Intelligent Sensors: Systems or Components?

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ABSTRACT

This paper reviews the field of intelligent (smart) sensor technology and describes some of the trends that have emerged over the last two decades. The functionality of intelligent sensors is discussed, together with an assessment of the various technologies that can be employed to achieve both the hardware and software aspects of the discipline. The current interest in sensor networks poses some interesting problems regarding power supply and signal extraction techniques. In particular, the issue of 'intelligent' power management and excitation control is of great significance in wireless sensor networks. Can we treat intelligent sensors as individual components, or are they really systems? In tackling this question, the author will refer to ongoing research within the School of Electronics and Computer Science at the University of Southampton.

Keywords: Intelligent sensors, smart sensors, sensor networks

1 INTRODUCTION

The emergence of intelligent sensors has arisen from the fortunate conjunction of technological demands and technological feasibility. In the past, engineers and scientists had to make do with a few basic measurements of physical quantities that *could* be measured, rather than seek sensors that accurately convey the information they really *needed*. There is an increasing need to determine precise values of physical, biological and chemical measurands independently of any other variables present. Advances in micro and nano technologies can provide solutions to the major problems posed by these needs.

As little as thirty years ago, when linear and continuous electronics dominated, the availability of sensors was limited by the stringent requirements on linearity, cross-sensitivity, freedom from drift etc. This meant that most of the vast panoply of possible sensor mechanisms had to be rejected out of hand. The magnitude of change brought about by the emergence of digital electronics has significantly altered the approach now taken.

Of equal importance with the steadily increasing power of devices is the remarkable decrease in cost. Not only has the density of transistors been doubling every two years (Moore's law [1]), but the cost of a logic gate has been halving every two years [2] and there is no sign of this trend abating.

The term 'intelligent' sensor has been used over the past twenty years or so to refer to sensors having additional functionality provided by the integration of microprocessors, microcontrollers or application specific integrated circuits (ASICS) with the sensing element itself. Intelligent sensors offer a number of advantages for sensor system designers. The integration of sensor and electronics, allows the intelligent sensor to be treated as a *component*, where the internal complexities of the sensor are kept remote from the host system. A classic example is the Analog Devices' range of MEMS accelerometers [4].

The concept of having a wireless, distributed network of intelligent sensors comprising low-power communications and localized processing has now become a reality [3]. Applications in the areas of environmental monitoring, structural monitoring, surveillance, condition-based equipment maintenance and ubiquitous computing are currently being examined. This scenario provides an example of the intelligent sensor acting as a *system*.

2 HARDWARE

Figure 1 shows an example of a generalized hardware structure of an intelligent sensor [5]. Specific examples may include all, or some, of these elements. The sensing element is the primary source of information into the system. The intelligent sensor may also have the ability to stimulate the sensing element to provide a self-test facility, whereby a reference voltage, for example, can be applied to the sensor

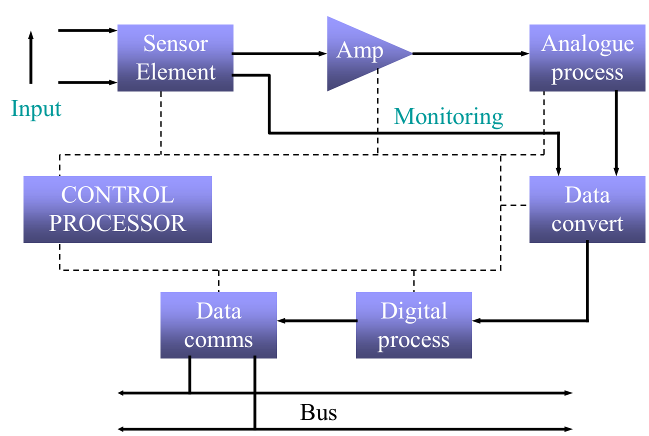

Figure 1: A generalised block diagram of the hardware structure of an intelligent sensor.

in order to monitor its response. Some types of **primary sensor,** such as those based on piezoelectrics, convert energy directly from one domain into another and therefore do not require a power supply. Others, such as resistive-based sensors, may need stable DC sources, which may benefit from additional functionality such as pulsed excitation for power-saving reasons. So excitation control is another distinguishing feature found in intelligent sensors.

Amplification is usually a fundamental requirement, as most sensors tend to produce signal levels that are significantly lower than those used in the digital processor. Resistive sensors, such as strain gauges in a bridge configuration, often require an instrumentation amplifier; piezoelectric sensors, on the other hand, will require a charge amplifier. If possible, it is advantageous to have the gain as close as possible to the sensing element.

Examples of **analogue processing** include anti-aliasing filters for the conversion stage. In situations where real-time processing power is limited, there may also be benefits in implementing analogue filters.

Data conversion is the module between the continuous (real world) signals and the discrete signals associated with the digital processor. Typically, this stage comprises an analogue-to-digital converter (ADC). Inputs from other sensors (monitoring) can be fed into the data conversion sub-system in order to implement various forms of compensation. Note that such signals may also require amplification before data conversion. Resonant sensors, whose signals are in the frequency domain, do not need a data conversion stage because their outputs can be fed directly into the digital system.

The **digital processing** element mainly concerns the software processes within the intelligent sensor. These may be simple routines such as those required for implementing sensor compensation (linearization, cross-sensitivity, offset etc.) or may be more sophisticated techniques such as pattern recognition methods (such as neural networks) for sensor array devices.

The **data communications** element deals with the routines necessary for passing and receiving data and control signals to the sensor bus. It is often the case that the intelligent sensor is a single device within a multi-sensor system. Individual sensors can communicate with each other and also to the host system. There are many examples of commercial protocols that are used in intelligent sensor systems, but we will not cover these here. It is sufficient to be aware that the intelligent sensor will often have to deal with situations such as requests for data, calibration signals, error checking, message identification etc.

The **control processor** often takes the form of a microprocessor or microcontroller. It is generally the central component within the intelligent sensor and is connected to the other elements. The software routines are implemented within the processor and these are stored within the memory unit.

3 SOFTWARE

It is no surprise that, like any other technological advance, intelligent sensors have progressed as a result of developments in both hardware and software. The early examples of intelligent sensors were tackling issues such as non-linearity and temperature cross-sensitivity; problems that are easily solved nowadays with a few lines of code.

Given that the availability of localized computational power has increased dramatically, it is no surprise that the degree of sophistication of the associated software within the intelligent sensor has increased proportionally. Modern-day devices have the ability to assess the quality of the information originating from the sensing element. In other words, intelligent sensors have the ability to *evaluate* the sensor signal. Other aspects of the evaluation process include the ability to identify fault conditions, undertake error detection and/or correction and perform self-test/self-calibration; all of which can be implemented in software.

The materials and structures associated with primary sensors contain dissipative, storage and inertial elements. These translate into the time derivatives appearing in the differential equation that models the sensor system. Hence a major defect is represented by the time (or frequency) response. The means that to neutralize this imperfection will involve filtering, which may be thought of in terms of pole-zero cancellation. If the device has a frequency response G(s) then a cascaded filter of response H(s)= 1/G(s) will compensate for the non-ideal time response. The realization of such a filter in analogue form presents a major obstacle that is greatly diminished in the digital case.

Figure 2 illustrates the basic principle of frequency response compensation for a second-order sensor such as a weighing transducer. In this example, the characteristics of the compensation filter need to be adjusted for different values of added mass.

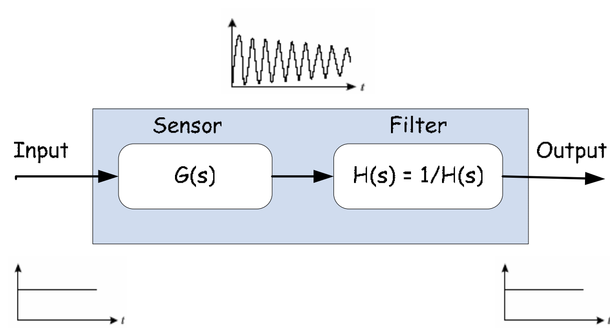

Figure 2: Improving the dynamic response of a sensor by pole-zero cancellation.

The result of a non-ideal frequency response is shown by the three graphs in figure 2. If an ideal step response is applied to the input (i.e. a weight is suddenly added to the load cell), then the sensor will ‘ring’ as depicted. The effect of the compensation filter will be to eliminate the ringing and produce the ideal, unity output.

Various methods of implementing the compensation filter have been assessed, including adaptive digital filters [6] and neural networks [7].

4 INTEGRATION

The ability to combine analog and digital circuits, mechanical elements with electronic circuits, microfluidic systems with sensors etc. into a single package is one of the key advances in intelligent sensor design. The problem with this approach, of course, is that as the system becomes more complex then the less reliable it becomes. Taking, as an example, the issues surrounding the integration of analogue circuits and microprocessors, it is possible to implement self-test and auto-calibration techniques to evaluate the system integrity. Software, one again, becomes an increasingly important element as this can ensure correct communication between the sensor and the host system, and can also be used to ensure that hazard conditions are eliminated during hardware development.

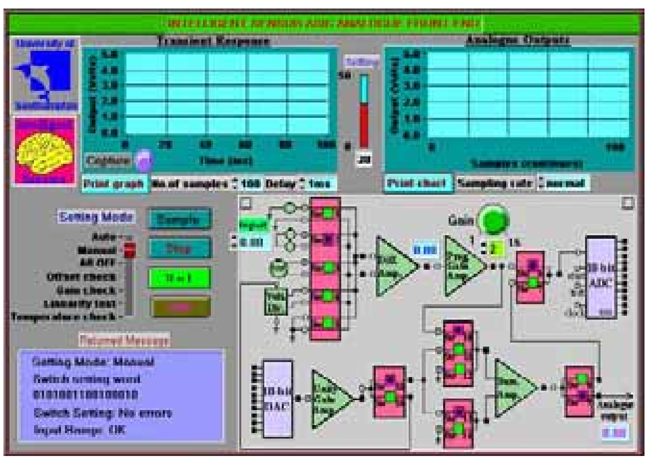

Figure 3: Virtual instrumentation panel (after Taner and Brignell [8]).

Figure 3 shows a virtual instrumentation panel, developed at the University of Southampton, for controlling an ASIC. The layout of the ASIC is an important part of the display. One of the main features of the virtual instrument is to prevent hazardous conditions occurring in the hardware. Various switches can be activated on screen and these are then passed to a software filter, which initially searches for forbidden settings. A process of binary masking is used to detect the forbidden conditions. The control word from the switch settings is logically ANDed with a mask. The number of bits in the result is counted and this is used to detect an invalid condition.

5 WIRELESS SENSOR NETWORKS

There has recently been a great deal of interest in the development of wireless networks of sensor nodes having the ability to collect and disseminate environmental data. Each node is an individual intelligent sensor having the ability to communicate via radio transmission. There are many scenarios in which these networks might find uses. Examples include environmental control in office buildings, robot control and guidance in automatic manufacturing environments, interactive toys, pollution mapping and intelligent buildings. The individual devices in a wireless sensor network (WSN) are inherently resource constrained. They are subject to limited processing speed, storage capacity, and communication bandwidth. The nodes have substantial processing capability overall, but not individually. In most applications, the network must operate for long periods of time and so the available energy resources (batteries, energy harvesting systems, or both) limit the overall functionality. To minimize energy consumption, most of the components, including the radio, will need to be turned off most of the time. The nodes are closely coupled to a changing physical world, and will therefore experience wide variations in connectivity and will, potentially, be subject to harsh environmental conditions. The dense deployment generally means that there will be a high degree of interaction between nodes.

Colleagues at the University of Southampton are involved in a project called GLACSWEB [9]. The need for monitoring the behavior of ice caps and glaciers is an important aspect understanding of the Earth’s climate. In order to study the sub-glacial environment, the measurement system must autonomously record glaciers over a large geographic area and for a relatively long time. Each sensor node is required to mimic the movement of stones and sediment under the ice, and is therefore required to be non-intrusive. Temperature, tilt and pressure are measured within each node and the data are transmitted, via a short range radio frequency link, to a base station on the surface of the glacier. The data are then relayed to a sensor network server, which is typically located a few kilometers away from the sensor nodes. The network server is a mains-powered server (located in Norway) that transmits information back to Southampton for further analysis.

A paper at Nanoetch 2005 [12] addresses the issue of maximizing the connectivity of a wireless sensor network by prioritizing the information content of the message and allowing for the available energy at each node. The assumption here is that the intelligent sensor nodes are powered by batteries and also exploit energy harvesting techniques (mechanical vibration, solar power, wind, thermal gradient etc.). Each node is capable of monitoring the amount of available power and will only attempt to transmit higher priority messages as the energy source depletes. The lower priority message will only be transmitted when the node has regained sufficient power, hence there is a trade-off between network connectivity and low priority messing.

6 ENERGY HARVESTING

Given the proliferation of devices associated with intelligent sensor networks, it is expected that each node within the network will need to be retrofitted. The costs associated with the cabling for the supply of power would be prohibitive. Of course, batteries are a possible solution to the problem, but these have a finite lifetime and there are maintenance issues associated with their regular replacement.

Energy harvesting has become a popular area of research over the past few years. The concept is to utilize energy available within the environment and use it to power the sensor. Solar cells are, perhaps, the most obvious example of an energy harvesting unit, gathering power from available sunlight. There are, however, many scenarios where solar cells may not be applicable, particularly if the sensor node is inside a building, or even embedded within a structure. An alternative approach is to use ambient vibrations as a power source [10, 11]. A block diagram of a generalized approach to the so-called self-powering of sensors is given in figure 4. A number of approaches for implementing the micro-generator have been studied, including the use of piezoelectrics and various electromagnetic configurations.

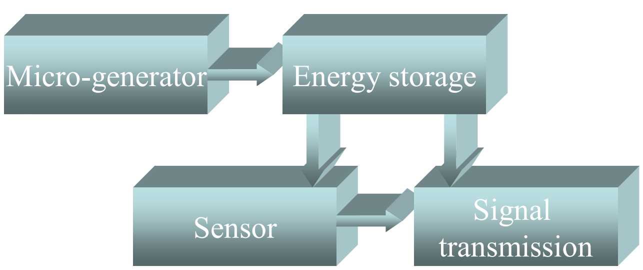

Figure 4: Block diagram of an energy harvesting system.

7 CONCLUSIONS

This paper has briefly studied some examples of intelligent sensors. The author has chosen to illustrate these with reference to previous and ongoing work at the University of Southampton. We have seen that the distinction between their behavior as a component or a system is somewhat blurred. Where do we draw the line? This is a largely a matter of opinion.

The main point is that the trend in intelligent sensing is leading towards the development of large and complex systems encompassing MEMS, electronic sub-systems, networks and software. One of they key issues for future designers of such systems is that we appear to have a scenario, not unlike the Internet, where the constituent sub-systems are distributed. Careful partitioning and constraints will therefore need to be considered.

REFERENCES

[1] GE Moore, Electronics, 38 (8), 1965
[2] JE Brignell, 'Quo vardis smart sensors?' Sens. Actuators, A37-38, pp 6-8, 1993
[3] D Culler, D Estrin and M Srivastava, 'Overview of sensor networks', IEEE Computer, 37 (8), pp 41-49, 2004
[4] www.analog.com
[5] JE Brignell and NM White, "Intelligent Sensor Systems", IOP Publishing, 1994
[6] WJ Shi, NM White and JE Brignell, 'Adaptive filters in load cell response correction', Sens. Actuators A, 37-38, pp 280-285, 1993
[7] SMT Alhoseyni Almodarresi Yasin and NM White 'The application of neural networks to intelligent weighing systems' IEE Proc. Sci. Meas. and Tech, 146, (6), pp 1-6, 1999
[8] AH Taner and JE Brignell, 'A graphical user interface for intelligent sensor ASIC reconfiguration', Proceedings of Sensors & their Applications VII, Dublin, pp 365-369, 1995
[9] K Martinez, JK Hart and R Ong, 'Environmental sensor networks, IEEE Computer, 37 (8), pp 50-56 2004
[10] M El-hami, P Glynne-Jones, N M White, M Hill, S Beeby, E James, AD Brown and J N Ross, 'Design and fabrication of a new vibration-based electromechanical power generator', Sens. Actuators, A92, pp 335-342, 2001
[11] F Discenzo: Parasitically powered sensing device, US patent 6, 304, 176, 2001
[12] G Merrett, BM Al-Hashimi, NM White and MR Harris, 'Information controlled wireless sensor networks with energy aware nodes', paper 1046, Nanotech 2005