MEMS FOR SPACE

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ABSTRACT

Future space exploration will emphasize on cost effectiveness and highly focused mission objectives. Missions costs are directly proportional to its total weight, thus, the trend will be to replace bulky and heavy components of space carriers, communication and navigation platforms and of scientific payloads.

MEMS devices are ideally suited to replace several of these components in the future, first by substituting larger and heavier components (e.g. a gyroscope), then by replacing entire subsystems (e.g., inertial measurement unit), and finally by enabling the microfabrication of highly integrated picosats. This progressive approach will also enable new mission scenarios and more detailed investigations of the space environment and of planetary surfaces.

Very small satellites (1 to 100 kg) stand to benefit the most from MEMS technologies because reaching the desired performance levels is only possible using a highly integrated approach. The small satellites are typically used for science or technology demonstration missions, with much higher risk tolerance than multi-ton telecommunication satellites. In addition, the ability to mass produce MEMS components opens a new approach to space exploration in the future by sending constellations of nano and picosatellites into space.

Examples of such miniaturization and successful use of MEMS for space and planetary missions are described in this paper.

KEYWORDS

MEMS, space, bioreactor, micromirror, AFM, Phoenix, Mars, Nano-/picosatellites, Micropropulsion, atomic clock, cubesat, swisscube.

MEMS DEVICES FOR SPACE

MEMS for use in space often have unique requirements, and are designed to meet performance specifications not always achieved in commercial off-the-shelf (COTS) parts. MEMS have been proposed for a number of space applications, as lighter and smaller replacement parts or as entire new systems [1,2,11], or as a means to provide affordable redundancy. While there have been many devices developed or considered for possible use in space, few MEMS components have been flown. MEMS in space are currently either quasi-commercial components such as accelerometers or gyroscopes that have been subjected to additional testing and qualification, or MEMS devices that are essential enabling technologies for science missions (such as the AFM on the Phoenix mission on Mars [3,19,20,21]) and were developed solely for that purpose.

In the coming years, we will see MEMS technology in the form of more complete sub-systems, such as attitude determination, attitude control, phased array antennas, Earth sensors, optical switches, whose size and mass will be reduced significantly compared to conventional solutions. In the longer run MEMS can enable new classes of small (1-10 kg), intelligent, self-managing and relatively low-cost picosatellites operating in constellations.

Most MEMS devices currently under development for specific space applications are not intended for picosatellites, simply because most satellites currently have masses larger than 100 kg. However pico and nanosatellites are the main users in space of COTS MEMS parts (pico and nanosats are also the main users in space of COTS components such as microcontrollers, batteries, etc. since the development budget of these small satellites often precludes using standard space grade components). The attitude determination subsystem is currently the part of the pico- and nanosatellites that relies on MEMS sensors.

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Some of the more developed MEMS areas for space are summarized in references [4] and [5] and references therein, and can be grouped into the following classes: Inertial Navigation, RF Switches and Variable Capacitors, Atomic Force Microscope, Bio and Microfluidics, Bolometers, Optical instrumentation, Optical Switching and Communication, Thermal control, and Micro-propulsion. Examples from the EPFL of several of these application areas are given in the following sections.

The degree of maturity of components for use in space is generally described by their Technological Readiness Level (TRL), a scale ranging from 1 (basic principles observed and reported) to 9 (flight proven). MEMS devices for space are mostly approximately between TRL 2 and TRL 5, with only the few devices that have flown being at TRL 9.

Reliability is a key concern for space hardware, in view of the near impossibility of carrying out repairs, and the long expected lifetime (15 years for a typical telecom satellite). The main space-specific reliability concerns are radiation, thermal cycling and thermal shocks, vibration and mechanical shock, and operation in very high vacuum. Ionizing radiation affects MEMS devices primarily by charging dielectrics, leading to performance changes or failures for electrostatically operated devices, as reviewed in [4]. MEMS reliability for space is reviewed in [6] and references therein.

SPACE BIOREACTOR

Miniaturization of scientific instrumentation for microgravity research leads to better use of the available resources (e.g. volume, mass and power), and allows the integration of more complex functionalities. The potential of microfabrication technologies to construct key components of small dimensions and to integrate them into high performance micro-instruments for use in space has been recognized as early as 1990 when the development of a miniature Space Bioreactor was started by a Swiss consortium [7], funded by the European Space Agencies PRODEX program.

Experiments with cells in space have shown that important cellular functions are changed in microgravity. These findings are of great interest for fundamental research as well as for possible biotechnological applications in space. For the cultivation of cells aboard a space laboratory, a miniature bioreactor has been developed. It incorporates a fluidic system for nutrient supply as well as a number of measurement and control functions. Thanks to the use of micro fabrication technology, this bioreactor is the first instrument that combines all the described features in a volume small enough to fit in a standard Type II experiment container of 85×60×60 mm^3.

The system uses a silicon micro membrane pump and a piezo-resistive flow sensor for controlled delivery of a total of 100mL nutrient solution to the reactor chamber. A microfabricated sensor incorporated in the reactor wall measures pH, redox potential and temperature of the culture. The pH of the culture is controlled with a unique electrochemical method that eliminates the need for corrosive alkaline solutions and requires very little additional room [8].

First experiments with the growth of yeast cells on Space Shuttle missions, STS-65 in 1994 and STS-76 in 1996 [9] have shown that microgravity does induce morphological changes in dividing cells. In a more developed version, flown on Columbia's unfortunate last mission STS-107 in 2003, the bioreactor has acted as a source of cell culture samples for further experiments. Currently a further automated version of that setup is under development for future experiments in space.

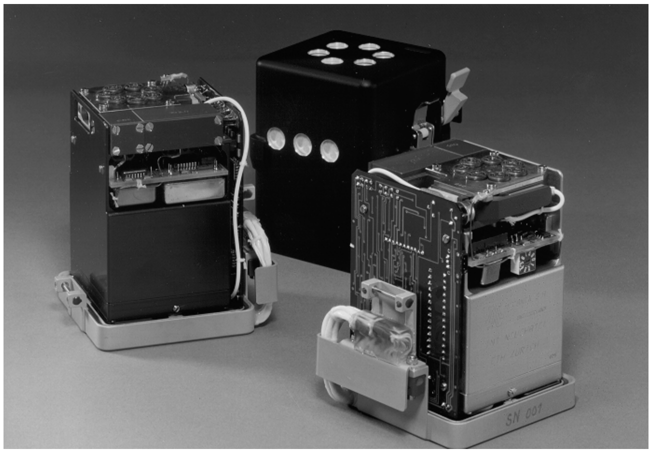

Figure 1 Flight Models of the Miniature Space Bioreactor

OPTICAL MEMS FOR SPACE

Small photonics systems require accurately displaceable micro-optical elements such as micromirrors, microlenses and gratings. Typical applications and systems are tunable cavities (interferometers, lasers, filters, etc), beam manipulating devices, e.g. scanners and deformable mirrors for adaptive optics, fiber-laser couplers, and spectrometers. In these configurations MEMS devices are often used as suitable solutions. Recent developments have shown that MOEMS-based devices and micromirrors can provide a high level of optical flatness at rest and dynamic positioning. This is important for two applications shown here: A) a large optical fiber switch for optical telecommunication on satellites and b) a programmable reflective slit mask for multiobject spectroscopy for astronomy.

In the ongoing ESA project "Large Optical MEMS switch for broadband applications" we develop – in collaboration with Thales Alenia Space, Toulouse, France

– an optical fiber switch for on-satellite switching of up to 50 input and 50 output fibers, respectively. The switch is an all optical, non-blocking 50x50 cross connect, which is based on an array of 4x32 MEMS micromirrors. The switch is intended to work in open loop without a feedback control. This is possible due to a unique electrostatic actuation scheme, where the two independent rotation axes work independently from each other and without inherent drift. The input/output fiber array consists of 128 optical fibers whose light is collimated by means of microlenses, which deliver a insertion loss of less than 3 dB. The overall optical design is very compact by folding the optical path with a macroscopic mirror and by using the same micromirror array for the input and output fibers. A first demonstrator was fully assembled and shows basic functionality with less than 15 dB insertion loss.

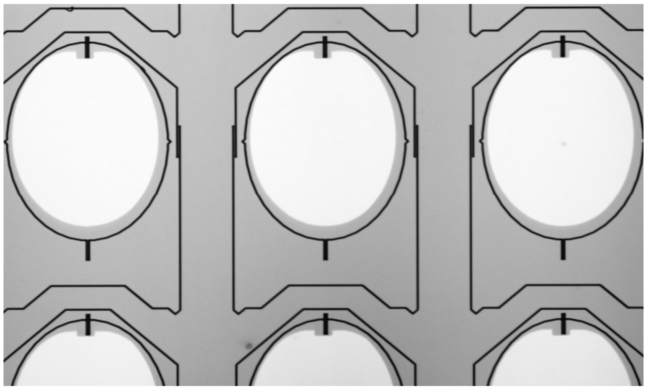

Figure 2: All-optical non-blocking fiber cross connect based on an array of 4x32 oval micromirrors, each measuring 600x900µm^2.

Multi-object spectrographs (MOS) help increasing the scientific efficiency of astronomical observations by recording simultaneously the spectra of hundreds of objects. They require a programmable slit mask in the focal plane of the telescopes for the object selection. We present a MEMS-based approach that utilizes a micromirror array as a reflective slit mask for next generation MOS, which was developed in collaboration with the LAM in Marseille. The objects are selected by tilting the micromirrors, which send the incoming light towards the spectrograph. The micromirrors are very flat, measure 100x200µm^2 and provide a mechanical tilt of 20°. The array has a very large fill factor of over 90%. The micromirrors and their package were tested mechanically and optically in cryogenic conditions at a temperature of 92K, which is necessary for mid-infrared applications. The devices showed no degradation in this cryogenic environment (<50nm peak-to-valley mirror deformation for Au-coated) [10]. Currently we work on large 2x2cm^2 arrays with 20’000 micromirrors with a line-column addressing scheme.

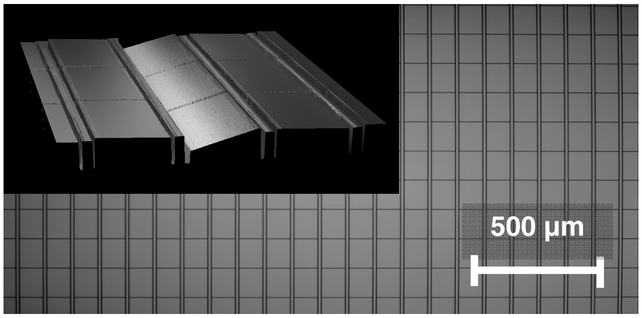

Figure 3: Micromirror array for multi-object spectrographs (MOS) for astronomy with 20° tilt angle and a fill factor of more than 90%.. Inset shows the flatness of tilted mirrors measured with an optical profiler.

MICRO-PROPULSION SYSTEMS FOR NANO-/ PICO-SATELLITES

In order to fulfill the mission requirements of small (0.1 kg to 10 kg) spacecrafts, new types of miniaturized thrusters are required offering thrust levels from micro-Newton (µN) to Newton levels with high overall thrust efficiency and with very low total thruster and power processing unit (PPU) mass. CubeSats (1 kg, 1 liter) are expected to be strongly based on micro-components such as MEMS (see section on the SwissCube for an example). It is foreseen that propulsion modules will be implemented to compensate the forces acting on the satellite, for orbital maneuvering and for the satellite altitude control. Attitude control is currently achieved using inertial wheels and magneto-torquers, and orbital maneuvers are currently not possible. Integration propulsion within CubeSats would greatly expand their functionality and potential mission scenarios: they allow orbit trimming and phasing maneuvers required for controlled formation flying, drag compensation, attitude control for precise pointing, trajectory corrections in probe missions, to name a few. There are two main families of propulsion systems, chemical and electrical based [11]. At the EPFL-LMTS and EPFL-SAMLAB we are developing both types of technologies, respectively on electrospray and solid propellant micro-thrusters.

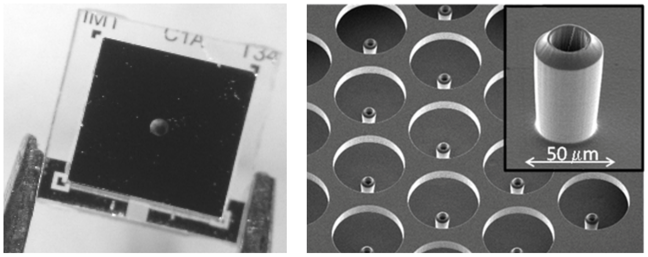

Figure 4:Left: picture of a single solid propellant thruster with the glass igniting chip covered with the propellant assembled with the silicon chamber/ nozzle part. Right: SEM image of an array of 19 microfabricated electrospray thrusters. Inset: SEM image of one silicon capillary.

The developed technology at LMTS offers the possibility to manufacture arrays of electrospray thrusters (sources of electrically accelerated ions or liquid droplets) on the wafer scale allowing thrust to be modulated from a fraction of micronewton for a single capillary to the millinewton level for large arrays. Several thruster prototypes were microfabricated and packaged using Low Temperature Co-Fired Ceramic (LTCC) technology [12]. In conjunction with this microfabrication process an onset voltage model was developed intended as design tool during thruster layout [13]. This model allows to predict the voltage at which particle emissions initiate for complex geometries and to estimate the effect of dimensional variations on parameters such as crosstalk in large arrays. Tests carried out with the MEMS thruster on single capillaries and on array of 19 capillaries with different ionic liquids show a well defined energy distribution of the particles and the possibility to modulate spray current by changing the voltage. Controlled variations in the fluidic impedance of the emitters allow to spray in either ionic or droplet mode. Time of-flight measurements with arrays show a beam composed of ions (monomers, dimers), thus yielding a high specific impulse of over 3500 s at 1.2 kV [14]

At SAMLAB in collaboration with RUAG, the development of a high performance propellant coupled with a reliable ignition technology based on Microsystems technology was achieved for the realization of solid propellant micro-thrusters arrays with reliable performances. A solid propellant was formulated in association with the development of a coating process and an igniting chip for a controlled and complete combustion of the propellant at the micro-scale level. The successful ignition and controlled combustion of the solid-propellant coated on the micro-igniting chips has been confirmed using a high speed camera, providing valuable real time date on the ignition and combustion characteristics of the propellant. Micro-thrusters with simplified architectures (two parts) and low ignition power were designed and fabricated based on this ignition concept. The characterization of the thrusters has demonstrated that a thrust force of few tens of milli-Newton and a specific impulse over than 100 s can be reached using this technology [15]. Compared to other chemical propulsion principles, the advantages reside in the fact that there is no need for a pressurized reservoir and leakage is inexistent, the fuel being stored in a solid form, there is a large amount of energy stored in small volume, and there is no mechanical part. However, these devices are single shot operation and the use of arrays is required to ensure a complete mission. We have also demonstrated the principle of large deformation (few mm) balloon actuators that could find application for the deployment of structures on small satellites [16]

SCANNING FORCE MICROSCOPE FOR THE MARS MISSION PHOENIX OF NASA

Light scattering experiments conducted on Mars [17] indicated that soil particles have dimensions around 1 µm. Particles in that range play an important role in the gas exchange between sub-surface water ice and the atmosphere. Their shape can help tracing the geological history and may indicate past presence of liquid water. The Phoenix mission [18] therefore decided to analyze soil and dust particles in the sub-micrometer to a few micrometer range using a microscope for the first time on another planet. The instrument [3,19,20,21] comprised an optical microscope (pixel size corresponding to 4µm, 1mm×2mm field of view) and a co-axially mounted scanning force microscope [SFM] with a resolution of 1 to 10nm and a scan range of 65µm in x and y, and 13µm in z.

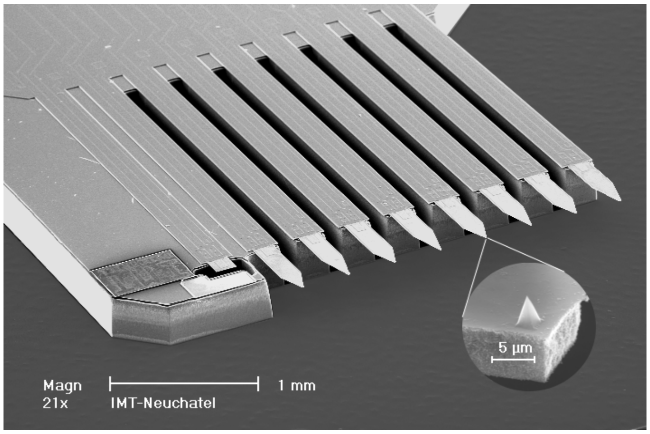

Figure 5: SEM image of the sensor chip with eight support beams and cantilevers. The inset shows the tip formed by KOH etching at the end of the cantilever.

A MEMS approach combined with mechatronic concepts for the scanner was selected for implementing the SFM. For redundancy, the sensor chip (Figure 5) featured eight, about 6µm thick cantilevers each with an KOH-etched 7 to 8 µm high silicon tip, fabricated from the 20µm thick n-type device layer of an SOI-wafer. The chip was tilted with two angles relative to the sample surface, such that only one cantilever was in measuring position at a time. The cantilevers could be cleaved off if contaminated. In order to prevent the body-chip from touching the substrate, cantilevers were mounted on support beams, which were also cleaved away. These beams were fabricated using DRIE to etch through the handle layer of the SOI. The cantilever deflection was measured using implanted, p-type piezo-resistors. Thermal drifts were compensated by a reference piezo-resistor. The chip was glued on a triangular platform, which was suspended from the rigid body of the scanner by means of symmetrically arranged polyimide springs. The later also contained the electrical contacts to the chip. Three magnets were attached in the corners of the platform. An electrical coil mounted underneath each magnet allowed deflecting them. The whole scanner measured 12mm×18mm×24mm and weighted 15g.

The SFM system was completed by a single-board electronic controller for static or dynamic, frequency modulation mode [22], and a sample wheel stage. The sample stage featured 10 sets of 6 substrates and 10 calibration samples. It could be moved out of the enclosure to receive a soil or air-fall sample. Once rotated in front of the microscope, the sample wheel moved first to the focus position of the optical microscope. An OM image was taken on which, the position for the SFM measurement was selected. The stage was then used to approach the sample to the SFM tip.

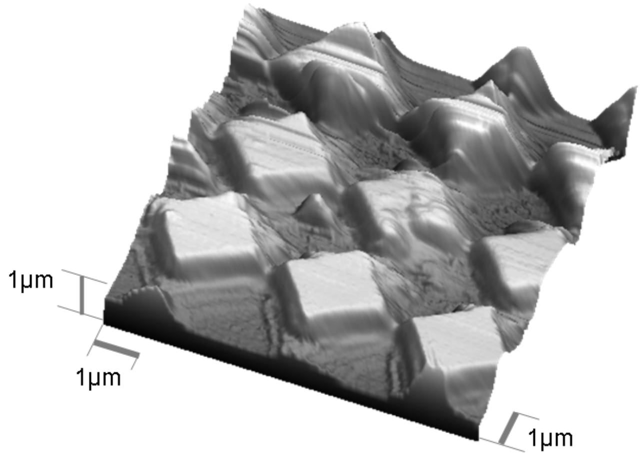

Figure 6: Dynamic mode SFM image of a 2D calibration sample recorded on sol 64 of the Phoenix Mission on Mars.

During NASA's Phoenix Mission, which operated on the red planet from May to October 2008, we could demonstrate successful SFM operations (see Figure 6). The instrument produced data of soil particles for scientific analysis. From an engineering point of view, operating the SFM within the constraints of a mission was the biggest challenge. For future applications, it is suggested to increase the autonomy of the instrument in terms of operation algorithms and data storage.

MEMS ATOMIC CLOCKS FOR SPACE

Atomic frequency standards provide stable and accurate timing references in all those applications that require better performances than quartz oscillators: network synchronisation, secure telecommunication, navigation, certified timekeeping, very long baseline interferometry, fundamental physics, etc. In an atomic clock, the output of a quartz oscillator is stabilised thanks to its comparison to the frequency of an atomic transition. This comparison is performed by magnetic resonance which induces transitions between two well selected atomic states. Observing that such a standard was much more stable than Earth rotation and any other device, in 1967, the SI second was redefined by the energy difference of a microwave transition between two hyperfine states of energy E_1 and E_2 in caesium (Cs) atoms, using the following basic formula:

$$\hbar\omega_0 = |E_1-E_2| = 9'192'631'770 \text{ Hz}$$

During the last forty years, a number of developments concerned atomic clocks for space applications such as satellite navigation (GPS, GLONASS, GALILEO, etc.) and fundamental science. For instance, the ACES (Atomic Clock Ensemble in Space) experiment on the International Space Station (ISS) will include a French laser-cooled Caesium clock and a Swiss active Hydrogen Maser. One current line of research at the newly created LTF (Laboratoire Temps-Fréquence) at the University of Neuchâtel concerns the utilisation of laser sources to further improve the clock stability [23]. More recently, there has been a strong effort to drastically reduce the size and power consumption of vapour cell atomic clocks [24,25]. The progress in this direction is driven by several factors such as the use low power laser diodes (VCSEL), Coherent Population Trapping resonances (CPT) [26], and micro-fabricated (MEMS) alkali-vapour cells. Here the micro-fabrication of vapour cells has proven a challenging task. All reported results use anodic bonding at high-temperatures (>300°C) to seal the cell [27]. However, the low melting point and high vapour pressure of the alkali-metal combined with long bonding-times (>1hour) complicate this process. The authors have recently developed a low temperature (~150°C) sealing technique with fast process time (<1min) based on soldering [28].

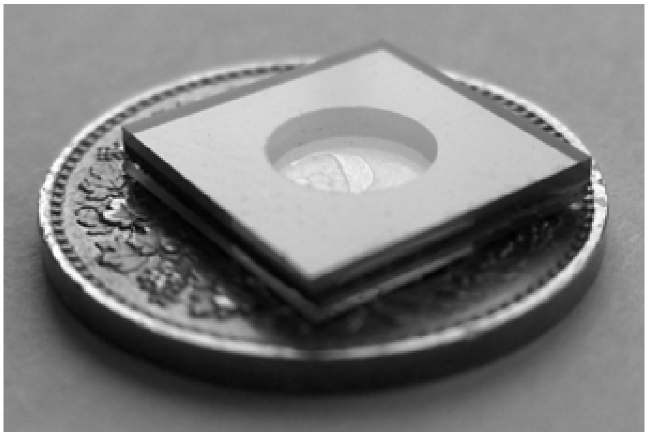

Figure 7 Micro-fabricated Rubidium vapour cell (courtesy of C. Schori and Y. Petremand). Dimensions: 10x10x1.5 mm.

In first approximation, the lowest fractional instability one may reach is inversely proportional to the quality factor Q of the magnetic resonance ($Q=\omega_0/\Delta\omega$, where ω_0 and $\Delta\omega$ are respectively the frequency centre and the width of the resonance signal). One method to further improve clocks is therefore to increase the centre reference frequency from the microwave to the optical domain. The fast development of optical combs has allowed to reducing the size of such *optical* frequency standards. One very promising development in this field concerns the use of microresonators [29] which – in combination with MEMS-based atomic vapour cells, will provide miniature optical frequency references and further extend the range of space applications, for instance to earth observation and atmospheric science.

(SWISS) CUBESAT

Cubesats are cubic satellites 10 cm on a side, with a mass of up to 1 kg. The Cubesat standard was defined in 1999 at the California Polytechnic State University, San Luis Obispo, CA and at Stanford University's Space Systems Development Lab, Palo Alto, CA, as a means to provide affordable access to space, initially primarily for academic institutions [30]. Cubesats are generally "piggy-back" launches: the main customer of the launch vehicle chooses the orbit for its conventional-size satellite; once that main spacecraft is in orbit, the Cubesats are ejected from the launcher. Cubesats serve in large part to teach students about system engineering and about space systems, and are also ideal vehicles for proving in novel technologies such as MEMS that lack flight history. There are currently approximately 80 Cubesats under development, and 40 have been launched from a variety of Russian, American, Japanese, and Indian launch vehicles.

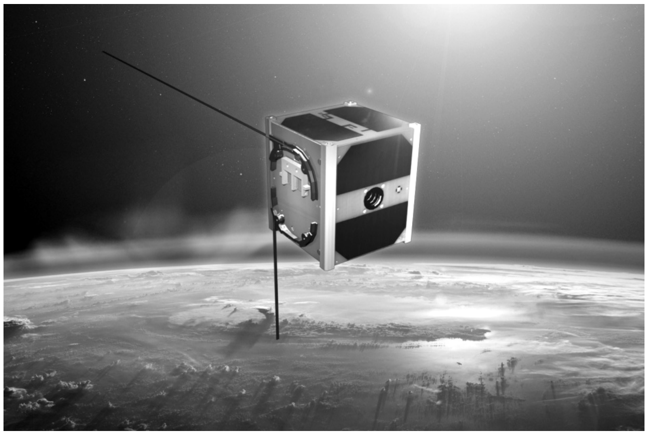

Figure 8: Artist's impression of SwissCube in orbit. The airglow can be seen at the green arc above the Earth. Photo credit: EPFL Space Center.

SwissCube [31] is a Cubesat developed in Switzerland, coordinated by the EPFL Space Center, with launch planned for April 24th 2009. It will image the atmospheric airglow, which is light emitted from an oxygen layer 85 km to 100 km in altitude, with the strongest emission at wavelengths of 558 nm and 762 nm. An artist's impression of SwissCube and the airglow is illustrated in Figure 8. To take pictures of the airglow, SwissCube must be pointed at the limb of the Earth, and requires attitude determination accurate to better than 1°. The only way to obtain the required performance within the mass, volume and power budgets is to use MEMS components. MEMS components are thus not used for the sake of using MEMS, but rather MEMS components are used for SwissCube because high-performance attitude determination on Cubesat missions is only possible with MEMS technology.

The MEMS gyroscope used in SwissCube is the ADXRS614 from Analog Device because of its low power consumption and a high sensitivity. The gyroscopes are needed principally during eclipses (approximately 30% of each orbit is in eclipse). A 3-axis magnetometer (Honeywell model HMC1053) is used to measure the local magnetic field vector. Knowing the position of the satellite in its orbit, and the local vector of the magnetic field allows determining the relative orientation of the satellite with respect to the Earth. When SwissCube is not in the shadow of the earth, the attitude determination system is completed by third set of MEMS sensors, micromachined Sun sensors developed and fabricated at the Danish Technical University (DTU) [32]. One sensor is mounted on each face of the spacecraft, as illustrated in Figure 9. If the position of the sun with respect to the Earth is known (e.g., from the time and from the orbit parameters), the orientation of the satellite with respect to the Earth can be readily obtained from the angle of one satellite face to the sun vector.

SwissCube provides an excellent platform for students to learn about system engineering, and a unique opportunity to build space hardware. The next satellite coordinated by the EPFL Space Center will carry MEMS devices from EPFL research labs to demonstrate their operation in space.

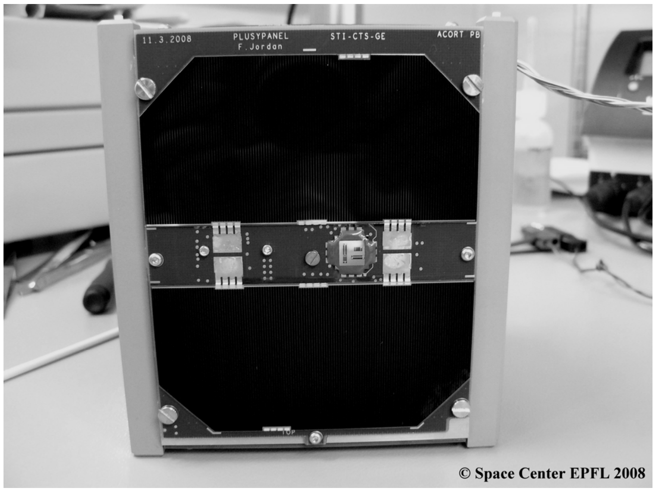

Figure 9: One side of SwissCube (10x10 cm^2). At the center of each face, between the top and bottom solar panels, the MOEMS sun sensor from DTU can be seen (just to the right of the central hole). Photo credit: EPFL Space Center.

CONCLUSIONS

We have presented several applications of MEMS components for space, going from simple integration of earth-bound, commercially available components, to highly dedicated and specially designed instruments. Some of the presented devices have reached a technological readiness level of 9, showing that the implementation of MEMS in space research can no longer be considered as a visionary prospect of the future. However, to reach the ultimate goal of sending completely microfabricated and integrated MEMS systems into space, many challenges lie ahead. Long term reliability of MEMS need to be assessed by experiments in space, which will require frequent launches in the near future. The top-down approach to this is to replace existing heavy and bulky components by MEMS, while the bottom-up approach is to send purely MEMS-based systems on special platforms (see Cubesat). Addressing the challenges by this double-oriented approach will ensure the successful integration of MEMS in Space.

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