

CAPACITIVE SENSORS

Design and Applications

Larry K. Baxter



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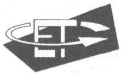
IEEE Press Series on Electronics Technology
Robert J. Herrick, Series Editor

IEEE Industrial Electronics Society, Sponsor

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The Institute of Electrical and Electronics Engineers, Inc.
New York

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10 9 8 7 6 5 4 3 2 1

ISBN: 0-7803-5351-X
IEEE Order Number: PP5594

The Library of Congress has catalogued the hard cover edition of this title as follows:

Baxter, Larry K.

Capacitive sensors: design and applications / Larry K. Baxter.

p. cm.

Includes bibliographical references and index.

ISBN 0-7803-11130-2

1. Electronic instruments—Design and construction.
2. Capacitance meters—Design and construction. I. Title.

TK7870.B3674 1997

621.37'42—dc20

96-15907

CIP

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1

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.

ESD transients

The short transient produced by an ESD event is handled in software by resampling each input after a millisecond or two to reject transients. Interrupt-driven software can handle ESD problems as well as switch bounce.

9.8 TOUCHPAD

The mouse serves personal computers well as an input pointing device, but it has not been as popular for portable computers, where a number of solutions have been tried. Recently, small capacitive touch pads integrated into laptop computers are becoming popular. Several manufacturers make these products, including Philips, Symbios/Scriptel, Synaptics, and Alps.

Synaptics' touch pad is smaller than a business card, with a smooth mylar surface. It handles cursor control by finger position, and also substitutes for mechanical mouse switches by interpreting a finger tap as a switch closure. The standard size is 50×66 mm, with smaller sizes available, and thickness is less than 5 mm. The resolution is better than 500 dots/in, so that fine cursor control is achieved by rocking the finger slightly. As the device is sensitive to the total finger capacity which will vary with pressure, a degree of z-axis pressure response is available, which could be used to modulate line width in a paint program or control scroll speed in a word processor.

Electrostatic discharge performance is good, with soft failures occurring at 15 kV and hard failures at 20–25 kV.

9.8.1 Sensing Technique

The sensing technique, an analog version of the keypad above, uses an x-y grid of wires etched on the upper two layers of a four-layer printed circuit board (Figure 9.20a).

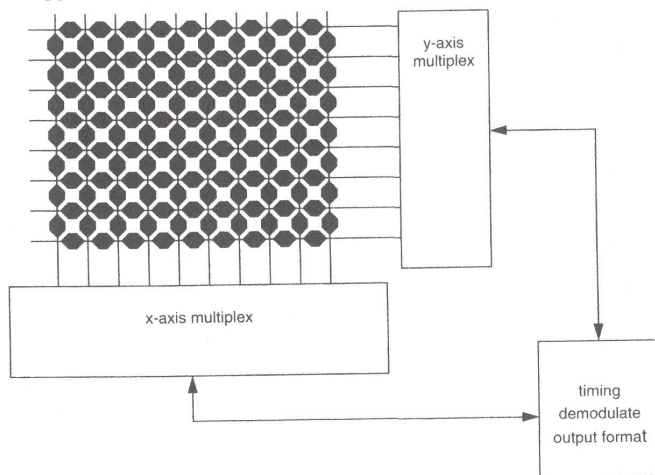


Figure 9.20a Example of the sensing technique

Capacitive coupling is improved by widening the traces, and finger capacitance is sensed as a decrease in coupling between adjacent electrodes caused by the shielding effect of the relatively high capacitance of the human body.

The electronics are surface-mount components on the bottom side of the board, including a mixed-signal ASIC and one or more digital chips if needed for special interface requirements. A combination of digital sensing and analog interpolation between wires is used to accurately determine finger location. The connections from the ASIC to the electrodes are designed to have equal capacitance despite unequal trace length.

Both the electronic and mechanical complexity of the touchpad are less than trackballs, and with no moving parts service life is much higher.

9.8.2 Accurate two-dimensional sensor

A more accurate two-dimensional transducer can be built with similar techniques if the finger is replaced with a close-spaced plane pickup electrode. Bonse et al. [1994] describe an 85×60 mm unit using a 14×10 array of 6 mm^2 square electrodes on the stator and a moving 3×3 electrode pickup. This device, fabricated with printed circuit board technology, demonstrated a 100 nm resolution and 200 nm repeatability. Sine wave excitation and a synchronous demodulator were used, and the major contribution to inaccuracy was determined to be the stability and tolerance of the printed circuit board.

9.9 SPACING MEASUREMENT

The CMOS 555-type timer and the RC circuit form an oscillator which changes frequency as $1/RC$. As the capacitance C is proportional to $1/\text{spacing}$, the output frequency is directly proportional to plate spacing and may be easily measured by counting pulses for some fixed interval of time (Figure 9.21).

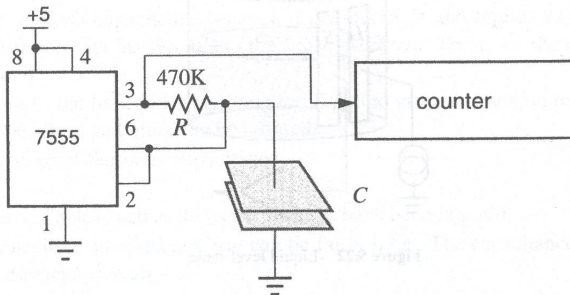


Figure 9.21 Spacing measurement system

If the plates are large and opened, a proximity detector is implemented which detects either dielectric or conductive material in the vicinity of the plates.

This circuit is not too accurate or sensitive, as the input capacitance of the 7555's pins 2 and 7 is about 15 pF and changes slightly with V_{cc} . For better performance, add a driven guard as described in Figure 4.3.

CAPACITIVE SENSORS

Design and Applications

A Volume in the IEEE Press Series on Electronics Technology
Robert J. Herrick, Series Editor

Accurate, inexpensive, and easily integrated with silicon chips, capacitive sensors have caused a "quiet revolution" in today's sensing technology. Capacitive sensors produce spectacular resolution of movement to one part in 10^{-10} meters and maintain exceptional long-term stability in hostile environments. They are increasingly used for a variety of jobs in consumer and industrial equipment, including wall stud sensors, keypads, lamp dimmers, micrometers, calipers, rotation encoders, and more.

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ABOUT THE AUTHOR

Larry K. Baxter (BSEE, RPI '61), in a long career as a consulting engineer, has designed and built many products that use capacitive sensors. His expertise is in electromechanical design, analog circuit design, and embedded microcomputer systems. He has authored numerous articles on various system design projects, has more than 20 patents, and has been a founding partner in several startup companies, including ECHOlaboratory, Inc., Kronos, Inc., and Everygame, Inc. He is now working as a consulting engineer at PictureTel, Inc. and answers e-mail at baxterl@pictel.com.



IEEE Press
445 Hoes Lane
Piscataway, NJ 08855-1331 USA
1-800-678-IEEE

IEEE Order No. PP5594

ISBN 978-0780353510



9 780780 353510