NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

AC/323(AVT-105)TP/79

www.rta.nato.int

RTO EDUCATIONAL NOTES **EN-AVT-105**

MEMS Aerospace Applications

(Les applications aérospatiales des MEMS)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Applied Vehicle Technology Panel (AVT) on 3-4 October 2002 in Montreal, Canada; on 24-25 February 2003 in Ankara, Turkey; on 27-28 February 2003 in VKI Brussels, Belgium; and on 3-4 March 2003 in Monterey, California, USA.

Published February 2004

Distribution and Availability on Back Cover

NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

AC/323(AVT-105)TP/79

www.rta.nato.int

RTO EDUCATIONAL NOTES **EN-AVT-105**

MEMS Aerospace Applications

(Les applications aérospatiales des MEMS)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Applied Vehicle Technology Panel (AVT) on 3-4 October 2002 in Montreal, Canada; on 24-25 February 2003 in Ankara, Turkey; on 27-28 February 2003 in VKI Brussels, Belgium; and on 3-4 March 2003 in Monterey, California, USA.

The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

The content of this publication has been reproduced
directly from material supplied by RTO or the authors.

Published February 2004

ISBN 92-837-1113-0

MEMS Aerospace Applications

(RTO-EN-AVT-105)

Executive Summary

Micro-Electro-Mechanical-Systems (MEMS) are miniature devices, which integrate actuators, sensors, and a processor (controller) to form intelligent systems. They are characterized by their close relationship to integrated-circuit components both in terms of manufacturing techniques and their potential for integrations with electronics. After its emergence in the late eighties, MEMS has developed into billion $ commercial markets, in particular in the automotive, medical, and telecommunication fields. The Lecture Series will address applications in the aerospace field, which encounter unique challenges related to harsh environment conditions and reliability requirements.

After an introduction into MEMS technology, six aerospace applications are described, where MEMS will enable the development of potentially new capabilities. They will allow introduction of low-cost, high-end functionality and thereby will enhance performance and extend lifetimes. For these applications, the status, R&D needs, barriers of implementation, and insertion strategies will be discussed.

Aerospace applications include (1) active control of thin boundary layer flows with the potential to eliminate conventional flight control surfaces, reduce drag, provide lift-on-demand, and enhance aerodynamic performance of compressors, turbines and low-observable intakes, (2) complete inertial and navigation units on a single chip which offer major advantages in terms of size, weight and cost over conventional systems, (3) fuzing/safety & arming systems for torpedo applications, (4) micro power generation using micro fuel cells and micro engines for potential standalone sensors and actuators with wireless communication, and micro rockets, (5) applications in harsh environments (e.g., high temperatures, large number of vibrational cycles, erosive flows, and corrosive media), and (6) applications for autonomous inventory & storage environments monitoring and for service life predictions. Following on from these MEMS applications, Micro-Optic-Electro-Mechanical-Systems (MOEMS) are described in the context of optical communication & sensing systems.

Les applications aérospatiales des MEMS

(RTO-EN-AVT-105)

Synthèse

Les MEMS sont des dispositifs miniaturisés intégrant des actionneurs, des capteurs et un processeur (dispositif de commande) et constituant des systèmes intelligents. Ils sont caractérisés par leur parenté avec les composants des circuits intégrés tant du point de vue de leurs techniques de fabrication que par leurs possibilités d'intégration dans l'électronique. Suite à son émergence à la fin des années '80, le MEMS a trouvé sa place sur des marchés commerciaux estimés à des milliards de dollars, en particulier dans les domaines de la médecine, de l'automobile et des télécommunications. Ce cycle de conférences examinera les applications dans le domaine aérospatial, qui doivent répondre à des conditions d'environnement et à des spécifications de fiabilité difficiles.

Suite à une introduction aux technologies du MEMS, six applications sont décrites où le MEMS permettrait de développer de nouvelles capacités. Elles promettent des fonctionnalités haut de gamme à coût modique qui permettront d'améliorer les performances et augmenter la durée de vie du matériel militaire. L'état d'avancement, les besoins en R&D, les obstacles à la mise en œuvre et les stratégies d'insertion de ces applications seront discutés.

Les applications aérospatiales comprennent (1) le contrôle actif des écoulements de couches limites minces pouvant éliminer les gouvernes classiques, réduire la traînée, fournir la sustentation à la demande et améliorer les performances aérodynamiques des compresseurs, turbines et prises d'air « indétectables », (2) des centrales inertielles et de navigation sur une seule puce qui offrent des avantages majeurs d'encombrement, de masse et de coût par rapport aux systèmes classiques, (3) des systèmes d'allumage/sécurité et mécanismes d'armement pour des applications torpilles, (4) la micro-production d'énergie à l'aide de micro-piles à combustible, et des micro-moteurs pour des capteurs et actionneurs autonomes avec communication sans fil et micro-fusées, (5) des applications pour environnements difficiles (par exemple, les hautes températures, les cycles vibratoires élevés, les écoulements érosifs et les milieu corrosifs) et (6) des applications pour le contrôle autonome d'environnements d'inventaire et de stockage, ainsi que pour la prévision de la durée de vie utile. Suite à ces présentations sur le MEMS, le systèmes micro-optico-électro-mécaniques (MOEMS) sont décrits dans le contexte de systèmes de communication et de détection.

Table of Contents

List of Authors/Lecturers

Lecture Series Director

Dr. Klaus C. SCHADOW
Consultant
2896 Calle Heraldo
San Clemente, CA 92673
UNITED STATES OF AMERICA

Lecture Series Authors/Lecturers

Dr Ayman EL-FATATRY
Head, Systems Department
BAE SYSTEMS Advanced Technology Centre
West Hanningfield Road
Great Baddow, Chelmsford
Essex CM2 8HN
UNITED KINGDOM

Professor Mehran MEHREGANY
Case Western Reserve University
10900 Euclid Avenue
Cleveland, Ohio 44106
UNITED STATES OF AMERICA

Dr. Clyde WARSOP
Senior Principal Scientist
Mathematrical Modelling Department
BAE SYSTEMS
Advanced Technology Centre
Sowerby Building, FPC 267, PO Box 5
Filton, Bristol, BS34 7QW
UNITED KINGDOM

Mr. Paul SMITH
Indian Head Division Naval Surface
Warfare Centre
Weapons Dept
101 Strauss Avenue
Indian Head, MD 20640-5035
UNITED STATES OF AMERICA

Introduction

Klaus C. Schadow
Consultant
Strategic Analysis, Inc.
2896 Calle Heraldo
San Clemente, CA 92673
UNITED STATES

TEL: 1 949 498 2308

E-MAIL: schadowkc@cox.net

After its emergence in the late eighties, MEMS (Micro-Electro-Mechanical-Systems) or MST (Microsystems Technology) has developed into billion $ commercial markets, in particular in the automotive, medical, and telecommunication fields. The Lecture Series will address applications in the aerospace field, which encounter unique challenges related to harsh environment conditions and reliability requirements. This Introduction will provide a brief introduction into the MEMS technology, discuss examples of commercial and potential aerospace applications, and introduce the lectures, which will focus on six specific aerospace applications.

MEMS are miniature devices, which integrate actuators, sensors, and processors to form intelligent systems. Functional sub-systems could be electronic, optical, mechanical, thermal or fluidic. MEMS are characterized by their close relationship to integrated-circuit components both in terms of manufacturing techniques and their potential for integration with electronics. One example of a true MEMS system, which will be discussed, is the "Smart Micro Skin" which combines sensors, actuators, and controller to detect and control flow separation at the leading edge of a delta wing.

Several manufacturing techniques are required to develop MEMS, including surface micromachining. In this process mechanical microstructures are fabricated on the surface of a wafer by depositing different types of layers. Deposited layers include structural layers, which form the final structures, and sacrificial layers, which are removed in the final stage of the fabrication through the edging process.

The advantages of MEMS are numerous. They include miniaturization (allowing distributed sensing and actuation coupled with redundancy), reduced cost of fabrication (through the use of microelectronics processing technologies), and real-time control (allowing on-line active process control and health monitoring). In addition, micro devices can control macro systems by using natural physical amplification characteristics of the system. For example, the control of flow separation at the leading edge of delta wings by micro actuators allows the control of the leading-edge-vortex position, which determines lift and moments.

Examples for MEMS commercial applications, which will be discussed, include digital micro mirrors for projectors and micro total analytical systems.

Many MEMS aerospace and military applications are being considered. Examples are micro jet arrays for flow control, IMUs (Inertial Measurement Units) for inertial measurement and navigation, fuze/safety and

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.

arming for munitions, health monitoring of machinery, and telecommunication for pico satellites. The MEMS aerospace applications are confronted with barriers and challenges, which are more severe than for commercial applications. This resulted in slow progress of inserting many of the potential MEMS aerospace applications.

Military MEMS applications are being addressed in the NATO RTO (Research and Technology Organization) MEMS Task Group AVT (Applied Vehicle Technology) –078. This Group is assessing potential applications, determining technology status and R&D needs, discussing barriers for implementation, and developing insertions strategies. The Task Group saw the need to enhance user and MEMS supplier interactions and to increase MEMS awareness as enabling technology for several applications. Because of this need, the Task Group has proposed these Lecture Series, which will provide an introduction into MEMS technology and then focus on six potential applications, namely micro-flow control, IMU, fuze/safety & arming, micro power, gas turbines applications, inventory and health monitoring of munitions. Also an introduction into MOEMS (Micro-Optical-Electro-Mechanical-Systems) will be provided.

Introduction to Microelectromechanical Systems

Mehran Mehregany
Department of Electrical Engineering and Computer Science
Case Western Reserve University
Cleveland, Ohio 44106
USA

Tel: 216 368 0755

E-mail: mxm31@cwru.edu

ABSTRACT

Microelectromechanical systems (MEMS) enable the development of smart products and systems by augmenting the computational ability of microelectronics with the perception and control capabilities of microsensors and microactuators. The sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and/or magnetic phenomena. The electronics process this sensor information and direct the actuators to respond by moving, positioning, regulating, pumping, and/or filtering, thereby controlling the environment for a desired purpose. MEMS devices are emerging as product performance differentiators in both commercial and defense markets such as automotive, aerospace, medical, industrial process control, electronic instrumentation, office equipment, appliances, telecommunications, and optical systems.

An introduction to the technology will be presented, including description of concepts, terminology, potential impact, and the multidisciplinary nature of the field. The lecture will also incorporate an overview of the technology in the form of example devices and applications. Anisotropic etching of silicon and etch stop techniques, as well as wafer bonding will be introduced. Surface micromachining with emphasis on polysilicon processes, as well as photoresist processes coupled with metal plating will be scanned. Mentions of MEMS design, modeling, material science, testing, reliability, and packaging will be made in the context of the examples included in the lecture.

BIOGRAPHY

Mehran Mehregany received his B.S. in Electrical Engineering from the University of Missouri in 1984, and his M.S. and Ph.D. in Electrical Engineering from Massachusetts Institute of Technology in 1986 and 1990, respectively. From 1986 to 1990, he was a consultant to the Robotic Systems Research Department at AT&T Bell Laboratories, where he was a key contributor to ground-breaking research in microelectromechanical systems (MEMS). In 1990, he joined the Department of Electrical Engineering and Applied Physics at Case Western Reserve University as an Assistant Professor. He was awarded the Nord Assistant Professorship in 1991, was promoted to Associate Professor with tenure in July 1994, and was promoted to Full Professor in July 1997. He held the George S. Dively Professor of Engineering Endowed Chair from January 1998 until July 2000, when he was appointed the BFGoodrich Professor of Engineering Innovation. He served as the Director of the MEMS Research Center at CWRU from July 1995 until July 2000. Professor Mehregany is

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.

well known for his research in the area of MEMS, and his work has been widely covered by domestic and foreign media. He has over 200 publications describing his work, holds 12 U.S. patents, and is the recipient of a number of awards/honors. He served as the Editor-in-Chief of the Journal of Micromechanics and Microengineering from January 1996 to December 1997, and is Assistant-to-the-President of the Transducers Research Foundation. His research interests include silicon and silicon carbide MEMS, micromachining and microfabrication technologies, materials and modeling issues related to MEMS and IC technologies, and MEMS packaging.

Mehran Mehregany is the Founder and served as the President (July 1993 to March 1999) of Advanced Micromachines Incorporated (Cleveland, Ohio), a company in the MEMS area. Advanced Micromachines Incorporated was acquired by The BFGoodrich Corporation in March 1999. He founded NineSigma, Inc., an information technology company, in February 2000 and served as its CEO (June 2000 to January 2001) and CTO (January 2001 to August 2001), during which period he successfully completed initial rounds of private financing and grew the company to 15 employees. He co-founded FiberLead, Inc., an optical telecommunications company, in September 2000 and served as its CEO until September 2001, during which period he successfully completed the early stage round of venture capital financing and grew the company to 5 employees.

Active Flow Control Using MEMS

Clyde Warsop
BAE SYSTEMS Advanced Technology Centre
Sowerby Building, PO Box 5
Filton, Bristol, BS34 7QW
UK

Email: clyde.warsop@baesystems.com

SUMMARY

This lecture presents an overview of the potential for the application of MEMS for the active control of fluid flows. In addition to providing a general overview of the underlying fluid mechanics and status of current research the relevance of this technology application to future military vehicle technologies is highlighted. The lecture identifies the potential benefits of the use of MEMS for controlling flow separation and reducing drag on a range of air vehicles and their propulsion systems. Because of the overview nature of this lecture the material presented has been extracted from a wide range of public domain sources both in the USA and Europe. Where, possible such material has been attributed to its originator. Apologies are made in circumstances where attributions have not been made.

1.0 INTRODUCTION

The performance, observability and affordability of most military vehicles are influenced by fluid physics either directly by their interaction with the surrounding air/water or indirectly through the many fluidic based systems they incorporate. The ability to manipulate a fluid flow to improve efficiency or performance is of immense technological importance and is currently one of the most high profile topics in fluid dynamics. The potential benefits of flow control include improved performance and manoeuvrability, affordability, increased range and payload, and environmental compliance. The intent of flow control may be to delay/advance transition, to suppress/enhance turbulence, or to prevent/promote separation. The resulting benefits include drag reduction, lift enhancement, mixing augmentation, heat transfer enhancement, and the suppression of flow-induced noise.

The desire to minimise drag (both skin friction and pressure) and to control flow separation in order to improve the high lift and propulsive performance of a wide range of vehicles is providing a driver for increased research activity in this field. In most cases drag and flow separation is dominated by the thin layer of fluid (often just a few millimetres thick), known as the boundary layer, that forms at the interface between the vehicle's components and the surrounding fluid. Over the last 20 years or so our knowledge about the evolution and propagation of boundary layers has increased significantly. This has been made possible through the advent of new experimental techniques and the development and use of computation tools such as Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS). Developments of new manufacturing technologies such as Microfabricated Electro-Mechanical Systems (MEMS) and solid state actuator technologies such as piezo-electric materials and shape-memory alloys has also led to the possibility for active flow control to be realised at both a macro and micro scale.

MEMS technology offers the potential for the large-scale active control of coherent flow structures within the boundary layer. This could lead to the reduction of skin friction drag or the postponement of flow separation through the use of 'smart skins' capable of detecting and reacting to the state of the local boundary layer.

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.

Despite over a century of intensive research, turbulence remains largely an enigma that is analytically unapproachable yet practically very important. The mysteries of turbulence are only now being solved by the use of physical and numerical experiments, which is a far-from-trivial task at the high Reynolds numbers of practical interest to the aerospace engineer. Controlling a practical turbulent flow to achieve a desired effect such as drag reduction, lift enhancement or noise reduction is a very difficult task. Passive control methods, while always preferable, are generally limited in their utility. Brute force suppression, or taming, of turbulence via active, energy consuming control devices is always possible, but the penalty for doing so often exceeds any potential savings. The challenge is to actively achieve a desired effect with a minimum of energy expenditure by utilising the natural instabilities within the fluid structures to amplify control inputs.

2.0 THE NATURE OF TURBULENCE

Shear flow turbulence is dominated by a quasi-periodic sequence of large-scale structures often referred to as *turbulent coherent structures.* Coherent structures are not only quasi-periodic, but are different in size and shape depending on the location of these structures within the flow. Furthermore, the coherent structures are born, grow and die within the boundary layer, evolving in both space and time. The precise dynamics involved in the turbulence activities are far from clear. Qualitatively, according to the generally accepted school of thought, the process starts with pairs of elongated, counter rotating, stream-wise vortices buried within the near-wall sub-layer region. These vortices are often referred to as 'hairpin' vortices and arise in the first instance during the latter, non-linear stages of transition from laminar to turbulent flow. These hairpin vortices exist within a strong shear layer and induce low and high-speed regions between them. The low speed regions, close to the wall, termed *streaks*, grow downstream and develop inflectional velocity profiles. At the same time, the interface between the low and high-speed fluid begins to oscillate, signalling the onset of a secondary instability. The low speed region lifts up away from the wall as the oscillation amplitude increases and the flow rapidly breaks down (*bursts*) into a completely chaotic motion. In the sequence of turbulent activities within the boundary layer, there are two important events for energy production, called *sweeps* (or inrushes) and ejections (*bursts*). Over 80% of the turbulent kinetic energy production occurs during these events. The process described above is self- regenerating resulting in the continuous cyclic propagation of near near-wall hairpin vortices, streaks and bursts. There is still much speculation concerning the relationship between the stream-wise vortices and the streaks and significant further research in this field is required.

Large peaks in turbulent wall-shear stress are produced between a pair of counter-rotating longitudinal vortices as the high momentum fluid is brought down towards the wall during the near-wall burst events. These shear stress peaks give rise to the large increases in skin friction drag associated with a turbulent boundary layer compared to one that is laminar (typically an order of magnitude greater). Most of the activity in turbulent drag-reduction and separation control, both passive and active, relies on the manipulation by suppression, enhancement or modification of coherent turbulence structures.

3.0 ACTIVE FLOW CONTROL USING MEMS

At the present time MEMS and turbulence control are seen as the "Holy Grail" of fluid mechanics. One potential application for MEMS technology is the control of fluid flows through the active manipulation of the coherent structures that develop in a boundary layer.

Various methods of flow control have been implemented in practical engineering situations using conventional technologies (suction, tangential blowing, riblets, and vortex generators). However, all of the technologies applied can be considered as either passive or at most open-loop control by the addition of energy. Not all of these technologies are entirely effective at the efficient control of either free-shear layer or turbulent wall bounded flows. There have also been severe limitations as to the efficiency of conventional flow control technologies. For example, in attempting to reduce skin friction drag by suction (hybrid laminar flow) the penalties (weight, energy expenditure, and cost) associated with the control technology often exceed the benefits derived from its use. A way is needed to reduce the penalties and increase the benefits in order to achieve a more efficient control strategy.

Flow control is most efficient when applied at a region of the flow where susceptibility is high. i.e. in the critical regimes of the flow where flow instabilities magnify rapidly. The regions of boundary layer transition and flow separation are such areas. Therefore the delay/advancement of laminar to turbulent transition and the prevention/suppression of flow separation are relatively easy tasks to achieve. The reduction of skin friction in a stable, non-separating turbulent boundary layer is a much more difficult task. New ideas for turbulent flow control are based on the manipulation of the coherent structures that develop close to the wall. On practical engineering products such as the wings of aircraft and in the nacelles and components of their engines these flow structures occur at scales of tens to hundreds of microns. Technologies such as riblets can affect the near-wall turbulence generation process to achieve skin friction drag reductions of the order of 8 to 12%. However, newer ideas for turbulent flow control employing active MEMS scale technologies, giving potential reductions in skin friction drag of 50% or more have been spurred on by recent developments in the understanding of boundary layer physics, chaos control and fabrication technologies. Futuristic concepts are envisioned where large arrays of inexpensive, intelligent, interactive flow sensors and actuators are built into aerodynamic surfaces to interact with the organised flow structures that occur randomly in the boundary layer to achieve efficient control of the flow.

Research into the application of MEMS for flow control has been ongoing in the USA for a number of years. Significant activity exists at a number of US universities where financial support from the Government via the AFOSR and DARPA among others, is being directed. Recent experiments and simulations in the USA have demonstrated the fundamental feasibility of active boundary layer control. Europe is also involved in a number of activities to study the potential of MEMS for active flow control. These activities involve both academic and industrial organisations. Most European research activities revolve around the promotion or delay of flow separation since this is perceived as being realisable within a much nearer timeframe than turbulent drag reduction. In addition to the issues of the fabrication and application of sensor and actuator technologies studies are also ongoing to develop optimum control strategies and to develop design and analysis tools.

4.0 CONCLUDING REMARKS

Although there are important activities going on to investigate the application of new technologies such as MEMS for active flow control it is unlikely that any will be mature for application, other than as a component of very simple systems, within the next decade or two.

Whether or not any of the flow control technologies will see a widespread application on a production aircraft in the future depends on two important factors:

- Does it work?
- Does it make practical economic sense?

The first question is probably the easiest criteria to address. In the first instance any new technology has to be demonstrated experimentally at large scale under relevant Reynolds and Mach numbers. It must then be proven to operate in the presence of real world conditions and shown to enhance or improve a valuable performance metric. Any system must be demonstrated to be manufacturable, robust, reliable, maintainable and inspectable. Any performance side effects must be acceptable.

The second criterion is more difficult to assess and the answer may change with evolving worldwide economic market and political conditions. To be viable any flow control application must have a favourable overall cost/benefit. The initial design/integration cost combined with the cost of energy expenditure during operation must be outweighed by any benefits obtained. Issues related to the legal/regulatory standpoints of product liability, safety, and environmental/acoustic pollution also need to be resolved.

Although many flow control technologies have been identified and researched at the basic level for many decades few have ever reached maturity and full-scale deployment on a commercial product. It could be argued that the basic research community is not sufficiently aware of the practical issues of implementation and that in some cases non-application useful research is carried out while in other areas the research is not carried far enough to allow technological evaluation. With the limited research investment available it is becoming essential that the research community work more closely with the application community to develop practical technologies in the most efficient manner. This requires all involved to work in a multidisciplinary environment to develop the basic tools and understanding and then to progress this towards large-scale demonstration and evaluation. It is important that unworkable concepts are filtered at the earliest possible opportunity in order to avoid unnecessary effort being directed at hopeless causes. Early in the assessment process it is essential that industrial studies be made to identify the potential benefits and practical implications of any new flow control technology. In order to do this industry requires robust, rapid tools with which to undertake aerodynamic analysis.

Turbulent flow control should not just be considered as a fix to solve a problem or a means of improving even further the performance of an already optimised design. Consideration should be given to employing turbulent flow control early in the design optimisation process. A commercially better design may be obtained by the use of flow control to recoup performance losses associated with simplifying other aspects of the design to reduce manufacturing costs, system complexity or structural weight (e.g., reduced sweep, thicker wings, smaller, simpler high lift systems).

MEMS Based Fuzing/Safety and Arming Systems

Paul J. Smith
Weapons Department
Indian Head Division
Naval Surface Warfare Center
Indian Head, Maryland 20640
USA

MicroElectroMechanical Systems or MEMS is a fabrication technology for creating mechanical devices on micron scale ($1x10^{-6}$ meters). But MEMS is more than miniaturization. By combining, photolithography, deposition, patterning and etching a fabrication technology has resulted for the production full-assembled, integrated electromechanical systems on a scale once reserved for electronic integrated circuits (IC). As the first M of MEMS implies, individual features are on the micron scale that is 10^{-6} meters but the resulting systems can be several millimeters in size.

Since MEMS has its roots in the IC industry, let's briefly examine the IC history. In the last half century the cost of logic 'NAND' gate has fallen by five orders of magnitude. This is a result of changes in manufacturing technology from hand-assembled vacuum tube gates to mass produced Very Large Scale Integration (VLSI) devices. In the last quarter century, the number of transistor/inch has doubled every 2.5 years. Recently, Intel has announced that the number of transistors on a chip will exceed 1 billion by the year 2010. While size and cost has decreased the performance has increased as indicated by the initial microprocessor clock rate of 4.7 Mega Hertz in 1980's to in excess of 2.0 Gig Hertz for today's units. These changes are a result of modern photolithography/batch fabrication techniques. Where as IC industry deposited/doped P and N materials, MEMS deposits and etches to creates mechanical structures.

MEMS and modern IC industry are based on a process of deposition-patterning- removal techniques. The process centers around deposition of material on a silicon wafer, patterning via a mask, and removal of un-patterned material. The basic process is repeated dozen of times with many variations. For example, a variety of material can be deposited (polycrystalline silicon, nitride, PMMA, photo resists, metals, etc), via photolithography using a mask and energy source (light, x-rays) either the exposed or the unexposed material can be altered and removed (chemically, ion etched, laser ablated) or silicon wafer can be replaced with silicon carbide wafer for higher temperature performance. Fabrication (Fig. 1) can be divided into three basic methods: Bulk Micro Machining, Surface Micro Machining, and LIGA. In bulk micro machining, part of the silicon wafer is removed by chemical etching or reactive ion etching. This method allows fabrication of diaphragms, cavities and thick structures (400 um). In Surface Micro machining, material are deposited on top of the silicon wafer. Structures may be anchored to the wafer, free floating or partially tethered to the silicon wafer. Structures are thin (<15 um) and are generally polycrystalline silicon, nitride, and metals. The third fabrication method (LIGA) begins with the deposition of layer of PMMA (plastic) on the silicon wafer. The PMMA serves as a mold for metal and plastic parts. It offers the advantage on tall structures as compared to surface micro machining. Thus, the design engineers have a variety of materials and dimensions available for designs.

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.

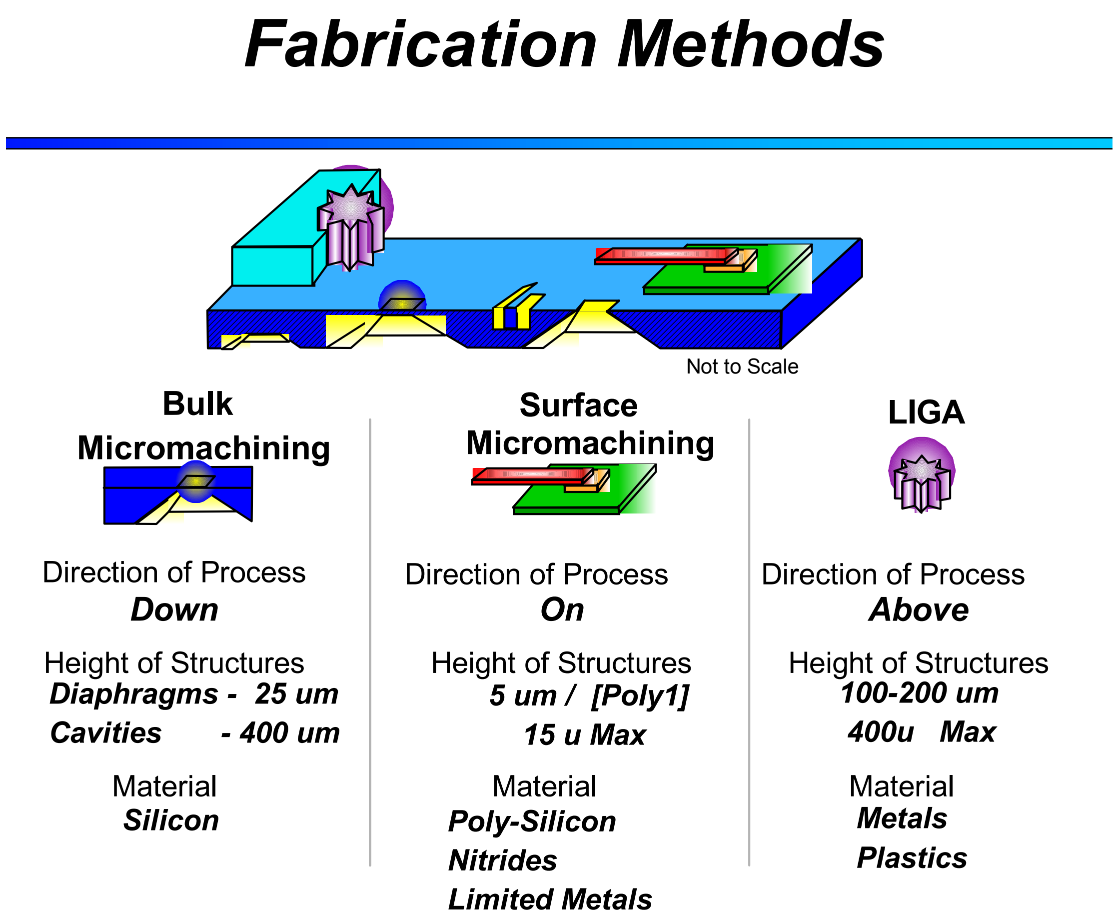


Figure 1.

The “S” of MEMS stands for System. A MEMS system has the ability to sense, process the data, and act. The last part developed was the actuator or device capable of producing movement. In 1991, Analog Device Inc (ADI) marketed the first full MEMS systems with the introduction of the air bag accelerometer for automobiles (Fig. 2). It has a proof mass to sense acceleration, capacitive fingers to sense its movement. The capacitor is an element in a tuned circuit oscillator. Frequency shifts are detected and produce a voltage proportional to the frequency shift, which is used to control a second set of inter-leaved fingers to apply a restoring force to the proof mass to return it to a neutral position. The restoring voltage is directly related to the acceleration (amplitude and frequency).

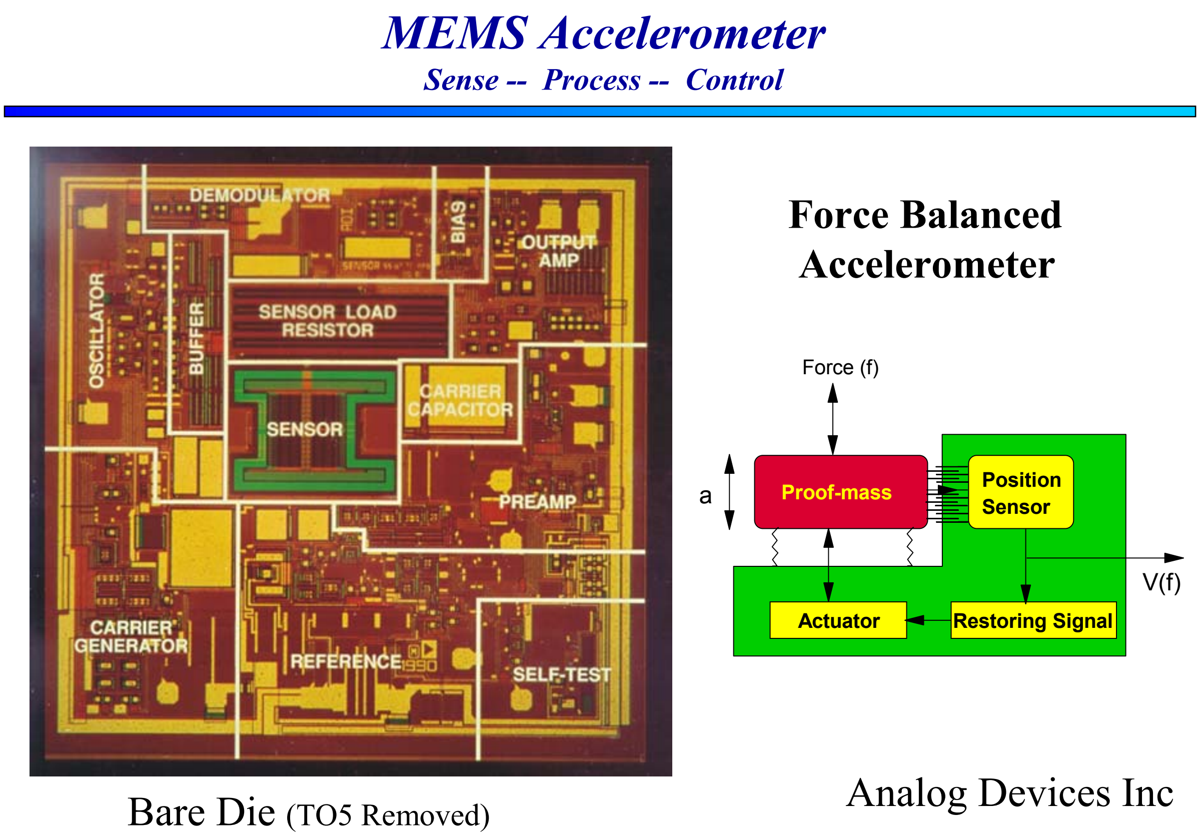


Figure 2.

MEMS is an ENABLING technology. It enables you to build systems on the micron scale. While individual features are on the micron scale the entire system can be several millimeters in dimension. It enables you to integrate mechanical and electrical systems. It enables batch fabrication of fully assembled systems. It enables systems that sense, process and control the environment. It is not a question of who will use MEMS but who uses MEMS. MEMS devices are currently used in automobile airbags, color inkjet printers, fuel injectors and automobile skid control system. MEMS will not only affect how things are made but what things are made. The technology will ultimately result in new medical devices for improved living and devices that improve automobile safety (air bags, skid control, etc.). MEMS also have the potential for improved safety devices containing energetic materials. In the first of two papers, I will discuss how energetic material are being integrated into a MEMS based Safety and Arming (S&A) system to create the next generation S&As.

A MEMS S&A has many advantages. First is the retention of classical mechanical lock for proven performance. MEMS offer a high level of integration between sensors and microprocessors. Improved environmental MEMS sensors (flow) means less reliance on pseudo environments (propeller turning counters). Due to reduce size and cost more sophisticated S&A can be applied to a larger variety of devices. As an emerging technology MEMS is an attractive choice to replace a declining S&A industrial base (bellows, miniature gear, etc.).

SAFETY & ARMING (S&A) SYSTEM

There are five basic requirements for an S&A system. First it must sense two independent post-launch environments to determine weapon launch. Secondly it must compute when safe separation between the weapon and launch platform has been achieved. It must "arm" the warhead when the first two requirements are met. It must provide a means to detonate the warhead at an appropriate time (fuzing). Finally it should provide a visual indication that the device is armed.

One of the engineering challenges of MEMS is using micro mechanisms to control macro events. How to scale up? We are using explosives to scale up. By using small amount of explosive (detonator) to ignite a larger quantity of explosive (booster) that in turn ignites a third charge (bulk charge) we can transition from the micron scale to the macro scale. A modified exploding foil initiation (EFI) (slapper) system has been designed. An EFI begins with a copper strip with a reduced cross section. Under the reduced cross section is an insulator over a barrel. Located at the end of the barrel is a secondary explosive. A large current is passed down the copper strip. At the reduced cross section the current density increase causing heat. The heat converts the copper to plasma. The plasma shears a pellet/flyer out of the insulator and launches down the barrel and into the explosive located at the other end. The flyer strikes the explosive with enough kinetic energy (1/2 mv^2) to create an explosion. Scientists and engineers at our facility have developed methods to mechanically open and close the barrel. Now that there is a mechanically moving structure it can be locked in a safe or armed position.

In our first generation S&A, three environmental sensors (a 'g' switch, a water pressure (hydrostat), a water flow sensor) were used (Figs. 3 & 4). The first sensor was a passive proof mass accelerometer that sensed launch acceleration and withdrew the locking pin from the slider/barrel. The hydrostat is a pressure sensor that directly moves a lever. A thin diaphragm was made in the silicon wafer by the bulk micro machining process. Using LIGA process a torsion beam was fabricated over the diaphragm. The movable end of the beam rested in a notch in the spring-loaded slider that formed the barrel of the EFI. When the underside of the silicon wafer was subjected to water pressure, the diaphragm would deflect upward pushing the beam upward and releasing the second lock. The third lock was a repackaged commercial differential pressure sensor. The two inputs were ported to the torpedo surface when a custom "Pitot tube" configuration was formed. Water flowing over the torpedo surface created a static and dynamic pressure where the difference was related to the speed via the shear profile function. Output of the sensor was connected to a thermal bent beam actuator. When heated by electric current the beam elongates, bends and releases the final lock. The devices and the spring-loaded barrel were fabricated on a single silicon chip. The chip when combined with high voltage initiation system, microprocessor, discrete logic and secondary explosive pellet formed the Safety and Arming system.

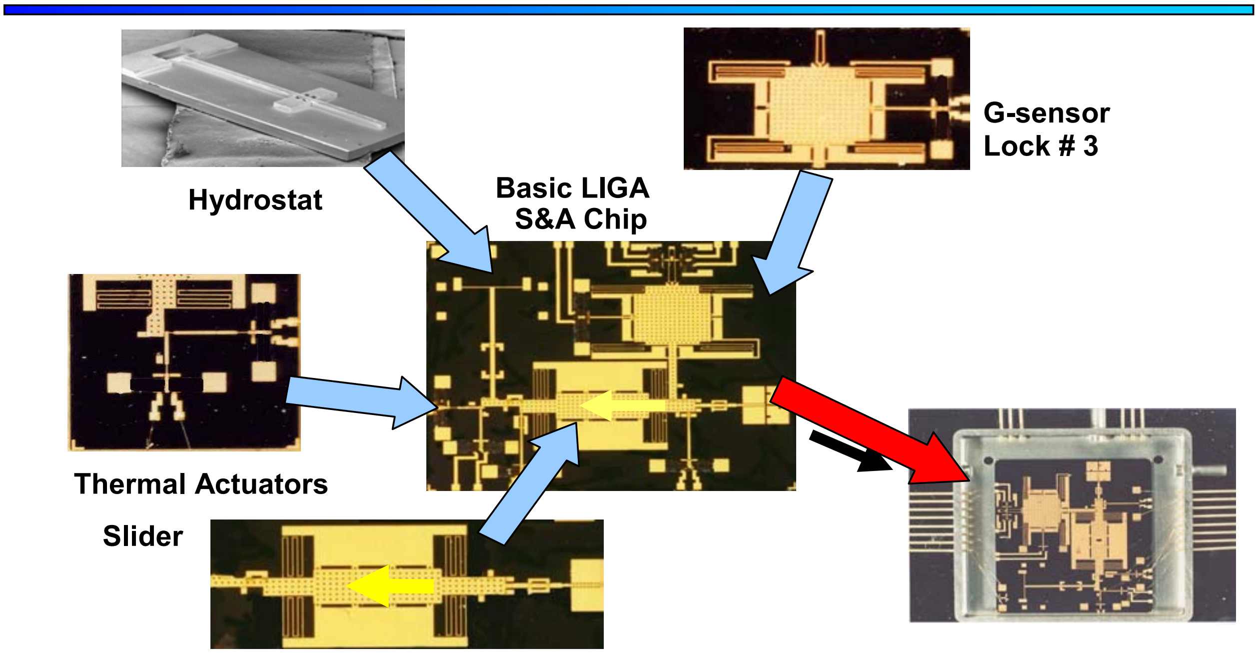


Figure 3.

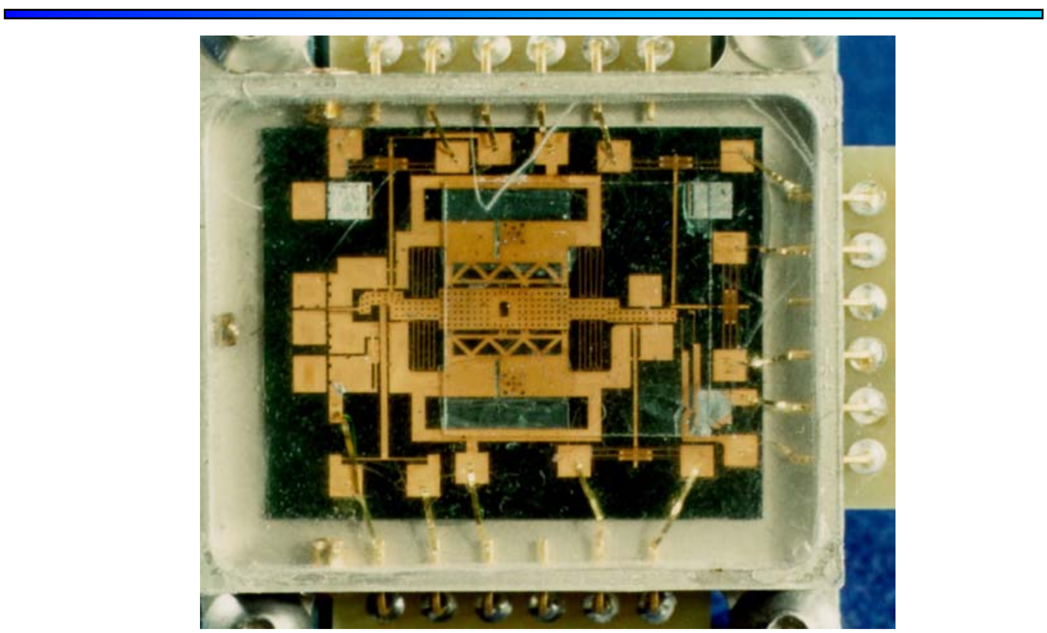


Figure 4.

After a series of laboratory screening test, two sea tests were conducted in summer of 2000. The device was subjected to a variety of real world environments such as transportation by truck over non-paved roads, shipboard handling, launch shock, and torpedo vibration. The device under test was inert but did contain a witness block to record functioning of the EFI. Following the sea test, explosive test were conducted to demonstrate the system ability to create a detonation if the barrel was aligned with the slapper and to demonstrate that no initiation occurred if the barrel was not aligned. The test clearly demonstrated the ability of MEMS based system to operate in real world environments and to perform arming operations for an EFI system.

The slider/barrel can be moved once the three locks are removed. The slider/barrel had to travel several hundred microns against a restoring spring force. An actuator that had both the force and the throw was not available. The task was accomplished by a series of small steps locking the slider/barrel between each movement, similar to pulling a rope by hand. When the locks are removed, the BRAKE is applied. The PULLING actuator is engaged to teeth on the slider via an ENGAGE actuator. The BRAKE is released and the pulling actuator moves the slider. The BRAKE is re-applied and the ENGAGE actuator releases the pulling arm. The arm spring back. The ENGAGE actuator re-engages the teeth on the pulling actuator to teeth on the slider and BRAKE is released, the sequence is repeated until the desired throw is accomplished.

As MEMS technology develops there continues to be many challenges for the designers. In order to accomplish the S&A goals we needed to design a chip that utilized all three-fabrication techniques. This challenge was met by working closely with fabrication foundries to develop a successful process flow. A second challenge is integrating explosives into the MEMS package. This required the design and construction of a clean room capable of meeting both clean room and explosive standards. For example the standard ESD polyester clean room gowns do not meet the conductivity or the fire retarding requirements for explosive handling. The explosive certified cotton gowns do not meet the low shedding requirement for clean room. Using technologies adapted from the space refueling and auto racing a Nomex suit/booties with conductive grid was designed to meet both sets of requirements. Current challenges are in the field of packaging where the device needs to be ported for input such as pressure, high voltage strip lines, fiber optics and explosive output but sealed to control humidity, organic out-gassing.

The next generation devices will make greater use of optical devices to transfer energy and shorten arming times. Ultimately there is a need to develop technology to allow energetic to be fully integrated onto the silicon wafer during fabrication as opposed to manual pellet insertion into bulk-etched cavities. When this challenge is met the S&A size and cost will be significantly reduced allowing wider use of the technology into device that currently do not have sophisticated S&A devices.

The Defense Advanced Research Projects Agency (DARPA) created the graphic shown in figure 5. It is a view of the future and where MEMS can take us. It is a plot of the number of transistor vs. the number of mechanical components or the ability to process data vs. the ability to move or control. Life up until now has been lived on the major axes. Computers are high on the vertical axis, while airplanes and cars are high on the horizontal axis. MEMS technology offers us a life in the first quadrant. The ability to sense, compute and act on an unimagined scale.

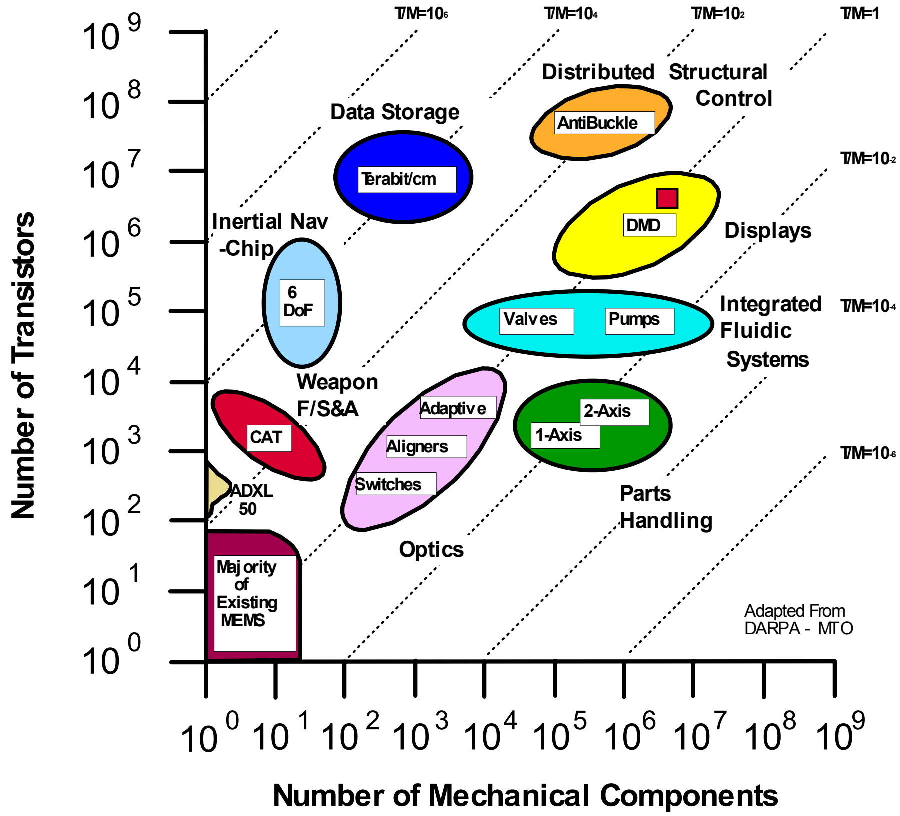


Figure 5.

Office of Naval Research
Code 333

Indian Head Division
Naval Surface Warfare Center
Code 40

Defense Advanced
Research Project Association
ETO

Inertial Measurement Units – *IMU*

Ayman El-Fatatry
BAE SYSTEMS – Advanced Technology Centre
West Hanningfield Road
Great Baddow, Chelmsford
Essex CM2 8HN
UNITED KINGDOM

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 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

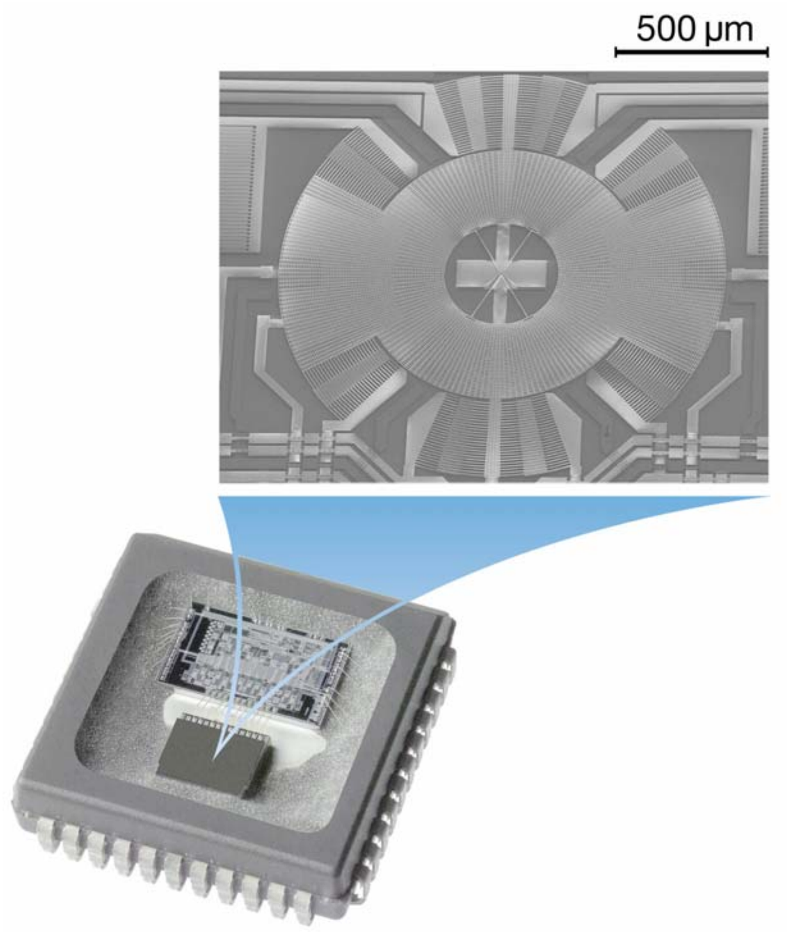
Gyroscopes

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:

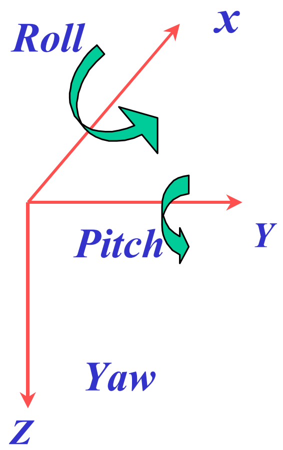
Europe: Bosch, BAE SYSTEMS

USA: Systron Donner

Japan: Denso, Sumitomo, Panasonic, Murata

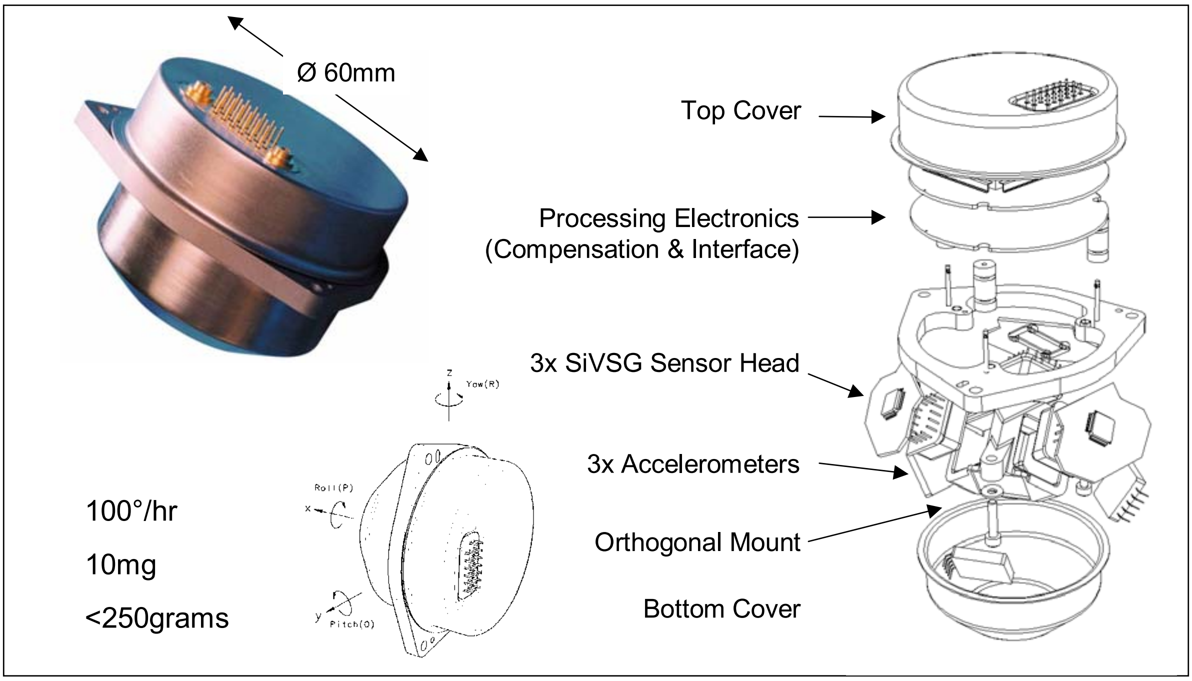
INTERTIAL MEASUREMENT UNITS

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.

Dr AYMAN EL FATATRY
PhD BSc CEng
Head
Systems Department

BAE SYSTEMS
Advanced Technology Centre
West Hanningfield Road
Great Baddow, Chelmsford, Essex CM2 8HN, Great Britain
Tel: +44-1245 242101, Fax: +44-1245 242124

e-mail: ayman.elfatatry@baesystems.com

Web Site: http://www.baesystems.com

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.

Micro Power

Klaus C. Schadow
Consultant
Strategic Analysis, Inc.
2896 Calle Heraldo
San Clemente, CA 92673
UNITED STATES
Tel: 1 949 498 2308
E-Mail: schadowkc@cox.net

This lecture discusses the Micro Power Generation Program (MPG) at DARPA and examples of micro rocket technology.

MICRO POWER GENERATION PROGRAM (MPG)

The goal of MPG, which was initiated by Dr. Bill Tang, is to generate power on the micro scale and to enable standalone sensors and actuators with wireless communication. Five DARPA projects will be reviewed, covering micro fuel cells and micro engine.

Prof. Savinell, Case Western Reserve University, is developing a micro hydrogen-air fuel cell with integrated fuel storage for autonomous operation, capable of delivering 10 mW continuous and 100 mW pulse power. The potential application is a wireless sensor with power, sensor, radio, and electronics in one package. Major tasks are to fabricate and test the fuel cell, develop novel polymer electrolytes with higher conductivity at low relative humidity, and investigate both on-board storage of hydrogen (using metal hydrides) and generation of hydrogen (from NaBH4). To date, an integrated device with on-board hydrogen supply based on NaBH4 has been tested with over 67% H2 utilization. A steady-state power output of 2 mW/cm2 and pulse power output of 10 mW/cm2 have been demonstrated. Future goals are to increase power output by improving porosity of substrate and enhance capability to manufacture higher voltage stacks.

Dr. Evans Jones, Battelle, is developing an integrated micro fuel processor and fuel cell. The fuel reformer coverts fuel and water into H2 and CO2 gas using mature catalyst technology and readily available fuels; the fuel cell converts H2 gas into H2O and electricity. Various fuels are being considered, which have the potential to exceed battery performance even at low conversion efficiency. A catalytic reformer system with 10 to 500 mW was fabricated and tested. The reactor volume was less than 5 mm2.

Prof. Fernandez-Pello, University of California, Berkeley, is a developing a MEMS rotary internal combustion engine for miniature-scale power generation using hydrocarbon fuels, which have a fuel specific energy significantly higher than the battery specific energy. Several research issues are being addressed to allow fabrication of micro engines, including combustion, fluid flow, fabrication, and materials. Steady combustion at the micro-scale below the quenching distance was demonstrated. Two generations of mini-engines with

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.

78 mm3 and 348 mm3 displacement were tested on a dynamometer, and a maximum power of 3.7 W at 9300 rpm was generated. These investigations provide the background for future development of micro engines.

Prof. Ho, UCLA, is developing a high electret generator energized by a MEMS based chemical-thermal reactor. The jet exhaust from a pulsed combustor of 35 mm length is driving a turbine of 20 mm diameter integrated with an electric generator. For the integration a CFDRC developed MEMS software simulation code is used. The pulsed reactor is a multiplayer silicon/ceramic structure.

MIT is developing MEMS heat engines with applications to micro gas turbines, micro rocket engines, and micro blowers. Enabling technologies include MEMS turbo-machinery, micro combustion dynamics, high temperature materials and packaging, gas bearings, and micro electromechanics. The operation of silicon turbine system with 21 mm diameter, 2 grams engine weight, and 1 million rpm has been demonstrated using hydrogen.

MICRO ROCKET TECHNOLOGY

Several organizations are developing micro rocket technologies. One example is the work at Mechatronic, which has developed cold-gas (N2) micro thrusters capable of thrust delivery up to 500µN. They are equipped with micro valves, pressure sensors, and electronics.

An experimental setup for testing the micro propulsion system in space is under development. The experiments will be performed on-board the micro satellite UNISAT-2, in the framework of a cooperation between Università di Roma “La Sapienza”, Mechatronic and INFM. Two pairs of micro thrusters mounted with their thrust direction orthogonal to the spin-axis of the spacecraft will be used to perform spin-up/ spin-down maneuvers.

Applications to Gas Turbines – Health Monitoring

Mehran Mehregany
Department of Electrical Engineering and Computer Science
Case Western Reserve University
Cleveland, Ohio 44106
USA

Tel: 216 368 0755

E-mail: mxm31@cwru.edu

ABSTRACT

The gas-turbine engine has been the focus of intense research since the first Whittle design in 1937. Although it has evolved into a very efficient source of power many areas remain open for advances. Many such advances however require instrumentation for monitoring and controlling transient phenomena. In particular, instrumentation needs are for distributed phenomena across the system, subsystems, components, … , which require spatially fine resolution at the local points. Microelectromechanical systems (MEMS) is a natural enabling technology to meet these instrumentation challenges. MEMS enable the development of smart systems by augmenting the computational ability of microelectronics with the perception and control capabilities of microsensors and microactuators.

The lecture will provide a review of instrumentation needs in gas turbine engine development where MEMS technology has been, is being, or is envisioned to be pursued. In the context of these pursuits, the specific MEMS research and development will be highlighted. The instrumentation (e.g., sensors, actuators, and control circuits) for the gas turbine applications must operate in high temperature environments compared to more pedestrian applications (i.e., in addition to many other harsh environment factors in a gas turbine engine). SiC MEMS technology holds great promise for applications which are characterized by presence of harsh environments (e.g., high temperatures, large number of vibrational cycles, erosive flows, and corrosive media). The lecture will introduce and review the state of SiC MEMS technology in the context of gas turbine engine instrumentation needs.

BIOGRAPHY

Mehran Mehregany received his B.S. in Electrical Engineering from the University of Missouri in 1984, and his M.S. and Ph.D. in Electrical Engineering from Massachusetts Institute of Technology in 1986 and 1990, respectively. From 1986 to 1990, he was a consultant to the Robotic Systems Research Department at AT&T Bell Laboratories, where he was a key contributor to ground-breaking research in microelectromechanical systems (MEMS). In 1990, he joined the Department of Electrical Engineering and Applied Physics at Case Western Reserve University as an Assistant Professor. He was awarded the Nord Assistant Professorship in 1991, was promoted to Associate Professor with tenure in July 1994, and was promoted to Full Professor in July 1997. He held the George S. Dively Professor of Engineering Endowed Chair from January 1998 until July 2000, when he was appointed the BFGoodrich Professor of Engineering

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.

Innovation. He served as the Director of the MEMS Research Center at CWRU from July 1995 until July 2000. Professor Mehregany is well known for his research in the area of MEMS, and his work has been widely covered by domestic and foreign media. He has over 200 publications describing his work, holds 12 U.S. patents, and is the recipient of a number of awards/honors. He served as the Editor-in-Chief of the Journal of Micromechanics and Microengineering from January 1996 to December 1997, and is Assistant-to-the-President of the Transducers Research Foundation. His research interests include silicon and silicon carbide MEMS, micromachining and microfabrication technologies, materials and modeling issues related to MEMS and IC technologies, and MEMS packaging.

Mehran Mehregany is the Founder and served as the President (July 1993 to March 1999) of Advanced Micromachines Incorporated (Cleveland, Ohio), a company in the MEMS area. Advanced Micromachines Incorporated was acquired by The BFGoodrich Corporation in March 1999. He founded NineSigma, Inc., an information technology company, in February 2000 and served as its CEO (June 2000 to January 2001) and CTO (January 2001 to August 2001), during which period he successfully completed initial rounds of private financing and grew the company to 15 employees. He co-founded FiberLead, Inc., an optical telecommunications company, in September 2000 and served as its CEO until September 2001, during which period he successfully completed the early stage round of venture capital financing and grew the company to 5 employees.

Health Monitoring of Munitions

Paul J. Smith
Weapons Department
Indian Head Division
Naval Surface warfare Center
Indian Head, Maryland 20640
USA

When mankind first began to accumulate 'stuff', it became necessary to keep track of 'the stuff', know the condition of 'the stuff' and determine how long 'the stuff' would last. As the quantities of 'stuff' increased these tasks have become more difficult. The 'stuff' is now in excess of 2 million tons. Through the ages various systems have been devised to achieve these goals. Many systems for inventory are labor intensive and prone to error. Once an error in inventory is made, it has a ripple effect to degrade the accuracy of the system. Inventories have the best accuracy the day they are taken and continually degrade until the next time the process is undertaken.

Today I will present a modern approach to reach these goals of accuracy with a low error rate. The United States has a vast array of weapons that spend most or all of their life in storage. Then upon removal from storage are expected of performing with high reliability of their designers. Weapons are made, procured, track, used and destroyed in lots. Lot sizes are statically chosen to posses certain characteristics. Periodically during the life of a lot of weapons a sample is randomly selected for detail destructive analysis. If it fails test requirements the entire lot may have to be modified or destroyed. Once the lot has been identified all its members have to be located for the appropriate action. When weapons leave the factory they are identical and have known life expectancies. It is known that a variety of environmental factors (temperature, humidity, shock, vibration, etc.) affect the weapons' condition and ultimate life expectancies. The older a weapon is the more possible variation in storage condition exist and hence variation in its life expectancies. If individual storage environments could be tracked individual life expectancies could be determined. Weapons reaching near end-of-life could be designated for training and save the cost of de-milling.

The larger the military is the larger the problem. Let's for a minute consider some simple movement of systems. Systems loaded on ships should be simple to track, but in recent years there has been an increase of at-sea transfer. This results in weapons systems leaving on one ship and being transferred to a second ship and so on and so on. Ordnance may be stored at advanced location by one group only to be left for a second group to use later. Locating what is stored and where often becomes a major task.

Solutions to solve these problems are being explored under a tri-service project by the Department of Defense. The goal of the Advanced Technology Ordnance Surveillance or ATOS is to give ordnance managers the ability to accurately locate and continuously determine the status of individual munitions on a near real-time basis while simultaneously updating prediction of their future condition and performance with a high level of confidence. There are three phases to achieving this goal: automated inventory, environmental storage condition monitoring, and insitu analysis of the health of the system. Currently the ATOS program is committed to completion of the first two phases.

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.

Two technologies (Figure 1) have come together to meet the challenges outlined above: Radio Frequency IDentification (RFID) and low power miniature MicroElectroMechanical Systems (MEMS) sensors. RFID systems are augmenting the standard bar code system with a low power short-range transponder to a local receiver and computer. This enables the timely accurate inventory data. When the RFID standard tag is coupled to an environmental sensor(s) (temperature, humidity, shock etc.) this data can be added to inventory data in a timely manner.

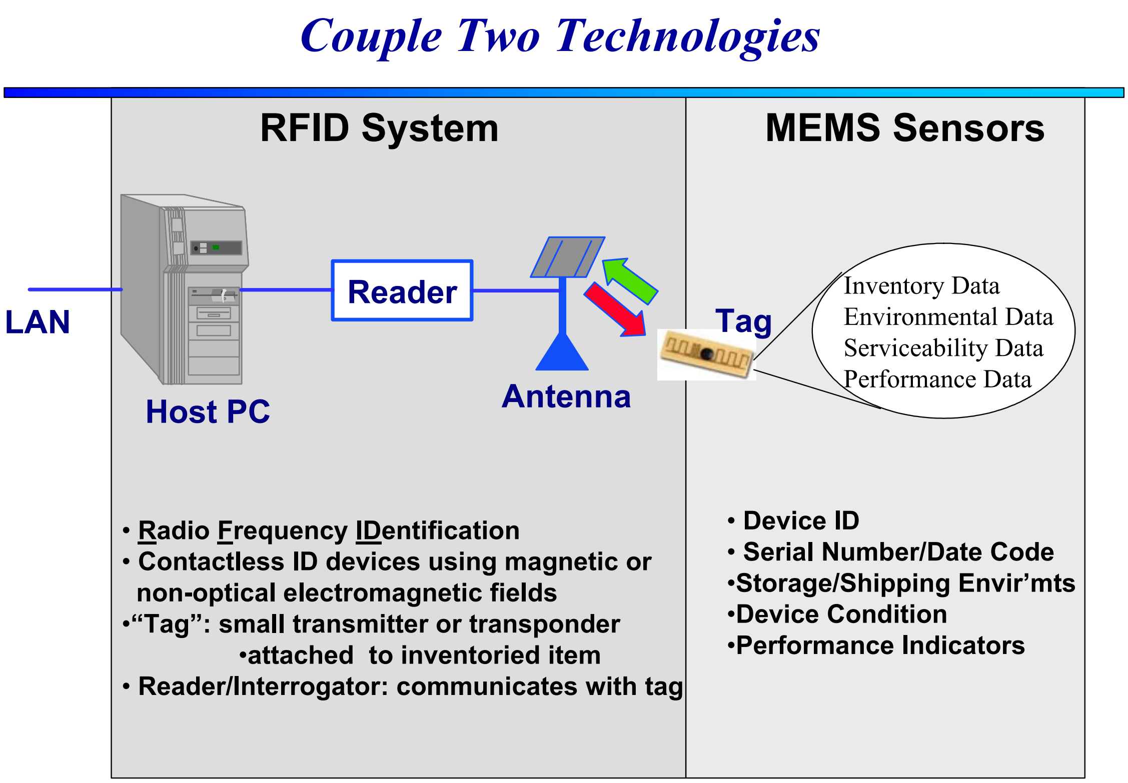


Figure 1.

One of the first challenges is powering the RF tags. RF power scavenging techniques have been developed. These systems have a central medium power level transmitter. The RF energy is received and rectified to produce power required to operate the tag for short periods. RF devices that are safe to be used in and around energetic material must be low power and meet HERO requirements. This precludes the use of current scavenging systems. The tag should be readable in standard magazines and warehouses. A range (open air) of in-excess-of 300 ft is desired. For the near future the tags must rely on battery power. Batteries currently available provide power for a five to ten year life. Battery life can be extended by using non-volatile read/write memory in conjunction with low duty cycle operations. Since the current ATOS tags will be external to ordnance, systems battery replacement is feasible. However, a long-term solution to power source is required for Phase 3 of the project. In addition, to these critical requirements the system must demonstrate better than 99% detect ability in real world environments.

The ATOS tag (Figure 2) has three types of information. First is inventory data (stock control number, serial number etc.) which have been defined by DOD Navy regulations. This allows seamless integration into existing inventory databases. The second type of data is environmental sensor data such as temperature and humidity. The third type of data is performance data. When a threshold has been exceeded a flag is set and during the next inventory interval the flag message is transmitted indicating degraded performance. For example, a locking passive shock sensor would record rough handling (dropping) of the ordnance and set a flag for future interrogation to indicate that the ordnance was not to be used or that further testing was required prior to use.

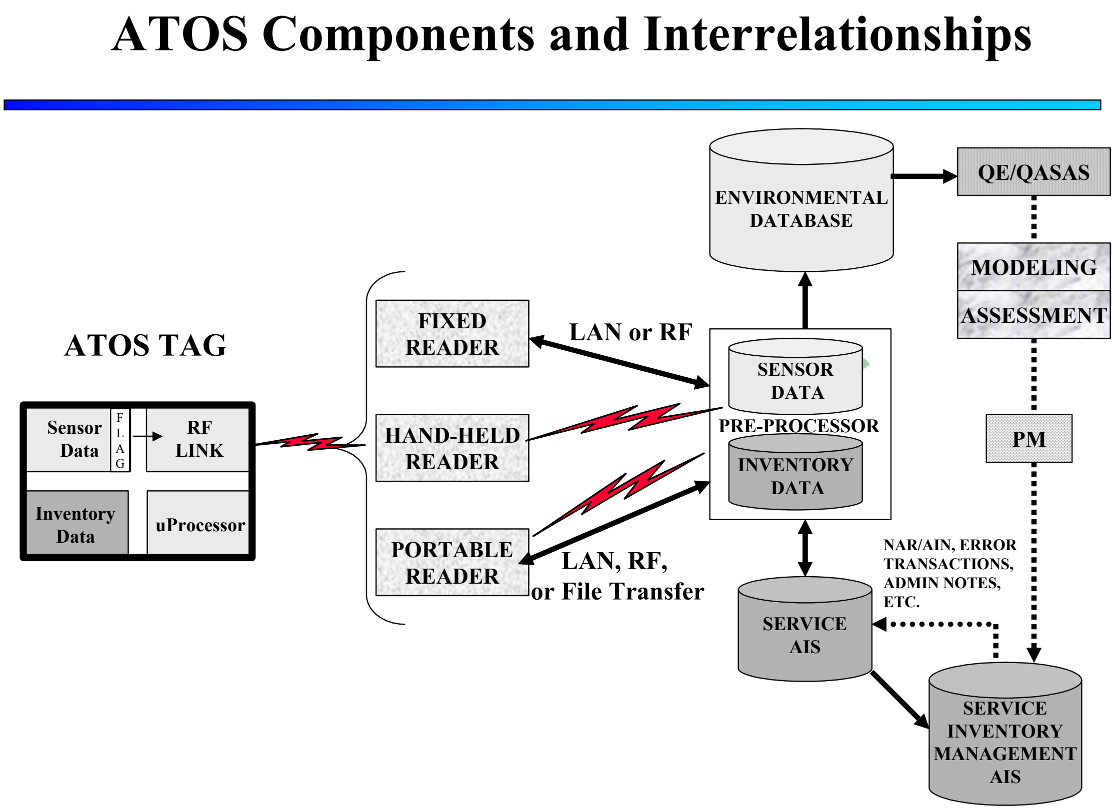


Figure 2.

Three methods of reading the tag data are envisioned. A fixed tag reader that is located in a warehouse or magazine. Or a portable reader to be used at a temporary field storage locations. And finally, a hand-held reader to be aid in shipping and receiving invoicing of ordnance. Once the data (inventory, sensor) is uploaded into a central computer system it would be split into environmental data and inventory data. The environmental data would be examined by QE for life expectancy models for updating predicted performance model. Preventive maintenance schedules for individual weapons would be drawn up. The data coding system has been selected. For temperature data, there are a series of 60- three degrees temperature bins ranging from –20°F to 155°F. Once an hour, the temperature is read and the appropriate bin is incremented. If data tags are read daily, a twenty-four data point profile is uploaded and the daily averages are calculated. Present plans are to read the tag once an hour.

As the project proceeds there have been a series of test to demonstrate features of the system. The RF energy levels must be kept low for explosive safety considerations. One of the initial questions was the RF performance in the presence of a number of metal storage containers that would preclude direct line-of-sight transmission between the reader and a tag. In the test, a typical magazine was filled with eighty-four containers representing six ordnance systems and a single reader. Two types of tags were tested. Five commercial backscatter or scavenger tags were tested. The RF system power of the reader was limited to meet explosive safety considerations. They were able to reliably read about 40 % of the inventory. Their free-space ranges were 6 to 70 feet. These types of tags are best suited for a portal type inventory system. The second class of tags (six) was emitter-type tags (i.e. battery). Two types were able to reliably read 100% of the inventory. The remaining four tags were able to reliably read 85 % of the inventory. When multiple readers were used results improved to 100%. In a second test, six tags (vendors) were chosen for a test aboard the USS Truman aircraft carrier. Located in the bow of the ship on the maintenance deck is a spare parts storeroom. The room has 190 metal storage bins containing 456 tags. During the two-week test, the tag system tracked spare parts being issued. Its performance was evaluated during normal shipboard activities (degaussing, radar operations, radio operations, etc.). The test was very successful and data is being evaluated. A vendor has been selected and is under contract for an upcoming system demonstration.

Now let us focus on the health monitoring aspect of the system. Critical parameters (Figure 3) such as stabilizers concentration are tightly grouped for a lot of ordnance when it is manufactured. Lot to lot variations results in some small additional scatter in the parameter values. Total scatter of a critical parameter diverges with time. Variations within a single lot are due mainly to environmental factors. If environmental factors and critical parameters are modeled, service life and performance can be predicted. The failure and ageing mechanism must also be understood, quantified and modeled. If individual weapon environmental data is available individual life expectancy can be predicted. As oppose life expectancy of the entire lot. Finally, there needs to be a surveillance program to validate models and identify shortfalls. Once such a system is in place, performance can be predicted and safe service life extensions can be evaluated.

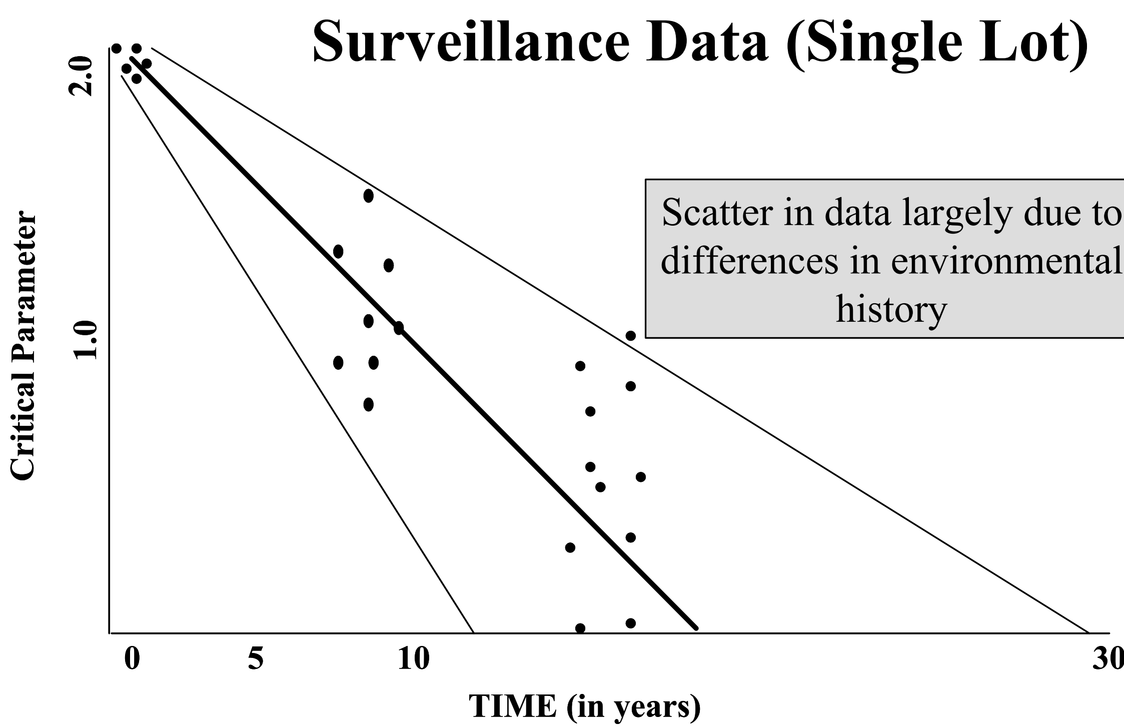


Figure 3.

In an earlier paper I spoke of integrating energetic in to MEMS to produce future Safety and Arming (S&A) systems. To complete the third phase of health monitoring, it is necessary to integrate MEMS into energetics- that is explosive and propellants. It is envisioned that in the near future MEMS technology will produce a "Chemistry Lab on a Chip". Initially these devices will be placed adjacent to energetic material and monitor the health of chemical compounds. The long-term goal is to embed this capability in new weapon systems at the time of manufacturing. Thus, allowing chemical/mechanical measurement in addition to environmental data for high fidelity models. Each of these phases will build upon the infrastructure develop by previous phases.

The goal is give ordnance managers the ability to accurately locate and continuously determine the status of individual munitions on a near real-time basis while simultaneously updating predictions of their future conditions and performance with a high level of confidence. In simple words, the age-old questions:

- What 'STUFF' Do I Have ?
- Where Is My 'STUFF' ?
- Does The 'STUFF' Still Work ?
- How Long Will The 'STUFF' Last ?

Optical Microsystems, Mechno-Optical-Electro-Mechanical Systems – *MOEMS*

Ayman El-Fatatry
BAE SYSTEMS – Advanced Technology Centre
West Hanningfield Road
Great Baddow, Chelmsford
Essex CM2 8HN
UNITED KINGDOM

ABSTRACT

The Telecommunications infrastructure across the world is expanding at a staggering rate in response to an ever increasing demand for mobility, interconnectivity and bandwidth. This is evidenced through the increasing use of mobile telephones and the proliferation of optical fibre and microwave (RF) systems for data transfer and internet systems.

The rapid, world-wide installation of optical fibre-based telecommunication systems has given rise to a phenomenal growth in the number and size of manufacturers of optical components and devices. Initially, such manufacturers relied on costly precision-based engineering to produce optical fibre connectors, splices and alignment structures. Such manufacturing techniques have, however, evolved to encompass micromachining as the basis of manufacturing for low cost, mass-produced components.

Currently, micromachining methods, combined with IC-based processing techniques, enable the fabrication of complex opto-electronic integrated circuits and micro-electromechanical alignment devices in production quantities.

This lecture will introduce MOEMS in the context of optical communication and systems, providing a historical perspective and an overview of the current state of the art of this technology.

TELECOMMUNICATIONS APPLICATIONS

The Telecommunications infrastructure across the world is expanding at a staggering rate in response to an ever increasing demand for mobility, interconnectivity and bandwidth. This is evidenced through the increasing use of mobile telephones and the proliferation of optical fibre and microwave (RF) systems for data transfer and internet systems.

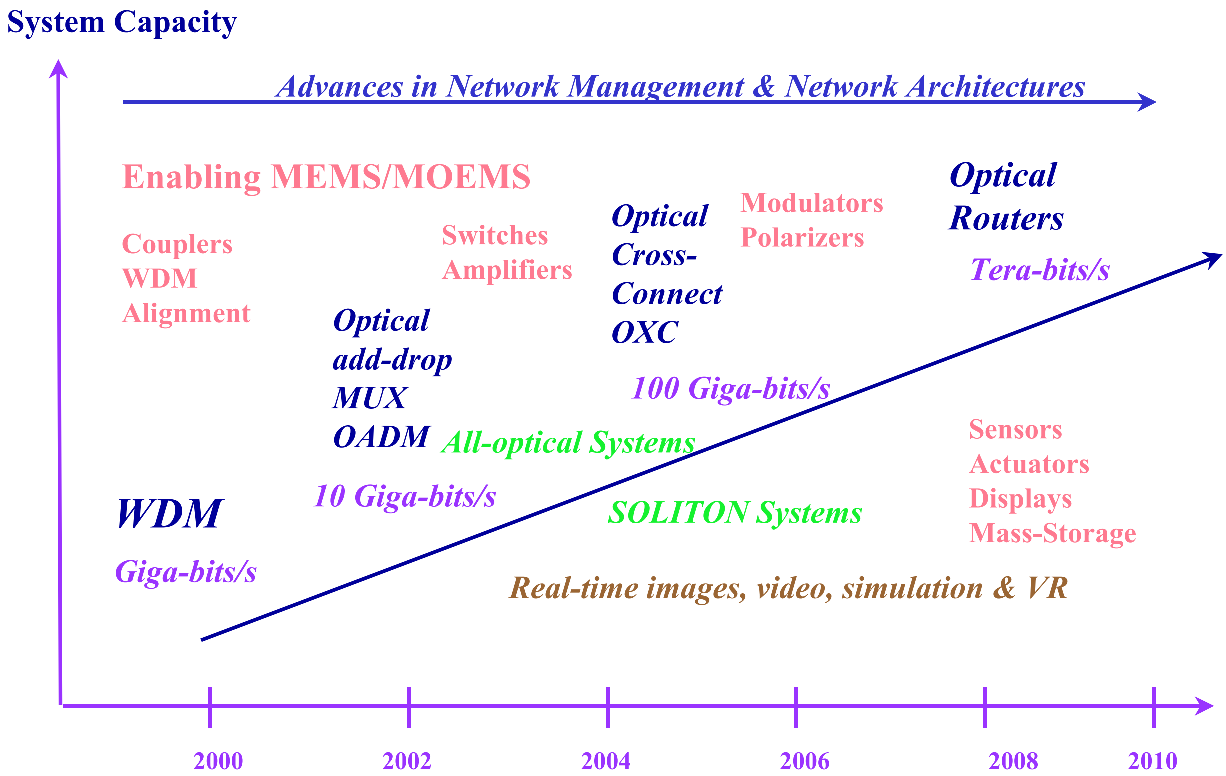
The rapid, world-wide installation of optical fibre-based telecommunication systems has given rise to a phenomenal growth in the number and size of manufacturers of optical components and devices. Initially, such manufacturers relied on costly precision-based engineering to produce optical fibre connectors, splices and alignment structures. Such manufacturing techniques have, however, evolved to encompass micromachining as the basis of manufacturing for low cost, mass-produced components.

Currently, micromachining methods, combined with IC-based processing techniques, enable the fabrication of complex opto-electronic integrated circuits and micro-electromechanical alignment devices in production quantities.

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.

MST IN OPTICAL TELECOMMUNICATION SYSTEMS

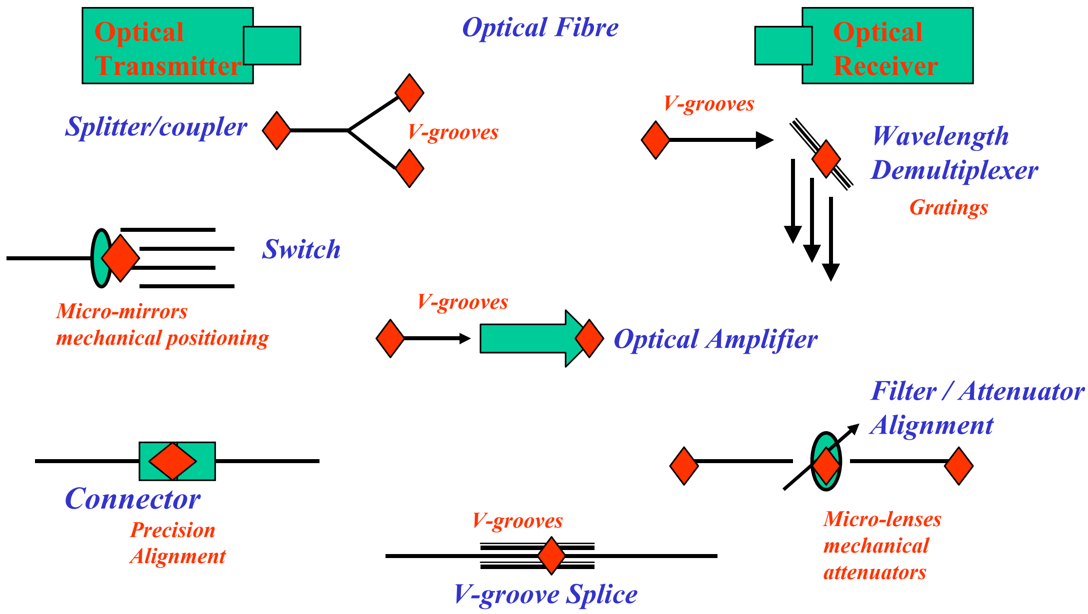
The European Network of Excellence in Microsystems, NEXUS, through its User-Supplier-Club for Telecommunications has produced forecasts for the growth of optical systems, over the next 10 years, in terms of bandwidth capacity and network configurations:



Evolution of Optical Systems & Related MST/MEMS Technologies.

Indeed, the introduction of high capacity Wavelength Division Multiplexed (WDM) systems, over the past decade, and the proliferation of optical fibre systems/networks in the business and home environments is increasing the demand for low cost micromachined optical components. Microsystems, for such applications, will provide a range of functionalities, some of which are illustrated, diagrammatically, in the following chart:

Microsystems within Optical Telecommunication Networks



Microsystems / MOEMS within Optical Telecommunication Networks.

This diagram identifies the range of typical components which are either fully based on a microsystem design/fabrication technology or incorporate some aspects of microtechnology such as v-grooves. A more comprehensive listing and description will include the following:

Optical Couplers

Components for coupling optical power from a single fibre (or optical source) onto a number (N) of output fibres. Most conventional designs are based on integrated optics waveguides (e.g. silica). The microsystems content is primarily associated with the v-groove alignment mechanism which is micromachined onto the substrate (e.g. silica). Simple 1X2 and 2X2 couplers, developed using the fused biconical all-fibre configuration, will, also, require some form of precision micromachined alignment mechanism such as a v-groove or a ferrule.

Optical Connectors

Demountable connectors for optical fibres based on precision engineered alignment mechanisms such as ferrules or v-grooves. The microsystems content is associated with the method of alignment adopted for such connectors.

WDM Devices

Wavelength selective components used for filtering-out and/or separating specific wavelengths from within a frequency / wavelength band. Such components rely on the use of dichroic filters or gratings. The latter are, usually, micromachined onto the surface of optical substrates (e.g. silica). WDM devices formed from wavelength selective fused biconical couplers will also require micromachined alignment mechanisms such as v-grooves.

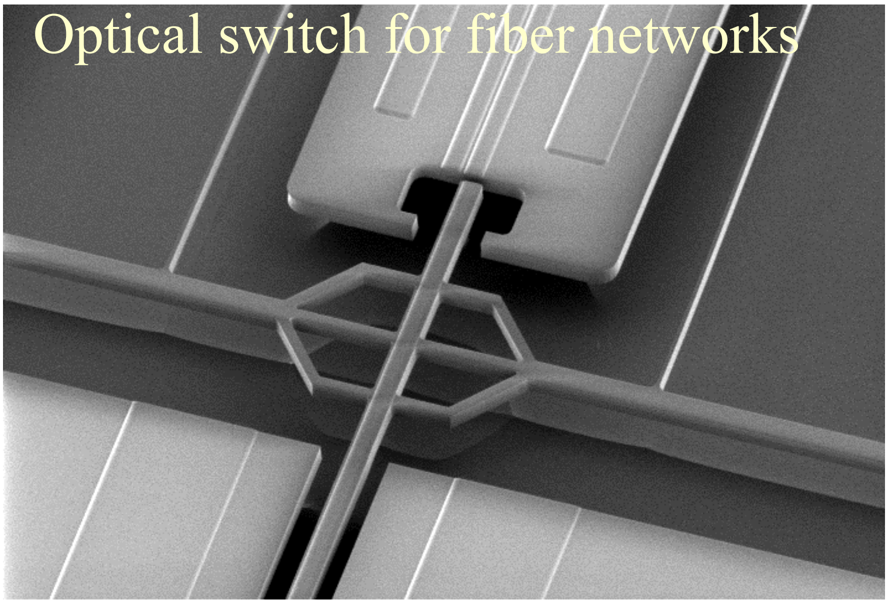
Wavelength Filters

Optical filters, such as WDM devices, may need to be tuneable. Such structures may be based on mechanically adjustable dichroic filters which could be constructed using microsystem-based mechanical shutters.

Optical Switches / Routers & Shutters

Optical switches enable optical signals to be routed from N inputs to M outputs. The routing / switching mechanisms are, on the whole, based on micromechanical mirrors / shutters and /or positioning structures. In this context, microtechnologies form an essential part of such systems for both functionality and interconnection.

A typical example of an optical switch design is shown below:



Optical Switch (Courtesy of Leti).

Optical Alignment Systems and Fibre Positioning Devices

Techniques for aligning optical fibre to either other fibre or to components are, increasingly, reliant on the use of micromachining and microtechnologies to satisfy the necessary sub-micron tolerances. Typically, such devices allow components (and fibre) to be micro-manipulated and positioned with high accuracy. Linear, rotational and 3-dimentinal movements are realised using microsystem-based mechanical transducers.

Polarisation Controllers

In some applications, including, coherent optical transmission systems, the need for controlling the state of polarisation of an optical signal is essential. Such a function could be achieved using mechanical structures for rotating and/or “squeezing” the fibres as appropriate. Additional complexities associated with the use of polarisation-maintaining fibre will also necessitate the use of high-precision alignment mechanisms that guarantee fibre orientation. Micromachining techniques and microsystems, clearly play an important role in realisation of such subsystems.

Optical Amplifiers

Optical amplification and signal regeneration using rare-earth (e.g. Erbium) doped fibre or waveguides are increasingly utilised for both long-haul as well as high density distribution networks. The content of microtechnologies within such components will, generally, be limited to alignment and positioning structures such as v-grooves.

Optical Attenuators

A number of applications demand the use of either fixed or variable optical attenuators in order to adjust optical signal levels at, for example, the receiving end. The construction of variable optical attenuators using microsystems rely on the use of mechanical adjusters for partially attenuating optical filters or shutters. These micro-mechanical structures are similar to those used for optical switches but with much simpler interconnections.

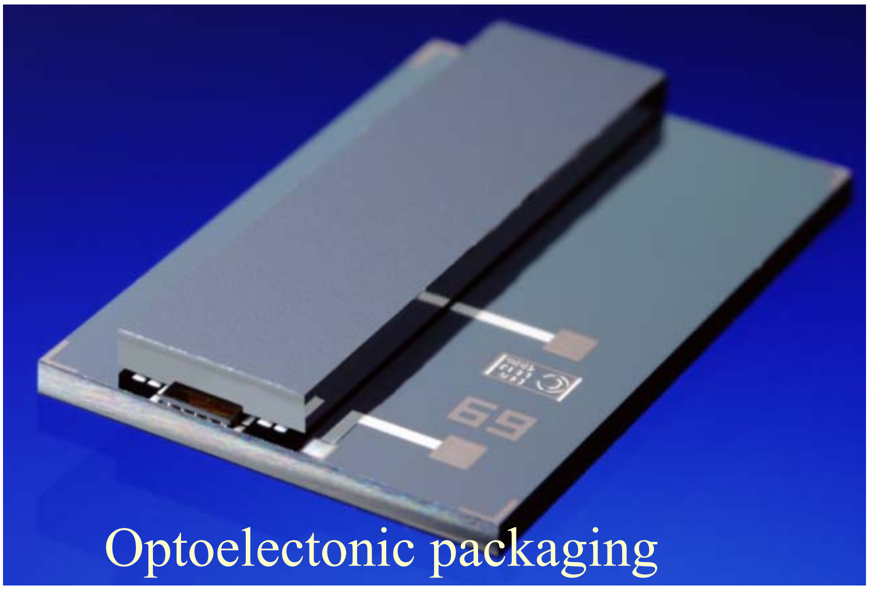
Micro-Lenses

Microtechnologies enable the fabrication of high precision lenses and lens arrays used for focussing and / or redirecting optical beams. Such micro-lenses may be used to maximise optical coupling between (laser) sources and fibre or between the input and output fibres of an optical switch. The lens structures are most likely to be integration with precision alignment microsystems.

Packaging

Complex optical devices and subsystems will, in future, demand rugged yet specifically-designed packages which could, in some application, allow for the external manipulation of the alignment mechanisms. In addition, packaging may become integral to the device construction. Microtechnologies provide the opportunity to integrate the process of device fabrication and its packaging. In future, "self-assembly" design techniques will be based on micro-mechanical constructions that link the devices with their associated housing.

An example of an advanced packaging system is shown below:

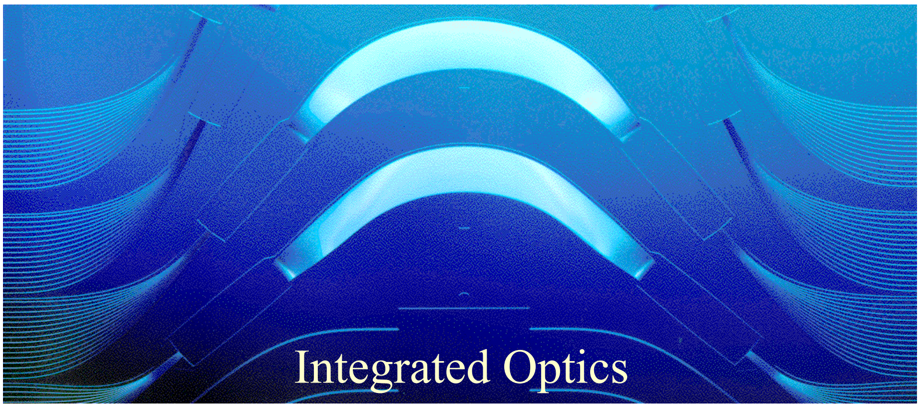


Optical Packaging (Courtesy of Leti).

Integrated Optic Circuits

The optical equivalent of electrical integrated circuits where optical signals are routed via waveguides (e.g. silica or polymeric). The waveguides form the basis of the optical circuits which may include embedded splitters, combiners, alignment devices (v-grooves) or switches. The microsystems content is high within such structures but, clearly, dependant on the functional complexity of the subsystem.

The following photograph illustrates a typical example of optical waveguides used for developing integrated optic circuits.



Integrated Optics (Courtesy of Leti).

In addition to the above examples, such systems will continue to require precision optical fibre connectors and splices which may, in certain applications, encompass some of these functional characteristics.

COMPANIES DEVELOPING OPTICAL MST/MEMS (MOEMS) COMPONENTS FOR TELECOMMUNICATIONS APPLICATIONS: (Information courtesy of VDI/VDE-IT)

ADC Telecom, Alcatel, Astarte, Axsum, C Speed, Calient, Corning / Intellisence, Cypress, Semiconductor / Silicon Light Machines, Fitel Technologies (Furukawa), Ilotron, Integrated Micro Machines, Ioλon, JDS Uniphase / Cronos, LightConnect, Lucent, Luxcore (Synchordia), MemLink, MEMSCAP S.A., Nanovation, Nortel / Xros / CoreTek, Onix Microsystem, Optical Micro Machines, PHS MEMS, Siemens, Standard MEMS, Zygo TeraOptix.

MICRODISPLAYS

In addition to the application of MOEMS within the telecommunication arena, microsystems and micromachining will play an important role in shaping the future of display technologies, in general, and micro-displays in particular.

In general, these applications can be classified as follows:

- Embedded **Direct View Systems**, where the image on the display is directly viewed by the observer
- **Front Projection And Rear Projection Systems**, where a real image is projected onto a screen and viewed from front or rear side
- **Near Eye Applications**, where a virtual image is projected internally within the eye

Direct View Systems are to be found within:

- Cell/ Mobile phones
- PDAs and other Internet Applications
- Computer games

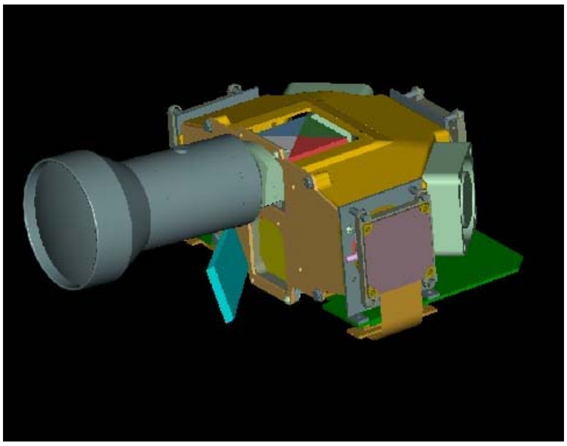
Direct View Application.

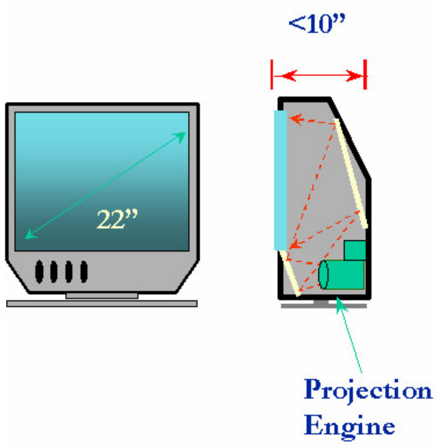
These applications are well-know and constitute the largest markets for conventional LCD-based technologies. At present, LCOS and MST/MEMS do not, as yet play a significant role. It is forecasted that Liquid Crystal on Silicon (LCOS) types of displays will in future penetrate these markets especially for high resolution applications. The direct view Field Emission Displays, which must also be considered as MST, will gain significant market share as from the year 2004.

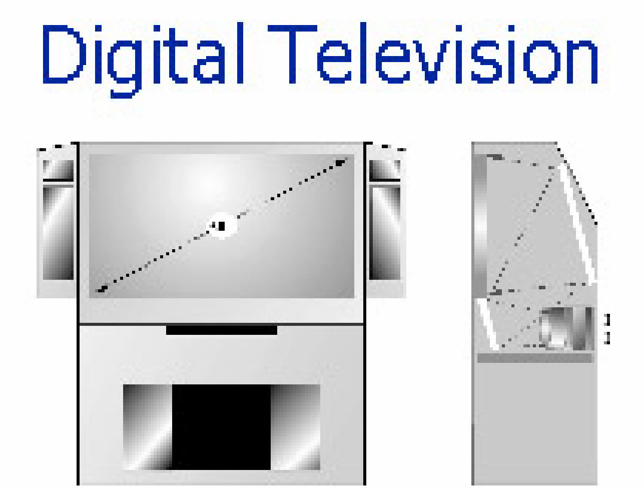
Front Projection Systems include:

- Presentation systems (conference/ board room)
- Home TV/home theatre and entertainment (future)
- Movie houses / cinemas (future)
- *perhaps*: Automotive (future)

The following picture presents an "artists" impression of a digital projection TV incorporating a projection system.







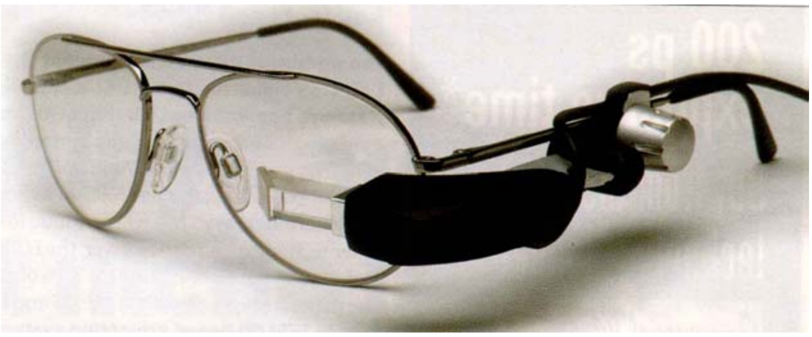
Front and Rear Projection Systems.

Rear Projection Systems include:

- PCs and computer desktops
- Home TV/home theatre and entertainment (future)
- Automotive (future)
- Avionics/cockpit applications (future)

Near Eye applications could include:

- Camcorders
- Digital cameras
- Head sets and personal viewers
- Head/helmet mounted displays



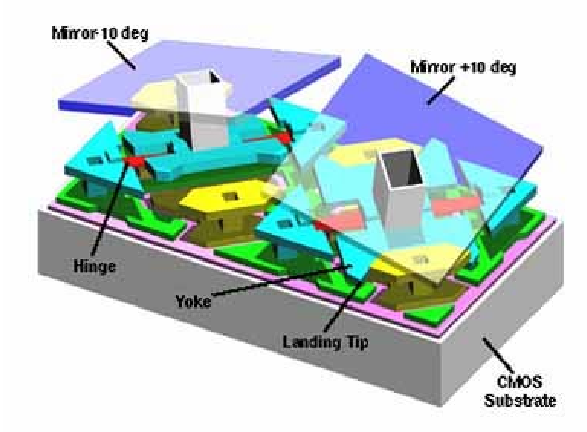
Technologies for Microdisplays

The following MEMS technologies are currently being developed for possible micro-display applications:

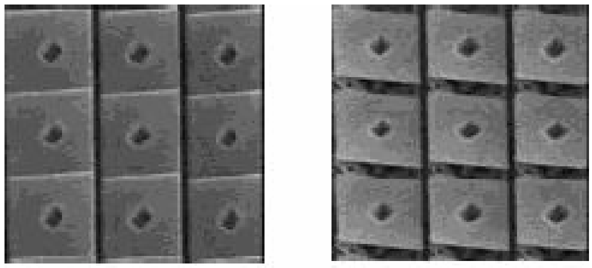
- Micro-mirror arrays (“MMAs”)
- Grated Light Valves
- Liquid Crystal on Silicon (LCOS)
- Field Emission Displays (“ThinCRT”).

Micromirror Arrays

Micromirror arrays are monolithically integrated MEMS structures fabricated over a CMOS control circuit. The MEMS structure consists of a silicon array of aluminized mirrors which can be rotated between two angles(TI approach: ± 10°). When the mirror is in its on-state, light from a projection source is directed towards a projection lens to appear as a pixel on a projection screen. In the off-position, the light is directed away from the lens and the pixel appears dark.



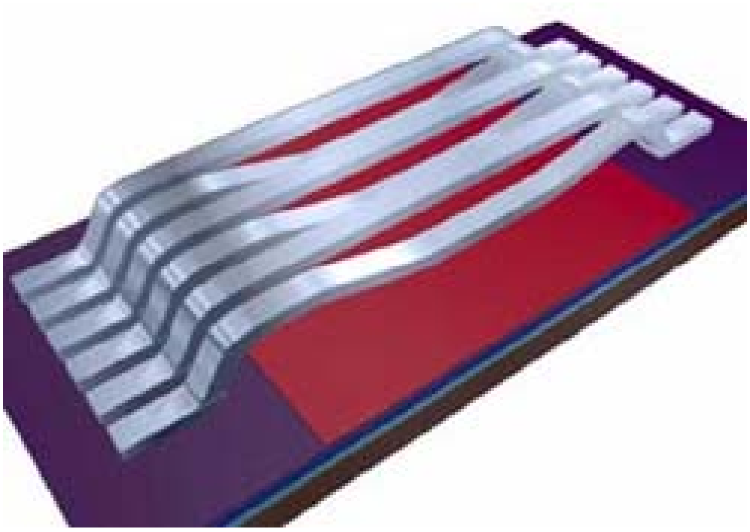
TI Micro Mirror Array.



SEM Video Images of Operating DMD.

Grating Light Valve

This technology was invented at Stanford University and is proprietary to Silicon Light Machines, CA. A Grating Light Valve pixel consists of an array of small ribbons, which can be moved up or down over a small distance by electrostatic forces. The ribbons are fabricated by surface machining MEMS techniques. These "ribbons" are arranged such that each element can either reflect or diffract light, hence, a beam of light can be switched between two directions at a very high speed. At present, only linear arrays are available. A microdisplay consisting of a grating light valve will require an additional linear scanner. The principle relies on the availability of cheap RGB laser sources.

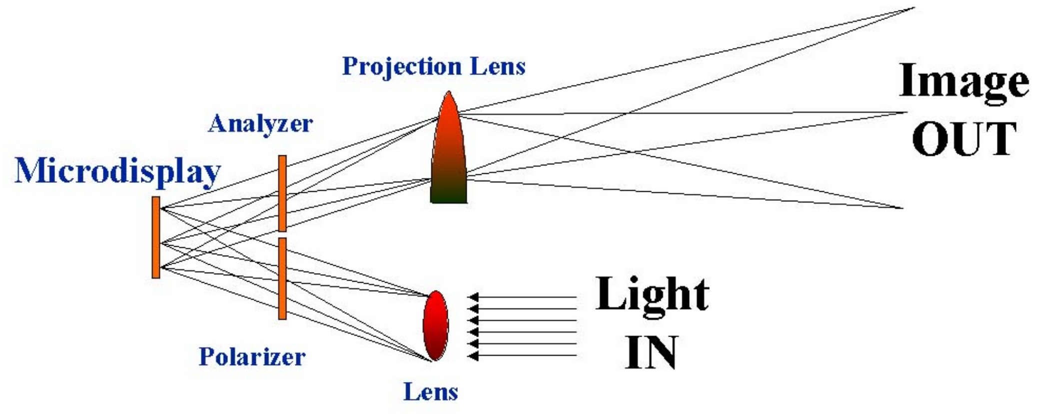


Grating Light Valve Pixel (from Sil_01).

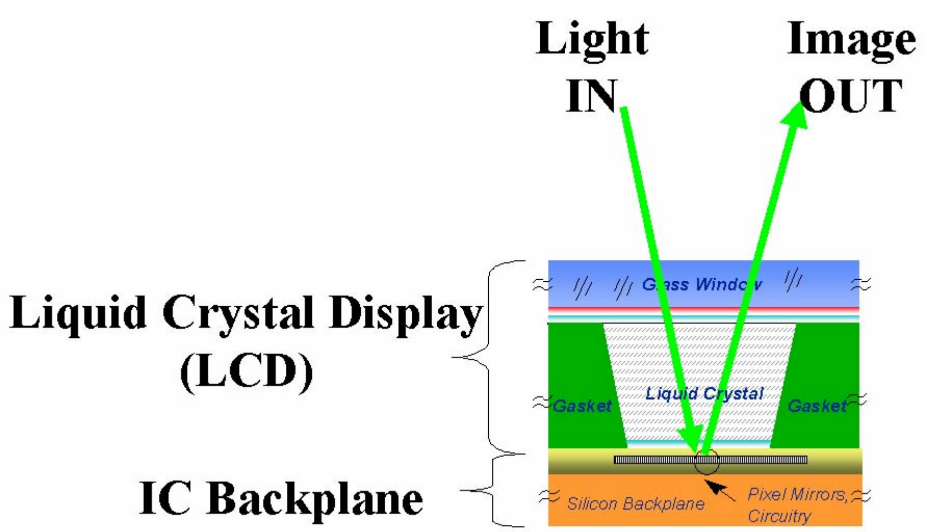
Liquid Crystal On Silicon (LCOS)

Microdisplays based on LCOS combine two mature technologies: IC and LC. Displays are constructed from a CMOS backplane (driving electronics) and a Liquid Crystal array. The devices are assembled in wafer-scale, allowing for a "fabless" business model, where design and integration companies, CMOS foundries and LC foundries operate together.

Microdisplays are realised by two approaches: transmissive LCOS, where the light passes through the chip, and reflective LCOS (rLCOS) as shown below. Reflective - rLCOS - offer several advantages including higher brightness, virtually no pixelation, and the possibility of higher electronics integration. As LCOS combines electronics, optical and micromachined functions (e.g. spacers), these structures are to be considered as microsystems.



Schematic of a Microdisplay using rLCOS Chips (from HAN_00).

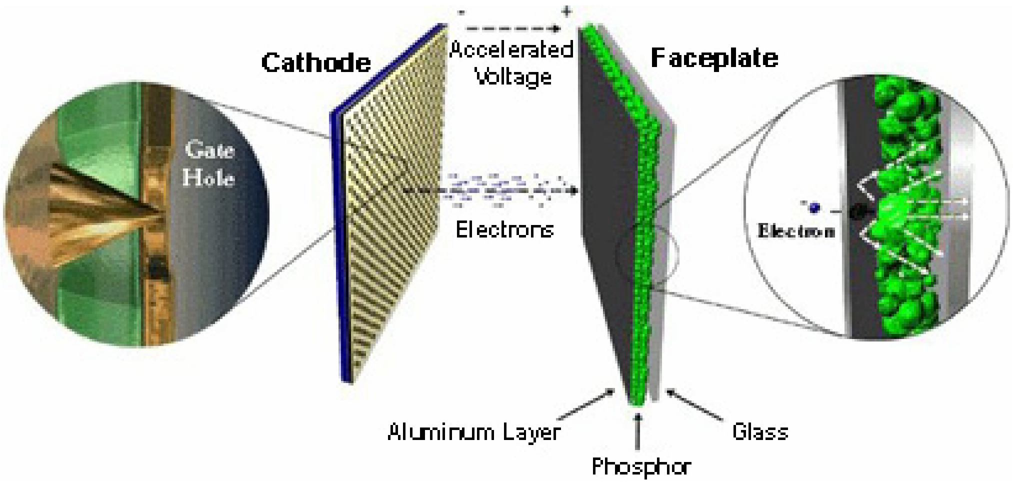


Schematic of a rLCOS Cell (from HAN_00).

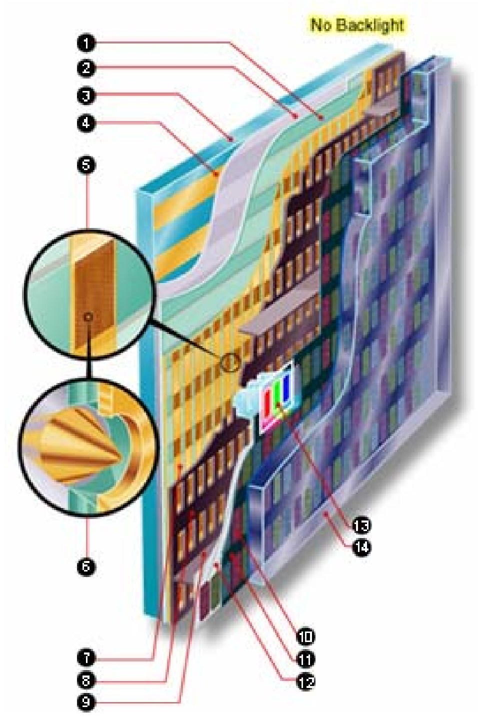
Field Emission Displays (“ThinCRT”)

This emerging technology is a combination of the familiar screen technology of a cathode ray tube (CRT) with a low-power, miniaturised cold cathode array to form a display that is only a few millimeters thick. Each pixel consists of thousands of emitter tips of approximately 0.15 μ in diameter. These tips emit electrons that are accelerated towards a phosphor screen on the faceplate to appear as a bright spot to the viewer. In contrast to the previous three technologies, which are spatial light modulators and require an illumination source as well as an optical projection system, Field Emission Displays are direct view systems.

The only company known to manufacture prototypes is Candescent (Can_01).



Principle of Field Emission Display ("ThinCRT", from Can_01).



1 dielectric
2 patterned resister layer
3 cathode glass
4 row material
5 emitter array
6 single emitter cone & gate hole
7 column material
8 focusing grid
9 wall
10 phosphor
11 black matrix
12 aluminum layer
13 pixel on
14 faceplate glass

Cross-Section of a ThinCRT (from Can_01).

MICROSYSTEMS AND THEIR FUTURE POTENTIAL IN TELECOMMUNICATION SYSTEMS

Advancements in microsystems are, primarily, driven by the requirements for intelligent diagnostic and sensing systems. The sophistication and complexity of such components is directly related to the increasing number of data sources, the processing power of the electronics and the simplicity of the transducted output. In essence, the microsystem of the future, will absorb multi-sourced data, process the data and produce a “decision”.

Researchers and developers predict that such, generically functional, devices will service all conceivable applications. In the telecommunications field, future microsystems will, it is stipulated, be networked and linked to the outside world. Within the home, microsystems will monitor the environment, safety and security and transmit this information to the user on command. Health monitoring diagnostic microsystems are, also, considered for incorporation within future communication devices. In essence, microsystems will form the basis of the “micro”-LAN of the future.

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:	**-65oC to > +125oC**
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.

Dr AYMAN EL FATATRY
PhD BSc CEng
Head
Systems Department

BAE SYSTEMS
Advanced Technology Centre
West Hanningfield Road
Great Baddow, Chelmsford, Essex CM2 8HN, Great Britain
Tel: +44-1245 242101, Fax: +44-1245 242124

e-mail: ayman.elfatatry@baesystems.com

Web Site: http://www.baesystems.com

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 super conductivity, 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.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References	3. Further Reference	4. Security Classification of Document
	RTO-EN-AVT-105 AC/323(AVT-105)TP/79	ISBN 92-837-1113-0	UNCLASSIFIED/ UNLIMITED

5. Originator

Research and Technology Organisation
North Atlantic Treaty Organisation
BP 25, F-92201 Neuilly-sur-Seine Cedex, France

6. Title

MEMS Aerospace Applications

7. Presented at/Sponsored by

The Applied Vehicle Technology Panel (AVT) in support of a Lecture Series presented on 3-4 October 2002 in Montreal, Canada; on 24-25 February 2003 in Ankara, Turkey; on 27-28 February 2003 in VKI Brussels, Belgium; and on 3-4 March 2003 in Monterey, California, USA.

8. Author(s)/Editor(s)	9. Date
Multiple	February 2004

10. Author's/Editor's Address	11. Pages
Multiple	64 (text) 378 (slides)

12. Distribution Statement

There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.

13. Keywords/Descriptors

Active control	Fuel cells	Military applications
Actuators	Inertial navigation	MOEMS (Micro-Optic-Electro-Mechanical System)
Aerodynamic characteristics	MEMS (Micro-Electro-Mechanical System)	Monitors
Boundary layer control	Microelectronics	Optical equipment
Control equipment	Microminiaturization	Reliability
Design criteria	Microsensors	Safety and arming (ordnance)
Electric power generation	Microsystems	Service life
Fabrication	Microtechnology	Wireless communications
Flow control		

14. Abstract

This Lecture Series provides an introduction into MEMS technology and then focuses on six potential applications, namely micro-flow control, IMU, fuze/safety & arming, micro power, gas turbines applications, inventory and health monitoring of munitions. Also an introduction into MOEMS (Micro-Optical-Electro-Mechnical-Systems) will be provided.

NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

BP 25
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int

DIFFUSION DES PUBLICATIONS
RTO NON CLASSIFIEES

Les publications de l'AGARD et de la RTO peuvent parfois être obtenues auprès des centres nationaux de distribution indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de la RTO, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus soit à titre personnel, soit au nom de votre organisation, sur la liste d'envoi.

Les publications de la RTO et de l'AGARD sont également en vente auprès des agences de vente indiquées ci-dessous.

Les demandes de documents RTO ou AGARD doivent comporter la dénomination « RTO » ou « AGARD » selon le cas, suivi du numéro de série. Des informations analogues, telles que le titre est la date de publication sont souhaitables.

Si vous souhaitez recevoir une notification électronique de la disponibilité des rapports de la RTO au fur et à mesure de leur publication, vous pouvez consulter notre site Web (www.rta.nato.int) et vous abonner à ce service.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr (FIZBw)
Friedrich-Ebert-Allee 34, D-53113 Bonn

BELGIQUE
Etat-Major de la Défense
Département d'Etat-Major Stratégie
ACOS-STRAT – Coord. RTO
Quartier Reine Elisabeth
Rue d'Evère, B-1140 Bruxelles

CANADA
DSIGRD2
Bibliothécaire des ressources du savoir
R et D pour la défense Canada
Ministère de la Défense nationale
305, rue Rideau, 9e étage
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Defence Research Establishment
Ryvangs Allé 1, P.O. Box 2715
DK-2100 Copenhagen Ø

ESPAGNE
SDG TECEN / DGAM
C/ Arturo Soria 289
Madrid 28033

ETATS-UNIS
NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076-1320

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72, 92322 Châtillon Cedex

GRECE (Correspondant)
Defence Industry & Research General Directorate, Research Directorate
Fakinos Base Camp, S.T.G. 1020
Holargos, Athens

HONGRIE
Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
H-1525 Budapest P O Box 26

ISLANDE
Director of Aviation
c/o Flugrad
Reykjavik

ITALIE
Centro di Documentazione Tecnico-Scientifica della Difesa
Via XX Settembre 123
00187 Roma

LUXEMBOURG
Voir Belgique

NORVEGE
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25, NO-2007 Kjeller

PAYS-BAS
Royal Netherlands Military Academy Library
P.O. Box 90.002
4800 PA Breda

POLOGNE
Armament Policy Department
218 Niepodleglosci Av.
00-911 Warsaw

PORTUGAL
Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide
P-2720 Amadora

REPUBLIQUE TCHEQUE
DIC Czech Republic-NATO RTO
VTÚL a PVO Praha
Mladoboleslavská ul.
Praha 9, 197 06
Česká republika

ROYAUME-UNI
Dstl Knowledge Services
Information Centre, Building 247
Dstl Porton Down
Salisbury
Wiltshire SP4 0JQ

TURQUIE
Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi Başkanlığı
06650 Bakanliklar – Ankara

AGENCES DE VENTE

NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076-1320
ETATS-UNIS

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
ROYAUME-UNI

Canada Institute for Scientific and Technical Information (CISTI)
National Research Council
Acquisitions, Montreal Road, Building M-55
Ottawa K1A 0S2, CANADA

Les demandes de documents RTO ou AGARD doivent comporter la dénomination « RTO » ou « AGARD » selon le cas, suivie du numéro de série (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Des références bibliographiques complètes ainsi que des résumés des publications RTO et AGARD figurent dans les journaux suivants :

Scientific and Technical Aerospace Reports (STAR)
STAR peut être consulté en ligne au localisateur de ressources uniformes (URL) suivant:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR est édité par CASI dans le cadre du programme NASA d'information scientifique et technique (STI)
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
ETATS-UNIS

Government Reports Announcements & Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 2216
ETATS-UNIS
(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

BP 25
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int

DISTRIBUTION OF UNCLASSIFIED RTO PUBLICATIONS

AGARD & RTO publications are sometimes available from the National Distribution Centres listed below. If you wish to receive all RTO reports, or just those relating to one or more specific RTO Panels, they may be willing to include you (or your Organisation) in their distribution.

RTO and AGARD reports may also be purchased from the Sales Agencies listed below.

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number. Collateral information such as title and publication date is desirable.

If you wish to receive electronic notification of RTO reports as they are published, please visit our website (www.rta.nato.int) from where you can register for this service.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Etat-Major de la Défense
Département d'Etat-Major Stratégie
ACOS-STRAT – Coord. RTO
Quartier Reine Elisabeth
Rue d'Evère
B-1140 Bruxelles

CANADA
DRDKIM2
Knowledge Resources Librarian
Defence R&D Canada
Department of National Defence
305 Rideau Street
9th Floor
Ottawa, Ontario K1A 0K2

CZECH REPUBLIC
DIC Czech Republic-NATO RTO
VTÚL a PVO Praha
Mladoboleslavská ul.
Praha 9, 197 06
Česká republika

DENMARK
Danish Defence Research Establishment
Ryvangs Allé 1
P.O. Box 2715
DK-2100 Copenhagen Ø

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72
92322 Châtillon Cedex

GERMANY
Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr (FIZBw)
Friedrich-Ebert-Allee 34
D-53113 Bonn

GREECE (Point of Contact)
Defence Industry & Research General Directorate, Research Directorate
Fakinos Base Camp, S.T.G. 1020
Holargos, Athens

HUNGARY
Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
H-1525 Budapest P O Box 26

ICELAND
Director of Aviation
c/o Flugrad, Reykjavik

ITALY
Centro di Documentazione Tecnico-Scientifica della Difesa
Via XX Settembre 123
00187 Roma

LUXEMBOURG
See Belgium

NETHERLANDS
Royal Netherlands Military Academy Library
P.O. Box 90.002
4800 PA Breda

NORWAY
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25, NO-2007 Kjeller

POLAND
Armament Policy Department
218 Niepodleglosci Av.
00-911 Warsaw

PORTUGAL
Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide, P-2720 Amadora

SPAIN
SDG TECEN / DGAM
C/ Arturo Soria 289
Madrid 28033

TURKEY
Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi Başkanlığı
06650 Bakanliklar – Ankara

UNITED KINGDOM
Dstl Knowledge Services
Information Centre, Building 247
Dstl Porton Down
Salisbury, Wiltshire SP4 0JQ

UNITED STATES
NASA Center for AeroSpace Information (CASI)
Parkway Center, 7121 Standard Drive
Hanover, MD 21076-1320

SALES AGENCIES

NASA Center for AeroSpace Information (CASI)
Parkway Center
7121 Standard Drive
Hanover, MD 21076-1320
UNITED STATES

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
UNITED KINGDOM

Canada Institute for Scientific and Technical Information (CISTI)
National Research Council
Acquisitions
Montreal Road, Building M-55
Ottawa K1A 0S2, CANADA

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Full bibliographical references and abstracts of RTO and AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
STAR is available on-line at the following uniform resource locator:
http://www.sti.nasa.gov/Pubs/star/Star.html
STAR is published by CASI for the NASA Scientific and Technical Information (STI) Program
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
UNITED STATES

Government Reports Announcements & Index (GRA&I)
published by the National Technical Information Service
Springfield
Virginia 2216
UNITED STATES
(also available online in the NTIS Bibliographic Database or on CD-ROM)

ISBN 92-837-1113-0