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Applications of microsystems in small satellites

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The past decades have experienced radical changes in fabrication and mass production of electronic systems. Sub-micrometer technologies have led to highly integrated systems with even increasing complexity and functionality. Microelectromechanical systems (MEMS) were developed to support the progress in microelectronics by providing similar integration levels in sensors and actuators. Nowadays, microsystems have widely been adopted in consumer electronics, including many critical applications, avionics, and health care. Adoption of microsystems has allowed increases in both performance and functionalities. Space technology is on the verge of similar development. The advent of small satellites, driven by the need of cost reduction, has created a demand for miniature systems that would improve the performance of spacecraft and enable new missions. The miniaturization of space systems can have significant influence on space technology all the more so as major restriction is high launch cost per kilogram. Currently, microsystems for space are still in their infancy and only a few systems have been operated in space. Reliability concerns and the conservative nature of space technology are preventing microsystems from being routinely integrated in satellites. However, small satellites offer a well suited platform for the demonstration of such systems in space.

This thesis maps current situation of microsystem usage in space applications and pinpoints the most potential technologies for future usage. The work presents also analysis of factors restricting the wider usage of microsystems in space and propose strategies to tackle current problems. As the thesis work is located at the crossing point of two disciplines, an overview of both areas is given to help readers who might have background only from one area.

Keywords: Microsystems, MEMS, satellite, CubeSat

Preface

As I was looking for a master's thesis position related to micro- and nanotechnology, working in a satellite project would not have looked like the most obvious option; however, after a bit more than a year in the Aalto-1 project, I can safely say that this was a very good idea. Besides getting support and advice to write my thesis, I had the opportunity to discover a new field of technology and to work as a research assistant for the satellite project, thus earning a truly valuable experience.

I would like to thank Ilkka Tittonen for supervising this thesis and Jaan Praks, first of all for his help and precious advice, but also for giving me the opportunity to be part of the Aalto-1 project. I also would like to thank the people of the Aalto-1 and Aalto-2 teams with whom I had the great pleasure to work. I wish the greatest success to the present and future satellite projects.

I want to say kiitos, merci, grazie and thank you to my dearest friends who have always been here for me and who made this time in Finland such a memorable and life-changing experience.

Finally, I thank my family who, despite the distance, has brought me an essential support in my life and my studies.

Enfin, je voudrais remercier ma famille, qui malgré la distance, m'a apporté un soutient essentiel dans ma vie et mes études.

Otaniemi, 19.05.2014

Bérenger Villat

Contents

Acronyms

ADCS attitude determination and control subsystem

AFM atomic force microscope

CAD computer-aided design

CMOS complementary metal-oxide-semiconductor

COTS commercial off-the-shelf

ESA European Space Agency

JWST James Webb Space Telescope

LEO low earth orbit

MCC mission control center

MEMS microelectromechanical systems

MeV mega electronvolt

MOEMS micro-opto-electromechanical Systems

NASA National Aeronautics and Space Administration

NEMS Nanoelectromechanical systems

NIEL non-ionizing energy loss

NIRSpec near infrared multiobject spectrograph

OBC on-board computer

PCB printed circuit board

PVD physical vapor deposition

RF MEMS radio frequency microelectromechanical System

ROIC readout integrated C circuit

SEU single event upset

TRL technological readiness level

UV ultra-violet

VTT Technical Research Center of Finland

1   Introduction

Satellites are extensively used for assignments with scientific, commercial, civil or military purposes, they provide data that are essential for the protection of our planet and to extend mankind's knowledge; also, satellites enable communication and navigation possibilities on which our society depends. Nevertheless, a typical satellite is a heavy system that weighs over a ton [1] and the cost of placing a satellite in Earth orbit ranges from € 2000 to € 20000 per kilograms [2]. Consequently, the cost of the launch is often a limiting factor for many countries or institutions in wider utilization of space technology. It also limits the satellite missions to those that bear higher potential in terms of results and returns on investment.

Using new technologies that enable higher integration of functionalities, space technology actors have started developing new classes of satellites. These new satellites can be several orders of magnitude lighter than their conventional counterparts with masses ranging from hundreds of kilograms to a few grams. These satellites are thus less expensive to place in orbit. As a result, space technology is at the reach of a wider community and small countries, universities or start-up companies can launch their own satellites. Small satellites are also interesting for space agencies since it provides them with new and inexpensive mission capabilities. A significant driver for the development of small satellites is the creation of standard such as CubeSat.

Reducing the size and the mass of satellites require the ability to downscale their subsystems while preserving their functionalities. The advances in microelectronics have been a major driver in this purpose. However, due to the conservative nature of space technology, technologies that could potentially enable further downscaling and new improvements of small satellites have only been partially integrated in space technology. Micro and nanotechnology, and especially microsystems, have triggered a revolution in consumer electronics and bear the potential to do likewise in space industry.

Microsystems can play an important role in the development of small satellites. They provide a wide range of possibilities to increases the functionalities of the spacecraft as discussed in scietific publications [3, 4, 5, 6, 7]. Microsystems have the potential to enhance the performance of small satellites. Moreover, they can also play the role in enabling technology for new scientific experiments. A relevant example of the use of microsystems as enablers of a new scientific mission is the atomic force microscope (AFM) that was sent on Mars on board of the Phoenix lander in 2007 [8].

Nevertheless, because of their lack of space heritage, microsystems are seldom the first choice for a mission in space. Solutions that are better known and whose reliability in space have already been demonstrated are preferred by the space community. Although, the advent of small satellites and their need for miniaturization is becoming a dominant driver for the development of micro and nano-scale systems

for space applications. Evidently, there are challenges and questions that need to be addressed to ensure the reliability of microsystems in space.

This thesis aims to explore the possible applications of microsystems in small satellites which are the most likely to drive and benefit from the development of sub-millimeter scale technologies. The limitations and the concern related to microsystems in space are also discussed as well as possibilities to overcome some of them.

Since this thesis is situated at the junction of two distinct fields, namely, satellites and microsystems, a background part is dedicated to each of them in the two next chapters. The fourth chapter presents different examples of applications of microsystems in small satellites. The fifth chapter discusses the challenges related to the usage of microsystems in space and presents potential solutions. Concluding remarks are given in the last section of this work.

2 Space systems and applications

A satellite is an unmanned spacecraft that are placed to orbit the Earth outside of its atmosphere for diverse types of assignments. It is a complex system that is designed to be highly reliable. According to [9], 1167 operating satellites were orbing the Earth on January 31st 2014. This chapter gives a general definition of satellites and their subsystems. The last parts of the chapter are focused on small satellites.

2.1 Satellites missions

After being a way to demonstrate the power of a country, space access has become a tool for civilian, scientific, commercial and military activities. Satellites are used to improve our knowledge of Earth and of space environment. They track the first moments of the universe by observing always further away in its depths. Satellites participate to the search of new planets that could resemble the Earth and shelter life. Satellites extend our communication capabilities and they have changed the way we navigate on Earth by providing accurate mapping and location services. Mankind has greatly extended its knowledge of Earth, of the weather and of the environment using remote sensing satellites. Satellites are important tools to understand the climatic changes, and the data that they provide are essential assets to protect the Earth and its environment. Many satellites are dedicated to Earth observation in order to monitor, for example, lands and water pollution, agriculture, forests or ice coverage, observation. Satellites are also extensively used for weather forecasts.

One reason to use satellites is that they can offer wide or global coverage of Earth; this is a necessity to be able to observe large scale phenomena, such as oceanic currents, weather or climatic changes. Global coverage is also useful for communication with remote areas. Another reason is that ground-based observations are often made difficult by the presence of the atmosphere that disturbs and attenuates the already weak signals or light coming from remote space objects. Therefore, some observations need to be performed outside of the atmosphere of Earth in order to return data that can be scientifically relevant.

As shown in Figure 1, different elements are typically necessary to conduct a satellite mission. The launch vehicle, to begin with, is a rocket that carries the satellite to space and performs the necessary manoeuvres to reach the orbit. At the moment, rockets are the only way to place a satellite in orbit. The launch is a critical part of a mission during which the satellite experiences extremely high level of stress due to vibrations, shocks. Besides, the launch vehicle sets a variety of constraints on the mission related to the mass and dimensions of the satellite or its structural solidity.

Another important part of a mission is the ground segment and the mission control center (MCC) which receives data and issues commands to the satellite

using one or several ground stations and a radio link. The MCC ensures the orbital operation, monitors the health of the satellite and, in the case of a scientific mission, gathers the results from the experiments.
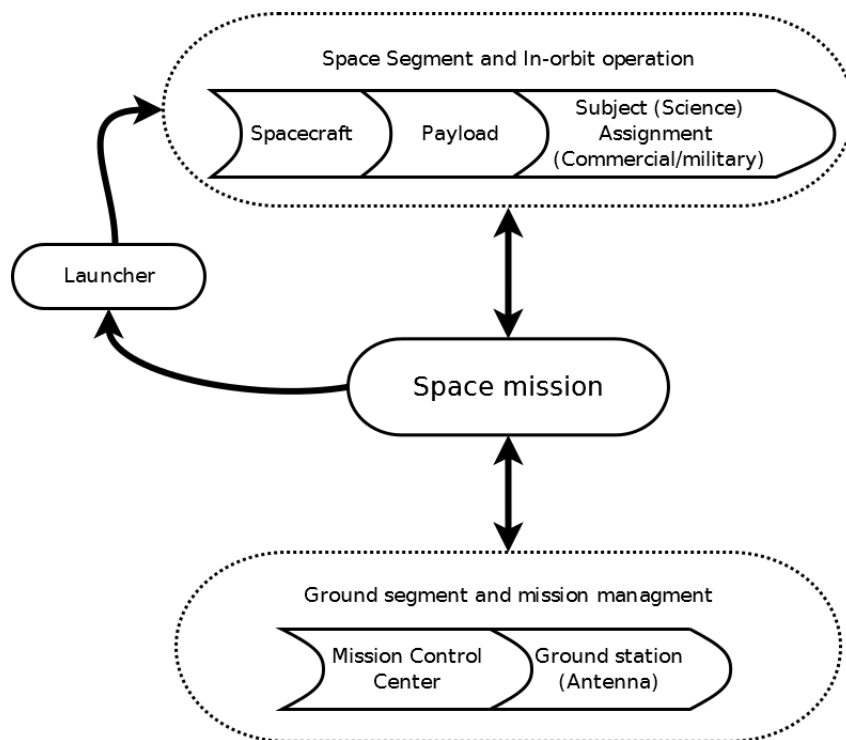
Figure 1: Typical elements that are needed to conduct a satellite mission. The launcher is used to place the satellite in orbit while the mission control takes care of operating the satellite and retrieving data using radio link.

2.2 Satellite design philosophy

A satellite is a complex system whose mission can last from several months to tens of years depending on the assignment and the orbit. During the time of the mission, a satellite needs to reliably operate its payload(s) as defined in the requirements of the mission. A satellite can only rely on radio link to communicate and it currently cannot be serviced in space. Moreover, satellites operate in harsh environment (see section 2.4). Therefore, reliability and risk elimination are at the heart of the design process of a satellite.

Designing a satellite is a long and complex process governed by stringent requirements coming from the assignment and from the launch capability. Amongst the requirements imposed by the mission design one can find the power budget (total amount of power that needs to be generated and stored as well as the fraction of this power available for each subsystem), the telemetry budget (bit rate and size of the data packets that can be transferred via the radio link), the orbit and the

ability of the satellite to orient itself. On the other hand, some requirements are determined by the launcher, such as the mass budget, the volume or the structural solidity of the satellite. The three main budgets, namely, mass, power and telemetry, are intrinsically related and subjected to compromise in order to match the requirements. For instance, if the average power of a satellite needs to be augmented, then one needs to increase the area of the solar panels; hence increasing the mass of the satellite. Another solution is to decrease performance of other subsystems needs to be reduced. Figure 2 shows some typical compromises that are made in the design of a satellite.

$$
\begin{array}{rcl}
\text{Total Mass} & \longleftrightarrow & \text{Launch cost} \\
\text{Surface Area} & \longleftrightarrow & \text{Solar power harvesting} \\
\text{Antenna size} & \longleftrightarrow & \text{Data rate}
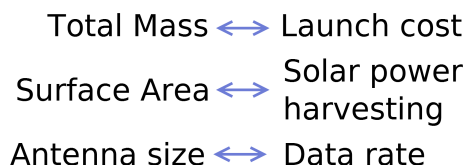\end{array}
$$

Figure 2: Typical compromises found in a satellite design process. The design of a satellite usually faces numerous requirements and constrains that lead to trade-offs on different parameters.

Considering the investments in terms of money and time necessary for its development and its placement in orbit, it is natural that a satellite has to be as reliable as possible. This makes quality management and systematic testing very important parts of the design process. Qualification of a satellite and its subsystems include vibration tests to verify that the spacecraft can sustain the launch phase. Figure 3 shows the typical acceleration levels encountered on board of a Vega launcher. Other tests, such as radiation, vacuum and thermal cycling are performed to verify that the satellite can operate in space environment (see subsection 2.4). Software testing is becoming an important part of the qualification testing due to the increase of the complexity of the software on board of satellites.

2.3   Structure of a satellite

A satellite is an assembly of several subsystems. Each subsystem is taking care of specific tasks according to the mission needs and objectives. The schematic in Figure 4 presents different typical subsystems of a satellite and their interconnections.

The typical subsystems of a satellite can be described as follow, more information on the subsystems is provided in [1] :

Payload(s): The instrument(s) carried by the satellite to perform the mission. The role of the satellite is to reliably operate the payload(s) in the conditions required by the mission. Hence, the rest of the subsystems of the satellite are designed and chosen according to the needs of the payload(s) and the specifications of the mission.
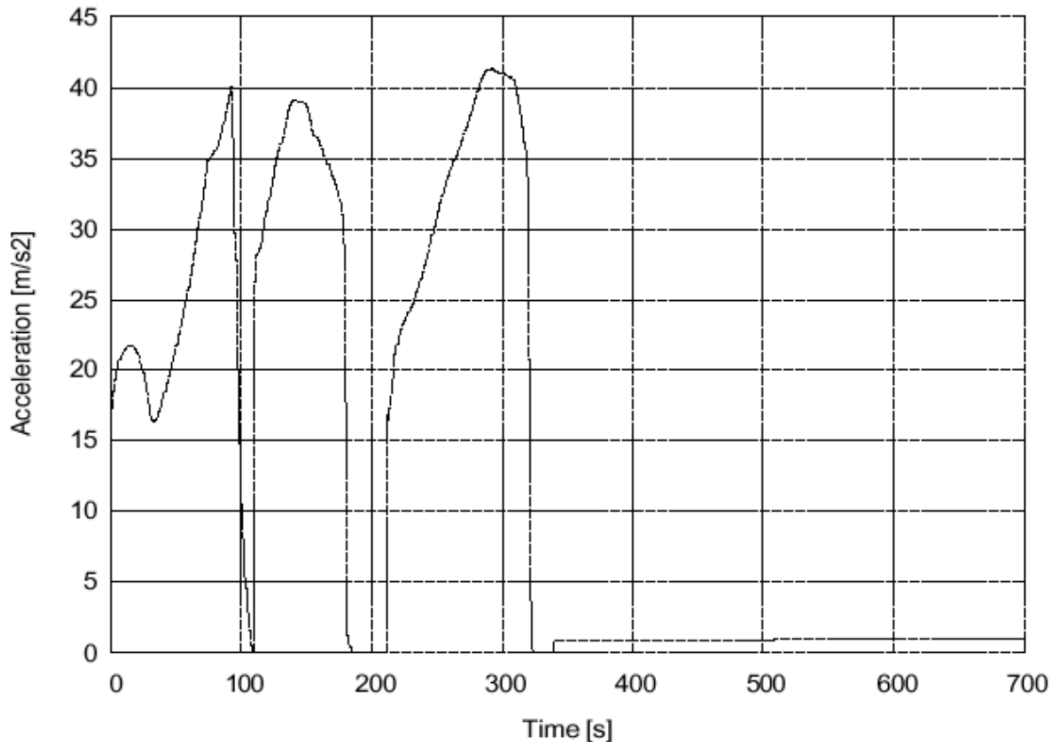
Figure 3: Typical longitudinal steady-state static acceleration occurring during the ascent of the Vega rocket. The accelerations are generated by the propulsions systems. The brutal decelerations are due to engine burnouts and separations of stages of the rocket during the ascent. Graph taken from [10].

Electric Power System: The EPS provides and adapts the electric power that is, in most of the cases, harvested using solar panels. The harvested power is typically stored in batteries.

Telemetry and communication: The typical radio system establishes the link between the satellite and the ground segment, it transmits the data back to earth and receives the commands issued by MCC. The transmitted data can be related to the assignments (communication data packets, observations, images) or to the satellite itself (health monitoring, position). The radio link is currently the only way to interact with a satellite in space.

Data handling: The on-board computer (OBC) processes the data from the different sensors of the satellites (temperature, attitude) to send them over telemetry or to perform house-keeping actions. It can also process the data from the payloads for example, to select or compress them before sending via the radio link. It is the OBC that schedules the tasks of the other subsystems.

Attitude and orbit control: It monitors the orientation of the satellite with respect to earth or sun. This can be done to point the antenna in the optimum direction, to orient the solar panels towards the sun or to orient the sensing

payloads when needed.

Structure: It provides the structural stability to all parts of the satellites and plays a critical role during the launch phase since it must sustain the vibrations and shocks (see Figure 3 for an example of the acceleration encountered during the launch phase).

Thermal management: It regulates the temperature inside the satellite in order to protect the other subsystems from the extreme temperature ranges (see 2.4).
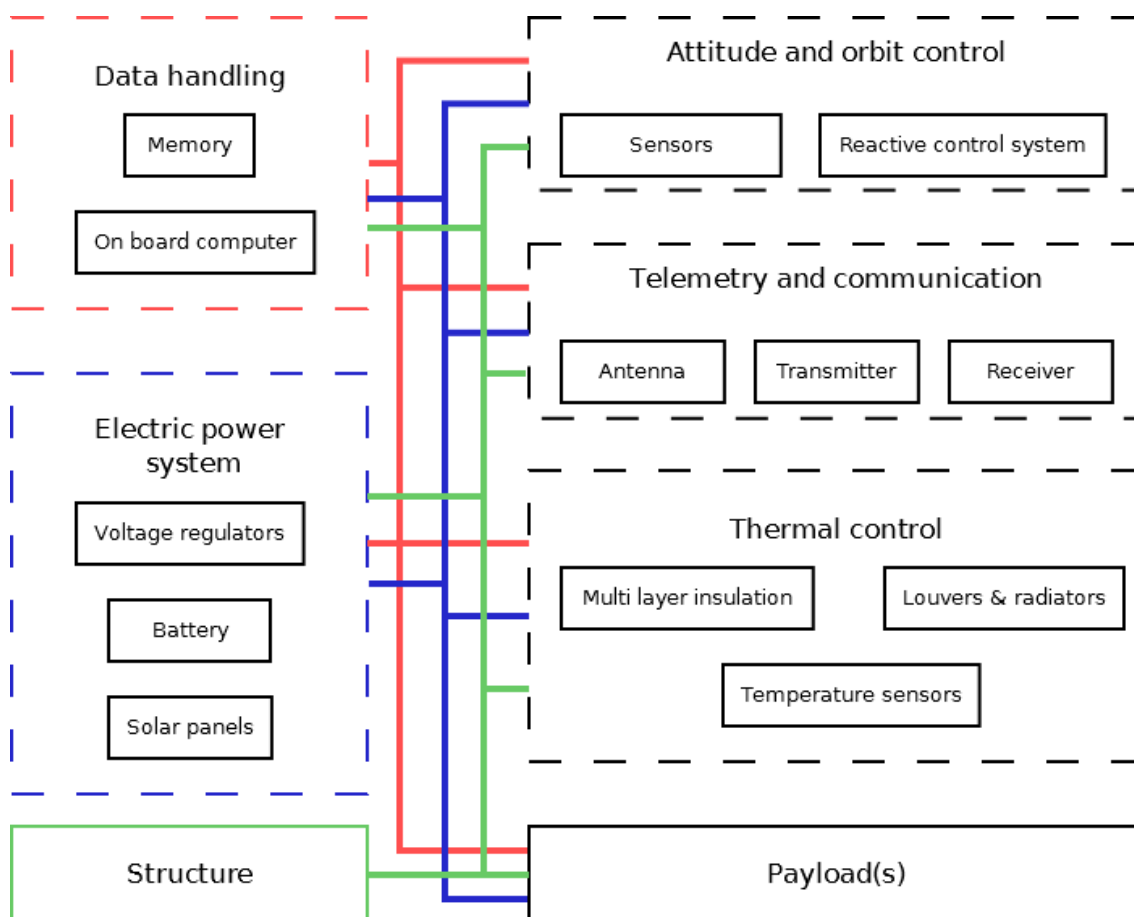
Figure 4: Overview of the typical subsystems of a satellite. The red line represents the data bus (scientific equipments results, health-status of subsystems, radio communication), the blue line the power bus (power is usually produced by the solar panels and stored in batteries) and the green one stands for the mechanical linkages.

2.4 Space environment and radiation

The environment in which a satellite operates strongly differs from the environment on Earth at sea level. The main elements of space environment that need to be con-

sidered during the design and the operation of a satellite, are vacuum, temperature cycles and high radiation.

Outer space is nearly a perfect vacuum with only a few atoms per cubic meter. The vacuum limits the possible materials that can be used to fabricate a satellite [11]. For example, materials such as plastics may outgas and disturb optical equipments, other materials such as lubricant oil rapidly evaporate in space and hence are ineffective for lubrication of movable parts. A satellite orbiting the Earth can be cyclically subjected to temperatures ranging from $-40°$ to $80°$ and beyond. Since a satellite is in vacuum, the heat cannot be dissipated by convection but only by radiation; which leads to the need for efficient thermal control system to either evacuate the heat or to keep it. Temperature cycles strongly affect the lifetime of the electronic components and the batteries of a satellite. The thermal expansion and retraction resulting from the cycles may also be harmful for the structure of the satellite and the soldering joints of the electronics.

The most challenging factor of the space environment is radiation. Radiation is omnipresent in outer space and is made of different types of particles and rays of variable energies and densities. Radiation in space is predominantly consisting of electrons, protons and cosmic rays (protons and alpha particles) of high energy [1, 12]. Moreover, the radiation environment is non-homogeneous and the total radiation levels received by a spacecraft in space depend on its orbit and time. Secondary radiation occurs when radiation from space interacts with materials of the satellites. This process can generate electrons and neutrons. One can distinguish three main sources of radiation in space [12] as summarized in Figure 5.

First of all, the sun is a major source of energetic particles, ultra-violet (UV) and x-rays are emitted as bursts. The intensity of solar particle emission follows a cycle of eleven years [1]. The Earth magnetic field partially acts as a shield against these particles.

Electrons and protons are trapped by the magnetic field of Earth forming belts called the Van Allen belts, they are situated at altitudes between 100 km and 65000 km [13]. The electrons within the belts have energies that can be up to some mega electronvolt (MeV) and the protons have energies of the order of hundreds MeV. Satellites may orbit near or within these belts.

Galactic cosmic rays are coming from the outside of the solar systems and are made of high-energy particles and heavy-ions. The incoming flux of cosmic rays is isotropic and continuous but is influenced by solar winds and the magnetic field of Earth.

Radiation effects on a satellite are detailed in [1, 14]. single event upset (SEU) are one of the effects of radiation, they usually result in the change of state of an electronic component ("bit flip"). Dielectric materials are effected by charging due to radiation which eventually leads to catastrophic failure of the component. Surface charging of surface dielectric materials is another concern related to radiation. This can lead to high potential differences with other parts of the satellite and to

electrostatic discharges which are likely to be catastrophic for the spacecraft.
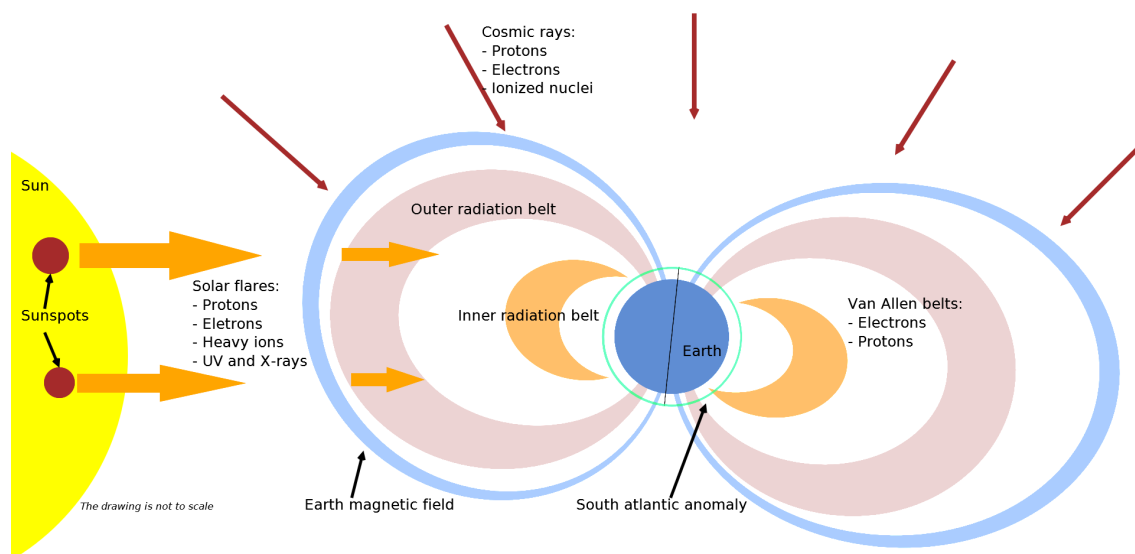

Figure 5: Main sources of radiation encountered by a spacecraft in Earth orbit.

2.5 Small satellites

The high reliability found in the systems of conventional satellites is often achieved using solutions that are tested in space and well established in space technology. These solutions typically rely on bulky components and shielding to resist the radiation and the mission environment such as the launch phase. As a result, conventional satellites are heavy and therefore expensive to launch. In order to reduce the high costs associated with launching heavy satellites, space engineering community has started developing smaller and lighter satellites. A small satellite is usually launched as "piggyback" alongside with conventional satellites or other small satellites. Typically, a small satellite is placed in low earth orbit (LEO) with an altitude between 160 km and 2000 km.

A small satellites has mass ranging from 1000 kilograms to a few grams. One possible classification of spacecraft according to their mass is given in table 1 from [1]. In this thesis, the word small satellite refers to the satellites with a mass below 1000 kg.

Despite their reduced size and mass, small satellites are alike conventional satellites; they use the same subsystems as described in 2.3 and their design is also relatively complex. In order to make satellites smaller, space engineers make use of new technological developments such as microelectronics and microsystems (see chapter 3). The components used in the subsystems of small satellites are not necessarily designed to operate in space and can be taken from the consumer electronics market and do not include shielding. commercial off-the-shelf (COTS) subsystems

are developed for space applications but are sometimes or even often based on non-space grade components in order to be lighter, easier to integrate and less expensive. Hence, their operation is not necessarily guaranteed in space environment.

However, it is important to notice that due to the small size, the mission possibilities are usually limited to the ones with small payloads and small power requirements. Nevertheless, the advances in the miniaturization of microcontrollers and microprocessors provide the small satellites with fairly high computing power allowing to perform complex experiments in space providing that the payloads can be operated by the satellite.

Table 1: Classification of spacecraft according to their mass, adapted from[1].

Class	Mass (kg)
Conventional satellite	>1000
Small satellite	500-1000
Minisatellite	100-500
Microsatellite	10-100
Nanosatellite	1-10
Picosatellite	<1

2.6 Design philosophy small satellites

2.6.1 Risk management

The reduced overall cost of small satellites allows a different approach in the way to manage the potential risks of the mission. The classical approach tends towards a drastic reduction of the risks by the means of expensive space-grade components, quality control and redundancy. Small satellites are designed tolerating higher risks, non-space grade components may be used and redundancy is used to distribute the risks. For example, components from the consumer electronics are often used in CubeSat projects (see 2.6.2).

Therefore, risks management is crucial in the design of a small satellite. Redundancy of the subsystems or components and careful design strategies help to mitigate the risks resulting from the integration of COTS components. Qualification testing is also performed as a mean to validate the operation of the subsystems in space.

2.6.2   Short development time

Another important difference between small and conventional satellites is the development time. While a normal satellite mission takes more than ten years of work prior the launch, a small satellite mission can be developed in a few months or years. Short development time is also a factor that reduces the cost of small satellites.

The rapid development of small satellites is extensively supported by the use of standards. The strong potential of standardization is well demonstrated by the CubeSat standard; that gives design rules for small cubic satellite units with a lateral dimension of 10 cm [15]. The CubeSat satellites can be made of one, two or three cubic units; a three unit CubeSat is shown in Figure 6. Standardization facilitates the deployment of satellites since the orbital deployers can also be standardized. Whilst the CubeSat standard was first created for universities projects, CubeSats are nowadays also used by companies such as Planet Labs [16] and space agencies such as National Aeronautics and Space Administration (NASA) (see section 2.9).

2.7   Missions of mall satellites

Even though the payloads and possible applications can be limited as compared to conventional satellites, small satellites offer the possibility to realise flexible and cost effective missions [17]. The low price and short development time increase the number of missions that can be designed in a given time. This can be highly beneficial for technological demonstration of subsystems [2, 18].

A launch vehicle can deploy tens of small satellites at once to create a distributed system. Constellations (coordinated formation of satellites) and swarm (non-coordinated formation of satellites) of small satellites make new forms of measurements in space possible [19, 20, 21]. Measurements can be conducted at different points of space simultaneously. The accuracy and the quality of the experiments can be enhanced. Constellations and swarms are also interesting in terms of risks management, since they offer a form redundancy between the satellites [21].

An example of an assignment that is well suited to a small satellite is spacecraft inspection [22]. The satellite would be used to take pictures and inspect the state of a larger satellite to prevent or understand failures. This requires the development of flight formations and propulsion capabilities for small satellites.

Disaster management is also a domain where small satellites can provide a flexible and rapid response. Natural catastrophe could be monitored with a high spatial and time resolution using small satellites in LEO [23].
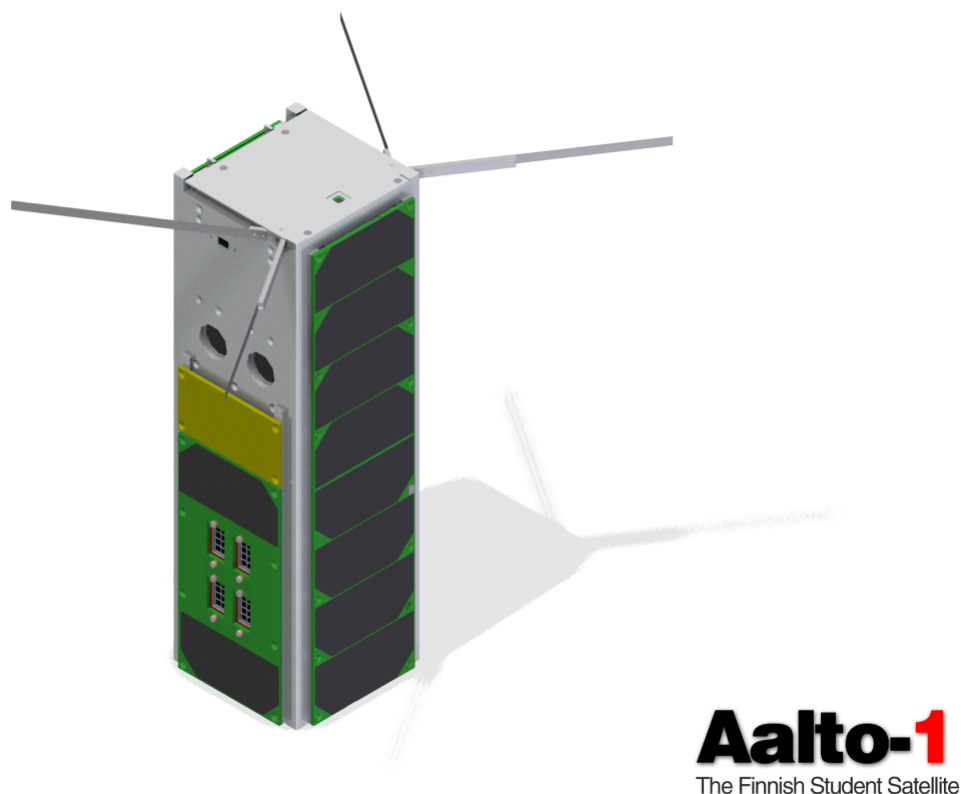
Figure 6: Computer-aided design model of the Aalto-1 student satellite. The satellite is based on the three units CubeSat standard. The dimensions of the satellite are 34,5 cm x 10 cm x 10 cm, the mass is of approximately 4.5 kg. The satellite is planned to be launched in early 2015.

2.8 The Aalto-1 student satellite

Aalto-1 [24] is a student nanosatellite project that has been initiated by the Radio Science Department of Aalto University School of Electrical Engineering in 2010. The satellite is currently in development and is planned to be launched in 2015, it will be the first Finnish satellite. Aalto-1 is developed by students following the CubeSat standard, it will weight around 4.5 kg and its dimensions will be 34,5 cm x 10 cm x 10 cm; a computer-aided design (CAD) model of the satellite is shown in Figure 6. The power will be provided by solar panels attached on the frame and will be stored in batteries. The satellite will be equipped with two radios, one for telemetry and commands and the other one for data transfer.

The development of the satellite is based on a consortium between Department of Radio Science of Aalto school of Electrical Engineering and other universities and industrial parters in Finland and in other European countries. Some parts of the satellites are fully developed by students while other are COTS subsystems provided by the industrial partners.

The satellite mission will last two years and consists of demonstrating the operation of three innovative payloads in space: a spectrometer for Earth observation, a radiation monitor and a plasma brake to deorbit the satellite [24].

The optical spectrometer is developed by the Technical Research Center of Finland (VTT) and will be the smallest interferometer for remote sensing used in space. This scientific payload is integrated alongside with an imaging camera. The spectrometer is based on a Fabry-Pérot interferometer with piezo-electric actuators and can image the Earth at different wavelengths [24].

The radiation monitor will be used to map radiation environment in the LEO. It is equipped with two detectors, a silicon detector and a cesium iodide doped with thallium scintillator. It can detect electrons with an energy above 60 keV with a resolution of about 500 keV and protons with energy above 1 MeV with a resolution of about 50 MeV [24]. The important novelty with this detector is mainly related to the read-out electronic that achieve higher count rates than conventional radiation detectors.

The third payload of Aalto-1, the electrostatic plasma brake, is a novel technology that ought to be tested in space. The main purpose of this device is to deorbit the satellite by using the Coulomb drag on a charged hundred meter long tether that will be deployed at the end of the mission.

2.9   Evolution of the number of CubeSats in space

Satellites based on the CubeSat standard are commonly called CubeSats, they belong to the category of nanosatellites and weigh typically between 1 and 4 kg. Other larger structures are nowadays possible with for example six or twelve units Cube-Sats. The graph in Figure 7 shows the total number of CubeSats launched since the creation of the standard. It clearly illustrates the increasing interest that the standard is receiving. The graph in Figure 8 shows the portions of CubeSats launched annually by the different actors of space technology. It can be observed that the main players in the CubeSats are formed by universities in the first place; this is mostly due to the great educational outcomes of CubeSat projects. Research faculties and private companies are also starting to show high interest for CubeSats. The example of CubeSat shows that small satellites are becoming popular and are used by different kind of institutions. The fact that private companies are starting to use the CubeSat standard is an important proof of the economical potential of the standard and a positive sign for its future.
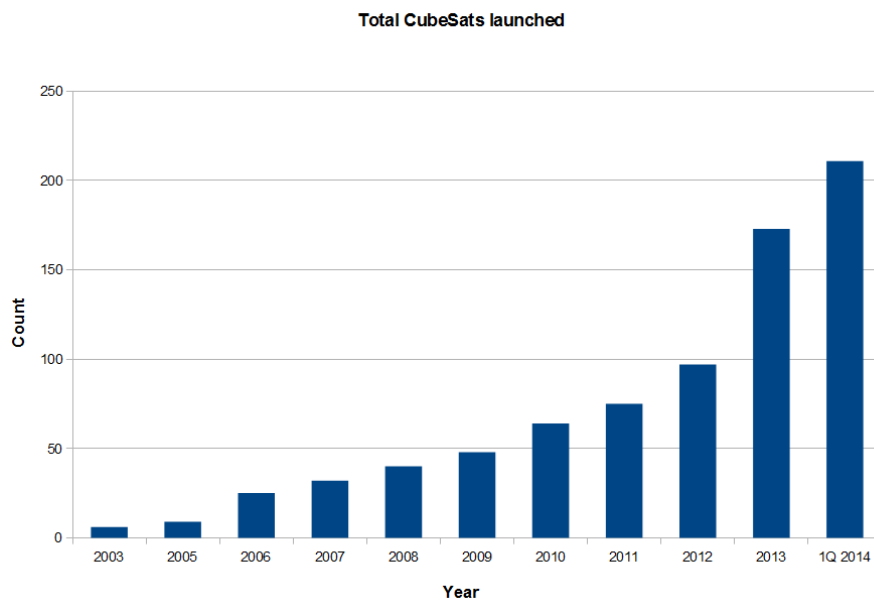
Figure 7: Total number of CubeSats launched since 2003 (The first CubeSats were launch during this year). The graph is taken from Juha Suokas bahchelor's thesis [25].
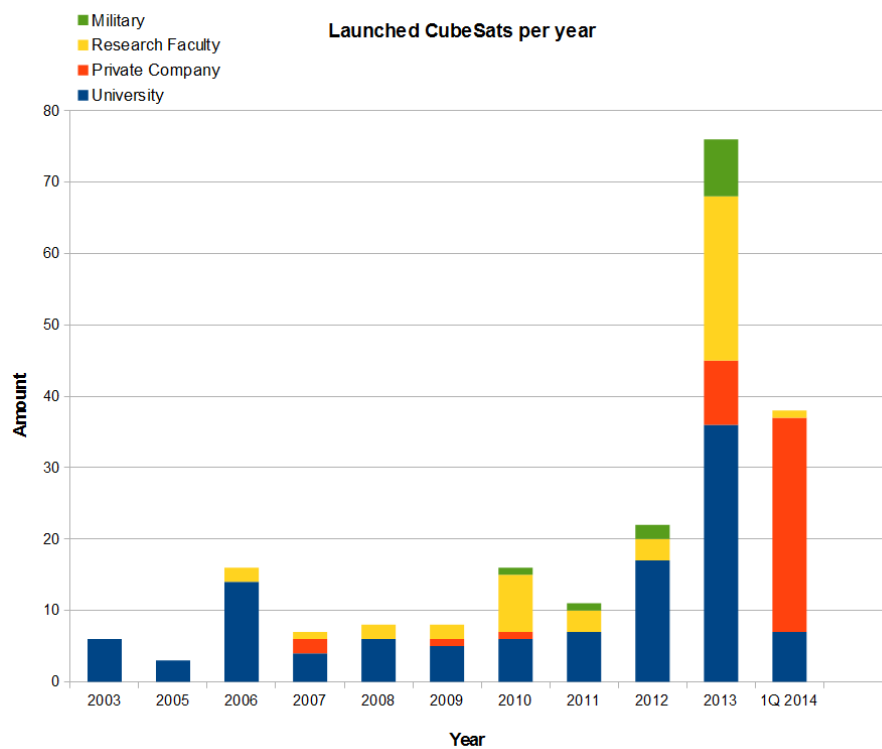
Figure 8: Number of CubeSats launched per year since 2003 (The first CubeSats were launched during this year) by different actors of space technology. The high number of CubeSats launched in 2014 by private companies is due to the Flock-1 mission which is a constellation of 28 earth-imaging satellites [16]. The graph is taken from Juha Suokas bahchelor's thesis [25].

3 Microsystems - technology and trends

3.1 Definition of microsystem

In 1959, Richard Feynman, suggested during a lecture called *There's Plenty of Room at the Bottom* [26], the possibility of scaling down machines as we know them in order to fabricate what he called *small machines*.

The rapid development of microelectronics in the last decades has followed Moore's law [27] which predicts that the count of transistors per unit of surface will double every two years approximately. A dramatic miniaturization of transistors and electronics circuits was achieved and is still ongoing. Silicon processing and other related techniques of fabrication have strongly been optimized to become economically efficient. As a result, integrated circuits and microelectronics are nowadays present in a large quantity of systems.

As a consequence of the development of microfabrication for microelectronics techniques, Feynman's idea finally became a reality few years after his speech. Since then, the *small machines*, called microsystems or microelectromechanical systems (MEMS) have experienced an ever increasing interest. These systems are nowadays commonly used and integrated in many devices such as printers, smart-phones or medical tools.

3.2 Basic principles of microsystems

Microsystem technology is strongly interdisciplinary and can integrate mechanical, optical, chemical or fluidic elements alongside with microelectronic systems. The main areas of application are actuation and sensing for consumer electronics, medical or military equipment. The most common examples of applications of microsystems are sensors such as accelerometers (car airbags), gyroscopes (smartphones), pressure sensors (blood pressure measurement), MEMS actuators are mainly used as micro-pumps and valves (drug delivery, ink-jet printer), switches and relays (RF systems), movable micro-mirrors (projector).

Microsystems benefit from the same advantages as microelectronic devices, namely, low production costs thanks to batch processing, high integrability and versatile applications. Microsystems are intrinsically related to microelecronics since this technology is needed to control the systems and process their data.

One fundamental difference between microelectronics and microsystems is the dimensions. Microelectronic devices are, at the moment, based on two dimensional technologies, on the other hand, most of the microsystems need to be designed in three dimensions to be functional.

Here, the word microsystem is used in a broad sense and includes systems and

devices with typical dimensions ranging from micrometers to nanometers. MEMS, are microsystems integrating mechanical parts. The word MEMS is often used to describe microsystems and vice versa. Microsystems that integrate optical parts are generally called micro-opto-electromechanical Systems (MOEMS), they also integrate mechanical components to actuate the optical ones. Further references on MEMS devices can be found in [28, 29, 30, 31].

Alike microelectronic devices, microsystems are developed in order to achieve extreme integration levels and high density of functions while consuming a minimum amount of power. High levels of integration are reached by reducing the typical length of the systems.

In practice, microsystems often enable new functions and provide solutions to achieve new forms of in-situ sensing. Making a system smaller does not only help to reduce the size of its footprint, it can also make it more reliable and more sensitive (sensing devices). A higher sensitivity means that a microsystem can make measurements with higher resolutions, for example bioMEMS only need an extremely small quantity of sample.

Also, systems that operate at the micrometric or the nanometric scales, can take advantage of phenomena such as quantum tunnelling that are only relevant at these scales.

From an economical point of view, the very small size of the devices makes the fabrication of very large batches possible and several thousands of identical devices can be fabricated from a wafer. High volume production is usually a necessity to make profit [32].

3.3 Common fabrication techniques for microsystems

The main principles of microsystems fabrication are derived from microelectronic processes, therefore it is natural that silicon plays a predominant role in MEMS. The starting element for the fabrication of MEMS is typically a wafer of silicon; other types of wafer can be used such as sapphire, glass, or silicon-on-insulator [33]. The fabrication steps are performed in clean room environment to avoid contaminations by particles that could severely alter the reliability of the devices.

MEMS processing borrows several techniques from microelectronics, this feature has accelerated the development of microsystems [30]. But microsystem technology has also its own sets of techniques to fabricate the moving elements from silicon, they are generally referred to as surface and bulk micromachining.

Microfabrication and micromachining are two very broad fields, details on the techniques can be found in references [33, 28, 29, 31]. The list below gives a short overview of some common techniques used in microsystems fabrication processes.

Lithography is the process of patterning a photoresist using UV-light and a mask, the exposed or the non-exposed part can then be removed by developing. The remaining photoresist protects the layers underneath from the following processes. The process is illustrated in Figure 9 (1,2).

Wet etching is a process which generally follows lithography, the wafer is exposed to chemical etchant and the parts that are not protected by the photoresist (or other layers) are dissolved. The etching pattern depends on the time, the orientation of the silicon crystals and the etchant. The basic process is illustrated in Figure 9 (3).

Dry etching (or plasma etching) is a set of techniques that uses accelerated reactive atoms or ions to bombard a subtract and remove material. The atoms and ions are accelerated by applying an electric field with the substrate being one of the electrodes. This technique allows to fabricate vertical walls with high accuracy.

Sputtering is a physical vapor deposition (PVD) technique where argon atoms hit a target material to eject atoms that will deposit onto the substrate. Sputtering can be used with almost any inorganic material and has the advantage of offering a good step coverage because of the randomness in the direction of the ejected atoms.

Oxidation is used to produce silicon dioxide (SiO_2) layers. Oxidation can be either dry or wet, the first one is slower but produces higher quality layers and is used for device operation. The layer produced with the later one are used for other fabrication steps or to isolate the device.

Epitaxy is a complex deposition process resulting, if done properly, in high quality layers. It is usually used to grow a doped layer of silicon over another silicon layer in complementary metal-oxide-semiconductor (CMOS) processing. The grown layer (epitaxial layer) has the same crystal properties (orientation) as the substrate layer. It can also be used to grow silicon over other substrate but the lattice constants need to be the same or almost the same, in the later case the process is called heteroepitaxy.

Wafer bonding is a set of techniques widely used in MEMS processing to mate two wafers. Microsystems are typically made of two or three wafers stacked together. For example, it is used to create channels or cavities underneath a membrane as shown in Figure 10 [33]. Bonding is also used to enclose movable parts in order to protect them and to control their environment.

3.4   Packaging of microsystems

Packaging is a critical step in the fabrication of a microsystem. It encompasses the processes and techniques to assemble the different parts and systems in order to form a useful device able to perform the intended functions. MEMS packaging techniques
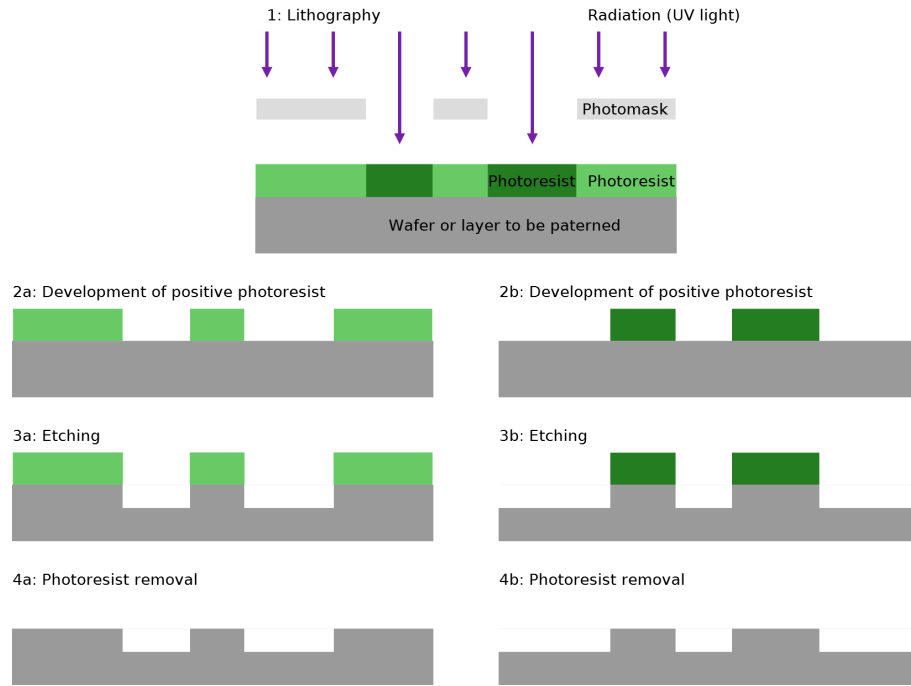
Figure 9: Schematic of lithography and etching processes with positive photoresist (a) and negative photoresist (b).

play a central role in the ability of integrating the devices in larger systems [34]. A MEMS package needs to provide the necessary interface for the device to operate and to be connected with other systems. A packaged MEMS devices is shown in Figure 17. Packaging of MEMS devices is a challenging process, unlike the packages of microelectronic devices, MEMS packages are often custom-built. This is due to the fact that microsystems are based on multiphysics phenomena and have versatile principles of operation. Indeed, many microsystems need to interact with their environment, either to sense or to actuate an external phenomenon. For example, a sun sensor needs to let light enter and reach the light-sensing element. Another example is the pressure sensor that needs to have its sensing element in contact with the exterior medium. Therefore, microsystems packages must be carefully designed depending on the application and thus, no standard packaging exists [30]. Another reason for the customization of MEMS packages is the use of micromechanical moving parts and out-of-planes structure. The package of the device must take into account those features in order to provide the necessary space for their operation [35].

Packages ensure different missions that are necessary to the reliable operation of the device. First of all, it connects the systems via the terminals that can be soldered onto a printed circuit board (PCB). The microsystem die is connected to the terminals of the package via wire bonding. A gold or aluminium wire connects the bondpad of the die to the terminals, the most common technique to do so is called thermosonic bonding as described in [30]. Another bonding technique
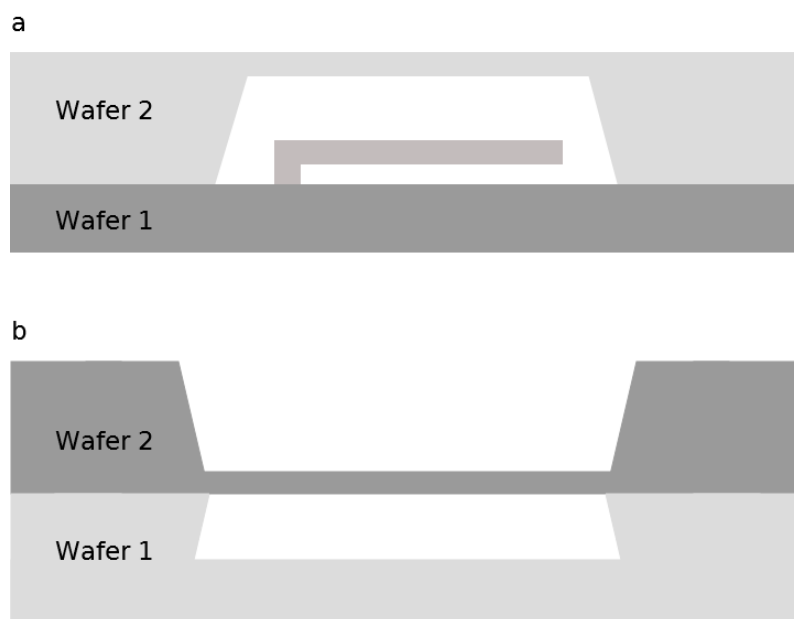
Figure 10: Schematics of two application of bonding techniques: (a) to enclose a moving part in order to protect it from the next processes or to control its environment (pressure, temperature), (b) to create a membrane.

that is interesting for microsystems is the flip-chip bonding. The die is soldered to the package using solder bumps on metallic pads. Using this technique adds more fabrication steps to make the pads but it allows a higher density of interconnects. In case of MEMS, it makes it easier to integrate several systems within one package such as control electronics die and sensing elements. In [30], it is made clear that, integrating several systems within one package is also possible with thermosonic bonding but the reliability might be decreased.

Packaging helps to protect the systems from mechanical and environmental stress. Some microsystems can be extremely sensitive to stress that can decrease their performance or give false values. Thermal management inside the package of microsystems may be important in order to prevent temperature fluctuations from altering the calibration of the devices. Besides, thermal actuators can be used in MEMS devices and need to be cooled down. Packaging offers the possibility to accurately control the environment of the microsystems. For example, the pressure inside a package can be critical for resonant structures since it has an effect on the damping. This is why more and more devices are enclosed in low pressure voids.

3.5   Common principles of operation of MEMS devices

Transducers rely on several physical phenomena to convert the energy and operate as sensors or actuators [28, 32]. The two following sections give a brief overview of

some principles commonly used in MEMS actuators and sensors.

3.5.1 Main actuation mechanisms

Electrostatic actuators are based on the Coulomb force which is the attraction of two bodies of opposite charge. This is the most common actuation strategy for MEMS devices at the moment [32]. Electrostatic actuation can be used to tilt elements, such as micromirrors or switches. It is also used to drive vibrating structures for sensing.

The basic component of this type of actuator is a set of two electrodes: a fixed electrode and a movable electrode usually combined with a spring (in practice the spring is a cantilever). The distance between the electrodes varies proportionately to the square of the applied voltage V. The electrostatic force F_e that can be created with a simple parallel electrode plates actuator is given by:

$$F_e = \frac{1}{2} \frac{\varepsilon A}{(d - x)^2} V^2 \qquad (1)$$

where ε is the permittivity, A is the surface area of the electrode, d is the gap between the plate at the nominal state and x is the displacement of the movable electrode as shown in Figure 11.
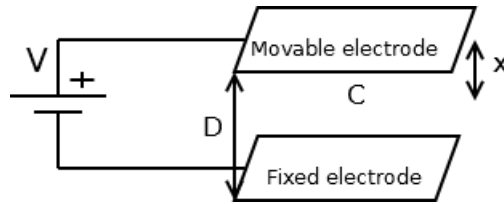
Figure 11: Capacitive plates actuator structure: the upper plate is attracted to the other plate when a voltage is applied. This is the basic element of an electrostatic actuator.

An important parameter that needs to be considered with electrostatic actuator is the pull-in voltage. When a voltage greater than the pull-in voltage is applied between the electrodes, the movable electrode will snap onto the fixed electrode; and will be released at the removal of the voltage. This effect can be wanted or unwanted depending on the application. The effect is described in detail in [32]. In case of a parallel plate electrostatic actuator, the pull-in voltage is given by:

$$V_P = \sqrt{\frac{8}{27} \frac{kd^3}{\varepsilon A}} \qquad (2)$$

where k is the the linear spring constant of the structure.

Piezoelectric actuators are based on materials that mechanically deform when subjected to an electric field. The generated displacement is usually small, it can, however, be amplified by stacking actuators [32].

Thermomechanical actuators use the thermal expansion that occurs when a material is subjected to heating. It can be based on the expansion of solid, fluid or gas. This effect can be increased using a structure made of materials with different thermal expansion coefficients.

3.5.2   Main sensing principles

Capacitive sensors measure the change of capacitance resulting from the mechanical movement of electrodes. Basically, the sensor uses a proof mass acting as one of the electrodes, while the other electrode is fixed. Mechanical movement of the proof mass changes the value of the capacitance formed by the two electrodes as shown in Figure 12. The capacitance of such a system is given by:

$$C = \varepsilon \frac{A}{d - x} \tag{3}$$

where ε is the permittivity, d is the gap between the electrode plates at the nominal state and x is the displacement of the proof mass.
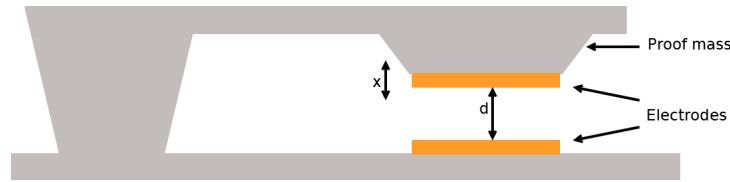
Figure 12: Basic capacitive sensor structure with a proof mass and two electrodes. Movement of the proof mass results in capacitance change that can be measured.

Piezoelectric sensors rely on materials that generate voltage when a mechanical stress is applied.

Piezoresistive sensors use materials whose resistivity is dependent on the applied stress.

3.6   Failure mechanisms of microsystems

Reliability of microelectronic devices is well documented and understood, this knowledge can help to study the reliability of microsystems. However, MEMS are based on a wider range of design and physical principles. Moreover, many of them include moving parts. Because of this diversity, the possible failure modes of MEMS are

numerous and can strongly differ from a device to another. Therefore, MEMS reliability studies need to include the design, the fabrication and the operating conditions of the devices as stated in [36].

Possible failure meachanisms of MEMS devices are detailed in [36, 37, 38]. The following list describes some of the most commonly encountered failure mechanisms in MEMS devices.

Mechanical fracture can result from shock or stress overload. It can also be induced by corrosion of the constituent materials of the device.

Stiction is a phenomenon that can occur between movable parts of devices, it can be permanent or temporary. It is very problematic for many devices since the surface to volume ratio of MEMS is typically high. Stiction may occur because of different physical phenomenon such as electrostatic charging where charges accumulate within the dielectric of electrostatic structures. Other causes of stiction are Van der Waals forces (due to atomic interactions at a range of 20 nm approximately), capillary effects (due to residual layer of water or etchant on the surface of the materials), chemical bounding between two surfaces or residual stress from the fabrication process.

Wear results from friction between two sliding parts. It can lead to the generation of small debris that may further alter the operation of the device.

Creep and fatigue are due to the combination of local stress and repeated motion. They may result in change of mechanical properties and cracks within the materials leading to mechanical fractures.

3.7   Trends in MEMS devices

The MEMS market is growing and changing fast. Figure 13 shows forecasts for the MEMS market in the coming years for different types of devices.

While the technology was first developed for military and aerospace applications, MEMS inertial sensors are being used as standalone systems in several consumer electronics applications such as in the smartphones or in the automotive industry [40]. The latest developments in microfabrication have allowed these sensors to be easily integrable within portable devices while preserving high performances. Figure 14 shows the evolutions of the accelerometer and gyroscope markets. The graphs in Figure 14 only takes into account the standalone sensors, which have only one MEMS sensor per packages. The forecasts for these markets indicates that they are now going to decline slightly. On the other hand, it also shows the growing importance of consumer electronics and automotive industries in the accelerometers and gyroscopes MEMS markets. The decline of the usage of standalone sensors is due to the recent development in combination sensors, commonly called "combos". These new types of sensors integrate several MEMS devices within one package,
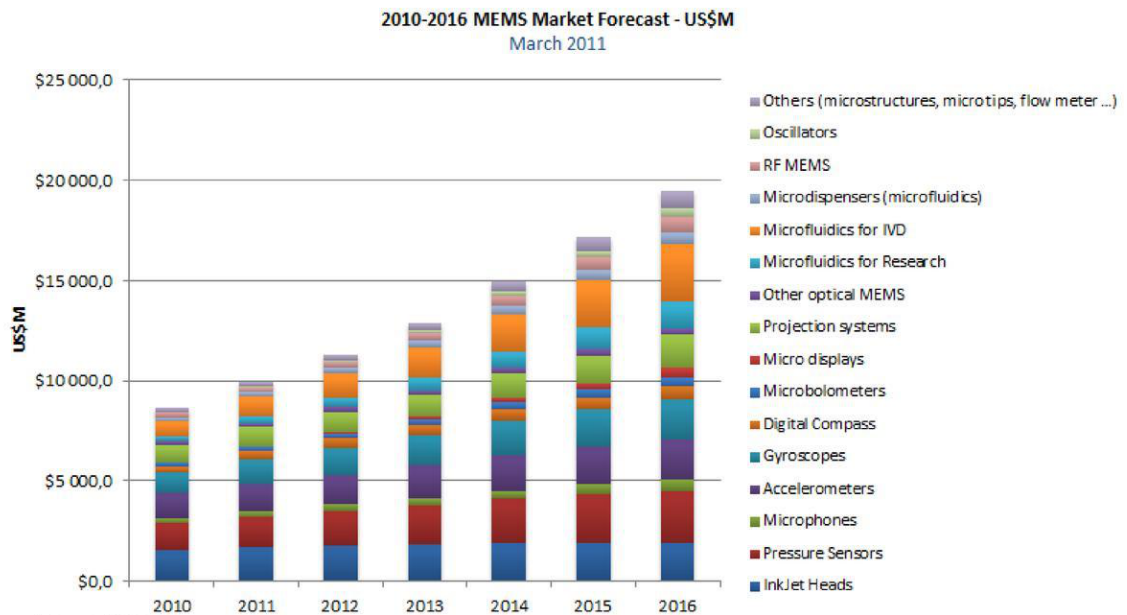
Figure 13: MEMS market forecast realised in 2011 for different applications of MEMS. From [39].

hence increasing the functionalities of the system. For example, combos of accelerometers and gyroscopes are more and more produced [40]. Figure 15 clearly shows that combos are gaining importance in the automotive and consumer electronics markets, they will represent 40% of the inertial sensors for the consumer electronics market in 2016 [40]. In [40], the authors outline the fact that combos will offer new functionalities thanks to sensor fusion data processing. On the other hand, combination sensors require more complex software and algorithms. Testing and calibrations are also made more complicated with combos. Anyway, the benefit for the integration as well as for the performance is still high.

Figure 14: Market forecasts for MEMS-based accelerometers (left) and gyroscopes (right) realised in 2012. This study includes only standalone sensors, the decline that can be obser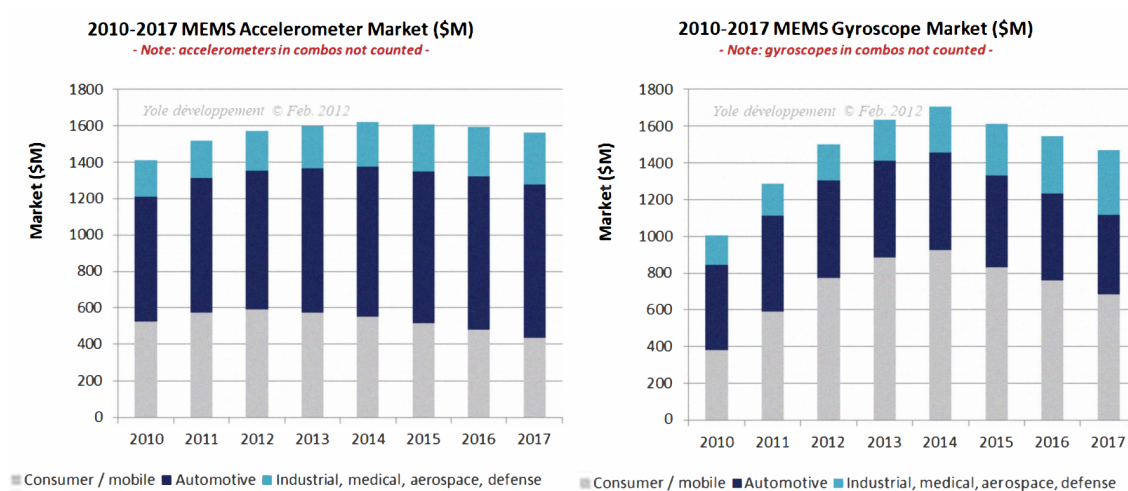ved in both cases after 2014 is due to the arrival of combination sensors ("combos") on the market. Graph taken from [39].
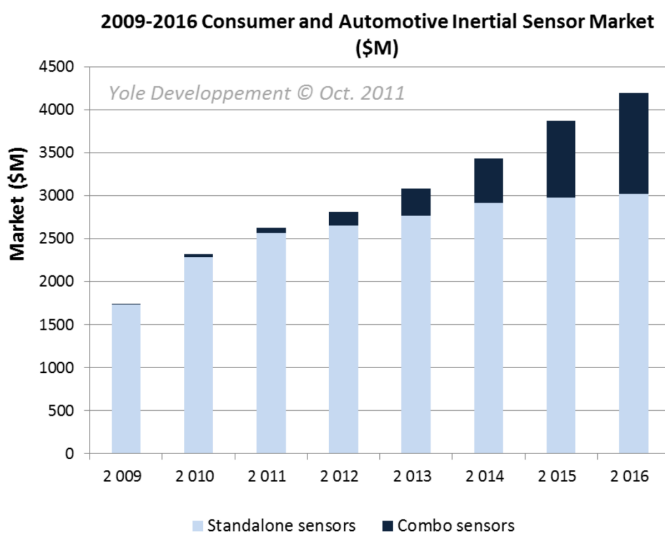

Figure 15: Market forecasts for standalone and combo inertial sensors in the automotive industry. Graph taken from [40].

4   Usage of microsystems for small satellites

The development of small satellites has created a need for subsystems that are smaller and consume less power. Microsystems were developed for a various range of applications in order to integrate more functionalities within a system with low power consumption. Therefore, microsystems appear to be a well suited solution for small satellites. They offer several possibilities to space technology such as improving the functionalities and performances of small satellites or enabling new functionalities for satellites in general.

Microsystems can help developing subsystems that need less power to operate leading to the possibility of reducing the size of the batteries and of the solar panels or making more power available for other subsystems. Likewise, the size and mass reduction of microsystems-based subsystems helps to reduce the mass and the volume of the satellite or to make more volume for other parts. For example, a satellite developed following the CubeSat standard faces rigorous volume requirements; hence, using microsystems is a straightforward solution to liberate volume for other subsystems. Power, mass and volume reduction are the primary reasons to choose and use microsystems in a small satellite since they facilitate the matching of the requirements and can decrease the cost of the launch. Another advantage of microsystems is the possible enhancement of the performance, especially in the case of MEMS sensors.

Moreover, the development of microsystems for satellites is a necessary condition to the realization of new experiments. Small satellite missions have the possibility to become even more meaningful by using cutting edge technology. Microsystems offer versatile possibilities to improve and enable new forms of missions in space. The first meaningful use of microsystems as en enabler in space was the Phoenix lander operated by NASA that landed on Mars in 2008 and used an AFM on Martian rocks [8, 4] . Of course, this achievement is not only due to micro- and nanotechnology, since other systems were required to make the experiment a success.

Nevertheless, it must not be forgotten that developing custom microsystems is a very expensive process and the cost reduction on the launch might not compensate the price of the devices production and development. Microsystems become economically interesting only when they are mass produced, which is unlikely to happen for devices designed for space applications. In the case of small satellites that are developed on a tight budget, the use of COTS subsystems is the only affordable way to implement microsystems. Fortunately, the mass production consumer market has become very appealing for microsystems which are inexpensive, efficient and reliable.

In [12], the author gives his vision of the future of microsystems for satellites as summarized in Figure 16. The increase of the integration level will lead to the possibility to first integrate subsystems in single packages therefore, reducing the size and volume of each subsystem. On a longer term, new classes of highly integrated

| -Discret components size reduction -Enabling technology for science | - Significant reduction of mass and size at the subsystem level | - New class of small satellites with highly integrated systems |

Figure 16: Potential future of microsystems and small satellites according to [12]. From left to right: present, near future and long term.

satellites could be created.

The following sections present example applications of microsystems in satellites. Many of them are specifically developed for space applications, but it is also important to point out that a large number of sensors used in small satellites such as CubeSats are provided by the consumer electronics market. Applications of microsystems in small satellites are discussed in references [3, 4, 5, 41].

4.1 Consumer electronics microsystems in space

Depending on the applications and the budget of the mission, microsystems can be either specifically developed for space operation or adapted from the consumer electronics market (COTS). Components from the later benefit from several advantages. First of all, they are mass produced, which means that their prices are low compared to space grade components. Commercially available devices also offer high reliability since a certain amount of them is designed to be used in safety critical systems such as the accelerometer in car air-bags. This kind of non-space grade components do not have any shielding and are not designed to operate in space, which makes qualification an important part of their integration. Besides, COTS subsystems and components from the consumer electronics market are typically used in standardised satellites. Therefore, the results of previous missions can be used to gather knowledge on the operation of these non-space grade components.

4.2 Sensors

Inertial sensors play an important role in satellites attitude determination and control subsystem (ADCS) and other space systems such as rovers. They are used to determine the orientation of the satellites in regards of the earth, the targets of their experiments, the ground station (for radio communication), the sun (for the solar panels). Commercial MEMS inertial sensors are already routinely used in space [3].

4.2.1 Accelerometers

Accelerometers are mostly used to monitor the vibrations and the shocks that the spacecraft is subjected to during the launch phase. They can also be used during the separation of the spacecraft from the launcher and the deployment of structures. Accelerometers typically use electrostatic or piezoresistive sensing principles.

4.2.2 Gyroscopes

Gyroscopes measure the angular rate of satellites, that is used by the ADCS. Using the data from the gyroscope, the ADCS is able to determine the attitude of the satellite. Like the accelerometers, gyroscope are usually based on electrostatic or piezoresistive sensing.
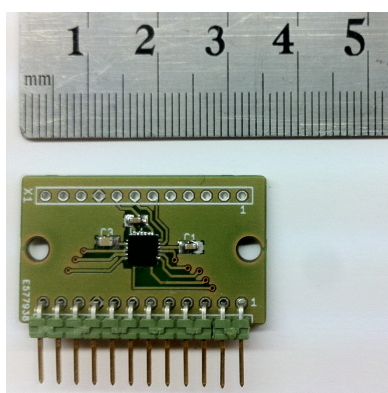

Figure 17: A gyroscope soldered on a PCB for testing purposes.

4.2.3 Sun sensors

Sun sensors provide measurements giving the relative orientation of the satellite with respect to the sun [42]. They are commonly used in satellites ADCS. Sun sensors are based on photodiodes which are semiconductors that generate a current when exposed to photons (photoelectric effect). One pair of photodiode is needed to measure the incidence angle of the sun vector along one axis as shown in the simplified schematic in figure 18.

A sun sensor specifically developed for space is presented in [43]. The sensor was used on a nanosatellite that operated successfully after its launch in 2009. The article gives details on requirements that must be fulfilled in order to correctly determine the orientation of the satellite. The sun sensors shall be able to provide the sun position in any orientation and therefore large field-of-views are needed. Besides, the resolution that required in space is lower than 0.5°. The 2-axis sensor presented in [43] has a field-of-view of 120°, in order to measure the sun-vector in
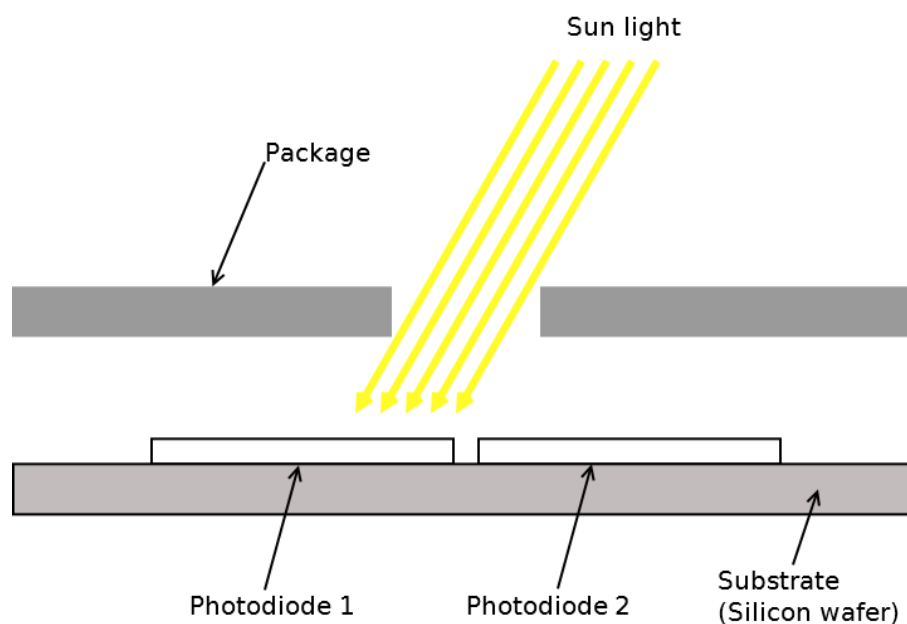
Figure 18: Simplified schematic of a one axis sun sensor based on two photodiodes.

any directions, several sensors must be placed at different points of the satellite outer structure.

4.3   Micropropulsion

In order to perform manoeuvres such as orbital station keeping or rendez-vous with another spacecraft, satellites need to be equipped with propulsion systems. However, conventional propulsion systems are bulky and they do not match the requirements of small satellites, this is why new systems have been and are being developed. MEMS based micropropulsion capabilities have received a big interest in the past decade. Apart for the reasons above-mentioned, micropropulsion can also be used for very accurate attitude control, since MEMS based micropropulsion systems usually offer thrusts ranging for micro to millinewton with a very high resolution. It is worth noting that micropropulsion can only be used for small manoeuvres and are not intended to perform orbit transfer. Use of propulsion may be limited with some standards, for example, the CubeSat standard does not allow the use of flammable fuel on board, which require the development of other forms of propulsion systems.

4.3.1   MEMS based cold gas thrusters

MEMS based cold gas thrusters rely on the same design as other larger scale cold thrusters, with the difference that components such as valves and pressure sensors are microfabricated. One of the most difficult element to scale is the propellant
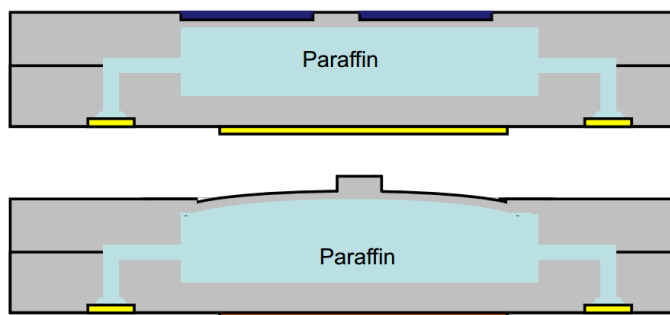
Figure 19: Microvalve based on the expansion of paraffin in phase transition. Image taken from [5].

tank. A MEMS cold gas thruster pod is described in [5], the system can achieve sub-milinewton range thrust. The MEMS based pressure sensor is based on piezoelectric silicon. It can measure pressures up to 1000 bar. The microvalves are based on the expansion of paraffin in phase transition. The paraffin is contained in a closed chamber. When heated up, the paraffin expand and pushes a membrane with the valve upward as shown in Figure 19.

4.3.2 Solid propellant micro-thrusters

Solid propellant micro-thrusters are probably the most simple way to create thrust for a small satellites. Figure 20 shows an exploded view of a solid propellant micro thruster. They are based on the ignition by joule effect of a small quantity of solid propellant stored in a cavity or chamber. When the ignition is triggered, the produced gas is exhausted and accelerated through a nozzle generating a thrust that ranges from micro to milli-newtons for duration of a few milliseconds. The produced thrust is heavily dependent on the design of the cavities (confinement of heat), the thickness of the membrane, the nozzle and the igniter [45]. Solid propellant micro-thrusters have the advantage of not relying on any moving parts which inherently simplifies their fabrication and increases their reliability. The major drawback of these thrusters is their non-re-usability, once a shot is fired, the cavity cannot be refilled since the top membrane is destroyed by the ignition. To overcome this issue, solid-propellant thrusters are designed under the form of arrays or matrices (as shown in the top part of Figure 20) within which, each thruster can be fired individually using an addressing scheme. When designing a matrix of solid-propellant thrusters, one must take into account the effects of thermal crosstalk between the thrusters to avoid unwanted firing. Also, it is important to notice that because of the array configuration, the thrust will always be generated at different points of the spacecraft.

The designs of microthrusters used in [45, 44, 46] are all vertical design allowing to stack the wafer with the nozzles on the rest of the microthruster. Planar designs are also possible where, all the elements of the thruster are fabricated on the same wafer [46]. The vertical designs are more complicated to fabricate, notably because of the stacking steps, but they do not require any further steps to integrate a matrix of thrusters. The different layers of the vertical design are described below.

Nozzle The fabrication process of the nozzle on a glass wafer is presented in [45] shown in Figure 21(2). The process relies on the anisotropic etching of a photosensitive glass. The shape of nozzle is obtained by etching on one side only. The average diameter of the nozzle throats are 416μm. The fabrication of the nozzle presented in [46] are fabricated using deep reactive ion etching of silicon with a negative angle of 10° followed by KOH etching to form a wider cavity before the throat of the nozzle.

Microigniter and membrane The design and the fabrication of a microigniter and the supporting membrane are presented in [44] and illustrated in figure 21(1). The microigniter is fabricated by patterning a μm wide platinum wire on a photosensitive glass wafer. The glass wafer is then etched from the back-

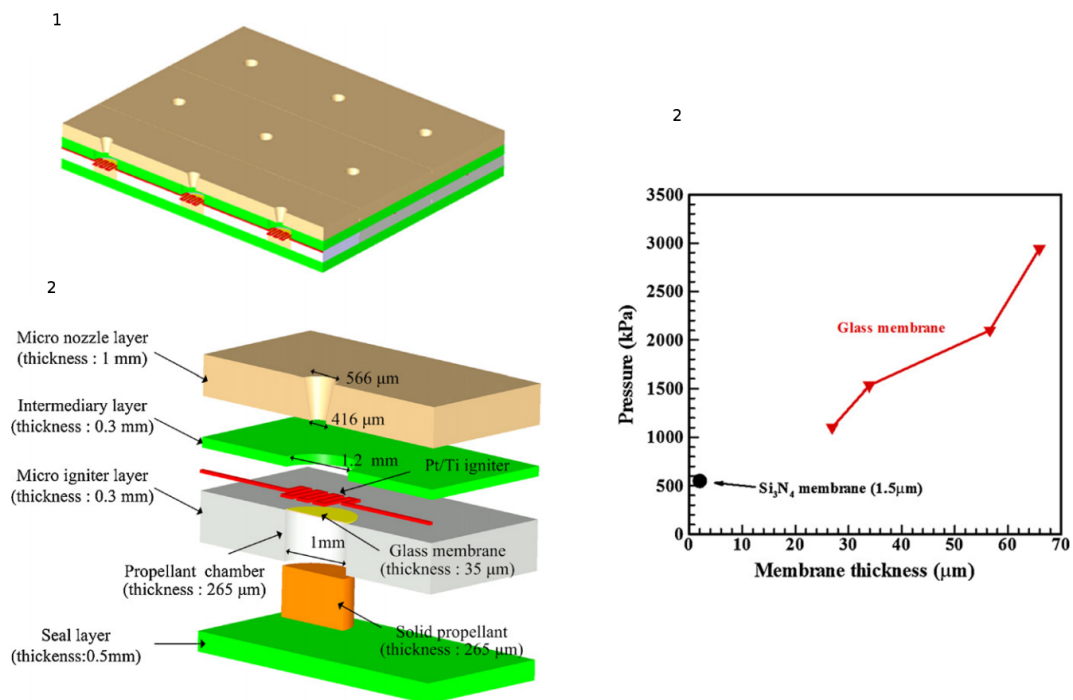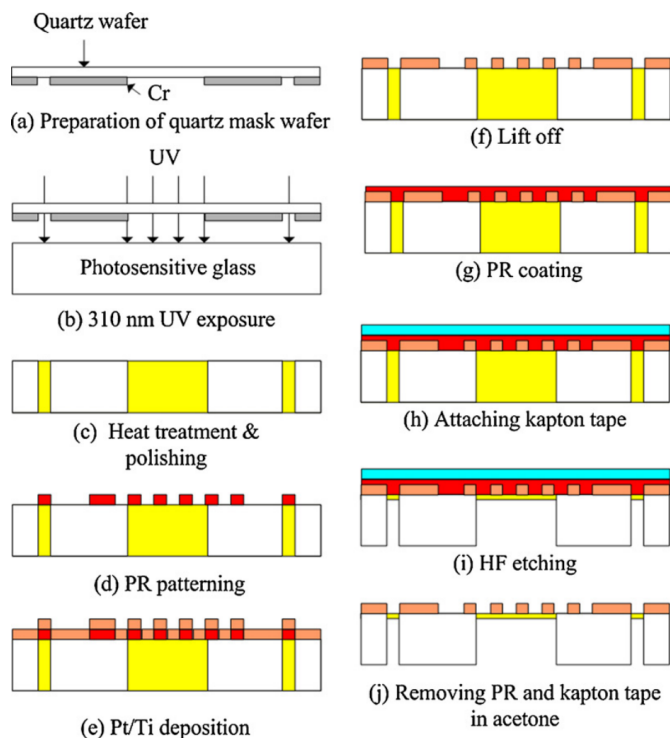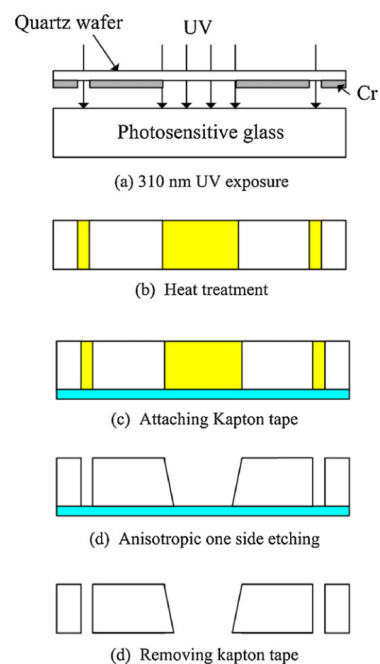

Figure 20: (1)Solid propellant micro thruster matrix. (2) The different layers of a solid propellant microthruster. (3) Fracture pressure of glass membranes of solid propellant microthruster with different thickness and a silicon nitride membrane. Images taken from [44].
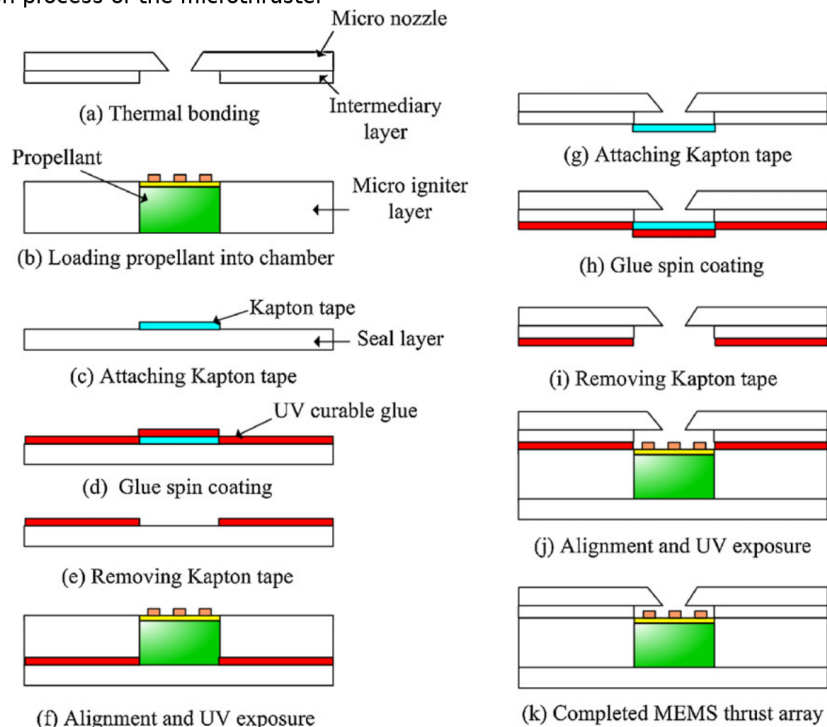
Figure 21: Fabrication process of a solid propellant micro thruster. Images taken from [45].

side to form a membrane with a thickness of 35 μm. The material and the thickness of the membrane were chosen in order to ensure that the membrane can resist to the propellant filling process and break under the pressure of the gases created after ignition. The pressure the membrane breaks, namely the fracture pressure, is 1531 kPa, Figure 20 (3) shows the fracture pressure for different glass membranes as well as for a silicon nitride membrane. Another design using different material is presented in [46]. The igniters are made of polysilicon and are doped in order to form threshold elements that are used for the addressing of the matrix, the heating for the ignition is produced by the thermal dissipation in the polysilicon elements.

Propellant chamber One important element that needs to be considered in the design of the propellant chamber is the heat isolation to prevent crosstalk with other elements of the matrix and the heat confinement to maximize the efficient of the combustion. The fabrication of chambers are presented in [46]. Different chamber designs are proposed using silicon wafer or glass wafer. The chamber fabricated with silicon wafers are separated with insulating grooves of either 250 μm or 500 μm. The results showed that the 250 μm were not sufficient to confine the heat and the combustion was not sustained. The 500 μm grooves allowed a better confinement of the heat, but glass was shown to be the best meterial for this application due to its very low thermal conductivity. The propellant chamber is sealed with a another wafer after the propellant filling.

4.3.3 Electrostray based thruster

Electrosprays are formed by extracting a conductive liquid from a capillary subjected electric field as described in references [47]. Under a strong enough potential difference, the liquid will form a cone, called Taylor cone, at the tip of the capillary. A jet of liquid forms at the apex of the cone and breaks into charged droplets forming an electrospray as shown in Figure 22. The speed of the droplet can be modulated by changing the voltage difference applied with the accelerator electrode situated after the electrode used for the extraction. Thus, it becomes possible to achieve very large specific impulse and considerably reduce the propellant consumption. Most importantly, the thrust that is generated is also modulated using with the voltage difference, which offers flexibility and precision. The downside of electrospray thrusters, is the very low thrust of the order of micronewton. Higher thrusts can be achieved with array configurations. Another is issue is that they require the generation of very high voltage to operate.

Micropropulsion systems using electrospray (Figure 22)are described in references [48, 49]. The fabrication of the capillaries for an array of nanoelectrosprays thruster is detailed in [48]. The capillaries are fabricated on a silicon-on-insulator wafer with subsequent deep reactive ion etching of the front side and the backside. The backside etching is partially delayed using silicon nitride mask in order to form a
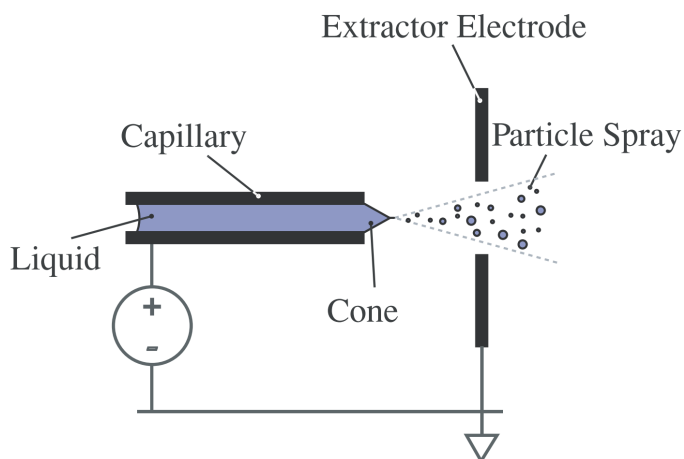
Figure 22: Basic schematic of the cross section of an electrospray thruster. Image taken from [48].
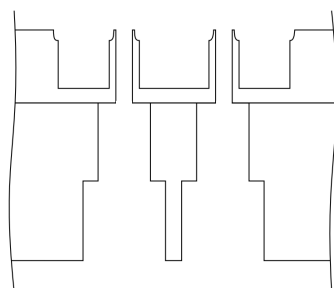
Figure 23: Profile of the capillaries fabricated for a nanoelectrosparay thruster array. The main fabrication process is deep reactive ion etching on the front side and then the back side of a silicon-on-insulator wafer. Image taken from [48].
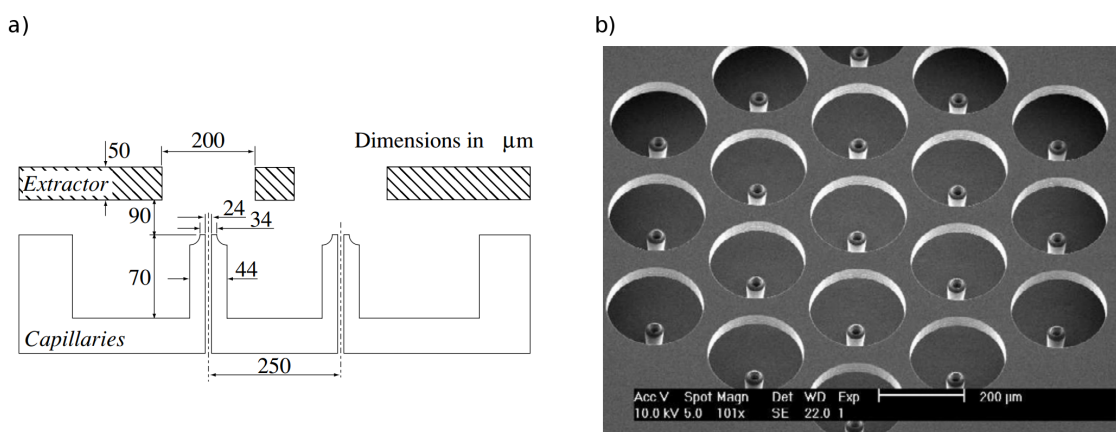
Figure 24: a) Profile and dimensions of the extractor electrodes assembled with the the capillaries. b) Scanning electron micrograph of the assembled structure. Images taken from [48].

structure with two different heights. The profile of the fabricated capillary is shown in Figure 23. The extractor electrodes are also fabricated with silicon-on-insulator wafer and deep-reactive ion etching. The wafer is then metalized with aluminium. The fabricated capillaries and extractor electrodes are shown in 24.

4.4 Thermal control

Since the satellites evolve in vacuum, their components cannot transfer their heat by convection as it is typically done in the atmosphere of Earth. Most of the heat is then evacuated by radiation. In many satellite missions, it may be required to accurately control the temperature of the scientific instruments to perform the experiments in the right conditions. Besides, heat can be very harmful for electronics and structural components of a satellite. It notably shortens the lifetime of electronic components. Extremely cold temperatures can also be encountered in space especially when a spacecraft is in eclipse. Therefore, a satellite needs to be able to either evacuate or keep the heat, depending on the situation. An efficient thermal management systems should not only protect the satellites from overheating but it also should avoid the satellites subsystems to be a very low temperature that can be harmful especially to the batteries. It can be noted that it is common to find batteries with dedicated heating systems. Large satellites are equipped with radiators and other thermal management systems. However, these systems do not necessarily scale well to fit the small satellites requirements, radiators are bulky and massive; besides, heaters have a high power consumption [50].

The high integration levels, that are characteristic of small satellites, lead to power densities that are higher than in conventional satellites [51]. Moreover, small satellites suffer from low thermal capacitance and smaller surface to radiate heat. As a result, the temperature can increase or decrease very rapidly reaching extreme values. Thermal control systems on board of small satellites need to be able to cope with those rapid changes with high heat flux removal capabilities.

The development of efficient thermal management systems is not necessarily incompatible with small satellites requirements and microsytems offer promising solutions as described in [51, 50].

4.4.1 Micro-louvers

One way to manage heat in conventional satellites is with louvers, they are, for instance, used in Hubble and Voyager [51]. These systems change the emissivity of a surface by exposing or not exposing emissive surface. The louvers blades are made of a low emissivity material in such a way that when the louvers are in a closed state, the heat is kept inside the satellite and is emitted when they are open. Thanks to the advance in micro-electromechanical actuators, it is possible to develop micro-louvers that are based on the same principle as their larger scale counterparts. The
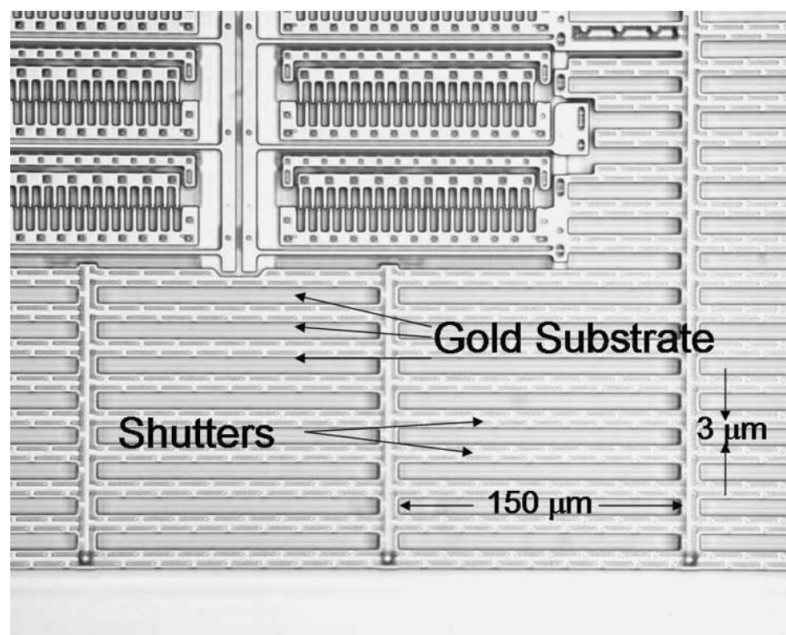
Figure 25: Optical microscope image of a micro-shutters system. The actuators can be seen on the top corner of the image. Image taken from [51].

micro-louvers cover a radiator or a surface with a high emissivity and are actuated using MEMS.

A micro-louver array system is discussed in [51], in which groups of polysilicon shutters are horizontally actuated by an electrostatic comb drive actuator to vary the exposition of a high emissivity gold substrate. The actuators can generate a displacement of 6 μm while consuming very low power. The dimensions of the micro-louvers described in [51] are shown in Figure 25. The comb-drive actuators occupy 20 percent of the surface area and only 50 percent of the remaining surface can be effectively exposed due to the design of the system. The dimensions of the array die are $12.6mm \times 13.03$, 36 of these dies are assembled on a radiator.

One of the challenge that was encountered with this design was the possible failure of the systems due to friction during operation and the shocks and vibrations during the launch. Designs trade-offs were necessary to ensure the reliability of the systems.

4.4.2   Thermal switches

Thermal switches are MEMS devices that establish or remove the contact between a radiator and a highly emissive surface [50]. In [50], an electrostatic thermal switch system is developed in order to match the small satellites power capabilities. An emphasis is put on achieving; a low actuation voltage of 28V instead of hundreds volts that are typically required in electrostatic actuation systems. The system is
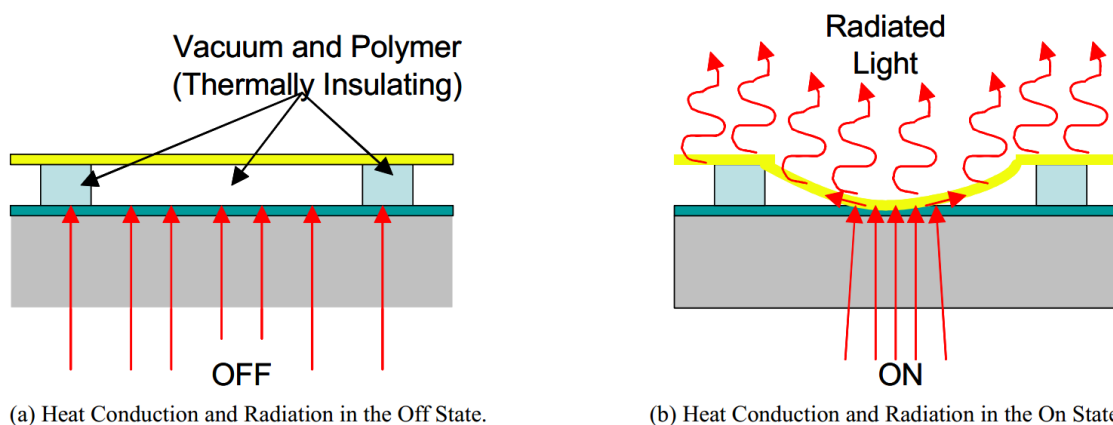
Figure 26: Basic principle of the operation of a thermal switch. Image taken from [50].

based on a gold membrane that is supported either by thermally insulating frame or posts made of SU-8 (polymer). Two designs were made in order to study different compromises between thermal performances and mechanical robustness. Hence, in non-contact mode, the membrane is thermally insulated from the radiator by vacuum and the supporting elements. When the applied voltage is above the so-called pull-in voltage, the membrane enters and remains in contact with the radiator and the heat is conducted. The devices presented in [50] suffered from low fabrication yield but the results obtained from working devices where in accordance with the theory.

4.4.3 Microfluidic system

Microfluidics is an area of microsystems that receive a large interest especially for medical applications. Pumps, valves and microchannels can nowadays be easily fabricated at the micro-scale. Microchannels and a working fluid can be used to remove heat from the electronic components. The microchannels are integrated beneath the components and the working liquid is pumped using micropumps to remove heat from the components and to transfer it to a heat sink or a radiator. A working microfluidic thermal control system is demonstrated in [52].

The microfluidic network can either be at the satellite scale or at a subsystems or even components scale. The two later solutions offer more flexibility for the integration and control possibilities.

4.5 Radio communication

A reconfigurable antenna is an antenna that has the possibility to alter some of its radiative properties such as the polarization or the frequency [53]. It is able to adapt the radiation patterns at a given frequency in order to enhance its performances. A

reconfigurable antenna can be used to avoid noise sources or to increase the security of the communications. One of the basic components of this type of antenna is RF-switch. Typically, the switching functions in RF circuits are carried by solid state switches based on GaAs FET structure and p-i-n diode [54]. While being the state-of-the-art, solid state switches are far from being optimal in terms of performance and loss [55]. Therefore, communication circuits often need the addition of components in order to compensate the loss from the solid states switches, which leads to higher mass, volume and power consumption. A suitable alternative to those solid state switches is the use of radio frequency microelectromechanical System (RF MEMS) switches. The operation of the device is typically based on a electrostatically actuated metallic cantilever that connects or not two RF signal lines. Successful operation of RF MEMS switches in space is demonstrated in [55], the foorprint of one relay is $250\mu m \times 250\mu m$. The actuation voltage of the switches ranges between 60 V and 80 V with a switching time of $10\mu m$.

4.6 Optical microsystems

MOEMS are of particular interest in space technology as a means to perform multi-object spectroscopy. At least two multi-object spectroscopy space telescopes mission are currently being developed by the NASA and the European Space Agency (ESA), namely, the James Webb Space Telescope - NIRSpec (planned to be launched in 2018) and the Euclid spacecraft (planned for 2020). Multi-object spectroscopy is not a new technology and is already used in many ground-based telescopes. The benefit of this technique is that it allows to simultaneously capture the spectra of a large quantity of objects at once, without suffering from spectral confusion or low signal to noise ratio. Two systems are being investigated by the space agencies to perform multi-object spectroscopy in space: the micro-mirror array and the micro-shutter array (discussed in 4.7.2). Both systems act as programmable multi-slit masks that can be remote-controlled, which is of prime necessity for space instrumentation. The multi-slit masks are used to direct light from the object of interest towards the spectrograph and to block light from other objects.

Micro-mirror arrays are already extensively used in consumer electronics in projection devices. As a result, these devices are already mass-produced and operate with high reliability and efficiency. However, the operating conditions (space environment instead of Earth atmosphere) of the micro-mirror arrays will be different and thus, some development is necessary to ensure the reliable operation of the device in space. The operation principle of the micro-mirror arrays is based on electrostatic actuation of each mirror independently. The mirror is placed on a beam and an electrode above a substrate with another electrode. When a voltage is applied, the beam and the mirror tilt at a certain angle. Each mirror can be held in two distinct stable states, either nominal (non-titled) or tilted. In [56] commercial micro-mirror array devices are tested for space operation in a multi-object spectroscopy system. The devices were shown to remain operational in vacuum and

in low temperature.

The Aalto-1 nanosatellite will be equipped with a spectrometer based on MOEMS technology [24]. The spectrometer is based on a Fabry-Pérot interferometer. The basic elements of the interferometer are two highly reflecting surfaces. The two surfaces are separated by a gap that can be tuned using actuators. The actuating solution chosen for the flight model is based on piezoelectric material. A monolithic MEMS solution was also studied for the spectrometer. In the version of the payload, the structure does not have any discrete actuation element. The gap is tuned by bending one of the mirrors with electrostatic actuation.

4.7 Examples of microsystems in scientific payloads

Alike other subsystems, scientific instruments can benefit from increased performance, lower mass, lower volume and lower power consumption by being based on microsystems. However, the main interest of using microsystems for scientific instruments is the wide set of new possibilities that are enabled. This section presents some examples of scientific instruments that are made possible by micro- and nanotechnology. Some of this instruments are not meant to be used in small satellites, but they are mentioned in order to clearly demonstrate the wide enabling power of submillimeter technologies.

4.7.1 The FAMARS instrument

The Phoenix lander that landed on Mars in 2008 was carrying (among other instruments) an atomic force microscope (AFM). The microscope is described in [8], the purpose of the instrument was to study Martian dust and soil particles in order to determine their size, their distribution and their shape.

An AFM sensing element is based on a sharp tip situated at the end of a cantilever which is deflected when the tip is brought to the vicinity of the sample. The sensor is placed on a scanner that can move in three dimensions using low voltage electromagnetic coils. Typically, the deflection of the cantilever is measured and kept constant by a feedback loop that changes the height relative to the sample of the scanner. A schematic of an AFM is shown in Figure 27, more details about the microscopy technique can be found in [31].

The AFM on board of the Phoenix lander was equipped with a sensor chip consisting of eight cantilevers for redundancy. The deflection of the cantilevers was measured using integrated piezoresistive sensors. The system successfully operated on Mars.
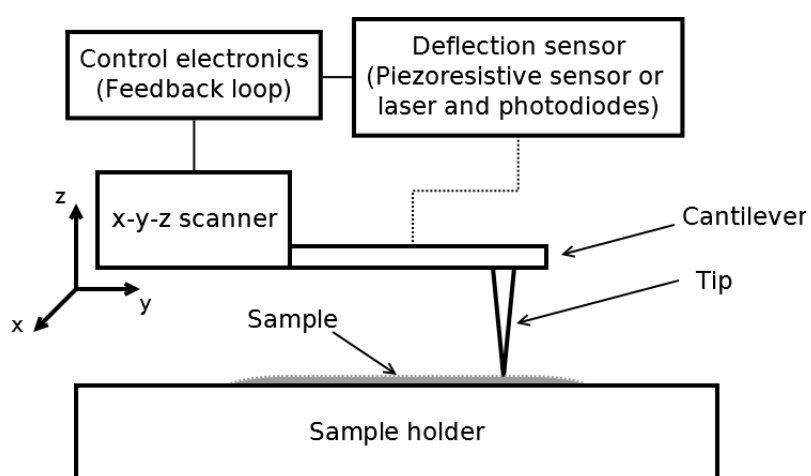
Figure 27: Simplified schematic representing the main elements of an atomic force microscope. The tip is scanned over the sample using electromagnetic coils. The surface topography deflects the cantilever via the tip, the deflection is measured with piezoresistive sensors and a feedback loop keeps it constant by moving the scanner in the z direction.
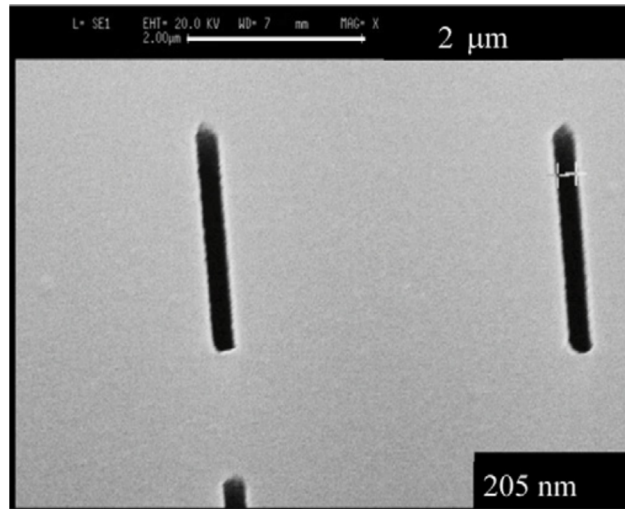
Figure 28: Nanoslits patterned on silicon nitride for the ELENA detector shuttering membrane. The shutters are used to control the incoming flux of particles. Image taken from [57].

4.7.2 Micro-shutters for the ELENA instrument

The ELENA (Emitted Low-Energy Neutral Atoms) sensor will be part of the Bepi-Colombo mission [57] and will study the interaction between the exosphere of the planet Mercury and solar winds. In order to accurately digitize time and space and control the incoming flux of particles without modifying their energy and trajectory, the instrument needs a shutter system. Silicon nitride membranes were patterned with nanoslits at micrometer scale to form micro-shutters. Figure 28 shows an electron micrograph of a shuttering element. One of the membranes is actuated in-plane using a piezoelectric element (the shuttering membrane) while the other one is fixed. The shuttering membrane can be actuated with a frequency of 100kHz with an amplitude close to 1 μm.

4.7.3 Micro-shutters for the NIRSpec instrument

A shutter system based on submillimeter technologies is also used in the near infrared multiobject spectrograph (NIRSpec), an instrument that will be equipped on board of the James Webb Space Telescope (JWST) and described in [58]. The NIRSpec will be used to observe the first instants of the universe. In order to do so, the instrument must be able to isolate the objects being observed from the other objects that form the universe. Micro-shutter arrays have been developed to stop or let pass the light of different object in the focal plane of the telescope. The micro-shutter of the NIRSpec are subjected to very high reliability requirement, with a number of failed open shutters that should not exceed 1% of the total number of shutters.

The micro-shutters are normally closed and transmit only a small fraction of
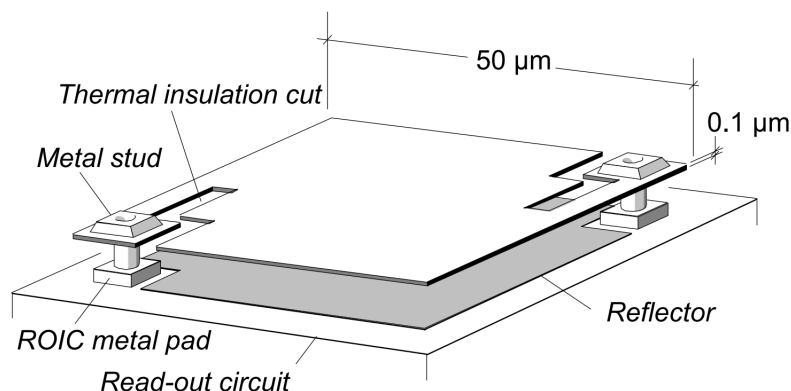
Figure 29: Pixel unit of a microbolometer. Image from [59].

light the rest being reflected. When the shutters are in open position, all light is transmitted to the detector. To be in open state, a shutter must rotate with an angle of $-40°$ form the rest position (closed state). The silicon nitride shutters are rotated and kept in open position using an hybrid latching magneto-electrostatic actuation. The shutter are coated with magnetic material and are actuated by scanning a magnet across the rows and the columns. The shutters are held in position by electrostatic latching using electrodes on the vertical walls. This system was chosen to minimize the area occupied by the actuation mechanisms, and maximize the area that can be open or closed with the shutters.

4.7.4   Microbolometers

Thermal infrared imaging is a widely used technique for Earth observation. The device that is typically used for this are mercury cadmium telluride photonic detectors [60, 61]. These detectors require cryogenic cooling to operate, which can be prohibitive in small satellites because of the mass and the power consumption of such systems. Uncooled infrared detectors have been actively investigated during the last decade and new type of devices called microbolometer was developed and created using micromachining of silicon [59]. These new devices rely on the measurement of thermal radiation coming from the target and not necessitate cooling system to operate. As a result, the microbolometers are smaller, lighter, more reliable and less expensive than their counterparts. The sensing area of the microbolometers is directly machined on top of the CMOS readout integrated C circuit (ROIC) as shown in picture 29 [59].

Application of a micobolometer is presented in [62]. The missions is based on two satellites equipped with microbolometer arrays [63]. Microbolometers are the most suitable solution to fit in the mass and power budget of the satellites.
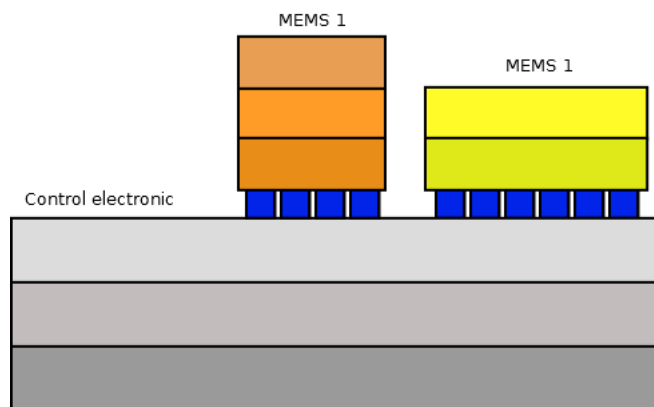
Figure 30: Subsystem integration at the wafer scale (the size and shape of the element is arbitrary).

4.8 Potential future of microsystems for small satellites applications

The applications presented in the previous section illustrated the present and the near future of microsystems in space technology and especially in small satellites.

The field of small satellites is growing rapidly and its commercial potential has been demonstrated in section 2.9. Microsystems can play a dominant role in future evolutions of small satellites by enabling new classes of even smaller spacecraft. Microsystems will also increase the performance and the functionalities of small satellites. This section describes some future evolutions of microsystems that can have the potential to bring and enable further improvements in small satellites.

4.8.1 Sub-systems integration

MEMS devices are nowadays evolving towards systems that integrate higher numbers of functionalities within one package (see section 3.7). This presents a tremendous interest for small satellites that need to reduce the size of their subsystems while preserving their performance and capabilities.

Heterogeneous 3-D integration technologies are actively researched. These technologies aim at integrating MEMS devices and CMOS electronics together even if they are fabricated using different techniques and materials as shown in the schematic of Figure 30[64, 65]. This opens the possibilities to create more complex and more advanced systems presenting higher performances and higher integration levels.

A concrete example is the ADCS, the sensing part of this subsystem relies mostly on inertial sensors as described in 4.2. In general, the sensors are integrated in the susbsystem as separated packages soldered on a PCB. One can imagine a package that would integrate all the needed sensing functions on top of the processing

electronics wafer. This would allow a higher integration level of the subsystems leading to size and mass reduction. It can also enable a higher redundancy of the subsystem itself since the volume that is made available can be used for another system.

4.8.2 NEMS

Nanoelectromechanical systems (NEMS) are devices whose size usually does not exceed some tens of micrometers and they have at least one sub-micrometer lateral dimension [41].

Besides being smaller by some orders of magnitude, NEMS based sensors (accelerometers, gyroscopes) offer a higher sensitivity and a shorter response time than their micro-metric counterparts. However, enhancements of the resolution are difficult to achieve due to limitations arising at this scale such as Brownian noise. Besides, their low signal-to-noise ratio is a major drawback; yet, it can be overcome by using arrays of sensors.

NEMS based memories have been proposed for space application. The interest of these memories lies in the inherent radiation-hardness and the high integration density that can be achieved with systems at the nanoscale [41]. For example, the mechanical part of the memory (the bi-stable switch) could be made using carbon nanotube as described in [66]. Fabrication of such systems is still challenging and further research is needed to create a device that could reliably be used in space.

NEMS devices present great interest in terms of integration and performance, they, however, still require more research to become fully functional and replace larger devices.

4.8.3 Graphene for thermal control

Graphene is considered as a two dimensional material, it is a carbon allotrope made of bounded atoms arranged in a single plane honeycomb pattern. Graphene presents interesting mechanical and electroncic properties as descibed in [31]. While this material bears the promises of major evolutions in nanoelectronics, it may also have other applications. In [67], the authors describe the possibility of using graphene radiators for the thermal control of the satellite. Graphene was chosen for its high thermal conductivity, which is between 3000 and 5300 W per millikelvin approximately while pyrolytic graphite thermal conductivity is between 1200 and 1600 W per millikelvin. It is also extremely lightweight compared to other materials. The use of graphene layers to fabricate the radiators would greatly decrease the mass of the thermal control system.

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│   Microsystems in small satellites   │
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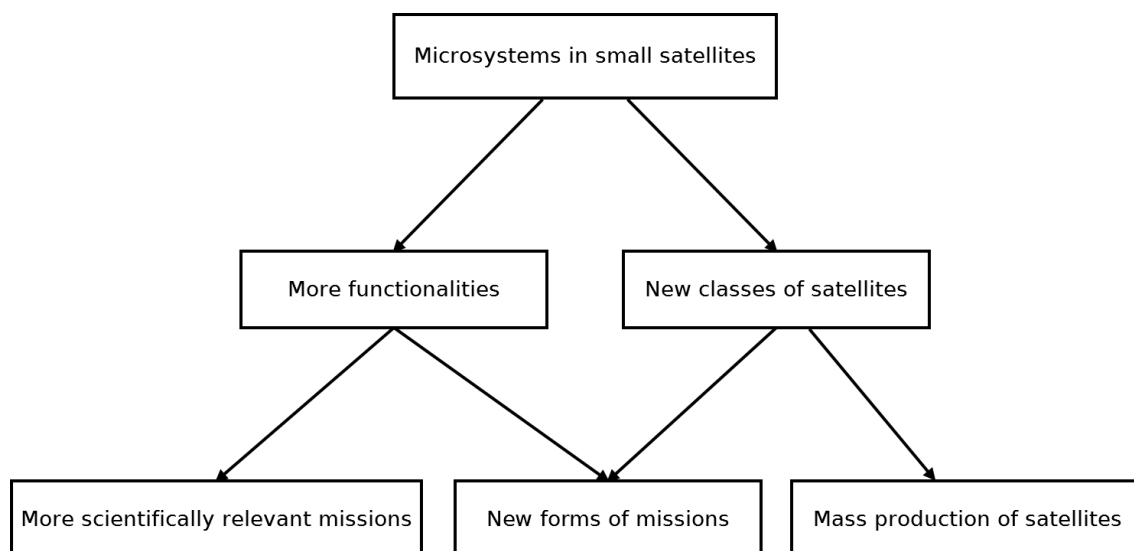
Figure 31: Outcomes of the development of microsystems for small satellites. The already existing classes of satellites will get more functionalities and new classes of highly integrated satellites will become possible.

4.9   Outcomes of the use of microsystems in small satellites

The examples of applications of microsystems given in this section demonstrate that a wide range of possibilities can be brought to small satellites. The future of small satellites is most likely to be dependent on the development of dedicated microsystems.

The two main outcomes of using microsystems in small satellites are shown in Figure 31 and detailed in the following paragraphs:

New functionalities in small satellites: Small satellites and especially the smaller ones (nano- and pico-satellites, see table 1) have a limited set of possibilities and are lacking capabilities to develop complex missions. Microsystems offer a way to address this issues. For example, MEMS based thermal control systems will allow satellites to carry more powerful and more integrated electronics with a reduced risk of overheating.

New classes of highly integrated satellites: The ability of integrating sensors and processing electronics within one package is critical to create new forms of satellites such as the femtosatellites that have a mass inferior than 1 kg. These satellites would mostly consist of one chip on which all the subsystems are soldered. Thanks to microsystems, these satellites could be equipped with sensors and actuators in order to perform scientific experiments. The main interest of femtosatellites is the possibility to deploy them in large quantity to form a swarm. This enables new forms of distributed measurements. One can imagine that with the progresses of microfabrication such as heterogeneous integration, these satellites could be mass produced like other microsystems.

Due to their small size and small power, femtosatellites are likely to suffer from the lack of long range communication capabilities. This can be addressed using short-range communication with a larger satellite (nanosatellite) that would have the possibility to retrieve and transmit the data.

4.10 Example of integration on microsystems in a CubeSat

The systems described in the previous sections bear a large potential for small and conventional satellites. This section describes the possible integration of two of these systems in the Aalto-1 student satellite (see 2.8). The subsystems presented in these examples are not integrated in the real satellite.

4.10.1 Micro-louvers for Aalto-1

A major concern that is common to most of the CubeSats is thermal management. High density of electronic components and small thermal capacitance of small satellites can lead to rapid changes of the temperature. This may result in early failure of the electronic components or reduced lifetime of the batteries of the satellite.

A radiator equipped with micro-louvers (described in 4.4.1) could be integrated on the satellite as shown in Figure 32. The goal of the micro-louvers is to radiate the heat away from the satellite when the temperature is too high in order to protect the electronics. When the temperature is too low, the micro-louvers can be closed in order to preserve the heat inside the satellite and protect the batteries.

The micro-louver arrays shown in Figure 32 are designed following the dimensions of the array dies ($12.65 \times 13.03mm$) presented in [51]. The radiator used in this example is covered with 12 array dies. The radiator is attached to the structure of the satellite at the level of the on-board computer and the batteries.

4.10.2 Microthruster arrays for Aalto-1

Micropropulsion is currently difficult to integrate in small satellites due to their size and mass. Solid propellant microthrusters (see section 4.3.2)are simple to integrate, they do not require a tank or any movable parts. Solid propellant microthrusters offer an alternative to cold gas thrusters. Another possibility is the use of electrospray thrusters (see section 4.3.3), but these devices require the generation of high voltage to operate, which can be especially difficult to achieve in the smaller classes of satellites. As explained in [45], only 340 mW are needed to ignite the propellant, which can be generated by most of the small satellites. These solid propellant microthrusters could be used to perform some slight orbital adjustments. One situation where an orbital adjustment can be necessary is to avoid a space debris. The thrusters could also be used to accelerate the de-orbiting of the satellites. The solid propellant thruster arrays shown in Figure 32, are based on the design presented in
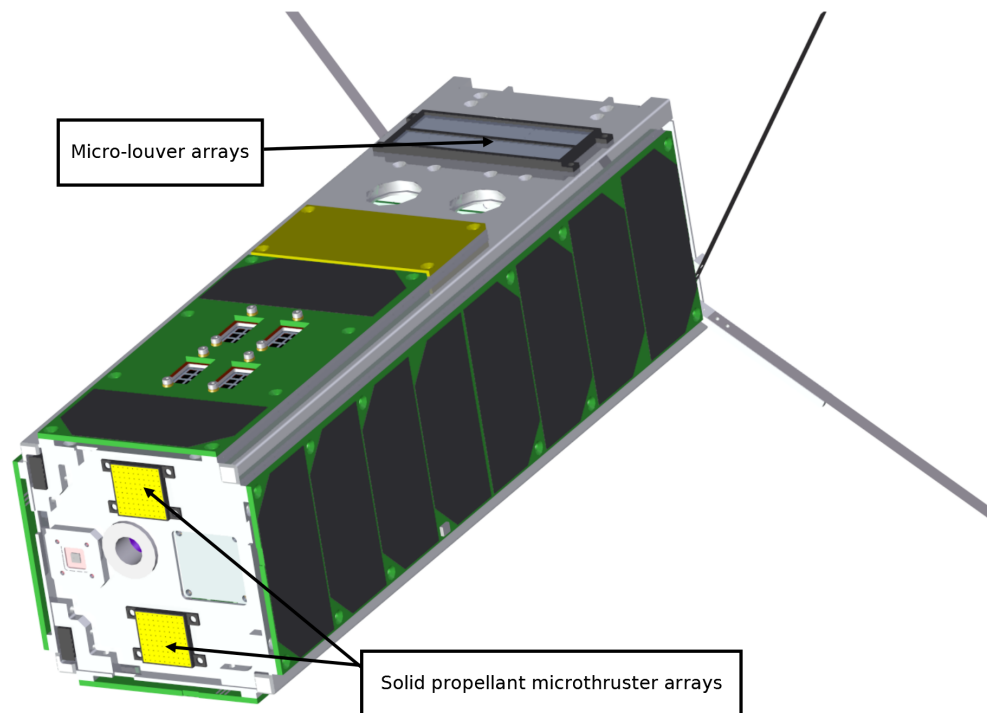
Figure 32: Integration of two subsystems based on microsystems: micro-louver arrays for thermal control, solid propellant microthruster arrays for micropropulsion.

[45]. Each array contain one hundred thrusters that can be ignited only once and independently thanks to an addressing scheme. The dimensions of the arrays are $24mm \times 24mm$.

4.11 Example of a highly integrated femtosatellite

An example of a "satellite on chip" concept is shown in Figure 33. The dimensions of the chip are $25mm \times 25mm$. The satellite carries a microfabricated scientific payload (4). The package number 3 contains the on-board computer, memories and attitude determination MEMS based sensors integrated using 3D heterogeneous integration. It allows the satellite to perform the scientific experiment and to store the data until it can be transferred. The short-range antenna(1) and the radio transmitter/receiver allow the satellite to communicate with a nanosatellite that can gather the data. The power is harvested using solar panels (6) and stored in the batteries (7). This satellite is to be deployed as a swarm of hundreds of similar spacecraft equipped with the same instruments in order to perform simultaneous mutli-point measurements. The large quantity of satellites within the swarm makes the mission redundant and hence more likely to be successful even though some satellites fail to operate.
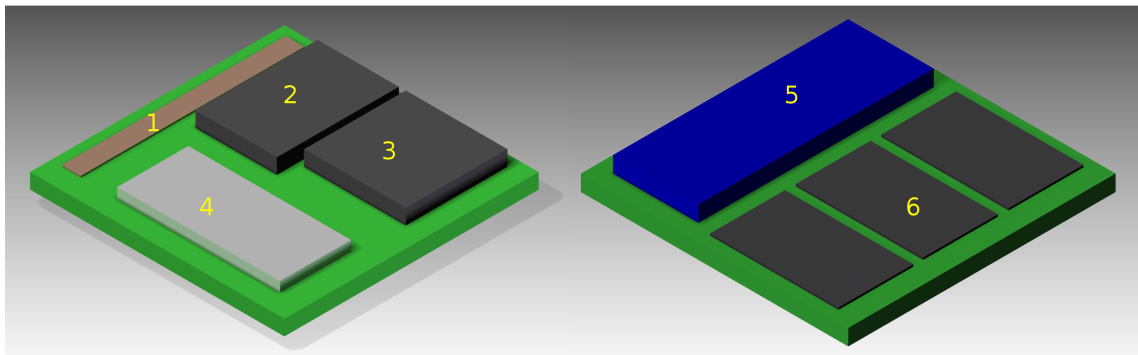
1: Short-range antenna
2: Radio emitter/receiver
3: On-board computer, memory and attitude determination sensors
4: Scientific payloads
5: Battery and electronic power system
6: Solar pannels

Figure 33: Concept of a highly integrated femtosatellite that could be mass produced and deployed in large quantity to form a swarm.

5 Challenges of microsystems in space

5.1 Reliability of microsystems in space

Reliability is at the heart of every space technology project since failure is rarely an acceptable option. Since many microsystems are still in their infancy, it is understandable that their reliability in space is subject to questions.

Microsystems for space face different environments during the mission. The environment, in which the microsystems are produced and assembled to the satellite, can be controlled relatively easily, with the use of cleanroom and rigorous quality control during the process. The other environments, to which the systems are subjected, are the launch and space environments. Both are harsh environments that raise several concerns related to reliability.

The launch phase subjects the spacecraft and all its components to severe vibrations and shocks that may affect microsystems. It is worth noticing that the micromechanical parts of MEMS are extremely light. Therefore, the effects of the accelerations are of lower amplitude than for heavier parts [68]. However, the package is likely to be affected by the vibrations and qualification testing remains a necessity.

The space environment can severely affect the microsystems and their performance. The extreme temperature cycles are sources of cracking and accelerated wear of the micromechanical components [68]. Alike many other components, MEMS may be soldered on a PCB. Temperature cycles are known to generate fatigue in solder joints, which is an important source of failure [69].

However, the reliability issues associated with microsystems can be mitigated using redundant design. In case a device would fail, another one could be used. The concerns related to calibration changes can also be addressed by using arrays of sensors that would make the same measurement. The next section presents another concern for microsystems reliability: the radiation.

5.2 Radiation

The operation of electronic devices in space faces major concerns related to radiation levels. Radiation levels are complex and strongly depend on the orbit and the time. Moreover, the origins and types of radiation are diverse as explained in 2.4. Conventional satellites are built with shielding to prevent some radiation from reaching the inner systems and the sensitive electronic parts [1]. The situation is, however, different for small satellites, which are designed to be mass and volume efficient. Thus, the fraction of the mass dedicated to the shielding does not offer the same protection against radiation. The redundancy of the subsystems that is typical in satellites partially mitigates the concerns arising from radiation.

The potential role of MEMS devices in the further development of small satellites require a deep understanding of the effects of radiation in order to prevent and mitigate the possible failures of the devices. MEMS and microsystems in general devices are complex; their design and the materials that are used are various. Hence, standard test procedures and assessment methods for MEMS in space radiation environment are missing. Several works have been performed with the objective of understanding the effects of radiation over the operation, the performance and the overall reliability of MEMS devices [70, 71, 12, 72].

5.2.1   Effects of radiation

Radiation interacts with a target with two different processes; usually, the interaction is a combination of both. The processes are called ionization and non-ionizing energy loss (NIEL) [73].

Ionization is the main process of interaction in terms of energy losses from radiation. It is the root for the creation of electron-hole pairs in the material affecting its electrical properties. The electrons and holes can move in an electric field with a very different velocity since electrons have a higher mobility. Hence, holes can be left behind and become trapped holes, which increases the conductivity of the materials. This strongly participates in the degradation of dielectric materials.

Non-ionizing radiation refers to the displacement of atoms within the target due to transfer of energy from the incoming radiation as shown in Figure 34. This increases the defect concentration in the semiconductor lattice of the materials, which ultimately decreases the carriers lifetime, mobility and concentration. In the case of metals, the electrical properties remain unaffected, but it can decrease the mechanical integrity (unlikely in the time span of a space mission).
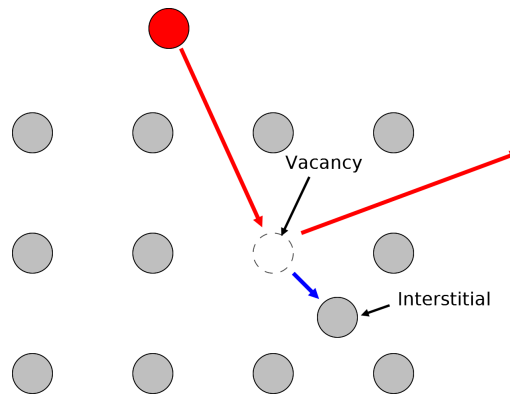

Figure 34: Displacement damage caused by non-ionizing energy loss.

5.2.2 Failures and effects on performance of microsystems due to radiation

As explained in the previous section, radiations can modify the properties of materials. Hence, microsystems can be affected by radiation. However, unlike electronic devices that mostly rely on transistors, MEMS are based on several physical principles as well as diverse materials. As a result, the effects of radiation on microsystems are strongly dependent on the materials, the design and the physical principle used in the components. The effects of radiation on some of the physical principles have been studied and identified.

One important outcome of the studies that have been made on radiation is its little effect on silicon [12]. Radition, even at high doses, barely affect the mechanical properties of the material. Thus, silicon, can be considered as radiation-hard when it is used as a structural material. However, in the case of devices in which the mechanical properties (Young's modulus) are of primary importance (resonant RF MEMS), minute changes in elasticity can strongly affect the performance of the devices. The effects of radiation on the mechanical properties are discussed in [70, 71].

Charging of insulators is a major concern for MEMS devices; especially in the case of electrostatically actuated structures [72, 71]. Electrostatic charging affects the calibrations of the devices. It can eventually lead to a failure by continuous actuation (the electrodes remain in contact even though no voltage is applied).

The effects of radiation on piezoresistive materials are summarized in [12]. The effects consist mostly of calibration changes and are of a lower amplitude than for electrostatic devices.

5.3 Risk analysis

The following table presents examples of possible failures associated with the usage of MEMS devices operating in space environment.

Table 2: Most relevant failure modes of MEMS devices in space.

Device	Possible failure mode	Consequences	Severity and mitigation
Accelerometer and gyroscope (electrostatic)	Transient electrostatic stiction due to charge accumulation in dielectric materials	Sensor is temporarily inoperative	Low-Medium, other sensors can be used (sun sensor), redundant design

Accelerometer and gyroscope (electrostatic)	Degradation of dielectric properties due to ionization	Change of device calibration	Medium, redundant design, in-orbit re-calibration
Accelerometer and gyroscope (electrostatic)	Dielectric conductivity catastrophically increases because of ionization	Device failure	Medium-high, redundant design
Accelerometer and gyroscope (electrostatic)	Material's Young modulus change	Change in device calibration	Medium, in-orbit re-calibration
Sun sensor	Change in doping levels due to radiation	Change in device calibration	Medium
RF Switch (electrostatic)	Transient electrostatic stiction due to charge accumulation in dielectric materials	Switch remains closed. Configurability of the transmission line is affected but not permanently	Low-Medium
RF resonator	Change in material properties due to radiation induced defects	Reference frequency is affected	
Solid propellant thruster	Mechanical fracture of the membrane	Ignition failure or thrust decrease. Uneven firing of solid propellant thrusters of a matrix that can lead to perturbation of the attitude and loss of control	Medium. High if it disturbs the attitude
Solid propellant thruster	Joule effect igniter failure	No ignition, device failure, can lead to uneven firing of a matrix	Medium. High if it disturbs the attitude
Solid propellant thruster	Igniter fail to produce high enough temperature	No ignition or delayed intention	Medium. High if it disturbs the attitude

Solid propellant thruster	Propellant is not ignited	No ignition and igniter may draw large quantity of power	Medium. High if it disturbs the attitude. Timer to turn off the igniter.
Cold gas thruster	Micro-valve fails to open	Thruster failure	Medium. Redundant design: valves in parallel
Cold gas thruster	Micro-valve fails to close	Continuous propellant leakage	Medium - Redundant design: valves in series
MEMS pressure sensor (piezoresistive) for cold gas thruster	Trapped charges in semiconductor material	Change of device calibration. In the case of the thruster, it may lead to error in the thrust measurements	Medium, redundant design of the sensors
Micro-louvers for thermal control	Friction	Creation of debris that can obstruct the movements of the lovers and lead to failure of the mechanism	High or medium - Reduction of the thermal control capabilities can be mitigated with redundant design on other surfaces
Generic MEMS device	Failure of CMOS read-out electronic	Device failure	High or Medium if the design is redundant
Generic MEMS device	Delamination because of coefficient of thermal expansion (CTE) mismatch of the device materials under thermal cycles	Device failure	High or Medium if the design is redundant

5.4 Technological readiness level of MEMS devices in space

The technological readiness level (TRL) is a figure ranging from 1 to 9 relative to the maturity of a subsystem for space application. Table 3 gives the definition of

the different levels according to the ESA.

Table 3: Definition of the technological levels according to the European Space Agency. Adapted from [74].

TRL	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and "Flight qualified" through test and demonstration (ground or space)
9	Actual system "Flight proven" through successful mission operations

The technological readiness levels of MEMS devices are strongly dependent on the applications. For example, the TRL of inertial sensors such as gyroscopes and sun sensors can be estimated to 9. On the other hand, the rest of the devices have low TRL that could be estimated around 5 or 6 in average. Some other systems such as MOEMS have very low TRL. Upcoming missions such as the James Webb Space Telescope will allow to increase the TRL of MOEMS in space [3].

The low TRL of microsystems is mainly due to the fact that many of those technologies are in their infancy and further development is needed. The only devices whose TRL can improve more rapidly are the components taken from commercial electronics; Since, development is needed, they can directly be integrated in a satellite. Nevertheless, qualification of the devices is necessary prior using them in space.

5.5 Using small satellites to increase the TRL of MEMS in space

As explained in section 5.4, most of MEMS devices suffer from low TRL and they are therefore avoided in many subsystems for the sake of reliability. As a result, the space heritage of MEMS is developing at a very slow pace and remains low or medium. The philosophy of small satellites is strongly based on risks management
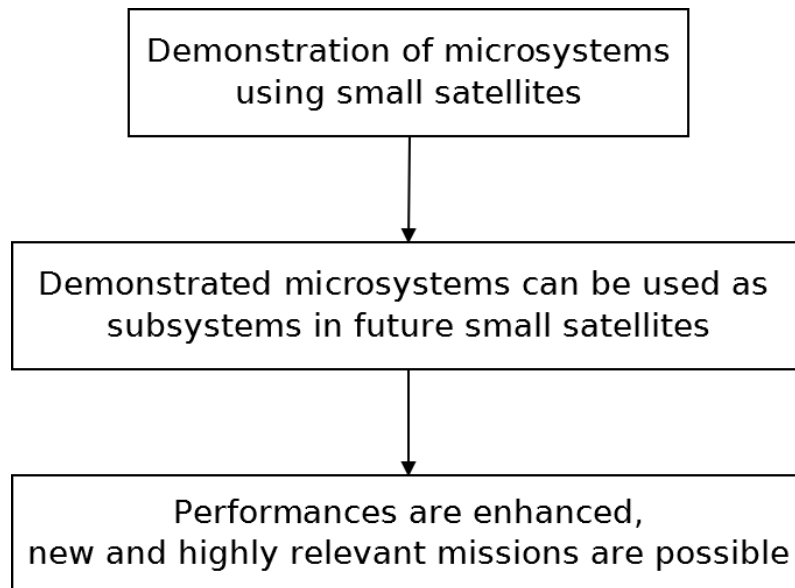
Figure 35: Workflow of the demonstration and the adoption of microsystems in space technology

and costs reductions. Besides, small satellite missions can be developed within a short amount of time using standards such as CubeSat. This makes small satellites an ideal platform for the demonstration of the operation of microsystems in space. Several MEMS components can be integrated as payloads of a CubeSat (or other type of small satellite) in order to be tested in space.

However, small satellite missions are often designed to last between a few months and a few years; therefore not allowing to gather data on the long term operation of the devices. This can be an issue for the development of devices that are meant to be used in larger satellites whose missions typically last more than 5 years.

Demonstrating the operation of microsystems in space with small satellites is an investment that can result in positive outcomes for space technology. Once a system is properly demonstrated, it can be used as a subsystem in a future satellite (Figure 35). Thus, the performances or the functionalities of the future satellite are enhanced and it may perform missions with higher relevance.

6 Conclusion

The examples given in this thesis show that the potential applications of microsystems in small satellites are numerous and diverse. Microsystems are not only going to enhance the performance of small satellites; but they will also enable new functionalities for scientific experiments and mission designs. For example, the development of micropropulsion will open new possibilities for formation flying of small satellites and accurate control of the attitude of conventional satellites. Another example is the NIRspec payload of James Webb Telescope that will be equipped with micro-shutters to perform multi-object spectrometry.

However, it has been pointed out that microsystems face some reliability challenges in space. One major issue is the charging of dielectrics due to radiation. It mostly affects the devices that are based on electrostatic actuation or capacitive sensing. Dielectric charging first leads to calibration changes but it may eventually trigger failure of the device. Radiation is also source of changes in calibration in other types of devices such as piezoelectric systems or silicon based resonant structures. Reliability of MEMS devices in space is difficult to address considering the wide variety of materials and designs that may be used.

Moreover, most of the devices, except inertial sensors, are still in their infancy and their TRL remains low. Consequently, the adoption of microsystems in space technology is slow; and these components are only chosen when they are critical for the mission. Increasing the TRL of microsystems require more demonstration of their operation in space environment.

Small satellites are well suited to perform technological demonstration missions that can benefit to microsystems. On the other hand, demonstrating the operation of microsystems can also become beneficial for small satellites. Indeed, microsystems have the potential to increase the performance and the capabilities of the spacecraft. Therefore, having data on the operations of microsystems in space is an important asset for the design of future satellites.

Since small satellites are gaining interest from different types of scientific institutions (universities, research centres and space agencies) and from private companies, it is clear that increasing their potential is of particular importance. Microsystems allow to perform more relevant missions, thus increasing the interest of using small satellites.

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