CHARGE TRANSFER SENSING

Spread Spectrum Sensor Technology Blazes New Applications

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There are probably hundreds of variations of capacitance sensors in use today, as any quick patent or literature search will quickly reveal. The concept of charge sensing, on which all capacitance sensors are inherently based, goes back to work done in England in the 1740's by William Watson and shortly after in America by the scientist/statesman Benjamin Franklin. By 1747, with the help of the newly available Leyden jar capacitor invented by Georg von Kleist, both Watson and Franklin had reached the conclusion that charge was a substance which, in an insulating system, is conserved. In 1752 Franklin, in typically colorful American style, conducted the first 'natural' charge transfer experiments with a kite flown during a thunderstorm; the reproduction of this experiment eventually laid to rest arguments about the nature of lightning as well as a number of its researchers.

Figure 1 *An early charge transfer experiment by the illustrious American statesman Benjamin Franklin, ca. 1752. Had a complete transfer of charge occurred, geopolitical history would surely have been written differently.*

While the transference of charge is an essential aspect of every capacitance sensor, a relatively new form of sensor makes overt use of the principle of charge conservation first deduced by Watson in the 1740's. Updated a bit with a microcontroller, mosfet switches, fet-input opamps and band gap references, the principle of charge transference can be used to create an extremely sensitive and stable device with unique properties that transcend those of more pedestrian capacitance sensors. Also known as 'QT' sensors, charge transfer sensors can have a dynamic range spanning many decades with noise floors in the sub-femtofarad regime, allowing differential resolutions of mere fractions of a femtofarad. Such sensors are proving to have unique applications considered heretofore impossible, while also proving themselves as replacements for much more expensive sensing systems using photoelectric, acoustic, RF, and optical imaging techniques.

Applications include human presence detection, fill level sensing, position sensing, material analysis, transducer drivers, keypads and touch controls, material imaging, and even in systems involving short range data transmission. Specific applications include in part intrusion and safety sensing, LVDT replacement, product moisture sensing, automatic water taps, in-keyboard 'mouse' replacement, lighting controls, CT imaging, fruit ripeness testing, and even to help devise a new form of 'smart card'. The wide dynamic range and low cost of the QT sensor permits application to a broad array of sensing problems, and opens up entirely new categories of potential applications.

HOW THE QT SENSOR WORKS

The QT sensor employs at its core the basic principles of physics explored by Messrs.. Watson and Franklin; its implementation is essentially an engineering exercise in switching circuitry. By charging a sense electrode (which can be anything electrically conductive) to a fixed potential, then transferring that charge to a charge detector comprising another known capacitor, the capacitance of the sense electrode can be readily ascertained. The charge and transfer operations are conducted by switches; while electromechanical switches would work quite well, in actual practice mosfet transistors are nearly ideal for the purpose. The control of these mosfets is ideally done by digital logic; in fact, the QT sensor is almost ideally suited to digital control and processing from start to finish. The only analog signal is a typically slow signal requiring no special precautions; conversion of this to digital can be performed by any of a number of commercially available ADC chips.

One form of QT sensor used for ground-referenced or 'open electrode' sensing involves the rapid charge and discharge of the sense element with respect to an earth return. An electrode element having a capacitance Cx is first connected to a voltage reference via a switch S1 (Figure 2), S1 is reopened after Cx is satisfactorily charged to the potential of the reference voltage Vr. Then, after as brief as possible a delay so as to minimize leakage effects caused by conductance Rx (Rx is inevitable in any system), switch S2 is closed and the charge Qx present on Cx is transferred into the charge detector. Once Qx is satisfactorily transferred, S2 is reopened; the charge is then read out of the charge detector and used.The charge detector can simply be another capacitor, made much larger than the expected value of Cx. As Figure 3 shows, a capacitor used as a charge detector must have a reset means (S3) to reset the charge between QT cycles, so that each transfer cycle has a consistent initial condition. The equations which govern the sensor are the centuries-old equations of charge transference:

Eqn1: $V_S = V_R \cdot \frac{C_X}{C_X+C_S}$

If Cx is much smaller than Cs, then the equation simplifies to:

Eqn 2: $V_S = V_R \cdot \frac{C_X}{C_S}$

The value of capacitance can be ascertained by a slight rearrangement -

Eqn 3: $C_X = C_S \cdot \frac{V_S}{V_R}$

An improvement on this scheme is to simply repeat the QT switching cycle many times before reading off Vs and then resetting Cs via S3; manipulating the switches this way results in a system which provides intrinsic signal averaging, since Cs acts as an integrator. This scheme also increases usable gain, since every added QT cycle adds more charge from the driven electrode. In one implementation, the system is run continuously, and S3 is replaced by a resistor (Figure 4). The Rs | Cs combination acts to produce a single-pole low-pass filter, and the 'charge gain' (expressed as volts per farad) is determined by the values of Rs, Vr, and the frequency at which the QT switches are run. In contrast, a burst-mode QT sensor's gain is determined by Vr, Cs, and the number of QT cycles in each burst. An advantage of burst mode is that the gain can be readily controlled by numerically controlling the burst length; this is not possible with continuous-QT circuits such as that shown in Figure 4.

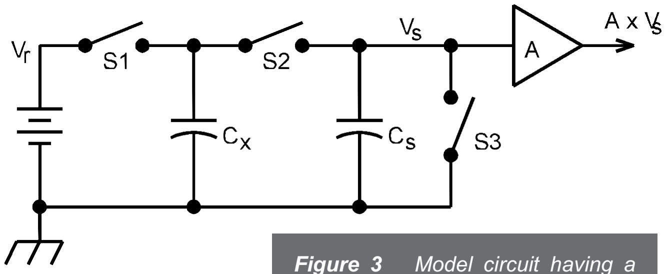


Figure 3 *Model circuit having a capacitor as the Q sampler; this is perhaps the simplest possible implementation of a QT sensor. S3 discharges charge detector cap Cs before each sample. Additional gain and signal averaging can be accomplished by repeating the QT switching cycle multiple times in a burst after each reset of Cs, then sampling the result. Burst-mode QT operation (BQT) has many advantages.*

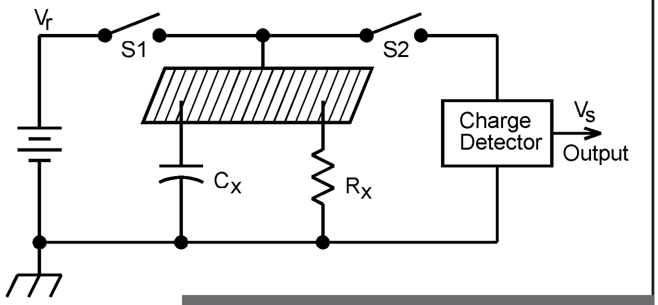


Figure 2 *The simplified QT sensor circuit model. Switches S1 and S2 operate in time-sequence without overlap. The charge detector can take many forms. Switches S1 and S2 are common, inexpensive mosfets.*

Another topology of QT circuit is shown in Figure 5; here, the charge detector is actually an opamp, whose output drives negative as the charge is accumulated. A topology similar to that of Figure 3 is effected by using switch S3 across the opamp; a topology similar to that of Figure 4 is effected via the use the resistor Rs as shown. The advantage of using an opamp is that it creates a virtual ground into which Cx is transferred, improving circuit linearity over a larger load range. The disadvantage is the need for a negative power supply, a burdensome requirement in many low cost applications.

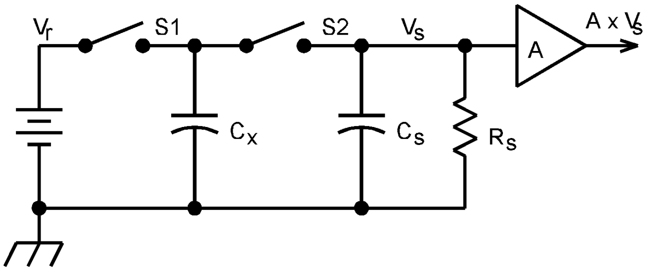


Figure 4 *A continuous duty QT sensor model with sampler configured as a low-pass filter. Gain is a function of the reference voltage Vr, operating frequency f, and resistor Rs.*

A topology which combines the linearity of the Figure 5 circuit with the single-supply simplicity of the Figure 3 circuit is shown in Figure 6. Here, a controlled voltage source Vz is used to 'buck' or cancel the buildup of charge on Cs by drawing charge out through Cz as the charge is building on Cs, in real time. Vz in practice is an opamp with a DAC driving it; during the course of a burst, the value of

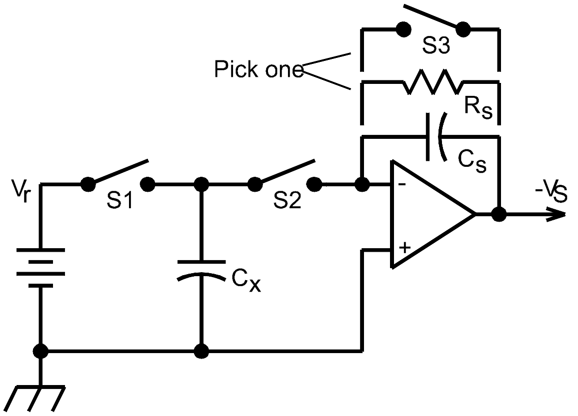


Figure 5 *Model circuit having an opamp integrator as the Q sampler; topologies similar to those of figure 3 and 4 are implemented by means of either a switch or resistor across the opamp to implement either a burst-mode or continuous-mode sensor, respectively.*

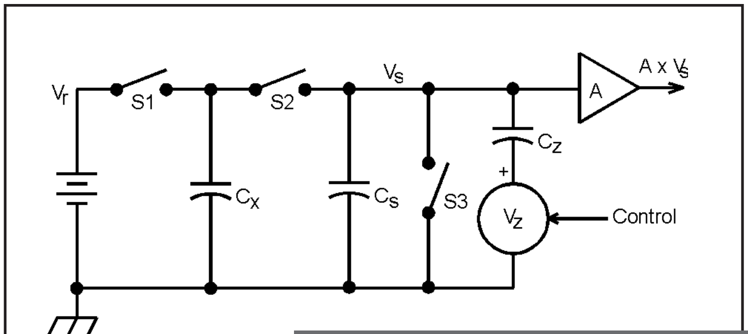


Figure 6 *A unipolar equivalent to the circuit of Figure 5. Operable in a burst mode, the circuit has the distinct advantage of being able to operate without a negative power supply, while maintaining excellent linearity over many decades of signal. Most of the circuit is easily integrated onto a chip.*

Vz is lowered with each QT cycle so that the charge transferred out of Cs is nearly as much as that flowing into Cs from Cx. To accomplish this, Vz must first be set to some appropriately chosen positive voltage while S3 is closed, so that it can be lowered during the course of the burst. The total output result is formed from the residual voltage left on Cs, which is amplified, plus the value of Vz itself, which can be iteratively determined; the value of Vz becomes a 'coarse' signal approximation, while the residual on Cs becomes the 'vernier'. In many systems where only differential capacitance is being monitored (e.g. motion sensing), the value of Vz is ignored, while the amplified value of the residue on Cs is used. Vz thus is really being used merely to cancel background capacitances which may be due to cabling or to the physical size and location of the sense electrode itself. The use of the Vz circuit extends the dynamic range of the sensor greatly.

The total system gain of Figure 6 can be expressed as:

Eqn 4: $$V_S = V_R \cdot \frac{C_X}{C_S + C_Z} \cdot n = knC_X;$$

where n = QT cycles per burst.

It is critical that the reference voltage Vr be stable. Also, the amplifier should have sufficient stability and low input bias current. Modern fet-input opamps fit the bill quite nicely.

Note that the system gain is easily alterable by simply changing the number of transfer pulses within a burst. Under microprocessor control, this is very easy to arrange. A microprocessor can also facilitate the incorporation of digital filtering, detection algorithms, and long term drift compensation.

Dynamic Range and Sensing Stability

In any real-world sensor application it is usually desirous to suppress background levels of Cx, while being able to detect, with appropriate sensitivity, changes in Cx, i.e. DCx. For example, the use of a remote sense electrode connected to the sensor circuit via a 50 ohm coaxial cable will introduce about 100pF/meter of capacitance in parallel with the signal to be measured. Furthermore, the actual length of cabling will vary widely from system to system, placing a stiff requirement on the adaptability of a suitable commercial sensor. Tuned-circuit, bridge, and RC timeconstant based capacitance sensors have enormous difficulties coping with wide variations in large amounts of background C automatically. By using variable charge cancellation at the front end, a QT sensor can accommodate a broad sensing range in one circuit, while still providing a high level of differential sensitivity without placing a great demand on the analog path or on an ADC. For example, it is not a great feat to design a QT circuit having a 5 femtofarad resolution while simultaneously tolerating anywhere from 0 to over 300 picofarads of background load; such sensors are now commercially available from Quantum Research Group Ltd. (Figure 7), who also offer embeddable QT IC's and modules.

The QT sensor does not employ many active components in its front end. In fact it could be argued that the mosfet switches S1 and S2 are for all intents passive, since they cannot introduce nonlinearities into the charge path (provided they remain closed long enough for sufficient charge to transfer); the remaining analog circuitry is composed of ordinary DC coupled opamps. This overt simplicity means the QT sensor can span many decades of range and maintain tremendous linearity throughout; the resolution, accuracy, and drift can be made as good as modern opamp and ADC technology will allow.

Susceptibility to external RFI is minimized by operating the transfer switches with short transfer times. During S1's closure, the sense electrode is forcibly held to a low impedance reference, min-

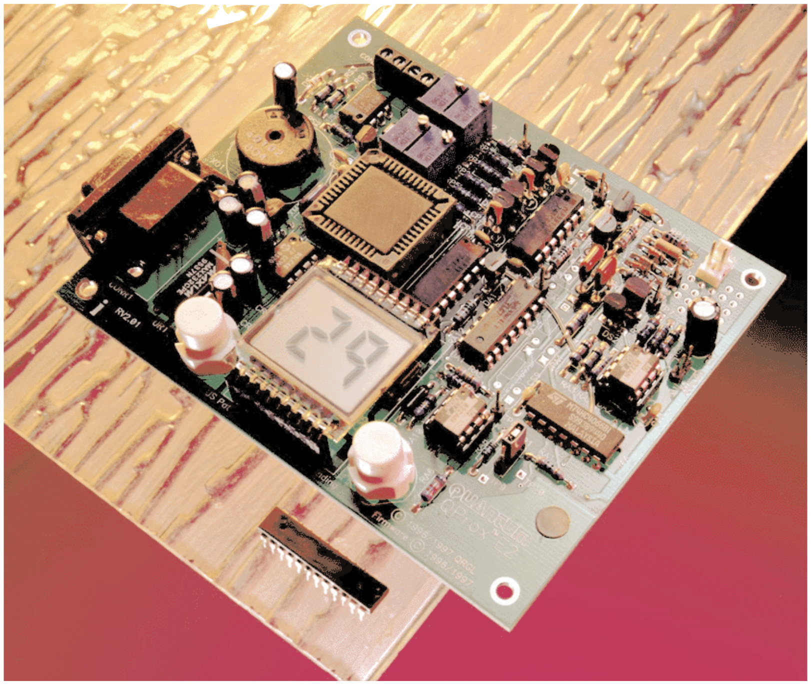


Figure 7 *Quantum's QProx E2S device is a 'smart' development sensor for experimentation with the QT effect that also provides a good tutorial on QT circuitry. Chip and module versions are also available.*

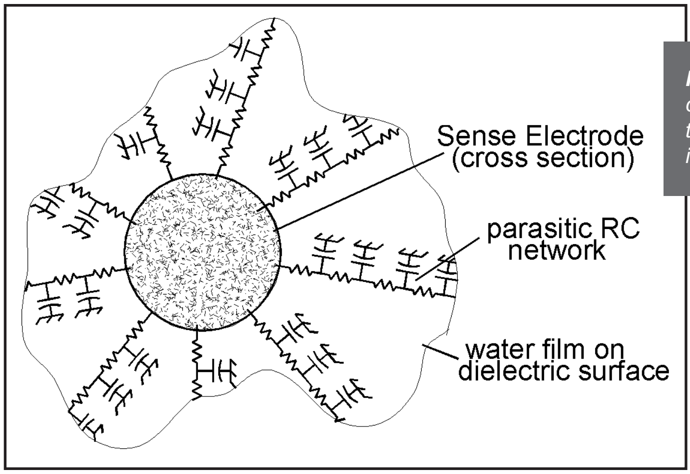


Figure 8 *An ionic film around the sense element, e.g. a water tap, causes a 'virtual spreading' of the capacitive electrode through the resistive water layer. The film's response is highly frequency dependent, and in the time domain pulse width dependent.*

imizing the fluctuations that an external field can induce. Only after S1 opens and S2 closes can external fields 'get inside' the signal path; keeping S2's operate time short helps to alleviate this problem. This brevity reduces the 'window of opportunity' for external fields to wreak havoc with the sensed signal. In contrast, RC based sensors have long exposures to external fields during their ramp times, while oscillator based circuits are continuously exposed to external fields.

Spread Spectrum Sensing

A significant advantage of burst mode QT ('BQT') sensors is the ability to provide a signal output in a repeatable amount of time, without having to wait for an asymptotic response to converge. The BQT sensor provides a repeatable and accurate result after each burst, which might last no more than a few microseconds. The step response is characterized by a specified delay after which full output is guaranteed. This delay time is the same as the burst repetition spacing. Thus, if the burst spacing is 100 microseconds, the sensor is guaranteed to generate a 100% accurate representation of a signal step within 100 microseconds.

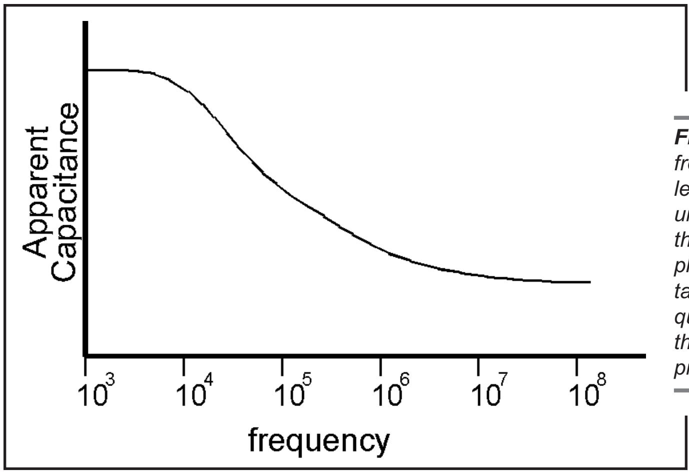


Figure 9 *An ionic film's capacitive frequency response. At its lowest level the value of capacitance measured is that of the electrode itself. At the highest level it is the electrode plus the aggregate parasitic capacitance of the film. By using high frequencies, or conversely short pulses, the effects of the film are largely suppressed.*

A fascinating spread spectrum effect can be easily implemented by manipulating the pulse and/or burst spacings in a psuedo-random manner. The introduction of timing randomness causes spectral spreading akin to the frequency modulation of a carrier with broadband noise. Again, this is an effect which most capacitance sensors would be hard pressed to emulate. Oscillator based capacitance sensors have a monotonic and usually continuous fundamental; the fact that these circuits usually operate continuously means that their spectral power density is relatively high.

In contrast the BQT sensor uses sparse pulses with long time gaps between bursts; total spectral power is therefore inherently weaker. A typical BQT sensor operating with a 1ms burst spacing can have a total burst length of 50 microseconds containing 16 QT switch cycles, for an effective 'burst duty cycle' of 50/1,000 or 5%. Since the individual transfer pulses can be very narrow, for example 5% or less of the intra-burst pulse spacing, the integrated spectral energy of each burst is quite low to begin with, with actual spectral content appearing as a harmonic comb. Adding randomization to the pulse and burst spacing spreads the already weak fundamental and its harmonics around to even lower spectral densities.

Palpable advantages of the spread spectrum mode include a marked desensitization to cross-sensor interference, reduced EMI problems, and reduced susceptibility to correlated noise. For a given power level at the sense element, the psuedo-random technique can greatly improve the odds of obtaining regulatory clearances for a given application.

Material Analysis Applications

Originally the author devised the BQT sensor to suit a specific project: the development of a sensor to control an automated water tap, whereby the entire tap is made into a prox sensor. Aside from requiring that the tap be electrically isolated, an easy matter, the largest problem was avoiding the effects of water splashes around the base of the tap. As Figure 8 shows, a water film ionically conducts the sensing current through its length and breadth, effectively increasing the capacitive load in a random manner, wreaking havoc with detection algorithms. Upon reflection, it was realized that a water film acts electrically as a low-pass filter composed of a resistive sheet with parasitic capacitances to earth; such a 'network' is highly frequency sensitive. At low sinusoidal frequencies, all parasitic capacitances attached to the sheet can be charged and discharged in unison, leading to a total value of Cx that includes them all. At high frequencies, the network 'disconnects' the capacitances of the sheet since they are resistively coupled; the limited conductivity restricts the ability to charge and discharge the parasitic C's. This effect results in a response curve with frequency as shown in Figure 9.

This simple insight led the author to develop the BQT sensor, employing inexpensive pulse methods instead of expensive, power

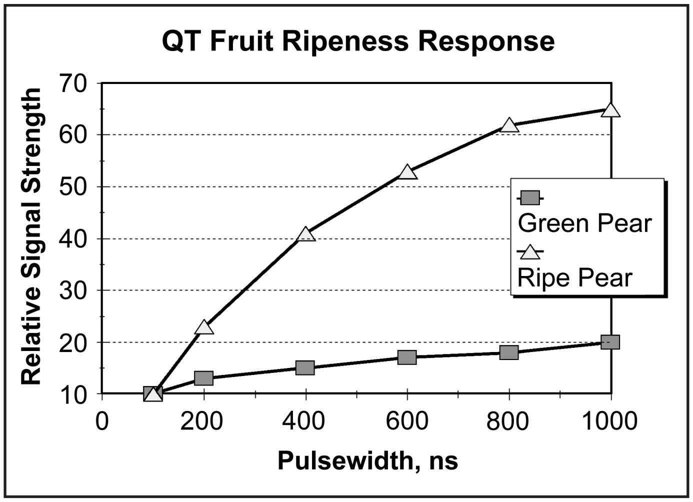


Figure 10 *Similar to the response of a water film, a fruit's response in the 'pulse domain' is highly dependent on its ripeness. A noninvasive, i.e. purely contacting instrument can be devised to take advantage of this effect. Fruits are not the only objects having such response curves.*

hungry CW oscillator based techniques of more conventional heritage. The resulting tap sensor operates on battery power, and is currently in test at several plumbing companies in the United States.

The ability of the QT sensor to be 'tuned' to suppress signals from a water film leads to a whole new realm of possible applications. As is well known, many insulating materials exhibit a frequency dependence in their properties such as dielectric constant and loss tangent; with some this dependence is negligible, however with a great many, especially organic compounds, this frequency dependence is significant. The QT sensor can capitalize on this effect by observing corresponding signal variations in the time domain. By varying the transfer times on a given sample over a range, one can obtain a signal curve which is characteristic of the underlying material. The shape or simply the slope of the curve at a particular point can be gainfully employed to deduce something about the material. A typical application of this might be to measure the moisture content of paper pulp, or to measure the ripeness of fruit. Figure 10 shows the example of the noninvasive capacitive response from two pears, one ripe and the other green; the curves are as obviously unique as can be. The electrodes used to measure the data were simply two parallel metal strips measuring 15mm by 3mm each and separated from each other longitudinally by a 0.5mm gap (Figure 11). Active work has now commenced in this area with citrus at the University of Florida using QT technology provided by Quantum Research.

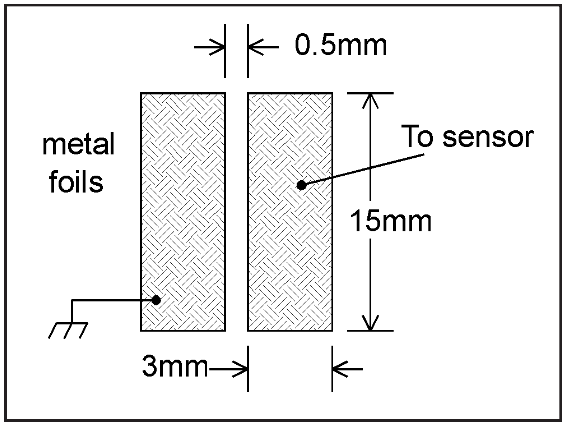


Figure 11 *Simple electrodes used to generate the curves of Figure 10.*

It can be envisioned that one day a hand held sensor would be taken by a consumer to the grocery to help select more desirous fruits and vegetables, or that a wholesaler or grocer would use such a device to presort fruits to accommodate the customer.

The method can potentially be used to determine the impurity content of fluids, for example water contamination of fuels, or to accurately gauge the phase transitions of various substances during processing. It could also be used to detect rain from within a car's windscreen, for example, to control a 'smart' wiper. It can also be used to drive transducers incorporating environmentally susceptible materials; for example, a hygroscopic material can be made into a detection film that responds to humidity. The number of applications are seemingly endless. The QT sensor enables, for the first time in an economical form, the translation of reference book data on the frequency characteristics of materials into useful products.

The Computer Mouse

One rather intriguing application of the QT sensor is to control a rather unusual keyboard 'mouse', whereby the 'mouse' is made to operate by merely skimming ones' four fingertips over the tops of the keys. Without even leaving the normal typing position, one can activate the mouse and use either hand to control the pointer. Devised originally for use in laptop computers where surface area comes at a premium, the unit takes no additional space and requires no little red 'joystick', ball, pad, or other indication of its presence whatsoever. The 'mouse' surface can be as large as the entire keyboard, but in practice occupies about half the keyboard surface area. Figure 12 show an array of sense elements which, embedded under the key switches establishes a ratiometric field, emerging from the keycaps to couple into the user's fingers. The electrode array is driven by a 4-channel QT sensor. The user's fingers cover several keys at a time when 'skimming' the keycaps, and so the sensor can derive an average of the response from multiple keys.

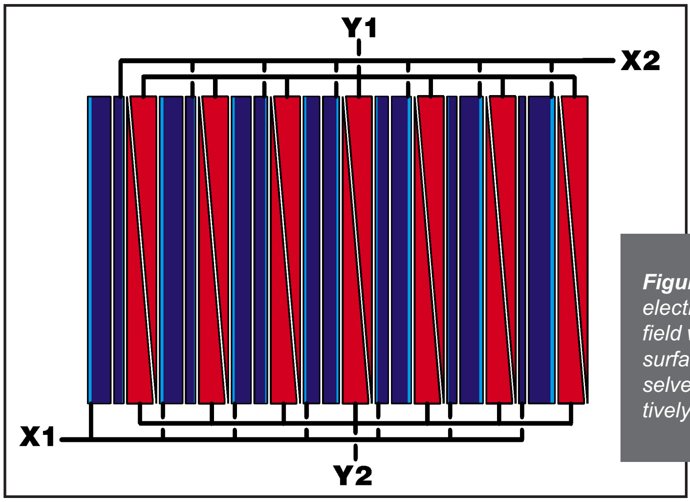


Figure 12 *The tapered elements of the electrode array provide a ratiometric field which is coupled through a covering surface, in this case the keys themselves, and 'mixed' to provide a relatively smooth and graduated field.*

The signal ratios of the X1/X2 and Y1/Y2 channels are used to locate the user's hand. Ratiometric operation involves first normalizing the signal levels to compensate for hand size and fingertip pressure. Each channel axis pair uses the equation:

Eqn 5:

$$\frac{X_1 - K_A}{X_2 - K_A};\ X_1 \geq X_2$$

and,

$$\frac{X_2 - K_A}{X_1 - K_A};\ X_1 < X_2$$

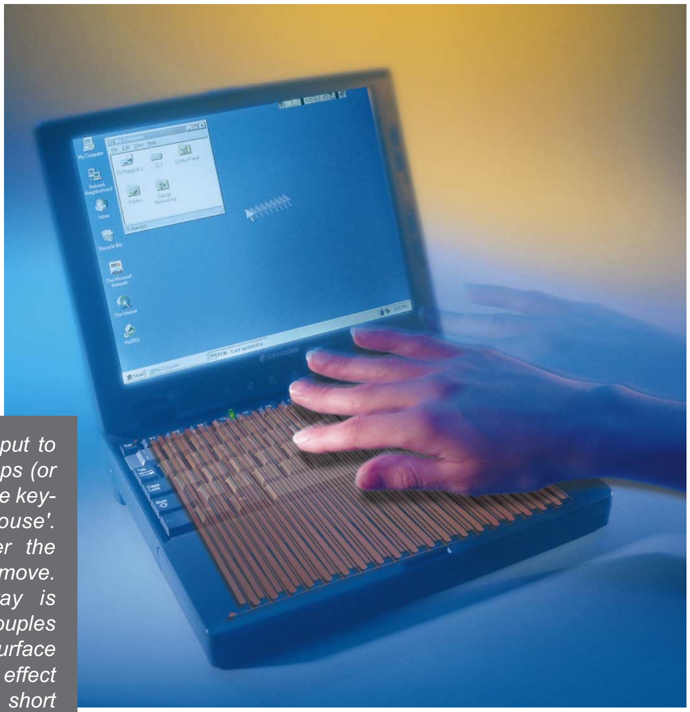


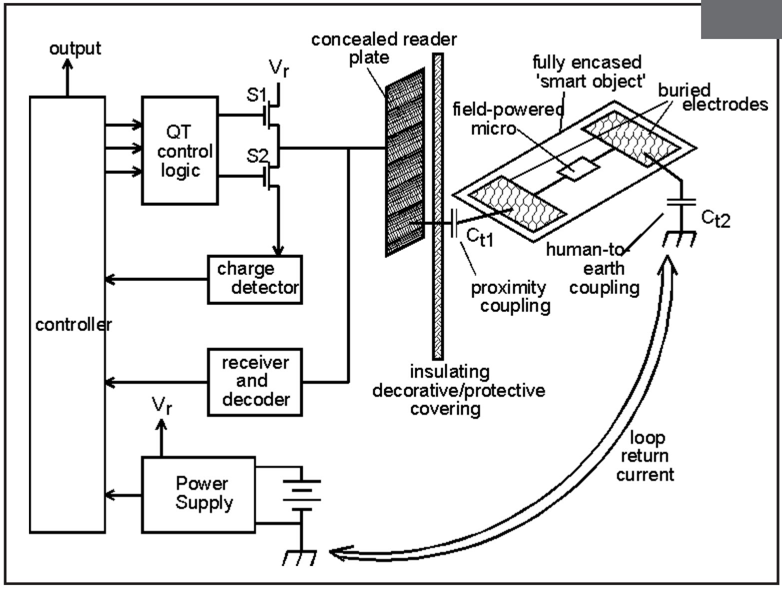
Figure 13 *The QT effect is put to good use in turning the keycaps (or almost any surface) of an entire keyboard into a 'virtual mouse'. Skimming one's fingers over the keycaps makes the pointer move. The tapered electrode array is buried under the keys and couples its field through each key's surface to sense finger position. The effect even can be made to work a short distance in air, giving the unit an ethereal 'crystal ball' like quality.*

Operation of the 'airmouse' has proven to be simple and intuitive, and much less granular than might be supposed. This application is currently being examined by several large computer vendors; it is currently under development by the AirPoint Corporation in the U.S. Other applications of this technology include inexpensive keypad replacement for 'pictogram' cash registers, graphics tablets, touch screens, appliance controls, and the like.

SmartCard Applications of QT Technology

The QT effect can even be gainfully employed with smartcards. Figure 14 shows a card reader can incorporate a QT sensor configured to operate on battery power, whereby the sensor detects the approach of a card containing a capacitively communicative circuit. When proximity detection is ascertained, the reader emits an E-field strong enough to self-power the card. Tests have shown that it is quite simple to power a low-cost CMOS microprocessor in this manner at clock rates fast enough to establish bidirectional 10kb/s data transfers, and have enough power to self-program a non-volatile memory inside the smartcard. This rate is more than enough for the types of transfers envisaged by smartcard vendors. An intriguing aspect of this configuration is that the smartcard need not be inserted into a reader 'slot'; the lack of exposed electrical contacts, and the ability to reverse the card end-for-end without ill effect (in fact, the user enjoys almost complete freedom of positional presentation to the reader) makes for a bulletproof system. Also, the 'smartcard' can actually be a pendant or article of jewelry such as a ring if desired; the physical form of the card is no longer important. The ability to operate the reader on battery power is a crucial factor in many applications, such as electronic locks embedded within a door. The ability to seal or conceal the reader behind an insulating surface adds additional design and marketing possibilities.

Figure 14 *QT based circuitry can implement a smartcard system composed of a battery powered slotless reader capable of being hidden behind almost any surface, for example within a door, while the smart card is self-powered from the field. Power couplings of 1mW are relatively easy to obtain. Data transmission occurs capacitively through a self-clocking scheme while the card is being powered from the same field; data flow is bidirectional.*



RF based ID systems have some of these traits, but fail to couple enough power reliably to do truly 'smartcard like' things. Security is also an issue with RF based cards, as the signals that are intentionally radiated from the system propagate freely. In contrast a capacitance based system does not radiate much RF energy, and its field is confined largely to the centimeter range. Capacitive systems operating at millimeter range (i.e. physical contact) should be acceptable in virtually all situations. A similar version of the capacitive ID system is also being investigated by IBM, while the system described here is currently available for license from Quantum Research Group Ltd.

Capacitive Tomography Applications

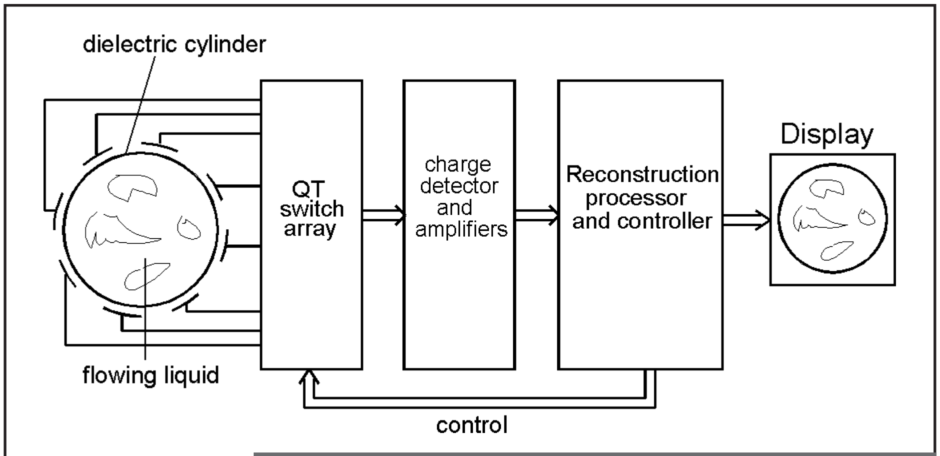


Figure 15 *Each electrode's capacitance to all the other electrodes around the cylinder is measured using a multiplexing technique. The method is fast enough to reconstruct images in real time at 160 frames per second.*

Work done at the University of Manchester and other universities on capacitive tomography has been ongoing since the early part of the decade. Capacitive CT work involves a variation on the QT sensor described in this paper; the QT sensor described so far is a single-ended system with an earth or chassis reference. CT technology requires the use of differential sensor methods to examine capacitances among a number of electrodes radially positioned on the outer surface of a dielectric pipe (or inside a metallic pipe). Cross-capacitances among the various electrodes are used to reconstruct images of the contents of the pipe in real time (Figure 15). The resulting images have been computed at frame rates up to 160/second and 32 x 32 pixel images, more than adequate to make respectable quantitative measurements on flowing materials at high speed. Higher pixel resolutions are obtainable at correspondingly higher cost. Other materials aside from fluids can readily be examined as well. Figure 16 shows images of a flame within a cylindrical housing approximating an engine cylinder; 6 capacitive electrodes are positioned around its inner walls. Figure 17 shows how each sensing channel is implemented. A switched driver composed of S1 and S2 pulses one end of the differential capacitance Cx, (which is any one of the permutations of capacitive couplings among the 6 electrodes around the pipe), while switches S3 and S4 are switched in quadrature with S1 and S2 respectively, presenting the opposite end of Cx with a virtual ground into which is captured an amount of charge Qx = Vr x Cx. Two lowpass filters provide an output for each edge transition; when the difference of these output voltages is taken the value of Cx can be ascertained:

Eqn 6:

$$V_S = V_B - V_A = 2f\,V_r R_f C_X + e2 - e1$$

where f is the operating frequency, and e1 and e2 are error voltages from mismatched edge transitions, switch charge injection, and the like. The errors largely cancel, while any residual error is subtracted algorithmically. The result is an extremely stable, repeatable signal, resolvable enough to reconstruct real-time images of great clarity with little additional filtering. A standard linear back projection algorithm is used to reconstruct images using an ordinary

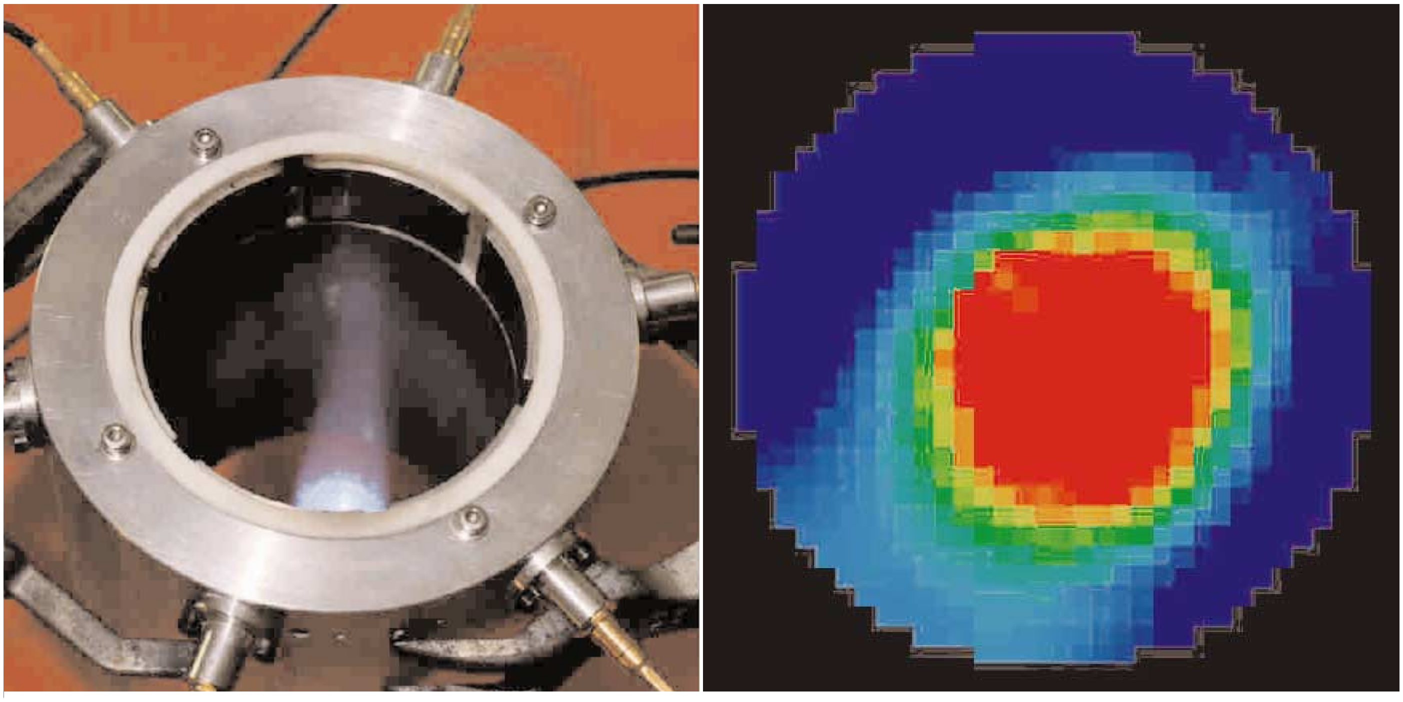


Figure 16. *The capacitive tomography system can even image ionized gases, such as this propane flame. Other applications include the imaging of multiphase oil pipelines and fluidized beds.*

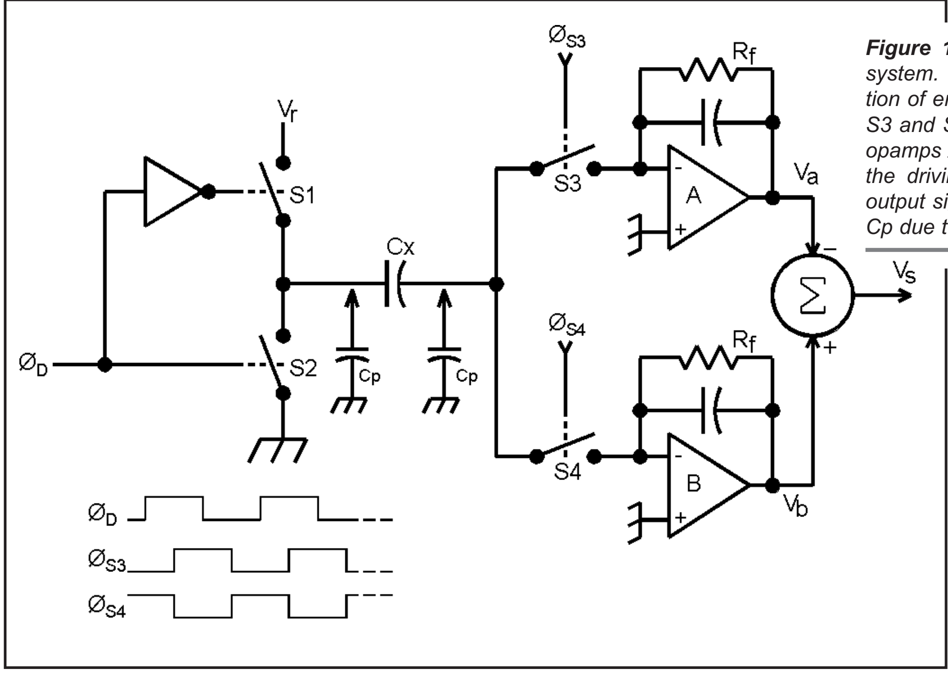


Figure 17 *Sense circuit for each channel of a CT system. Differential circuitry promotes the self-cancellation of error terms in the resulting signal. The switches S3 and S4 close in quadrature with S1 and S2, so that opamps A and B receive charge from opposite edges of the driving signal. The difference Vb - Va gives an output signal representative of Cx. Parasitic capacitors Cp due to cabling etc. are effectively ignored.*

Pentium-class PC. Systems of up to 12 channels are currently being manufactured by Process Tomography Ltd.

A characteristic of this type of circuit is the ability to tolerate large amounts of parasitic capacitance Cp in the cabling and switches. Since this version of the QT sensor employs differential sensing, capacitances to earth are effectively suppressed. Differential sensitivities of 0.1 femtofarad have been achieved routinely for some time using such circuitry, while improvements are now permitting resolutions approaching an almost unimaginable 0.01 femtofarad.

Design Considerations

An Achilles heel of the QT sensor when used with open sense elements is its need for a good quality ground reference in the local sensing environment, and low impedance connections to both ground and sense object. For self-contained sensing heads this is not a large concern, as the ground reference and sense plate are built into the sensor and are in close proximity to each other. However, for large freestanding electrodes the effects of rapid transfer currents should not be underestimated. Poor, excessively inductive wiring with short S1/S2 closure times and high Cx loads will create serious ringing and ground bounce problems which destroy transfer efficiency and linearity. These effects can be minimized by keeping connections short and of low inductance; they can also be minimized by simply using longer S1/S2 closure durations. Adding a series-R to the sense lead will provide damping to stop ringing. With small, close by objects ringing is not so much an issue; usually there is enough resistance in the switches, and voltage slew rates can be slowed enough to prevent observable problems. In any QT sensor application however, the effects of connection quality should be fully evaluated and understood.

In designing a QT circuit care should be taken to understand the nature of charge injection from the transfer switches. Not all switches are equal, and few make good choices. That being said, there are still a good number of suitable devices commercially available at reasonable cost. Parameters to look for are low output and reverse transfer capacitances, while maintaining suitably low on-resistances to allow sufficient settling time within the transfer duration. A poorly documented source of capacitance is the output capacitance due to the substrate diode found in nearly all mosfets. This lack of documentation means that the designer must rely on vendor-supplied Spice models, or resort to 'real-world simulation', i.e. testing samples.

While it is tempting to use commercially available integrated analog switches for S1 and S2, the designer should be aware of the effects of control delay time. In many sensing systems a large time gap between the opening of S1 and closing of S2 is fatal; during such an interval leakage currents across Cx can drain Cx's charge, making the resulting signals noisy and unpredictable. Most analog switches, even those purporting to be fast are fast only in the sense that they will have a wide signal bandpass, not have a fast turn-on or turnoff time. Using mosfets as switches gives the designer more control over transfer timing, and is potentially less expensive as well.

The designer should also be aware of reference voltage stability issues. Most series-pass voltage regulators do not have nearly enough transient stability to cope with the rapid transfer of charge into the sense electrode; load recovery times only prolong when using large supply bypass capacitors, often making the situation worse. Some of the newer IC pass regulators promise reference-diode stability, but the truth is that these too suffer from transient load recovery problems due to slow internal feedback paths. For the highest sensitivity QT systems there is no substitute for a fast, high stability reference diode.

Conclusion

Grounded in a principle dating to the 1700's, the QT sensor offers a new twist to high reliability capacitive proximity sensing. Offering tremendous new potential, QT sensor technology promises to not only replace older sensor designs at lower cost and higher performance, but to find its way into a wide variety of novel applications heretofore considered impossible.

PATENT NOTIFICATION

Considerable material disclosed in this article is the subject of patents granted and applied for. Consult appropriate party for details.

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Figure 1 courtesy The Granger Collection.

FOR FURTHER INFORMATION

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