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CAPACITIVE SENSING IN PROCESS INSTRUMENTATION

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Abstract

This paper addresses the use of capacitive measurement principles for process instrumentation. A brief review on capacitance-based sensors to measure industrial process parameters is provided. A capacitance-to-digital conversion system developed at the Sensors Group at our Institute is presented. Applications of capacitance-based process instrumentation for moisture sensing, flow velocity determination, fill level measurement and proximity sensing are discussed in detail.

Keywords: capacitive sensing, process instrumentation, moisture, flow velocity, fill level, proximity.

1. Introduction

Mostly due to their low production cost and their large range of applications [1], capacitive sensors have been widely used in industry for many years [2-4]. Capacitive sensing can be applied for different types of measurement tasks. Among the most popular applications are pressure sensors [5], flow sensors [6] (including combination of pressure and flow sensors [7]), accelerometers [8], sensors for angular and linear position [9], for proximity [10] and fill level [11], but also for the determination of parameters in chemical processes such as concentration [12] or pH value [13]. The capacitive sensors mentioned have in common that (ideally) one physical parameter of the process (namely the parameter we are interested in) directly or indirectly affects the capacitance between two electrodes of the assembly or between an electrode and surrounding earth. This capacitance variation may be caused by geometric variations (*e.g.* due to pressure or angular momentum) or by means of variation of the dielectric properties of the material in-between the electrodes (*e.g.* due to altered fill level or chemical concentration). The capacitance values to be measured are typically in the pF range and sometimes far below [14, 15]. The demands on reliability and reproducibility are hence rather high, especially when we bear in mind that the sensor has to work in a harsh environment in most industrial applications, which includes the presence of electromagnetic fields caused by motors and other actuators, charges caused by triboelectric effects, and dust or moisture.

There are many parameters to be considered for the design of a capacitive sensor front-end. The measurement range and sensitivity of the setup (*i.e.* the distance from the sensor front-end, in which variations of the physical parameter can be reliably detected, and the impact on the measurement value) are most often of interest. Also an examination of robustness to electromagnetic interference and the evaluation of shielding strategies are crucial preparatory work in the design phase of a capacitive sensor. The surrounding of a capacitive sensor for example can adversely influence a measurement, it is thus important to enhance the sensitivity

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to useful parameters while to minimize the sensitivity to others [1] (*i.e.* to keep cross-sensitivity low [16]).

When a new electrode design is tested in a real-life industrial environment, electrically conductive contamination, moisture and dew may come in contact with the sensor [2]. When evaluating possible electrode topologies for capacitive sensing it is thus desirable to test these structures by means of a rapid prototyping platform [17]. The aim of a versatile hardware platform is to allow for rapid prototyping and efficient testing of capacitive structures and topologies in various applications without the need to develop data acquisition, communication and implementation of the settings.

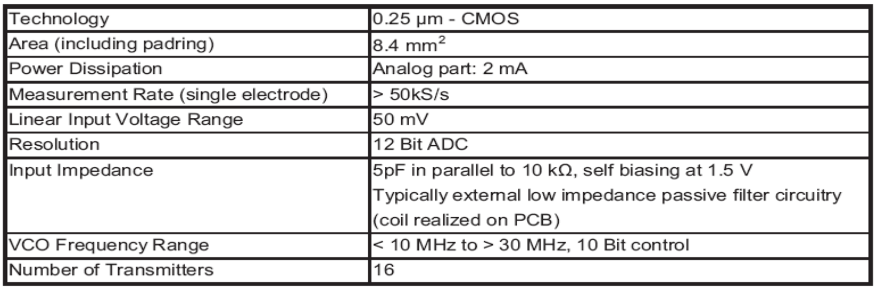
Industrial processes – and the parameters required for the safe and efficient operation of these processes – are miscellaneous and so are the realizations of different capacitance-based sensor approaches in process instrumentation. It is not possible to cover all different sensors in detail in this article. The aim of the paper is to focus on four common measurement tasks in process instrumentation that can be handled by means of capacitive sensing: moisture (Section 3), flow parameter (Section 4), fill level (Section 5), and proximity (Section 6) sensing will be addressed.

2. Capacitance to Digital Conversion

For capacitance-to-digital conversion (CDC), a capacitance measurement system implemented in an Integrated Circuit (IC) is used (refer *e.g.* to [17-20]). A functional block diagram of the capacitance measurement IC based on a high frequency (HF) carrier frequency principle is illustrated in Fig. 1. The transmitter electrodes T_1 and T_2 are sequentially excited by high frequency carrier signals. Thus, displacement currents depending on the coupling capacitances C_1 and C_2 are injected in the common receiver electrode R. These displacement currents enter into a current-to-voltage converter. The output of the current-to-voltage converter is mixed with the carrier signal for the In-phase (I) channel. A 90° phase shifted carrier is used for the Quadrature phase (Q) channel. The outputs from the I and Q channel mixers are low-pass filtered and offsets in both channels are removed before the signals enter Programmable Gain Amplifiers (PGA). The outputs from the I- and Q-channel PGAs are fed to a Successive Approximation Register (SAR) Analog-to-Digital Converter (ADC) which provides the final digital output.

The capacitance-to-digital converter IC was fabricated in 0.25 μm CMOS technology. A 12-Bit SAR-ADC is used for analog-to-digital conversion. The Voltage Controlled Oscillator (VCO) is realized as a differential ring oscillator. Up to 16 transmitter outputs feature current-limited output driver stages for slope limitation of the excitation signals. In Table 1, relevant parameters of the sensor IC are summarized. The total area including the pad ring amounts to 8.4 mm^2.

Table 1. Summary of relevant parameters of the integrated capacitance-to-digital converter [19].



Technology	0.25 μm - CMOS
Area (including padring)	8.4 mm^2
Power Dissipation	Analog part: 2 mA
Measurement Rate (single electrode)	> 50kS/s
Linear Input Voltage Range	50 mV
Resolution	12 Bit ADC
Input Impedance	5pF in parallel to 10 kΩ, self biasing at 1.5 V Typically external low impedance passive filter circuitry (coil realized on PCB)
VCO Frequency Range	< 10 MHz to > 30 MHz, 10 Bit control
Number of Transmitters	16

The main advantages of a capacitive measurement system based on an integrated circuit approach compared to a discrete one are reduced stray fields and hence comparably small stray capacitances, low power consumption, typically more versatile application, and low costs for volume products.

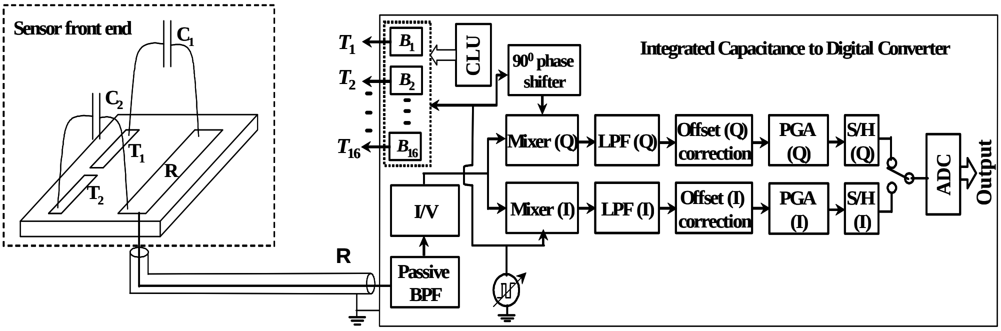


Fig. 1. Block diagram representation of an integrated capacitance-to-digital converter connected to a planar sensor front end with transmitter electrodes T_1 and T_2 and a common receiver electrode R. HF excitation signals are sequentially applied to the transmitter electrodes using a time division multiple access scheme. The injected displacement currents enter a current-to-voltage converter and are subject to I/Q demodulation followed by gain and filtering stages.

3. Moisture Sensing

The measurement of moisture content in bulk solids is crucial for many industries and applications such as the use of coal dust or wood chips in furnaces, transport and charging of waste, storage of crops, fertilizers, processing of powders in pharmaceutic industry or processing of corn, milk powder, coffee, *etc.* in food industry. For example, the moisture content may have an effect on corrosion and decomposition of material, affects discharging behaviour for solids, the lifetime of food products, or the effective calorific value of fossile fuels. Reliable determination of moisture content, especially in bulk solids, is beneficial to the producer and the consumer alike. The moisture material content MC is typically defined on a wet basis as [21]:

$$\mathrm{MC} = \frac{m_{\mathrm{wet}} - m_{\mathrm{dry}}}{m_{\mathrm{wet}}} \times 100\%, \tag{1}$$

where *m* denotes the mass of the sample.

Capacitive sensing in the field of moisture determination features the advantage that the permittivity of the media (usually $\varepsilon_{\mathrm{r,media}} \approx 2$ to 4) to be examined typically differ significantly from the permittivity of water ($\varepsilon_{\mathrm{r,water}} \approx 80$). Compared to microwave technology, lower frequencies are employed for capacitive sensing and measurements are conducted by evaluating an electrical field instead of wave propagation. Here, the sensing volume and the penetration depth can be suitably designed and multi-path propagation problems are avoided. A very common approach for capacitive moisture sensing in materials and products is to make use of inter-digital electrode structures. With a suitable design of the sensor front-end (*i.e.* electrodes), moisture measurement by means of capacitive sensing has been reported for various products [22-24].

The application of a parallel-plate setup with larger dimension used for the determination of moisture in municipal solid waste is shown in Fig. 2. The active electrode and the measurement electrode are both 45 mm by 10 mm and are placed 140 mm apart. Since the heterogeneous test medium can be seen as a complex impedance with capacitive (imaginary part) and resistive (real part) components, I/Q demodulation is used on a carrier-frequency-based technology. Measurement results for different levels of added water (*i.e.* different moisture levels) are shown in Fig. 3 [21].

The reliability and reproducibility of the measurement system is analyzed over a wide range of material moisture by evaluating the variation of the signal amplitude.

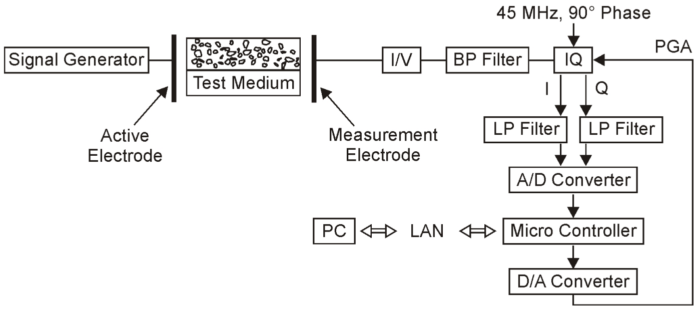


Fig. 2. Block diagram of the designed electronic circuitry for the measurement of the moisture content in waste. The test medium is placed in-between the active electrode and the measurement electrode and the complex impedance of the waste is determined by means of I/Q demodulation [21].

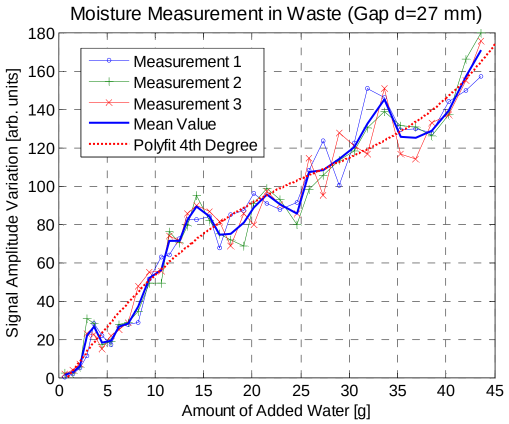


Fig. 3. Experimental results with a parallel plate setup using the circuitry shown in Fig. 2: A heterogeneous material, municipal solid waste, is measured at different moisture levels [21].

For a variety of applications in industry, a measurement setup with a one-sided, planar structure is favoured over a setup sensing the moisture through the cross-section of a pipe or a channel. Reasons therefore are limited access to opposed sides of a conveyor piping system, weak sensitivity and long wiring between the two electrodes (especially for pipes with larger diameters), as well as costly fabrication and Teflon coating for two devices.

Fig. 4 shows the model and the experimental setup to test the applicability of planar and parallel-plate capacitive moisture sensors for powdery and granular material such as wood pellets.

The sensing unit basically consists of the capacitance-to-digital converter presented in Section 2, which has been connected to an Analog Devices Blackfin DSP board [17]. The measurement hardware uses a carrier frequency of about 2 MHz to determine I and Q channels of the complex impedance. At frequencies lower than typically 1 MHz, dissipation losses prevent reliable measurements of material with high moisture content [24]. On the other hand, higher carrier frequencies require a robust setup and proper grounding since parasitic capacitances have an increasing impact on the measurement result.

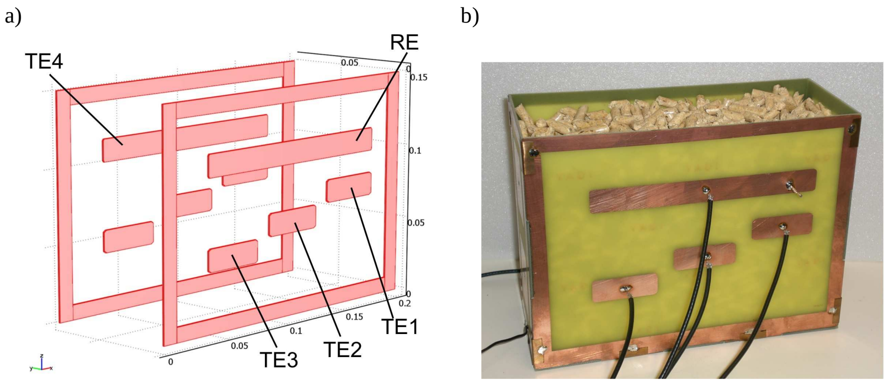


Fig. 4. a) Model of the prototype sensor front-end with receiver electrode RE and transmitter electrodes TE1 to TE4 and b) Photo of the setup filled with wood pellets [25].

One long horizontal electrode, RE, is used as a receiver electrode, *i.e.* the displacement current is measured at this receiver electrode [25]. Four different excitation patterns are used for testing by subsequent activation of transmitter electrodes, TE1 to TE4, to obtain inter-electrode capacitance values.

Fig. 5 presents results for wood pellets being dried over several hours in a drying chamber.

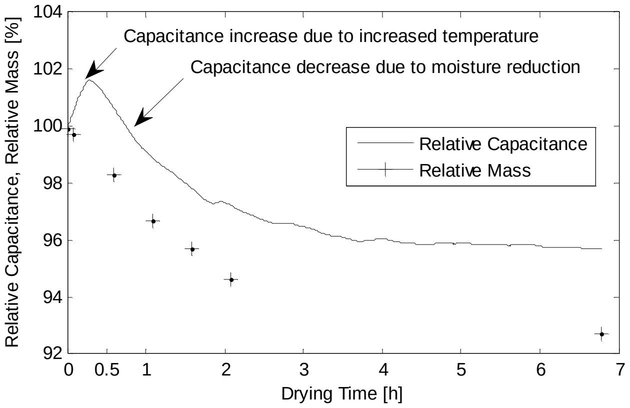


Fig. 5. Results for the capacitance signal during a drying time of approx. Six hours under constant temperature (103°C) for a medium gap of a planar structure TE2 and RE (full line) and the moisture loss (mass loss) of the wood pellets sample (dotted line).

The electric field between TE1 and RE (*i.e.* planar pattern) has rather low penetration depth into the material due to the small inter-electrode gap. For the planar pattern TE3 and RE, and especially for the parallel plate pattern TE4 and RE, the electric field features significantly higher penetration depth [25]. The capacitance signal of the medium planar capacitance (TE2 and RE, see Fig. 4a) is depicted as well as the relative mass, which shows the material moisture loss. This behaviour is similar for all electrode topologies, they only differ in the (vertical) scale and small time shifts. The slight increase in capacitance at the beginning of the measurement most likely originates from a change in capacitance due to the sample temperature increase [33].

4. Flow Velocity Determination

For the determination of the flow velocity in single phase gas or liquid flows, capacitance based flow meters exploiting the pressure drop due to diameter reduction or capacitively coupled vortex flow meters are used [26]. Capacitive flow sensors, as described in this section, require varying dielectric properties. Such variations can be caused by variable concentrations in multi-phase flows or mixtures, alternating liquid and gaseous phases, or temperature variations within the medium. A common measurement task in industrial applications is the determination of particle velocities in gas-solid flows, as can be found in various transportation processes such as pneumatic conveying. Major challenges are the abrasive nature of the material and particle velocities of 40 m/s and more [27]. Two different (though related) methods are used: Correlative velocity measurement and the spatial filtering method.

4.1. Correlative Principle

In a capacitive correlative principle, two sensor layers, namely an upstream and a downstream electrode layer are used as shown in Fig. 6a. Electrodes are placed on the outer surface of a non-conducting pipe section to enable a non-invasive measurement principle. A setup with segmented transmitter electrodes that can be activated individually allows for spatially resolving flow velocity measurement and the determination of particle flow velocity profiles [18]. Since both measurement layers are located at a short distance, the cross sectional distribution of permittivity does not change significantly within the measurement section thus yielding good correlation results. The maximum in the cross-correlation between the signals indicates the time shift Δt and thus permits for constant and well-known inter-layer distance Δd the calculation of the material velocity.

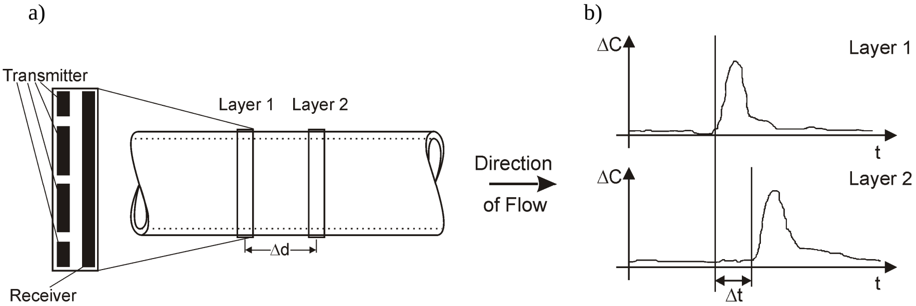


Fig. 6. a) Setup using two capacitive sensing layers for cross-correlation based flow velocity determination and b) Exemplary signals of up- and downstream measurement layers with time shift Δt.

An advantage of the correlative principle is that the overall length of the sensor can be kept low.

Fig. 7 shows measurement results for a granular gas-solids flow (pneumatically conveyed plastic pellets) obtained by using a capacitive cross-correlation flow meter. The relative concentration profile is determined by means of evaluation of the signal energy in the autocorrelation function [28]. The particles used for the experiments had a mean diameter of

3.78 mm. A capacitive sensor with Δd=40 mm was mounted on a glass pipe with 50 mm inner and 60 mm outer diameter.

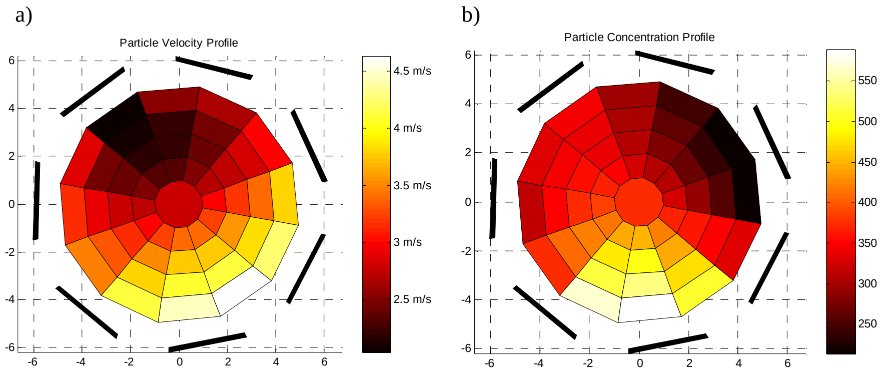


Fig. 7. Examples for measurement results: a) Particle velocity profile; the particles at the bottom have higher velocities. b) Relative particle concentration profile; the particle concentration is higher at the pipe bottom [28].

4.2. Spatial Filtering Principle

The basis of spatial filtering methods is the evaluation of signal amplitudes caused by moving flow inhomogeneities (*e.g.* particles) through a grating-like structure of a sensor arrangement. The output signals of these sensors are cumulated (*e.g.* by means of a lens in optical systems [29]). Bypassing inhomogeneities have an impact on the readout of the measurement signal, which is dependent on the media velocity and on the geometrical dimensions of the sensing volume. Due to the structure of the setup, a fluctuation in media properties can cause a quasi-periodic signal for the length of stay in the assembly. For a given sequence of sensitive volumes with a certain extent in flow direction, a small velocity will cause lower frequency contributions than a fast one will. For axis-parallel flow trajectories, the signal-to-noise ratio can be improved with an increasing number of segments. A simple sequence of transmitter and receiver electrodes and their sensitivity is shown in Fig. 8. This figure also shows exemplary sensor signals in the time and frequency domains.

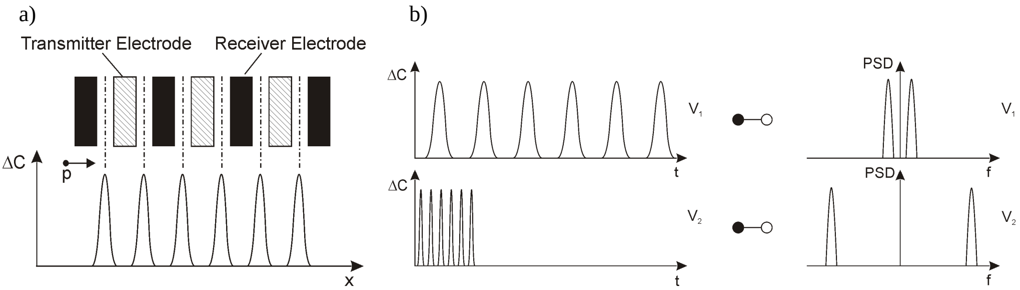


Fig. 8. a) Sensitivity function along the flow direction and b) Sensor signal for slow flow velocity (top) and fast flow velocity (bottom) in time domain (left) and frequency domain (right) [17].

5. Fill Level Sensing

For many applications with two and more phases within a measurement volume, additional a priori knowledge can be presumed. A rather simple gas-liquid two phase system is found for fill level determination. Due to the significantly different densities of the two phases and the impact of gravity, usually a clear phase boundary layer is present, even in the presence of foam. When the two phases show different dielectric permittivity, the fill level can be reliably determined by capacitive means. The most common types of capacitive liquid level sensors are based on coaxial cylindrical capacitors that are immersed into the liquid. An alternative non-invasive approach is shown in Fig. 9. An electrode structure, *e.g.* consisting of a receiver and a (segmented) transmitter is mounted on the outer surface of a non-conducting vessel or pipe. The inter-electrode capacitance between an active transmitter electrode and a receiver electrode usually increases when a liquid with permittivity $\varepsilon_{r,liq}$ higher than the permittivity of the gas $\varepsilon_{r,gas}$ is present in the vicinity of the electrodes. Instead of evaluating absolute capacitance values, only their relative changes due to variations of the fill level are considered (Fig. 9b). The absolute value of the offset capacitance is adjusted by means of an offset compensation unit of the capacitance-to-digital converter (compare [19]). Although the principle is simple, it turns out that "field draining" effects occur (Fig. 9b) in this configuration that can cause difficulties. The capacitance for those electrodes located below the fill level is high. However, for electrode 10, which is close to the surface of the liquid, the effective capacitance is reduced due to field draining effects. For the remaining electrodes located above the fill level, the capacitance remains low. Despite the field draining effect, the relation between the sum of the capacitances and the fill level is fairly linear. Therefore – despite of the simplicity of the measurement task and the simplicity of the sensor front-end – a good model of the electric field is required to obtain a reliable fill level measurement.

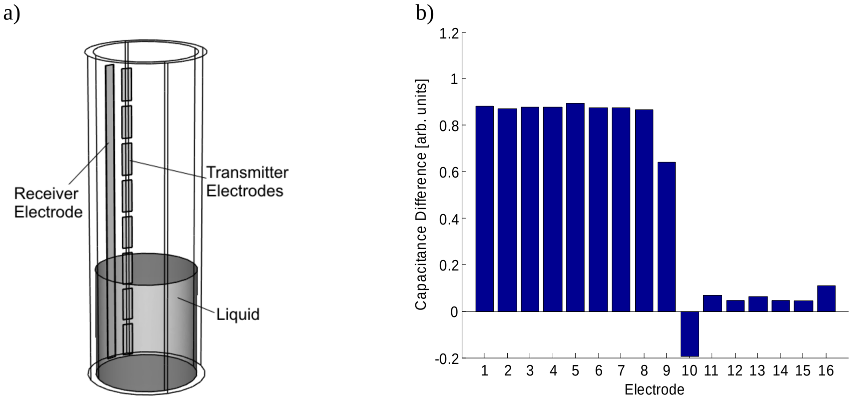


Fig. 9. a) Electrode topology with segmented transmitter electrodes and a continuous receiver electrode used for fill level determination. b) Measurement results for water with half filled vessel, showing deviations from a classical "on-off" characteristic due to field draining effects [30].

6. Proximity Sensing

Capacitive proximity sensors are employed in industrial applications for non-contact detection of either conductive or insulating objects, *e.g.* of conveyed objects [4]. In the automotive environment, capacitive sensors could be an interesting alternative to ultrasound-based distance sensing for parking aids. Here, capacitive technology offers the advantage of a volumetric measurement principle, which allows for both detection and classification of objects. This could be further exploited for various safety applications ranging from pedestrian safety to roll-over prevention of children during backing up.

Fig. 10a depicts a photography of a capacitive proximity sensor for a robust non-contact input device applicable to harsh industrial environments [18]. The position of the fingertip on the left and right slider can be determined based on the capacitance measurements. A corresponding equivalent circuit of the sensor front-end is shown in Fig. 10b. Several impacts on the measurement capacitance C_{AB} are encountered [16]:

- Direct coupling between electrode A and electrode B through capacitance C_{AB}.
- Coupling between the object and ground through capacitance C_{OG}.
- Coupling C_{AO} between electrode A and object O, electrode B and the object through capacitance C_{OB} respectively.
- Offset capacitances $C_{AB,Offs}$ and offset conductance $G_{AB,Offs}$ (*e.g.* due to contamination with conductive material).

Depending on the nature of the object (dielectric, conductive floating, conductive grounded) within the sensing volume of the capacitive proximity sensor, several coupling mechanisms are concurrently present.

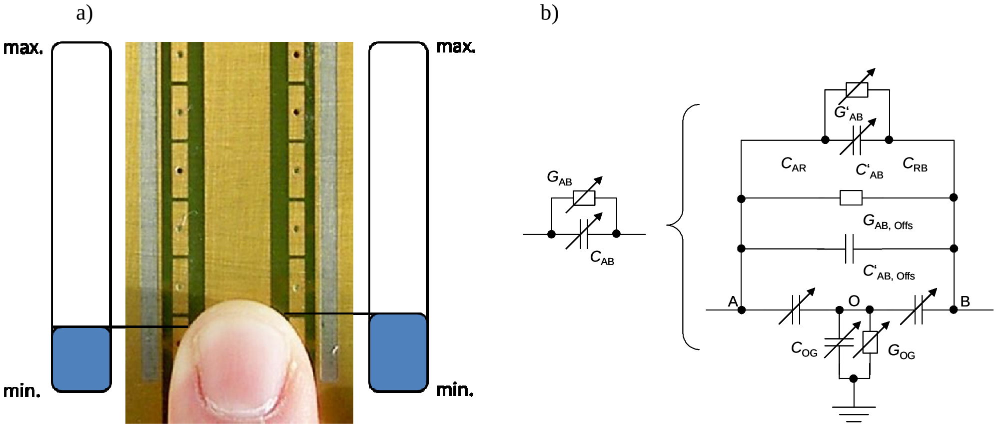


Fig 10. a) Photography of a capacitive slider sensor with two sliders [18]. Along the left line, only the left slider is set, along the right line only the right slider is set. When touched perfectly in between, both sliders are set to the same value. b) Equivalent circuit for encountered coupling mechanisms in a capacitive sensor [18]. Although the coupling capacitance C_{AB} is of primary interest, several competing mechanisms due to capacitances C_{AO}, C_{OG}, C_{OB} have to be taken into account. Furthermore, substantial fractions $C_{AB,Offs}$ of the total capacitance between the electrodes are not affected by the measurand and have to be considered by the evaluation circuitry.

The impact of different coupling modes in a sensor front-end is illustrated in Fig. 11. It presents results of experimental investigations on the coupling modes for a capacitive proximity sensor for the detection of a human hand [31]. The measurement system consists of a planar electrode topology and a capacitance-to-digital converter (refer to Section 2). The measurement data given in Fig. 11b depict the capacitance variation observed while a human hand enters the vicinity of the sensing volume close to touching the sensor plane and finally moves away. The obtained signal trace could be explained by means of the front-end model depicted in Fig. 10b. As long as the capacitance C_{OG} between the object (*i.e.* the human hand) to ground remains high with respect to capacitance C_{OB} (this is valid for moderate distances between the human hand and the sensor plane), the sensor operates in shielding mode (*e.g.* [32]). The effective capacitance decreases with decreasing distance between sensor and hand. When the hand is sufficiently close to the sensing area, the capacitances C_{AO} and C_{OB}, respectively, become large compared to capacitance C_{OG} to ground. An indirect coupling path is formed and a significant part of the dielectric current enters electrode B, thus increasing the received signal. In this configuration, the sensor operates in coupling mode [32]. When the hand is moved back, the sensor behaviour falls back to shielding mode.

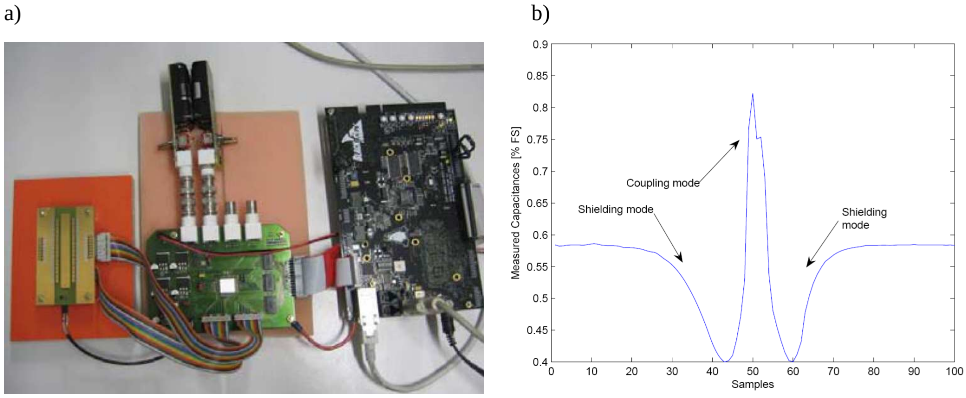


Fig. 11. Experimental investigations of different coupling modes observed in a capacitive proximity sensor [31]. a) The measurement system consists of a planar electrode topology connected to a capacitance-to-digital converter. b) A human hand enters and leaves the vicinity of the sensing volume close to touching the sensor plane. Depending on the values of the capacitance C_{OG} and capacitances C_{AO} and C_{OB}, shielding mode or coupling mode is observed, which leads to an increase (coupling mode) or decrease (shielding mode) of the received signal. For a detailed discussion, refer to the text.

7. Conclusion

Capacitive sensing features several advantages for process instrumentation in industrial applications, such as non-invasive measurement principle and low cost production. The measurement principle for proposed moisture-, flow velocity-, fill level, and proximity sensing is based on the determination and analysis of the complex impedance of the medium to be examined. The design of a multi-purpose capacitance-to-digital conversion hardware, capable of being operated under several carrier frequencies, allows for fast and efficient front-end and sensor design. The harsh environmental conditions in industrial processes require robust strategies against electromagnetic disturbances, discharge effects or dust to ensure reliable sensing.

Acknowledgement

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