Microelectronics Journal

Microelectronics Journal 33 (2002) 107–119

www.elsevier.com/locate/mejo

Microsensor clusters

David J. Nagel*

Department of Electrical and Computer Engineering, The George Washington University, 2033 K Street, N.W. Suite 340J, Washington, DC 20052, USA

Received 26 December 2000; accepted 21 August 2001

Abstract

The ready availability of MicroElectroMechanical Systems (MEMS) sensors and other microsensors makes it possible to use modern manufacturing technologies to produce affordable and highly functional groupings (clusters) of the small and capable sensors. They beneficially share computational, communication and power resources. Printed circuit boards a few centimeters on a side, populated with the sensors and other components by fast pick-and-place machines, can form the backbone of clusters for many applications. Uses include, but are not limited to: small weather stations; systems for analysis of the atmosphere and water; monitors of fluid and power distribution systems, machinery operation and the status of buildings, facilities and highway systems; and robots for a variety of applications, notably solar system exploration. The calibration of microsensors and the reliability of such sensors and clusters containing them, are issues that require additional research. Microsensor clusters offer near term benefits that will not soon be supplanted by the 'systems on a chip' currently under development. © 2002 Published by Elsevier Science Ltd.

Keywords: Microelectromechanical systems; Microsensors; Microsensor clusters; Smart sensors; Distributed sensors; Networked sensors; Wireless sensor networks; Microcontrollers

1. Introduction

It is difficult to overestimate the importance of sensors within advanced societies. The Sensors Magazine buyer's guide [1] lists over 100 types of sensors based on more than 80 technologies and mechanisms. Typically, 15–150 companies manufacture each of these types of sensors. The global market for sensors is now about $15 B annually [2].

Data obtained from sensors have two general uses. In the first, the data is displayed or stored, but is not the basis for automated action. In the second, sensors are part of reflexive control loops, so the data they supply is used, eventually, with or without manipulation, to determine the function of some kind of actuator. In both cases, sensors have generally been used individually. However, many practical functions require the concerted use of multiple co-located sensors. The determination of weather conditions is a prime example. Sensors for temperature, barometric pressure, humidity, wind speed and direction, precipitation and even haze and cloud height are needed if adequate information is going to be provided to weather forecasters, pilots and other users of weather information.

There are three commercial technologies that now make the co-location of multiple sensors both possible and effective. They include the small, low-power and high performance microsensors, highly capable microcomputer chips and multiple options for the communication of information. The microsensors range from relatively new MicroElectroMechanical Systems (MEMS), notably pressure sensors and accelerometers, to old standards, such as photodiodes and electret microphones. The microcomputer options are flexibly programmed microcontrollers, digital signal processors and field programmable gate arrays. Communications technologies include many wireless radio frequency (RF) and optical systems, plus copper or optical cables.

There are two reasons why co-location of sensors is compelling in many cases. The first springs from the small size and required power of the sensors themselves, and the rapidly increasing commercial availability of MEMS sensors. The second is because the different sensors can share common computation and communication capabilities, in addition to using the same power supply. Systems containing several sensors are often called 'clusters'. In fact, they are doubly so, being both a cluster of several sensors with each other, which is clustered with a shared base of ancillary devices. Although the terminology 'microsensor cluster' is not commonly used now, it accurately describes the essence of the functional systems of interest here. There are several examples already available. Some will be cited

* Tel.: +1-202-994-5293; fax: +1-202-994-5505.
E-mail address: nagel@seas.gwu.edu (D.J. Nagel).

0026-2692/02/$ - see front matter © 2002 Published by Elsevier Science Ltd.
PII: S0026-2692(01)00110-0

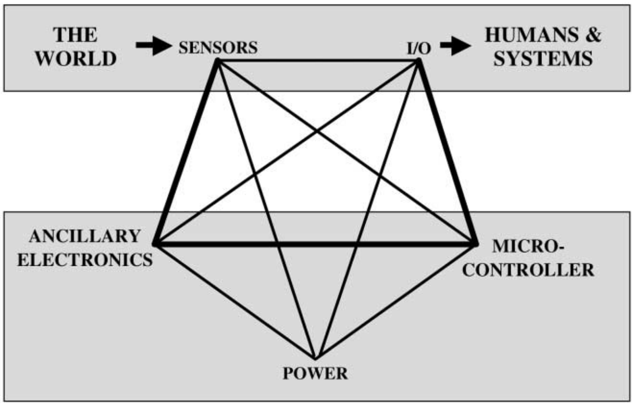

Fig. 1. Diagram showing the relationships between the components of a microsensor cluster. The printed circuit board and the housing (not shown) overlay the entire system. Heavy lines show the connectivity between the world and users of information within the top box. Critical but hidden components are inside the bottom box.

in Section 2. It is likely that the number of microsensor clusters will increase significantly in the coming years as their benefits are more widely realized. If modern manufacturing technology is brought to bear the incremental cost of adding more sensors, with their associated interfaces, to a single sensor-computer-communication-power module will be little more than the cost of the sensors and microelectronics. Power for more sensors may be a consideration, but size will not often be a factor.

This paper deals with the character, components, issues and applications of microsensor clusters that are possible now because of the availability of MEMS sensors and other new technologies. The concept of sensor clusters is presented in more detail in Section 2, along with demonstrated and emerging examples. Then, Section 3 reviews the required components and discusses options. Issues concerning the design and production of clusters, and their calibration and reliability, are presented in the following sections. Then, both proven and potential applications are addressed. It is concluded that board-level clusters of sensors will prove to be very widely useful.

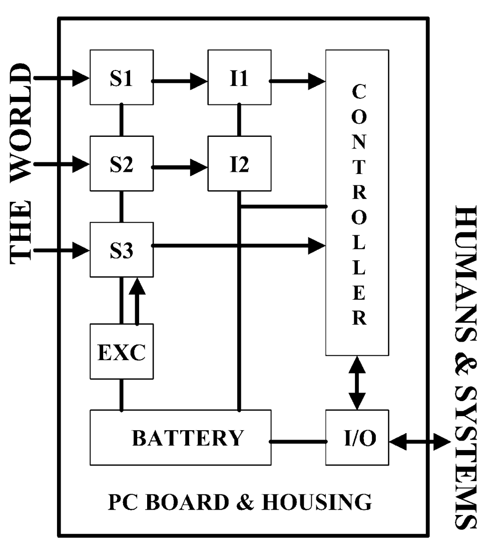

Fig. 2. Block diagram of the components within a microsensor cluster. (S = sensor, EXC = excitation, and I = interface).

2. Microsensor clusters

In the past, as in many cases today, sensors were unavoidably large. They were often powered with wires and had separate cables for data transmission. The co-location of microcomputers and batteries with sensors made it possible to turn data into information at the sensor, and to display or transmit to the user fewer bytes of that information. Such so-called ‘smart sensors’ are increasingly important. The availability of wireless and Internet communication modalities spawned the concept of the ‘smart sensor web’. While many conventional sensors are small, it was a general practice to use sensors singly, and sensor systems tended to remain relatively large. The availability of many more miniature sensors due to micromachining has lead to the development and marketing of numerous small, often hand-held single sensor systems and to some commercial and prototype sensor clusters. It is noteworthy that hand-held computers called Personal Digital Assistants (PDAs), such as the Palm Pilot, are merging with cell phones. That is, computers and communications are already being integrated in small, cheap systems. PDAs can be outfitted with small sensors now. This combination is closely related to the microsensor clusters of interest in this paper, if the PDA is used for computations on the sensor data, and not merely for data logging.

The concepts and components involved in microsensor clusters are indicated in Figs. 1 and 2. Both figures show that seven items are necessary, the multiple sensors, interface electronics for sensor excitation and signal conditioning (notably amplification), a microcontroller or some other means of computation (with associated memory), a means for communication information out and possibly receiving commands or new programs, a source of power, a printed circuit board and a housing. Note that the microsensor cluster concept contrasts with another common approach to multiple sensor systems. Many commercial systems have nodes that include most of the same functions, but the sensors are connected and not integrated [3]. In those cases, protocols such as IEEE 1451 [4] identify Transducer Electronic Data Sheets (TEDS) and allow various sensors to be connected to the same node. The main idea here is to identify common functions, such as weather determination, and use available manufacturing technology to produce compact and affordable *integrated* microsensor clusters. Essentially, the flexibility of ‘plug and play’ macrosensor systems is traded for the small size and lower required power of microsensor clusters.

The number of already demonstrated microsensor clusters

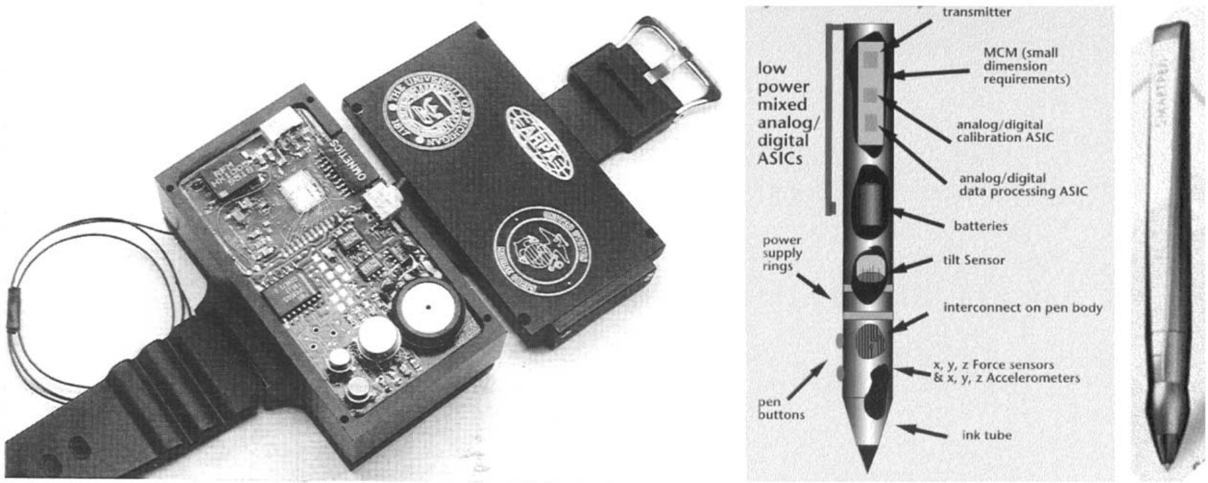

Fig. 3. Left: Prototype microsensor cluster with temperature, pressure, humidity and acceleration sensors. Right: diagram and photograph of the SMART-PEN™ containing three accelerometers, three force sensors and two tilt sensors for signature verification.

is still small. Fig. 3 shows two such systems. The wrist-worn environmental monitor was the result of a PhD Thesis in the mid-90s [5]. The smart pen is a development that is being commercialized in Europe for signature authentication at the point of a sale [6]. Both systems have wireless links for communication of sensor information. Microsensor clusters for chemical sensing [7], making pressure and other measurements on aircraft surfaces [8] and for detection of the strains in composite materials [9] have also been made and tested.

Fig. 4 shows a pair of microsensor clusters developed recently at the University of California at Berkeley [10]. The RF system has a range of about 10 m and the optical system was tested at a range of over 20 km. All the systems in Figs. 3 and 4 have the seven major units that constitute a microsensor cluster, as shown schematically in the first two figures.

Several other microsensor clusters are under development. They have different sizes and power requirements, as indicated in Fig. 5. The 'Smart Dust' program is aiming to produce modules including one or more sensors, computations, communications and power in a volume of about 1 mm^3 that have power consumption on the order of 10 μW [11]. A variety of single and multiple sensors, such as those shown in Fig. 4, can be integrated into these systems. Optical communication links will be used. The clusters for the NASA Sensor Web will include meteorological and chemical sensors, and use RF communications [12]. In both the Smart Dust and Sensor Web systems, the communications network will be self-configurable. The Wireless Integrated MicroSystem (WIMS) program has just started [13]. It seeks to produce microsensor clusters with overall dimensions of 1 cm^3. Our interest is in systems that are

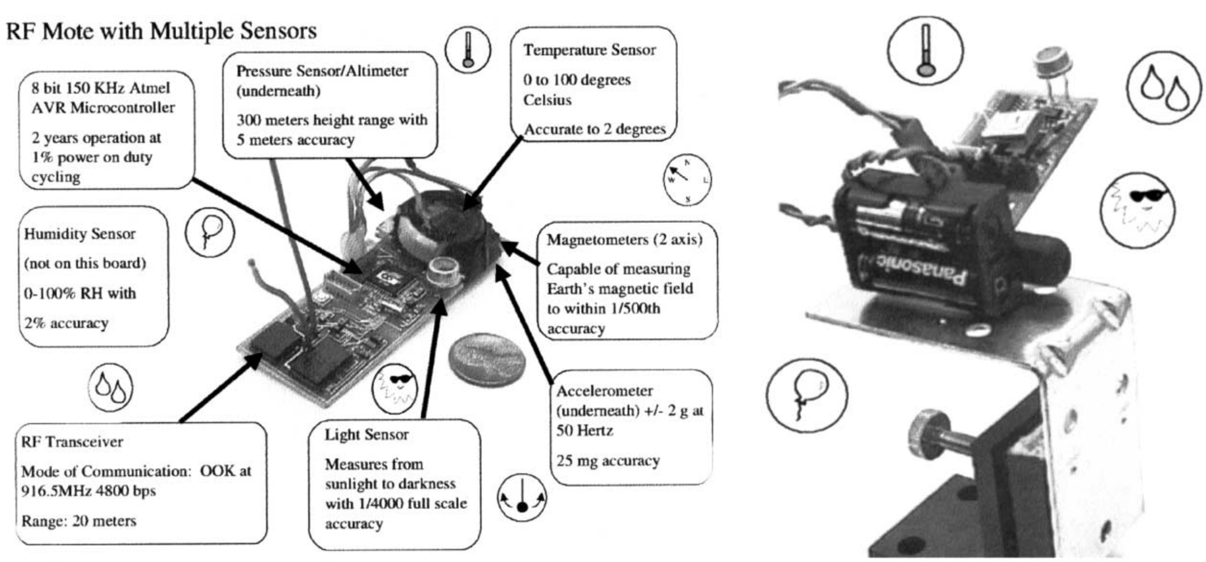

Fig. 4. Two prototype microsensor clusters, the one on the left with RF communications and the other with an optical link for communications. Both have temperature, pressure, humidity and light sensors. The RF system also has an accelerometer and magnetometer.

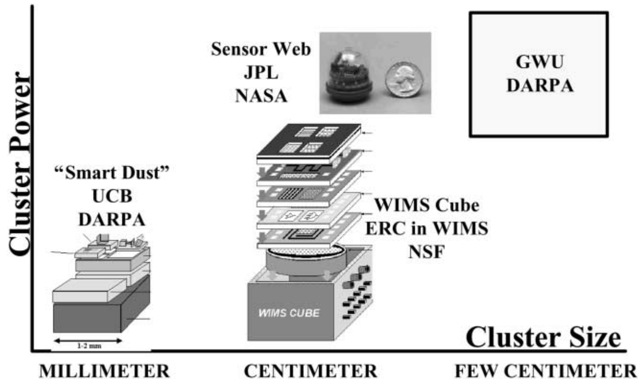

Fig. 5. Microsensor clusters under development in the US at the University of California at Berkeley (UCB) and The George Washington University (GWU) under funding from the Defense Advanced Research Projects Agency (DARPA). The Sensor Web is a National Aeronautics and Space Administration (NASA) program at the Jet Propulsion Laboratory (JPL). The WIMS is a new program of the National Science Foundation (NSF) at an Engineering Research Center (ERC) spanning three universities in the state of Michigan.

made on printed circuit boards, such as those shown in Fig. 4. However, we aim to exploit modern manufacturing technology, so that the clusters are both affordable and highly reliable. While such systems have neither the smallest size nor the lowest power, there are many applications for which functionality and low cost are major factors.

The design, manufacturing, calibration and reliability issues for microsensor clusters are discussed in Sections 4 and 5. However, we first briefly review the status of the micrometer-scale sensors, computational and communication technologies that enable the development of small and high performance multiple-sensor clusters.

3. Microsensors, microcomputers and microcommunications

While the realities of powering microsensor clusters are a major limitation for many applications, the increasing availability of low-power, small and high performance sensors, computers and communications components both relieves the power requirements and enable new applications. In this section, we will first review some of the generalities and specifics of micromechanical sensors that are now on the market and available for incorporation into clusters, or are expected soon. Then, options for satisfying the computational requirements of sensor clusters will be enumerated, with particular attention to one family of microcontrollers. Finally, communications options are reviewed with emphasis on the increasing availability of wireless connectivity and the advantages of packet communications. We note here that electronic tags are small and cheap, so they can be incorporated into most sensor clusters in order to provide identification. Global Positioning System (GPS) chips can similarly be made part of a multiple sensor cluster to monitor its movement.

3.1. Microsensors

MEMS involve the integration of micromechanics with microelectronics [14]. It is a large field, which includes passive (stationary) structures and active (mechanical) sensors, actuators and systems as its four major categories. Sensors were the first components to be commercialized, and will be described in more detail is the following paragraphs. Actuators, usually powered by electrical or thermal means, are now becoming very important, commercially. Micromirrors for switching light signals in 'all optical' fiber networks will soon be employed in very large numbers. They are already in early field trails, and six start-up companies were sold in the year 2000 for a combined value of about \$6 B (in stock). Micromechanical switches, capacitors and resonators for the manipulation of RF and microwave signals are now under development and on the verge of commercialization. They come on the scene right in the middle of the 'wireless revolution', and they promise to improve the performance and reliability of many RF and microwave devices. Microfluidic systems, the so-called 'lab on a chip', have been offered for sale by several companies in the past few years. Their integrated and disposable character is enabling small table-top and even hand-held systems that can be brought to the point of care for medical applications or into the field for environmental measurements.

Returning to sensors, micromechanical sensors already have a two-decade history of increasing use. Pressure sensors were the first micromachined devices to be commercialized [15]. The two major markets were, and remain, measuring the manifold air pressure in automobile and other engines and disposable blood pressure sensors. Many other applications have been demonstrated. A recent search of the Internet showed that approximately 50 companies now make or sell micromachined pressure sensors. They are available in a wide variety of configurations, such as absolute, gage and differential pressure sensors. Dynamic ranges extend up to pressures exceeding 10 kpsi (about 100 MPa). The annual production of pressure microsensors is estimated to exceed 10 million units.[1]

Microaccelerometers were the next MEMS sensors to become commercially significant [16]. The initial market was for automobile airbag triggers. The early products measured acceleration along one direction. Recently, controllers for toys became a major application. Devices for both automobiles and game controllers now measure accelerations along two orthogonal axes. The two-dimensional character of these devices enables their use as angle (tilt) sensors in a vertical plane. MEMS accelerometers are finding a wide range of opportunistic applications. Vibration monitoring is one important example. They are also manufactured or resold by about 50 companies. Currently,

[1] Estimates made by the author based on discussions with MEMS manufacturers.

the annual sale of microaccelerometers is in the range of tens of millions of devices.[1]

Both angular rate sensors and chemical vapor sensors are already on the market. The commercial availability of both of these types of microsensors should grow rapidly in the near future. It is noted that very small and low-power imagers are now available. These include microelectronic detector arrays of use in the visible region and micromechanical sensor arrays that respond to infrared radiation. Images are critical to many sensing applications and it is relatively straightforward to incorporate small imagers into clusters. Of course, the compaction of images requires significant computation, and their transmission can require relatively large bandwidth and consume significant power. Many biosensors have been prototyped and will become available in the coming years. They can analyze bio-chemicals, such as toxins, as well as viral and bacterial entities.

3.2. Computational devices

The computer functions required within microsensor clusters include turning data into information by use of calibration curves or tables stored in memory within the cluster, applying compensations for temperature, humidity and other variations, analysis such as averaging and Fast Fourier transformations, storage of information prior to its transmission and manipulation of the information to prepare it for communication. Embedded microcontrollers can also enable reprogramming of a sensor cluster, and responses to commands received by wireless or other means.

There are three broad choices for the components needed in microsensor clusters to provide the needed computations. They are general-purpose microprocessors (usually called microcontrollers), digital signal processors (DSP) and field-programmable gate arrays (FPGA). The first of these is the most important and will be discussed in more detail in the following paragraphs. DSP chips can be viewed as specialized microcontrollers in which flexibility of programming has been traded for performance, usually speed. They are widely found in products that do not need diverse programming by users, but do require the ability to process signals quickly. Communication devices such as digital cell phones are major markets for DSP devices. DSP chips are available from several major and other companies. FPGA are, as the name implies, gate arrays that can be programmed by users to execute diverse logic operations. Hence, they can perform a wide variety of computational functions, including those required within microsensor clusters. FPGA devices fall into two primary categories. In one, the gate array is configured irreversibly by the user at the outset. This has the advantage of surviving programmed or accidental power loss, but it does not permit reconfiguration in response to error detection or operational changes. In the other category, the gate array is configured electronically and can be changed later. In this case, restart after loss of power requires reloading of the program from a nearby non-volatile memory device. It is likely that both DSP and FPGA devices will be employed in some commercial microsensor clusters in the future. However, the flexibility and performance offered by available microcontrollers now makes them the primary choice for performing the computations needed within sensor clusters.

Microcontrollers are essentially general-purpose computers on a single chip. Over the last decade, the ever-increasing number of transistors that can be put on a chip, due to shrinking line widths, made such devices both highly capable and quite inexpensive. The microcontrollers now available have many of the same characteristics of the microprocessors at the heart of desk and portable computers. However, they do not have such high clock speeds and they often include integrated analog-to-digital (ADC) converters for signal acquisition in digital form. The high speed is not needed for most embedded applications, including microsensor clusters, and the on-board ADC are very convenient for interfacing with sensors that provide analog signals. Another reason for the popularity of microcontrollers is the trade-off they offer between computational efficiency and programming language convenience. They can be programmed in machine or assembly languages that take relatively less memory and run fast, but are usually specific to particular devices or families of devices. Alternatively, they can be programmed in more widely known high-level languages, such as Basic or C, which are easy to use and have many library sub-routines, but take more memory and run slower.

Families of microcontrollers are offered by many companies.[2] Of these, the PIC devices from MicroChip Technology are diverse, capable and popular [17]. The PIC microcontrollers range from small devices of limited capability to very facile chips. They commonly have several integrated ADCs, ranging from 4 8-bit ADCs to 10 12-bit ADCs. The number of I/O ports varies in the PIC family of controllers from 6 to 84. Speeds for the PIC controllers vary from 4 to 40 MHz. Fig. 6 is a plot of the program and data memory for PIC controllers. As is the case for the other large families of microcontrollers, there is a great deal of software for PIC microcontrollers available from servers on the Internet [18]. The choice of a microcontroller family, and a specific device within the family, for a sensor cluster is dictated by several factors. These include the required performance specifications, notably the number and accuracy of the ADC channels, the number of digital I/O ports, clock speed, calculational power (MIPS), (re)programmability and the program and data memories, plus critical constraints, especially the power and size.

3.3. Communication options

In some cases, the information from microsensor clusters

[2] Microcontrollers are made by Hitachi, Intel, Microchip Technology, Motorola, Oki Electric, Philips, Siemens, STMicroelectronics and Texas Instruments.

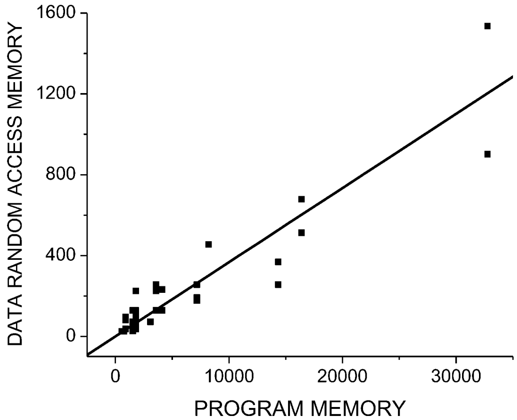

Fig. 6. Plot of program memory and data memory (both in bytes) for the family of PIC microcontrollers.

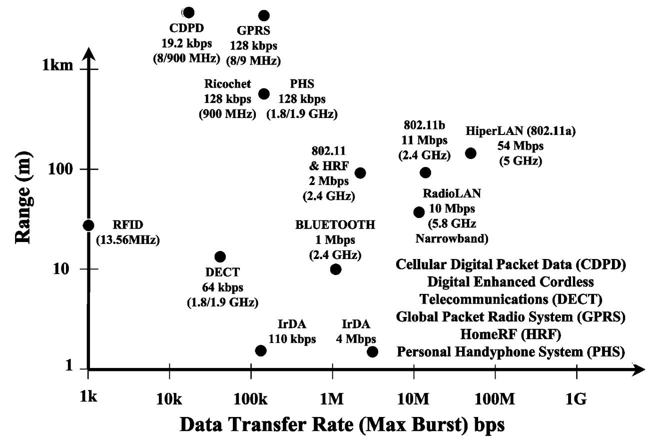

Fig. 7. The range and maximum bits per second (bps) for various RF technologies.

can be used or stored locally. However, a basic advantage of small, low-power and inexpensive sensor clusters is the ability to deploy them widely, which requires a means to forward the information from the cluster to a collection or use point. In some cases, two-way communication is needed to pass commands to a cluster or to reprogram it. The possibilities for communication from a cluster fall into two primary categories, namely transmission through conduits or through the air, the wireless option. In the first category are electrical wires and optical fibers. Both these options suffer from the same installation and maintenance costs that burden power lines to sensor clusters. If there are power lines to a cluster, they can be used for the transmission of information at high frequencies well separated from the frequency of the provided power. Optical fibers offer, in a sense, the opposite option. Their primary function is high bandwidth communication, but they can also serve as conduits for powering a sensor cluster by the use of different optical wavelengths. No instances of using optical fibers for both powering and communicating with a sensor cluster are known to this author.

The wireless option for one-way or reciprocal communications with clusters is very attractive if enough power is available. RF communications offer broad antenna patterns, high bit rates and a wide variety of technologies, as illustrated in Fig. 7 [19]. The existing IEEE 802.11 protocol [20], the new Bluetooth technology [21] and the cellular telephone infrastructure are being used for sensor communications, in addition to communication satellites. The power requirements and costs of RF communications are serious considerations for most applications. Optical communications without fibers offer very high bandwidth, usually much greater than is needed for sensor clusters. They require precise pointing if power usage is to be minimized, and must be put in place by the users of information from clusters. Importantly, optical communications are more sensitive to weather than RF links. Acoustic communication is possible in principle. However, it would have to be limited to frequencies above about 50 kHz to avoid bothering humans and animals. The attenuation length of ultrasound in air falls off as the frequency squared. At 100 kHz, the attenuation length is only about one meter. Hence, there is a narrow window in which ultrasound could be used as a carrier for communications over short distances and for bit rates below around 10 kHz.

Most sensor cluster applications do not require continuous communications. In some cases, only a small number of bytes of information are generated infrequently. For example, information from a weather station might consist of less than 20 bytes every 1–10 min. In other cases, where readings are taken constantly, averaging for a period of time and forwarding only the averages again leads to a low average transmission rate. Another strategy to reduce communications and the associated required power is to cache the sensed information on a roll-over basis, and to forward readings only on infrequent programmed intervals, or else when the readings are outside of preset bounds. These approaches to communicating information from a sensor cluster at infrequent intervals naturally lend themselves to packet transmission protocols [22,23]. The low duty cycle inherent in the use of burst-mode communications can greatly reduce the energy required for the communications function. Because of the need to warm-up and stabilize components in the communication part of the cluster, the savings is less that the actual duty cycle for broadcast or receipt of information.

Wireless communication of information from sensors makes it possible to have networks in which the sensor nodes are mobile and the connectivity is reconfigurable [11–13]. Power minimization is crucial to the long-term use of wireless sensors and clusters [24]. Hence, past and current wireless-sensor development programs have focused on energy conversation. One of the programs, the Wireless Integrated Networked Sensors (WINS) program [25] spawned the company Sensoria [26]. Two other companies, CrossBow Technologies [27] and Graviton [28], offer wireless systems for macro- and microsensors. Another company, Millennial Net [29] offers low-power integrated microcontrollers and RF communications modules that can be further integrated with sensors. A review of wireless sensor networks is forthcoming [30].

4. Design and production of clusters

Integration of components is one of the hallmarks of modern engineering. The networking of transistors results in integrated circuits. The integration of microelectronics and micromechanics yields MEMS. Here, we are dealing with the further integration of devices, as indicated in Figs. 1 and 2. At this level, the substrate is the printed circuit board. The PCB can perform multiple functions beyond providing electrical connectivity and mechanical support. Antennas can be printed, so the PCB might be a component in the communication system. It can also serve as part of the housing for the cluster.

The design of sensor clusters is challenging because of the diverse technologies involved and the number of interfaces. Each of the interfaces shown in Figs. 1 and 2 is electrical, thermal and mechanical, with acoustic coupling sometimes being important. Software for self-consistent calculation of the electronic, mechanical, thermal and other energies and their effects at the chip level in MEMS is available [31]. Many of the design and simulation challenges for sensor clusters are similar to those involved in the PCBs for cell phones, cameras and other common electronic devices. Software for the design and simulation of PCBs is needed for system-level performance and trade-off studies for microsensor clusters [32,33]. Very High Speed Integrated Circuit (VHSIC) Hardware Definition Language (VHDL) and VHDL-AMS (Analog Mixed Signal) software is as applicable to the board level system as it is to the chip-level systems for which it was initially developed [34,35]. SpecC is another system-level design language that should be applicable to multiple-sensor clusters [36,37]. As far as this author knows, neither of these software technologies has yet been applied to the design of a microsensor cluster. It seems likely that this will happen soon because of the need to optimize the design of clusters for performance while minimizing power consumption.

The provision of power to microsensor clusters is often the size-determining and lifetime-limiting factor in their design. There is two basic options that are practical for the near future, namely the use of replaceable batteries and the use of rechargeable batteries in association with solar cells. Wires to supply electrical power, or fibers for transmission of optical power, are possible but expensive and hard to maintain. Schemes for supplying power by optical or radio beams, and even acoustic tones, are possible in principle, but not often employed now. Similarly, the scavenging of kinetic (motion or vibration) energy for sensor clusters seems to be in the future. A great deal of work on trade-offs for the provision and use of power within sensor clusters remains to be done, although power usage is very case specific. Partitioning of energy expenditures between sensing (and the required interface electronics), computing (and the memory) and communications is a complex and critical choice in microsensor cluster design. Fig. 8 indicates the time variable power usage in a sensor cluster that takes data periodically, which is then subjected to calculations and communication. The currents required for the microsensors in the RF system in Fig. 4 are in the range of 0.2–0.65 mA at 3 V [10]. The power required to operate microcomputers scales with the performance, especially the clock speed. In the 'sleep' mode, PIC controllers draw about 1 μA. Their maximum power consumption is tens of mA. The use of burst mode (packet) communications, where possible, can significantly reduce average power consumption. For a 1% communications duty cycle, a reduction in power of almost 50% relative to constant full-power communications can be realized. This would be the case where communications consumes half the power, with the sensors, associated electronics and the microcontroller sharing the rest of the power (sometimes, about equally). Since the communications function is generally the most energy-consumptive part of the sensor cluster, very significant savings in battery size, or the associated solar cell area, can be realized with burst-mode communications. Alternatively, the reduction in required power can be taken as an increase in battery lifetime.

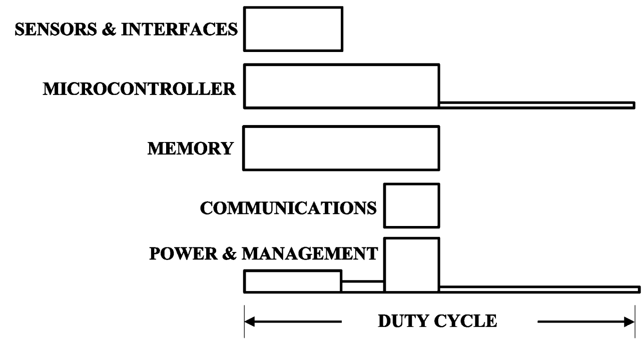

Fig. 8. Schematic of the power usage in a microsensor cluster with a duty cycle. The vertical scales for the sensors, electronic interfaces, microcontroller and memory are relative to their maximum values. The vertical scale for the overall power usage is meant to indicate that the communications are usually the most power consumptive part of a sensor cluster.

An immense manufacturing base exists for the design, production and population of PCBs. The idea here is to use these capabilities to manufacture microsensor clusters. Pick and place machines can put parts as small as 500 μm square and as large as a few centimeters onto PCBs at rates exceeding 5 Hz. Now, MEMS and other microsensors are available in large numbers for tape feeding into pick and place machines. Hence, it is possible to emplace most of the components for sensor clusters quickly and cheaply, including battery holders. Temperature sensitive components, notably batteries, would be installed after solder reflow. The concept is to make several few centimeter square sensor

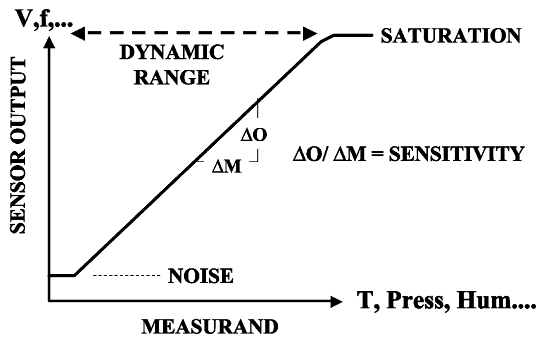

Fig. 9. Generalized calibration curve showing the dynamic range as limited by the measurement noise and sensor or system saturation.

cluster boards on a standard sized PCB and then to 'dice' the large PCB to make multiple copies of the same cluster. It is evident that the option is available to have different cluster designs on the same board and to populate each with the appropriate sensors and components. There are many companies capable of these operations. The Contract Services Directory of Surface Mount Technology magazine lists about 150 companies that perform board assembly [38].

5. Calibration and reliability of microsensor clusters

Microsensors share with all sensors and instruments the need for calibration. The curve relating the desired measurement, say, humidity or acceleration, to the output of a sensor, often a voltage, is termed a calibration curve. Fig. 9 is a generic calibration curve. It can be stored in the microcontroller as a table or fit with a mathematical function. The calibration curve or its equivalent is used in the process of reducing data to information. Initial calibration of a sensor requires having a means to vary, and to independently know, the values of the measurand, a process that is much easier for some variables (acceleration) than others (chemical vapor composition). Calibration curves are often sensitive to the ambient temperature and humidity. Hence, they have to be determined with these parameters as variables also to permit compensation of the measured output for unwanted ambient variations. Redetermination of the calibration curve during sensor use varies between difficult and impossible. For the several cases in which highly reliable electrostatic or piezoelectric actuators can be integrated with microsensors, one-point recalibration, essentially a built-in test, is possible. This is the case for most air bag triggers.

Even when calibration is not an issue for a microsensor, its reliability is a question. This is especially true for a new technology like MEMS, where there is not a long history of use of the technology. When a technology is new, component-by-component estimates of reliability can be employed to get a semi-quantitative idea of the system reliability [39,40]. Once a technology is available, early and limited tests will verify designs and cull out devices that fail early, the so-called 'infant mortality'. Devices that pass this stage and go into service provide a database on reliability of the technology and specific embodiments. At this point, in the history of MEMS, airbag accelerometers have already proven to be highly reliable. There are nearly 100 million such devices in use now,[1] each of which is turned on and off many times and used for long hours. The digital mirror display (DMD) from Texas Instruments is not a sensor, but it attests to the reliability of micromechanical devices. Each DMD has over 500,000 moveable mirrors that are expected to last for 10 billion cycles. The number of such devices now in service exceeds 100,000.[1] Other estimates of MEMS reliability could be made for automobile and medical pressure sensors, because they have been made in large numbers. In short, microsensors have the potential for being reliable parts of clusters. Moving from the component to the systems level, other reliability questions are germane. The principles of reliability engineering can be applied to clusters, but this apparently has not been done.

6. Applications of microsensor clusters

We already noted the diversity of MEMS, in general, and micromechanical sensors, in particular. The same is increasingly true of microsensor clusters. They are already significant, and their applications should grow greatly, in type and number, in the coming years. Several possibilities are discussed in this section, most of which have both ordinary and military utility. In general, the contemplated systems have not yet been designed, manufactured, tested, and used. However, it is the view of this author that all of them are possible and most of them will be at least prototyped before long. Once there is widespread use of any of the clusters for any application, then the design and manufacturing experience base will be available for the flexible production of clusters for many other applications. The range of applications will greatly exceed those discussed in the next pages. Other discussions of the applications of microsensor systems are available [11–13,23–29,41].

6.1. Weather stations

There are many production and developmental weather stations. Three commercial systems are shown in Fig. 10. All these systems have important deficiencies. One is relatively large and costly. The others are more compact, but still expensive. Even the smaller commercial systems have moving parts for the anemometer and the rain gauge. The prototype wrist system shown in Fig. 3 lacks the wind and rain sensors commonly wanted in a weather station. Similarly, the microsensor cluster in Fig. 4 has only temperature, pressure, humidity and light sensors. A small, hand-held multiple-sensor device is available with temperature, pressure, humidity and wind speed readouts

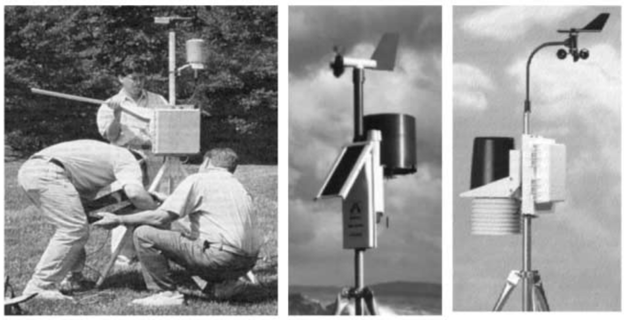

Fig. 10. Commercial weather stations from Sutron (left), Rainwise (center) and Davis (right). The large system on the left costs about $5000, while the two half-meter-scale integrated systems each cost about $700–800.

[42]. Radiosondes are an example of weather instruments made in large numbers, but without rain gauges.

Because of the technologies discussed earlier, it is now possible to make a full-service weather station in a compact, cylindrical format, as shown in Fig. 11 [43]. The temperature, pressure and humidity sensors can be integrated on a single board with the microcontroller and other electronic chips. The rain gauge for this system works by counting drops from a capillary at the bottom of the collection funnel. A simple light emitting diode (LED) and PD serve as the drop detector. A device with no rotating parts is under development to measure the wind speed and direction. One candidate is a cylindrical stalk topped by a sphere. Its deflection by the wind would be sensed by four microstrain gauges mounted at 90-degree intervals around the stalk. Opposite pairs would form components in two bridge circuits, the output of which would provide data sufficient for calculation of both the speed and direction of the wind. Other designs for measuring the wind with compact devices are also being evaluated. It is noted that mounting an upward looking laser and a detector to measure back-scattered light on the side of the primary cylinder could permit measurement of haze or fog (and possibly cloud height, if there were sufficient pulsed laser intensity).

The availability of inexpensive and reliable weather stations would have two kinds of impacts. First, they could provide data on a relatively dense grid for benchmarking of supercomputer simulations of the weather. Second, they could supply observational data of broad importance to people and businesses, including the insurance industry, and also to the military for use in operational planning.

6.2. Atmospheric chemical analysis

Weather is dominantly concerned with the physical properties of the atmosphere. The composition of air is of interest both out of doors and within buildings. The vapors of many chemicals are important to know for health, safety, and other reasons. Many of the motivations and industries for which atmospheric chemical analysis is germane are given in Fig. 12.

There are several different technologies for sensors that are responsive to trace and higher levels of chemical vapors in the air, and most of them are already commercialized. They include thin chemo-selective polymers on surface acoustic wave and other oscillatory structures such as microcantilevers, micrometer-sized conductive particles embedded in such polymers, semiconductors in which the resistance or transistor characteristics vary with chemical absorption, catalytic and other electrochemical methods, chemo-selective dyes (colorimetry), various mass and optical spectrometers, and means such as chromatography for the separation of different chemicals. The methods that relate changes in sensor output to composition of a particular species of vapor vary with these different mechanisms. Pattern recognition, usually involving neural networks, is commonly employed in systems with polymer-based or

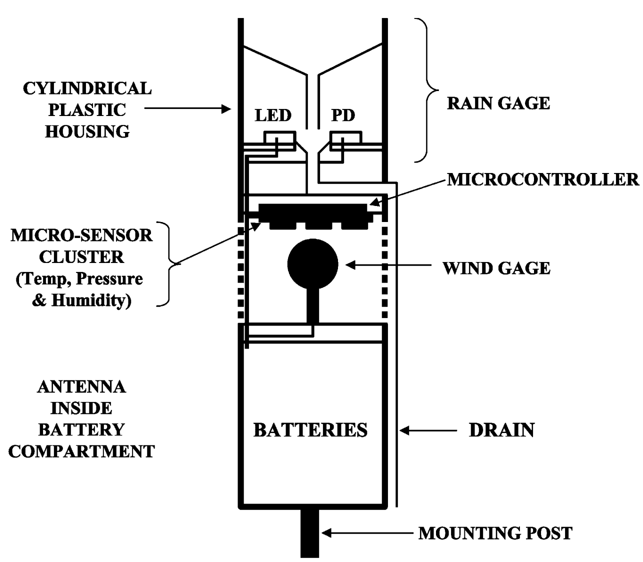

Fig. 11. Schematic cross section of a weather station in a cylinder (about 5 cm in diameter).

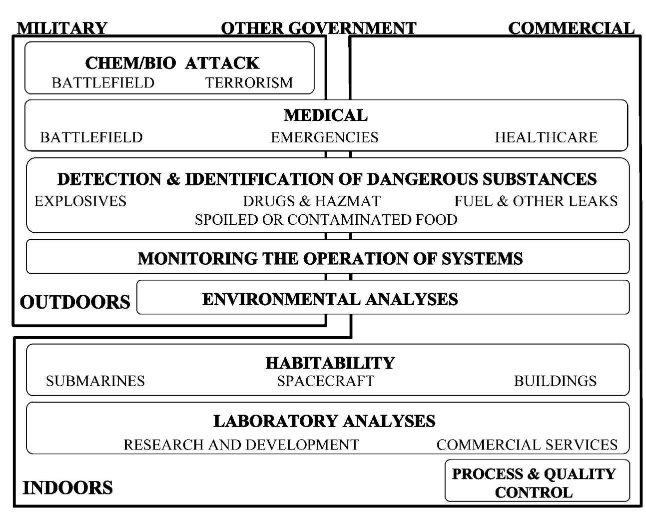

Fig. 12. Diagram showing the outdoor and indoor, military, other government and industrial applications of 'electronic nose' and other technologies for analysis of the atmosphere.

semiconductor sensors. There is usually a unique relation between species and peaks in spectra, with the size of the peaks giving information on the amount of a specific vapor that is present. Chromatography involves the sequential measurement of the separated chemicals by electronic, optical, or other means. Sensors based on all of these technologies have been reduced to micrometer scale in at lease one and sometimes two dimensions [44]. They variously involve micromachined or micromechanical structures.

Sensor clusters for atmospheric analysis contain several sensors that are now usually of one technology and type. The common need to get information on more than one vapor species requires a related number of sensors. In the near future, multiple sensor technologies will be integrated into the same microsensor cluster for two reasons. Alternative technologies are sensitive to different chemical species, so the ranges that are be analyzed by a cluster can be broadened, possibly with regard to the useable concentrations, in addition to expanding the variety of analytes. Multiple technologies can also serve to provide redundant, and hence, higher-confidence measurements of the same species. Because most chemical sensor technologies for gaseous analysis are also sensitive to humidity (water vapor) and are temperature sensitive, analytical microsensor clusters will commonly incorporate sensors for these two variables. The microcontroller will then perform compensation as well as other calculations.

6.3. Chemical and biological analysis of water

Humans can go only a few minutes without air, a few days without water and a few weeks without food. Provision of clean air generally involves only avoidance of chemical pollution since air is usually free of biological hazards and it automatically reaches people. Techniques, such as those enumerated in the last sub-section, can be used for monitoring of atmospheric chemical pollution. Provision of clean water requires active means both to purify water and to deliver it. Water purification demands attention to chemical composition, biological contamination, and particulate matter. The same concerns apply to water in rivers and lakes, and in open seas and oceans. Emplaced systems make it possible to determine what chemicals are in the environment, their location, concentrations and their movements over time. Automatic, unattended monitors of water composition are highly desirable in all cases. This is particularly true for oceanographic research buoys and for prospective autonomous underwater vehicles that might be built to map the floor of all the world's oceans [45]. In most cases, environmental analytical systems will include sensors for physical properties of water, notably temperature, density, and conductivity (salinity). Macroscopic integrated multi-sensor systems for such measurements are commercially available [46].

The equipment currently used for analysis of water generally does not involve microsensors. However, there are several microfluidic systems now on the market primarily for the analysis of medical samples. They are usually of the type where a disposable plastic or glass system of microchannels performs sample mixing, transport, and separation functions when inserted into a desk-top or hand-held system that provides controls, analyses and data manipulation. It is expected that microfluidic systems will be developed for analysis of the dissolved and suspended constituents of water. Such systems will be clusters of sensors and other technologies. They generally will not have the printed circuit board base found in most of the clusters discussed in this paper, although the use of PCBs as substrates for microfluidics should be possible.

6.4. Fluid distribution systems

The pumping, transport, conditioning and use of gases and liquids is a major engineering activity in most societies. Gases of great utility include natural gas (methane) and conditioned air. Liquids of prime interest include oil, gasoline and, of course, water. The size of fluid distribution systems ranges from the scale of continents to relatively small systems, such as a window air conditioner or the engine cooling system within an automobile. Monitoring the pressure and flow of such systems is a common requirement. The integration of sensors for determining these parameters, and temperature, can result in a microsensor cluster of the type discussed in this paper.

Fig. 13 is the schematic representation of a concept for a pressure and flow monitor based on two micromachined pressure sensors, essentially a 'smart plug'. The first ($P1$) is on a flat surface and the second ($P2$) is on a surface curved in the direction of flow (normal to the page). In the absence of flow, $P1 = P2$. The velocity-dependent decrease of $P2$ permits measurement of the flow from the ($P1 - P2$) difference. The sensors are connected to interface electronics, which mate with the battery and communication system (represented in the figure by unlabelled black rectangles). The communication link could be a simple radio system in which the frequency was related to the values of $P1$ and $P2$. Low communication rates would serve to prolong the battery life. A temperature sensor could be incorporated in the plug cluster. If ultrasonic emission intensity would be

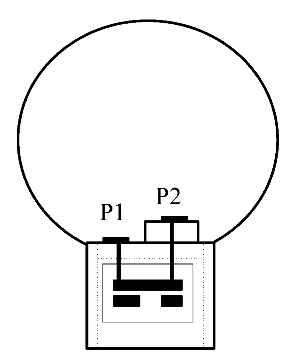

Fig. 13. Cross section of a pipe plug with MEMS pressure sensors.

shown to be a useful measure of flow (or possibly corrosion in the pipes), a MEMS microphone could also be added. Almost one million differential pressure flow sensors were sold in 1999, mainly to the oil and gas, chemical, water and energy industries [47]. Integrated flow systems with multiple sensors are made by at least two companies.[3,4]

6.5. Electrical power monitors

Means for the generation, distribution and use of electrical power are a basic part of the infrastructure of modern society. Diverse generation stations are in use. The power grid is an evident part of the landscape. Factories and homes powered entirely by electricity are commonplace. Sensors are needed to monitor the condition and performance of power systems at all phases of the generation, distribution and use of electrical energy. The options for power systems sensors include (a) temperature and humidity sensors, which yield information on the conditions under which the power systems operate, (b) acoustic sensors for listening to the characteristic hums, plus any corona or breakdowns, (c) accelerometers to pick up vibrations, (d) field sensors that provide information on the electric, magnetic and electromagnetic fields associated with power conduits and devices, (e) optical sensors that provide information on unwanted corona and small arcs or the normal emission of circuit breakers, (f) ionization sensors for determination of breakdowns and over-voltage conditions and (g) chemical sensors for sniffing emissions from overheated or burning insulation materials. Examination of the return of information from each type of sensor relative to their cost and complexity shows that the sensors listed in the first four categories would provide a great deal of return for the investment. All these sensors can be integrated into a cluster with a common set of supporting electronics, including computation, and a means for communicating the obtained information.

6.6. Machinery monitors

Rotating and reciprocating machines are also fundamental to a technological society. Monitoring their operation permits early detection of the need for maintenance. The suite of sensors that can be used for this application is similar to the sensors recommended above for monitoring power systems. Temperature is a key parameter to be obtained. Accelerometers provide information on vibrations at relatively low frequencies, while microphones cover both low and high frequencies. Inexpensive two-axis accelerometers are available and low-cost three-axis sensors are in prospect. The integration of such sensors into a cluster is relatively easy since none of them requires sampling of the atmosphere. A wireless (Bluetooth) multi-sensor cluster for monitoring machinery has become available recently [48].

6.7. Building and facilities

The power and fluid systems, and the machinery just discussed, are mostly found within structures. However, building and facilities, such as factories, have additional requirements that can be satisfied by clusters of appropriately chosen microsensors. These include personnel access, safety (notably fire and leak detection), and the movements of goods, materials, and wastes. Currently, systems to accomplish such tasks involve separate video cameras, smoke detectors and, rarely, electronic tags, plus associated displays. Now, it is possible to integrate small, uncooled infrared imagers for detection of both personnel and hot areas with normal visible cameras. Further, electronic chemical detectors can be integrated with particle detectors to make smart smoke detectors.

6.8. Transportation applications

Intelligent Transportation Systems (ITS) are being developed in the US, Europe and Japan in order to save time and increase safety [49]. Such systems involve road, rail, and other modes of movement. Road ITS requires integrating technologies, especially for communications, both into vehicles and near the roads. Sensors along roads that monitor the type and flow of traffic will be a part of an ITS. They are already in use in some regions [50]. It is clear that the microsensor clusters of the type discussed in this paper offer the possibility of monitoring traffic. The use of different sensor technologies, for example, optical and acoustic, might enable robust determination of desired information on traffic under widely varying weather conditions. Providing power to and communications from traffic monitors are challenges.

6.9. Autonomous robots

Many mobile land and aerial robots have been developed. They were initially operated by humans, usually via radio links. In the last decade, numerous autonomous robots have been prototyped, mostly in engineering research projects and several experiments involving multiple robots (up to about three dozen) have been performed [51]. Recently, interest in the behavior of swarms of insects (ants, bees and termites) and animals (fish and birds) has lead to many complex computer simulations of swarm behavior [52]. Now, it is desirable to perform experiments with many (hundreds or more) interacting robots in order to understand the emergence of cooperative, whole-system behaviors. Such experiments have not been performed because of robot cost and reliability factors. Concepts are being developed to use the same manufacturing technologies discussed above for production of low-cost and

[3] Honeywell makes the SMV 3000 Smart Multivariable Flow Transmitter that measures absolute and differential pressures and temperature, and computes mass and volume flow and other parameters such as viscosity.

[4] Rosemont offers a Model 3095MV Mass Flow Transmitter with the same functionality as the Honeywell SMV 3000.

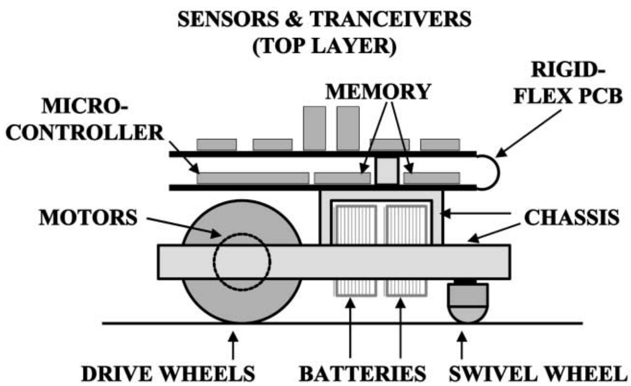

Fig. 14. Side view of a conceptual small robot carrying a microsensor cluster.

long-lasting microsensor clusters to make cheap, reliable and high-performance robots for swarm experiments. Fig. 14 is a sketch of a possible small robot, about 8 cm long and 5 cm wide, equipped with a suite of sensors, microcontroller(s) and communications channels on a rigid–flex–rigid printed circuit board. The chassis would be made of plastic by injection molding at low cost. Two wheels driven by computer controlled reversible motors would provide mobility. The robot will essentially be a microsensor cluster with wheels. Robot swarm behavior should prove to be widely varied.

6.10. Solar system exploration

The Sojourner robot on Mars both produced significant scientific data and attracted widespread interest in 1997. Currently, two 150 kg rovers are being prepared for landing on Mars in 2003 [53]. The deployment of more numerous and smaller mobile explorers to Mars or other bodies in the solar system, such as the moons of the Earth, Mars, Saturn and Jupiter, is attractive. They will be constrained to sizes large compared to microsensor clusters by requirements of mobility and power. The sensor clusters envisioned here, which offer significant functionality in small and low-power packages, will be of use to rovers on planets or moons. For these applications, as for most of those discussed, there will be great emphasis placed on performance of the microsensor cluster, including calibration, and on its reliability.

7. Conclusion

In some cases, historically, there is a trend from individual components, such as sensors, to integrated systems, now on the level of chips. The focus in this paper on board-level systems involving multiple microsensors might strike some readers as strange because of the great deal of attention given to 'systems on a chip' or SOC in recent years. The appeal of SOC for micromechanical devices is clear. If micromechanics can be successfully integrated with microelectronics within a MEMS device, maybe it is possible to integrate multiple MEMS sensors on the same substrate. Doing this might be possible in some cases, but there are three primary reasons why it will not generally be done for microsensor clusters. In some cases, the processing required to produce one kind of sensor might not be compatible with the processing for another sensor needed for a functional cluster. Further research might overcome such problems, just as a great deal of work has produced alternatives for integration of micromechanics with microelectronics. However, the wide variety of MEMS sensors and the many combinations in which they can be used make the development of compatible processes for different sensors unlikely in general. If all the sensors in a cluster are sealed from the atmosphere, as in the case of a machinery monitor, then their integration onto one chip is easier. However, if even one of the microsensors has to be open to the atmosphere in some fashion, then having it on the same substrate as sensors that should not be exposed would be problematic. Most importantly, because of the size of batteries and the need for other microelectronic chips in a cluster, especially the relatively large microcontroller, the space and weight savings from having two or more sensors on one substrate would not greatly impact the overall cluster size.

The essential point is that smaller systems than the board-level clusters discussed above are possible in some cases. However, microsensor clusters with volumes on the order of cubic centimeters can be made now with mass production technologies and embedded in many locations and systems. A recent book was titled 'When Things Start to Think' [54]. What is discussed in this paper, and future micro- and nano-technologies, raise the possibility of things starting to sense. In fact, analogies can be drawn between the components of microsensor clusters and living beings: the sensors are like the eyes, ears and other senses; the printed circuit board, interface electronics and microcontroller correspond to the central nervous system and the brain; power from batteries or elsewhere and the circuitry to condition it have food and the digestive system as correlates; the input and output systems can be viewed as analogous to hearing and speech; any actuators are like muscles in function; and the housing is structural, sort of an exoskeleton. When microsensor clusters are part of mobile robots, then the list of parallels has another addition.

Acknowledgements

This work was sponsored by the MEMS Program in the Microsystems Technology Office of the Defense Advanced Research Project Agency (Contract N66001-98-1-8923). Mothusi Tladi compiled the specifications of PIC microcontrollers that were used to make Fig. 6. Jeffrey Poston provided Fig. 7. Mothusi Tladi, Jeffrey Poston, Brian Bischoff, who pointed out the commercial flow sensor systems, and one of the referees who provided additional references, are thanked for their assistance.

References

[1] See the Sensors Magazine Buyer's Guide: http://www.sensorsmag.-com.

[2] Sensor Sourcebook, Technical Insights. 3rd ed., Wiley, New York, 1998.

[3] M. Horton, Standard Wireless Protocols Create New Sensor Networks, NASA Tech Briefs, September 2000, pp. 30–31.

[4] NIST IEEE 1451 Site: http://129.6.13.102/.

[5] A. Mason, W.G. Baer, K.D. Wise, A low-power wireless microinstrumentation system for environmental monitoring, Digest International Conference on Solid-State Sensors and Actuators, Stockholm, June 1995, pp. 107–110.

[6] LCI Technology Group: http://www.lcigroup.com/.

[7] C.L. Britton Jr., et al., Battery-powered wireless MEMS sensors for high-sensitivity chemical and biological sensing, Advanced Research in VLSI, Proceedings of the 20th Anniversary Conference, 1999, pp. 359–368.

[8] B. Kim, et al., MEMS sensor multi-chip module assembly with TAB carrier pressure belt for aircraft flight testing, Proceedings of the Electronic Components and Technology Conference, 2000, pp. 689–696.

[9] S.C. Galea, A.A. Baker, Smart structures approaches for health monitoring of aircraft structures, Proceedings of the Symposium on Smart Materials and MEMS: Smart Structures and Devices, SPIE, vol. 4235, 2001.

[10] S. Hollar, COTS Dust, MS Thesis. Department of Mechanical Engineering, University of California at Berkeley, 2000 (available at http://www-bsac.EECS.Berkeley.EDU/(Nshollar)

[11] Smart Dust Web Site: http://robotics.eecs.berkeley.edu/(pister/SmartDust/.

[12] Sensor Web Project: http://sensorwebs.jpl.nasa.gov/.

[13] Wireless Integrated Microsystems Web Site: http://64.78.45.100/.

[14] N. Maluf, An Introduction to Microelectromechanical Systems Engineering, Artech House MEMS Library, 1999.

[15] R. Frank, Pressure sensors merge micromachining and microelectronics, Sensors and Actuators A 28 (1991) 93-1-3.

[16] R.A. Kant, D.J. Nagel, Characteristics and performance of MEMS accelerometers, in: M.J. Berliner, J.F. Lindberg (Eds.), Proceedings of the Conference on Acoustic Particle Velocity Sensors: Design, Performance and Applications, AIP Conf Proceedings, vol. 368, 1996, pp. 166–176.

[17] The MicroChip Technology Corporation: http://www.microchip.com/.

[18] Software for PIC microcontrollers: http://www.piclist.com/.

[19] Jeffrey Poston, unpublished.

[20] IEEE Standard 802.11 Web Site: http://www.manta.ieee.org/groups/802/11/.

[21] Bluetooth Web Site: http://www.bluetooth.com/.

[22] G.S. Lauer, Packet Radio Networks, in: M. Steenstrup (Ed.), Routing in Communications Networks, Prentice-Hall, Englewood Cliffs, NJ, 1995, chapter 11.

[23] Tucson Area Packet Radio: http://www.tapr.org/.

[24] UltraLow Power Wireless Sensor Web Site: http://www-mtl.mit.edu/(jimg/project_top.html.

[25] WINS Web Site: http://www.janet.ucla.edu/WINS/.

[26] Sensoria Web Site: http://www.sensoria.com.

[27] Cross Bow Technology Web Site: http://www.xbow.com.

[28] Graviton Web Site: http://www.graviton.com.

[29] Millennial Net Web Site: http://www.millennial.net/overview.html.

[30] D.J. Nagel, Wireless Smart Sensor Networks, ISA Emerging Technologies Conference, Houston, TX, September 2001.

[31] D.J. Nagel, Design of MEMS and microsystems, Proceedings of Conference on Design, Test and Microfabrication of MEMS and MOEMS, SPIE, 1999, 3680, pp. 20–29.

[32] R. Merker, W. Schwarz (Eds.), System Design Automation: Fundamentals, Principles, Methods and Examples, Kluwer, Dordrecht, The Netherlands, 2001.

[33] B. Tabbara, A. Tabbara, A. Sangiovanni-Vincentelli, Function/Architecture Optimization and Co-design of Embedded Systems, Kluwer, Dordrecht, The Netherlands, 2000.

[34] J. Bhasker, A VHDL Primer, Prentice Hall, Englewood Cliffs, NJ, 1998.

[35] P.J. Ashenden, The Designer's Guide to VHDL, 2nd ed., Morgan Kauffman, Los Altos, CA, 2001.

[36] D.D. Gajski (Ed.), SpecC: Specification Language and Methodology, Kluwer, Dordrecht, The Netherlands, 2000.

[37] A. Gerstlauer, R. Dower, J. Peng, D.D. Gajski, System Design: A Practical Guide to SpecC, Kluwer, Dordrecht, The Netherlands, 2001.

[38] http://smt.pennnet.com/ProductGuide/NewCategoryList.cfm?section = ONLINE_PRODUCT_GUIDE&Publication_ID = 35&Cat = 50079&tlc = 50079.

[39] D.M. Tanner, Reliability of surface micromachined microelectromechanical actuators, Proceedings of the International Conference on Microelectronics, 1999, 1, pp. 97–104.

[40] Exponent MEMS Testing and Reliability: http://www.exponent.com/practices/MEMS/testing.html.

[41] J.M. Kahn, R.H. Katz, K.S.J. Pister, Next century challenges: mobile networking for smart dust, ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 99), Seattle WA, August 1999.

[42] Kestrel 3000 Pocket Weather Meter Web Site: http://www.nkhome.com/ww/3000/3000.html.

[43] D.J. Nagel, Unpublished.

[44] D.J. Nagel, Micromachined and Integrated Electronic Nose Technologies, presented at the Seventh World Micromachine Summit, Frieburg Germany, 30 April 2001.

[45] P.R. Vogt, W.-Y. Jung, D.J. Nagel, GOMaP: a matchless resolution to start the new millennium, EOS (Transactions of the American Geophysical Union) 81 (23) (2000) 254–258.

[46] One of the companies making integrated Conductivity, Temperature and Depth (CTD) instruments is Falmouth Scientific: http://www.falmouth.com.

[47] M.T. Berger, Analysis of the differential pressure flowmeter market, M and C news, September 2000, pp. 44–45.

[48] Oceana Sensor Technologies Web Site: http://www.oceanasensor.com/.

[49] F. Pena, "I want 75 of our largest metropolitan areas outfitted with a complete intelligent transportation infrastructure in 10 years", Speech by the US Secretary of Transportation at the Transportation Research Board in Washington DC on 10 January 1996.

[50] DDG Gesellschaft für Verkehrsdaten mbH: http://www.ddg.de/.

[51] L.E. Parker, G. Bekey, J. Barhen (Eds.), Distributed Autonomous Robotic Systems 4, Springer, Tokyo, 2000.

[52] E. Bonabeau, M. Dorigo, G. Theraulaz, Swarm Intelligence, Oxford University Press, Oxford, 1999.

[53] NASA to Send Rover Twins to Mars: http://mpfwww.jpl.nasa.gov/mep/missions/announce2.html.

[54] N. Gershenfeld, When Things Start to Think, Henry Holt, New York, 1999.