

POTENTIAL APPLICATIONS OF MICRO AND NANO TECHNOLOGIES ON SPACE TRANSPORTATION SYSTEMS

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ABSTRACT

This paper highlights the current state of art of Micro and Nano technologies and also describes the Research and Developments activities going on at EADS-Space transportation with CNES and ESA. A diverse range of MEMS COTS/MOTS (MEMS Commercial off The shelf) are available in the markets that are primarily applicable to Space Transportation vehicles particularly on the Telemetry Sub systems with some specific upgrading activities. For the "End-User", reliability assurance is an integral part of the space qualification process. The testing methods/protocols are also very device dependent. EADS-ST has participated with CNES, ESA and research labs for the development of PoF (Physics of Failure) modelling on reliability prediction.

In order to apply MNT's (Micro and Nano Technologies) in the space domain (launchers, satellites, probes), validation of these devices under space launchers environment is essential. Flight opportunities are a key issue since technologies not qualified in-orbit are usually seen as risky and are discarded by the Space Industry. There are some flight opportunities for MNT in-orbit demonstration with Ariane 5 launchers. For that, we propose to develop a recurrent Technology Test Bed (TTB), which could offer standard interfaces with technology experiments.

The target in short term (5 years) is the development of "Low cost telemetry sub-systems" by using smart MEMS sensors. For that, we started the following works for coming three years (2005-2007):

Phase 1: Spatialisation (up grading), qualification and adaptation of MEMS COTS for a flight demonstrator on Ariane 5 launchers environments

Phase 2: Realization of test bed to make flight demonstration of MNTs for space transportation use

Phase 3: Study of "Low cost telemetry sub-systems" by using smart MEMS sensors,

1. Introduction

The explosion in Micro Electro Mechanical Systems (MEMS) and Nano Electro Mechanical Systems (NEMS) has occurred primarily within academic and research institutions. These institutions have concentrated for the most part on demonstrating the proof-of-principle for novel MEMS/NEMS devices. The silicon integrated circuit technology is the initial enabler for MEMS, the initial "top-down" lithographic fabrication approach has been augmented with a "bottom-up" self assembly approach. The "bottom-up" approach has been effective in NEMS, in order to bridge the gap between atomic dimensions and the limits of high-resolution lithography techniques. Since the past decade, ink-jet print-head, micro-sensors and micro-actuators based on silicon and other technologies have been developed rapidly. In many of these instances, the successful transition occurred either as a result of the initial development being undertaken by the in-house research department within a company, and followed by transfer to the manufacturing division or as a result of a successful partnership between a company and an external institutions. The smart sensors, realised with MEMS (Micro Electro Mechanical Systems), have already proven their great interest in the fields of applications such as automotive, medicine, geophysics.

Nanotechnology - in its various forms such as nanoelectronics, nanoelectromechanical systems, ultra small and highly sensitive sensors, multifunctional materials, biologically inspired materials, systems and architectures, and possibly many others scientists have not yet thought of - is expected to play a strong and critical role in future space transportation and exploration

Since these technologies offer great advantages in terms of reduction of mass and on board power, it should be interesting to apply them in the space domain in order to increase performance and probably to lower overall costs of existing space programs and also develop new concept space missions.

The Micro and Nano Technology team at EADS-ST has taken the right approach at right time of attempting to develop within the EADS group, and through partnership with external organizations like ESA and CNES, the end-to-end expertise required for taking emerging technologies from concept to system level demonstrations. The ideal solution developed to overcome the "TRL Gap" problem has been to fly MEMS/NEMS devices at the low and Mid TRL stage development. Flight demonstrations are a key issue since new technologies like MNT not qualified in-orbit are usually seen as risky and are discarded by the Space Industry. In order to speed up the development completion and the validation phase of MNTs for space use (transport vehicles, satellites, and probes), the flight demonstration through Ariane 5 launch is a good opportunity.

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2. State of development of the Micro and Nano technology

- **Micro Systems Technology/MEMS:**

The Microsystems technologies (MST) have become a key technology with an astonishing innovation potential for many industrial sectors as well as for emerging technologies in the world. The integration of numerous materials and functions and the trend towards miniaturization have been a powerful factor for development of new innovation fields within the automotive, the chemical, life science and aerospace fields.

The key features of MEMS are the miniature Mechanical systems with micron feature size, batch fabricated with no assembly required and exploits microelectronics infrastructure for Common technology base for sensors, actuators and electronics. The MEMS are not only making things small but also: the microelectronics revolution changed the world because of cost, not size. The MEMS offers a way to make complex ElectroMechanical systems at low cost. The cost and the performances must be the driver In order to fully realize the potential benefits of MEMS. The Cost issues are favourable due to: maintain batch fabrication, use IC standard materials and Leverage "Standard" Technologies and Processes.

Micro sensors are miniature devices that convert information about the environment into electrical form that can be read by instruments. Sensors are increasingly used as computer input devices as computing power increases and become less expensive. Sensors thus function as the eyes, ears, nose, and touch for the computer, making it aware of its environment.

- **Nano technology:**

Nanotechnology is the creation of useful, functional materials, devices, and systems through controlling and manipulating matter on the nanometre-length scale (1-100 nanometres), and exploiting novel phenomena and properties (physical,chemical,biological,mechanical,electrical)at that length scale. The prefix "nano" means a billionth - a nanosecond is one-billionth of a second, a nanometre is one billionth of a meter, and so on. For comparison, the head of a pin measures one million nanometres across. A red blood cell has a diameter in the range of thousands of nanometres. Ten nanometres is 1,000 times smaller than the diameter of a human hair. DNA molecules are about 2.5 nanometres wide. An individual atom measures a few tenths of a nanometre in diameter.

Useful applications for nanotechnology exist in areas as diverse as materials, manufacturing, bio-medical, electronics, computing, and transportation. Nanostructured metals and ceramics, for example, could be made into exact shapes without machining. Abrasives, coatings, paints, and composites all could be made stronger and better using nanoparticles. Integrated nanosensors would enable massive amounts of data to be acquired, processed, and shared with minimal size, weight, and power consumption. Less expensive remote and in-vivo devices would provide new routes for drug delivery. More durable, rejection-resistant artificial tissues and organs could be created. And in automobiles, nanotechnology can lead to wear-resistant tires, improved battery technology, and lightweight composites for increasing fuel efficiency. The NASA Ames computational nanotechnology researchers have designed a CNT-based nanogear [1] shown in Fig1.

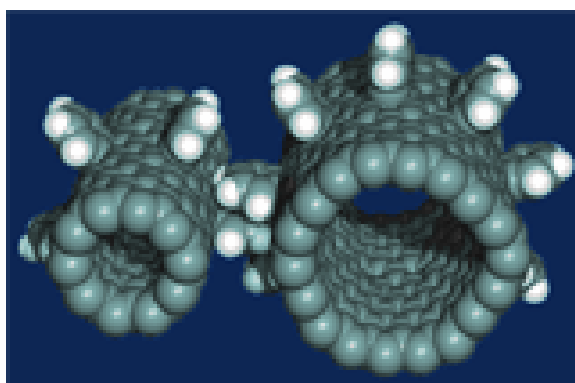


Fig 1 CNT-based nanogear with benzyne molecules bonded as teeth

The world research focus [2], summarized in Table 1, covers a wide range of subjects: carbon nanotube (CNT) synthesis, characterization, functionalization, electrode fabrication sensor development, application of CNT in atomic force microscopy (AFM), inorganic nanowires for sensor and detectors, protein nanotubes, nanotechnology in genomics, development of quantum device simulator, computational optoelectronics, atomic chain electronics, and bacteriorhodopsin (BR) based holographic data storage.

Research Focus	
* Carbon Nanotubes • Growth (CVD, PECVD) • Characterization • AFM tips - Metrology - Imaging of Mars Analog - Imaging Bio samples • Electrode development • Biosensor (cancer diagnostics) • Chemical sensor • Logic Circuits • Chemical functionalization • Gas Absorption • Device Fabrication * Molecular Electronics • Synthesis of organic molecules • Characterization • Device fabrication * Inorganic Nanowires * Protein Nanotubes • Synthesis	• Purification • Application Development * Genomics • Nanopores in gene sequencing • Genechips development * Computational Nanotechnology • CNT - Mechanical, thermal properties • CNT - Electronic properties • CNT based devices: physics, design • CNT based composites, BN nanotubes • CNT based sensors • DNA transport • Transport in nanopores • Nanowires: transport, thermoelectric effect • Transport: molecular electronics • Protein nanotube chemistry * Quantum Computing * Computational Quantum Electronics • Noneq. Green's Function based Device Simulator * Computational Optoelectronics * Computational Process Modeling

Table1. World Nano technology Research focus

Why Nanotechnology for Space?

The world-wide boom in nanotechnology funding and far reaching innovation pushed the space community to screen the applicable specific nanotechnology. The NASA is established a Nanotechnology roadmap, reach up to 20 years in the future. Here are the positive arguments for Nanotechnology space applications.

- Advanced miniaturization is a key thrust area to enable new science and exploration missions
 - Ultra small sensors, power sources, communication, navigation, and propulsion systems with very low mass, volume and power consumption are needed
- Revolutions in electronics and computing will allow reconfigurable, autonomous, "thinking" spacecraft
- Nanotechnology presents a whole new spectrum of opportunities to build device components and systems for entirely new space architectures :
 - Networks of ultra small probes on planetary surfaces
 - Micro-rovers that drive, hop, fly, and burrow
 - Collection of micro spacecraft making a variety of measurements
- New Radiation shields:
 - Research in new protecting shields for space missions
 - Identify shielding Principles:
 1. Radiation Interaction Mechanisms
 2. Choice of material
 - Test shielding effectiveness
 3. Particles, Energy spectrum

As illustrated in figure 2, for space domain, we should work on three major sectors like nanoelectronics and computing, sensors and structural materials. Revolutions in electronics and computing will allow reconfigurable, autonomous, "thinking" spacecraft.

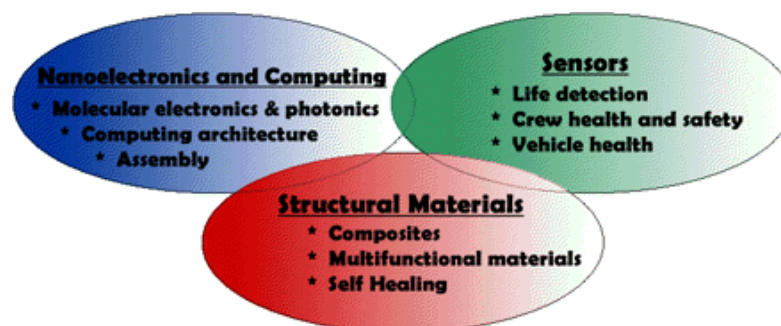


Fig 2: Nanotechnology major sectors

3. Technology Readiness Level Definitions

But applying MNT's (Micro and Nano Technologies) in the space domain (launchers, satellites, probes,) needs validation of these devices under space launchers environment. The development of advanced MEMS/NEMS technologies for space applications faces a similar dilemma in successfully "maturing" new concepts. The space agencies (NASA,ESA) measures a means of evaluating the maturity of technologies, known as the Technology Readiness level (TRL) scale, that has now found widespread use in industry. The TRL scale ranges from levels 1 through 9, with levels 1-3 being at the so-called "Low-TRL", basic research into demonstrating the proof-of-concept, while levels 4-6 correspond to "Mid TRL" development, which is the reliable demonstration of subsystems based on the new technologies, and finally, levels 7-9 "High TRL" correspond to successful utilization of these subsystems in space missions.

Technology Readiness Level	Description
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins with to be translated into applied research and development. Example might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in a operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and 'flight qualified' through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system 'flight proven' through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

It appears that radiation effects testing may begin at TRL=5, but hardening by design can begin earlier even at TRL=3.

4. MNTs needs for space transportation systems

For today's space transport vehicles like Ariane 5 expendable launcher, the miniaturization is not prerequisite, since the propulsion function drives their overall volume and architecture, and there are places enough for electrical devices and equipment.. But for payloads (satellites/probes/ re-entry vehicles.) and future re-usable launch vehicles, the mass and the volume are the major constraints, hence miniaturization becomes very interesting. And by the way, it should interfere on the launcher by reducing its performance needs so as to change the launchers performance requirements? There are rooms of interest to use MNTs for space transportation vehicles.

Just, we quote of few:

- **Telemetry** : much more measurements to have a better knowledge of the launcher, resulting in a so called **“learning launcher”**,
- **Multi-sensors guidance** : to have a **“self-controlled launcher”**, avoiding the use of expensive inertial plants,
- **Active Control**: to reach a **“Quiet launcher”** needs to control the propeller vibrations, payload environment and aerodynamics/ flight mechanics for re-entry vehicles.
- **Health Monitoring** : to have a **“safe launcher”**, for ground and flight controls for example on re-usable launchers,
- **High strength structures**: to realise **“economical launchers”** with high-pressure tanks with carbon nano-tubes filaments.
- **Future launchers**: our aim is to significantly reduce launch costs by using emerging technologies like Micro and Nano technologies.
 - System studies and stage architecture
 - Research, technology, development: Preparing the next generation: Reusable Launch Vehicles (RLV's)
 - Demonstrators: studies and development on Pre-X,
 - Heat shields for interplanetary probes, Thermal protection system,

As a consequence, we have to reconsider, at least partially, the architecture of some electrical sub systems and structures to get the real benefit of using Micro and Nano technologies for short term (≤ 5 years). The MNTs can procure some advantages like reduction of global cost with better reliability. And also, it allows in the future using the up to date technologies and devices available in the market for our space equipments and systems.

Today, nanotechnology is really in low TRL 1-3, but it presents a whole new spectrum of opportunities to build device components and systems for entirely new and bold space architectures such as “thinking” launcher.

• LAUNCHERS TRAJECTORIES

Operational since 1996/97, the baseline Ariane 5 launcher has been launched by 20 times up to now. The standard Ariane 5 launcher, designed to place 7 tons payloads into GTO, will carry 10.5 tons in the ESC-A version and 12 tons in the ESC-B version by 2006. Several trajectories are possible with Ariane 5 family: GTO (Geo-stationary Transfer Orbit), SSO (Sun Synchronous Orbit), HEO (High Elliptical Orbits), MEO (Medium Elliptical Orbits), LEO (Low Elliptical Orbits). The life mission may vary from 45 min to 5 hours. Hence, there is a wide range of in-flight qualification opportunities.

• LAUNCHERS ENVIRONMENT

Many physical parameters are studied to monitor the performances of the launch vehicle Ariane 5: measurements of temperature, pressure, vibration, acceleration, etc.... For example, the level of temperature ranges from low level 20 Kelvin (cryogenic tanks) up to 1100 Kelvin (engine gases). The pressure range reaches 500 bars, and vibration levels could reach 1000 g. To study accurately these different physical parameters, all kind of sensors are settled in all stages of the launcher. These sensors need to be efficient and reliable in their operating domain.

The number of parameters studied during a flight is high enough, between 570 for a generic launch until 1100 measures for a technological one.

The range of each sensor depends on the operating domain. There exist various physical ambiances inside Ariane 5. To efficiently monitor all kind of measurement we need to have sensors with different technologies. Some sensors need to be very sensitive, some needs to have a large operating range and some needs to have a fast response. These differences lead to use different technologies for a same physical unit studied. For example, it is possible to use either piezo-resistive or piezoelectric systems for vibration measurement.

In the table 2, we define the range of minimal and maximal measurements used for the main physical parameters in the launch vehicle Ariane 5.

PHYSICAL PARAMETERS	Minimal Range	Maximal Range	Units
Acceleration	-500	500	m/s ²
Acoustic	-40	40	dB
Constraint	-10	10	% deformation
Current	0	2	A
Voltage	0	45	V
Fluxmeter	20	1500	KW/m ²
Angular speed	-100	100	deg/s
Level	0	464	mm
Pressure	25 .10 ⁻³	500	bar
Power	0	30	W
Temperature	-253	1473	°C
Vibration / Shock	-100000	100000	m/s ²
Rotation Speed	250	68000	rpm

Table 2: Main parameters from Ariane 5

5. Principal MEMS COTS SENSORS AVAILABLE

Sensor technologies have matured through high-production usage in industries such as automotive and aircraft manufacturers. Several basic sensor transduction mechanisms are useful for designing sensing and actuation mechanisms. These transduction mechanisms are used in the design of MEMS devices such as pressure sensors, accelerometers, thermal conductivity monitors, electrostatic actuators, and thermal actuators. Finally, these devices are integrated into systems. The concept of systems-on-a-chip and methods for monolithically integrating MEMS with controlling microelectronics is illustrated with some examples [3].

• Pressure Sensors

Probably the largest potential for automotive silicon micromachined sensors is pressure sensing. There are applications for absolute, gage and differential pressure sensing. Pressure ranges vary from a few millibar to hundreds of atmospheres. Measured fluids range from clean dry gas to corrosive dirty liquids. Each application requires careful attention to element and package design. Absolute pressure sensing and differential sensing element are manufactured in industry (Eg.VTI Hamlin). These designs allow for wide variations in sensing ranges by simply varying either diaphragm thickness or area. Both designs will withstand very high over pressure because the diaphragm simply bottoms with little stress. This is a distinct advantage over piezoresistive devices which are subjected to high stresses to obtain measurements. Many packages are available. Plastic surface-mountable or through-hole packages with the absolute pressure elements provide for manifold absolute pressure (MAP) or barometric absolute pressure (BAP) sensing. Similar packaging with the differential pressure elements provides for gage pressure sensing (such as for fuel vapour pressure) or true differential pressure sensing (as required in certain exhaust gas recirculation systems). Metal-housed, isolated element sensors are used for high pressure aggressive environment pressure sensing. In these designs, the sensed fluid is ported to a stainless-steel diaphragm which transfers the pressure to an intermediate benign fluid (such as silicone oil). The sensing element is immersed in the intermediate fluid in a closed chamber and then connected to the outside world via glass-to-metal seals.

KRISTAL RES15 / RES19: RES15 and RES 19 OEM pressure sensors are particularly suitable for system and instrument manufacturers. They are versatile in application and can be used to measure pressures from 20 to 1000 bar in liquids and gases in three temperature ranges between - 40°C and 150°C. These sensors meet the highest measuring requirements by reason of their high natural frequency, good attenuation behavior, excellent linearity, combined with negligible hysteresis and high reproducibility. This an European source (Switzerland/Germany)

MEMCAPS SP82: Piezo-resistive pressure sensor. Available in absolute relative (Gauge) & Differential configurations. This an European source (France)

SENSOROR SP12: SP12 is a **piezoresistive** pressure sensor and accelerometer designed for tyre pressure measurement applications. This is a European source (Norway)

• Yaw rate sensors

TEMIC (A company of Daimler Benz) has developed a yaw rate sensor which is the heart of the vehicle dynamics control system in a car and ensures that the car holds the road well even under difficult external conditions. The sensor DRZ-75X is designed as a microsystem and detects movements of the car about its vertical axis (yaw axis) such as occur as a result of skidding. The vehicle dynamics control system can then react in a specific manner, for example by controlled deceleration of individual wheels, to keep the vehicle on course and to prevent

it from breaking away. The yaw rate sensor consists of a tuning fork with a size of just a couple of millimetres, two ASICs for signal conversion and conditioning and several discrete components. Metalled tines allow the resonance frequency of the quartz tuning fork to be piezoelectrically excited by means of an oscillator circuit. The Coriolis effect serves as the basis for measurement of the rotational speed. This acceleration initiates a torsional vibration at an angle of 90° to the excited bending vibration in the tuning fork. A suitable design of the signal tap metallization on the tines allows the amplitude of the torsional vibration, which is proportional to the acting rate of rotation, to be measured as electric current. The current signal is amplified by two application-specific ICs and converted into an analog voltage signal. There is naturally a constant self-test of the sensor system. Various designs can be produced by means of bulk micromachining methods for further development of the yaw rate sensor.

- **A Microsystem Gyroscope**

Delco Electronics has combined Electroformed LIGA structures with CMOS technology to produce a micromachined angular rate sensor. The sensor has 1mm diameter metal micromachine and is formed on top of a CMOS IC. This ring vibrates. The vibration pattern is capacitively monitored and changes when rotation occurs. The CMOS circuits are used to amplify and interpret the signals produced by the micromachined ring. By fabricating several hundred of these sensors on a single silicon CMOS wafer, the price of a microsystem gyroscope can be much lower than a traditional spinning wheel or tuning fork angular rate sensor.

This small gyroscope is used to indicate when an automobile is turning or swerving. Other applications for this sensor include its use to assist a GPS system in automobile navigation.

- **Accelerometers**

Silicon Designs developed one of the first accelerometers with miniature surface structures using micro-electro-mechanical systems (MEMS) technology. This accelerometer contains two major components: a MEMS sense element die or chip and an application-specific integrated circuit (ASIC). Sense elements, which detect acceleration, are fabricated on the surface of a wafer using integrated circuit methods combined with selective electroforming. Radiation-hard integrated circuits, in turn, measure and digitize the acceleration detected by the sense element.

The technology developed was unique in two ways. First, it offered a digital output, rather than analog, avoiding noise problems. It also could be directly connected to a microprocessor, minimizing the size of the control electronics. Second, it was designed to survive 500 kilorads of radiation without upset or damage. During the BMDO SBIR project, Silicon Designs tested the accelerometers for radiation hardness.

Capacitive based microelectromechanical systems (MEMS) accelerometers are devices that measure acceleration based on a change in capacitance due to a moving plate or sensing element. These devices have been implemented in many commercial applications, such as automobile air bags, navigation, and instrumentation. These devices have been employed in these and many other applications because they generally offer more sensitivity (more mV/g) and more resolution than similar piezoresistive accelerometers. For most commercial applications, the maximum g-sensing level (MGSL) employed in capacitive accelerometers is 500 g. However, in many applications, there can be high-frequency components to an acceleration profile that are much higher than the MGSL of an accelerometer. Some commercial MEMS-based capacitive accelerometers (Silicon Designs, Inc. 1220, Analog Devices ADXL, 181-1000, and Endevco 7290A-100) or piezoresistive 7270-A accelerometer. The radiation hardness of these devices (and those from other manufacturers Motorola, ST, VTI.) should be evaluated as a first screen of MOTS candidate for Space applications.

However, low-g sensors enter also new application areas like inclinometry and vibration sensing (activity monitoring for pacemaker control). Presently the low-g sensor market, which partially covers also the Inertial Measurement Module (IMM) market is gaining weight and speed.

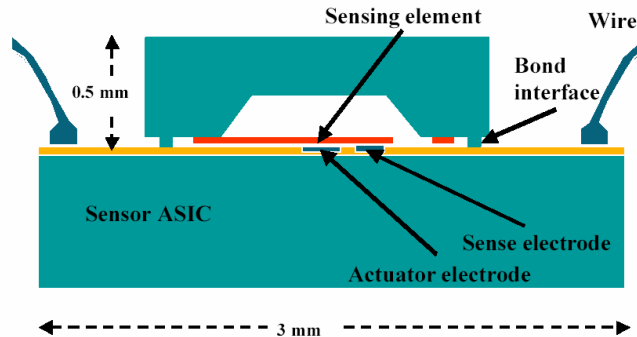
Industrialized concepts of hybrid accelerometers are available, comprising comb like sensor elements as well as out-of-plan movable beam/cantilever like structures made from dedicated MEMS processes (e.g. Bosch, Motorola, VTI, and Sensoror). They are based on piezoresistive or capacitive measurement principles. Signal processing is placed on a separate IC. Sensor elements and signal processing ICs are packaged in one body, forming the hybrid system. Hybrid systems allow optimized sensor structures as well as the signal processing part to be realized by dedicated and well established manufacturing processes. Larger size and still a considerable packaging effort are the weak points of the hybrid concept. Bosch's hybrid accelerometers are based on Surface Micromachining using EPI-poly Silicon with DRIE and cap for first level packaging. The concept requires larger sensing elements due to the less sensitive external signal conditioning. This concept is well suited for high performance accelerometers and also supports special applications (e.g. angular acceleration sensor), however the cost structure is an issue and the concept is not suitable for high vacuum applications due to out-gassing of glass seal ring. Similar concepts are used by a number of other MEMS companies (e.g. ST).

The Colibrys MS7000 series accelerometers are MEMS capacitive sensors, based upon a bulk micro-machined silicon sensor, a low power ASIC for signal conditioning and a micro-controller for storage of compensation values. The Colibrys is a Switzerland company, spin-off from CSEM.

VTI TECHNOLOGIES is a Finnish factory, which had experience of more than 20 years in acceleration and pressure measurements products. VTI TECHNOLOGIES offers solutions for a wide global customer range in application areas: acceleration, motion, shock, vibration, inclination and pressure. VTI's factory is dedicated to high quality micromachining, and it manufactures products from sensing elements to complete stand-alone units.

Actually the product line covers the measurement range of $\pm 0.5\text{ g}$ to $\pm 12\text{ g}$. **This is a European source**, very interesting for future space applications, and in addition the procurement of the samples may be easier.

Analog Devices is the first and major manufacturer of MEMS based accelerometers. Even though, Analog Devices is an American source, it is very easy to procure in short delay and low cost. The ADXL 150, is 1 axis, 50 g full scale with 10 mg resolution, analog output. It could be used for vibration measurement, shock detection, machine condition monitoring, fleet monitoring and event recording



- **Gyros**

The ADXRS150 from Analog Devices Inc, operates on the principle of a resonator gyro. Two polysilicon sensing structures each contain a dither frame, which is electrostatically driven to resonance. This produces the necessary velocity element to produce a Coriolis force during angular rate. At two of the outer extremes of each frame, orthogonal to the dither motion, are movable fingers that are placed between fixed pickoff fingers to form a capacitive pickoff structure that senses Coriolis motion. The resulting signal is fed to a series of gain and demodulation stages that produce the electrical rate signal output. The dual-sensor design rejects external g-forces and vibration. Fabricating the sensor with the signal conditioning electronics preserves signal integrity in noisy environments.

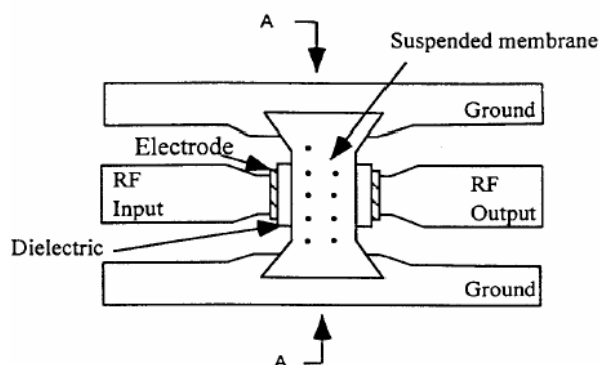
The electrostatic resonator requires 14 V to 16 V for operation. Since only 5 V is typically available in most applications, a charge pump is included on-chip.

The ADXRS gyro is mounted inside a small 7 X 7 X 3 mm ball grid array (BGA) package.

The BAE SiRRS01 and SRS03 are manufactured for defense applications by British Aerospace (UK), the only available European source today.

- **RF-MEMS**

RF MEMS devices are used in wireless and satellite communication systems. Novel configurations are developed for MEMS variable capacitors, MEMS tunable inductors and RF MEMS mutiport switches. The tuning range of the variable capacitor far exceeds that of the traditional parallel plate MEMS variable capacitors. The MEMS tunable inductor is realized using MEMS fixed inductors, capacitors and a variable MEMS capacitor. Some proposed MEMS mutiport switch has demonstrated a superior RF performance up to 20 GHz.



These specific devices (MEMS Off The Shelf or MOTS) should be quickly evaluated to know their radiation resistance and to investigate radiation degradation mechanisms.

6. MNT DEVELOPMENT ACTIVITIES AT EADS-SPACE TRANSPORTATION

The Micro and Nano Technology team at EADS-ST has taken the right approach at right time of attempting to develop within the EADS group, and through partnership with external organizations like ESA and CNES, the end-to-end expertise required for taking emerging technologies from concept to system level demonstrations.

Since 2000, EADS-ST is worked in different fields of Micro and Nano technology for space transportation applications and we conducted co funded works with CNES and ESA and also internal EADS funding, related to Low and Mid TRL (1-6) on:

- MEMS reliability issues, including space radiation for space applications
- MEMS COTS evaluation for space launchers applications
- MEMS micropack demonstration

MEMS reliability issues, including space radiation for space applications

Reliability testing of MEMS COTS devices is currently in its infancy and is complicated by the fact that there are relatively few devices available for the generation of a statistically significant database. The successful use of COTS devices in space applications is closely joined to their reliability under space environmental conditions. EADS-ST and CNES were conducted two co funded thesis works on MEMS reliability issues. The first thesis is dedicated to "bottom-up" approach, mainly based on tests related to technology vehicles [Muriel] and second thesis dedicated to "top-down" approach, based on Physics of failure [Petra]. It is hence necessary to develop methods that ensure the reliability of these components for a given mission. In the following we present two different approaches:

a) Reliability approach based on tests [4]

The first reliability approach is based on reliability tests. Before entering the market a COTS product has already passed a lot of qualification steps. The tests are necessary to fulfill the required norms and safety standards. These standards are always specific to one application domain (such as automotive). The devices reliability in an other application domain cannot be automatically assured, above all not in environment severe such as space environment. In this case reliability assessment can be done by complementary reliability tests.

These complementary reliability tests give a precise vision of the devices reliability in an other than its nominal use environment. The objective of such a campaign of evaluation is not to determine the aptitude of a device to pass a certain number of tests, but to get to know its technological and functional limits and to explain eventual failures. Three different types of analyses and tests are performed. The first type is carried out to determine technological parameters. These parameters are not known to the buyer of a COTS device due to intellectual property reasons, but they might be interesting for reliability aspects. The second analyses' type of are verifications of the values presented in the data sheet, such as the noise level, the consumption..... A third analyses' type are reliability tests. During these tests the device has to work under various environmental conditions: temperature cycles, space radiation. The occurring failures are analyzed and based on the results the limits of a component are determined. In order to evaluate the aptitude of the component for a given mission, these limit usage conditions are compared to the mission profile.

b) Physics of Failure approach [5]

The second approach is based on the Physics of Failure (PoF) methodology. It has been used for decades in the civil engineering domain and during the last years the CALCE (Computer Aided Life Cycle Engineering - University of Maryland) has applied it with some success to electronic modules. The PoF approach anticipates issues due to environmental stresses and estimates, based on simulations, component lifetime for a particular mission profile. Its principal advantage is that it incorporates reliability aspects in the design process and enables that way reliability enhancement or even assessment already during the development process of a product.¹

However, MEMS failure mechanisms are not well understood today. A preliminary work is necessary to determine influent factors and to model physics of phenomena. The development of the models used in a Physics of Failure approach and adapted for life-time estimations combines three different points: a precise knowledge of the process parameters, environmental tests and different modeling approaches.

The use of modeling and simulation tools is used for the rapid and cheap estimation of the impact of variations to the microsystems component and the system containing it. The variations can be intrinsic (i.e. technology parameters, geometry, etc.) and external (gazes, etc.) to the microsystem component. Moreover the use of modeling and simulation tools can increase the reliability of a microsystem by modeling failure mechanisms and developing tests by faults injection. There are two main modeling approaches: finite element analysis (FEA) and behavioral modeling in VHDL-AMS. FEA is used on the physical level for microsystem component simulation. It is very exact, but unfortunately also very processor and time consuming. A behavioral modeling approach is used for microsystem based system simulation and can be used to evaluate the reliability of a microsystem at system level by fault injection. Behavioral models are based on analytical equations, experimental results and/or FEA simulations.

MEMS COTS evaluation for space launchers applications

The smart sensors based MEMS technology has already proven great interest in the other fields particularly at automotive. Some of the announced performances of MOTS are close to space transportation requirements, without the guarantee in harsh environments. EADS-ST has conducted the evaluation tests on MEMS accelerometers, (ESA Contract n° 167181/02/NL/MV). EADS-ST has selected two important sources for accelerometer for space transportation evaluation:

- Analog Devices (US) is the world leader for accelerometer and angular rate sensor.
- VTI – Technologies (Finland) is a potential European provider for accelerometer.

The evaluation of a MEMS based sensor is very different from the evaluation of a microelectronics circuit. The test conditions are mainly based on our general specifications related to Ariane 5 launchers. The accelerometers SCA 600 C35H16 are manufactured by VTI Technology (Finland). The results obtained after each tests on VTI SCA accelerometers are the global characterization of both sensing element and signal treatment circuits. The total dose radiation results are very promising particularly for a COTS (Commercial-Off The Shelf) product. All samples tested are functional until a total dose of 31 krad. Globally the results obtained are most promising for space transportation requirements and also in general for space use [6]. Some of the tests should be enlarged and also implication of the manufacturer VTI is important in order to improve for the required space transportation performances.

The space qualification activities of these MEMS accelerometers under GSTP-4 are planned to start before end of the year 2005 with close collaboration of VTI (Finland).

Micropack demonstration

EADS recognizes the potential for MEMS to disrupt and revolutionize the space industry, where it can dramatically reduce mass, size and power requirements and therefore mission cost. Therefore, from 2002, EADS is developing a novel modular approach to packaging integrated microsystems for space applications called "Micropacks".

The micro-pack consists of 5 ceramic layers, consisting an atmospheric sensor unit (e.g. pressure sensor), acceleration sensor unit, power supply unit and data handling unit. The size of the micropack will be approximately a mere 20X25X25mm³, with power consumption of less than 100mW and a mass just 25g as shown in fig.3 [7].

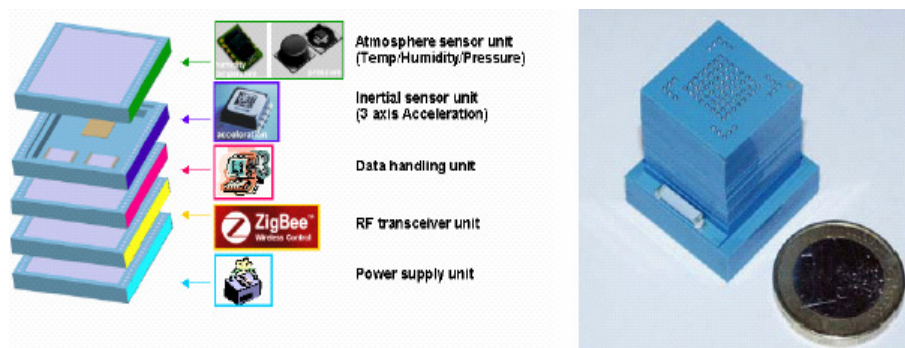


Fig 3: EADS Micropack concept

FLIGHT DEMONSTRATION

The key advantage of in-flight demonstrations is that it is the unique way to test and qualify MNTs under real flight environment especially for acoustic, pressure, temperature, vibrations, space radiation, and EMC constraints. We hope, by having flights at low TRL one can either "screen" the technology for space-worthiness or alternatively, build in the requisite robustness, far more cheaply and cost-effectively, than at higher TRLs. Screening space-suitable devices at an early stage in the development cycle avoids wastage of effort and investment over several years into technological "dead-ends". On the other hand, design changes necessary to incorporate robustness into MEMS/NEMS are far easier and cheaper at low TRL.

TECHNOLOGY TEST BED CONCEPT

A feasibility study has been performed (ESA Contract n° 17832/03/NL/MV) by EADS-ST to identify and define a flight opportunity on Ariane 5 that could be recurrent and low cost, targeting simple technology experiments like MEMS sensors and small devices. The study was focused on what are the dimensions and interfaces of a technology experiment that could fly on the Ariane 5 using a negligible amount of resources left and where it could be located. The goal is having an experiment that is seen as standard Ariane 5 equipment and not as a

payload [8]. This Test Bed would be located in a part of the launcher that will stay some times in-orbit. It will not be ejected into orbit, rather staying attached to the launcher, and providing a reduced telemetry downlink.

Output of the study shows that a technology experiment can still be considered as negligible in a box of a few litres and few kilos using a few watts and a few telemetry lines. The study is also quantified the interfaces and resources and shows the way to prepare the experiment, qualify according to Ariane standard and deliver it for integration in the launcher.

Although such “TTB flight opportunity” does only cover some small and simple applications, it is a valuable support to European space industry because of its low cost and simple and recurrent access.

The figure 4 shows a Technology Test Bed prototype for a MEMS sensor. This test-bed is composed with a part of classical sensors and MNTs sensors. The interest of this experiment is to valid MNTs technology in terms of launch vehicle compliance or to compare their metrology performances with the classical one. First, a precise selection of MNT/ MEMS COTS (Commercial Off The Shelf) devices is needed to replace the space traditional sensors. Then a development of a prototype is required for early launch into space in order to evaluate the metrology performance and reliability of the MNT in space conditions by comparing the results to the traditional sensor.

This can be considered as a short mission with the following characteristics:

- Typical demonstrated technology : MEMS sensor like accelerometer or pressure,
- Power and data acquisition required during the launch and up to one hour in-orbit,
- Low power consumption and low mass

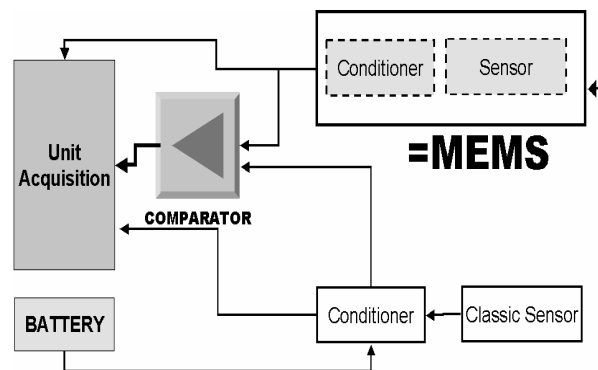


Figure 4: A prototype Technology Test Bed for a MEMS sensor.

7. CANEUS Network

EADS-ST is an active member of **CANEUS** [9]: is an international community of expertise that can scan for and recognise real opportunities in Canada, Europe, Japan and the US; it can package concepts and market them to end users in each of these regions; and it can deliver polished end products and processes –all rapidly and low cost. This will help CANEUS close the so-called Technology readiness Level (TRL) gap for aerospace MNT technology development.

CANEUS host biennial conferences (2002, 04, 06.) that are fully integrated into its technology transition pipeline. This international assembly of experts will analyse concepts presented for further development in concert with end users to apply a true market test to the proceedings. The conference structure is given in fig. 5

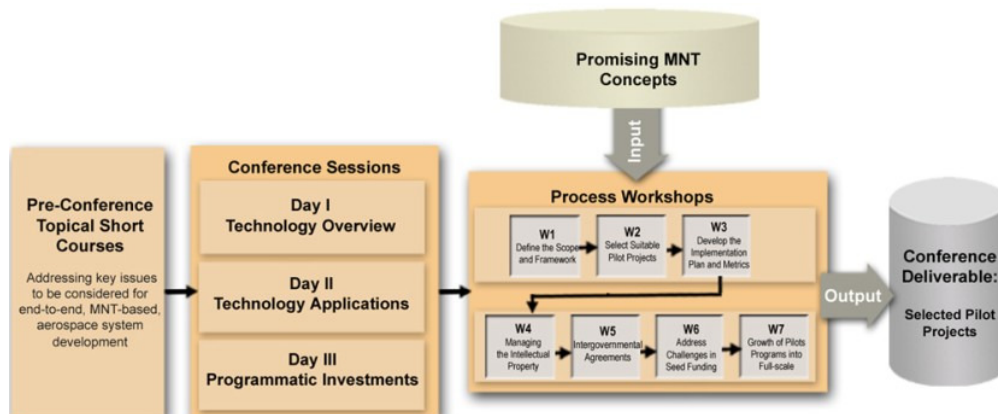


Fig 5: CANEUS Conference Structure

8. CONCLUSION

In this paper we presented the state of art of Micro and Nanotechnology for space applications and also different works undergoing at EADS-ST for promoting the use of MNT on space transportation systems.

The target in short term for coming 5 years (2005-2010) is dedicated to the development of "Low cost telemetry sub-systems" by using smart MEMS sensors. For that, the work is split in 3 phases:

- Phase 1: Spatialisation (up grading) and Adaptation of MEMS COTS for a flight demonstrator on an Ariane 5 launchers environments
- Phase 2: Realization of Technology Test Bed (TTB) to make flight demonstration of MNTs for space transportation use
- Phase 3: Study and realization of "Low cost telemetry sub-systems" by using smart MEMS sensors,

This recurrent TTB could offer standard interfaces with technology experiments. If we succeed the TTB concept for MNT in Ariane 5 family launcher, then we feel that an important step is made towards the use of MNT in European space sector. By the way, these elements should open rooms to more in-flight demonstration opportunities for other technologies.

The final targets are the development of:

- The recurrent Technology test Bed (TTB) to make flight demonstration of MNTs for space use (transportation, satellites, probes,)
- Low cost and high efficient Sub System Telemetry (SSTM) with MEMS based sensors.
- Use of MNT in different structures, subsystems and systems in space transportation business.

Thus, the benefit of these in-flight experiences can promote further applications on all space systems (satellites, probes, re-usable launchers and re-entry vehicles).

Today, nanotechnology is really in low TRL 1-3, but it presents a whole new spectrum of opportunities to build device components and systems for entirely new and bold space architectures such as "thinking" launcher.

LIST OF ABBREVIATIONS

CANEUS: CANadian, European and USA

CNT : Carbon Nano Tubes

MEMS: Micro Electro Mechanical Systems

MNT: Micro Nano Technologies

MST: Micro Systems Technologies

MOTS: MEMS Off The Shelf

PoF: Physics Of Failure

SSTM: Sub System Telemetry

TTB: Technology Test Bed

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REFERENCES

1. J. Han, A. Globus, R. Jaffe and Glenn Deardorff, «Molecular Dynamics Simulation of Carbon Nanotube Based Gears», Nanotechnology, Vol. 8, pp. 95-102 (1997).
2. M. Meyappan, H. Partridge, and T.R.Govindan "Nano and bio technology research at NASA Ames", December (2002).
3. R. Gaillard, Concept Paper A03 at CANEUS 2004, Monterrey, CA, November 2004
4. M. Dardalhon, "Reliability of MEMS by approach bottom-up" PhD Thesis, University of Montpellier, 2003
5. P. Schmitt, "Reliability of MEMS by approach top-down", PhD Thesis, University of Toulouse, 2004
6. ESA contract, Final report from EADS-ST, TE624 n° 143 179, dated 11.01.05, "Evaluation test results on the accelerometer VTI SCA 600"
7. S. Eckersley, O. Coumar, J. Schalk, M. Kluge and K. Koppenhagen "The EADS micro pack project. A novel, flexible approach to packaging integrated Microsystems for space applications", 1st symposium on potentially disruptive technologies and their impact in space programs, Marseille 4-6 July 2005
8. ESA contract, Final report from EADS-ST, TE611 n° 141 729, dated 02/06/2004, "Definition of possible flight opportunities on Ariane 5"
9. <http://www.caneus.org/CANEUS06>