

Inertial Measurement Units – *IMU*

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ABSTRACT

It is recognised that Micro-Electro-Mechanical-Systems / MEMS will enable the development of new military capabilities. Such capabilities will allow the introduction of low-cost, “high-end” functionality, to military systems, thereby, extending their performance and lifetimes. Examples of such novel capabilities include the development of complete inertial and navigation units on a single chip.

These capabilities will be realised through developments in civil applications which will be advanced to satisfy the military requirements.

The development of inertial systems is a common goal of the military and commercial MEMS communities alike, and have been universally recognised as offering major advantages in terms of size, weight and cost over conventional systems. Early predictions of both cost and performance have not, as yet, been fulfilled and current state-of-art characteristics falls somewhat short of the required inertial performance. To date, the MEMS accelerometer performance is close to that demanded by most military systems, but the rate sensor remains the weak link in the chain.

Inertial systems, can be classified into two main subsystems:

- ***IRS** (Inertial Reference Systems) based on either optical RLGs (Ring Laser Gyros) and accelerometers or electromechanical systems.*
- ***AHRS** (Attitude & Heading Reference Systems), aided by GPS/GNSS (through hybridisation), to enable the use of less accurate accelerometers and gyros and, thereby, the incorporation of MST/MEMS for each sensor or a combination of accelerometer/gyro multi-sensor systems.*

This lecture will introduce the basics of microsystems design techniques, the advantages of such novel devices and the evolution of the designs towards the realisation of microsystem-based IMUs.

AIMS OF THE LECTURE SERIES

- Introduce MEMS to the Defence community / NATO
- Familiarise the audience with MEMS technology its potential and capabilities
- Acquaint the audience with specific MEMS components (e.g. Inertial and Opto-electronic devices)
- Introduce a few typical examples of commercial products
- Discuss (propose) technology roadmaps and insertion plans

Paper presented at the RTO AVT Lecture Series on “MEMS Aerospace Applications”, held in Montreal, Canada, 3-4 October 2002; Ankara, Turkey, 24-25 February 2003; Brussels, Belgium, 27-28 February 2003; Monterey, CA, USA, 3-4 March 2003, and published in RTO-EN-AVT-105.

- Introduce related study groups, networks, associations and national/international programmes involved in MEMS
- Invite responses / comments and interest
- Solicit support for developments and research

LECTURE OUTLINE

- Microsystems (MEMS / MST and Micromachines): an Introduction
 - Definitions
 - Fabrication techniques
- Military applications of microsystems
- Commercial applications of microsystems and markets
- Microsystems-based components for IMUs
 - Gyros
 - Accelerometers
- Inertial measurement units
- State of the art: Developments and commercialisation
- Future outlook and general trends

LECTURE NOTES

Background

The AVT Panel and RTB have approved the formation of a MEMS Task Group (AVT 078 / TG 019) to define specific MEMS requirements for military applications, to assess MEMS status and COTS availability, to develop roadmaps for component and system insertion, and to suggest potential joint technology demonstrators. As part of this activity, the MEMS Task Group proposed holding a series of lectures covering some of the main developments in MEMS. More specifically, these lectures will address:

- An Introduction into MEMS Technology
- An Overview of Micro Power MEMS
- Applications of MEMS to Gas Turbines & Health Monitoring
- MEMS for Health Monitoring of Munitions
- MEMS for Fusing, Safing & Arming
- MEMS and Inertial Measurement Units – IMU
- Micro-Opto-Electro-Mechanical Systems – MOEMS
- Micro-Flow Control

The following notes have been, specifically, prepared for this series of lectures¹. The notes are aimed to assist the audience through the lecture presentations which will include sufficiently more details and explanations.

¹ The contents and the information has been, primarily, derived from two sources: (1) BRAMMS; a CEPA 2.30 contract no. 98/RFP 02.30/014 on the Broad Requirements for Advanced Military Micro-Systems and (2) NEXUS; the European Network of Excellence in Microsystems.

MEMS: Definitions

There are different definitions for Microsystems used in Europe, the USA and Japan:

In Europe:

“A microsystem (*MST*) is defined as an intelligent miniaturised system comprising sensing, processing and/or actuating functions. These would normally combine two or more of the following: electrical, mechanical, optical, chemical, biological, magnetic or other properties, integrated onto a single or multichip hybrid”. (Microsystems in the 4th Framework IT, Sept. 1996)

In the USA:

“Microelectromechanical systems, or *MEMS*, are integrated micro devices or systems combining electrical and mechanical components, fabricated using integrated circuit (IC) compatible batch-processing techniques and varied in size from micrometers to millimetres. These systems merge computation with sensing and actuation to change the way we perceive and control the physical world”. (MCNC, 1996)

In Japan:

“*Micromachines* are composed of functional elements only a few millimetres in size which are capable of performing complex microscopic tasks”. (Micromachine Centre 1996)

A drawback of these definitions lies in their, rather, narrow scope of interpretation. For example a micronozzle fabricated out of Nickel for fuel injection, produced by lithography and electroplating, or a microfilter produced in silicon would not belong to the aforementioned definitions, although they belong to this collective field of microstructures.

In essence, the definition of a microsystem is a fairly nebulous one; Basically, a microsystem is an “intelligent” device that may comprise any combination of actuators, controllers and sensors. These functional sub-systems could be electronic, optical, mechanical, thermal or fluidic. What sets microsystems apart from conventional devices is their close relationship to IC components both in terms of manufacturing techniques and their potential for integration with electronics. To date, microsystems are developed using a variety of micromachining and/or IC processing techniques to produce devices with micron-size features, having applications as diverse as inertial guidance controllers and asthma medication vaporisers.

Further generalisations for microsystems will include:

- ASIMS (Application-specific-Integrated-Micro-instruments)
- MOEMS (Micro-opto-electro-mechanical systems)
- MEMtronics (Micromechanical structures)
- Nanoelectronics (atomic / molecular)
- MESO-technology (Modules /w many microstructures)
- μ Engineering
- Smart structures

MST/MEMS devices and components are, in general, fabricated on silicon using conventional silicon processing techniques. Although silicon may be the ideal material for many applications, other materials are gradually becoming more commonly used. Over the past few years, promising materials have been

investigated for the development of advanced MST/MEMS products, suited specifically, for defence applications. Examples include:

- SOI, SiC, Diamond microstructures & films
- « Smart cut type » substrates (SiC, II-VI and III-V, Piezo & Pyro & Ferro)
- Shape memory alloys
- Magnetostrictive thin films
- Giant magneto-resistive thin film
- II-VI and III-V thin films
- Highly thermo-sensitive materials

Common processing techniques that are used to “sculpt” mechanical structures include:

- bulk micromachining
- surface micro-machining
- high-aspect ratio micromachining (LIGA – Lithographie/Lithography, Galvanoformung/ Electroplating und Abformung/Moulding)

Advantages of MEMS

Micromachining techniques and microsystems offer a number of currently realisable advantages as well as potential promises which include:

- Small size (volume, mass and weight) through miniaturisation
- Low power consumption
- Increased functionality
- Modular design methodology
- Low fabrication costs via mass production processes

MEMS for Defence Applications

To date, MEMS technologies have been demonstrated to provide elements of intelligent functional characteristics both as commercial and development devices/components. Indeed, a significant amount of scientific literature reports on MEMS components such as:

- Accelerometers
- Chemical Sensors
- Electronic nose
- Flow Sensors
- Fluidic valves
- Geo-phones
- Gyroscopes
- Inclinometers
- Infrared Imagers
- Injection Nozzles
- Lab-on-chip
- Micro-bolometers
- Micro-channels
- Micro-displays (DMD)
- Micro-mirrors
- Micro-motors
- Micro-optics
- Micro-positioners

- Micro-spectrometers
- Micro-tip AFM
- Micro-Thrusters
- Micro-tweezers
- Micro-relays
- Optical Filters
- Optical Switches
- Pressure Sensors
- RF components
- Temperature Senso

Over the past few years, the automotive industry has become a major user of MEMS devices for air-bag sensors. Printer manufacturers also continue to invest heavily in this technology for the development of, high resolution, micromachined ink-jet printheads. The pharmaceutical and medical businesses are also keen to apply this technology to their products as are the telecommunication industries. Indeed, it was confirmed that the, world-wide, MEMS market tripled by the year 2002 to approximately \$38bn and is estimated to increase to \$60bn by 2005.

Studies have established that most of the future military applications will have the following, generic, system requirements:

- Intelligent / unmanned operation
- Inter-linked communication channels
- Multi-sensing capabilities
- Inertial Navigation Systems
- Integrated Fluidic Systems
- Optical devices and systems
- Displays and adaptive optics
- Radiation hardness
- Ultra-Electronic Systems:
 - Massive computer operations (trillions of operations per sec.)
 - Massive storage (terabits / sq.cm)
 - Low power (nanowatts / gate)

These, generic, requirements, will form the basis of applications which are common across the various military platforms. More specifically, land, sea, air, space and missile applications will require one or more of the following functions:

- Nuclear & Bio/Chemical Sensors
- Micro Un-manned aerial / underwater vehicles
- Covert, autonomous, unmanned ground sensors, detection and treatment systems
- Optical systems and Imaging systems
- RF Components and Communication
- Distributed, agent-based, Evaluation & Sensor Array Systems
- Energy / Power generators
- Microthrusters
- Inertial Instruments

Inertial Measurement Units – IMU

- Mass Data Storage units
- Fluid Sensing, control & Transport
- Fuel Storage systems
- Arming & disarming

It is recognised that MEMS will help enable the development of these new military capabilities. Such capabilities will allow the introduction of low-cost, “high-end” functionality to military systems, thereby, extending their performance and lifetimes. Examples of such novel capabilities include the development of:

- Complete inertial navigation units on a single chip.
- Distributed sensing systems for monitoring, surveillance and control.
- Miniature and integrated fluidic systems for instrumentation and bio-chemical sensors.
- Embedded sensors and actuators for maintenance and monitoring.
- Identification and tagging systems using integrated micro-opto-mechanical MEMS.
- Smart structures and components.
- Mass storage and novel display technologies.
- Systems-on-a-chip with increased packing density and robustness.

These capabilities will be realised through developments in civil applications which will be advanced, if necessary, to address the military requirements.

In the context of military systems, the performance of MEMS devices must, clearly, satisfy the stringent specifications and environmental conditions expected to be posed by such applications.

In general, such operational and environmental requirements will also include; resilience to radiation, high temperatures (including sharp cycles in excess of 150 °C), vibration & shock (up to 100,000g levels of force) and electromagnetic compatibility. In addition the technologies should take into account the non-accessibility after launch, in certain circumstance, which dictate the need for “first-time-right” qualification.

Packaging for military MST/MEMS is, therefore, more critical than that for commercial applications of the technology, and even there it is regarded as a prime discriminator between commercial success and commercial failure. For commercial microsystems, packaging is said to account for 80% of the cost and 80% of the failures. The proportions of both in a military environment is not likely to be lower, and will in all probability be even higher.

Packaging is inextricably linked to the environmental specifications, and is often all that stands between the delicate and complex microstructure and the hostile world around it. Properly designed and implemented, it can protect the microsystem from the worst excesses of a military application. It is significant that for existing MEMS products (e.g. those developed specifically for automotive use), the only feature that distinguishes the commercial product from variants marketed as say “aerospace quality” is the packaging and final testing.

MEMS ACCELEROMETERS AND GYROS

Acceleration Sensors

The primary market in terms of unit sales for accelerometers is that of the automotive business. In this context, such devices serve applications such as airbag deployment, vehicle dynamics control and active suspension. A fully equipped airbag system may contain up to seven accelerometers whilst an active suspension system typically uses between three to five of such devices. Other applications are in (Anti lock brake) ABS-Systems or as tilt-sensors for intruder alarm and detection.



Side Airbag Acceleration Sensor.
Source: Bosch

Technology

Silicon micromachining is by now the dominating technology for the accelerometer markets where small size, low cost and high volume are required. For the automotive market it is estimated that more than 90% of all accelerometers supplied in 2000 were silicon micromachined. The remaining few were mostly of the piezo-ceramic type.

Currently, the majority of the silicon accelerometers are of the surface micromached type. However for low-g, high-performance applications bulk-micromaching is still a widely used technology. Here functional advantages overcome the higher production cost.

Recently, alternative techniques such as thermal measurement principles, using on silicon membranes, have been proposed for low-frequency tilt measurements (Vogt, Memsic).

Major Manufacturers include:

Europe: Bosch, VTI-Hamlin, Temic, Sensoror

USA: Analog Devices, Motorola

Japan: Denso

Gyroscopes

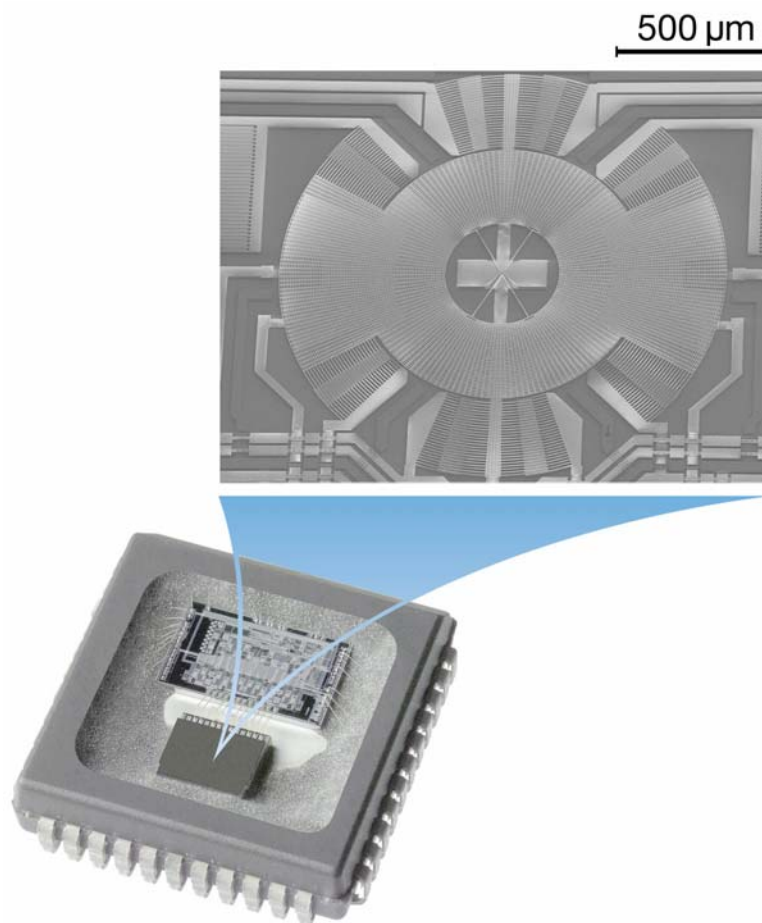
Gyroscopes are inertial sensors used to measure the rate of rotation (measured in degree/s) of a body with respect to a reference system.

Inertial Measurement Units – IMU

Gyroscopes are used in all kinds of applications where the rotational movement of a body or structure needs to be monitored. One of the main applications for such devices is in navigation. Most navigation systems currently available are GPS-based. However gyroscopes can improve the accuracy of the system and are essential as a backup when satellite signals are unavailable. In recent years several, new, automotive applications have been identified, including vehicle dynamics control and rollover-protection. These applications are expected to constitute a major part of the unit volume market over the coming years.

Other applications which will entail the development of improved gyros, include:

- Vehicle navigation
- Avionics navigation
- Navigation for space and weapons applications
- Vehicle dynamics control systems
- Rollover-protection
- Image stabilization for cameras
- Handheld navigation systems
- Medical applications



Silicon Micromachined Gyro for Application in Navigation Systems.
Source: Bosch

Technology

Gyros measure the rotation either by means of the Coriolis force or by the relative phase shift of coherent light circling in opposite directions in two glass fibres (FOG).

The FOG, which is not considered to be a microsystem, sells at prices of several thousand dollars for high end applications requiring resolutions of up to $0.001^\circ/\text{s}$ (e.g. aerospace or weapons applications). These stringent requirements will probably not be satisfied by MST-based gyros in the near future.

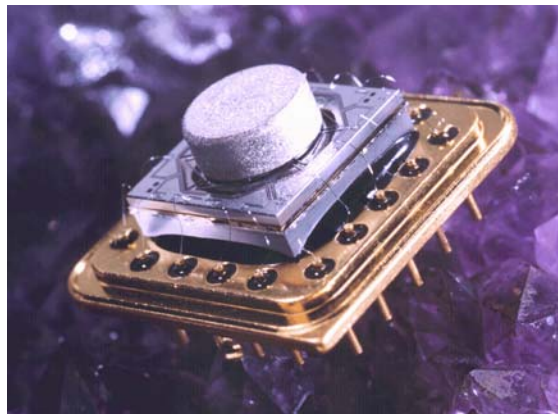
The strength of MST-base gyros lies in the low to medium performance applications where mass-production is required. Two main technologies are now established in this segment:

- Quartz tuning forks
- Silicon micromachining

Gyros manufactured by both technologies use the Coriolis effect. Drive and detection for quartz forks are usually piezoelectric, whilst silicon based gyros use piezo-, electrostatic or electromagnetic drives and piezoelectric or capacitive detection schemes.

Quartz technology has been successfully used for many years by companies such as Systron Donner, Panasonic and Murata, while the first silicon based sensors have been commercialized by Bosch in 1998. In the future a trend towards silicon is anticipated because it is amenable for mass production in batch processes and holds the potential for continued size reduction and integration with electronics. Many companies are currently involved in research, development and commercialisation of Si-based gyros such as Analog Devices, Delco, Sensoror, BAE SYSTEMS, Samsung, Murata and Sumitomo.

Resolution requirements for the low to medium performance applications are in the order of $0.01^\circ/\text{s}$ to $2^\circ/\text{s}$ range and can be achieved by either technology.



BAE SYSTEMS' Si Gyro.

Major Manufacturers include:

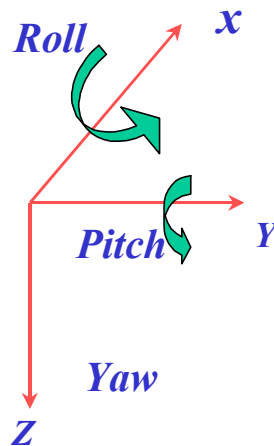
Europe: Bosch, BAE SYSTEMS

USA: Systron Donner

Japan: Denso, Sumitomo, Panasonic, Murata

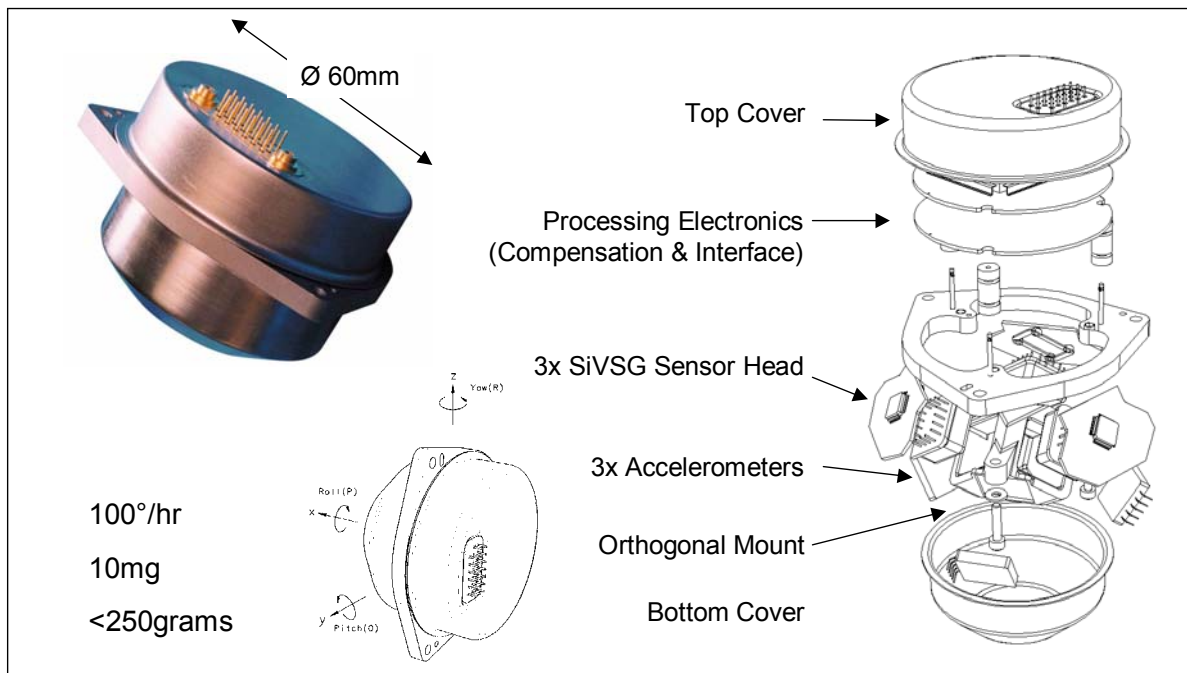
INTERTIAL MEASUREMENT UNITS

The measurement of Roll, Pitch and Yaw entails the use of 3 linear accelerometers and 3 rate gyros to measure rotational velocity. These components are geometrically positioned to provide X, Y and Z co-ordinate-based measurements, respectively:



IMU designs are, currently, being assessed by manufacturers including BAE SYSTEMS. Research is also underway at some organisations aimed at developing components capable of sensing inertia along orthogonal planes.

In summary, progress in the development of accelerometers, gyros and IMUs is likely to rely heavily on a market pull that is entirely driven by civil applications. Novel encapsulation, packaging and integration techniques will, however, be necessary to address the requirements of defence applications.



THE CHALLENGES

Whilst the important role of MEMS is confirmed for future military platforms, further developments in the design and performance of these devices is, however, necessary in order to satisfy the stringent requirements set for military applications. More specifically (and typically):

- **Military specifications (including aircraft, missiles and munitions) are particularly demanding (for example):**

Vibration:	20 to 3,000 Hz (for 5g to 20g)
Structural Resonance:	> 3,000 Hz
Temperature:	-65°C to > +125°C
Mechanical shock:	up to 100g for fighter aircraft up to 300g for missiles more than 15,000g for gun launched munitions
Angular Acceleration:	>500,000 rad/S² (spinning gun launched munitions)

Other, more generic, challenges will also need to be addressed, namely:

- **Military MEMS will depend, heavily, on the commercial / civil MEMS developments as low volumes, for the military markets, will attract high costs.**
- **Military product life-cycles exceed those for commercial / consumer products where, both process availability and product obsolescence become a major concern.**
- **Access to military-specific MEMS developments by the civil markets may have security implications.**
- **Repair of MEMS is not, normally, feasible and diagnostics is difficult.**

In spite of these hurdles, there is little doubt that microsystems will proliferate within military platforms providing intelligent functionality and enhanced performance.

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Ayman received his BSc from Loughborough University of Technology, UK in 1978 and his PhD from the University of Kent, Canterbury, UK in 1986. He joined the General Electric Company's Hirst Research Centre in 1978.

From 1984 to 1989, he worked in the Optical Fibres Division, where he contributed to the development of various novel optical fiber components and to photonics research. From 1990 to 1994 his responsibilities steadily increased including managing R&D in high temperature superconductivity, vacuum microelectronics, micromachining and biosensors, and later Fuzzy Logic Control, vision systems, high performance computing, advanced signal processing techniques and olfaction.

During May 1995, following Hirst's amalgamation within GEC Marconi Materials Technology (GMMT), Ayman was given charge of a newly formed Applied Technology Laboratory encompassing several additional technologies on Modelling and Simulation, Control and Decision Algorithms. In May 1996, he was appointed manager of the Signal Processing, Control and Communications Laboratory, amalgamating all the theoretical and signal processing activities within one laboratory.

Following the re-organisation of the research centres within Marconi, in 1998, Ayman was appointed Business Group Manager for the Data Analysis & Techniques Group as well as Deputy Manager for the Communications & Information Systems Division based at the Marconi Research Centre. The Group has 40 qualified staff whilst the Laboratory has 80 staff in total. This research establishment has recently become part of BAE SYSTEMS Advanced Technology Centres.

Ayman is, currently, manager of the Systems Department of the Advanced Technology Centre. The Department has four main Groups of researchers: (1) Space Systems, dealing with SAR signal processing and algorithms, sensor data fusion and ground-station IFMS systems. (2) Intelligence Systems, encompassing work on mathematical techniques, control systems and data processing systems. (3) Communications Systems, directed towards defence applications and the battlespace. (4) Signal Processing Systems for rapid prototyping, noise and vibration control and high performance computing.

Finally, Ayman is also an active member of NEXUS, the European network of excellence in multi-functional microsystems, was prime co-ordinator of BRAMMS, a European collaborative project on Military MEMS/MST and is also involved in many other national and international initiatives in this field of technology.