

# Advanced Sensors and Their Interface Circuits: Review and Perspective

Ramon Pallàs-Areny, *Fellow, IEEE*

Electronic Eng. Dept., Technical School of Castelldefels (EPSC), Technical University of Catalonia (UPC)  
Avda. del Canal Olímpic s/n, 08860 Castelldefels (Barcelona), Spain

**Abstract** — Sensor development started with process control demands but it is currently fostered by applications requiring sensors embedded in products, packages, and our environment. Sensors developed for specific markets often create unexpected markets. Sensor advances are linked to progress in materials and IC manufacturing technology, and benefit from both classical and novel sensing principles. MEMS, ceramics, thin films, organic polymers, and fiber optics have yielded sensors that are both displacing legacy sensors and opening new application areas. Sensor interface circuits benefit from: (a) more accurate and less expensive general purpose analog components; (b) IC signal conditioners tailored to specific sensor types; and (c) low-cost mixed signal circuits able to provide inexpensive computation and communication capabilities. The convergence of computing, communications, and sensors is leading towards sensors networks. Autonomous sensors in wireless sensor networks nodes need power-efficient signal and power conditioning, as well as signal communication and network management.

**Index Terms** — Sensors, sensor interface circuits, autonomous sensors.

## I. INTRODUCTION

Electronics pervades our world to the extent that it permeates our daily life. Every citizen of any developed or developing country interacts with electronic equipment a few times a day: from mobile phones to personal entertainment equipment, from digital clocks to TVs. Less visible but more pervasive, millions of data processors control and communicate a myriad of systems whose existence has become inherent to our civilization, often determining some of their characteristic tracks. Utilities, transportation systems, financial institutions, hospitals, and factories, to name a few, depend on data processing. Whenever data come from physical or chemical quantities, sensors are involved, so that sensors are ubiquitous.

Sensors are devices or systems that yield an electrical output from a different physical or chemical input. They rely on (a) material properties that depend on the sensed quantity or (b) geometry changes produced by the physical input (Fig. 1). Some quantities are better sensed by system-based solutions rather than component-based solutions. Sensor systems often work by detecting changes (e.g., in

amplitude, frequency or direction) undergone by some radiation (mechanical, electromagnetic, corpuscular) as a result of its interaction with the object, process, or system whose property must be detected (Fig. 2). Sensor arrays have been common in military applications for several decades. Nowadays, the convergence of computing, communications, and sensors is leading towards sensors networks.

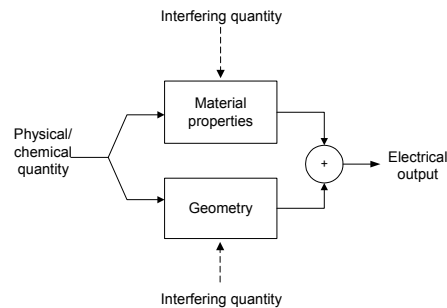


Fig. 1. Sensors are based on material properties or on changes in geometry.

Sensors seldom yield an electrical signal directly suitable for the ensuing signal processing stage, which often is a digital processor. Sensor interface circuits provide signal conditioning and conversion, and their performance has improved to the extent that the accuracy and resolution of sensor-based measurement systems is currently limited by the sensors themselves, not by the ancillary electronics.

This paper reviews some recent developments in sensor components and their interface circuits, and in sensor systems, providing specific examples that illustrate some significant changes in those areas. Also, a perspective is given of current trends that may lead to possible future advances.

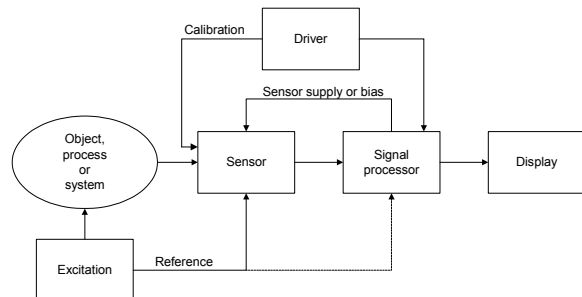


Fig. 2. Basic structure of a sensor-based measurement system

## II. DEVELOPMENTS IN SENSORS AND SENSOR SYSTEMS

Electronic sensors were born in industrial process control and automation, where they became common by mid 20<sup>th</sup> century. Initially, they relied mostly on old principles discovered during the 19<sup>th</sup> century, to the extent that some early sensors were but a robust implementation of contrivances used in experimental science [1] [2]. They were labor-intensive to manufacture, bulky, and heavy, often used expensive materials, and their installation and maintenance costs were high. Potentiometers, thermocouples, LVDTs, and RTDs are typical examples of those macrosensors.

The invention of the transistor and the integrated circuit in the 1950s, and the consequent better knowledge of semiconductors and semiconductor processing, brought a new paradigm: sensors specifically developed for industrial and medical applications, some of which were feasible because of the advances in electronics.

Nowadays, sensors are not only built in production equipment to perform physical (machinery) or chemical (food, cosmetic, drugs) measurements; they are increasingly embedded into products. Strikingly enough, it soon turned out that electronic equipment itself needed sensors for proper behavior and user interaction, and this opened new markets. Thermal management in computers boards is a good example.

### A. Sensor Materials

Silicon has become the material with stronger impact in sensors, because of both its electrical and mechanical properties, and because of its use in electronic circuit interfaces. However, whereas the impact of silicon-based signal processing was immediate, the impact of silicon-based sensors took more than 20 years to be felt, through micro-electromechanical systems (MEMS). Piezoresistivity was first observed in germanium at Bell Labs in 1954. Germanium strain gages were made by researchers at Toyota in 1956.

The first silicon pressure sensor was produced by Honeywell in 1962. Silicon strain gages were first made commercially available by Kulite in 1975. But it was the pursuit of a suitable low-cost sensor for sensing fuel and air pressure in order to meet the EPA (USA) standards on pollution control in internal combustion engines that lead to the first MEM pressure sensor in 1976. A few years later they were also used as disposable catheter-tip blood pressure sensors. It took yet a few more years before the first textbooks about sensors based on silicon [3] and other semiconductors [4] were published.

Fiber optic (FO) sensors were unheard of before 1977, but a review published five years later [5]

showed that their inherent advantages and the prospect of reduced costs because of the rapid development of FO communications had resulted in an impressive research effort in many different application areas. Most FO sensors use the cable as a light-channeling tool to perform photoelectric measurements in reduced spaces, remote locations, intrinsically-safe environments, harsh environments with strong electromagnetic interference, or for small-object detection. Some FO sensors rely instead on changes in index of refraction or mechanical deformation.

There are commercial FO sensors available for temperature, pressure, strain, displacement, force, and load. But their high cost often restricts them to special applications. Nevertheless, the ring laser gyroscope (RLG), which is based on interferometry, has been a major breakthrough. Because of its reduced volume, weight, and cost, it is displacing traditional spinning-mass gyroscope systems in aircraft.

Ceramics consist of a large number of crystals randomly-oriented with respect to one another and joined together via grain boundaries. Ceramics respond to physical or chemical quantities through changes in their bulk, grain boundaries, or surface properties. NTC and some PTC thermistors and piezoelectric sensors are built from ceramics. Ceramic gas sensors based on zirconia ( $ZrO_2$ ),  $SnO_2$ , and  $TiO_2$  have been available for more than 30 years, but many other materials are being tested to improve sensitivity, specificity, and service life. Ceramics resist corrosion, abrasion, and high temperature, so that they are also used as resistive elements in potentiometers, and as a support for other sensing materials, for example diaphragms in high-temperature pressure sensors, or thin-and thick-film gas sensors, which need temperatures as high as 700 °C to work properly.

Organic polymers are macromolecules formed when many equal molecules (monomers) bind together by covalent bonds. Polyvinylidene (PVdF) is a polymer with piezoelectric properties discovered back in 1969. Improvements in its manufacturing process and in electrode deposition have extended its application to hydrophones, tactile sensors, musical instruments pickup devices, switches, and infrared detectors (because it is also pyroelectric).

Polymers become conductive when relatively good conductors such as powdered silver or carbon are added to them. Alternatively, layers of polymer and conductor are superimposed to make pressure-dependent resistors. Conductive-polymer-based gas sorption films are the basis of the so-called electronic noses and electronic tongues. Polyelectrolytes, which absorb water vapor, make humidity sensors. Polymeric resistors with positive temperature

coefficient of resistance (PPTC) are used as resettable fuses and overcurrent protectors.

Materials are not only the basis of many sensors, they also make the package that interfaces and protects a sensor from the environment. Stainless steel packages common in industry applications are too expensive and heavy for some non-industrial uses. Ceramic packages have replaced metal packages for MEMS-based accelerometers, and are being replaced by surface-mount plastic packages. Mold-injected plastic packages have already reduced the foot print and cost of many sensors, so that they suit consumer products.

### B. Sensor Technology

Silicon integrated circuit manufacturing produced CCD cameras already in 1970 (in Philips' Research Labs and Bell Labs, independently), and has led to Microsystems technology (MST), probably the most important change in sensors in the last 10 years. MEMS-based pressure and acceleration sensors are annually shipped by the millions: from 3 million (mostly traditional) pressure sensors shipped in 1985 to 40 million microsensor units in 1995, nine years after their introduction; Analog Devices shipped its the first commercial surface-machined accelerometer (for automotive airbags) in 1993, and in 2002 shipped its 100 millionth unit, some of them with two-axis sensitivity.

MEMS-based thermopiles, microphones, and silicon resonators and quartz tuning fork gyroscopes are also commercially available. Many different microsensor types are under development [6]. Photoelectric sensors and CMOS cameras and color sensors are other results of IC technology, which has brought radical improvements in size, efficiency, versatility, and cost-effectiveness. Interestingly, pressure and acceleration sensors developed for the automotive industry have found application in several other areas. Acceleration sensors, for example, are also used for tilt, inclination, and position measurement, and for platform leveling.

Thin-film materials, either insulating (PVdF, polyamides, and some plastics) or conducting (platinum, permalloy), are used in sensors because they permit a better control of the desired properties than bulk materials, i.e., a good sensitivity to the desired quantity and a reduced sensitivity to interfering quantities (Fig. 1). They also result in smaller (hence, faster) sensors: the classic Pt100 wound-wire temperature sensor, is making room for the Pt1000 and Pt10000 thin film units, far less sensitive to lead resistance changes. Surface acoustic wave (SAW) devices, able to detect small amounts of gas through physical resonance in selective thin- and thick-film layers, are becoming increasingly important

because safety- and security-related applications involving gas sensing are mainstream areas for sensor development.

### C. Sensing Principles

Most MEMS sensors are based on classic sensing principles: pressure sensors rely on piezoresistivity or capacitance variation, accelerometers use (tiny) seismic structures together with capacitance variation or piezoresistivity, microphones use a diaphragm and capacitance variation, thermopiles are based on the Seebeck effect, and quartz gyroscopes use a tuning fork. Nevertheless, there are microsensors that would not be practical as macrosensors, for example the thermal microaccelerometer in Fig. 3, where a heated air bubble is displaced in the sensor cavity under applied acceleration, and yields a difference in temperature between the two temperature sensors. The result is a small, accurate, robust, and inexpensive accelerometer.

The application of other classic principles to sensors has become feasible thanks to improvements in interfacing electronics. The charge transfer sensor in Fig. 4 [7] is based on the charge conservation principle: when a capacitor holding a charge is connected to an uncharged capacitor, there is a charge transfer from the first capacitor to the second, so that the voltage across them is the same. No charge is lost in spite of energy dissipation in the switches and wiring.

During the charging phase, the unknown capacitance is charged at a reference voltage; next, the charge is transferred to a known capacitor ( $C_s \gg C_x$ ) and the voltage across it is measured. The main advantage of this sensing principle is its simplicity, because any pair of conductive surfaces can become the electrodes of  $C_x$ , whose value will depend on their separation. High resolution in capacitance measurements has also lead to electrical absolute digital encoders, which have less power consumption and vibration sensitivity, and more durability and temperature range than optical encoders.

Coriolis mass flowmeters were first marketed in 1978. They remain unaffected by changes in fluid pressure, density, temperature, or viscosity, and the accuracy of modern models is better than 0.2 %. Cost reductions derived from technology improvements have resulted in their increasing market share, particularly in the pharmaceuticals and food and beverage industries. Technology improvements have also brought a revival of interest in the Wiedemann effect, which is the basis of magnetostrictive position sensors.

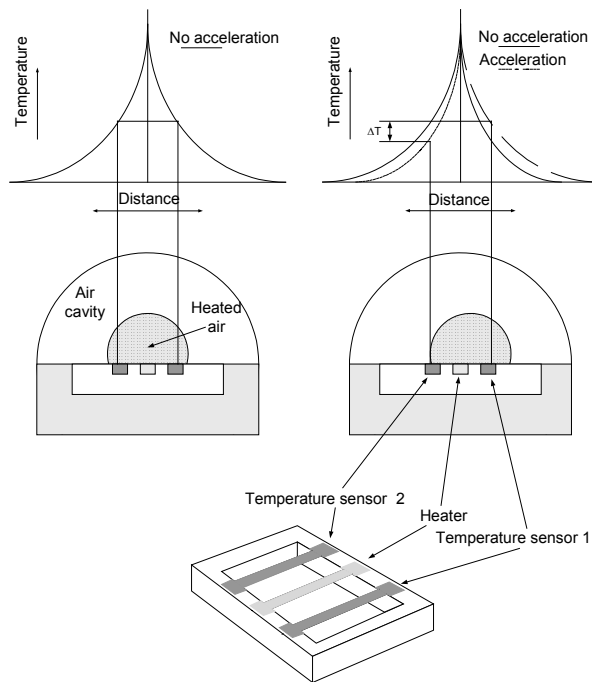


Fig. 3. Thermal accelerometer (Memsic)

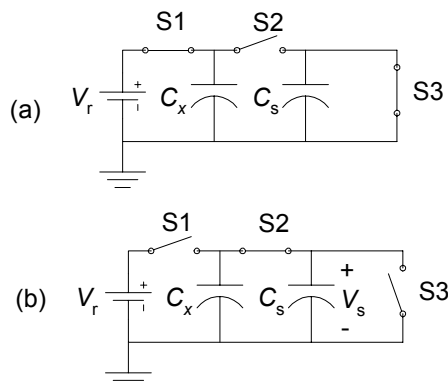


Fig. 4. Basics of the charge-transfer sensor: (a) Charging phase; (b) Charge transfer and voltage reading

Novel sensing principles also result from material research. The giant magnetoresistive effect, first observed in 1988 in a multilayer of nonmagnetic and magnetic thin layers, led to GMR sensors in less than 10 years. They are more sensitive and have a larger bandwidth than classic AMR sensors.

#### D. Sensor Systems

Sensor systems have been common in military applications since Cold War years [8]. Surveillance hydrophones and radars were connected in a point-to-point or star topology where sensing, processing, and communication were separate. Control applications in industry initially adopted such a centralized architecture, but the advent of the microprocessor

progressively led to distributed control systems based on a digital bus. Different buses predominate in different industrial sectors, in spite of standardization attempts. Sensors have remained analog until recently, which implied large installation and maintenance costs. The IEEE 1451.x family of Standards for Smart Transducer Interface for Sensors and Actuators (Table I), aims to provide plug-and-play capabilities for smart sensors in various buses.

Impedance- and radiation-based sensor systems enable non-intrusive and, in some cases, non-contact measurements that would otherwise be difficult or impossible to perform. Ultrasound, microwave, and infrared (IR) radiation are used in robot navigation and are the basis of commodity sensors for intruder or presence detectors. Ultrasound flowmeters, first marketed in 1955, suit measurements in the food and pharmaceutical industries, medical and waste-water applications, and are increasingly used for custody transfer of natural gas. Microwave and TDR (time-domain reflectometry) are replacing float and differential-pressure level sensors in tanks containing other than clean fluids.

TABLE I

FAMILY OF IEEE 1451 STANDARDS

Standard	Description
1451.1	Network Capable Applications Processor (NCAP) Information Model
1451.2	Transducer-to-Microprocessor Communications Protocols and Transducer Electronic Data Sheet (TEDS)
1451.3	Digital Communications and TEDS Formats for Distributed Multidrop Systems
1451.4	Mixed-Mode Communication Protocols and TEDS Formats
1451.5	Wireless Communication Protocols and TEDS Formats

Process tomography is the non-invasive imaging of the concentration distribution, flow regime, vector velocity, thermal, and other physical properties in closed vessels. It can use ionizing radiation, microwave, ultrasound, or, most commonly, electrical resistance or capacitance measurements [9]. Process tomography started at the end of the 1980s and it is still a research area but there are already several systems working in industry. The variety of situations often calls for custom solutions. Fig. 5 shows the basic elements of Electrical Capacitance Tomography: an array of electrodes around the intact vessel inject a voltage or current using a pair of electrodes and the voltage difference between other electrodes pairs is measured. The injecting and detecting electrodes are switched under computer control, and an image reconstruction algorithm calculates the distribution of electrical permittivity (or conductivity).

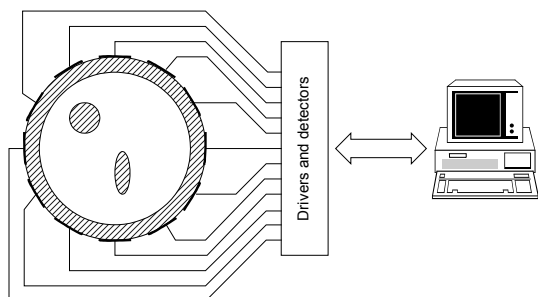


Fig. 5. Electrical capacitance tomography

Impedance spectroscopy is another powerful, and non-intrusive, sensing technique that depends more on signal processing than on rare materials or expensive technology. Electrical impedance is a property inherent to all materials that is sensitive to many physical and chemical quantities. The frequency dependence of that impedance permits us to identify several discrete components describing it [10]. If the quantity of interest modifies the value of those components, its value can be obtained from impedance measurements. Fig. 6 shows two representations of the frequency dependence of a three-component impedance. Those components can be measured by using a single square wave, which is convenient in digital systems [11].

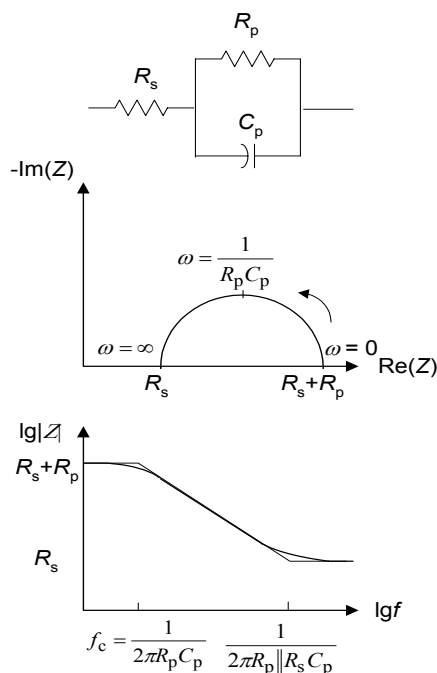


Fig. 6. Frequency-dependent impedance

Ion mobility spectrometry (IMS) identifies chemical substances by measuring the time it takes for each specific molecule to reach a collector electrode after being ionized in a chamber. Ion mobility spectrometers can detect chemical agents in gas samples in seconds, which make them good candidates for airport checks. Nuclear quadrupole

resonance (NQR) is a competing technology based on processing the faint RF echo from the nuclei returning to their initial orientation after an RF pulse of specific frequency has been applied to the material.

### III. DEVELOPMENTS IN INTERFACE CIRCUITS FOR SENSORS

Sensor devices need signal conditioners to adapt their output for further signal processing, transmission, display, or recording. Signal conditioning involves amplification, level shifting, filtering, impedance matching, modulation, demodulation, isolation, and other functions [12]. Modulating sensors also need a voltage or current supply or bias (Fig. 2). Control transmitters integrate sensors and signal conditioners to yield a standardized transmission signal. The evolution of electronic circuits performing those functions has resulted not only in a better system performance but also in changes in sensor structure, leading to the so-called smart sensors, which integrate sensing and processing. Another development has been the addition of analog outputs to sensors that formerly offered only a discrete (digital) output, such as photoelectric, inductive proximity, and ultrasound proximity sensors.

#### A. Analog Signal Processors and Converters

The first signal conditioners for sensors were mostly resistance or impedance bridges derived from 19<sup>th</sup> Century circuits, and dc amplifiers based on chopper techniques implemented with discrete components. IC op amps brought the first major change to signal conditioners in the early 1970s. They offered low-power consumption and high reliability at a relative low cost. Today, op amps with less than 1  $\mu$ V offset voltage and 0.1  $\mu$ V/ $^{\circ}$ C drift are readily available. IC instrumentation amplifiers reduce component count and permit us to easily implement signal conditioners for fully-differential signals [13] and other analog processors unrelated to legacy bridge circuits. Voltage-reference ICs are helpful in building constant current sources and offer accurate voltages for system calibration.

Analog-to-digital converters (ADCs) are the sensor interface circuits that have undergone the more spectacular evolution. In the middle 1970s, the typical resolution was 10 b and high performance meant 14 b with 25  $\mu$ s conversion time. The advent of monolithic sigma-delta converters in mid 1980s changed the paradigm. Today, they offer 24 b resolution at 40,000 samples/s (25  $\mu$ s/sample) for about 5 USD. This high resolution makes amplifiers redundant in some applications. Further, some sigma-delta ADCs integrate fast multiplexers and even programmable-gain instrumentation amplifiers, so that, in spite of an effective resolution below 19 b, they are much more accurate than common sensors. Voltage references do

not achieve that accuracy, but many sensor interfaces measure ratios, not absolute values. Yet other models offer a programmable digital output filter. Current ADCs with 14 b resolution offer a sample rate of  $125 \times 10^6/s$ . Fast ADCs permit the direct conversion of ac signals, for example for digital demodulation. In the last decade, sigma-delta and successive approximations ADCs with differential input have become available; they are more immune to interference than common units with single-ended input.

Signal isolators are a common solution for ground loops but they are also increasingly used because many current designs require multiple voltages. Optoisolators (or photocouplers) use compound semiconductors IR emitters, such as gallium arsenide, which need specific technology processes. Non-optical isolators such as those based on planar magnetics and GMR use technologies that are compatible with silicon ICs, hence less expensive.

### B. Specific Sensor Interfaces

Some sensor types are so common that dedicated sensor interfaces ICs are available that permit us to build a sensor-based measurement system using a minimum of parts, hence increasing its reliability. Thermocouples, for example, need cold-junction compensation and this function is now electronically provided by specific ICS (AC1226, LT1025), some instrumentation amplifiers (AD594/5) and monolithic data-acquisition systems-on-chip. LVDTs need ac supply and synchronous demodulation, which are also available in a single IC (AD598, AD698). The UTI (Smartec) can provide interfacing for capacitive sensors, RTDs, thermistors, resistive bridges, and potentiometers. Some ADCs designed for sensor interface include auxiliary functions such as excitation current for RTDs. The ADE7758 (Analog Devices) is an energy-metering IC with less than 0.1 % active energy error over a 1000:1 dynamic range, which includes a current sensor interface for current transformers and an on-chip digital integrator for  $di/dt$  sensors.

Bridge type circuits such as MEMS-based pressure and acceleration sensors are very sensitive to temperature, which is a serious shortcoming in automotive applications, their main market. Common ICs do not withstand the extreme temperatures involved ( $-40^\circ\text{C}$  to  $125^\circ\text{C}$ ), and this has led to specific signal conditioners that perform the necessary drift corrections, and even linearization. Some examples are: EM6415 (EM Microelectronics), MAX145x and MAX146x (Maxim), MLX90218 and MLX90308 (Melexis), and ZMD31051 (ZMD).

### C. Smart Sensor Systems

The interest of integrating signal processing functions in sensors was soon recognized after the advent of ICs. In the early 1980s, Honeywell had integrated amplification, temperature compensation, and output normalization in pressure sensors. In the early 1990s, digital signal processing and communication capabilities were added to many sensors in multichip solutions. Digital potentiometers, introduced in the late 1980s, simplified circuit trimming and gain selection under digital control. The effort for making sensors “intelligent” came from opposite ends in the measurement chain. Analog sensor makers added mixed signal conditioning to their devices, so that they provided a high-level, or even digital or quasi-digital output, easy to interface with digital processors. Obviously, this solution worked only for silicon-based sensors, such as pn-junction temperature sensors, photodiodes, and Hall-effect sensors. ADC manufacturers added front-end functions and a microcontroller core plus some ROM and RAM in order to accept low-level inputs from sensors and control the data acquisition and processing functions.

The AD590 was the first IC temperature sensor [14]. It produced an output current proportional to absolute temperature ( $1 \mu\text{A/K}$ ), with a  $\pm 1^\circ\text{C}$  calibration error and  $\pm 0.5^\circ\text{C}$  nonlinearity error in 1978 models (AD590L); the current AD590M has  $\pm 0.5^\circ\text{C}$  calibration error and  $\pm 0.3^\circ\text{C}$  nonlinearity error. The TMP05 uses the same sensing principle but integrates a sigma-delta modulator in the same chip to produce a PWM output with  $\pm 1^\circ\text{C}$  typical error from  $0^\circ\text{C}$  to  $70^\circ\text{C}$ . Similarly, the TSL257 is a light-to-voltage converter that integrates a photodiode, op amp, and feedback resistor on an IC, whereas the TSL245 is an infrared light-to-frequency converter that combines a silicon photodiode and a current-to-frequency converter on a monolithic CMOS chip. Other temperature sensors (ADT7301, DS1291, LM75) feature a serial-digital output, some with programmable set point facilities and logic outputs for undertemperature and overtemperature sensing.

Linear Hall-effect sensors have also experienced deep changes since digital models were first introduced to avoid mechanical bouncing contacts in keyboards. Some linear IC models integrate the Hall-voltage generator, signal amplifier, chopper stabilization, and MOSFET output in a small, inexpensive package. Other, such as the MLX90251 (Melexis), compensate offset errors and have programmable sensitivity and output voltage for  $B = 0$ . The CSA1 (Sentron) is also CMOS and programmable, but unlike conventional Hall sensors, that only measure the field component perpendicular to the chip surface, it responds to fields parallel to the chip surface.

Microcontrollers oriented to smart sensors design are a hot topic with many players. Fortunately, some IC manufacturers, such as Analog Devices (ADuC 812) and Goal Semiconductor (VERSA MIX devices) offer products compliant to Std. IEEE1451.2. Microcontrollers with analog and mixed signal components (comparator, ADC, op amp) are increasingly available, which reduce the number of parts needed to build a smart sensor system. Digital Signal Controllers (DSCs), processors whose architecture combines elements of microcontrollers and DSPs, are new players in this field [15].

#### D. Direct Sensor-Microcontroller Interfaces

Traditional analog sensor interfaces rely on ADCs preceded by signal conditioning and, sometimes, analog signal processing. ADCs can be direct or indirect. Direct converters rely on multilevel voltage comparison and indirect converters rely on counting the elapsed time between a start and a stop instant, one of which at least is determined by a voltage trigger. Some microcontrollers embed a timer/counter with trigger input, which involves a single voltage comparison. Therefore, microcontrollers can easily implement an indirect ADC and, if the time interval to measure (pulse width, signal period) is a sensor output, they provide a simple sensor-to-digital code converter. By carefully reducing the trigger noise, which depends on power supply noise and program-related transients [16] [17], it is possible to build direct sensor-to-microcontroller interfaces for resistive sensors, either single, differential, or connected to form a four arm bridge, able to correct zero and gain errors, to achieve 12 b resolution [18]. Direct microcontroller interfaces for capacitive and inductive sensors are also feasible. Self-generating sensors need a previous conversion from their output to frequency.

Fig. 7 shows a method to directly connect a sensor bridge to a microcontroller [12]. The sensor bridge is considered to be a resistor network with three inputs and one output. The resistance from each input to the output depends on the measured quantity. Using each input in turn to charge a capacitor connected to the output, with the two other ports at high impedance state, we obtain three times. Calculating  $(t_1 - t_3)/t_2$ , yields the fractional resistance change in each arm (assuming it is linear and equal for the four arms). This low-cost method is suitable for embedding sensors in home appliances and common objects.

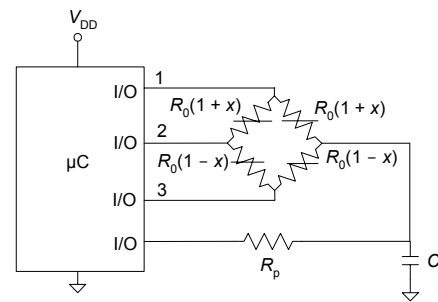


Fig. 7. Direct sensor-bridge to microcontroller connection

#### IV. TRENDS IN SENSORS AND THEIR INTERFACE CIRCUITS

Recent development (and, in some cases, market analysis) suggest that:

- (1) An increasing number of sensors will be developed for specific markets, many of which will be new and belong to non-industrial areas: automotive, aircraft, biomedical and consumer. Sensors will be increasingly common in personal devices (mobile phones, PDAs, garments, medical surveillance). Overall, the compound annual growth rate (CAGR) will be larger for modern sensors than for traditional sensors, but these will continue to grow because of their better performance and capability to withstand harsh environments.

The tendency will continue to embed sensors in: (a) a variety of products (cars, trains, airplanes, ships, electrical appliances, communication and entertainment equipment, computers); (b) packages (for identification, location tracking, condition monitoring); and (c) our environment, for comfort, safety, and security (public buildings; infrastructure: bridges, highways, roads; air, water, radiation and noise monitoring, continuous patient assistance, biometrics). Cars will need new sensors for mechatronic braking (current, position, and force measurement), seat occupancy detection, navigation, and collision avoidance. Safe fuel cell deployment will need faster hydrogen sensors. Sensors will of course remain essential for process control.

- (2) Modern sensors (both microsensors and macrosensors) will achieve greater sensitivity and better specificity, extended measurement ranges and withstand harsher ambient conditions than current sensors. Ocean bottom exploration and exploitation, oil rigs, aerospace, and military applications will push the limits for extreme conditions operation (temperature, pressure, shock, vibration, liquid environments).

When considering sensitivity and specificity limits in sensors, Nature still poses challenging targets for both sensing (Table II [19]) and perception.

TABLE II  
SENSITIVITY OF SOME BIOLOGICAL SENSORS

Biological sensor	Sensitivity
<b>Acoustic (ear)</b>	0.5 nm vibrations
<b>Displacement (scorpion)</b>	0.1 nm
<b>Electric field (fish)</b>	0.01 $\mu\text{V}/\text{m}$
<b>Infrared (snake)</b>	0.1 $\text{mW}/\text{cm}^2$ at 300 K
<b>Magnetic (pigeon)</b>	1 $\mu\text{T}$
<b>Seismic (frog)</b>	1 $\mu\text{g}$
<b>Sight (dark-adapted eye)</b>	10 photons/s $\text{cm}^2$
<b>Smell (moth)</b>	1 molecule
<b>Ultraviolet radiation (bird)</b>	$10^{10}$ photons/s $\text{cm}^2$

- (3) Most future sensors will be based on traditional sensing principles applied to new materials or using MEMS or nanotechnology involving electrical and optical signals. Time to market for those sensors will be shorter than it was for the first MEMS sensors, perhaps less than five years.

The same as MEMS-based pressure and acceleration sensors were targeted to the automotive industry because of mandatory regulations, further regulations and the current emphasis on personal and homeland security will foster sensor development for particular markets and then diffuse to other markets. MEMS-based pressure sensors in particular would undergo a further thrust if tire pressure (and temperature) monitoring became mandatory. Other MEMS-based sensors such as accelerometers, gyroscopes, gas and liquid flow sensors will also grow. Magnetic sensors will benefit from spintronics and developments in computer data storage research, which may bring new sensing principles or devices, such as the ballistic magnetoresistance effect (BMR), magnetic tunnel junctions, and nanopillars.

Nanosensors and nano-enabled sensors are very attractive because their small size makes them fast, light, and low-power. They can be built using top-down manufacturing and also bottom-up methods, which use atoms and molecules to build structures. Some of the problems to solve are similar to those for microsensors [20]: interface requirements, heat dissipation, and the presence of electrical and mechanical interference.

- (4) Non-contact, non-intrusive (radiation-based) sensors will replace legacy contact sensors such as potentiometers and floats.

Macrosensors and sensor systems will continue to benefit from developments in non-measurement application areas and in electronics. For example, virtual cavity surface emitting laser (VCSEL) developed for optical communications may reduce its costs to become available for industrial application.

Microcontrollers will embed a larger number and variety of better analog components (op amp, comparator, voltage reference, ADC), so that adding more intelligence to sensors will be inexpensive. Field-Programmable Analog Arrays (FPAA), which offer programmable connectivity and parameter control, may finally find market acceptance for reconfigurable signal conditioning and filtering.

- (5) Image-based sensing will grow spurred by personal and homeland security-related applications and enabled by the reduced costs of vision sensors and digital signal processors.

Compulsory identity cards with biometric data would create a huge market for face and fingerprint recognition. The former is based on cameras, whereas the later is based on capacitive, optical, thermal, and electric field sensors. Vision systems, often used with robots to find parts and position tools, will be increasingly applied to applications needing high-speed, accurate inspections, data collection, and networking. The integration of digital images with software and controllers will convert cameras in motion-control sensors, rather than simple inspection devices.

- (6) Biosensors, which use biological materials such as immobilized enzymes, antibodies, cells, or tissue slides, to provide a specific response to a particular substance, will solve specificity, durability, and packaging problems to become more reliable.

Biosensors rely on the recognition of a given molecule followed by the transduction of that recognition in a useful signal. Carbon nanotubes, which can have conducting or semiconducting properties, are good candidates for biosensors by functionalizing their ends for molecule recognition.

- (7) Autonomous sensors for mobile robots and wireless sensor networks will rely on energy-harvesting methods and lead to new energy-efficient analog and digital signal-processing methods.

Autonomous sensors in wireless sensor networks do not have any material connection with the system they belong to. They must be battery-supplied or harvest the necessary power from their environment, and have very low power consumption. Consequently, sensing methods, communication and network protocols must be optimized for energy consumption. Novel, efficient, power and signal conditioning methods will be developed. In order to deploy a large number of autonomous sensors, they must be cheap. Advances in IC manufacturing technologies will further reduce manufacturing costs for MEMS-based sensors and electronic devices. In particular, wireless on chips will drastically reduce communications costs. Further



cost reduction will result from signal processing applied to interference compensation, which will relax the specificity requirements for sensors.

- (8) Wireless sensor networks will be common in buildings (for safety, security, and energy and comfort management), industry (machine condition monitoring, data acquisition), traffic and transportation control, and for environmental monitoring.

Sensor networks will be one of the most disrupting technologies in the forthcoming years. Wireless sensor networks in particular will create many opportunities for novel applications. They will benefit of developments in consumer mobile telephones and from defense-oriented research. A panel of experts convened by Battelle in 2003, named the following among the ten top innovations in national security and defense by 2012 [21]:

- A. Information and Intelligence Management: Advanced integrated sensors and reliable networks will provide enormous amounts of real-time information about security threats. The new information technologies will take advantage of rapid progress being made in sensors.
- B. Renewable Energy Sources: New energy sources will appear as advances are made in new generations of alternative energy and batteries. Fuel cells will likely be available by 2012, in both large sizes for tanks and small sizes for soldiers. We will have fuel cells for soldiers with hydrogen cartridges, much like disposable lighters, that will have at least 10 times the energy density and life of a battery.
- C. Advanced Detection and Tracking Systems: We will have non-invasive biological, chemical, and weapon detectors as reliable and easy to use as *x*-rays or metal detectors today. We will see integrated sensors and detectors at airports. By 2012, we will see a new generation of tracking with radio frequency identification tags, homing devices, cameras, and global position systems (GPS) for tracking weapons and other potentially threatening materials.
- D. Individual Warning Devices: In addition to developing chemical and biological detection systems for battlefields, inexpensive sensors will be available to people worried about exposure to unhealthy air, water, and food.
- E. Safe Buildings: The heating, cooling, and ventilation systems of office buildings, public places, and homes were not designed to protect people from biological and chemical threats to their health. New flow control designs, integrated sensors, filtration methods, and automated

response mechanisms will significantly improve the quality of both indoor air and water.

- F. Advanced Multi-Functional Materials: Strides in material science and engineering will greatly improve what soldiers wear and use on the battlefield. Advances in textiles will allow clothing to better camouflage, protect, and even monitor soldiers' health. Remote physiological status monitoring will allow commanders to know the exact physical status of soldiers.

This convergence of defense and personal interest can assure the necessary research funding for sensors and sensor networks.

## V. SUMMARY

Traditional sensors that performed a simple conversion to electrical signals have evolved towards smart sensors that include signal conditioning, A-to-D conversion, and signal processing capabilities able to provide self-diagnostics, environmental (temperature) compensation, and communication. Smart sensors are the nodes in distributed wired sensor networks. Wireless sensor networks need autonomous sensors, where power and signal conditioning must be simultaneously designed for power efficiency.

Silicon-based sensors first relied on the electrical properties of silicon. MEMS exploit in addition the mechanical properties of silicon. Future sensors will use materials manufactured using either top-down or bottom-up methods to design nanometer-scale structures. Many sensors will need in-chip interference cancellation and other signal-processing capabilities, so that compatibility with low-cost IC processes will be essential to achieve the low cost necessary to embed sensors in products, packages, and our environment. Some progress in sensor will result from advances in areas such as communications (wireless technology, lasers) and computer electronics. Research in these areas can also contribute new sensing principles, such as those derived from surface quantum effects.

Sensor interface circuits no longer limit the accuracy and resolution of measurement systems. High-resolution ADCs make amplifiers unnecessary in some applications and fast ADCs permit direct digital demodulation. Direct sensor-microcontroller interfaces, low-cost semiconductor-based, capacitive, and magnetic sensors will make embedded sensors inexpensive, even disposable.

Many advances in sensors can be traced back to research programs. World War II increased the demand for aviation fuel, which led to the development of the chemical process industry and an associated demand for process-control sensors. The Manhattan project and the Apollo program similarly

required sensor development for new quantities or in harsh environments. We can expect that mandatory regulations, for cars and buildings for example, and personal and homeland security will foster the development of future sensors, particularly nanosensors and nano-enabled sensors, whose time to market will be shorter than the 10 to 20 years it took for the first MEMS-based sensors to become commercially available.

#### ACKNOWLEDGMENT

The author appreciates the support of his colleagues from the Instrumentation, Sensors, and Interfaces Group at the EPSC-UPC. This work has been partially funded by the Spanish Ministry of Science and Technology (MCYT) through project PDI2002-00707.

#### REFERENCES

- [1] K. P. Neubert. *Instrument Transducers*, 2<sup>nd</sup>. ed. Oxford: Clarendon Press, 1975.
- [2] E. O. Doebelin. *Measurement Systems Application and Design*, 3<sup>rd</sup>. ed. New York: McGraw-Hill, 1983.
- [3] S. Middelhoek and S. A. Audet, *Silicon Sensors*. London: Academic Press, 1989.
- [4] S. M. Sze (ed.), *Semiconductor sensors*. New York: John Wiley and Sons, 1994.
- [5] T. G. Giallorenzi et al., "Optical fiber sensor technology," *IEEE Journal of Quantum Electronics*, vol. QE-18, no. 4, pp. 626-665, April 1982.
- [6] J. W. Gardner, V. K. Varadan, and O. A. Awadelkarim, *Microsensors, MEMS, and Smart Devices*. Chichester: John Wiley and Sons, 2001.
- [7] H. Phillipp, "The Charge Transfer Sensor," *Sensors*, vol. 13, no. 11, pp. 36-42, November 1996.
- [8] C.-Y. Chong and S. P. Kumar, "Sensor Networks: Evolution, Opportunities, and Challenges," *Proceedings of the IEEE*, vol. 91, no. 8, 1247-1256, August 2003.
- [9] R. A. Williams and M. S. Beck (eds.), *Process Tomography: Principles, Techniques, and Applications*. Oxford: Butterworth-Heinemann, 1995.
- [10] J. R. Macdonald, *Impedance spectroscopy*. New York: John Wiley and Sons, 1997.
- [11] J. Lario-García and R. Pallàs-Areny, "Measurement of three independent components in impedance sensors using a single square wave," *Sensors and Actuators A* (in press).
- [12] R. Pallàs-Areny and J. G. Webster, *Sensor and Signal Conditioning*, 2<sup>nd</sup> ed. New York: John Wiley and Sons, 2001.
- [13] R. Pallàs-Areny and J. G. Webster, *Analog Signal Processing*, 2<sup>nd</sup> ed. New York: John Wiley and Sons, 1999.
- [14] M. P. Timko, "A two-terminal temperature transducer," *IEEE J. Solid-State Circuits*, vol. SC-11, no. 6, pp. 784-788, December 1976.
- [15] P. Sinha, "Smart sensing power on a chip: Digital Signal Controllers," *Sensors*, vol. 20, no. 9, pp. 42-51, September 2003.
- [16] F. Reverter, O. Casas, J. Jordana, and R. Pallàs-Areny, "Trigger uncertainty in period-to-code converters based on counters embedded in microcontrollers," *Sensors and Actuators A* (in press).
- [17] F. Reverter, J. Jordana, and R. Pallàs-Areny, "Program-dependent uncertainty in period-to-code converters based on counters embedded in microcontrollers," *Proceedings IEEE IMTC 2003 Conference*, Vail (CO, USA), 20-22 May 2003, pp. 977-980.
- [18] J. Jordana, F. Reverter, and R. Pallàs-Areny, "Uncertainty in resistance measurements based on microcontrollers with embedded time counters," *Proceedings IEEE IMTC 2003 Conference*, Vail (CO, USA), 20-22 May 2003, pp. 1078-1082.
- [19] J. Lenz, "What is a sensor," *Scientific Honeyweller*, vol. 8. no. 1, Fall 1987.
- [20] S. Smith and D. J. Nagel, "Nanotechnology-enabled sensors: possibilities, realities, and applications," *Sensors*, vol. 20, no. 11, November 2003, pp. 22-28.
- [21] Available at: [www.battelle.org/forecast](http://www.battelle.org/forecast)