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.

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- 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 lectures[1]. 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)
- µEngineering
- 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

Micomachining 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

- 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, Sensonor

USA: Analog Devices, Motorola

Japan: Denso

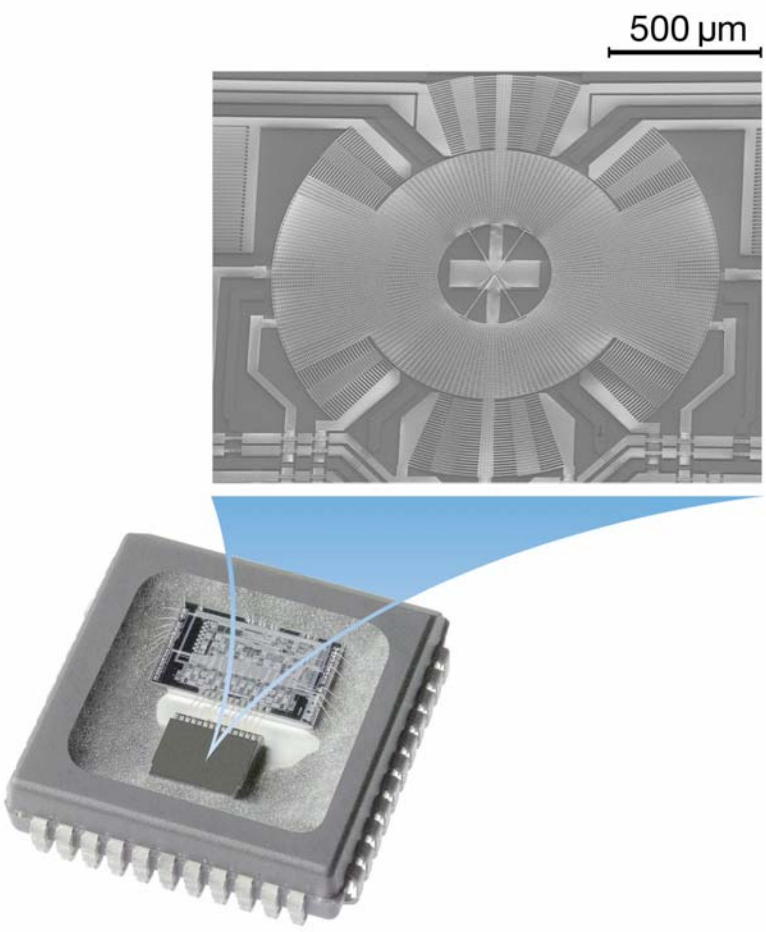
Gyroscopes

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

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°/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, Sensonor, BAE SYSTEMS, Samsung, Murata and Sumitomo.

Resolution requirements for the low to medium performance applications are in the order of 0.01°/s to 2°/s range and can be achieved by either technology.

BAE SYSTEMS' Si Gyro.

Major Manufacturers include:

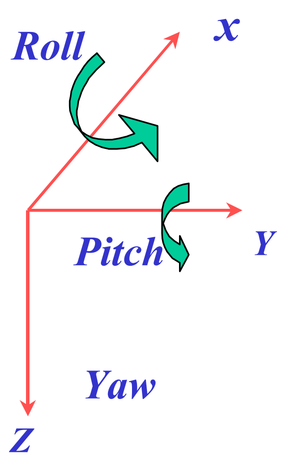
Europe: Bosch, BAE SYSTEMS

USA: Systron Donner

Japan: Denso, Sumitomo, Panasonic, Murata

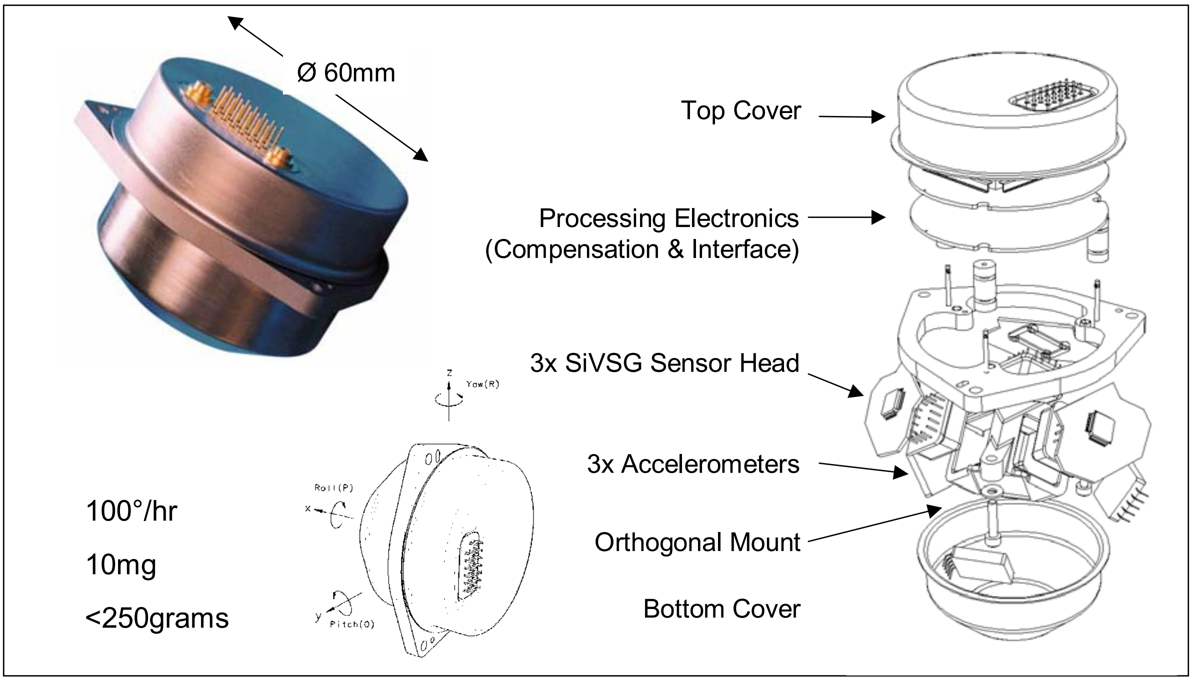
INTERTIAL MEASUREMENT UNITS

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/S^2 (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.

MEMS Aerospace Applications

Les Applications Aerospatiales des MEMS

An AVT-105 Lecture Series No. 235
organised by the
Applied Vehicle Technology Panel

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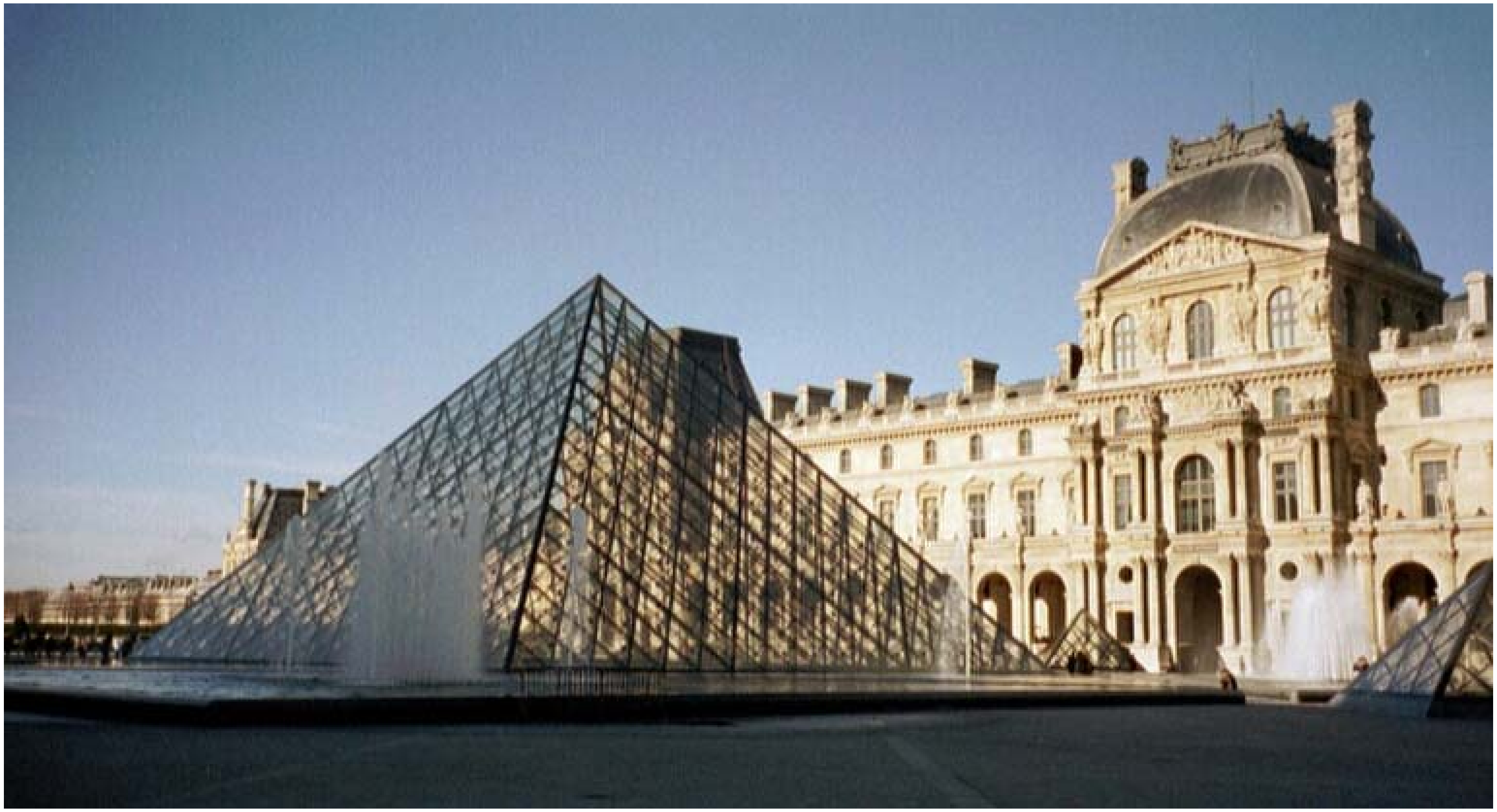

NATO RESEARCH AND TECHNOLOGY ORGANIZATION (RTO)

APPLIED VEHICLE TECHNOLOGY (AVT) PANEL

- **TASK GROUP "MEMS APPLICATIONS FOR LAND, SEA, AND AIR VEHICLES"**

Task Group Chair: DR. KLAUS SCHADOW, STRATEGIC ANALYSIS, INC - US
Task Group Co-Chair: Dr. AYMAN EL-FATATRY, BAE SYSTEMS - UK

Objectives (2000 - 2002):

(1) define military needs, status, and potential applications for MEMS components and systems,

(2) select and prioritise applications,

(3) explore potential collaborations,

(4) develop roadmaps for potential R&D collaborations and joint technology insertions, and

(5) write and submit final report.

NATO RESEARCH AND TECHNOLOGY ORGANIZATION (RTO)

- **First Task Group Meeting:** was held October 10-12, 2000, Ankara, Turkey, in conjunction with the RTO Symposium “Unmanned Vehicles (UV) for Aerial, Ground, and Naval Military Operations”
- **The second meeting** was held May 7-9, 2001, in Loen, Norway, in conjunction with the RTO Symposium “Advanced Flow Management: Vortex Flows and High Angle of Attack – Military Vehicles”
- **The third meeting** of the Group will take place during AVT-099: Novel and Emerging Vehicle and Vehicle Technology Concepts, scheduled for April 22-26, Paris.
- PLUS **RTO Lecture Series “MEMS Aerospace Applications”**

Montreal, 3 and 4 October 2002

Ankara: 24 and 25 February, 2003

Brussels: 27 and 28, 2003

Monterey: 3 and 4 March, 2003

BAE SYSTEMS

Lecture Outline

- Introduction to the Series
- The Presenter
- Microsystems (Definitions)
- Applications
- The BRAMMS Report
- Principals & Configurations
- COTS & Products
- Accelerometers
- Gyros
- IMUs
- Markets and Opportunities
- Trends and RoadMaps

Aims of the Lecture Series

- Introduction to MST/MEMS
- Focus on specific applications & devices
- COTS MEMS
- Programmes and Initiatives
- Discussion
- Support

Acknowledgements

- BAE SYSTEMS
- MoD
- WEAG
- NEXUS
- NATO

BAE SYSTEMS

The Advanced Technology Centre

The Advanced Technology Centres are involved in research, development and technology acquisition helping ensure BAE SYSTEMS remains a world leader in the defence and aerospace market.

Ayman El-Fatatry

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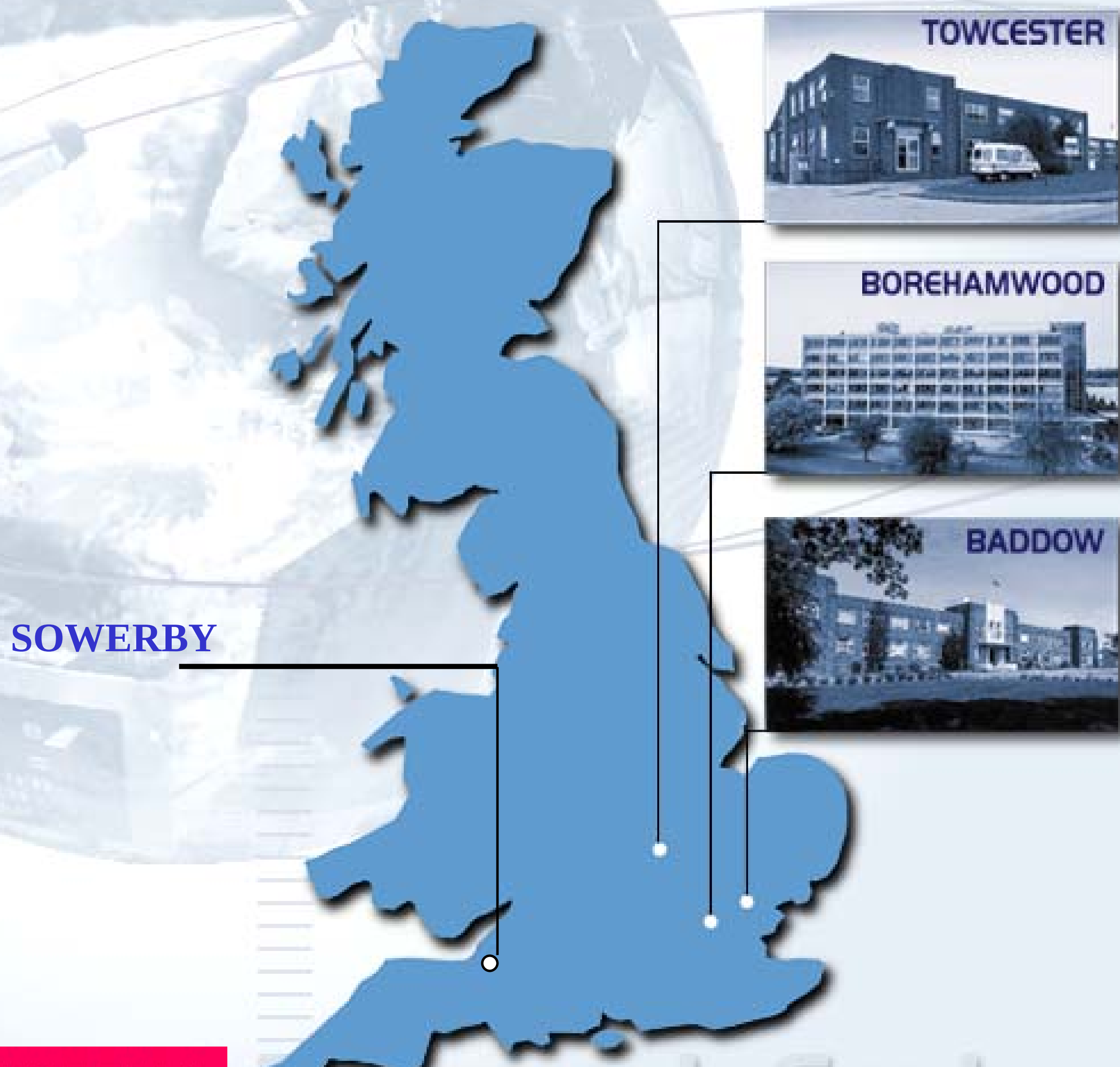

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BAE SYSTEMS

As for the presenter, ME !

NAME: Ayman El-Fatatry

[redacted]

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Education: School (Cairo)
Loughborough Univ. (BSc)
Canterbury Univ. (PhD)

Professional Career:
GEC's Hirst Research Centre (1978)
re-named MRC, GMMT and, now BAE SYSTEMS' - ATC.
Currently, Head of Systems Department

Expertise:

Optical Fibre systems, Optical techniques, Sensors & Biosensors
Microsystems

Interests / hobbies: Art, music & Poetry
"Other" Interests: Red wine & …...

BAE SYSTEMS

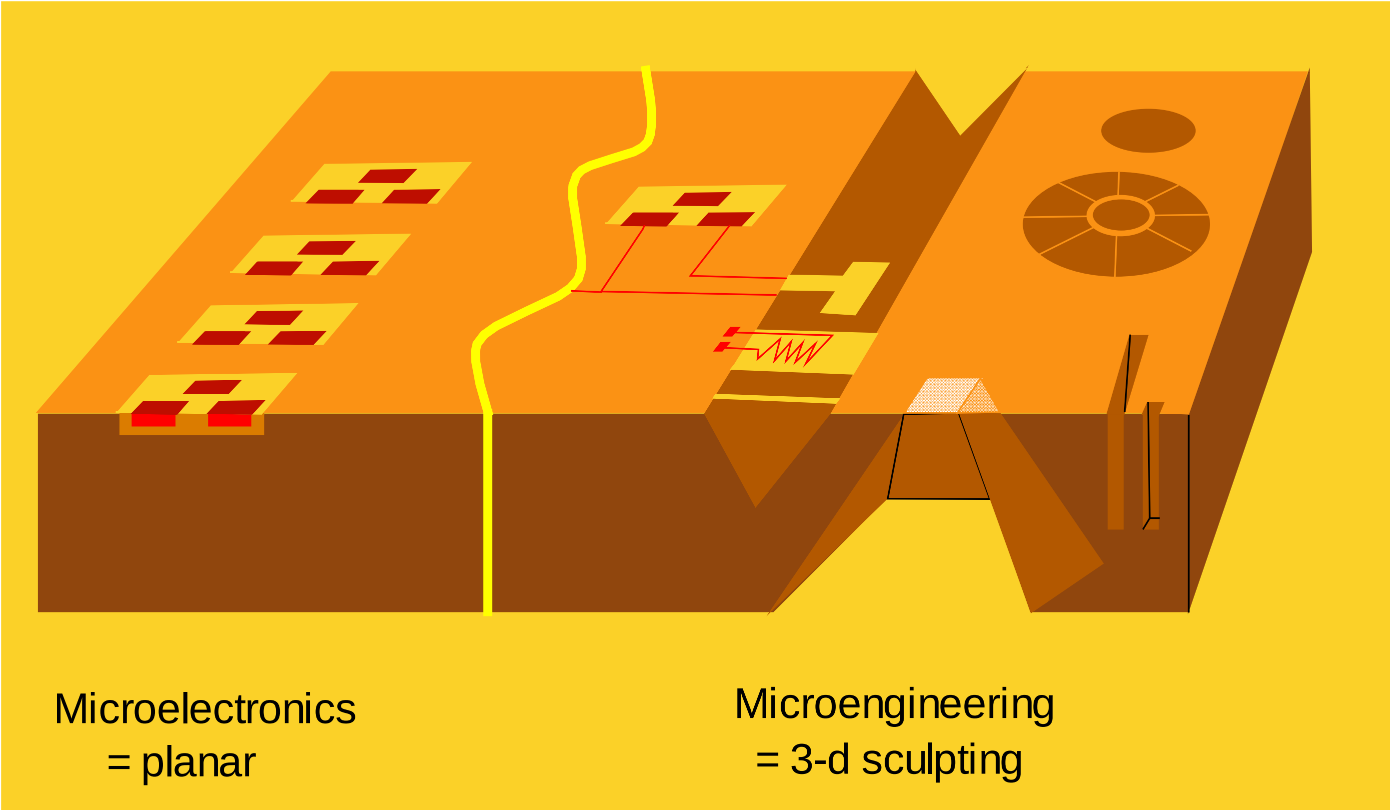
MEMS / MST

Definitions !

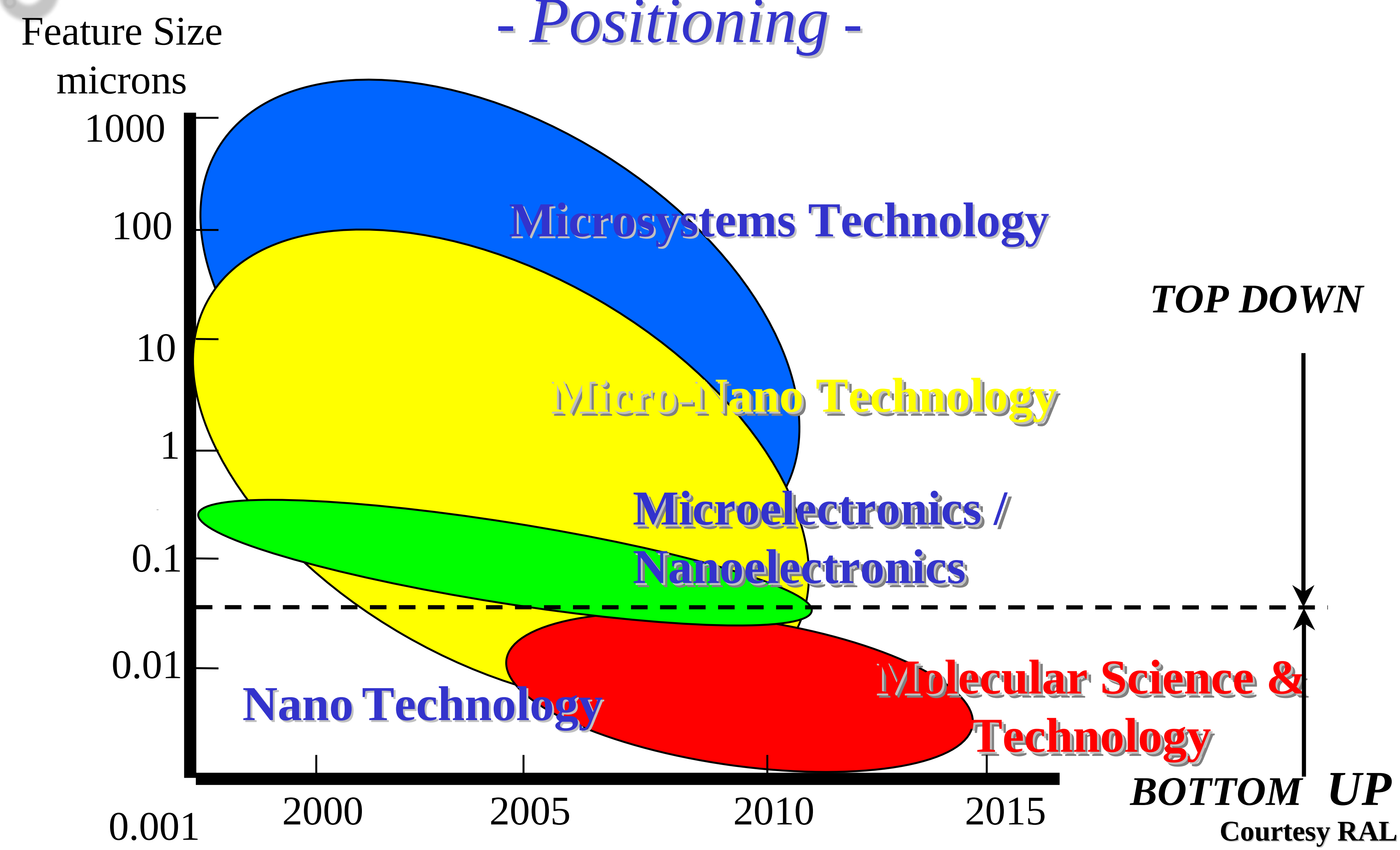
A plethora of Acronyms !

- **MST**: European for Micro-System Technology (sensing + processing + actuation)
- **MEMS**: American for Micro-Electro-Mechanical-Systems (electrical + mechanical + IC compatible processing)
- **Micromachines**: Japanese for miniaturised factories / robots
- Also: MOEMS / MEMtronics / ASIMS and µSystems

Differences between Micro-Electronics & Micro-Engineering



Micro, Nano and MNT
- Positioning -



Courtesy RAL

Micro, Nano and MNT
- *What is what* -

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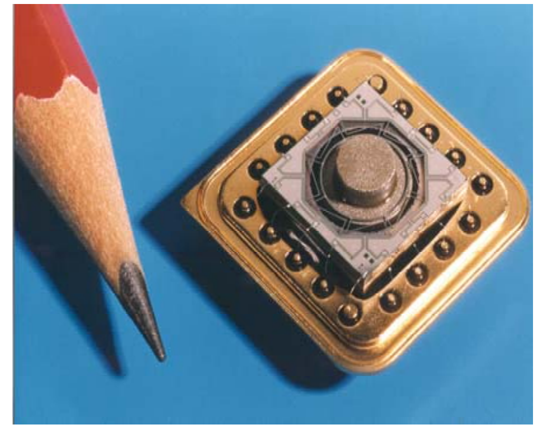
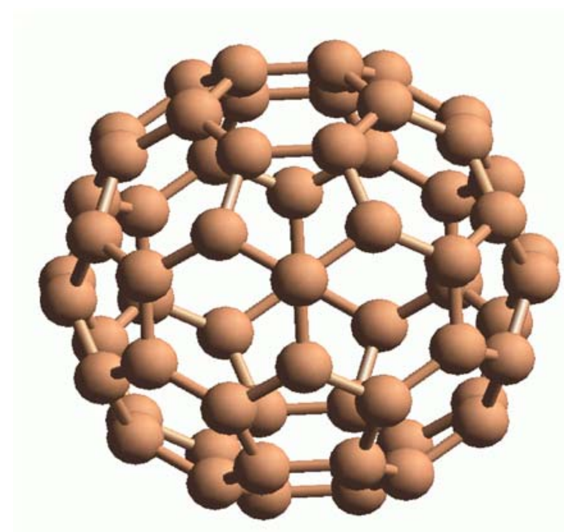
Microtechnology



is the fabrication of millimetre sized devices with micron and nano-sized rules by bulk deposition and patterning millions of atoms in any part.

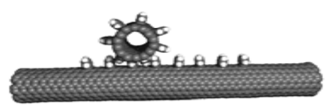
Micro-Nano-Technology

is the use of the properties of micro and or nano-technology in micro and macro applications for further shrinking, integration and miniaturisation of sensing & actuating functions and for microsystems.



Nano-Technology (Molecular T)

is the building up of structures or materials in an atom-for-atom specific way; every atom counts Theoretically anything could be built



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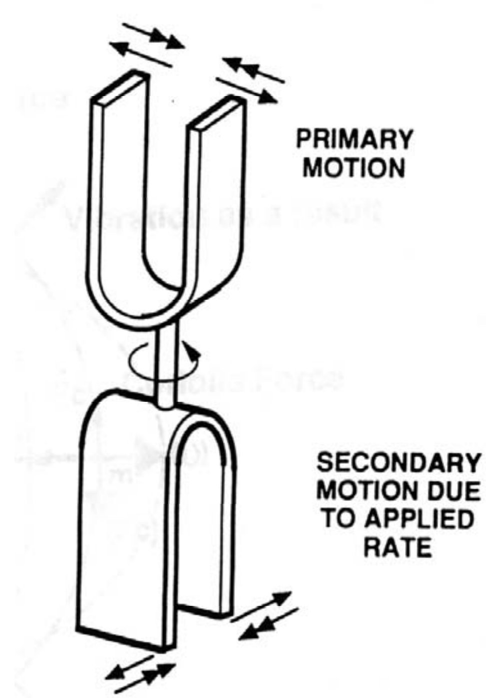
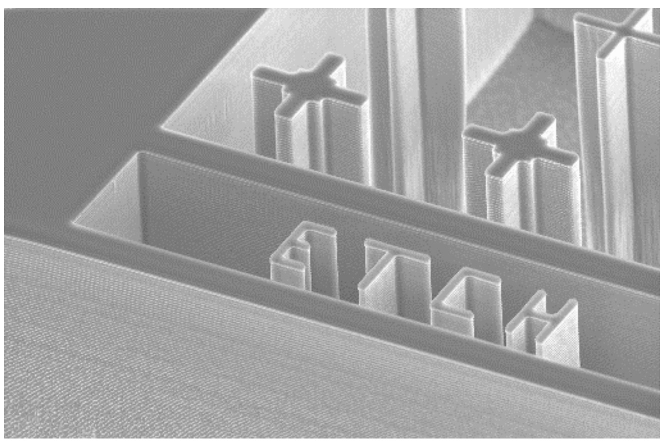
Advanced fabrication techniques

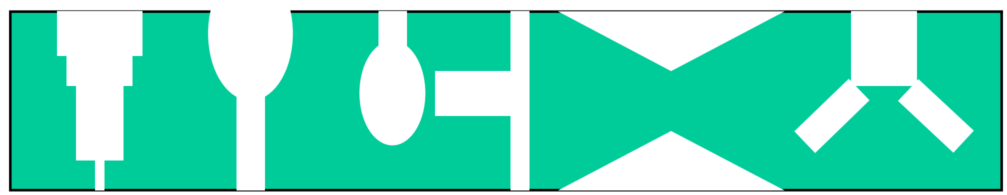
- ***Development of etching and bonding techniques***
- ***Introduction of new equipment***

Facilitating the next steps in MEMS technology
to provide improved design flexibility for future devices





Present 2 1/2 D deep etch is
limited to ‘extrusion’ in 3rd dimension

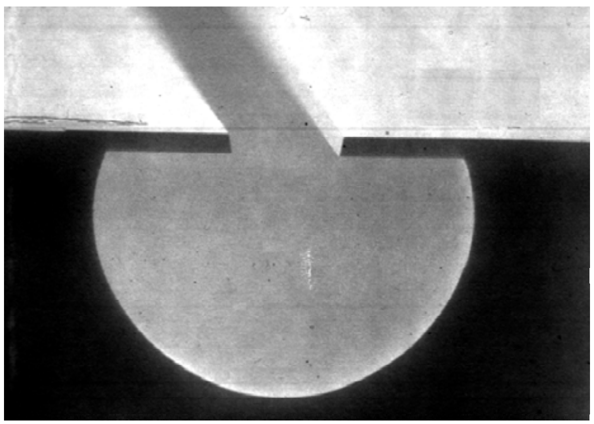


These proposed structures will lead to new
or improved devices, eg miniature pneumatics
thrusters, fuzing elements, actuators, motors etc

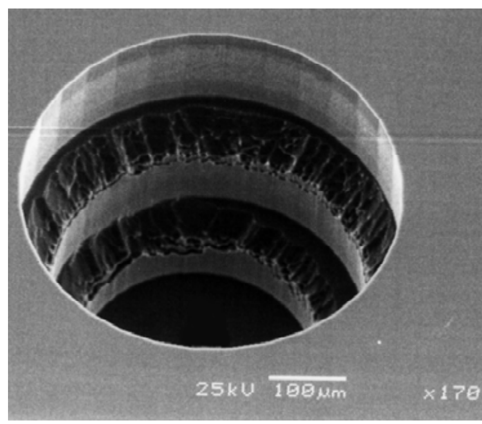
BAE SYSTEMS

Advanced fabrication progress

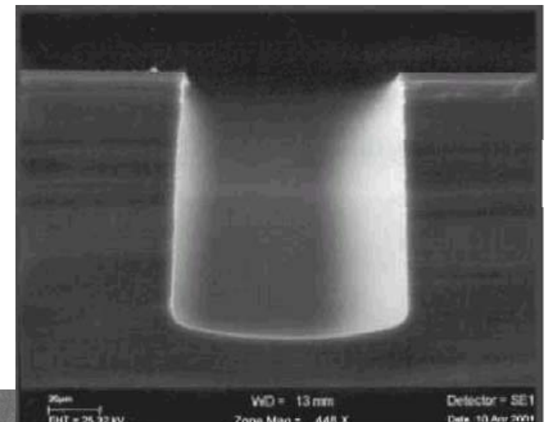
Some first attempts at profile control



Isotropic etch



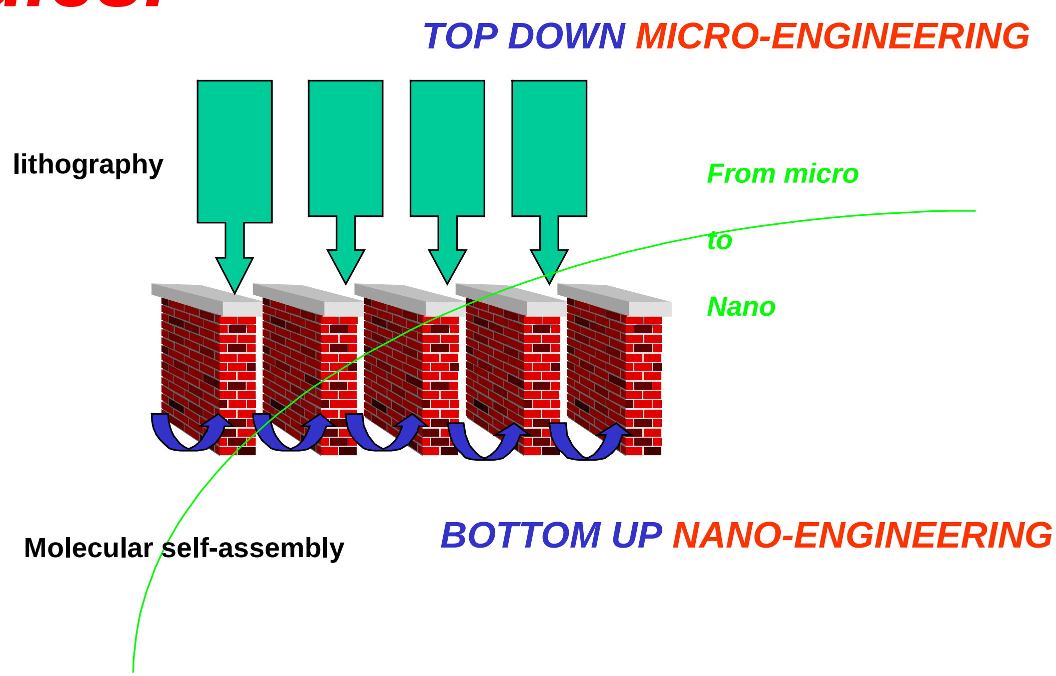
Sequential lithography



Deep reactive ion etch

Nanotechnology - (yet another) Definition

"A process for manipulating smallest natural structures (atoms & molecules) where Quantum mechanics rules."



MEMS / MST

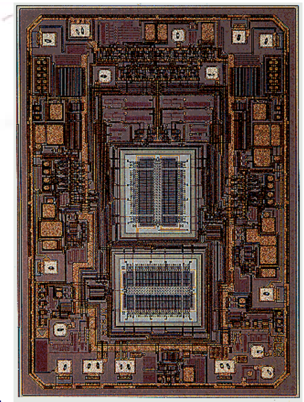
Advantages (proven & potential)

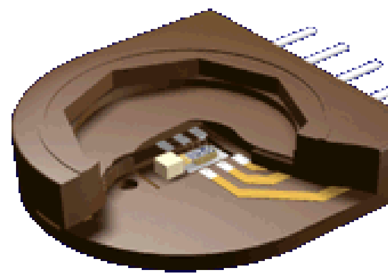
Sugar crystal
ship
on top of a
pin-head

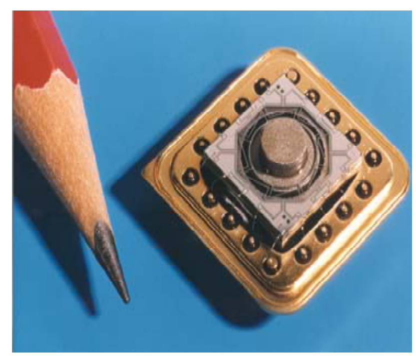
"There's no question that there is enough room on the head of a pin to put all of the Encyclopaedia Britannica" - Richard P Feynman, 1959

Potential Advantages of Micro-Engineered Devices

- Smaller size
- Lighter
- Cheaper
- Lower power
- Higher reliability
- Increased levels of integration
(on board electronics, self test)
- Multi-functional
(accel, yaw, temp and pressure)







BAE SYSTEMS

The BRAMMS Project

A study of MEMS and Defence Applications

Western European Union (WEU)
Western European Armaments Organisation (WEAO)
Research Cell (WRC)

B.R.A.M.M.S.

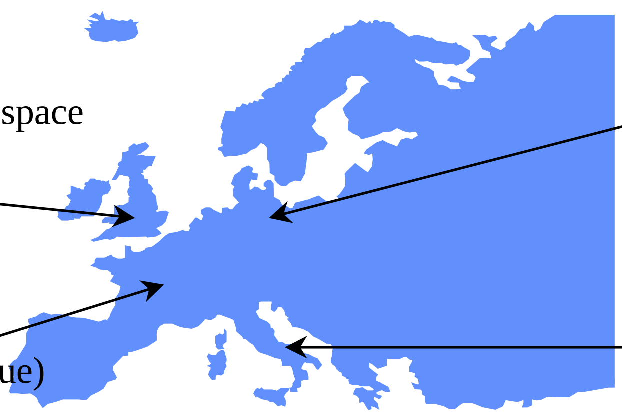
Broad Requirements for Advanced Military Micro-Systems

A collaborative study for **RTP 2.30**

Partners

UK :
BAE SYSTEMS
Smiths Industries Aerospace
CLRC - RAL

FR :
Thales (Sextant Avionique)
Thales (Thomson-CSF Optronique)
CEA-Leti



NL :
TNO-FEL

I :
Alenia Difesa
Alenia Radar Systems

BAE SYSTEMS

BRAMMS CONCLUSIONS

MEMS / MST technologies will, it is foreseen, proliferate within the following main system-based applications:

- Inertial Systems for missile guidance & control
- Health monitoring systems
- Power management systems
- Displays (cockpit and helmet-mounted)
- Chemical & biological sensors
- Battlefield damage assessment and target identification systems.

BAE SYSTEMS

BRAMMS Conclusions - The hurdles

- **Military MEMS will depend, heavily, on the commercial / civil MEMS developments.**
- **Low volumes, for the military markets, will attract high costs.**
- **Military product life-cycles exceed those for commercial / consumer products. 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 feasible. Diagnostics is difficult.**

Tough Requirements on MEMS !

BAE SYSTEMS

- **Typical specifications for military applications have been drawn:**

Vibration:	**20 to 2,000 Hz**
Structural Resonance:	**> 2,000 Hz**
Temperature:	**-65^{o}C to > +125^{o}C**
Mechanical shock:	**>10,000 g**
Angular Acceleration:	**>500,000 rad/S^2**

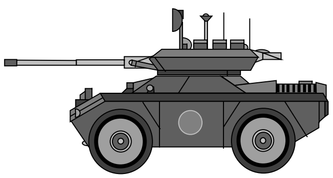
The BRAMMS Project

Defence Applications

BAE SYSTEMS

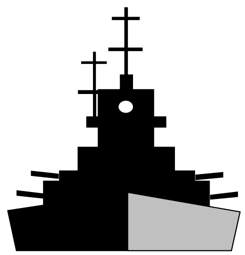
Military MEMS/MST ; Main Applications

LAND



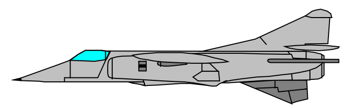
- Smart & Competent Munitions.
- Gun Launched Munitions
- Communication Systems
- Soldier / Combatant Equipment
- Surveillance Systems

SEA



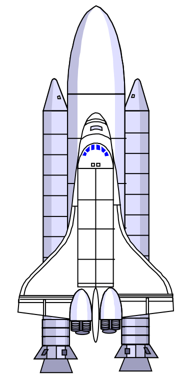
- Torpedo Control
- Communication Systems
- Platform Stabilisation & Control Systems

AIR



- Aircraft Platform Control Systems
- Avionics & Flight Control
- Equipment Monitoring & Failure Prediction
- Communication Systems
- Combat Systems

SPACE



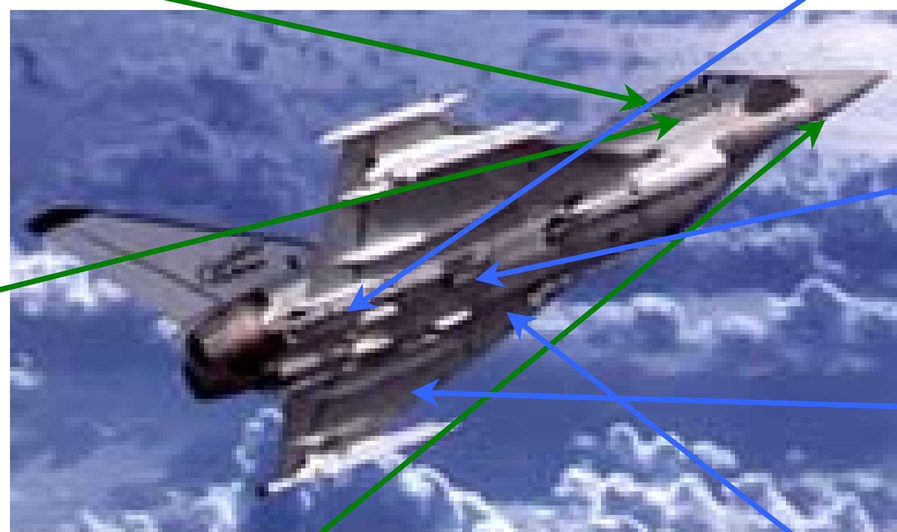
- Guidance & Control
- Communication Systems

Future MEMS applications for Military aircraft

BAE SYSTEMS

Navigation & attitude
Radar
Air Data, Instruments,
Flight Control,
GPS receiver & antennas
Inertial Measurements Units

Man machine interfaces
Displays, Head up Displays
Sighting, Integrated helmet
µIMU Standby Instruments



Engine & reactors
FADEC
Hydraulics

Energy management
Generation monitoring
Pressure, Humidity..

Structure monitoring
Stabilisation
Vibrations
Structure fatigue
Smart skin

Landing systems
Hydraulic pressure
Tyre pressure, etc..

Navigation Optronics
Radar, FLIR,
reconnaissance sensors

Mission Optronics & electronics
target detection
E.O. missile guidance
E.O.C.M.
I.F.F systems

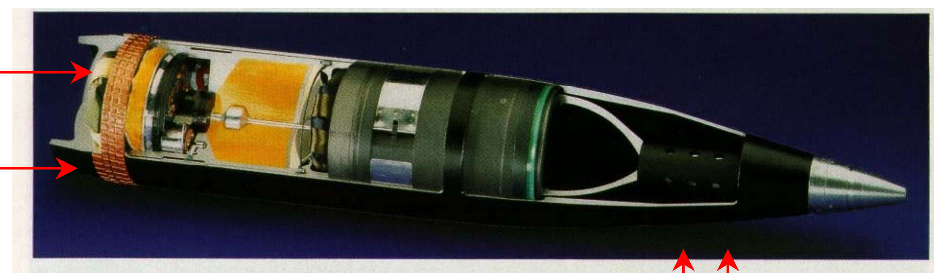
FUTURE MEMS APPLICATIONS FOR SMART AMMUNITIONS

BAE SYSTEMS

SMART SURFACES

IMU/GPS CONTROL UNIT

GUIDANCE LINK



FLOW AND PRESSURE CONTROL

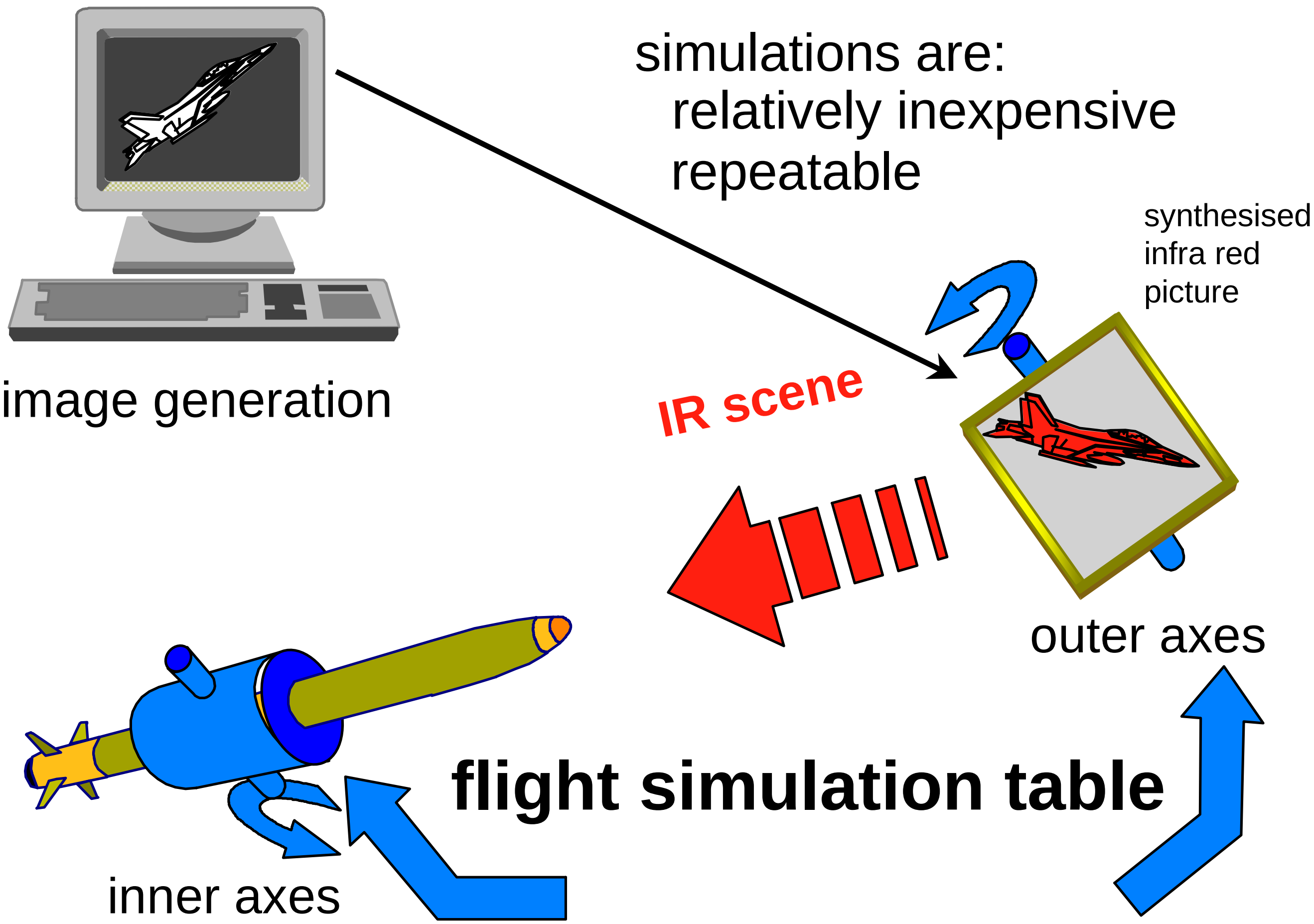
SAFING AND ARMING

FUZE AND SIGNAL PROCESSING

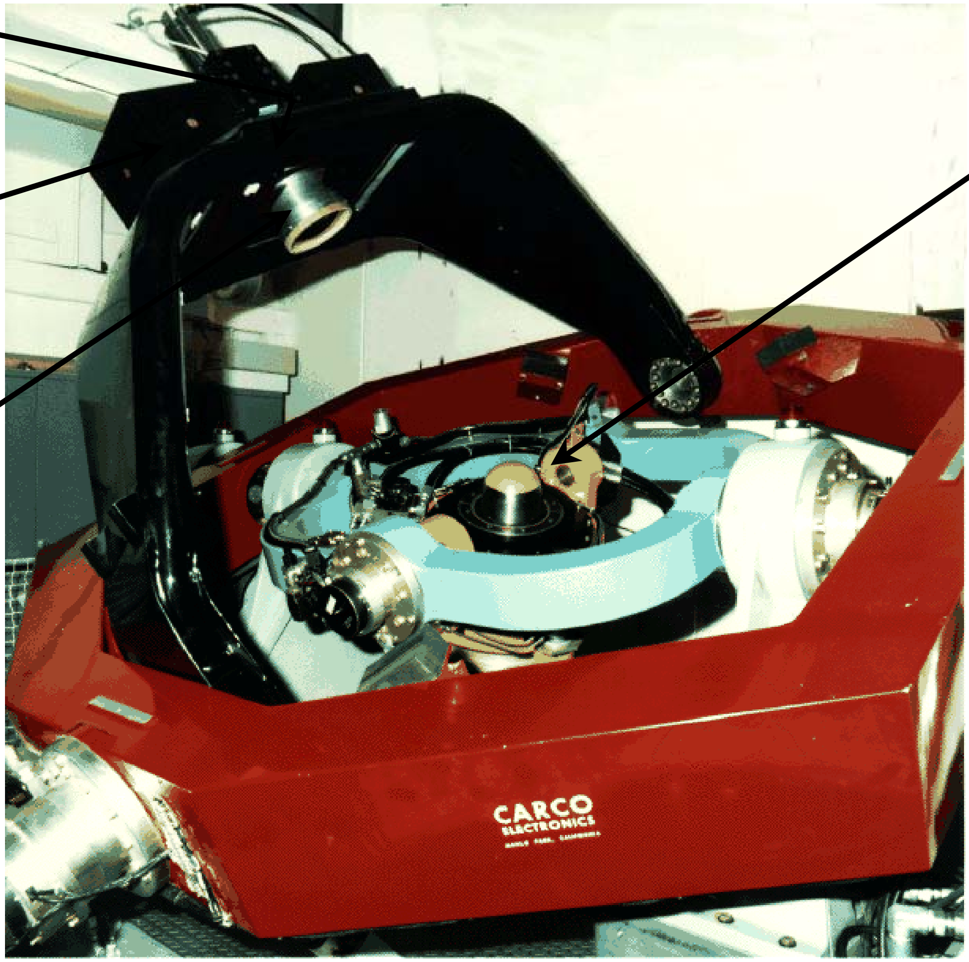
MEMS subsystems and Components	Military systems									
	Smart Munitions	MicroUAV	Aircraft	Rotary wing Aircraft	Missile	Land Vehicle	Ships&Boat	Space Vehicle	Soldier Systems	Ground Systems
μIMU	•	•	•	•	•	•	•	•	•	
ISIS			•	•		•	•	•	•	
Three axis vibration measurement Unit			•	•		•	•	•		
μActuator for fligth control	•	•	•		•			•		
RF Comunications front end	•	•	•	•	•	•	•	•	•	•
HUMs		•	•	•	•	•	•	•		•
Power management Systems		•	•	•		•	•	•	•	•
Fast Scanners	•	•	•	•	•	•	•	•	•	•
Compass and vertical axis measurement unit		•	•	•		•	•	•	•	•
Active vibration control		•	•	•	•			•		
Biochemical Sensors		•	•	•		•	•		•	•

BAE SYSTEMS

Thermal Picture Synthesiser (TPS) - Infra red missile development and proving

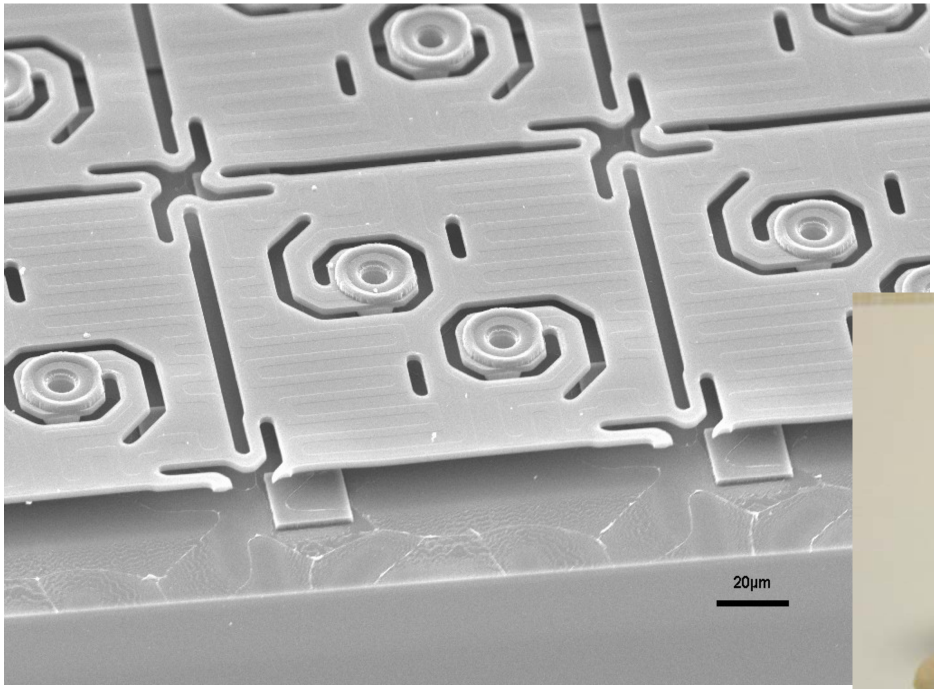


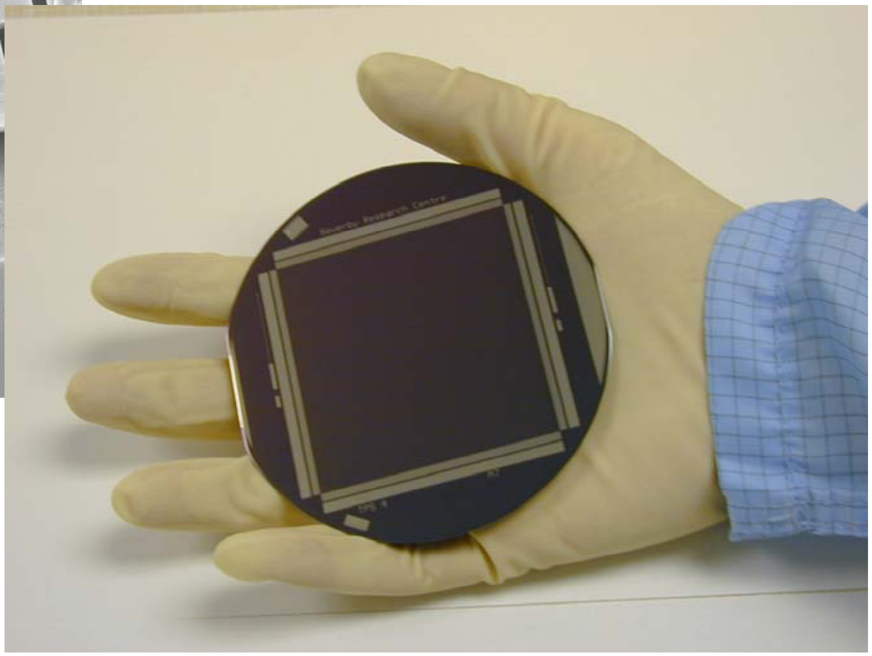
TPS System on Flight Table



TPS Pixel detail

BAE SYSTEMS

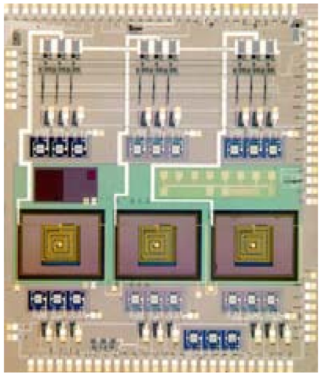




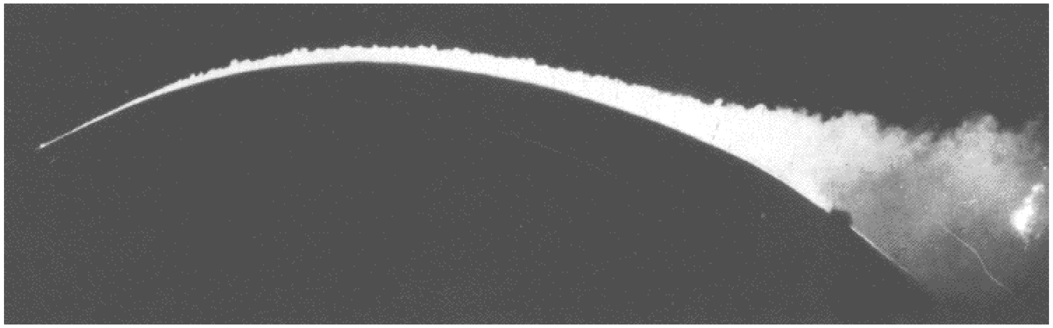
TPS 5 'chip' on 100mm wafer

Aerodynamic Applications of MEMS - Flow Control Possibilities

Vortex Control



Skin Friction Drag Reduction



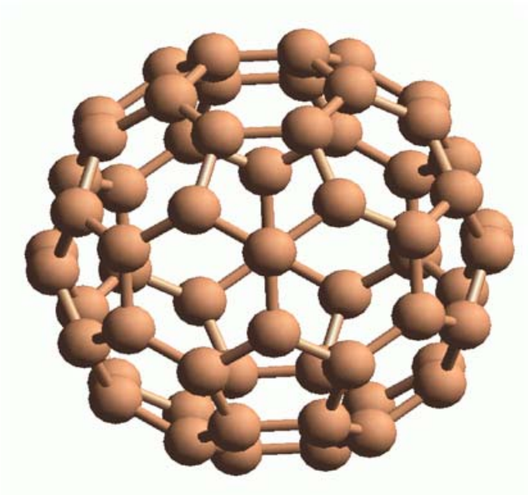
Separation Control

BAE SYSTEMS

Francis Crick 1916
British molecular biologist

Almost all aspects of life are engineered at the molecular level, and without understanding molecules we can only have a very sketchy understanding of life itself.

What Mad Pursuit (1988) ch. 5



BAE SYSTEMS

MEMS Aerospace Applications

Les Applications Aerospatiales des MEMS

An AVT-105 Lecture Series No. 235

organised by the

Applied Vehicle Technology Panel

Part 2

Accelerometers

MEMS Accelerometers - Example Applications

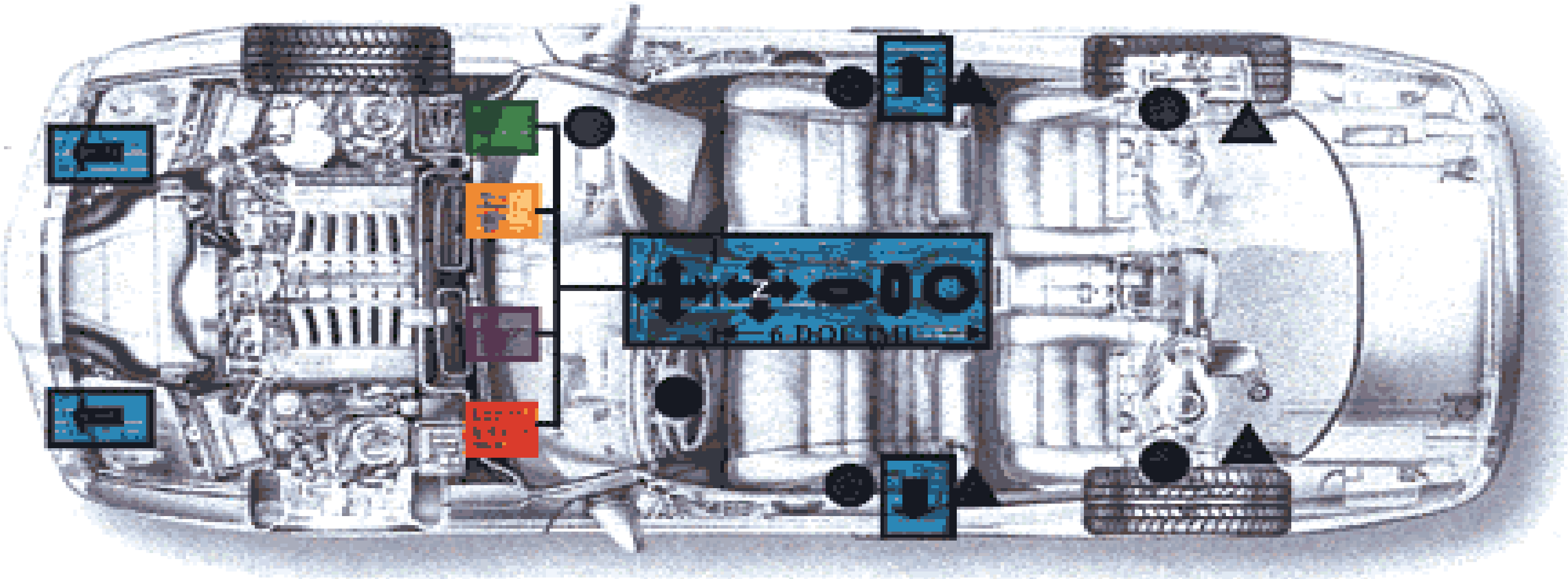
- **Automotive**
  - Airbags
  - ABS
  - Suspension
  - Tilt
- **Medical**
  - Pacemakers
- **Consumer**
  - Security
  - Smart homes
- **Industrial**
  - Noise & Vibration monitoring / control
- **Aerospace**
  - Navigation & IMUs

BAE SYSTEMS

Accelerometers for:

- **TILT or INCLINATION:** static acceleration driven by the Earth's gravity force (1g).
  - Car Alarms (motion detection)
  - Patient monitoring
- **INERTIAL FORCES:** velocity, distance or force (2g - 50g).
  - Airbag sensors
  - Navigation systems
- **SHOCK & VIBRATION** (2g - 50g)
  - Machinery health & condition monitoring
  - Event monitoring
  - Earthquakes

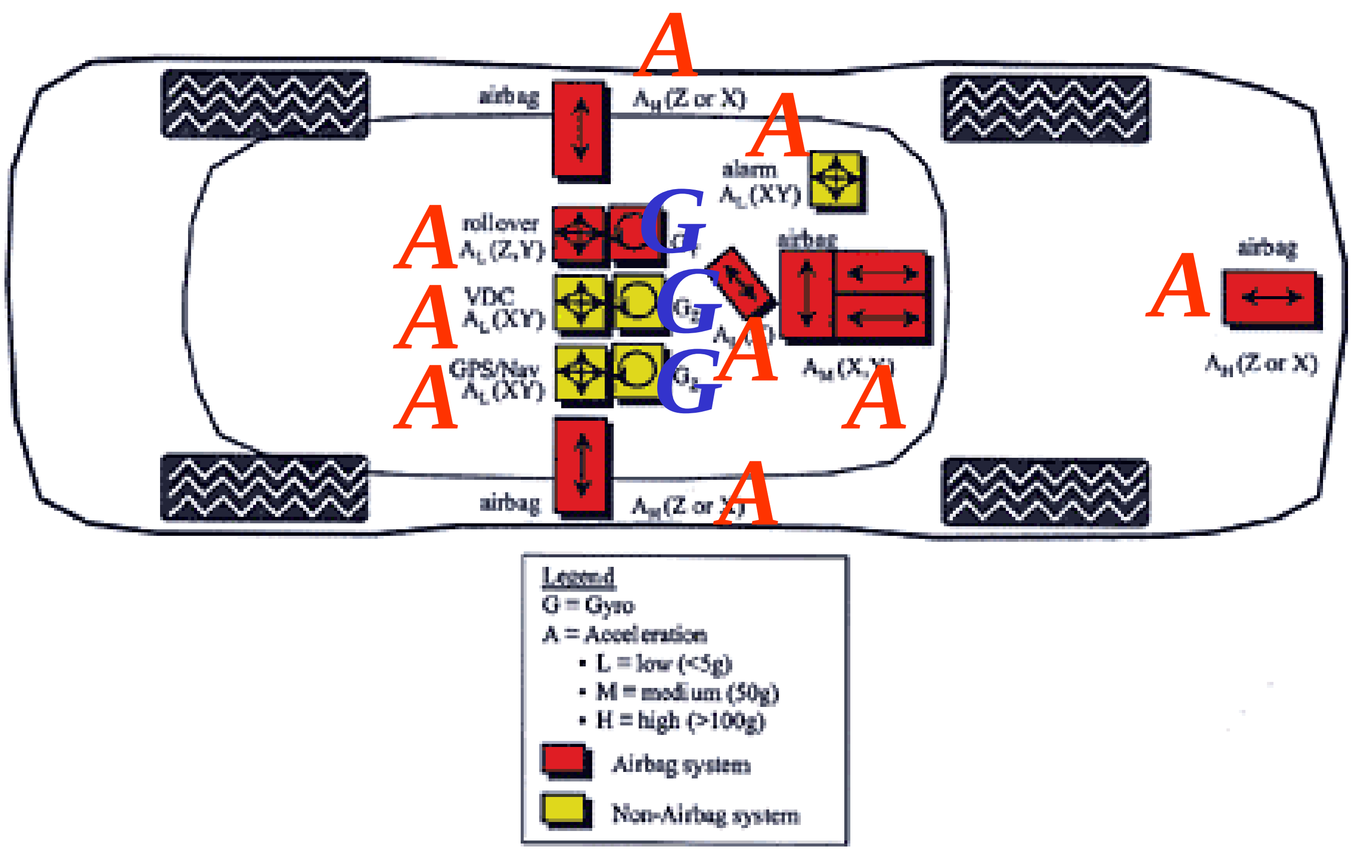
Automotive Sensors



- *Crash Detection System*
- *Vehicle Dynamic Control System*
- *Navigation Information System*
- *Body / Chassis Control System*

- *Satellite Sensor*
- *Airbag*
- *Seatbelt Sensor*

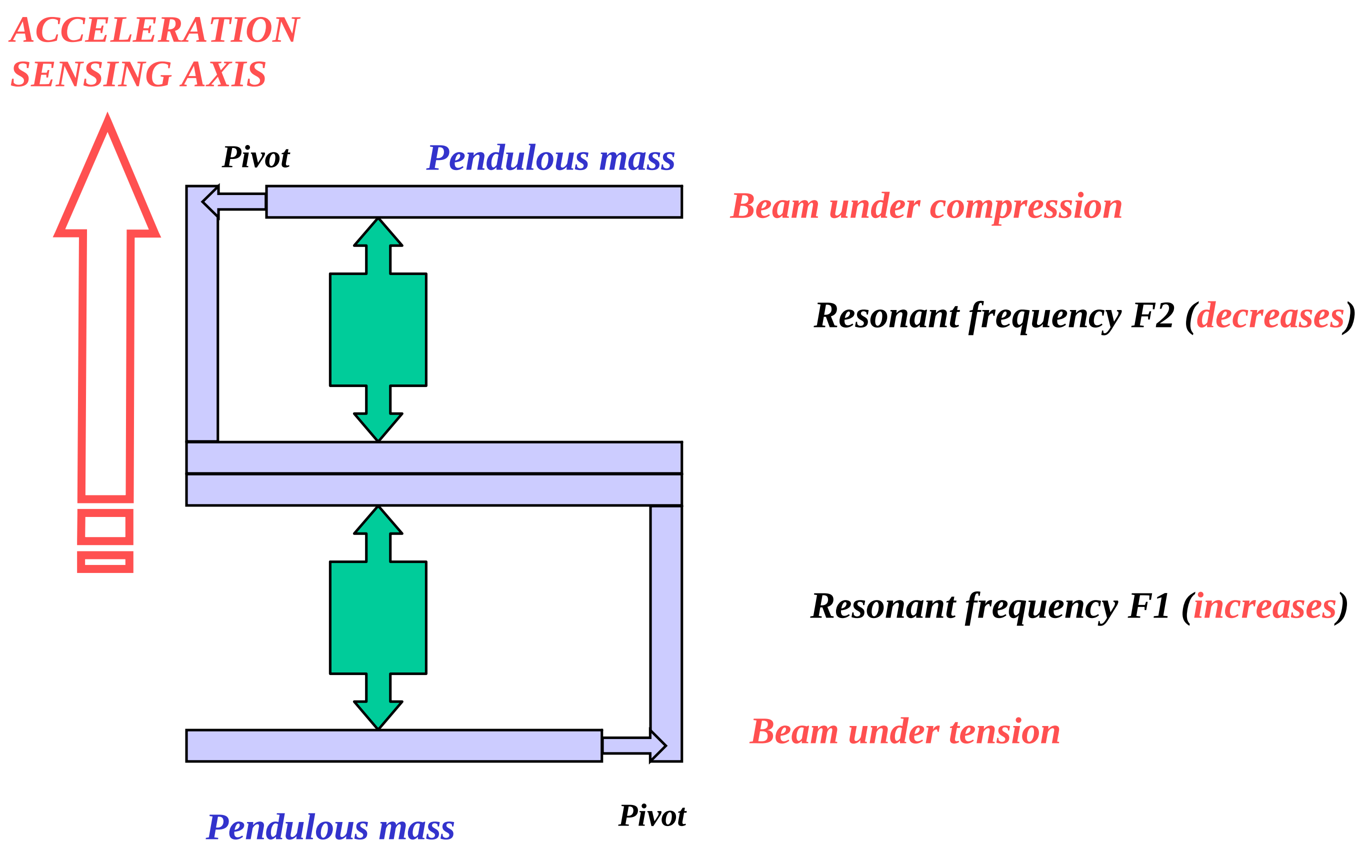
Accelerometers & Gyros in Vehicles



Vibrating Beam Accelerometer

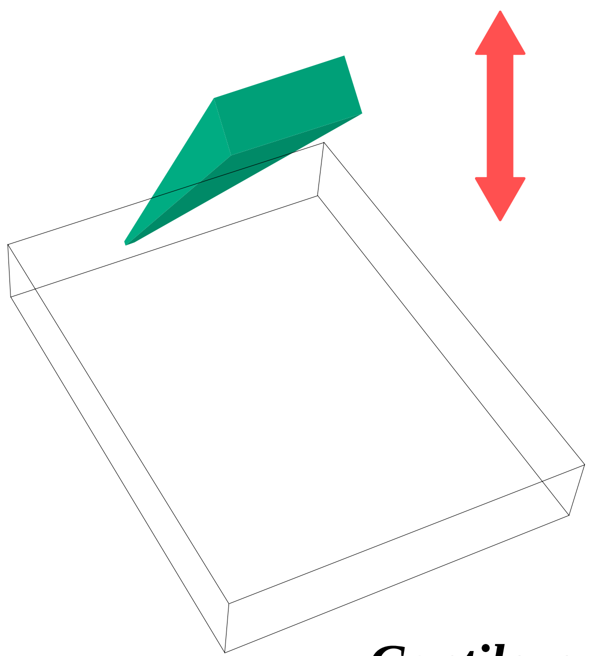
BAE SYSTEMS

Acceleration = f (F2 - F1)

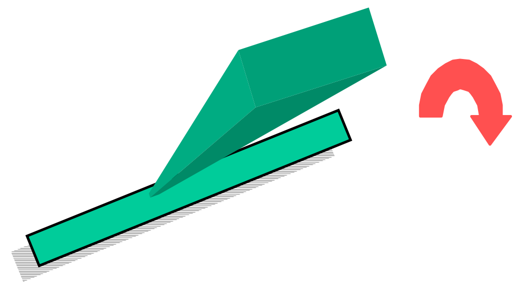


BAE SYSTEMS

Bulk Accelerometers



Cantilever

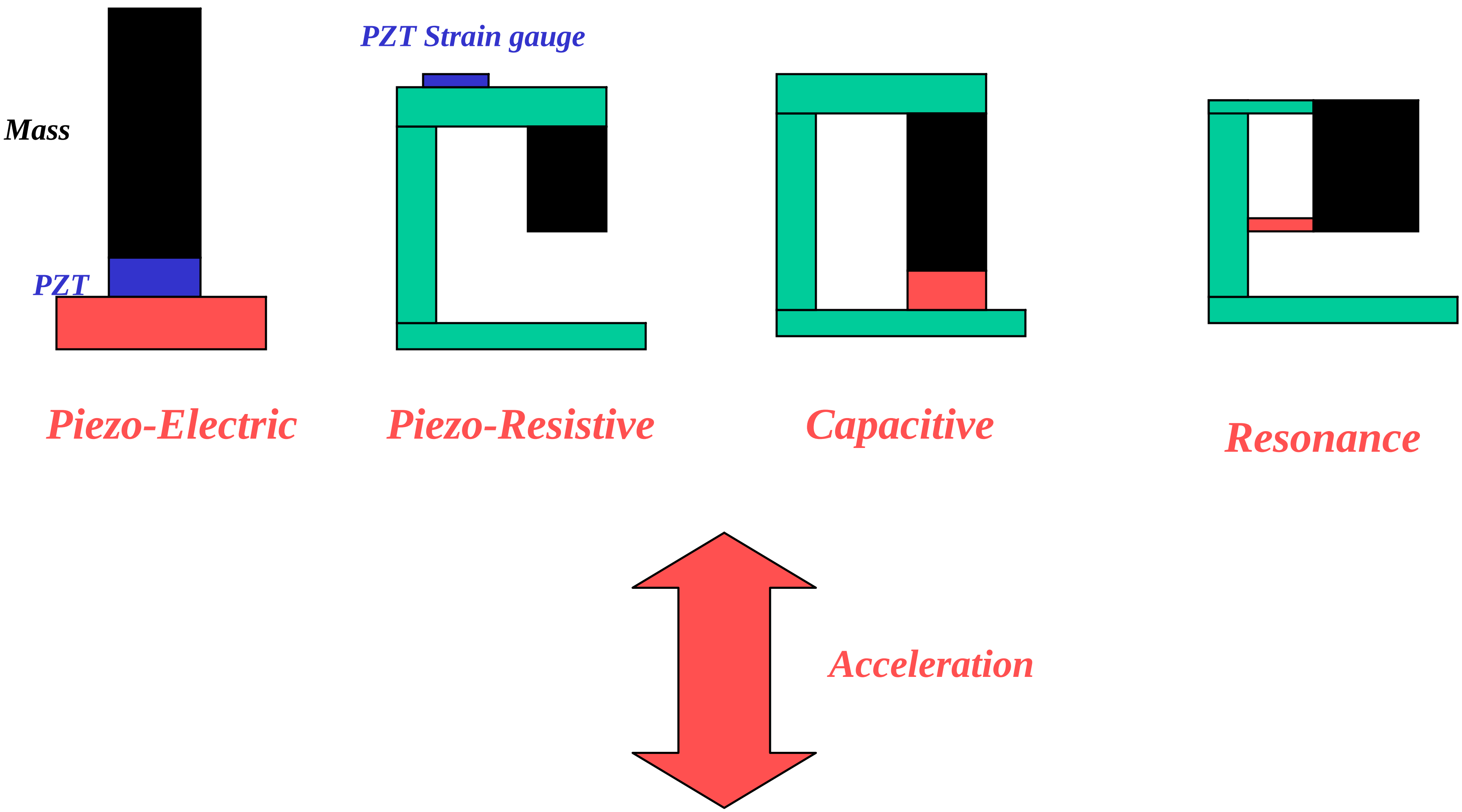


Torsional bar

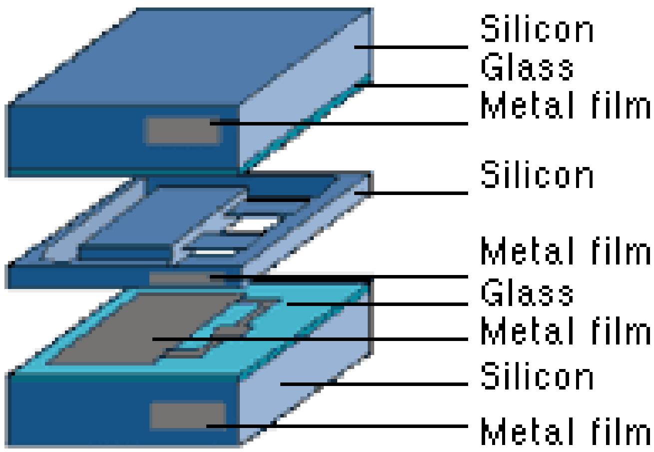
Bridge structures

BAE SYSTEMS

(some) Detection Techniques



Bulk Capacitive Accelerometer
VTI Technologies



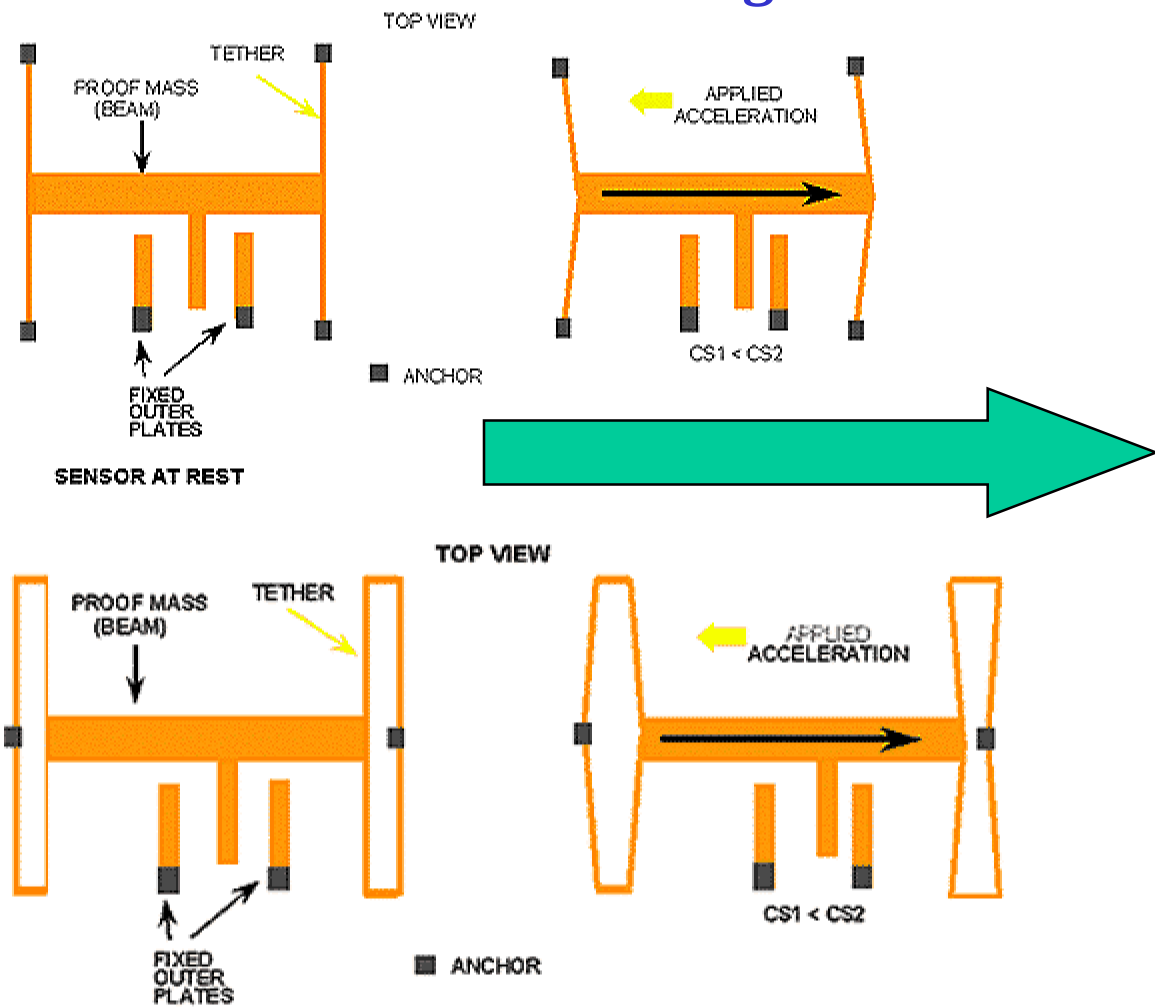
Sandwiched Silicon bends with force and changes capacitance

BAE SYSTEMS

Surface Micromachined Capacitive Accelerometers

Analog Devices

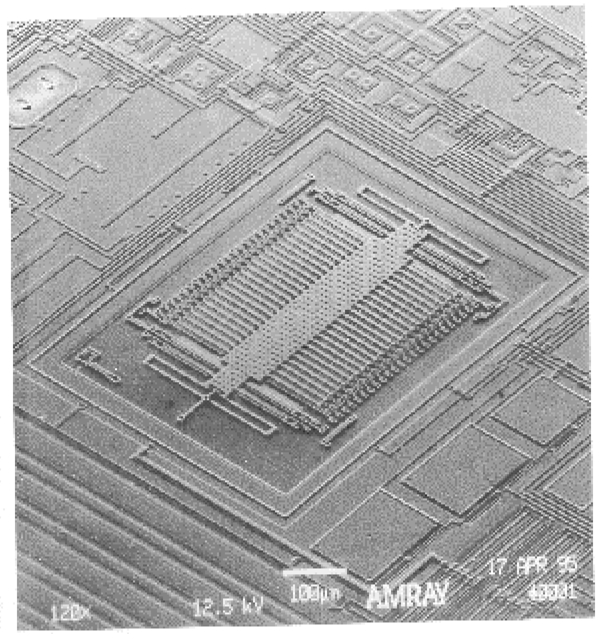
Capacitive Comb Detection



Acceleration

BAE SYSTEMS

Surface Micromachined Capacitive Combs from Analog Devices



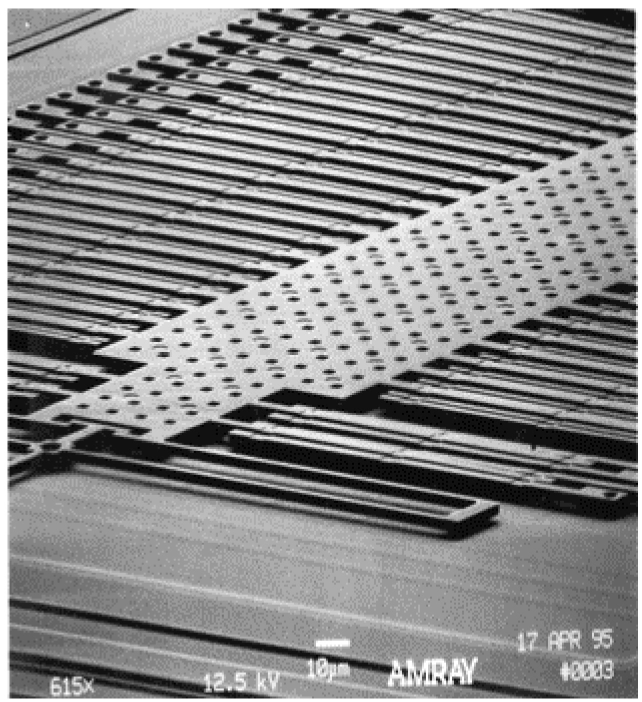
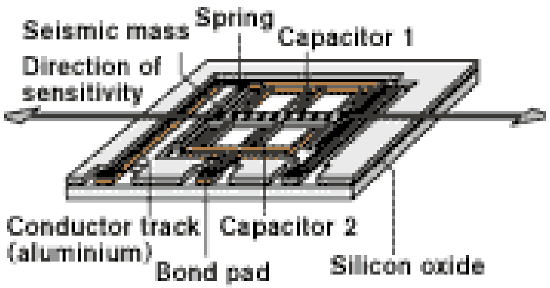


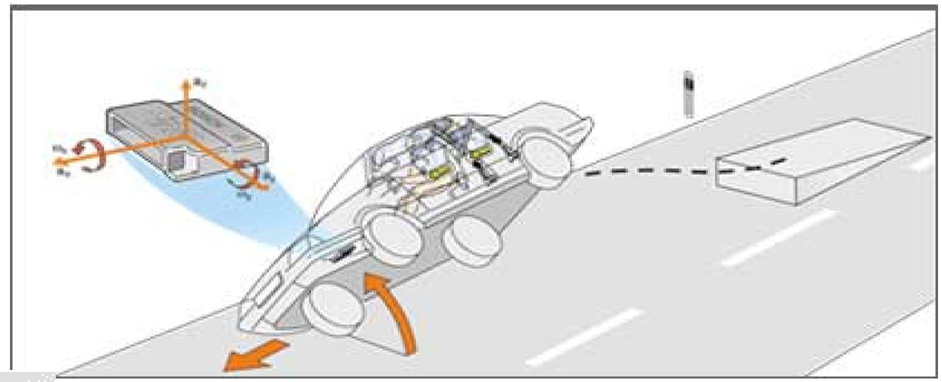
Figure 6. iMEMS accelerometer in surface mount package

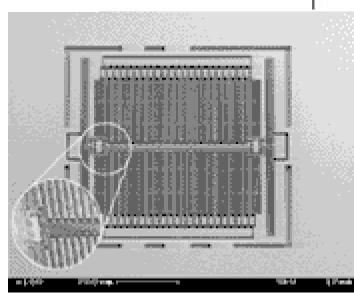
Surface Micromachined Capacitive Accelerometers

Robert Bosch GmbH

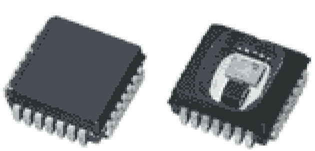


Functional principle

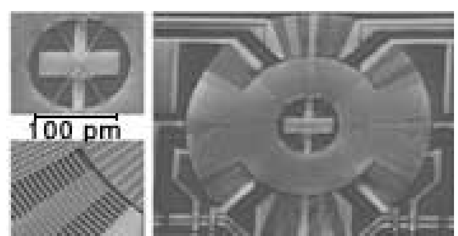




Surface micromachined sensor element



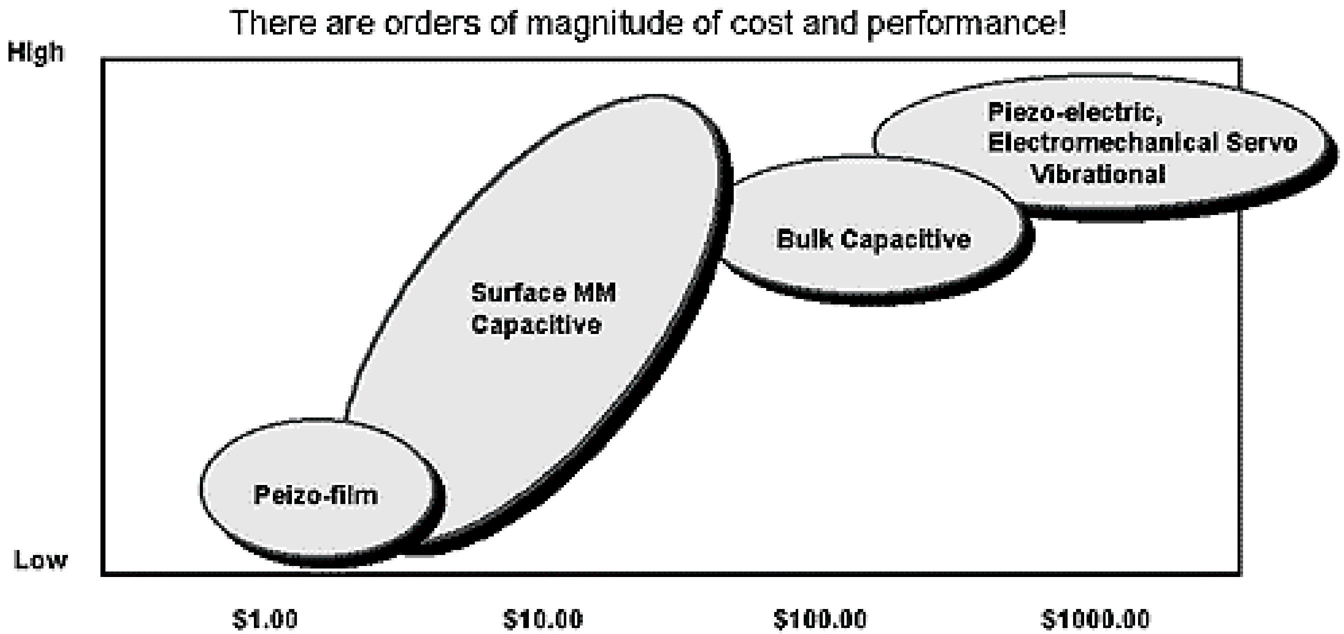
SMD Packaging PLCC 28



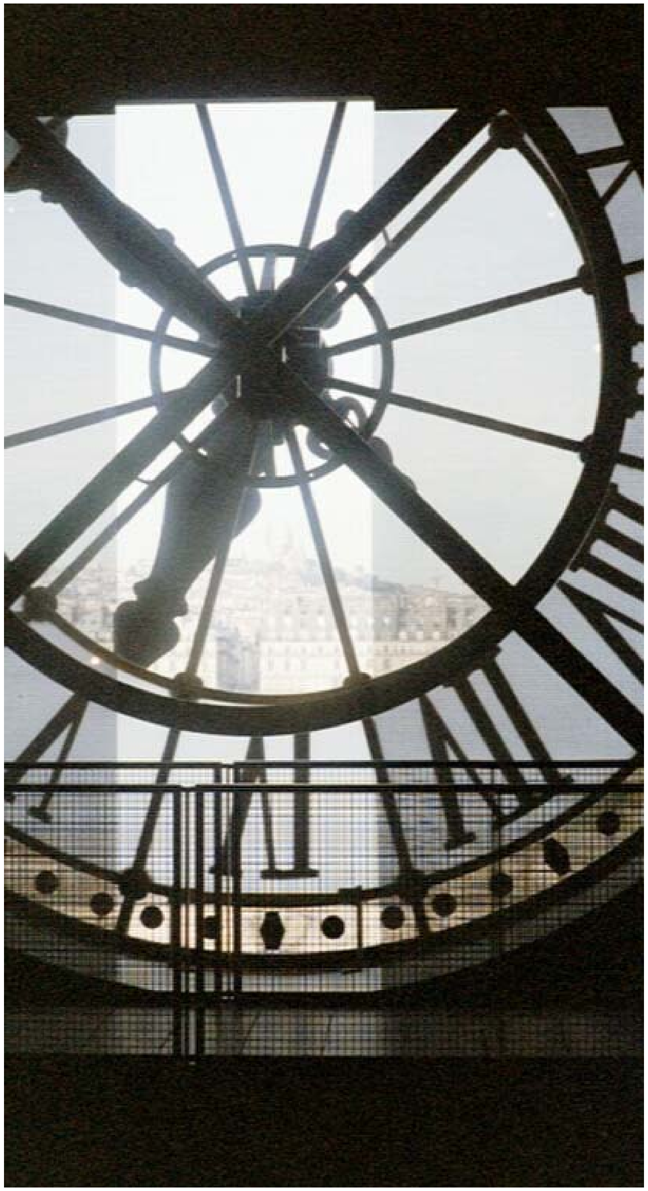
Rollover Sensors
Front Airbag Sensors
Side Impact/Upfront Sensors
Anti-Lock Barking
Vehicle Dynamics Control
Headlight Levelling Systems
Navigation
Car Alarms
Virtual Horizon

Comparative Characteristics

	Capacitive	Piezoelectric	Piezo-resistive
Impedance	High	High	Low
Size	Medium	Small	Medium
Temperature Range	Very wide	Wide	Medium
Linearity	High	Medium	Low
Sensitivity	High	Medium	Medium
Cost	Medium	High	Low



Performance Vs Cost (Analog Devices information)



BAE SYSTEMS

MEMS Aerospace Applications

Les Applications Aerospatiales des MEMS

An AVT-105 Lecture Series No. 235

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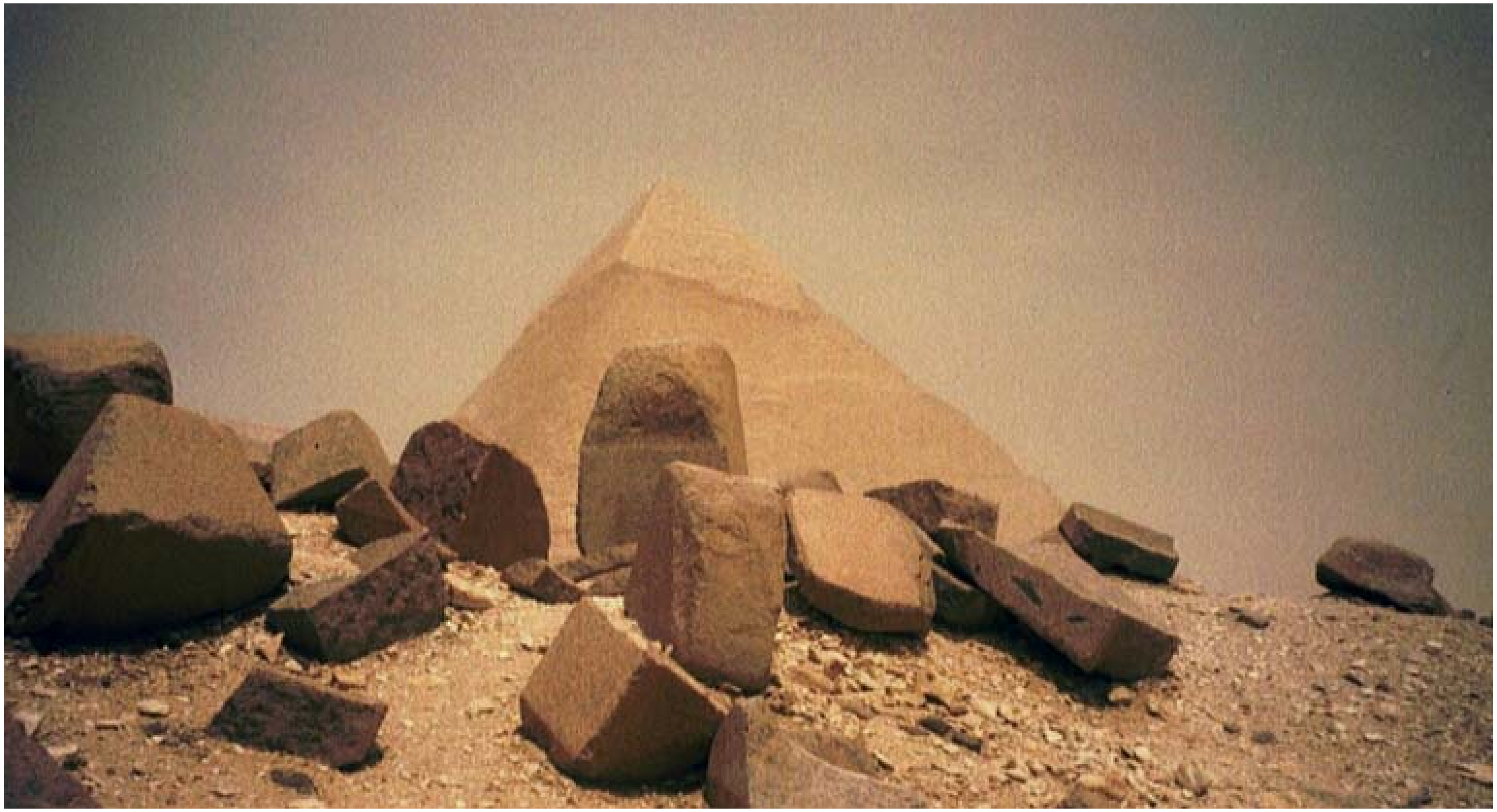
Applied Vehicle Technology Panel

Part 2
Gyros



Gyroscopes ?

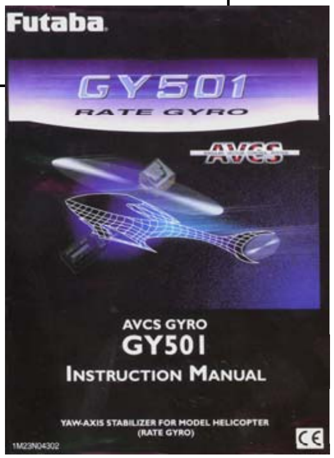
- Measures rotational values (speed of rotation / rates)
- degree per second (º/sec or º/h)
- Mechanical or Optical
- Accuracy and performance judged by:
  - Bias (º/sec or º/h) = offset error output when sensor is static
  - Scale factor error (% of full scale) = linear deviation from true rate
  - Noise = drift and background/non-deterministic behaviour

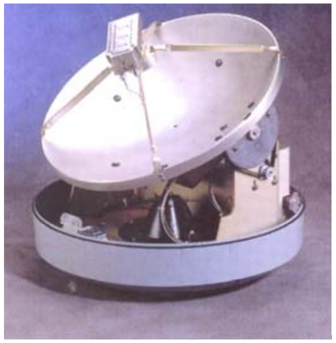
Applications - Defence & Aerospace

- **Missile guidance**
- **Smart shells / guided projectiles**
- **Antenna stabilisation**
- **Unmanned Airborne Vehicles**
- **Flight Instrumentation and Training Pod**
- **Back-up flight instrumentation**

Applications - Commercial

- **Antenna Stabilisation**
- **Marine Autohelms**
- **Adult Toys - Futaba model helicopter, Sony pet dog**
- **Personal Navigators - (with GPS)**
- **IMUs - tracking systems, 3D computer mouse, orthopaedic**
- **Wheelchairs**
- **Racing Cars**



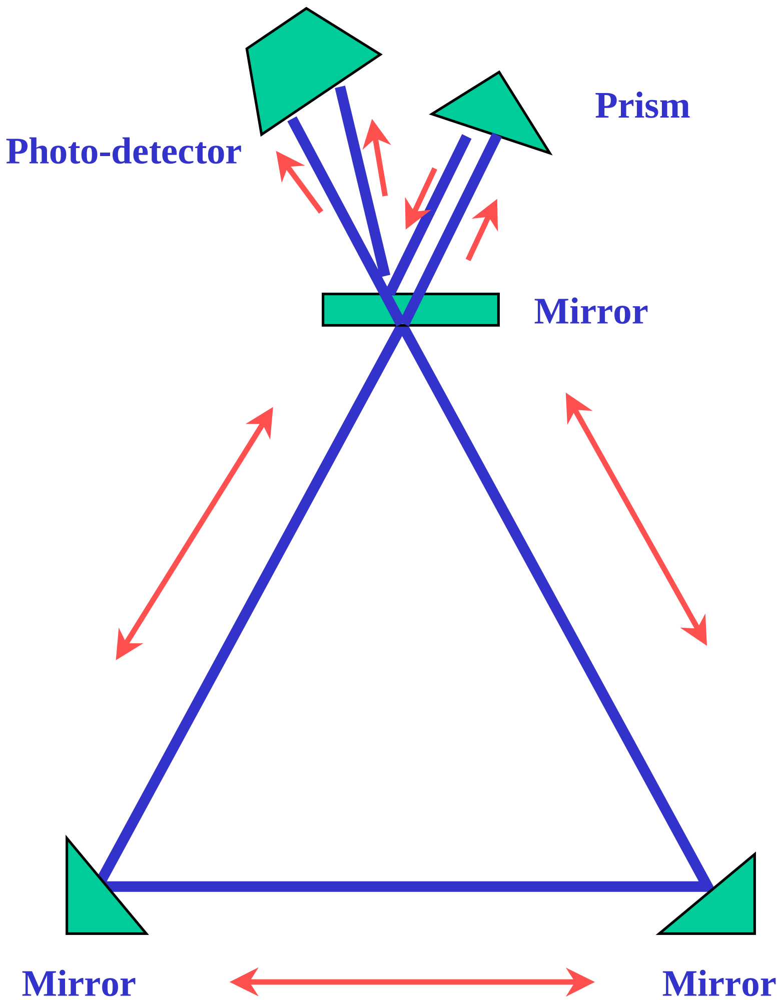


Applications - Automotive

- Advanced Braking Systems
- Navigation
- Rollover Protection
- Autonomous Cruise Control
- Headlamp Steering

Laser Gyros

BAE SYSTEMS



Fringe angle change

$$\Delta \Phi = [\,(8 \pi A) / \lambda L\,]\, \Delta \theta$$

Integrated rate input angle change

A = Area enclosed by the laser beam

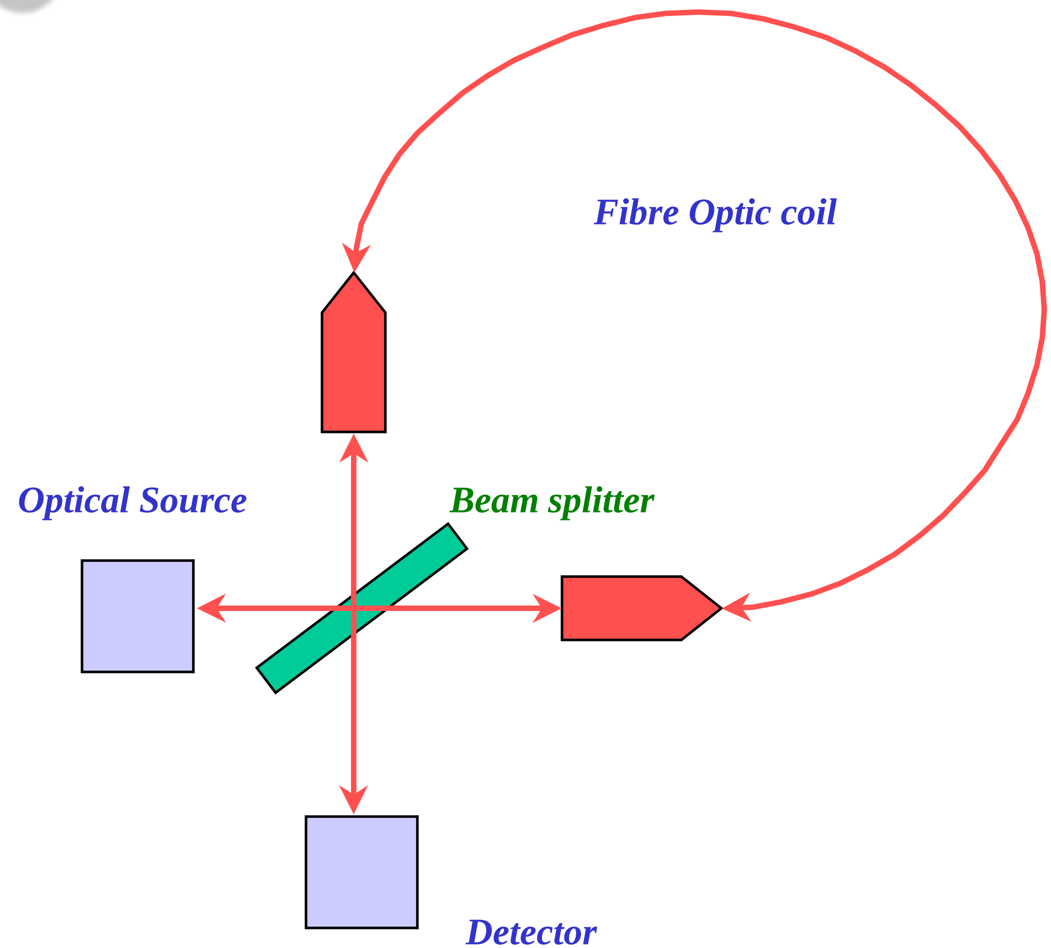
L = Length of laser beam path / perimeter

λ = Laser wavelength

Sagnac Effect*: *difference in transit time between two light waves propagating through the same path in opposite directions

Fibre Optic Rate Sensors

BAE SYSTEMS



Phase shift

$$\Delta \phi = 2\pi (L\, D / c\, \lambda)\, \omega$$

L = Length of fibre

D = Coil diameter

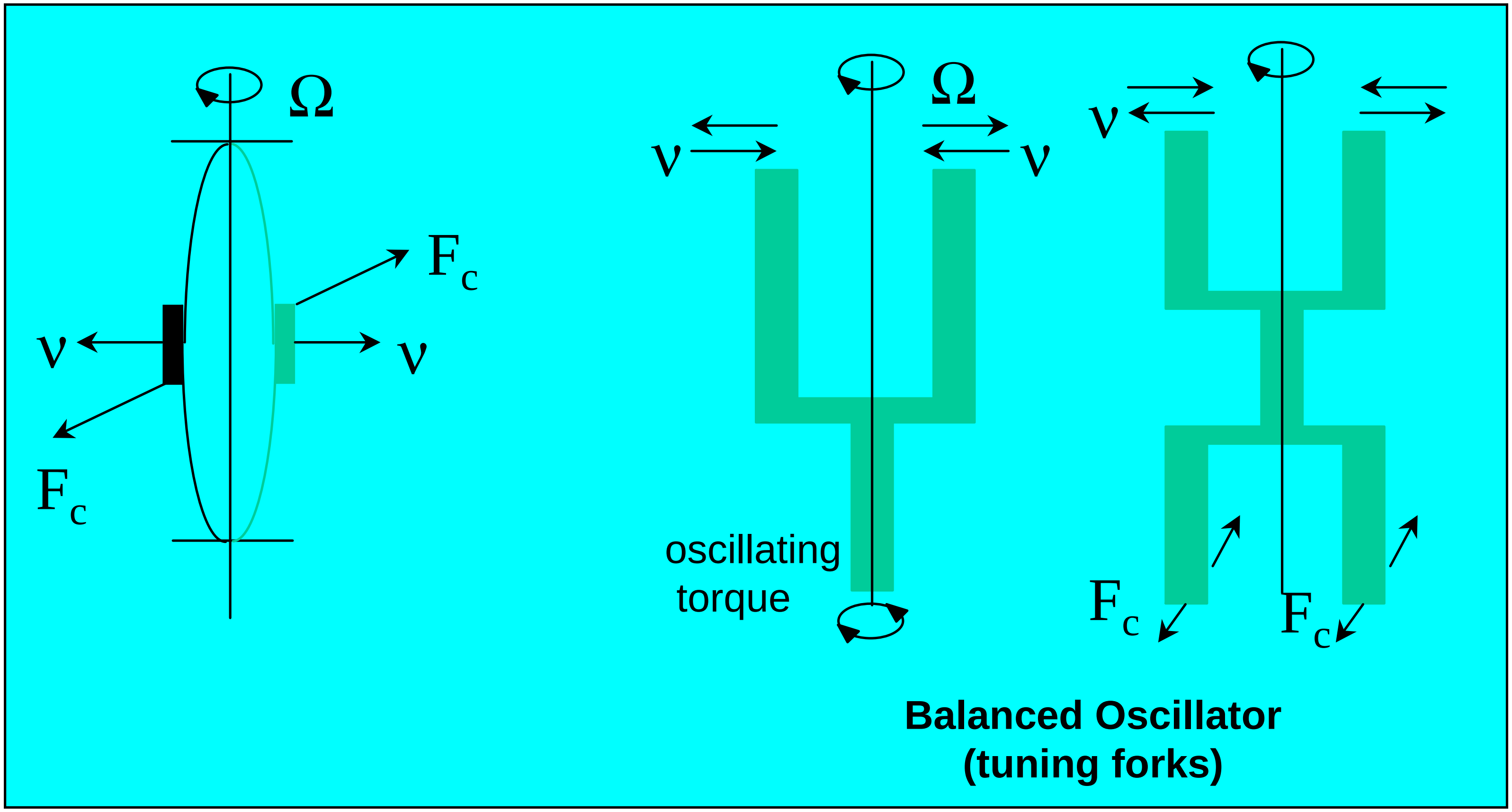
ω = Input angular rate

c = Speed of light

λ - Wavelength

***Sagnac Effect**: difference in transit time between two light waves propagating through the same path in opposite directions*

Simple Oscillator Gyros



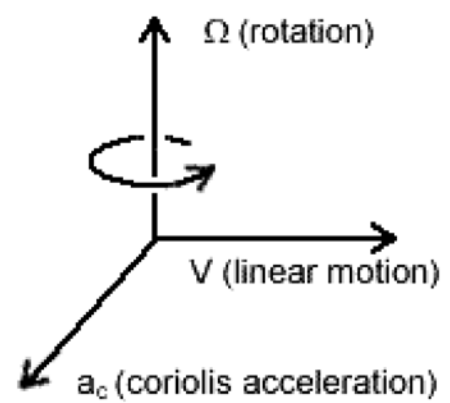
The vibration of the tuning fork, whilst rotating, creates Coriolis acceleration

Tuning Fork / Vibration Gyros

The Coriolis Effect

All vibrating gyroscopes rely on the Coriolis acceleration. This acceleration is experienced by a particle undergoing linear motion in a rotating frame of reference, where the rotation axis is perpendicular to that of the linear motion.

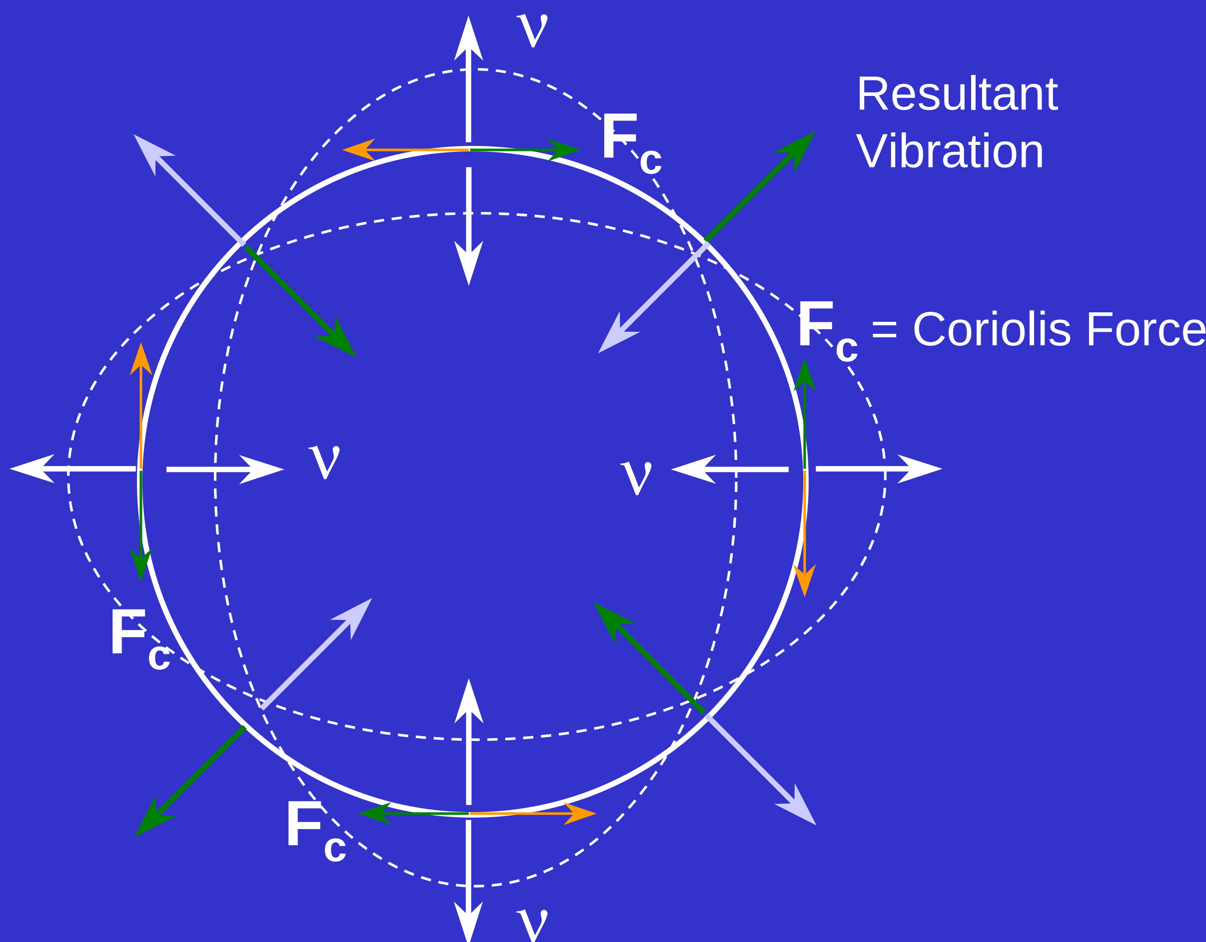
The resulting acceleration, which is directly proportional to the rate of turn, occurs in the third axis, perpendicular to the other two axes.

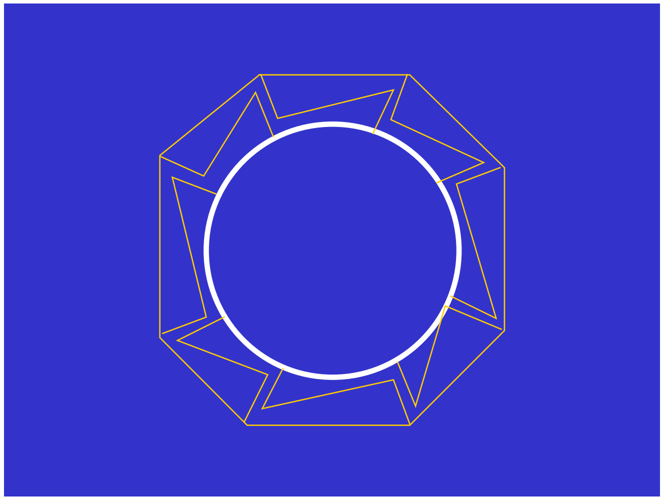


Coriolis in Gyros

- Reminder - the coriolis force causes the rotation (acceleration) from linear motion in a rotating frame
- Acceleration force is proportional to the rotation rate
- In a gyro, linear motion is the vibration mode in a solid body
- Under rotation, energy is coupled from one vibration mode to another
- The magnitude of the vibration in this second mode defines the rotation rate sensed by the gyro

Balanced Shell Resonator Gyro (SiVSG)





Coriolis Explained/Demonstrated

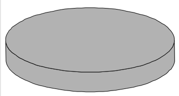
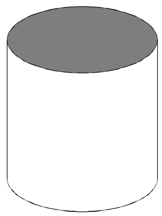
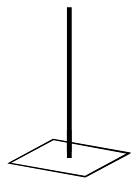
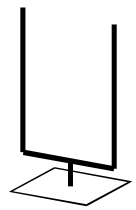
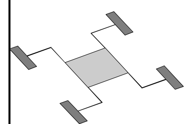
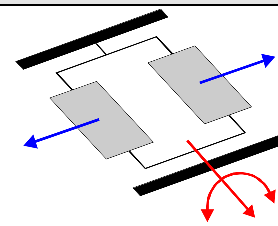
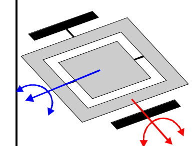
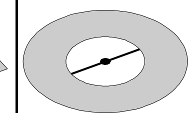
- **Linear motion in a rotating frame**
- **Ball's motion is linear with respect to the playground**
- **Ball's motion is curved with respect to the roundabout**

Coriolis is most often encountered in earth systems (e.g. weather and navigation) but affects every rotating body.

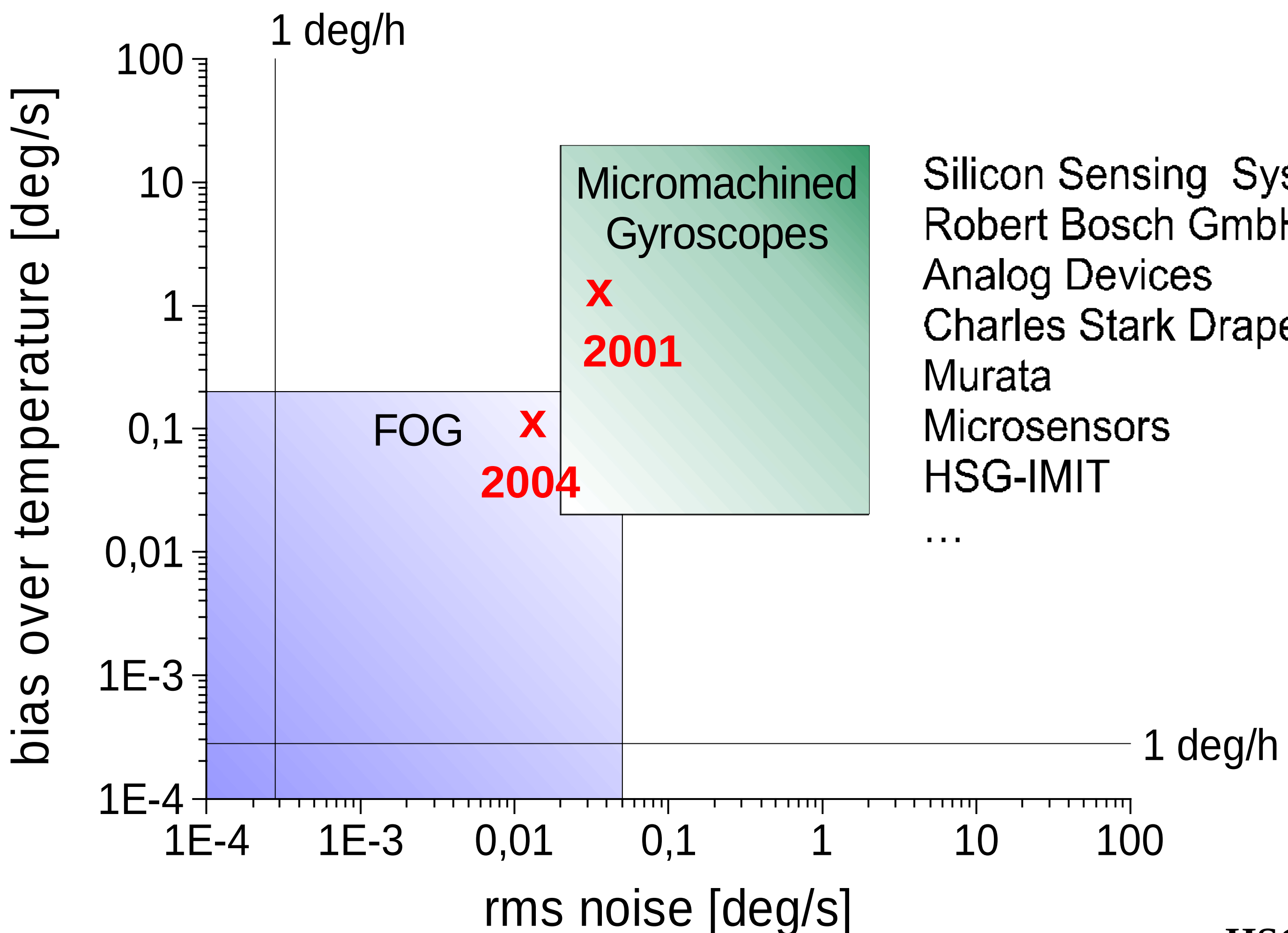
Principles of Micromachined CVG

HSG IMIT

BAE SYSTEMS

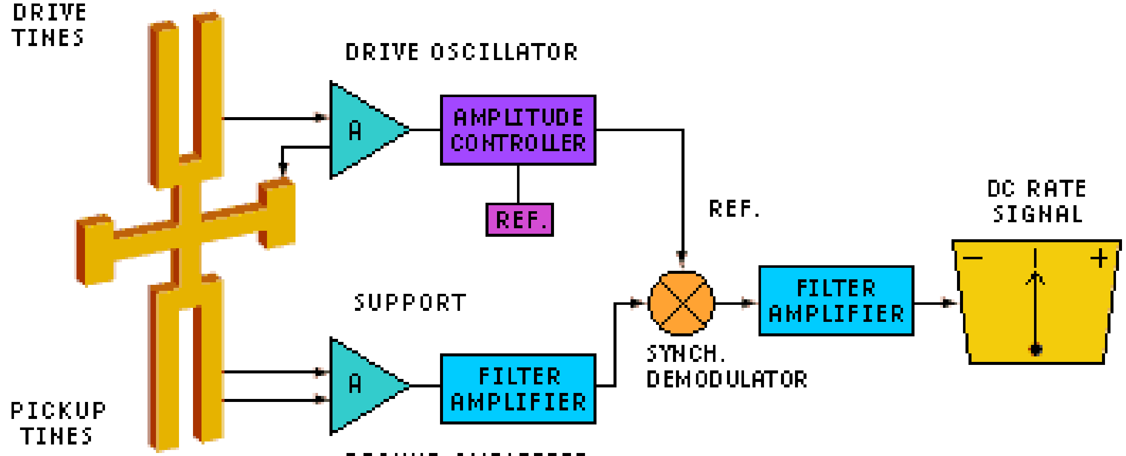
Primary Mode	Rotating	Vib. Shell	Flexural Vibration		Linear Oscillation			Rotary Oscillation	
Features	levitated				1 proof mass	2 proof masses antiparallel		out of plane	in plane
Fig.									
Secondary Mode			Flexural Vibration		Linear Osc.	Linear Osc.	Rotary Osc.	Rotary Osc.	Rotary Osc.
BMM (Bulk Micro Machining)		BASE	T. Seiki	Daimler		Neuchâtel Bosch	Toyota/ Tohoku	CSD VTI JPL/UCLA	
SMM (Surface Micro Machining)	SatCon Sheffield	Michigan			Murata HSG-IMIT Samsung Berkeley ADI		CSD Bosch HSG-IMIT		Motorola Berkeley Bosch HSG-IMIT CSD Samsung

Performance of Micromachined CVG



Silicon Sensing Systems
Robert Bosch GmbH
Analog Devices
Charles Stark Draper Lab.
Murata
Microsensors
HSG-IMIT
…

BEI GyroChip (Systron Donner Inertial Division)



Vibrating Quartz Tuning Fork (fabricated from thin-film single-crystal PZT quartz)

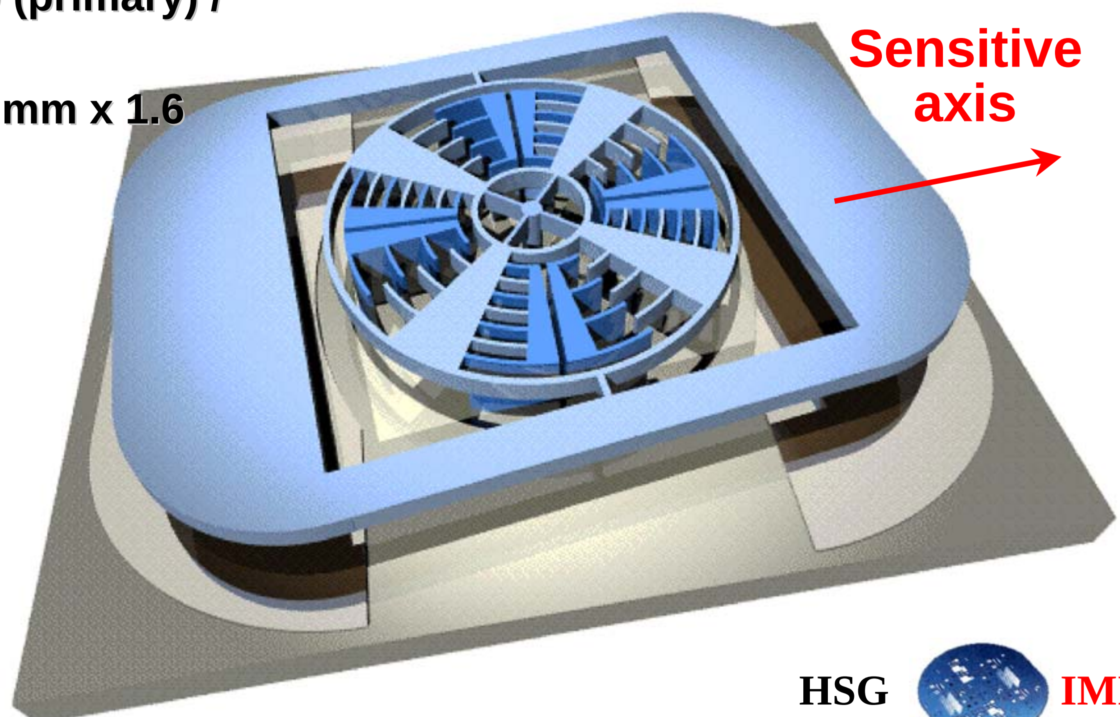
BAE SYSTEMS

DAVED-RR: Principle of operation

Resonance frequencies: 2 - 3 kHz

Quality factor (at 4 hPa): 300 (primary) / 10 (secondary)

Overall dimensions: 1.2 mm x 1.6 mm

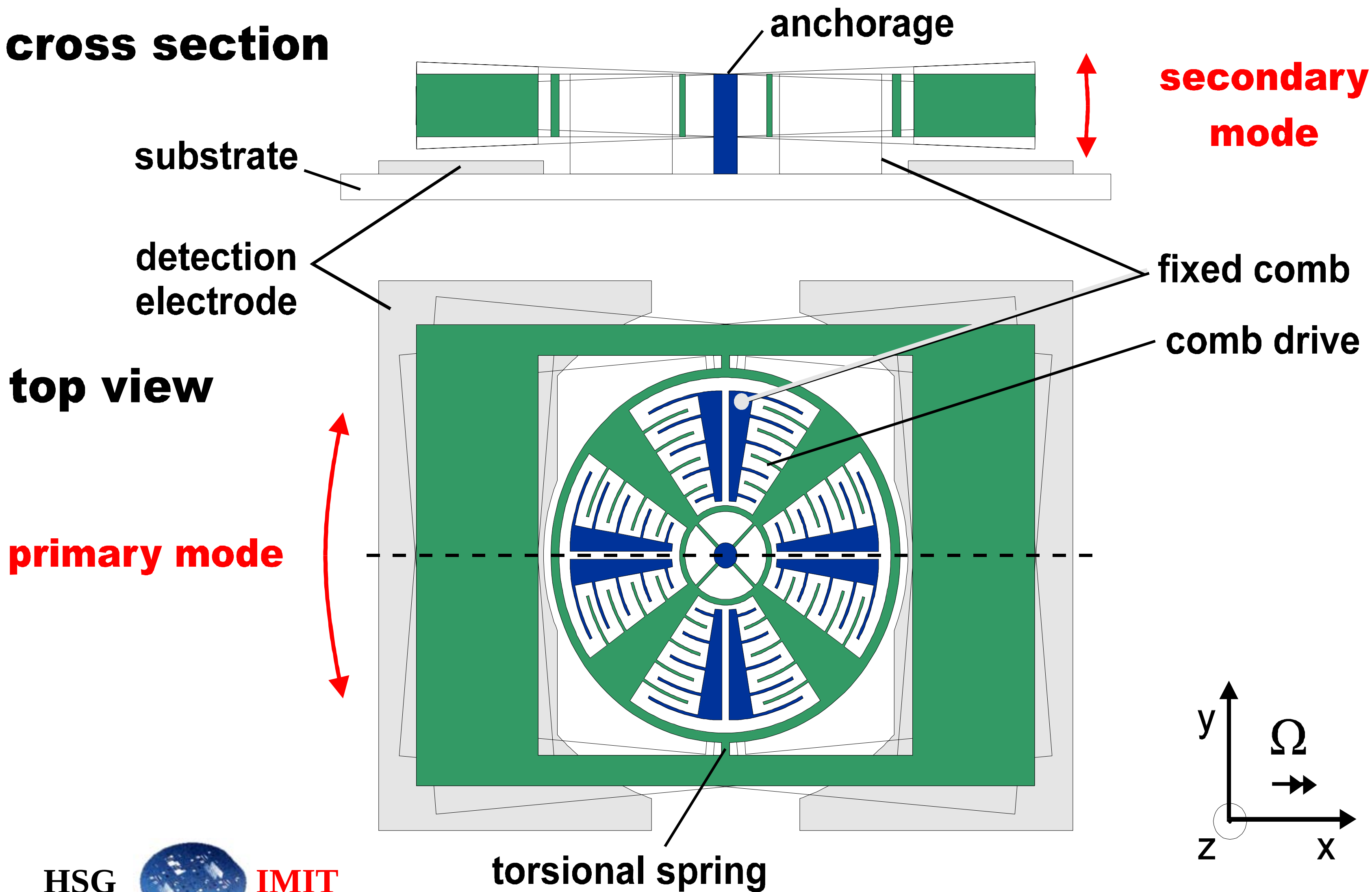


Excitation Mode

Detection Mode

HSG IMIT

DAVED-RR – Principle of Operation

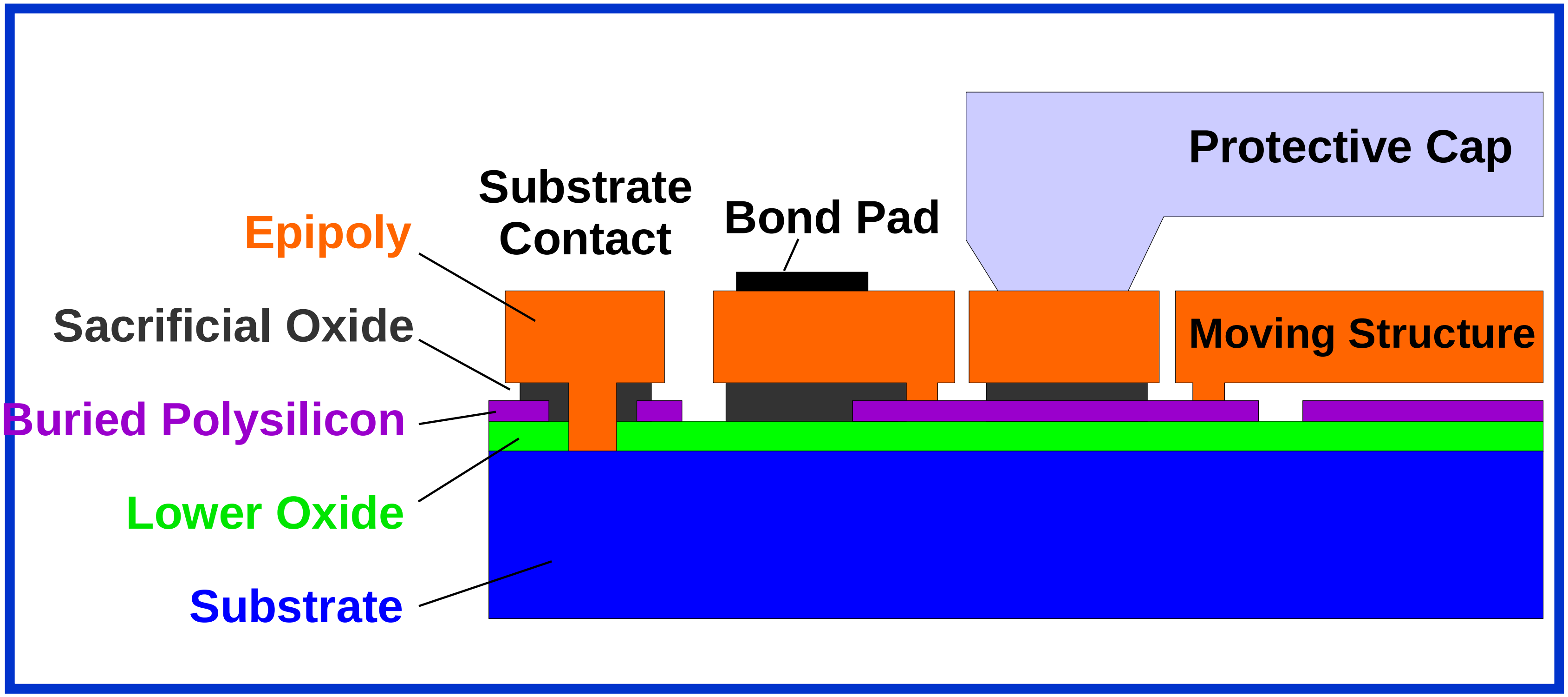


HSG IMIT

DAVED-RR: Technology

BAE SYSTEMS

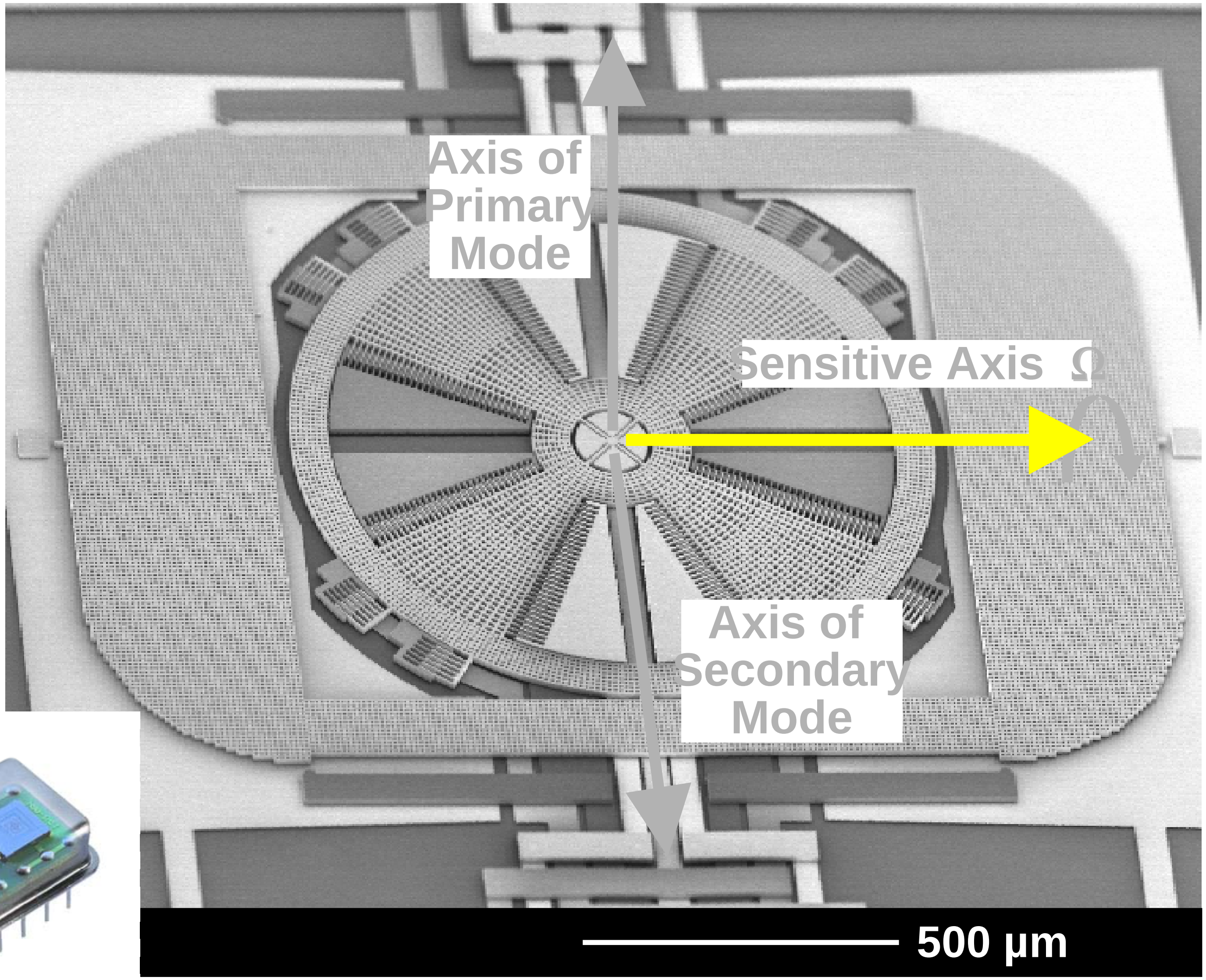
Surface-Micromachining Foundry



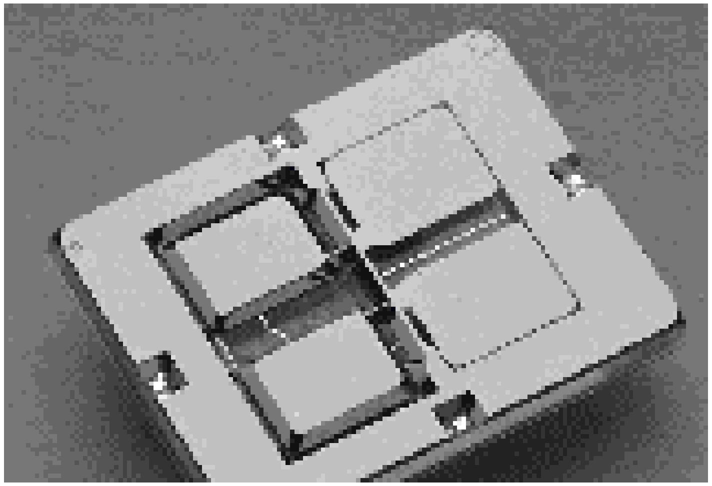
Robert Bosch GmbH

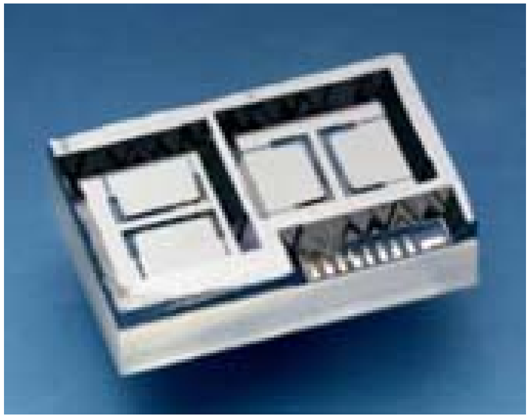
DAVED-RR: SEM-Graph

BAE SYSTEMS



Imego's 3-axis "Butterfly" Gyro





Resonant Vs Capacitive

BAE SYSTEMS

Parameter	Bulk Capacitive	Thin-Film Capacitive	Resonant
S/N Ratio	-	-	+
Accuracy	-	0	+
Self-Test	+	+	++
ASIC cost	0	+	+
Reliability	0	-	+

BAE SYSTEMS

Evolution of VSG Technology SiVSG®

VSG Evolution

The SiVSG® shell resonator technology has evolved into silicon from other solid state products; the VSG (piezo-ceramic cylinder) and the RG4550 (metal ring).

Si-VSG Gyroscope

BAE SYSTEMS

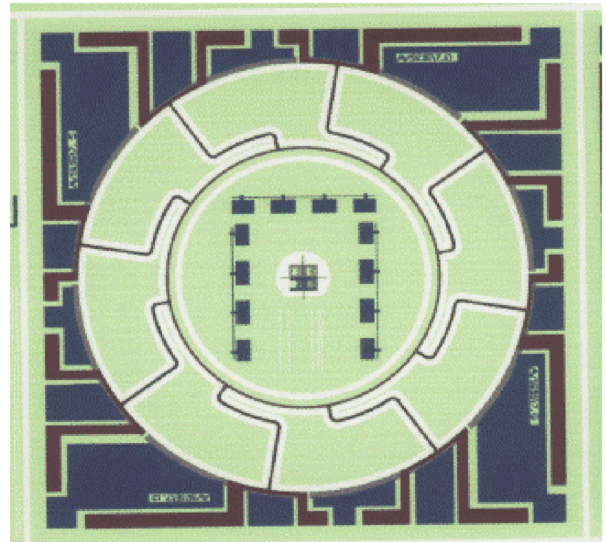
•Exploits previous experience
on solid state sensors
-shell/cylinder formats

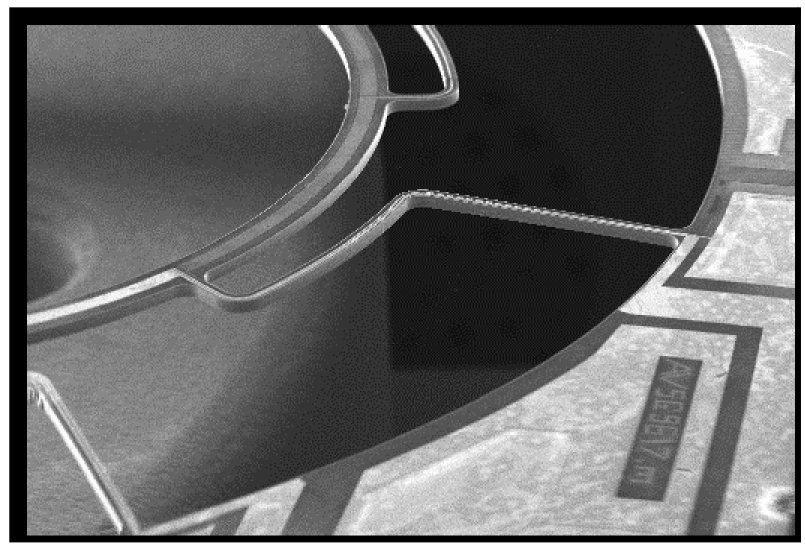
•Adds new process technology
- Silicon D-RIE Process

•Demonstrated @10mm ring
(Inductive device)

•Volume production @6mm ring
(Inductive device)

•R&D @ 4mm ring
•(Capacitive device)





BAES silicon gyro - a model development

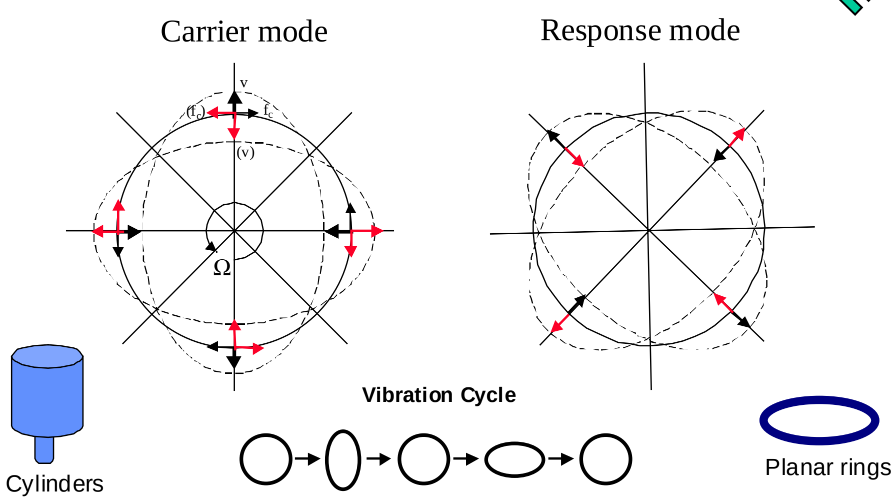
BAE SYSTEMS

Application knowledge

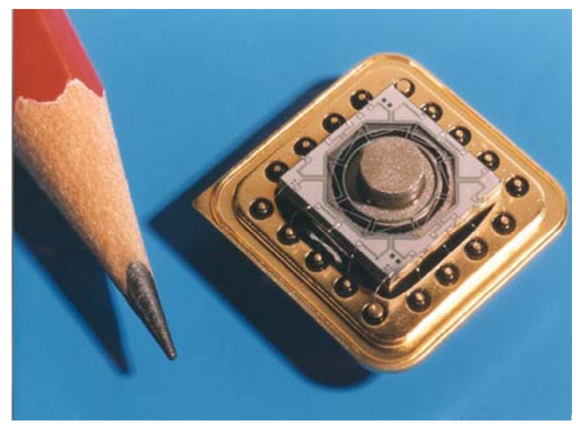
MEMS device expertise

Product understanding

Vibrating Structure Gyro Principles



Successful product



Si-VSG Gyroscope

BAE SYSTEMS

Silicon Sensing Systems
A Joint Venture between
BAE SYSTEMS and
Sumitomo Precision Products

Typical Automotive Packaging solution

Si-VSG Production Device 6mm Ring

Silicon MEMS Sensors

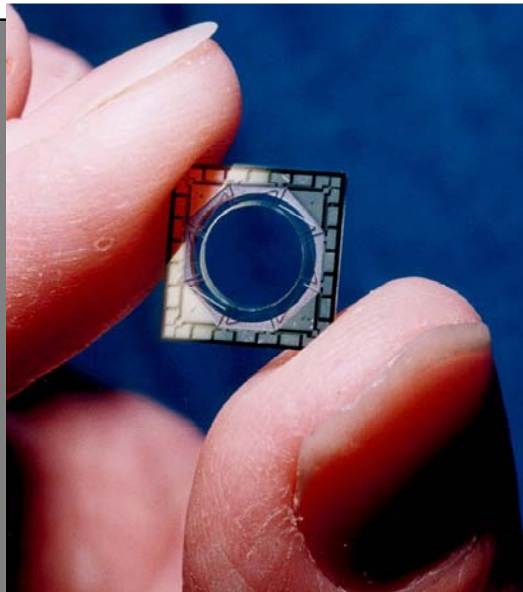
Off-the-shelf, single axis, rate sensors and inertial measurement units.

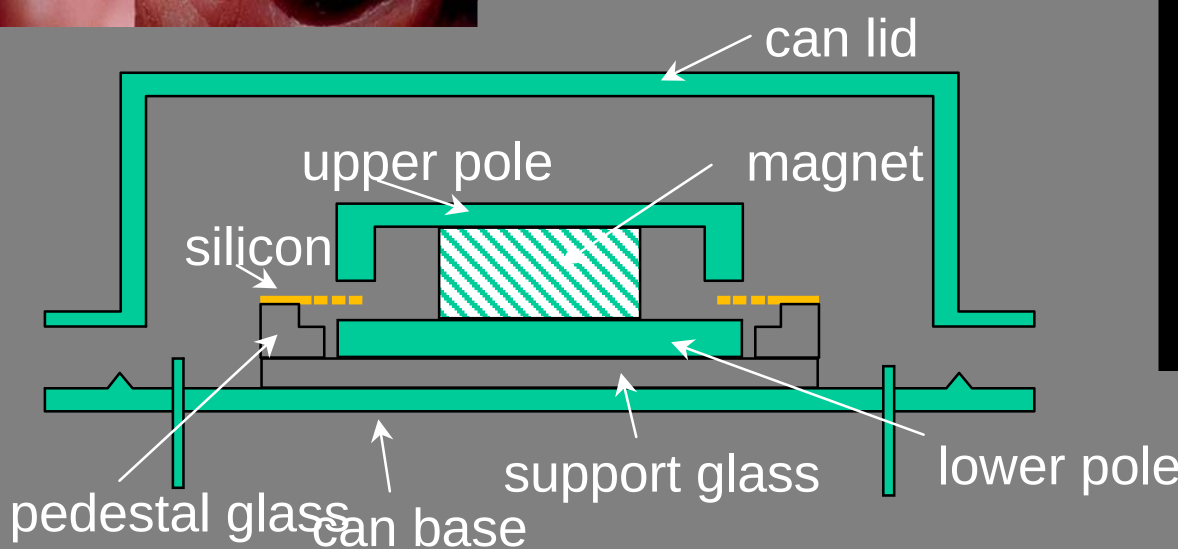
Excellent shock and vibration performance.

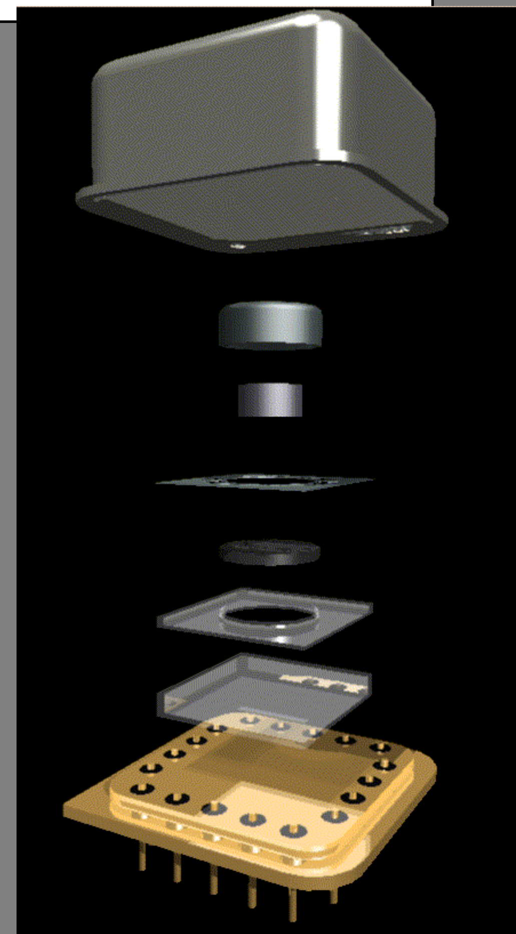
G-hardened to withstand over 22,000g.

Compact, lightweight, with long life and exceptional reliability.

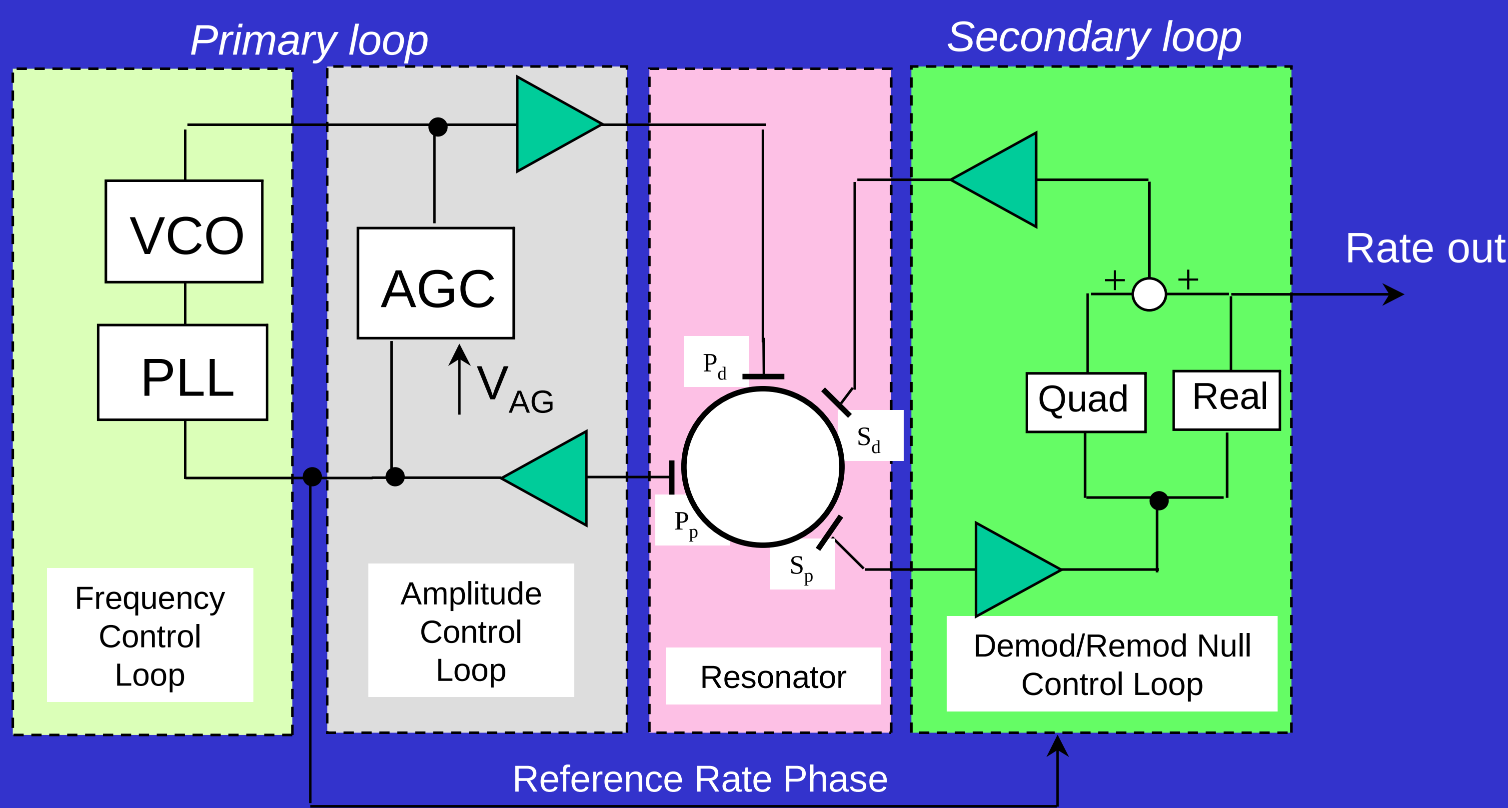
Silicon Sensor Head







SiVSG - Systems Schematic



BAE SYSTEMS

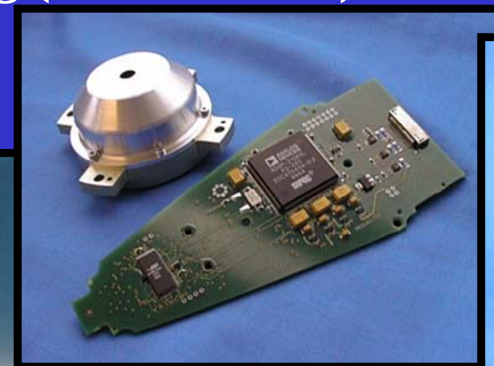
Achievements and Successes - Military

MR-Trigat (TRIGAN):	Guided firing
VL Seawolf:	Production contract
ERGM:	High-g Launch Controlled Flight (CTV1)
AGS:	Selected for ATD phase
RAM:	HWIL Testing at China Lake Proving Grounds
LCPK:	Successful ITV1 firing
C-KEM:	Static trials at Redstone Arsenal
Netfires:	Under contract for ATD

Either selected or being evaluated for other programs including: Longbow, Javelin, NLAW, WCMD, Small Diameter Bomb, Project X.

BAE SYSTEMS

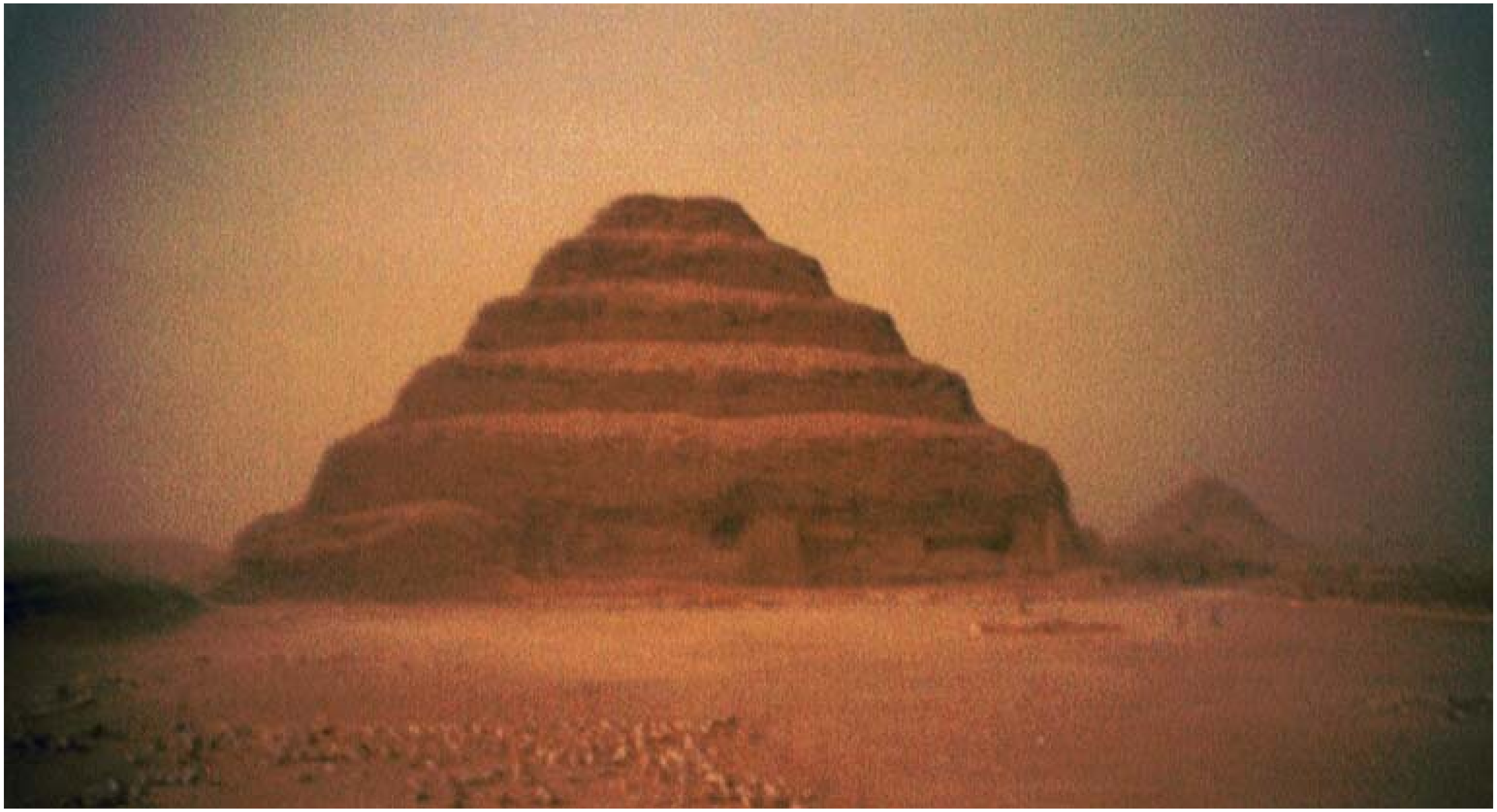
Controlled High-g Test Firing (White Sands)



3-axis HWIL testing at China Lake and Bourges

- Repackaged SiIMU01
- Selected as baseline for Raytheon’s ERGM program
- G-hard package

Guided Missile Firing



BAE SYSTEMS

MEMS Aerospace Applications

Les Applications Aerospatiales des MEMS

An AVT-105 Lecture Series No. 235

organised by the

Applied Vehicle Technology Panel

Part 4 (and final)

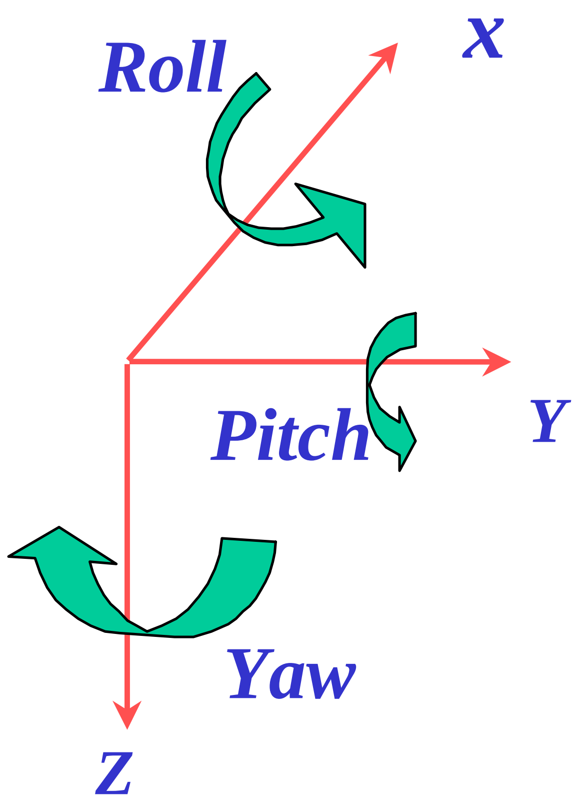
IMUs

Strap-Down Systems

- Inertial Measurement Units measure motion in three orthogonal axes
- Relies on three single-axis gyros mounted “strapped down” orthogonally (X, Y and Z)
- Together with 3 (orthogonal) accelerometers, the six sensors form a sensor co-ordinate system.
- Attitude-Heading Reference Systems (AHRS) measures the dynamics of a system by augmenting heading using a magnetic compass or GPS
- Inertial Navigation Systems integrate GPS data to calculate orientation and position

BAE SYSTEMS

INERTIAL MEASUREMENT UNITS

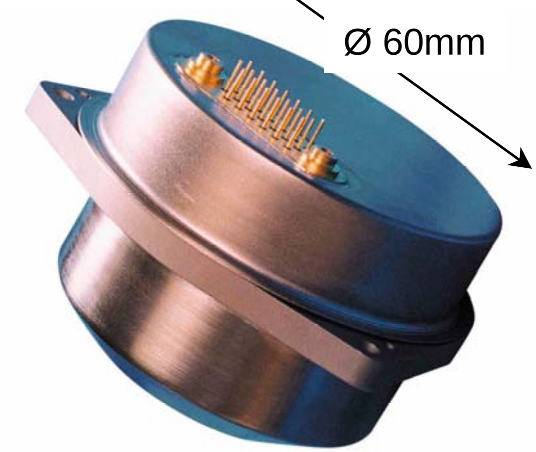


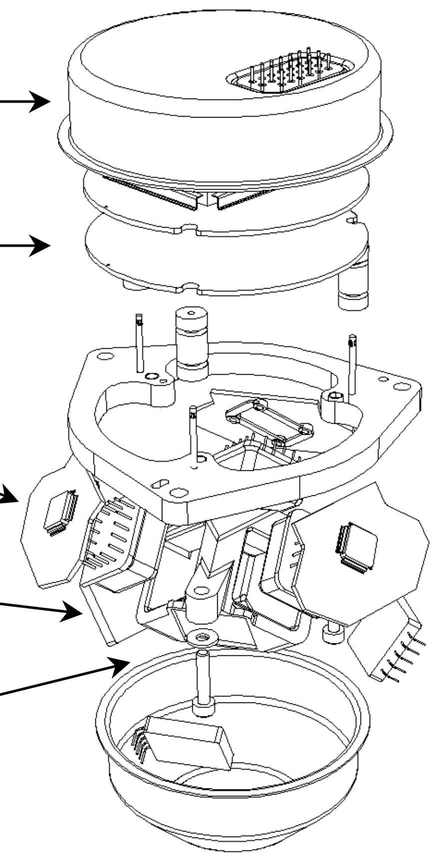
SIX INERTIAL SENSORS :

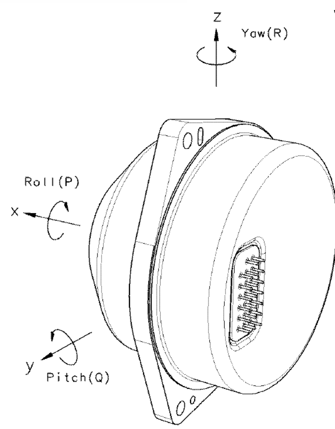
3 linear accelerometers
+
3 rate gyros to measure rotational velocity

BAE SYSTEMS

SiIMU01 - All-MEMS Inertial Measurement Unit







100°/hr

10mg

<250grams

Honeywell's IMUs

The HG1900 is a MEMS gyro based Inertial Measurement Unit suitable for various commercial and military guidance and navigation applications. It uses Honeywell MEMS gyros and RBA500 accelerometers.

The HG1910 is a Gun Hard MEMS Inertial Measurement Unit used for which is suitable for guided projectile applications

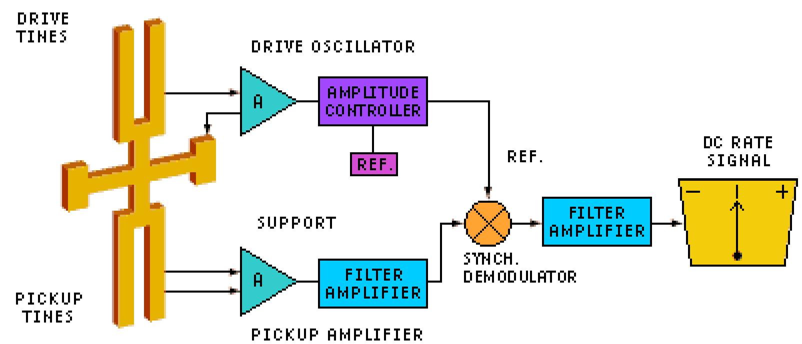
Crossbow's AHRS

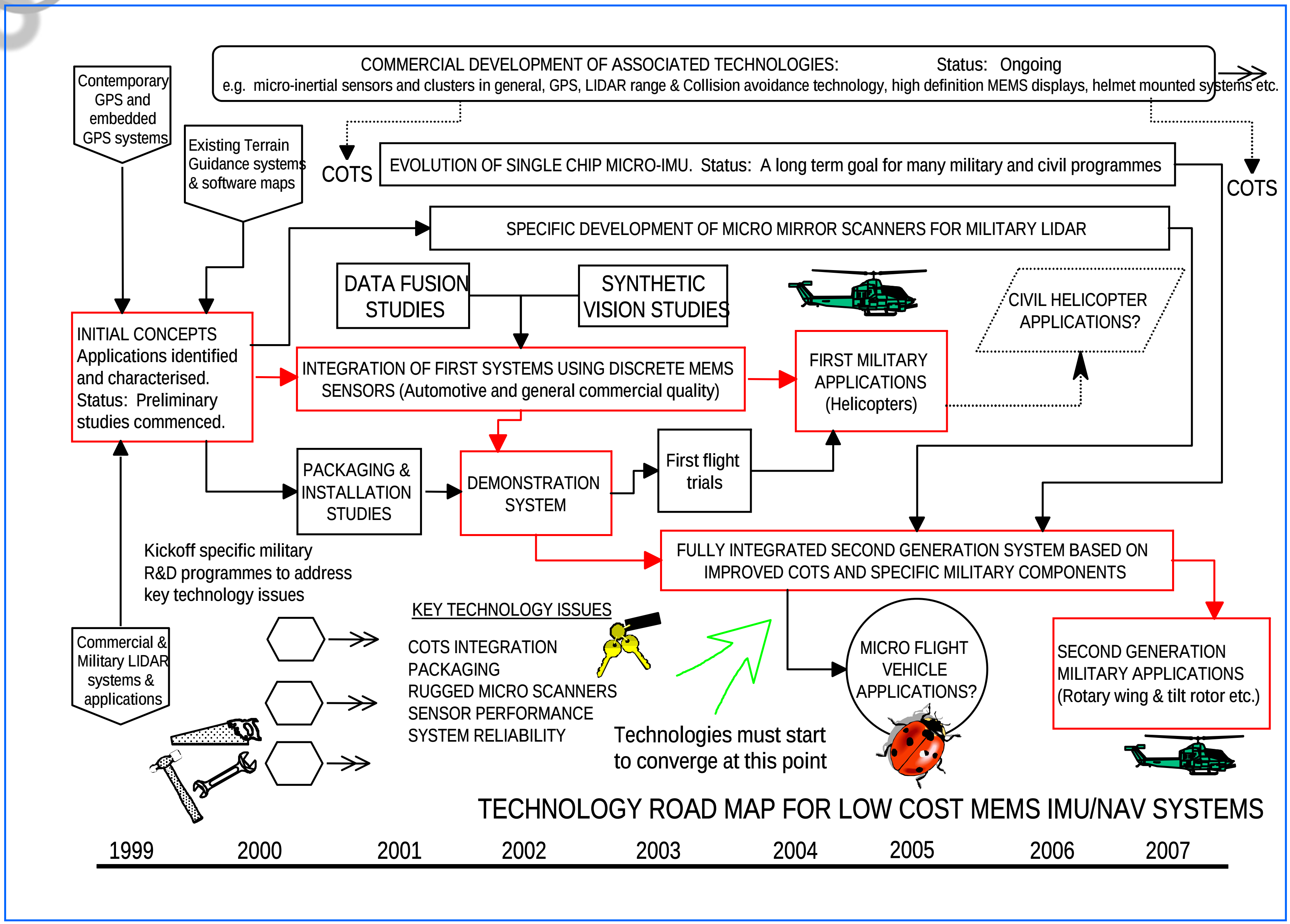
The Crossbow Solid State Gyro, known as an Attitude-Heading Reference System, or AHRS, uses 3-axis accelerometer and a 3-axis rate sensor to make a complete measurement of the dynamics of a system. The addition of a 3-axis magnetometer inside the Crossbow AHRS allows it to make a true measurement of magnetic heading without an external flux valve. The Crossbow AHRS is a solid-state equivalent of a vertical gyro/artificial horizon display combined with a directional gyro and flux valve.

BAE SYSTEMS

BEI Systron Donner's Digital Quartz IMUs

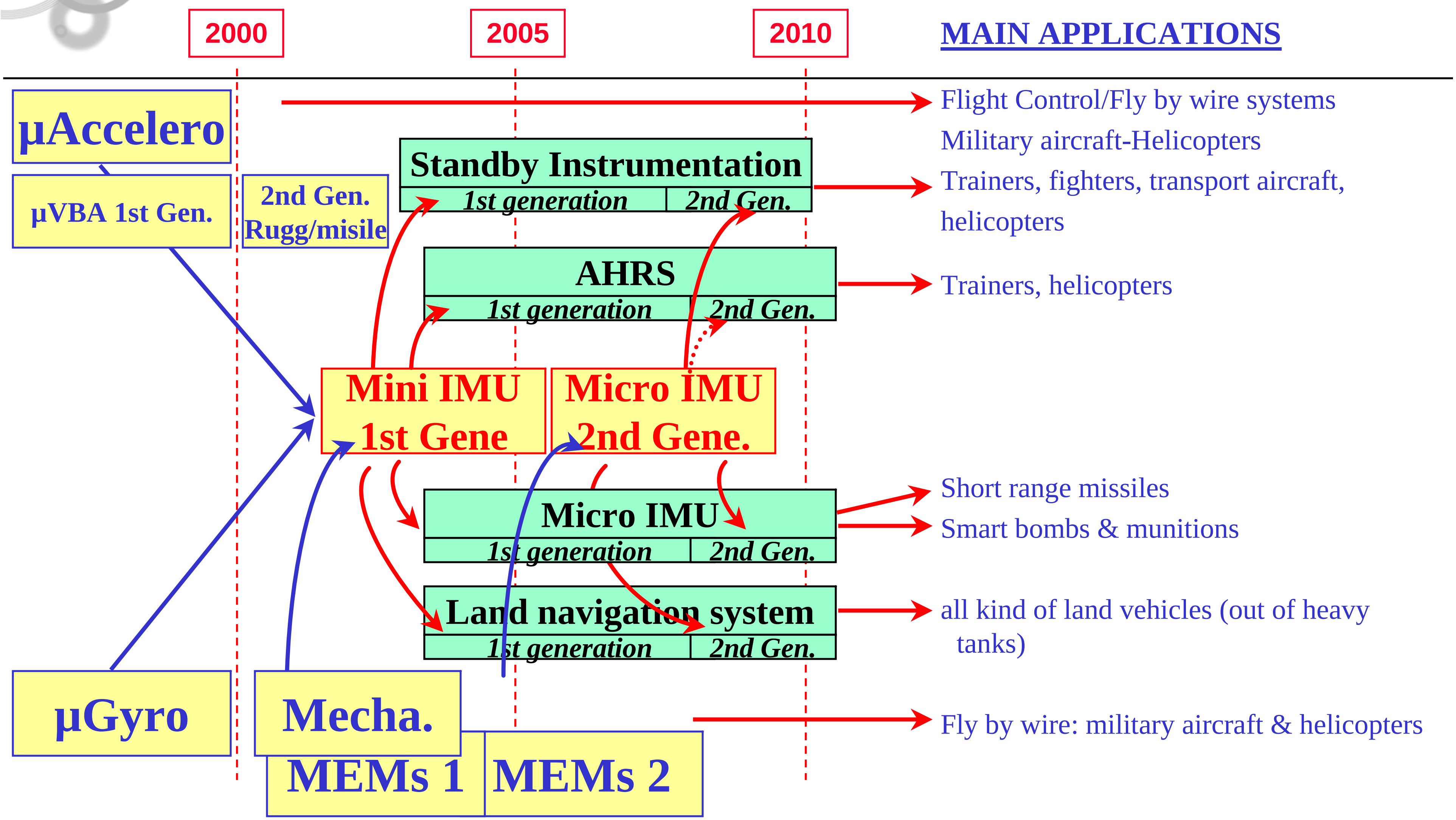
- *Tactical missiles*
- *Precision guided munitions*
- *Unmanned vehicles*
- *Land vehicles*
- *Avionic systems*
- *Range instrumentation systems*

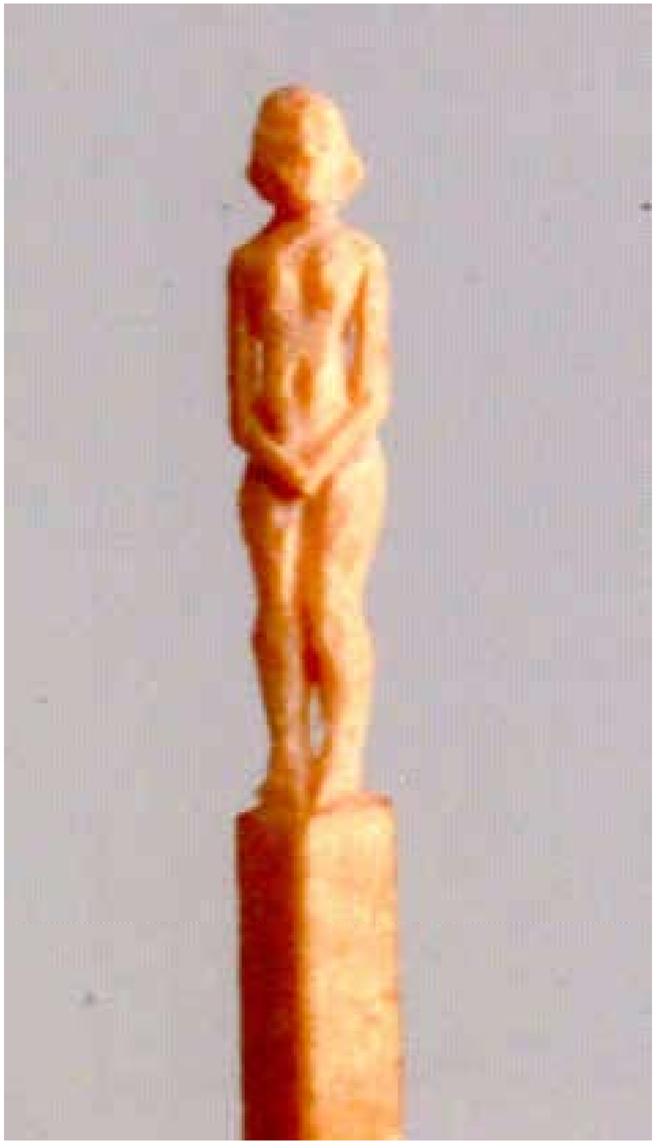



COMMERCIAL DEVELOPMENT OF ASSOCIATED TECHNOLOGIES: Status: Ongoing
e.g. micro-inertial sensors and clusters in general, GPS, LIDAR range & Collision avoidance technology, high definition MEMS displays, helmet mounted systems etc.
Contemporary GPS and embedded GPS systems
Existing Terrain Guidance systems & software maps
COTS
EVOLUTION OF SINGLE CHIP MICRO-IMU. Status: A long term goal for many military and civil programmes
COTS
SPECIFIC DEVELOPMENT OF MICRO MIRROR SCANNERS FOR MILITARY LIDAR
DATA FUSION STUDIES
SYNTHETIC VISION STUDIES
CIVIL HELICOPTER APPLICATIONS?
INITIAL CONCEPTS Applications identified and characterised. Status: Preliminary studies commenced.
INTEGRATION OF FIRST SYSTEMS USING DISCRETE MEMS SENSORS (Automotive and general commercial quality)
FIRST MILITARY APPLICATIONS (Helicopters)
PACKAGING & INSTALLATION STUDIES
DEMONSTRATION SYSTEM
First flight trials
Kickoff specific military R&D programmes to address key technology issues
FULLY INTEGRATED SECOND GENERATION SYSTEM BASED ON IMPROVED COTS AND SPECIFIC MILITARY COMPONENTS
Commercial & Military LIDAR systems & applications
KEY TECHNOLOGY ISSUES
COTS INTEGRATION
PACKAGING
RUGGED MICRO SCANNERS
SENSOR PERFORMANCE
SYSTEM RELIABILITY
Technologies must start to converge at this point
MICRO FLIGHT VEHICLE APPLICATIONS?
SECOND GENERATION MILITARY APPLICATIONS (Rotary wing & tilt rotor etc.)
TECHNOLOGY ROAD MAP FOR LOW COST MEMS IMU/NAV SYSTEMS
1999
2000
2001
2002
2003
2004
2005
2006
2007

IMUs development/applications

BAE SYSTEMS





Sculpting a match-stick

Thank You

Ayman El-Fatatry