Military/Aerospace MEMS Applications – AVT Task Group 078

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ABSTRACT

The paper summarizes and updates progress of the Applied Vehicle Technology (AVT) Task Group "MEMS Applications for Land, Sea, and Air Vehicles". During its 4-year existence (2000 to present) the Task Group held four meetings to assess future potential military applications. For five high pay-off military applications, which include micro-flow control, inertial measurement units (IMU), fuze/safety&arming, gas turbine applications, and health and inventory monitoring, status of MEMS technologies, R&D needs, and insertion strategies & barriers were determined. The Task Group has also promoted MEMS awareness by organizing lecture series and MEMS sessions at the RTO Spring 2003 symposium. The final Task Group report is planned for September 2003.

1.0 INTRODUCTION

MEMS (Micro-Electro-Mechanical-Systems) are miniature devices, which integrate actuators, sensors, and processors. Functional sub-systems could be electronic, optical, mechanical, thermal or fluidic. MEMS are characterized by their close relationship to integrated-circuit (IC) components both in terms of manufacturing techniques and their potential for integration 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 military is challenged to define its own specific applications, which would utilize the benefits of MEMS technologies to enable more compact (smaller), more efficient, and more "intelligent" systems to improve performance & efficiency and to extend capabilities (functionalities) at reduced cost and weight/volume.

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NATO's Research and Technology Organization (RTO) has formed the AVT (Applied Vehicle Technology) Task Group – TG 078 "MEMS Applications for Land, Sea, and Air Vehicles" to explore aerospace and military applications, which encounter unique challenges due to special reliability and harsh environment requirements. The Task Group (TG) initially discussed a number of military applications, where MEMS would enable enhanced functionalities by increasing maneuverability, autonomy, reliability, affordability, range, and enhanced service life. Subsequently, the TG focused on high pay-off military applications, which include micro-flow control, inertial measurement units (IMU), fuze/safety&arming (S&A), harsh environment applications, and health and inventory monitoring. The paper provides a progress report on the TG, which is considered a follow-on of the BRAMMS (Broad Requirements for Advanced Military Micro-Systems) Project funded by the Western European Union (WEU) [1].

2.0 TASK GROUP OBJECTIVES

The objectives of the Task Group (TG) are to (1) discuss future military requirements for which MEMS can provide enabling technologies, (2) determine potential MEMS military applications, (3) assess the status of MEMS technologies for selected high pay-off applications, (4) determine R&D needs, (5) develop insertion strategies including roadmaps, (6) identify barriers for component insertions and system developments, (7) discuss potential collaborations, and (8) promote dialog between military leaders, members of the defense S&T community, and leading researchers from industry and academia. These activities of the TG fall within the scope of AVT related activities, including fluid dynamics, propulsion, and structures and materials.

3.0 APPROACH

The Task Group (TG) held four meetings, organized MEMS sessions at a symposium, and organized lecture series. The Final Report will be delivered in September 2003. An up-date on the TG activities is provided in this paper.

The first TG Meeting was held 10-12 October, 2000, Ankara, Turkey, in conjunction with the RTO Symposium "Unmanned Vehicles (UV) for Aerial, Ground, and Naval Military Operations". The objectives were:

1) To discuss MEMS activities and interest in participating NATO nations
2) To identify military MEMS applications
3) To select candidates for short term and long term applications
4) To explore interest in S&T collaborations and joint technology insertions

Seven NATO nations participated in the meeting (Belgium, BE, France, FR, Germany, GE, Poland, PL, The Netherlands, NL, United Kingdom, UK, and United States, US) (Appendix 1). Twenty presentations provided an overview of MEMS activities and interest in the participating countries. A list of potential military MEMS applications was developed and matched against the AVT Vehicle Platform Technologies and Propulsion & Power Technologies. Selected MEMS applications were then grouped into three categories: (1) devices ready for insertion, (2) ongoing R&D activities for potential collaborations, and (3) future concepts. Five MEMS topics were selected for further discussions at future TG meetings. An Interim Report and a CD with the viewgraphs have been prepared.

The second TG Meeting was held 7-9 May, 2001, in Loen, Norway, in conjunction with the RTO Symposium "Advanced Flow Management: Vortex Flows and High Angle of Attack – Military Vehicles". Six Nations with a total of 30 participants attended the meeting (Appendix 1). Presentations and discussions focused on the five selected MEMS topics, for which Chairpersons were selected as indicated in the following:

1) Micro-Flow Control (Clyde Warsop, UK)
2) Inertial Measurement Units (IMUs) (Ayman El-Fatatry, UK)
3) Fuze/Safety&Arming Devices (Paul Smith, US)
4) Sensors and Actuators for Harsh Environment (Jih-Fen Lei, US)
5) Health Monitoring Systems (Howard Last and Betsy DeLong, US)

In addition, Ron Derr, US, presented a paper on necessary contacts with NATO Armament Groups for the purpose of standardization, collaboration, and technology pull. The necessary contacts with NATO Armament Groups were identified.

In the discussions the following questions were addressed for the five selected topics:

1) Why MEMS?
2) What are the applications?
3) What is the implementation strategy?
4) What are the barriers?
5) What are the recommendations?
6) What is the interest in collaborations?

An Interim Report and a CD with viewgraphs have been prepared.

The third TG meeting was held in Paris, 22-26 April, 2002, in conjunction with the "Reduction of Military Vehicle Acquisition Time and Cost through Advanced Modelling and Virtual Product Simulation" Symposium. The meeting focused on five topics.

1) MEMS Applications to Harsh Environment (Gas Turbine Applications)
2) Role of MEMS in Combating Terrorism
3) Update of Selected Topics
4) Potential Collaborations and a potential Coordinated Demonstration of Technology (CDT)
5) Review of Draft of Final Report

The topic of gas turbine applications was addressed in a workshop, which brought together MEMS technology developer & turbine engine experts (Appendix 1) and addressed the following questions:

1) What are the requirements and challenges for future gas turbines?
2) Why MEMS? What is MEMS? How can MEMS mitigate challenges?
3) What is the status of MEMS technology (related to gas turbine applications)?
4) What are the implementation strategies or roadmaps?
5) What are the barriers for implementation?

The topic of combating terrorism was addressed in a brainstorming session to discuss the role of MEMS in this application.

The fourth TG meeting was held in Aalborg, Denmark, in conjunction with the RTO "Combat Survivability of Air, Sea, and Land Vehicles" Symposium, 23-26 September, 2002. A proposal for a Coordinated Demonstration of Technology (CDT) for munitions monitoring was prepared, and MEMS sessions at the Spring 2003 RTO Symposium in Brussels were organized.

To enhance MEMS awareness, the TG had proposed a Specialists' Meeting, which was integrated into the RTO Spring 2003 Symposium. In addition, a Lecture Series were prepared for presentation in Canada, Europe, and US.

In the following conclusions from the four TG meetings are summarized.

4.0 FUTURE REQUIREMENTS

MEMS will play a critical role to meet future requirements considering current demands for more compact (smaller), more efficient, and more "intelligent" systems, which would improve performance and efficiency, and extend capabilities (functionalities), including increasing maneuverability, autonomy, reliability, affordability, range, and enhanced service life. In other words, MEMS will enable the development of new military capabilities, which will allow the introduction of low-cost and "high-end" functionality to military systems, thereby, will extend their performance and lifetimes. Examples of such enhanced capabilities include the development of the following devices and systems:

1) Multi-parameter sensors and monitoring chips
2) Distributed sensing and smart structures for health and utilization monitoring as well as surveillance and control
3) Intelligent guidance and control through inertial navigation units integrated onto electronic chips
4) Miniaturized mechanical actuators for fuzing, safeing, and arming
5) Miniaturized and integrated fluid control actuators for fluid/gas manipulation
6) Integrated multifunctional components for biochemical sensing and monitoring
7) Miniaturized optical elements for display and, possibly, mass storage techniques
8) Miniaturized optical or RF transmit/receive units for tagging and networked communication
9) Micro-aerodynamics manipulation and control

Enhanced capabilities also include demands for more compact, light-weight engine designs, which are very fuel efficient and highly reliable, and the vision for future "intelligent" engines. Specifically for military aero-engines gas turbines, the long-term goals of doubling thrust-to-weight ratio for increased maneuverability require new enabling technologies. MEMS will also play a dominant role in developing "intelligent" combustors, which, in addition to controlling combustor dynamics, may provide real-time capabilities of overall health monitoring, controlling damage and in-service degradation, and self-healing capability. The challenges associated with these enhanced capabilities are high temperature, need for novel materials, distributed control, active control, reduced lifecycle costs, management of volumes of data, increased intelligence and versatility, and signal and power connectivity. MEMS has the potential to mitigate these challenges.

Because of recent events, Combating Terrorism (CT) has become a priority topic and has been addressed at the Paris Task Group meeting. The role of MEMS for the following future CT requirements [2] was seen to be focused on enabling the following capabilities:

1) Smart, autonomous sensors and monitoring
2) Distributed and networked sensing
3) Multi-parameter sensors and alarms
4) Miniaturized, unmanned, autonomous vehicles

5.0 POTENTIAL MEMS APPLICATIONS

MEMS technology has numerous attributes, which can mitigate challenges to meet future military requirements. They include miniaturization (allowing distributed sensing and actuation coupled with redundancy), reduced cost of fabrication (through the use of microelectronics processing technologies), real-time control (allowing on-line active process control and health monitoring), and control of macro physical processes through micro action (allowing for example aerodynamic control of delta wings by micro actuators).

The TG has developed a list of potential of MEMS applications for military systems, which is in part based on [1]. MEMS will enable enhanced functionality for the following applications:

1) Intelligent/unmanned operations
2) Inter-linked communication channels (RF or optical)
3) Multi-sensing capabilities; distributed, agent-based, or sensor array systems
4) Inertial navigation systems
5) Integrated fluidic systems including fluid sensing, control & transport
6) Optical devices and systems, and displays
7) Nuclear & bio/chemical sensing
8) Covert, autonomous, unmanned ground sensors, detection and treatment systems
9) Energy / power generators and management
10) Micro thrusters
11) Fuze/safety & arming
12) Micro-satellite and unmanned surveillance systems
13) Health monitoring and utilization monitoring systems
14) Logistic tagging systems
15) Self assembly/healing and reusable modules/subsystems

These, generic, functional elements, can be integrated across the various military platforms for land, sea, air, space and missile applications. In addition, MEMS will enable the realization of advanced platforms for avionics and aircraft systems, miniaturised spacecraft, smart unmanned land vehicles, robots and sentinels, stabilized platforms and launch-pads, smart missiles and bombs, as well as underwater vehicles.

6.0 HIGH PAY-OFF MILITARY APPLICATIONS

The AVT MEMS Task Group has focused on five topics, which are considered high pay-off MEMS applications and have reasonable changes of a successful insertion. These applications will be discussed in the following, based in part on the contributions by the Chairpersons, who are responsible for the selected topics.

6.1 Micro-Flow Control

One potential MEMS application is active control of boundary layer flow separation on the aerodynamic surfaces of air vehicles and within their propulsion systems. Research over the last decade has established that “smart skins” employing arrays of MEMS sensors and actuators have the potential to create macro-scale effects by the manipulation of micro-scale features of the boundary layer flow. There is sufficient evidence to suggest that MEMS flow control technology could ultimately replace conventional flight control surfaces and produce drag reductions of up to 80%. MEMS flow control technology could be exploited to achieve lift-on-demand for applications such as agile missiles and uninhabited tactical aircraft together with low-drag, non-intrusive methods to maneuver vehicles and projectiles for extended range and precision. Micro flow control could also be used to enhance the aerodynamic performance of propulsion systems through improving the aerodynamic performance of compressors, turbines and low-observable intakes. Other military applications include the use of MEMS-based flow control for aerodynamic control of micro-air vehicles, on-chip cooling of electronics components, and enhanced mixing and control of flows within "lab-on-chip" bio/chemical sensors.

6.2 Inertial Measurement Units (IMUs)

Another novel, low-cost and "high-end" functionality application is the development of complete inertial and navigation units on a single chip.

The development of inertial systems is a common goal of the military and commercial MEMS communities. It has been universally recognized that they offer major advantages in terms of size, weight and cost over conventional systems.

MEMS applications are of interest to Inertial Reference Systems (IRS), which are based on either optical ring laser gyros and accelerometers or electromechanical systems, and Attitude & Heading Reference Systems (AHRS), which are aided by GPS/GNSS through hybridization to enable the use of less accurate accelerometers and gyros. Thereby, the incorporation of MEMS for each sensor or a combination of accelerometer/gyro multi-sensor systems is possible.

6.3 Fuze/Safety&Arming Devices (F/S&A)

MEMS based F/S&A devices are considered for torpedos and missile propulsion. They will be of future interest for bombs and guided missiles. MEMS components for these applications will also incorporate setback-and-spin sensors, micro-detonators, and shock stable RC oscillators.

The advantages of MEMS for this application include (1) retaining mechanical locks to meet existing safety requirements, (2) achieving small size (electronic IC scale) which relates to more applications without large volume/weight penalty, and (3) improving sensors, which directly measure environment and are less likely to be fooled.

6.4 Sensors and Actuators for Harsh Environment (Gas Turbine Applications)

The application of MEMS to propulsion systems can improve the performance through increased engine performance (via control), life extension of propulsion systems (via monitoring, logistics), and reduced manufacturing costs (via intelligent processes). Specifically for gas turbines, MEMS technologies can mitigate the challenges in several areas, including fault tolerance, power scavenging, wireless connectivity, in-situ processing, and spatial/temporal distributed sensing and actuation. Near term applications are health monitoring of large blades or bearings, high-resolution model validation, Low Pressure Turbine (LPT) flow control, and active control. Ultimately MEMS will revolutionize design and operation. The requirements/specifications for these applications are demanding as discussed later.

6.5 Health Monitoring Systems

MEMS military applications include inventory control, environmental monitoring, and service life prediction for munitions. This will be achieved by integrating Radio Frequency Identification (RFID) and MEMS environmental sensors into weapons/weapon systems to provide real time status of individual munitions to the field command and logistic supply command. The system will indicate system availability and will predict remaining individual weapon service life. MEMS sensors can be applied to munitions to monitor temperature, moisture, vibration and other parameters during munitions life cycle the condition.

7.0 STATUS OF HIGH PAYOFF APPLICATIONS

7.1 General

Concepts for the various MEMS applications have been verified, however additional R&D is required for practical implementations, to achieve increased robustness & performance and develop new materials for harsh environment applications. IMU and F/S&A are in the most advanced stages of implementation.

7.2 Micro-Flow Control

The status of MEMS application to flow control was assessed by evaluating investigations of three leading institutions in this field: (1) University of California at Los Angeles (Prof. Chih-Ming Ho) with California Institute of Technology (Prof. T.C. Tai), (2) Georgia Institute of Technology (Prof. Ari Glezer), and (3) BAE SYSTEMS (Dr. Clyde Warsop). It was shown that the physics of flow control is reasonable well understood, and concepts have been verified; however practical implementation requires additional R&D, in particular for the development of practical, robust actuators. The investigations demonstrate the potential of achieving macro affects in the flow field using micro actuators placed at the right place in the boundary layer flow.

UCLA/Caltech has explored the coupling of micro-actuators with the thin boundary layer of a delta wing, to control the position of leading edge vortices and therefore to control moments associated with roll, pitch and yaw. For this control of flight maneuverability by flow separation control, three MEMS components were developed on a smart micro-skin around curved leading surfaces: (1) distributed shear stress sensors (to determine separation point), (2) distributed balloon actuators (to control position of separation point), and (3) an integrated circuit. Shear stress sensors and balloon actuators were flight-tested up to 1.5 Mach and 12000 m. The smart skin was attached to an UAV model having a 2 m wingspan, and its flight maneuverability was demonstrated at 0.15 Mach flight conditions.

Georgia Tech is using MEMS-based actuators and sensors for fluidic-based aerodynamic flow control. Actuation is achieved using pulsed jets that in some cases were operated in a “synthetic” (i.e., zero net mass flux) mode. The jets were integrated into the flow boundary. The interaction of these actuator jets with an external cross flow over the surface can displace the local streamlines and induce an apparent or virtual change in the shape of the surface. Thereby global flow changes are produced on length scales that are one to two orders of magnitude larger than the characteristic scale of the jets. This approach emphasizes an actuation frequency that is high enough so that the interaction domain between the actuator and the cross flow is virtually invariant on the global time scale of the flow. Therefore global effects such as changes in aerodynamic forces are effectively *decoupled* from the operating frequency of the jet actuators. The efficacy of this approach for aerodynamic flow control has been demonstrated for the suppression of separation at post-stall angles of attack and for substantial reduction in drag at low (typically cruise) angles of attack.

BAE SYSTEMS has assessed, quantified, and demonstrated the viability of employing MEMS components for a medium term aerospace flow control applications. This work is part of the European Commission (EC) supported ‘AEROMEMS’ research program. It was concluded that a commercially viable flow separation control system based on the application of MEMS pulsed-jet actuators could be matured for commercial application within a 10 – 15 year timeframe, or perhaps quicker with sufficient development effort. A follow-on research program ‘AEROMEMS II’ has been started, which will include large-scale industrial wind tunnel demonstrations, development/validation of flight-worthy MEMS hardware, evaluation of system integration issues (maintainability, reliability), environmental testing of MEMS flow control devices to demonstrate robustness, and preliminary assessment of high volume MEMS production issues (process, cost, reliability). The MEMS applications to flow separation control will be demonstrated on wing leading and trailing edge high-lift systems, intake ducts, and engine compressors.

7.3 IMU

Inertial measurement units on a single chip are being considered to provide position, attitude and velocity data. IMUs will consist of gyros, accelerometers and signal processing circuitry to measure rates, angles, δv and δq (depth and flow rates for underwater applications).

Early predictions of both cost and performance have not, as yet, been fulfilled and current state-of-the-art characteristics fall 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.

Today’s micro-machined Coriolis Vibratory Gyroscopes (CVG) developed in the US and Europe have an “accuracy” (noise and bias stability) in the range of 1-10 °/s. Sensors under development already show an accuracy better than 0,1°/s with costs of approximately $1000. New concepts with noise below 0,025°/s and a bias stability better than 0,03°/s are also developed. This performance is near the domain of FOG. The first military application was considered by the US Air Force Air Armament Center for conducting a captive flight demonstration of MEMS IMUs integrated into the Wind Corrected Munitions Dispenser (WCMD). However this program was cancelled because of non-technical reasons.

7.4 Fuze/Safety&Arming

Development of F/S&A devices are being explored in France, United Kingdom, and the US. The goal of the US development at the Indian Head Division of the Naval Surface Warfare Center (IHDNSWC) is to produce a fully functioning F/S&A that will be an order of magnitude (10:1) smaller than the last torpedo F/S&A. The design integrates existing developed sensors and actuators and uses industrial infrastructure for device fabrication. The system relies on Commercial-Of-The-Shelf (COTS) and modified COTS devices to reduce development time and cost. Final assembly and packaging that combine MEMS components with explosives will be performed at government facilities. Full-scale sea-run torpedo tests have demonstrated the robustness of MEMS to operate in real world environments. Current efforts are directed at (1) refining simulation based modeling and process controls, (2) designing an integrated F/S&A system package, (3) evaluating and testing the actuator, (4) incorporating major components of an IMU to measure weapon/platform separation, and (5) developing optical energy transfer MEMS F/S&A concepts.

7.5 Harsh Environment (Gas Turbine)

Potential improvements of propulsion systems through MEMS applications rely on novel materials. Silicon carbide (SiC) holds great promise for these applications, which are characterized by the presence of high temperatures, large number of vibrational cycles, erosive flows, and corrosive media. The SiC material is explored in different countries such as UK (TRW), France (Schlumberger) and the US. In the latter, Case Western Reserve University machined fuel atomizers from SiC and nickel using novel molding processes. Techniques to reduce irregularities in the surface morphology were developed. Successful performance and erosion tests were performed on these atomizers. In addition, the first MEMS-based pressure sensor was developed by Kulite in collaboration with NASA Glenn Research Center. This sensor has been successfully tested under realistic operational conditions.

7.6 Health Monitoring

MEMS applications for health monitoring are explored in several countries. In the US, Army and Navy programs are addressing the need for health monitoring of ordnance. The Navy is also addressing the need for health monitoring and condition-based maintenance on ships and other platforms, as well as inventory control.

In the UK and France, the needs for environmental monitors to enable lifetime prediction of defence materiel are addressed. Testing of COTS devices and existing MEMS processes is carried out against the harsh environments likely to be experienced by defence equipment during its typical life between procurement, storage, transportation and use. The UK program is also investigating how effective power management can be undertaken to ensure a long operational lifetime for these sensors systems for monitoring humidity, temperature, and shock & vibration.

In general, the expertise of various commercial health monitoring systems can be utilized for military applications. For example, biomedical applications address similar challenges such as wireless telemetry and sensor reliability.

8.0 R&D NEEDS

8.1 General

Improvements in reliability, robustness, packaging, and long-time performance were identified as R&D needs for the various applications. Specific needs for the high pay-off applications were also identified, as discussed in the following.

8.2 Micro-Flow Control

For this MEMS application, many of the basic physics and concepts have been demonstrated, however the technology is immature for real applications. Development of components and their demonstration under practical conditions is needed to demonstrate reliability and robustness.

8.3 IMU

Implementation of IMU MEMS components is possible at this time. R&D needs remain in the area of reliability and packaging.

8.4 Fuze/Safety&Arming

The primary R&D need for F/S&A is a low-cost/small-volume/low-voltage MEMS firing train to replace the high-voltage slapper. This need is addressed in several countries. Also long term performance for F/S&A devices now under development is needed.

8.5 Harsh Environment (Gas Turbine)

Several MEMS applications for gas turbine health monitoring were identified which require operations at high temperature, high pressure, and high vibration levels. Lifetime and durability of present approaches using SiC and other novel materials has to be assessed, and new packaging methods have to be developed. Also the failure mechanism of critical components has to be determined to avoid no-catastrophic failure.

8.6 Health Monitoring

One of the major R&D needs is the development of power sources for stand-alone sensors. This need is currently being addressed in the DARPA Micro Power Program with power generation using micro turbines, micro internal combustion engines, and micro fuel cells. Also reliability questions of health monitoring systems need to be addressed.

9.0 INSERTION STRATEGIES

9.1 General

Military MEMS will have to draw heavily on commercial MEMS in order to exploit the cost benefits associated with mass-market products. In many, if not in the majority of future applications, military systems will rely entirely on devices developed for the commercial and consumer market. Mass-market products available for potential aerospace applications include accelerometers, chemical sensors, embedded sensors, flow sensors, fluidic valves, humidity sensors, gyroscopes, injection nozzles, lab-on-chip devices, micro-spectrometers, micro-thrusters, pressure sensors, temperature sensors, wireless communication components, and other devices. In the context of military systems, however, the performance of such devices will need to satisfy the stringent specifications and environmental conditions required by the defense market. For the selected high pay-off applications, COTS and new developments are being considered as shown in the following discussion of insertion strategies.

For one high payoff applications (gas turbines) a roadmap for MEMS insertion was developed and is summarized below.

9.2 Micro-Flow Control

MEMS technology for this application is currently immature with new areas of research continuously being identified. It is estimated that manned vehicle applications may be possible in 10 – 15 years, and UAV applications may be possible in 5 years. These expectations depend on sufficient funding and technology pull both from military and commercial users. It is critical to find the right application opportunity where MEMS can provide new functionalities, identify road maps for technology implementation, demonstrate & quantify benefits, build confidence, and get “buy-in” from industry/end-users. International collaborations may be required to maintain a critical mass. Such collaborations were discussed in the Task Group between the US and UK to develop realistic actuators for flow control.

COTS devices (in particular actuators) are not available for flow control. Presently unique actuators (and in many cases unique flow sensors) have to be developed and fabricated. This is costly and time consuming, which accounts for the difficulties to realize MEMS applications in this area. If possible, it is desirable to tap into future consumer applications, if they become available with devices such as fans and pumps in the automotive, air conditioning, and refrigeration sectors.

Micro-jets are one example for preferred flow control actuators. The application of available micro-thruster technology may be of interest for these actuators. In fact, Georgia Institute of Technology is investigating MEMS pulsed, reacting jets to achieve improved control authority on boundary layer active control.

9.3 IMU

Insertion strategies should preferably consider COTS, tailored COTS, and/or modular COTS. If absolutely essential, new developments should be funded. Because of the wide availability of commercial devices, military implementation is possible now. In fact the NATO Task Group has identified several systems, which are receptive with the following technology insertion windows: (1) for underwater applications: 2002/3 and 2006, (2) for flight applications: now, and (3) for space applications: already implemented for trials (gyros to be used by 2002/3).

9.4 Fuze/Safety&Arming

Implementation of these devices is possible either as new components during development of new weapon systems or as upgrades of existing systems to add new capabilities with more/expanded sensors. For example, IMUs could be added to the torpedo S&As. The recent development of torpedo S&As has utilized several COTS sensors. This resulted in reduction of cost and time in the initial development. Also modified COTS devices have been used.

9.5 Harsh Environment (Gas Turbine)

Implementation should start with the fan & compressor areas and gradually move to more challenging areas such as the turbine and combustion chamber. When moving the technology from laboratory R&D to engine production, lifetime/durability issues of the MEMS devices need to be further addressed. Novel devices should be evaluated on test beds, and results should be made available to engine designers. This will increase awareness to the stakeholders and will allow design-stage entry into new systems. Attention should be paid to the failure mechanism of the device to ensure “gentle” failures.

Commercial MEMS devices generally do not meet the requirements and specifications for harsh environments, which include for gas turbine applications: (1) high temperatures from 200-300°C (fan/compressor), to 900°C (turbine), and 1200°C (combustor), (2) high pressure, (3) high vibration levels (1000 Hz and higher), (4) high noise (>140dB) and force levels (10G → 25G), and (5) harsh environments associated with water, humidity, and dust. New materials are required to replace silicon, generally used in commercial MEMS devices. Significant progress has been made in manufacturing SiC structures, including lateral resonators and filters, structures for mechanical property measurements, mirror-based flip-up optical devices, capacitive pressure sensors and shear stress sensors, electrical characterization structures, micro-motors, and flow sensors. Some of the SiC components have been tested up to nearly 500°C.

The MEMS Task Group has developed a roadmap for gas turbine applications. It is summarized in the following.

MEMS technology has the potential to mitigate challenges expected with future gas turbine developments, including flow separation and flow instability control, combustion instability control, noise control, emission control, vibration control, health monitoring, and other. It can be anticipated that MEMS applications will occur in different stages with increasing complexity, namely (1st) to propulsion system ground testing, (2nd) to propulsion-system on-board health monitoring, (3rd) to active control for increased engine performance, and (4th) to intelligent engine development. Different time spans for technology insertions were identified, from near term (1 to 3 years), to mid term (3 to 5 years), and far term (over 6 years). The near-term applications are associated with health monitoring tasks in the inlet/fan region and at the exit, and with active control of noise, emission, and high cycle fatigue. Mid-term applications are associated with health monitoring of combustors and with active flow instability control in fans and compressors. Also wireless data acquisition is considered as a mid-term application. Far-term applications include blade vibration monitoring & active control, damage/fault accommodation in control systems, and development of intelligent engines. The anticipated time spans are depended on the development of supporting technologies, such as packaging, wireless telemetry, and power sources, all capable of working in harsh environments.

9.6 Health Monitoring

Demonstrations of health monitoring systems should be given highest priority to further implementation planning and to foster user/sponsor interest and commitment. For munitions monitoring several COTS sensors are being used to determine munitions exposure to storage and transportation environments. These include sensors for temperature, humidity, and vibration & shock as described in detail later in a proposal for a NATO collaboration in this area.

10.0 BARRIERS FOR INSERTION

10.1 General

The use of COTS components for military applications is highly desirable as discussed earlier. Clearly, the total reliance on commercial MEMS poses a number of barriers, which are addressed in the following in part based on [1]. This is followed by discussions of barriers for the insertion of the high pay-off applications.

10.1.1 Reliability

The high cost and complexity of military systems, and in particular military aerospace systems, has traditionally made it essential that they are repairable under battlefield conditions. Major suppliers have set up extensive world-wide support facilities to complement those run by the services themselves. Product support and repair form a significant part of their overall business. However, MEMS devices are in general not considered to be repairable or salvageable, and, like their electronic counterparts, failure in service will inevitably require replacement of the entire micro system. Provided that packaging and integration of the MEMS device take this requirement into account, repairs to the overall system or platform could be simpler and faster. However, there are likely to be important commercial and operational impacts on the defense industry if the introduction of MEMS becomes widespread.

10.1.2 Reliability of Supply Availability

Military MEMS will depend on the commercial / civil MEMS developments, as low volumes for the military markets will attract high costs. In order to reliably supply many of the devices and systems for MEMS defense applications, advances in present capabilities are needed to take MEMS technology to the higher performance levels. For example, the sensitivity and stability required for inertial navigation on a chip have to be three to four orders of magnitude better than the best MEMS accelerometers or gyroscopes available today. Since current inertial sensing device performance is more than adequate to meet the anticipated needs of automotive markets (the primary non-defense market for inertial sensors), the commercial sector alone will not drive the development of the MEMS technology to the densities of integrated electronics and mechanics needed for inertial navigation on a chip.

For other MEMS defense applications, including munitions safety & arming and condition-based maintenance, existing or near-term commercial MEMS technologies and products need to be adapted and qualified for military use. For example, signal detection and processing requirements are likely to vary, which will mean different co-fabricated electronics designs and changes in the ways signals are detected (e.g., different ranges or thresholds).

10.1.3 Obsolescence (Particularly for COTS)

Military product life cycles exceed those for commercial / consumer products. Both process availability and product obsolescence become a major concern. The total product life cycle for the embedded MEMS technology in a military application could therefore be in the region of about 30 years. This should be contrasted with the life cycle of commercial and consumer products, which could be as little as one year. It certainly exceeds the expected life of state-of-the-art commercial fabrication facilities and processes, which may require major update or renewal every 5 years. This marked difference between the military and commercial product life cycles and the corresponding life cycle of the associated fabrication processes and equipment raises the question of process availability and product obsolescence.

10.1.4 Packaging

Packaging for military MEMS is even more critical than that for commercial applications, and even here it is regarded as a prime discriminator between commercial success and commercial failure. For commercial micro systems, packaging is said to account for 80% of the cost and 80% of the failures. The proportions of both in a military environment 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 micro systems 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 with “aerospace quality” is the packaging and final testing.

10.1.5 Lack of Standards (Terminology, Test Procedures and Interfaces)

In general, the stringent operational and environmental standards, dictated by the military, will also include: resilience to radiation, high temperatures, vibration & shock, and electromagnetic compatibility. In addition, the technologies will need to take into account the non-accessibility after launch, in certain circumstance, which dictate the need for “first-time-right” qualification.

10.1.6 Security Aspects

Access to military-specific MEMS developments by the civil markets may have security implications. There are a number of possible routes for military requirements to exploit the cost and volume advantages of commercial and consumer MEMS production. Dual use of technology developed entirely in the commercial sector is clearly the most desirable option, but this assumes that the performance and environmental capability will be adequate for the intended military application. For critical security applications, it would be essential not just to make the device unusable in a military system by a third party, but also to physically destroy or remove the design details of how the improved performance or functionality was achieved in the first place. The integration and implementation of these security concepts into a commercial wafer fabrication environment without defeating the object of commercial high volume manufacture is an aspect that will require much thought.

In addition to these general discussion of barriers for using COTS components in a military environment, barriers for insertions for the selected high pay-off devices is discussed in the following.

10.2 Micro-Flow Control

MEMS technology in this area is primarily a technology “push”. It is still perceived as high risk and immature/unproven for real applications. This results in low commitment from potential sponsors. With research activities mainly at laboratory level and often lacking a critical mass, it is critical to obtain “pull” and commitment from customers & system integrator, create a critical mass of research possibly through collaborations, undertake realistic practical demonstrations and quantify cost/benefits, and educate “end users” technology integrators.

MEMS application to flow control is one of the most difficult tasks from the high pay-off selections. Although the physics of flow control is reasonable well understood, significant challenges with the development of MEMS sensors and actuators have to be addressed. While traditionally MEMS devices are remote from the application environments through hermetic packaging, flow control devices must directly interact with the environment. This poses severe implications on design and packaging, when considering reliability, maintenance & repair, and safety & certification. It is anticipated that the first MEMS applications will utilize limited number of sensors & actuators, cover small & localized surface areas, and will have limited intelligence (simple on-off action). Likely applications will be initially in inlet ducts for control of flow separation and on small UAVs for maneuvering and lift improvement. Substantial advances are still required to achieve flow control on large areas, including enhanced understanding of the fluid physics and improved process technologies to fabricate robust, affordable, and reliable devices.

10.3 IMU

Insertion should be based on commercially available components if at all possible. Modifications or new development should be carried out through national and international collaborations. For example, the services in the US are jointly developing an IMU for different applications. These collaborations should be expanded to the international level as it had been planned between the US and UK as discussed earlier. Also, collaborations are hampered by the lack of standards for terminology, test procedures and interfaces.

Progress in the development of IMUs is likely to rely heavily on a market pull driven mainly by civil applications. Novel encapsulation, packaging, and integration techniques will be necessary to address the requirements of defense applications. Military specifications (including aircraft, missiles and munitions) are particularly demanding with examples shown in the following:

Vibration:	20 to 3,000 Hz (for 5g to 20g)
Structural Resonance:	> 3,000 Hz
Temperature:	-65°C to > +125°C
Mechanical Shock:	from 100g (aircraft), to 300g (missiles) to more than 15,000g (gun launched munitions)
Angular Acceleration:	>500,000 rad/S^2 (spinning gun launched munitions)

In spite of these unique requirements, microsystems will proliferate within military platforms providing intelligent functionality and enhanced performance.

10.4 Fuze/Safety&Arming

Although the F/S&A is being successfully inserted into a torpedo system in the US, long-term performance needs close evaluation. The failure mechanisms are not known and may be related to various sources: many parts, new materials with unknown interactions, and out-gassing of adhesives and explosive. Barriers for additional insertions include non-existence of “small/cheap” firing train and sponsor & user unfamiliarity with MEMS technology.

MEMS-based S&As are presently being considered in high-end smart munitions (i.e. torpedoes, missile, rockets, etc). As the technology develops and cost is reduced, they will also become attractive to lower-cost, high-volume weapons (i.e. artillery shell, bombs, sub-munitions grenades etc.).

The goal of the first generation MEMS based S&A is to produce a fully functioning S&A for the next generation torpedo that will be an order of magnitude (10:1) smaller and will provide ½ order of magnitude (5:1) reduction of the total life cycle cost (procurement and maintenance) relative to the current torpedo S&A. This is accomplished by using a mechanically locked MEMS slapper detonator. Tests have demonstrated the robustness of the MEMS devices to operate in real world environments.

The next generation of S&A devices will incorporate major components of an IMU to measure weapon/platform separation and will explore development & integration of fiber optics and optical energy transfer techniques into MEMS S&A concepts. Also low-cost, small, low-voltage MEMS firing trains, which will integrate energetic materials (explosives and propellants) into the MEMS device, will be pursued.

10.5 Harsh Environment (Gas Turbine)

MEMS insertion to gas turbines is affected by the generally long life cycles for new products, which is about 10 years for civil and about 30 years for military systems. In addition, low MEMS awareness, requirements for new regulatory regulations, and a relatively small market size for MEMS components pose severe barriers for insertion. In addition, technical barriers remain, including reliability for surviving in harsh environment, packaging & interfacing, and real-time processing of large amount of data-information. In lie of these barriers, retro-fitting and add-on approaches will most likely to succeed first, relative to development of new systems.

10.6 Health Monitoring

Advancements in MEMS technology in the areas of power, wider availability, and reliability are needed. A roadmap for munitions health monitoring systems to be integrated into existing inventory monitoring system was developed as part of the Task Group activities. This roadmap is the basis for a proposal for a Coordinated Demonstration of Technology (CDT) described in the next section.

11.0 POTENTIAL COLLABORATIONS AND TECHNOLOGY INSERTIONS

Health monitoring of munitions has been identified as an opportunity for a Coordinated Demonstration of Technology (CDT). A proposal for an Exploratory Team (ET), which would explore the feasibility of a CDT to be supported by several NATO Nations, was prepared and presented to the AVT Technical Committee Propulsion and Power Systems (TC PPS). A summary of the proposal is given in the following.

Objectives: The CDT has the following objectives: (1) demonstrate an integrated individual munitions health monitoring and inventory system based on COTS components, (2) demonstrate prototype MEMS sensors, and (3) develop a proposal for a NATO monitoring concept.

Military Benefits: Weapon systems are designed to have an expected life if maintained and stored according to known guidelines. Present service-life determinations are based on manufactured groups or lots. However the useful life expectancy has a strong dependency on environmental factors such as storage temperature and humidity. These weapon-specific life evaluations and predictions will lead to significant cost savings by eliminating the need for premature demilitarization of assets.

Approach: MEMS technology has resulted in the development of low cost, miniaturized, low power & high-resolution sensors. Monitoring systems built upon this technology have the ability to monitor the storage environment of individual weapons. Knowledge of the individual exposure to operational conditions (temperature, relative humidity and shock loads) enables evaluators to evaluate safe life based on chemical and mechanical aging models of particular weapon systems.

The CDT would consist of three parts. The first two parts would be hardware/software demonstrations. The third part of the CDT would address joint concepts for NATO meeting the needs to (1) inventory assets, (2) track assets during deployment, (3) provide high-resolution environmental data under unusual circumstances, (4) validate aging models, and (5) improve interoperability for joint operations.

Representatives of several NATO Nations (CA, NL, PL, UK, US) on the MEMS Task Group have expressed interest in participating in the proposed Exploratory Team to explore the feasibility of the proposed CDT. National support for the potential CDT would be required. The potential ET and CDT would be chaired by the US (Betsy DeLong, US Navy).

In addition to munitions health monitoring, other potential collaborations have been discussed within the MEMS Task Group. In the area of flow control, collaborations between BAE SYSTEMS and Georgia Institute of Technology in the area of practical flow control actuators have been discussed, and collaborations between BAE SYSTEMS and Case Western Reserve University in the area of SiC technology are being considered.

12.0 MEMS AWARENESS AND USER/SUPPLIER INTERACTIONS

12.1 Lecture Series

The Task Group had proposed the Lecture Series "MEMS Aerospace Applications". The lectures were approved for presentation in Montreal, Canada (October 2002); Ankara, Turkey; Brussels, Belgium; and Monterey, US (all in February/March 2003). The announcement for the lectures is summarized below.

The lectures will start with a description of concepts, terminology, basic micro machining processes, potential impacts, and the multidisciplinary nature of the field using example devices and applications.

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

One potential enabling technology is active control of thin boundary layer flows that develop on the aerodynamic surfaces of air vehicles and within their propulsion systems. MEMS sensors and actuators can create macro-scale control effects by the manipulation of micro-scale features of the boundary layer flow, 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.

Subsequently, the development of complete inertial and navigation units on a single chip will be discussed offering major advantages in terms of size, weight and cost over conventional systems. This lecture will describe the evolution of the designs towards the realization of MEMS-based IMU.

In addition, the basic principals and requirements of Fuzing/Safety and Arming (F/S&A) systems will be presented. A notional MEMS based F/S&A concept will be developed by integrating Commercial-Off-The-Shelf (COTS) sensors/actuators with modified COTS and custom made MEMS devices, followed by a discussion of system level integrated packaging. Also, full-scale torpedo test results will be presented.

Micro power generation using micro fuel cells and micro engines will be discussed to potentially enable standalone sensors and actuators with wireless communication. Also, micro rocket technology to perform spin-up/spin-down maneuvers on satellites will be addressed.

For gas turbine applications, MEMS needs for future engine developments will be reviewed, including requirements for future intelligent engines. SiC MEMS technology will be described, which holds great promise for these applications, which are characterized by the presence of harsh environments (e.g., high temperatures, large number of vibrational cycles, erosive flows, and corrosive media).

Furthermore, MEMS applications for autonomous inventory & storage environments monitoring and for service life predictions will be addressed. In-situ tests of first generation systems using Radio Frequency IDentification (RFID) will be presented, and planned second and third generation efforts with embedded environmental MEMS sensors will be described.

The final lecture will introduce MOEMS (Micro-Optic-Electro-Mechanical-Systems) in the context of optical communication & sensing systems and will provide a historical perspective and an overview of the current state of the art of this technology."

12.2 Symposium

The Task Group has organized 6 MEMS sessions with a total of 19 papers at the "Novel Vehicle Concepts and Emerging Vehicle Technologies" symposium, 7-10 April 2003, Brussels.

13.0 CONCLUSION AND FUTURE PLANS

MEMS technologies will enable more compact (smaller), more efficient, and more "intelligent" systems to improve performance & efficiency and to extend capabilities (functionalities) at reduced cost and weight/volume. The Task Group has identified five high pay-off applications, which increase maneuverability, autonomy, reliability, affordability, range, and enhanced service life. These selected applications are micro-flow control, inertial measurement units (IMUs), fuze/safety&arming, harsh environment applications (for example to gas turbines), and health and inventory monitoring. The technology status, R&D needs, insertion strategies, and barriers for insertions were identified for the selected applications. Also future R&D directions in advancing MEMS applications were outlined. For gas turbine application a roadmap was developed, while for the other topics general directions in future R&D were described. The benefits of using COTS components for military applications were discussed. COTS applications are desirable to utilize the cost benefits associated with mass-market products, however barriers exist because of the unique military requirements. Furthermore a proposal for Coordinated Demonstration of Technology (CDT) for munitions monitoring was prepared. In addition, lecture series and a symposium were organized to increase MEMS awareness and supplier and user interactions.

14.0 ACKNOWLEDGEMENT

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15.0 REFERENCES

[1] BRAMMS (Broad Requirements for Advanced Military Micro-Systems) Project funded by Western European Union (WEU), Final Report dated 18 January 2000.

[2] RTO Workshop "Combating Terrorism", 5-7 February 2002, Arlington, VA, USA.

16.0 APPENDIX 1

The participants in the four Task Group meetings are identified in the following: (1) Ankara, Turkey (10-12 October, 2000); (2) Loen, Norway (May 7-9, 2001); (3) Paris, France (22-26 April, 2002); and (4) Aalborg, Denmark (23-26 September, 2002).

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