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Introduction

Capacitive sensors electronically measure the capacitance between two or more conductors in a dielectric environment, usually air or a liquid. A similar technique is electric field measurement, where the electrostatic voltage field produced by conductors in a dielectric environment is picked up by a probe and a high impedance amplifier.

A high frequency excitation waveform is normally used, as the reactive impedance of small plates in air can be hundreds of megohms at audio frequencies. Excitation frequencies of 100 kHz or more reduce the impedance to a more easily handled kilohm range.

Some systems use the environment as a return path for capacitive currents; a person, for example, is coupled capacitively to the building or the earth with several hundred pF. More often, the return path is a wire.

The range of applications is extreme. At the small end, silicon integrated circuits use the capacitance between micromachined silicon cantilevers to measure micrometer displacements. The dimensions are on the order of 100 μm, and the gap can be a μm or less. At the large end, capacitive personnel and vehicle detectors have plate dimensions of several meters. Capacitive sensors have been used for video-rate signals in one of the early video disk storage technologies. At the sensitive end, one researcher [Jones, p. 589] reports on an instrument with movement sensitivity of 10^{-11} mm.

1.1 SENSOR TRENDS

1.1.1 Market

The world market for sensors [*Control Engineering,* 1993] is over $2.3 billion, growing at an annual rate of 10%. Consumer products, including imaging sensors, make up 64% of the market, with accelerometers accounting for 19% and a variety of specialized sensors completing the total.

Venture Development Corp., Natick, MA, (508)653-9000, in *The U.S. Market for Proximity, Photoelectric, and Linear Displacement Sensors* (1995), forecasts that market segment's size to grow from $429.6 million in 1995 to $548 million in 1999. U.S. consumption in 1999 is forecasted as

Magnetic	1.2%
Ultrasonic	1.9%
Capacitive	3.1%
Magnetic-actuated	4.7%
Inductive	42.2%
Photoelectric	46.9%

1.1.2 Technology

Sensor technology is in the process of a slow migration from discrete "dumb" instruments, expensive and inflexible, to smart, self-calibrating, silicon-based units, and the measurement method of choice for silicon devices as well as for discrete instruments is moving from a variety of transducer technologies, such as magnetic, optical, and piezoelectric, to capacitive.

Capacitive sensors can be used for many different applications. Simple sensors are used for go-no go gaging such as liquid level in reservoirs, where their ability to detect the presence of a dielectric or conductor at a distance allows them to work through a nonconducting window. Similar devices (StudSensor) can find wood studs behind plaster walls. Very high analog accuracy and linearity can be achieved with two- or three-plate systems with careful construction, or multiple-plate geometries can be used with digital circuits to substitute digital precision for analog precision.

Capacitive sensors are also useful for measuring material properties. Materials have different values of dielectric constant as well as dielectric loss, and the values of both properties (particularly dielectric loss, or "loss tangent") change with temperature and frequency to give a material a characteristic signature which can be measured at a distance. Appendix 2 lists the dielectric properties of different materials vs. frequency.

1.1.3 Integration

Tools are available to fabricate many different types of sensors on silicon substrates, including micromachining which etches silicon wafers into sensor structures like diaphragms and cantilevered beams (Chapter 15). The decision to integrate a sensor can be done in stages, with the sensor and its electronics integrated together or separately, and usually is considered when the volume reaches 250,000 per year for total integration. Advantages of integration on silicon [Keister, 1992] are

- Improved sensitivity
- Differential sensors compensate parasitic effects
- Temperature compensation
- Easier A-D conversion
- Batch fabrication for lower cost

- Improved reliability
- Size reduction
- Less assembly required
- Lower parasitic capacitances for smaller capacitive electrodes

Capacitive technology is particularly useful for integration, as it is temperature-stable and problems of parasitic capacitance, lead length, and high impedance nodes are more easily handled on a silicon chip than on a PC board.

1.1.4 Intelligence

Smart sensors increase their value to the system by handling low level tasks such as calibration, self-test, and compensation for environmental factors. The gage factor of smart sensors can be scaled automatically so that one sensor type can be used in many locations, and sensor-resident software may help with communications by managing its end of a sensor data bus.

1.1.5 Sensor bus

Most sensors use point-to-point connections to the host, with contact closure or TTL level digital signaling or 4-20 mA current loop or 1-5 V voltage signaling. As the sensors proliferate in an application, the difficulty of wiring and testing complex systems encourages a single-shared-wire bus connection. One effort to establish smart sensor bus standards is pursued by the IEEE Instrumentation and Measurement Society TC-9 committee [Ajluni, 1994]. This group is drafting "Microfabricated Pressure and Acceleration Technology." A joint IEEE and National Institute of Science and Technology group is developing guidelines for standardization of protocol and interface standards for system designers and manufacturers.

Another proposal for a smart sensor bus is Fieldbus, from the Smar Research Corp. of Brazil [Ajluni, 1994]. Fieldbus works with WorldFip and ISP protocols, and is defined for all layers of the ISO seven-layer communications structure.

1.2 APPLICATIONS OF CAPACITIVE SENSORS

Some different applications listed below show the variety of uses for capacitive sensors.

1.2.1 Proximity sensing

Personnel detection Safety shutoff when machine operator is too close.

Light switch A capacitive proximity sensor with 1 m range can be built into a light switch for residential use.

Vehicle detection Traffic lights use inductive loops for vehicle detection. Capacitive detectors can also do the job, with better response to slow-moving vehicles.

1.2.2 Measurement

Flow Many types of flow meters convert flow to pressure or displacement, using an orifice for volume flow or Coriolis effect force for mass flow [Jones, 1985]. Capacitive sensors can then measure the displacement directly, or pressure can be converted to a displacement with a diaphragm.

Pressure With gases or compressible solids a pressure change may be measured directly as a dielectric constant change or a loss tangent change.

Liquid level Capacitive liquid level detectors sense the liquid level in a reservoir by measuring changes in capacitance between parallel conducting plates which are immersed in the liquid, or applied to the outside of a nonconducting tank.

Spacing If a metal object is near a capacitor electrode, the coupling between the two is a very sensitive way to measure spacing.

Scanned multiplate sensor The single-plate spacing measurement concept above can be extended to contour measurement by using many plates, each separately addressed. Both conductive and dielectric surfaces can be measured.

Thickness measurement Two plates in contact with an insulator will measure the thickness if the dielectric constant is known, or the dielectric constant if the thickness is known.

Ice detector Airplane wing icing can be detected using insulated metal strips in wing leading edges.

Shaft angle or linear position Capacitive sensors can measure angle or position with a multiplate scheme giving high accuracy and digital output, or with an analog output with less absolute accuracy but simpler circuitry.

Balances A spring scale can be designed with very low displacement using a capacitive sensor to measure plate spacing. A similar technique can measure mass, tilt, gravity, or acceleration.

1.2.3 Switches

Lamp dimmer The standard metal-plate soft-touch lamp dimmer uses 60 Hz excitation and senses the capacitance of the human body to ground.

Keyswitch Capacitive keyswitches use the shielding effect of the nearby finger or a moving conductive plunger to interrupt the coupling between two small plates.

Limit switch Limit switches can detect the proximity of a metal machine component as an increase in capacitance, or the proximity of a plastic component by virtue of its increased dielectric constant over air.

1.2.4 Communications

Wireless datacomm Data are capacitively coupled across a short gap in a device which replaces the optical isolator.
RF propagation in the near field can be sensed by a receiver with a capacitive plate antenna.

1.2.5 Computer graphic input

***x-y* tablet** Capacitive graphic input tablets of different sizes can replace the computer mouse as an *x-y* coordinate input device; finger-touch-sensitive, *z*-axis-sensitive, and stylus-activated devices are available.