CHAPTER 1

MARKETS AND APPLICATIONS

1.1. Technology at Crossroads

This book concerns a particular class of Micro Electro Mechanical Systems (MEMS) device: Intelligent or smart sensors. The general area of MEMS is one that has been the subject of speculation and 'futurology' over the past few years, some of which has been quite unhelpful in providing a real appreciation of the huge potential of this technology. In the first days when micromachining became feasible, there were extreme predictions of the potential of the new technologies — micromachines that would revolutionise every aspect of daily life were predicted, often based more on science fiction that any sober assessment of the capabilities of the technology. More recently, the futurologists have turned their attention to nanotechnology, MEMS being old news. Strangely, however, the prediction that MEMS technology would affect our daily lives has turned out to be entirely true, but the effect has been in ways both more subtle and profound than envisaged by the original forecasts. MEMS has indeed proved to be a potent technology and the application of MEMS that has been most important for the realisation of this potency has been sensors: sensing, a seemingly prosaic area of technology, has been revolutionised by MEMS to the extent that the basis has been laid for completely new types of engineering systems. There is now the possibility of designing complex MEMS based systems that are sensitive and reactive to their environment and able to respond and adapt to it. In turn, this responsiveness may be used to address some of the large scale engineering problems which are crucial to the major concerns of the world today: efficiency, energy saving and environmental monitoring. This book is about the design concepts and methods that will be necessary to realise these new systems, building from the technological base provided by MEMS sensors.

One of the major problems in realising the potential of MEMS is that the fundamental characteristics of the technology, the ability to manufacture huge numbers of sophisticated electromechanical systems, gives it the power to produce systems of staggering complexity, which is reflected in the difficulty both of designing and building them. Therefore this book focuses on these systems level issues, rather than the technologies which allow fabrication of ever more capable MEMS devices — that has been extensively covered elsewhere. It charts the developments in the supporting systems technologies which enable the unique properties of MEMS sensors — mainly to do with tiny size and very low cost — to be used to build real operational systems of increasing power and capability.

The book is written at a time when there is something of a crisis of confidence in MEMS technologies, and, as suggested earlier, they are somewhat in the shade of nanotechnologies. Stephen Senturia, who has been a leading light in the field since its inception, wrote: "much of the energy and dynamism that has characterised the field for more than 20 years may flag and fail" [1]. As someone who was present at the inception of the pioneers' dreams, it is natural that Senturia should detect a waning of enthusiasm. However, those first dreams have been replaced with new, more achievable aspirations, allowing confirmation of the observation made above: that MEMS is indeed a technology which will change the world in which we live, although perhaps not in the ways which were originally put forward by the futurologists.

Crucially, for the state of the art in this field, we now have enough visibility of the world changing applications of MEMS to be able to see clearly the path towards their realisation. It is the belief of the authors that to achieve this new potential a new research agenda will be necessary, one which will include workers from other disciplines than the materials scientists and electronics engineers who have traditionally formed the mainstream of this domain. We start by surveying the importance of MEMS in the world today, the reasons for the over expectations in the past and the real potential for the future.

1.2. The Present — MEMS in the News

To understand the ways in which MEMS sensors are indeed changing the everyday world in which we live, we look at some of the recent news releases in the technical and popular press. MEMS sensors are contributing to profound developments in a number of day to day activities:

Healthcare

> *"Microelectromechanical Systems (MEMS) range from the mundane to the spectacular. At one end of the spectrum are devices such as the precisely machined nozzles used in ink jet printers. At the other extreme, MEMS are enabling the blind to see." — Semiconductor International, June 2003. [2]*
>
> *"... and then there are really esoteric MEMS devices. Researchers have created microscopic MEMS motors and minuscule mechanical manipulators that can grasp a single red blood cell.... What's not small about MEMS is their growth potential." — Design News. [4]*
>
> *"Emerging inertial sensors fashioned from microelectromechanical systems, or MEMS, promise to enhance medical equipment in ways that make them easier and safer to use. Such devices are already being aimed at defibrillators and patient-monitoring systems. MEMS technology, in the form of a DNA lab-on-chip, will also in the future play a key role as part of a set of instruments for making quick analyses of microbiological samples."*

— EE Times, August 2004. [3]

Transport

> *"Drivers in the INDY racing league have a new piece of kit this year and it isn't under the hood but in their ears. Embedded in the driver's radio earpiece is a tiny MEMS sensor system (4.5 × 4.5 × 2 mm) developed by engineers at Delphi that measures the dynamic forces applied to the drivers head during an accident. The g-force data collected will provide researchers a clearer picture of what happens in the split second of time that it takes for a crash to occur, leading to better design of the driver restraint system and safety devices."*

— Design News, May 2003. [4]

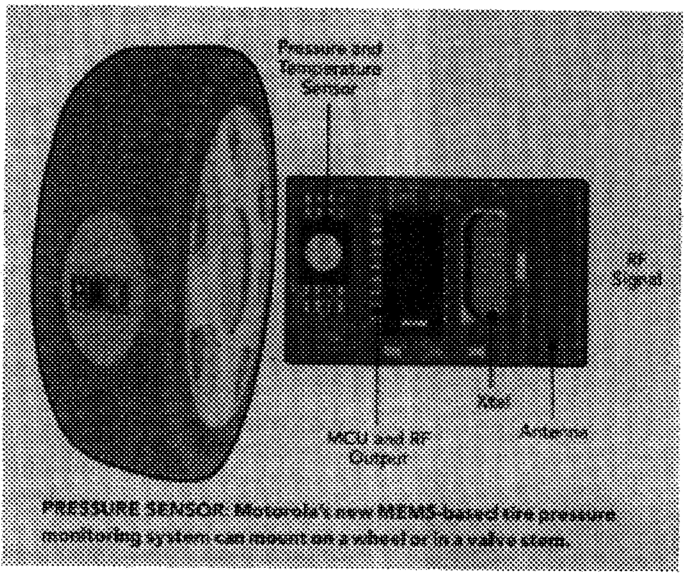

Figure 1.1: Tyre pressure sensor. From [4].

> *"From now on, even tyres will contain electronic components. Motorola's MPXY8000 tire-pressure monitoring system goes inside a tire or onto a tire's valve stem to constantly check for dangerous tire deflation (See Figure 1.1). The system wirelessly transmits information to a car's remote keyless entry receiver, where software can alert a driver to stop and add air."*

— *Design News, May 2003. [4]*

> *"June 10 2004 — Crossbow Technology Inc. has launched a series of systems that provide navigation, position and leveling information to air and watercraft. The NAV420 series packs MEMS-based accelerometer and gyro clusters with a global positioning satellite receiver and other sensors and software in a 3-inch cube.... The system provides information to an autopilot or display on whether the craft is straight and level, and the direction it is going, within 1 degree of accuracy. It is designed to replace larger and less reliable mechanical sensors."*

— *Small Times, June 2004. [5]*

"The accelerometers from Analog devices that deploy airbags in car crashes exhibit less than one failure per billion hours of operation."

— Design News, May 2003. [4]

"The automotive industry, already the largest market for MEMS devices, will use more of them... 9.1 per vehicle in 2007... up from 5.0 in 2002."

— Design News, May 2003. [4]

Leisure and consumer

"Mitsubishi Electric Corp. has designed a motion sensor by MEMSIC Inc. into a mobile phone manufactured for Vodafone Group PLC. The accelerometer enables a pedometer to measure distances and provides image orientation for the camera in either portrait or landscape modes. The sensor also allows a user to use the phone as a joystick for video games."

— Small Times, June 2004. [6]

"Says Benedetto Vigna, manager of MEMS development for ST, 'I believe this will be the decade of MEMS inertial sensors for consumer applications.' Part of the impetus of new MEMS applications comes from increasingly sophisticated features. ... Performing as very sensitive motion and tilt sensors, they're starting to provide one-handed, keyless scrolling of displays on cell phones and PDAs. To scroll a mobile phone's tiny display, you just tilt the phone in the appropriate direction. ... To zoom in, you raise the phone or PDA a bit; to zoom out, you lower it."

— Design News, May 2003. [4]

> *"Analog Devices Inc. has announced that its iMEMS accelerometer technology will be used in multiple platforms of IBM's ThinkPad mobile computers featuring the Active Protection System technology. An ADI accelerometer on the ThinkPad motherboard detects shocks or free-fall conditions, suggestive of an imminent impact, and within a fraction of a second signals the drive's R/W heads to temporarily park, helping prevent contact with the disk drive until the system is stabilized."*

— *EE Times, January 05. [7]*

Communications

> *"A 80-channel optical communications switch that adopts MEMS mirrors, achieving a switching speed of 1 ms (claimed to be the fastest switch to date) was developed by Fujitsu. Measuring 150 × 400 × 300 mm, the switch offers an optical power stability within 0.5 dB. The tilt of the MEMS mirrors is precisely controlled through a feedback loop in a built-in control function which maintain the optical power at a fixed level."*

— *EE Times, October 02. [8]*

Industry and construction

> *"Because engineering departments are run leaner and need to concentrate on core activities, design engineers are increasingly looking for complete solutions. Complete solutions are recognized as being economically attractive or perhaps more attractive because with a complete solution somebody takes overall responsibility. . . . to be effective and have wide ranging impact, smart sensors must work with a complex maze of networks and computer interfaces."*

— *Industry News, December 01. [9]*

"Engineers may no longer have to struggle with wires and batteries in monitoring the structural health of buildings and bridges. A wireless, battery-free microsensor system that would enable engineers to accurately assess and monitor structural health has been developed by researchers at Sandia National Laboratories in Albuquerque, New Mexico. The energy-capturing portion of the system takes the form of a 32 by 62 by 0.5 mm strip of piezoelectric material 20 mm thick that is embedded in a concrete or steel structural element of a building or bridge along with its associated hardware."

— *Civil Engineering, August 02. [10]*

A conclusion that can clearly be drawn from these clips is that MEMS sensors already affect in a fundamental way people's day to day lives. The size of the MEMS industry today is huge (in financial terms, obviously, as the size of the physical output is tiny). The market for MEMS devices, taking a 'narrow' view of MEMS (i.e. excluding ink-jet print heads and the like) is expected by In-Stat/MDR (part of Reed Electronics Group) to grow from $3.9B in 2001 to $9.1B in 2006, with most of the growth in traditional areas, although bio-MEMS (lab-on-a-chip for DNA analysis) and RF MEMS are the fastest growing. NEXUS take a broader view, grouping MEMS with larger systems such as hearing aids and cardiac pacemakers and expects this "Microsystems" market to increase from $30B in 2002 to $68B in 2005. [11]

1.3. The Past — Great Expectations

Senturia himself gives a fascinating account of the very early days of MEMS sensor research [1]. Discussing the 1981 Materials Research Society meeting, he notes the following:

> *Eighty researchers in the field of 'Solid State Transducers' gathered from around the world to share their experiences, both technical and organisational... the only 'physical sensors' discussed during the symposium, in addition to pressure sensors, were magnetic sensors, the microdielectrometer for low frequency dielectric analysis of resins, a temperature sensor, and a dew point*

> *sensor. Chemical sensors, including both gas sensors and ion-sensitive devices, were prominent. Accelerometers, flow sensors, gyros, switches, relays and actuators of any type were nowhere in sight.*

Interestingly, the sensor types that Senturia's group was bemoaning the lack of was precisely the group that now forms the mainstay of the burgeoning MEMS industry: accelerometers, pressure sensors and gyros. The automotive industry alone consumes huge numbers of these types of sensor (primarily pressure sensors and accelerometers), and their use is growing (9.1 per vehicle in 2007... up from 5.0 in 2002) [4]. However, in 1981, one of the world's leading symposia in the field failed to consider these seriously at all. How could this be?

The answer to this question lies in the motivations and drivers of those doing the basic, underlying research in a topic. There is always pressure on researchers operating at the practical end of their domain to work in areas which are thought of as revolutionary, rather than evolutionary. The areas that are thought of as revolutionary are generally defined by the visionaries and futurologists. At this time, the ambitions of researchers were set very much higher than the mere improvement of such prosaic articles as accelerometers and pressure sensors. Some of the research agendas that were being set at the time can be judged by looking, for example, at that of the Japanese Micromachine Program I the 1990's. In a report on the Micromachine Symposium, in 1994, Kahaner summarises its goals [12]:

> *The ultimate goal of mechanical engineering is to replace human functions and labour by machines. To reach this advanced state, we must develop machines as clever as ourselves, and enable them to move according to their own decisions as our body does.*
>
> *To meet the second requirement, it is necessary to make machines much smaller, as may be realised from the fact that human movements rely on cells and their constituent substances including proteins and other biological molecules.*
>
> *Reducing machine dimensions has lagged behind the R&D of intelligent machines. However, this challenge must be faced for the progress of mechanical engineering. Developing micromachines may provide us with great innovations in industrial technologies as did the development of intelligent machines.*

> *Unfortunately, micromachinery has not found any definitely promising applications yet. Worse, the research investment will certainly be huge. In the private sector, therefore, research of micromachines will be too limited to achieve technological innovation.*
>
> *The Industrial Science and Technology Frontier Program has been set up to develop micromachine technology to strengthen industrial technologies as well as mechanical engineering.*

Later the three major goals of the program were set out.

(i) Advanced maintenance system for power plants

This is a micromachine system for the maintenance of fine tubes in power plants. The system will consist of a microcapsule, a base machine, inspection module and operation module. Necessary mechanical components (e.g. microscopic power generator and energy transmitter) of the system have been specified. The component devices are being fabricated.

(ii) Medical micromachines

Micromachines are applicable to examination and treatment inside the body cavity. A micromachine will possibly be inserted through a catheter for diagnosing and curing, for example, cerebral thrombosis and aneurysm. Component devices of such medical machines are being fabricated.

(iii) Microfactories engineering

A system for manufacturing tiny precision parts of watches, cameras, and electronic appliances with much smaller production equipment than predecessors. The system will greatly reduce energy consumption in production. The miniature equipment should be no larger than 2–10 times the size of the product. Component devices of the equipment are being fabricated.

Moreover, in a another article [13], contemporaneous with Kahaner's, Voelker states:

> *Micromachinery also has important potential applications in "conventional" medicine; scientists in Japan and elsewhere are working on "microrobots" designed to circulate in the bloodstream and relay temperature, pressure, pH and other conditions back to an*

> *external computer, in the manner of the miniaturized submarine in the movie "Fantastic Voyage".*

In the second reference, the Science Fiction drivers are explicit. Obviously, one cannot assume that the goals of the whole research community are represented by these two statements, but it does indicate that during the 1980's and early 90's there was at least a strand of research setting near term goals for microtechnology that were visionary but ultimately unrealistic, without any clearly defined development path towards them. The actual pace of development was actually very different. Senturia wrote:

> *There has been no shortage of bright ideas in the area of microsensors, microactuators and microelectromechanical devices of all sorts. However, the track record on converting those ideas into commercially successful products has seemed uneven to some, both inside and outside the field. It has taken 15 to 20 years (or more) between early research prototypes and full commercialisation for such devices as silicon pressure sensors, accelerometers and optical displays. [1]*

At the time, the agenda for sensor researchers was being set by visions of the 'science fiction' type, which, twenty years later, have still to be achieved. Against such a background, MEMS rapidly gained a reputation as a technology that was failing to deliver. Fortunately, the stolid and reliable sensor and transducer technologists have pursued an incremental development path, resulting in technology which can deliver real benefits in real applications and which finds applications numbered in the millions. MEMS is now once again seen as a pervasive technology, affecting and enabling a host of related technologies. It will become even more so in the future.

1.4. The Future — Maturity and Pervasive Applications

The current state of the art in MEMS, particularly when linked with associated developments in VLSI and pervasive computing, has provided a basis for a new round of 'dream applications'. While still clearly visionary, these are not in quite the same grandiose league as the 90's 'fantastic voyages'. Instead they are generally designed to deliver some quite tightly specified advantages in real world applications, such as environmental monitoring, adaptive aerodynamics or scientific exploration. Unlike the previous fantastic journies, these applications highlight real research challenges, ones for which it is possible to scope and plan a line of research that can realistically deliver working technology. Below, a few such applications are surveyed, starting with near future proposals for which the technology is actively being developed, leading on to more 'blue skies' proposals, which are still at the level of feasibility studies. This is, in itself, a major qualitative difference from the proposals seen previously, which were often put forward without any well reasoned case made for feasibility.

Until recently, space research, or more colloquially 'rocket science' has been seen as one of the primary drivers of technological development, and it is to be expected that a number of visionary applications of Microsystems will apper in this domain. Some are proposed by Stenmark [14], as follows:

- *Thermal control* — using thin film technology or 'functional surfaces' (micro actuators embedded in the skin of a spacecraft — in which the thermal emittance can be changed by using an electrical control signal. It is proposed that such a system can replace mechanical louvers.
- *A Micro Propulsion Cold Gas Thruster* system — this was a multiwafer design which contained many functions in one unit (nozzle, heat exchangers, valves, pressure sensors, electronics, etc.). It is suggested that this system allows very accurate attitude control. This was achievable taking into account the state of the research art in microsystems in 2001 [15], and so is a 'safe' technology prediction.

More speculative sensor based dream applications are the Berkeley 'smart dust' proposals, based on so-called 'motes', (wireless autonomous smart sensors), which are deployed in their thousands for various environmental and battlefield sensing applications [16]. Derived from this is the GEMS proposal [17], which imagines global deployment of motes into the atmosphere for meteorological sensing. Another proposal, from NASA, is the 'ageless aircraft' in which smart materials integrate intelligent condition monitoring sensors and actuators to continuously sense and correct structural aging problems [18]. The basis for such proposals comes from the inherent, natural MEMS properties of size and potentially low cost, which encouraged the liberal usage of these devices in applications. Such usage, in turn, leads to the need to rely on and/or add efficient and clever processing of data generated by the sensing device, before such data reaches the outer world. The nature of this processing, and the design methods used to specify and code it, are rarely put forward in detail by the proposers of the application, although they are a pre-requisite for its realisation. These design methods form an important topic of this book.

Another proposal discussed here is from one of several NASA studies [19]. It proposes the use of wireless intelligent sensors (called 'tranceivers') to predict the failure of equipment (see Figure 1.2). If impending failure is predicted then a replacement, or replacement consumables can be ordered and installed 'just in time'. A block diagram of the intelligent sensor node is shown here. As well as sensors (of unspecified type) it contains a GPS system (so that it can determine its location) and radio for connection to the internet. The proposal goes on to suggest that:

> *Intelligent transceivers would have dimensions of no more than a few centimetres. They could be mass-produced relatively inexpensively by use of established integrated-circuit fabrication techniques. An intelligent transceiver would be connected with "smart-part" microchips that would be designed into major components and subassemblies of the equipment to be monitored (see figure). These microchips would contain sensors and sensor circuitry for monitoring the physical conditions and statuses of components and subassemblies.*

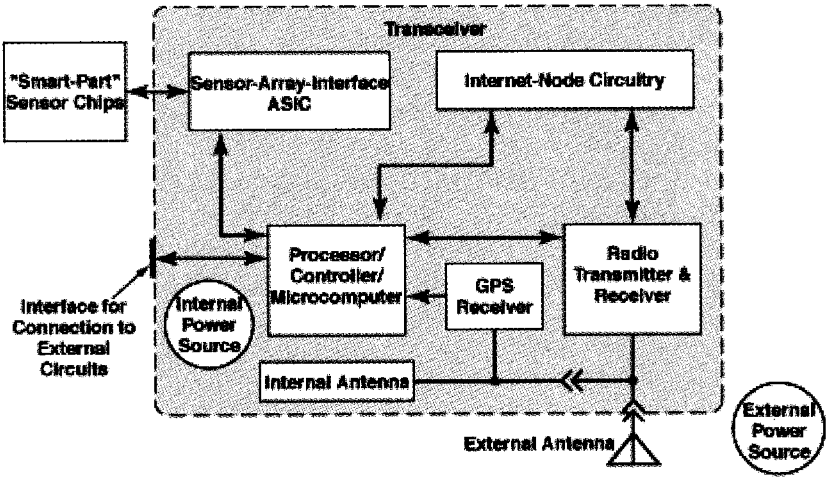

Figure 1.2: Block diagram of 'tranceiver'. From [19].

A transceiver on a damaged piece of equipment could interrogate other damaged pieces of equipment to determine what components could be salvaged and whether a replacement for a damaged component in its own damaged piece of equipment was locally available.

Each transceiver would be capable of "learning" and updating its "knowledge" of the rates of wear of critical components. An "Intelligent" Transceiver connected with "smart-part" sensor chips would provide information on the status of the equipment in which the sensor chips were embedded.

This, and the other applications put forward in this section, have a common factor that the scenarios are being detailed to the point of precise specification of the sensing devices, elaborated accounts of their function and interaction and some quite precise estimates of their size, cost and component parts. It would be possible, in most of these cases, for a suitably qualified engineer to take the scenario and start an outline design for the hardware (and this book would be a good guide for such a task). It is on this basis that these applications can be said to be feasible. However, the detail of how the interaction between the many sensing components occurs, how it is planned, designed and implemented, is much more sketchy. Research into how to undertake these tasks is a prerequisite for the realisation of all of these applications.

1.5. Drivers for Progress

The 'dream applications' for the future, presented above are all academic or agency studies. Whilst impressive, and in some cases technologically thorough and possibly feasible, none of them will be realised unless there are very sound and hard-headed reasons to make the investment necessary. Some of the scenarios proposed have been detailed precisely to encourage speculation on the potential of the technology, and therefore encourage the raising of the required funding and sponsorship. Although the scenario provides some kind of 'road map' for the technological development, the precise direction in which it will proceed is, more often than not, driven by the nature of that funding, and the concerns and motivations of the sponsors. In general, these concerns and motivations derive from five high level issues: (the market, impact, competition, technology and manufacturing [2]), which are discussed below.

(i) The market

In order for a development project to go ahead, its funders need to know that the development investment will be returned, with a profit. Prediction of future markets, their possible size and growth is not an exact science, so this development funding always entails a risk. The risk is minimised if the new market is a straightforward extension or derivation of an existing market. But while such markets are more predictable, the possible returns are smaller, since the opportunity for massive growth is likely to be less than with a completely new market. A good example of such a 'developmental' market (although in the generality of MEMS, rather than sensors specifically) is that of MEMS RF filters. The MEMS products have significant size, and cost advantages over traditional filters. At the same time, given the growth of wireless technology, small, cheap RF filters are likely to be in huge demand. Thus, for instance, the development of MEMS RF filters is not a big risk.

(ii) Impact

In some cases, where the new technology offers a paradigm shift, enabling completely original products, or ones with radically different functionality from their forebears, the risks are high, and the size of the market very difficult to estimate. On the other hand, the returns can be huge. Such developments will be funded by large corporations (where the risk may be spread over a large overall development investment) or by venture capital. In either case, the sponsors' decisions are likely to be driven by the potential of the final product, rather than incremental device improvements.

(iii) Competition

In a competitive market, if one manufacturer gains an advantage by moving to a MEMS based product, then its competitors are under strong pressure to follow suit, hopefully with an improved, rather than 'me too' product. If the MEMS product radically changes the market, then manufacturers failing to follow suit are at risk.

(iv) Technology

A manufacturer's decision on whether or not to develop a product will be influenced by the investment it has to make in the technology to develop it. It is here that prior investment (either direct, or by sponsoring research organizations) in technology demonstrators (such as the 'dream applications' discussed above) may pay off. Manufacturers with existing MEMS products will be at an advantage compared to those that have to buy in (specialist MEMS foundries providing some means of 'catch-up' for these). Designs that can use or adapt existing technologies will be favoured over those requiring completely new ones.

(v) Manufacturing

Designers of technology demonstrators or research products are unlikely to consider too seriously the manufacturability of their design. On the other hand, for low cost, mass market products, issues such as device yield, plant design and calibration and configuration costs are key. Self-configuring, calibrating and fault tolerant designs will be at an advantage, so long as the "in use" cost advantages are not outweighed by higher unit costs.

In practice, it can be seen that all of these drivers are at work, pushing forward the practical limits of MEMS sensor technology. It is upon the progress currently being made that further developments will be made, which in turn will enable the 'dream applications'. Below is a survey of technological progress on three fronts, the improvement on MEMS devices themselves, the integration of those devices with other system components and functions, such as the 'intelligence' required for our 'dream applications', and finally the design methods to enable large and complex sensing systems to be realised.

1.6. Progress — Device Improvement

The maturity of the MEMS technology is shown by the subtle and sophisticated device designs now being realised. Again, looking at current press reports indicates that the ingenuity of MEMS designers has reached a very high level. Utilising tiny components to fabricate accurate and robust devices is commonplace, as indicated by the report below (see Figure 1.3).

> *"The proof mass in Analog Devices MEMS gyroscope weighs only 8 millionth of a gram. It is suspended only two microns over the device's electronic circuitry. The proof mass in accelerometers from MEMSIC beats even that. It's nothing but a gas that moves in a sealed chamber,*

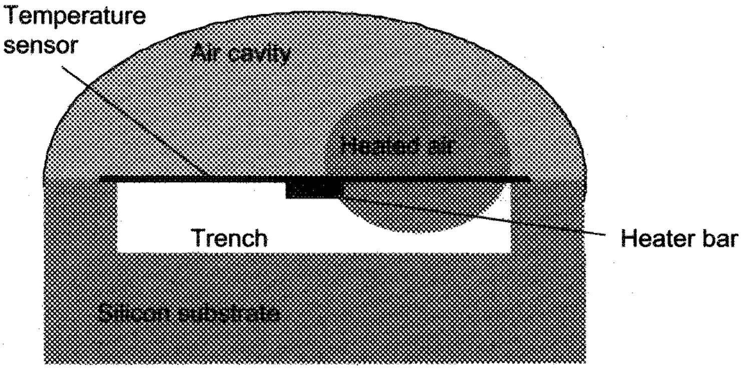

Figure 1.3: In MEMS accelerometers from MEMSIC, a heated gas changes position as the device moves. Temperature sensors measure the gas's shift to determine acceleration. From [4].

> *and because gas is the only thing that moves, there are no parts which can break. MEMSIC claims its device can withstand shocks of up to 50 000 g."*

— Design News, May 2003. [4]

However, the necessary improvement of MEMS processes to create devices such as the one presented above is not straightforward or inexpensive. We will see later the cost in dollars and time of the development of the technology on which the Analog Devices integrated MEMS systems, lauded in the quote above are based. Such technological progress is often piecemeal and can be painfully slow. For instance, Bryzek follows the development of a single MEMS sensing component, the piezoresistor — used for instance in pressure and force sensors, through more than four decades [20], from the original components fabricated by Kulite as part of a pressure sensor in 1961. The major problem that has plagued the design of this component has been stability. Successive process improvements were made by different workers to improve stability, starting with high-energy ion implantation (Honeywell, 1966), a specialised, and therefore expensive process. This process was also patented, leading other workers to look at alternative methods, ICT developing a very deep junction piezoresistor in the late 70's and NovaSensor creating a Faraday shield round the resistor using metallisation and ion-implantation in 1987, a design still in mass production. Thus, in twenty-six years, steady competitive development had

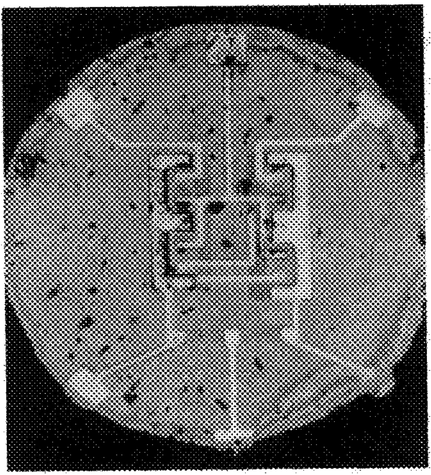

Figure 1.4: The first integrated circuit, 1961. Illustration from Fairchild Inc.

translated an effective but flawed and expensive component into one with essentially the same functionality, but without the stability problem and priced suitably for inclusion in mass market products. By any account, this is slow progress.

If, by comparison, we look at the progress of the digital VLSI industry over the same period, the slowness of progress in MEMS is seen very explicitly. In 1961 Fairchild Semiconductor (actually 'Fairchild Camera' in those days) introduced the first commercially available integrated circuit with two transistors, shown in Figure 1.4.

By 1987, 26 years later, the 'commodity' microprocessor was the Intel 386, shown in Figure 1.5, with 275 000 transistors, which outperformed $100 000 'supermini' computers of just five years before, and was produced cheaply enough to make personal computers an economic possibility for many homes. VLSI electronic process development has proceded much faster than MEMS process development. The mass markets are obvious and established, and therefore the investment is available to fund hugely expensive process development projects. By contrast, in MEMS the mass markets are just now becoming clear, and the vast scale of investment available for new VLSI processes is still not there for MEMS. Much MEMS process research is still occurring in publicly funded university research laboratories, whereas VLSI process improvement is solely the domain of the large corporations.

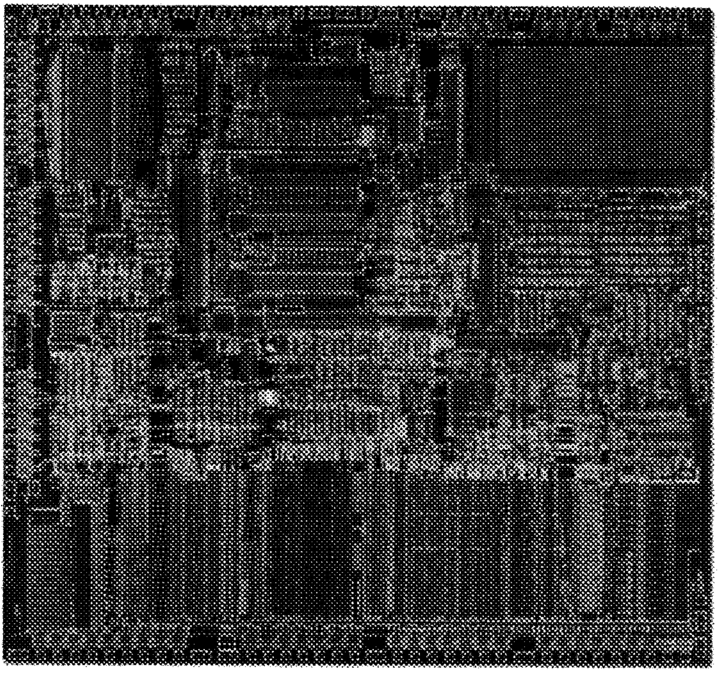

Figure 1.5: Progress by 1987, Intel 386. Illustration from Intel Corp.

If MEMS process development does not proceed at the same rate as VLSI development, perhaps it is possible to use VLSI technologies, and therefore hitch a ride on that train. The use of VLSI technologies, with ultra fine scale lithography and precise control of material characteristics can make it possible to improve the performance of the transducers themselves. It is possible to use signal processing, implemented in VLSI, to ameliorate shortcomings of the MEMS transducers, and much of this book is about this very subject. The key to doing this economically is to integrate the signal processing with the MEMS sensor component. Thus device integration is a major research topic, which will be discussed in the next section.

1.7. Progress — Device Integration

This book concerns the development of intelligent sensors. We will discuss the precise meaning or interpretation of that term in Chapter 8. For the purposes of this section the salient point is that an intelligent sensor integrates electronic circuitry to enhance the performance of the sensor or to provide system level functions. Ultimately, the cost of sensor, be it intelligent or not, depends on the number of separate (as opposed to integrated) components and complexity of assembly. Given that many MEMS processes were originally derived from VLSI processes, and that typically electronic circuitry needs to be integrated with the mechanical assemblies, there is a continuing drive to integrate a 'system on a chip', although this is not always the optimal solution for a given application, as we shall see.

Some commentators see the achievement of further integration as a major constraint on progress. Ohr raises the question of why increasing levels of integration are not routinely achieved [21].

> *High on the list of obstacles slowing the proliferation of silicon micromachines is the task of integrating the sensors of microelectromechanical systems with signal-conditioning circuitry on the same CMOS chip.... "If Itanium uses 100 million transistors, why not MEMS?" asks Analog Devices' Bob Sulouff. Motorola's Dragan Mladenovic and Dave Monk say that high-density mixed-signal processes (like the company's SmartMOS7) would enable competent integration. But a single-chip MEMS controller is still a possibility for the future.*

Sometimes, integrated electronics give the only possible solution to the problems posed by the very fine scale of MEMS devices. Design News discussed this issue. [4]

> *The changes in capacitance that a MEMS device detects are just as tiny as MEMS mechanical components... (at the order of zeptofarads)... so small that having on-chip circuitry to measure it and process the reading is preferable to off-chip circuitry, which can affect readings.*

Just as device integration can make some sensors possible to produce, it can also be used to improve the performance of a device. To illustrate this, we return to Bryzek's tale of the development of the piezoresistor [20]. In the previous section, we saw how process improvement had eliminated the stability problems over a 26 year period. A parallel process, at least to the latter part of that time, has been the use of integrated signal processing to eliminate these same stability problems. ICT started such a development in the 1970's but it was shelved due to lack of development capital (we can speculate that had the process improvement been essential to the development of commodity semiconductors, the funding would have been found). The baton was taken up by National Semiconductor, firstly with integration of active temperature stabilisation circuitry, and secondly with integrated on-chip bipolar analogue signal processing circuitry for a mass-market automotive application. Both were ultimately unsuccessful. Finally, Honeywell succeeded in the early 1980's, on the back of funding for a high value aerospace application. Motorola achieved a low cost integrated solution in the 1990's. Subsequently other manufacturers have produced integrated MEMS with on chip analogue and digital electronics, but no 'standard' process has become established — a testament to the difficulties of integration. Bryzek summarises the existing approaches to integration [20].

> *The first is integration of the MEMS components on top of a fabricated IC. The major constraint is the need for strict process compatibility, which rules out many common MEMS process steps, such as LPCVD polysilicon and silicon fusion bonding. Another restriction is that the exposed materials, typically a low-temperature oxide and aluminum, limit the chemistries available for processing.*

One of the most successful products built with this approach is Texas Instrument's optical display chip, the Digital Light Processor DLP. A complete account of this technology, and the process required to produce it is given by Hornbeck [22]. The DLP chip is an array of articulated mirrors, each of which can be individually swivelled using electrostatic forces. A visualisation of an individual mirror is shown in Figure 1.6.

The complex micromachining process required to build this structure on top of a CMOS chip is shown in Figure 1.7.

The length of development (17 years) and the amount of money spent ($1B) is a good indicator of the difficulty of using this approach. Hornbeck presents a chart (Figure 1.8), showing the incremental design improvements that have been made during those years.

> *A second approach is lateral or side-by-side MEMS and IC Integration. Here, any CMOS incompatible processes are fabricated first,*

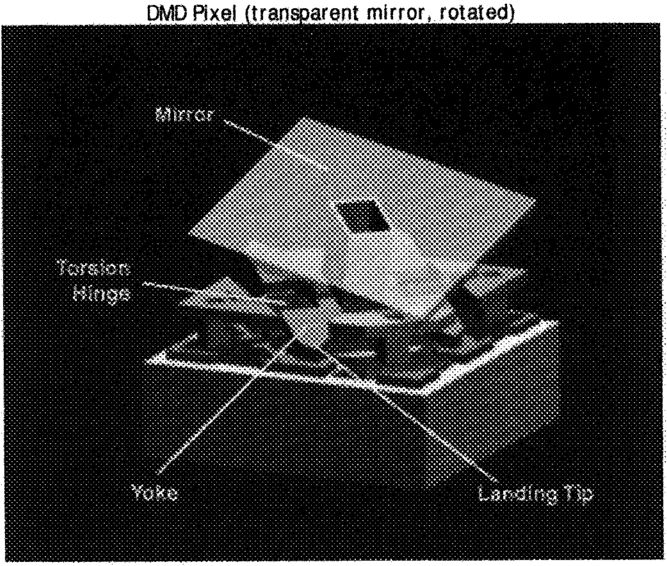

Figure 1.6: Digital light processor mirror assembly. From [22].

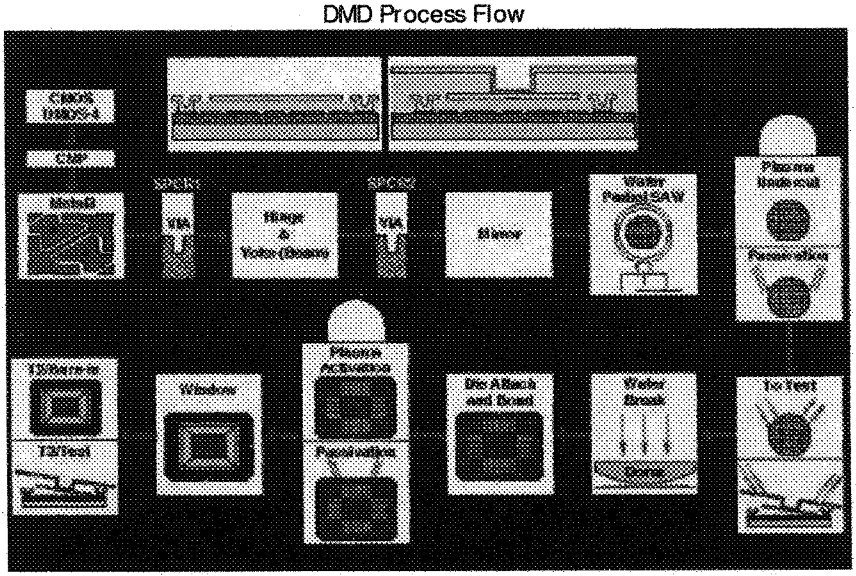

Figure 1.7: Process flow for Digital Mirror Device. From [22].

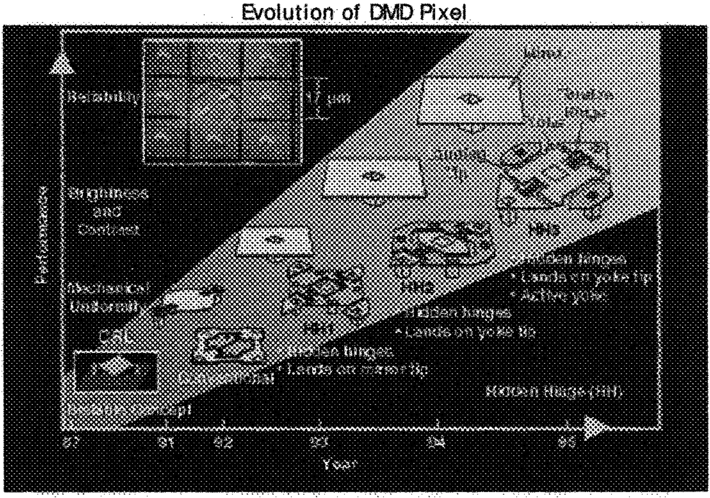

Figure 1.8: Evolution of DMD over nine years. From [22].

> *and the CMOS circuitry fabricated second, along with process compatible MEMS steps. However, this approach is does not appear to be a great deal more straightforward to develop.*

Analog Device's acceleration sensors, which adopted this approach, took about 10 years to debug MEMS-IC integration process and design. The prize which kept such a development on hand was the supply of millions of acceleration sensors for use in the automotive industry, in the kinds of application (airbags and active suspension) discussed earlier.

Both of the single chip integration approaches discussed above required a significant process development effort, stretching across multiple years and costing hundreds of millions of dollars. However, in both cases the market potential of the resultant product was sufficient for the companies to persevere with such a protracted and costly development. Both Texas instruments and Analog Devices are large corporations. It is doubtful whether small or start-up enterprises could have completed successfully such a technological development. The end result is, however, that both approaches to device integration have been proven to yield viable products.

1.8. Smart MEMS — The Research Agenda

The conclusion to be drawn from the digest of the 'news' given in Section 1.2 is that integrated 'smart' MEMS is now a technology which is mature enough, at least at the device level, to begin to plan some of the 'dream applications' that the new generation of visionaries in the field have proposed. It is now possible to fabricate an integrated assembly of MEMS based transducers and the required ancillary analog and digital electronics, to combine MEMS and VLSI to produce a systems component with the required sensory and processing capabilities, to enable at least some of these applications. Moreover, it appears that it should be possible to produce these devices at a cost which does not render the proposed scenarios infeasible — particularly if the volumes of device required are really huge.

The authors of this book have been active in the development and detailing of a scenario for the use of a multiplicity of MEMS based intelligent sensor devices for planetary exploration, which is detailed in the final chapter. When one comes to look closely at the way such an enterprise would actually work, it becomes apparent that the necessary hardware technologies are very nearly there. Those which have not already been developed can be seen as the likely end-point of current research programmes. However, this does not mean that trying to make the scenario a reality is straightforward. As the detail of the operation is studied with more precision, it is clear that there is a great deal of research and design elaboration to be done, but little of it is in the areas that have traditionally been the preserve of MEMS researchers. While continued improvements in the technologies discussed above will be welcome, and will increase the possible scale of the scenario, or decrease the possible costs (which will be enormous), or give the designers more degrees of freedom in planning the envisaged system, none of them, at the current state of development, or one that could be extrapolated for the very near future, is actually a necessary precondition as a part of the basic research to enable the scenario to go ahead. Rather, there are a number of problems with its design for which no simple solutions are available in the research literature. These broadly fall into two areas:

(i) If MEMS sensors are to be built into systems expressly designed around them, how does this affect the design of the sensor devices themselves? Are there constraints put on to the design of MEMS systems by current applications, which could be removed, thereby making new design solutions possible at the device level? Another possibility, which is being explored by several researchers is that of integrated intelligent multisensor devices. Such devices would make little sense in the context of traditional applications, but can provide an attractive building block for some of the large sensory systems being proposed, at the same time making best use of the scale and integration potential of MEMS technologies.

(ii) Does the integration of processing capability onto a MEMS sensor affect either the design of the sensor itself, or the system into which it is designed? As we have seen above, the original purpose of integration of signal processing into MEMS devices was to overcome shortcomings of the devices themselves. The integration of a great deal more processing power may open up new possibilities in sensor design, by using advanced calibration and linearisation techniques, such as the Artificial Intelligence based techniques described later in the book. Another possibility is to enable new types of sensor, by using computational power to derive the desired quantity from other sensory data. A third is to use computational power local to the sensor to ameliorate resource shortages in other parts of the system, perhaps reducing data to minimise communication bandwidth, or offloading computation from a central processor.

Both of these questions are essentially positioned around the design of sensor components themselves. They pose the possibility of a change in design motivation for these devices from one that is essentially 'bottom-up', working from an isolated specification of the sensing device itself, and then subsequently working that into a system design. Often this bottom-up motivation is based around the prior development of a set of technological solutions to the design of certain types of sensor. Sometimes there are completely new ideas for sensor operating principles, such as, for instance, the MEMSIC accelerometer, but the end result is still designed towards a relatively fixed end point, defined by the existing applications and usually defined by older technologies. The presentation of the development of MEMS technology in Sections 1.6 and 1.7, suggests that the developments that have been successful (usually those for which the organisations responsible have had very deep pockets) have been those in which the resultant device forms a part of some existing system, or linear development of it. For instance, the Texas Instruments DLP does not (currently) enable new types of system, it enhances existing ones (although TI has an active programme to encourage third parties to think of entirely new applications). DLP's are used to build data projectors, televisions and digital image printers. For each application there are alternative technologies available. Looking at the other MEMS sensor development discussed extensively here, the MEMS accelerometer, we find here these were initially designed to replace macro-machined accelerometers, and designed to have similar characteristics. Later examples have been designed to be a part of various automotive systems, particularly air-bag deployment systems. The salient point here is that within the system design, the accelerometers are acting entirely as sensors, the design of the system has taken no account of the potential of intelligent MEMS, and conceptually could be built just as easily with non-MEMS accelerometers (except, of course, it would be too expensive to be viable).

By contrast the future systems we are looking at are precisely those enabled only by intelligent MEMS. For these systems, the design goals of the intelligent sensor components will probably be quite different from those designed to fit into existing systems. The new design motivation will be 'top-down', working from a starting point of problem solving in large scale application domains, through solutions which make use of the intrinsic properties of intelligent MEMS devices, namely tiny size, large scale reproducibility, low cost and inbuilt intelligence and autonomy. In turn, the specification of the devices themselves will be derived from the overall systems design. This book includes several chapters intended to open up discussion and lead to research and development in the design methods appropriate to this way of working.

Consideration of the second question above leads on to another question. Given that under consideration is the building of systems, which explicitly use the potential of intelligent MEMS devices, these systems are likely to consist of very many autonomous devices (as can be seen from several of the 'dream applications'). Thus the third question is:

(iii) Can we solve the design and organisational issues involved in the realisation of well-defined and reliable systems composed of a multiplicity of autonomous intelligent devices? The sole example we have presently of a system of this type, of the scale envisaged is the Internet. This cannot be an exemplar of future practice for at least three reasons. Firstly, the Internet depends on a huge infrastructure of communications lines and intelligent switches and routers, that would not be practical in a sensor system; secondly, the resources needed by the nodes are at a level above those likely to be found in an intelligent sensor node, even given a period of further development; thirdly, the levels of reliability achieved by the Internet, while impressive in absolute terms, are below what will be required for some of the applications being proposed.

A complete work addressing the full potential of MEMS based sensing systems must therefore address these issues of large scale organisation as well. Without an understanding of the overall function and organisation of the system, it is impossible to take the top-down view on which successful design of sensing systems such as those envisaged in the 'dream applications' is predicated.

1.9. Structure of the Book

Working from the discussion above, this book needs to have a scope which proceeds from the basic, enabling MEMS technologies, through to the design principles on which are based the ability to produce operational examples of systems using thousands or millions of MEMS devices. In between those end points, the various ancilliary technologies, necessary to produce a complete system design, must be covered, along with examples and case studies of particular areas of interest which are met along the way. The book is structured as follows:

Firstly, in this chapter, the overall area has been surveyed, with a perspective of gaining an understanding of the fundamental nature of intelligent MEMS sensor devices (that is, a view unconstrained by reference to previous technologies).

Chapter 2 concerns itself with MEMS design and fabrication techniques, to gain a view of the potential and constraints imposed by the methods of design and fabrication which have been developed for implementing MEMS devices and the underlying concepts of MEMS sensor systems, particularly concerning itself with the physical, mechanical and electrical operating principles, and how they utilise the mechanical components that can be fabricated using the techniques described in the chapter.

The next five chapters cover the design of the anciliary systems which are necessary to use the underlying MEMS technology to its best advantage, and will be included in any complete MEMS based sensing system.

Chapter 3 examines the priciples and design of the anciliary electronic systems required to make the electro-mechanical part of a MEMS sensor operative.

Chapter 4 studies the use of integrated electronics to allow calibration and compensation of the intrinsic faults of transducers. The next three chapters present case studies which explore aspects of integrated MEMS/electronic systems.

Chapter 5 shows how sigma-delta modulation techniques can be used to provide an accelerometer with enhanced performance characteristics.

Chapter 6 is concerned with the design and implementation of advanced optical MEMS systems.

Chapter 7 examines how integrated signal processing using artificial intelligence can be used to ameliorate the basic shortcomings of a sensor device.

In the following chapters the discussion moves to the wider systems level and begins to look at the issues surrounding the third question posed in Section 1.8, looking specifically at how large systems may be built from autonomous intelligent MEMS sensors.

Chapter 8 surveys the potential of integrated artificial intelligence to provide a higher level of functionality, a level dubbed the 'cogent sensor' by the authors. Here, the sensor device not only collects data, it also provides a level of interpretation, transforming the data to information, thereby simplifying the design of applications systems, by freeing them from the need to collect and interpret large amounts of raw data from a multiplicity of sensors.

Chapter 9 considers the scope, applications and device design (at the integration, not hardware level) of advanced sensor systems of this type.

Chapter 10 discusses how systems may be designed and built using very large arrays of intelligent sensors networked together to form a single integrated system.

Finally, Chapter 11 looks forward, detailing one of the 'dream applications' that are being proposed and relating the way such an application could use the technologies and methods explored in the rest of the book, and how ongoing and future research might inform their design.

Taken together, the book is intended to provide a newcomer to the field, or a worker in one of the sub-disciplines involved in MEMS based system design, with a broad enough scope to appreciate the requirements, and also opportunities, which follow as the result of a top-down view of the design of the kind of future-shaping applications currently being proposed by visionaries in the field. It is to be hoped and expected that several of these visions are sufficiently practical that at least some readers of this book will be involved in their development in the near future.

References

1. Senturia, S.D. (2003) Perspectives on MEMS, past and future: the tortuous pathway from bright ideas to real products, *Proc. of the 12th Int. Conf. on Solid State Sensors, Actuators and Microsystems Transducers'03*, Boston, MA, pp. 10–15.
2. Device Basics, (June 2003) *Semiconductor International*, pp. 128, www.semiconductor.net.
3. Grieco, B. L. (August 2004) S MEMS advance medical electronics, *EE Times.*
4. Legg, G. (2003) Cover story, *Design News*, pp. 73, www.designnews.com.
5. Crossbow integrates GPS with MEMS, *Small Times*, http://www.smalltimes.com/document_brief.cfm#brief_4.
6. MEMSIC sensors in Mitsubishi mobile phone, *Small Times*, http://www.smalltimes.com/document_brief.cfm#brief_4.
7. New Products (2004) ADI MEMS accelerometers prevent information loss, *EE Times*, http://www.eetasia.com.
8. New Products (2003) Fujitsu optical switch based on MEMS mirrors, *EE Times*, http://www.eetasia.com.
9. Industry news (December 2001) *Standard Challenge For Sensor Vendors*, p. 5.
10. Harris, C. A. (August 2002) Structural health monitors go wireless, *Civil Engineering*, Vol. 72, Issue 8, p. 19, 1/3p, http://search.epnet.com/direct.asp?an=7278400&db=buh.
11. Device Basics (June 2003) Semiconductor International, p. 128, www.semiconductor.net.
12. Kahaner, D. K. (November 1994) Micromachine Center Progress, *Micromachine Symposium*, Tokyo, http://www.atip.org/public/atip.reports.94/micromac.94.html.
13. Voelker, M. A. (1992) Synchrotron etches microstructures for tiny 3d components, *SPIE*, OE Reports, p. 104.
14. Stenmark, L. (2001) Microsystems in Space exploration, *Proc. of Transducers'01*, paper no. 3A1.01.

15. Kohler, J. *et al.* (2001) A hybrid cold gas microthruster system for spececraft, *Proc. of Transducers'01*, paper no. 3A1.02.
16. Pister, K. S. J., Kahn, J. M. and Boser, B. E. (1999) Smart dust: wireless networks of millimeter-scale sensor nodes, Highlight Article in *1999 Electronics Research Laboratory Research Summary.*
17. Manobianco J., Evans, R. J., Pister, K. S. J. and Manobianco, D. M., GEMS: A revolutionary system for environmental monitoring, *Proc Nanotech 04*, pp. 422–425.
18. Abbott, D. *et al.*, Development and evaluation of sensor concepts for ageless aerospace vehicles, *Threats and Measurands, NASA*, http://techreports.larc.nasa.gov/ltrs/PDF/2002/cr/NASA-2002-cr211772.pdf.
19. http://www.nasatech.com/Briefs/June00/NPO20699.html.
20. Bryzek (October 2003) MEMS-IC integration remains a challenge, *PlanetAnalog.* http://www.planetanalog.com/showArticle.jhtml?articleID=15800098.
21. Ohr, S. (October 2003) MEMS, EE Times, http://www.eetimes.com/article/showArticle.jhtml?articleId=18309906.
22. Hornbeck, L. J., *Digital Light Processing: A New MEMS-Based Display Technology*, Texas Instruments White Paper. http://www.dlp.com/dlp_technology/dlp_technology_white_papers.asp.