the sensor electrodes is grounded. They are typically connected to low-ohmic ports, which automatically reduce the influence of the cable capacitance and other possible parasitic capacitors to ground without the need to use a bootstrap technique. Sometimes this type of capacitive sensor interfacing is called “auto-balanced bridge technique”, as the voltage at the inverting input of the current-to-voltage converter (*i-u*) is automatically

kept close to the potential of the non-inverting input by the high gain of the OpAmp and the feedback reference capacitor C_{ref}.
A special case of the two-port interface is the non-balanced capacitive bridge. It can be used effectively with differential cap sensor configuration, as is shown in Figure 4. The advantage of using the ratio of the two capacitances of the differential sensors to measure displacement, is that the relative dielectric constant is no longer present in the transfer function (see equation (4)), and its variation due to change of the working conditions, for example pressure and humidity, will not affect the measurement result.



$$V_{out} = \frac{d}{\frac{1}{2} \cdot D} \cdot V_{ref} \qquad (4)$$

Figure 4. Differential cap sensor.

The excitation plates of the sensor are driven by voltage sources with opposite phases. The middle plate is connected to a high-input-impedance preampifier. Any paracitic electrical link from the middle point to “the rest of the world” will lead to extra drift, non-linearity, and reduced sensitivity. That is why the same requirements for the input amplifier are also valid, as with the “one-port” interface.
The closer the middle plate of the differential sensor is to the central (balance) point, the smaller the effect of the paracitics and the limited input impedance of the preamplifier will be. Unfortunately, the precise alignment of such differential constructions during the assembly of the host machinary is a difficult, time-consuming and very expensive procedure.

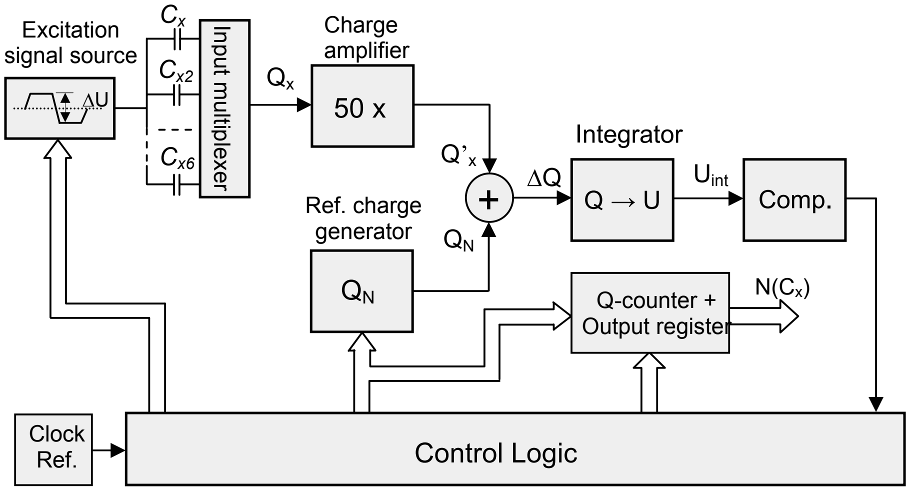
IV. Methods to improve performance

In this section, we will focus on three important features of the capacitive sensor performance: stability and accuracy, immunity to interference, and sensitivity and resolution. We will also discuss methods to improve these performance parameters.

a) Stability and accuracy

The accuracy of the reference element(s) and the precision of the calibration procedure set the limit of the sensor system accuracy. External reference(s), as well as built-in references, are used. The calibration can be either periodic, when the measurement system is stable (very slowly drifting), or continuous, for which reference(s) is (are) measured every time the unknown capacitance is measured [1, 9].
In industrial applications, it is highly preferable to avoid external calibration at any moment after the capacitive sensor system has been mounted. This means that during its lifetime, under the specified working conditions, the stability of the capacitive sensor system has to be within the accuracy budget. To deliver such performance, the capacitive sensor electronic interface needs to have a built-in reference and a simple continuous or periodic auto-calibration algorithm. Using a capacitor as a reference provides a simple calibration process. Unfortunately, capacitors are not the most accurate and the most stable components. There are references that are much more accurate and stable such as are frequency, DC voltage, and resistor. However, the cost of using these references is a more complex circuit and calibration algorithm.
An example of a very accurate and stable interface is the presented in [11, 12]: a 14-bit capacitance-to-digital converter (CDC) based on a charge-balance technique. The conversion time is less than 100 μs and the measurement range is one pico-farad. With careful design and the right choice of components, the transfer characteristic comprises only a resistor, a resistor ratio, and a crystal-stabilized clock frequency. All these components can be very stable and accurate. Among them, the least accurate and least stable component is the single resistor. When using resistor type Vishay S105KT500K000-0.1%, the

measured thermal drift of the CDC is less than 5 ppm/K. The tolerated cable capacitance reaches/can reach 10 nF, which corresponds to an approximately 10 m coax cable.
Figure 5 shows the block diagram of the charge-balance CDC. Among other innovations, to increase the resolution, a true charge amplification function has been introduced with a gain of 50. The CDC can interface up to 6 sensors with the help of input multiplexer.



b) Immunity to interference

The capacitive sensor and the electronic interface can be well-protected from external electromagtetic fields by means of shielding. What is more problematic is that the cables connecting the sensor with the electgronic interface create a loop which acts as an antenna for magnetic fields. Creating such a closed loop is unavoidable for all interface principles. The best solution for minimizing the sensitivity to external magnetic fields is to keep the area surrounded by the loop as small as possible. Unfortunately, this is not always possible, as the routing of the two cables, which connect the two sensor electrodes with the electronic interface, can be different due to other higher-priority requirements.
One way to circumvent this problem is to use a floating target and to split the sensing electrode into two equal parts, which creates two equal capacitors C_{x1} and C_{x2} with the target (see Figure 6). This idea is similar to what is suggested in [13].

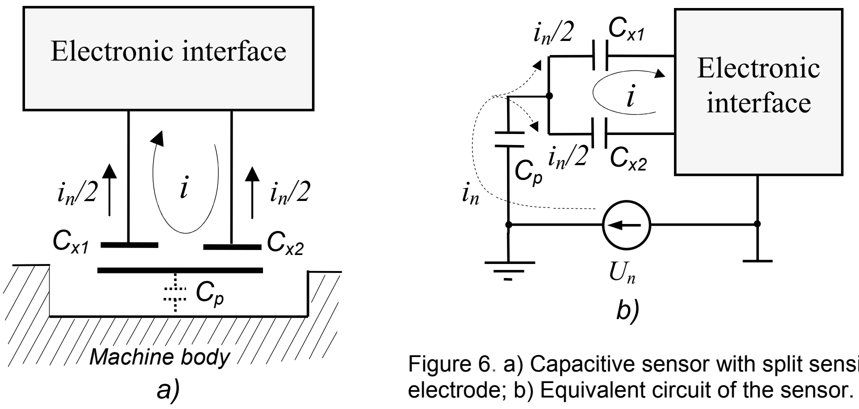


Figure 6. a) Capacitive sensor with split sensing electrode; b) Equivalent circuit of the sensor.

Such a configuration has two loops. One is the measurement loop, through which the measurement current i runs. This loop can be created using one single measurement cable with two wires that are well-shielded from each other. Such a loop is highly insensitive to magnetic fields. The other loop runs through the machine ground, the paracitic capacitance C_p between the target and the machine body, and the measurement cable. The generated noise U_n (see Figure 6b) in this loop creates parasitic current i_n, which is split into two parts by the two signal wires, and which appears as a common mode input signal for the interface electronics. By using an input stage with a high CMRR (common mode rejection ratio), the noise signal can be significantly supressed.
The costs of using such configuration are: (1) four times reduced sensitivity; (2) a more comlex electronic interface; (3) the risk of charging the target electrode with static electricity.

c) Sensitivity and resolution

The sensitivity of the capacitive sensor $\Delta C/\Delta d$ is inversly proportional to the square of the distance d between the electrodes. If the small displacement in the nanometer range needs to be measured, it is very beneficial to position the electrodes of the capacitive sensor close to one another, for example, a few micrometers. Unfortunately, the assembly of large machines cannot guarantee such accurate positioning of the capasitive sensor electrodes without a significant increase in the assembly time and costs. Individual manual alignment of each capacitive sensor in the machine after assembly, if possible, faces similar challenges: time and costs. A possible solution to this problem is to use an auto-alignment sensor head. To do so, the sensor head has to accommodate: a micro-actuator, an actuator electronic driver, and a built-in position reference An interesting candidate for such an actuator is reported in [14], which is called a thermal slider (stepper). Figure 7 shows a possible realization of a capacitive sensor sensing electrode mounted on a thermal slider.

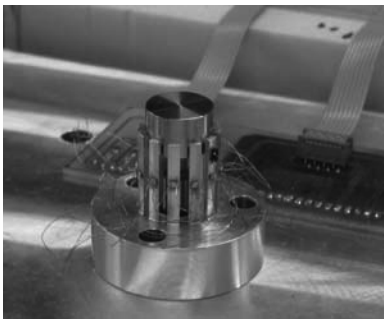


Figure 7. Sensing electrode mounted on a thermal slider.

Conclusions

Most of the industrial applications of capacitive sensors put additional requirements and limitations on the sensor performance, which very often transform an easy design into a great challenge. Frequent additional restrictions are: limited space for the sensor head; no power dissipation allowed in the sensor head; large alignment tolerances; long distance between the sensor head and the electronic interface; no possibility for calibration. At the same time high readout of speed, high resolution, and high stability, are required.

This paper has addressed the basic limitations in the performance of capacitive sensors and the opportunities to improve them. Examples have been given for very stable interface solutions, a self-alignment technique, and increased immunity to electromagnetic interference.

References

[1] F. M. L. van der Goes and G. C. M. Meijer, “A novel low-cost capacitive-sensor interface,” *IEEE Trans. on Instrum. Meas.,* vol. 45, no. 2, pp. 536-540, April 1996.

[2] K. Francois, “A high-resolution capacitance-to-frequency converter,” *IEEE J. Solid-State Circuits,* vol. SC-20, no. 3, pp. 666-670, June 1985..

[3] S. M. Huang,, A. L. Stott, R. G. Green and M. S. Beck, “Electronic transducers for industrial measurements of low value capacitances,” *J. Phys. E: Sci. Instrum.,* vol. 21 , pp. 242-250, 1988.

[4] Smartec, *Universal transducer interfaces (UTI)*, Data sheets and user manuals, http://www.smartec.nl.

[5] R. Nojdelov, S. N. Nihtianov and E. van Doren, “A fast charge-meter for interfacing capacitive sensors,” *Proceedings of IEEE Africon 2007*, September 25-28, 2007, Windhoek, Namibia, pp. 1-6.

[6] W. C. Heerens, “Application of capacitive techniques in sensor design,” *Phys. E: Sci. Instrum.,* vol. 19, pp. 897-906, 1986.

[7] T. R. Hicks and P. D. Atherton, *The nanopositioning book*, Queensgate Instruments Ltd., 1997.

[8] S. Nihtianov, “Capacitive sensor surface quality considerations when measuring sub-nanometer displacement,” *Proc., Electronics-ET’08*, September 24-26, 2008, Sozopol, Bulgaria, Book 1, Electronic Systems in measurement and Control, ISBN/ISSN no. 1313-1842, pp.15-18.

[9] F. N. Toth, G. C. M. Meijer and H. M. M.Kerkvliet, “A very accurate measurement system for multi-electrode capacitive sensors,” *IEEE Trans. on Instrum. Meas.,* vol. 45, No. 2, pp. 531-535, April 1996.

[10] A. Heidary and G. C. M. Meijer, “An integrated interface circuit with a capacitance-to-voltage converter as front-end for grounded capacitive sensors”, *Meas. Sci. Technol.*, vol. 20, issue 1, January 2009.

[11] R. Nojdelove and S. Nihtianov, “A fast interface for low-value capacitive sensors with improved accuracy,” *Proc., IEEE I2MTC’8*, May 12-15, 2008, Vancouver, Canada, pp. 1756-1760.

[12] X. Guo and S. Nihtianov, “Precision measurement of the low-frequency noise of highly-stable capacitive-to-digital converter,” To be published in the *Proc. 9th ISMTII*, 29 June – 2 July, 2009, Saint-Petersburg, Russia.

[13] Lion Precision technical note, “Capacitive sensors – ungrounded targets,” LT03-0022, June, 2006, http://www.lionprecision.com/tech-library/technotes/tech-pdfs/cap-0022-ungrounded.pdf.

[14] J. P. van Schieveen, J. W. Spronck, R. H. Munig Schmidt and S. Nihtianov, “Thermal stepper: a new high stability positioning system for micro adjustment,” To be presented at the *9th EUSPEN international conference*, 2-5 June, 2009, San Sebastiaan, Spain.