Chapter 5
Miniaturization and Micro/ Nanotechnology in Space Robotics

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Abstract

Space is an exciting but fundamentally unfriendly environment for humans. Space robotic systems (robots in orbit, planetary rovers or even satellites) are of great importance to space exploration and perform tasks hazardous or impossible for humans. Using micro and nano technologies in space robotic systems results either in miniaturized systems in terms of volume and mass, while retaining or increasing their capabilities, or in space robots with increased capabilities while retaining their size due to the nature of their tasks. Examples of miniaturization possibilities for space robots and satellites are given, focusing on the challenges and the enabling technologies. The miniaturization process and the use of advanced nano and microtechnologies in space will have a large beneficial impact in the years to come.

Keywords

Miniaturization, space robotics, satellites, microtechnology, nanotechnology, MEMS, micromechanisms, nanorobots, microrobots, scaling, microsensors, microinstruments, sensor islands, nanosatellites, micropropulsion.

5.1 Introduction

Space is an exciting area of activities for mankind. These activities allow us answering fundamental questions about the origins of the universe, assist our life on earth (e.g. meteorological and GPS satellites) and improve our scientific and technological capabilities resulting in a wide range of inventions and new processes. However, space is a highly unfriendly environment for humans. Harmful radiations, extreme temperatures, lack of suitable or lack of any atmosphere, huge distances to be covered, and long communication lags and interruptions, are only a few of the factors that render space a hostile environment for humans. It is well known that the need for astronaut extravehicular activities (EVA) increases the cost of a mission dramatically, due to the life support systems and precautions that must be taken to ensure astronaut safety during EVA.

A solution to these problems is the use of robotic devices, capable of operating for long times with minimum supervision or even autonomously. Such devices have been developed during the last fifty years and include robotic spacecraft, on-orbit robotic arms, rovers for planetary exploration, robots for space structures, and satellites. Additional plans for robotic space hardware of all types are in the development phase. Clearly, the future of space exploration and commercialization will include robots as a vital enabling technology.

Space robotic devices tend to be very big in size. For example, in orbital systems, the Canadarm of the Space Shuttle is 15 m long, weighs 431 kg, and handles payloads up to 14 tons [1]. The reason is that it must be able to handle satellites and other equipment, which are of large dimensions due to the instruments they carry, or due to the need for being compatible with the human scale. For exploration systems, the small Sojourner Mars rover was also at the human scale, weighing about 10.6 kg with its dimensions being 0.65 m high, 0.30 m wide and 0.48 m long [2]. Subsequent rovers were bigger and heavier by at least one order of magnitude due to the need for carrying instruments and for travelling larger distances.

On the other hand, on earth an important current trend is miniaturization of devices and processes and the capability of acting at very small scales, including and in some cases less than the nano scale. Such miniaturization offers significant gains in volume, mass, and power for devices, leads to materials with unparalleled properties, and capabilities of intervening at the cell level. Miniature mobile robots at the scale of a few cm and with resolution of a few microns have been developed to provide mobile microinstrumentation, to assist in cell manipulation in biological experiments, and in micromechanism or microelectromechanical system (MEMS) assembly. Besides mobility, these robots include capabilities such as object manipulation with force feedback, two way communications, on board controllers, visual feedback, and significant power autonomy. In addition to the above developments, smaller robots operating at the nanometer scale are being envisaged. The size of such nanorobots may be in the range of 0.1-10 micrometers and could be implemented through the use of controlled biological microorganisms [3] or the use of magnetic nanocapsules steered by improved gradient coils provided by Magnetic Resonance Imaging (MRI) systems [4].

A natural question appears then regarding the degree to which space robotic activities are affected by the miniaturization trend observed on terrestrial applications in general, and more specifically in robotics. One can identify similarities and differences. For example, in robotics the terms micro or nano refer either to the size of the robot itself in terms of micrometers or nanometers, or to the resolution in micrometers or nanometers that this robot has in dealing with its environment. This is because human scale robots that operate in human scale tasks are taken as the basis for comparison. However, in space the scale of tasks is very different and to be more exact, much bigger. Both space exploration and orbital systems scales in terms of orbits, distances, power requirements, etc. are very large compared to the terrestrial human scale. Therefore, despite the evolving miniaturization process, the same terms refer in most cases to different scales of magnitude. This can be seen clearly in the case of nano or even picosatellites, both of which will not qualify as such according to terrestrial robotic terminology.

Miniaturization affects space robotic systems in two fundamental ways (a) by reducing the size and weight of components, thus allowing a space robotic system to increase its overall capabilities by maintaining more or less its size, and (b) by reducing its overall size, maintaining the same capabilities. In the first case, the robotic system cannot be reduced in size, because the objects it operates on remain of large size, for example the case of the International Space Station (ISS) robotic manipulators. In the second case, the size can be reduced by maintaining more or less, the initial capabilities; this is the case of nanosatellites. As mentioned earlier, the base scale is large enough so that any size reductions at the device or component scale will not qualify as nanodevices on earth.

In the subsequent sections, we examine the existing space robotics applications and classify the robots that are being used. The ways in which these robots can be miniaturized, using our terrestrial experience are addressed. The interesting subject of satellite miniaturization and subsequent proliferation is presented next. Finally, we outline the future trends for miniaturization of space robotics systems and components and address briefly the challenges ahead.

5.2 Space Robotics Applications

Usually the term space robotics is used to characterize semi or fully autonomous, teleoperated exploration and servicing systems, and a few specialized experimental systems. However on a broader sense, almost everything that has been sent into space, integrates a form of automation in some degree, and therefore can be characterized as “automated or robotic”. The emphasis here is given to systems that are flight proven, they still operate, or are in the final construction phases and the state-of-the-art in their class.

5.2.1 Exploration

From the very beginning of the space exploration age, rovers were considered as the main exploration platform and appeared early in the space programs of both the USA (with the Surveyor Lunar Rover Vehicle, 1963) and the USSR (with Lunokhod, 1970). The former program was cancelled and substituted by the Lunar Roving Vehicles of the Apollo program, while the latter (Lunokhod 1 in 1970) was the first remote controlled rover to land on the moon [5]. NASA has also sent to the Moon stationary explorers (Rangers and Surveyors [6]).

Since the late 70's, the exploration focus turned to Mars and other distant bodies. At first, it was necessary to achieve the goal of reaching the target, e.g. the Viking Landers in 1975 [7]; however it appeared soon that the scientific objectives should not be limited to the landing area. Time delays due to the distance to Mars rendered teleoperation impossible; this paved the way for semi and fully autonomous systems. Due to technological limitations, early designs such as Marsokhod and Robby were massive and frequently impossible to fit in the available launchers [8]. Smaller systems could not be autonomous and/ or integrate adequate scientific instrumentation.

The radical changes in microtechnology enabled prototype miniaturization, which lead in 1996 to the first flight proven planetary explorer with advanced capabilities, the Sojourner Rover [2]. After some unsuccessful efforts, the Mars Exploration Rovers Spirit and Opportunity were sent to Mars in 2003 [9]. The two identical rovers were larger than the Sojourner; however they included more scientific instrumentation and were capable to travel for kilometers. Today, rovers are a main programmatic goal of all space agencies. Primary missions include the Mars Science Laboratory (MSL, 2011) [10], and the NASA and ESA Exomars and Mars Sample Return cooperative missions, still in the design phase [11]. Stationary explorers, such as ESA's Beagle 2 [12] and the successful Phoenix Mars Lander [13] were and still are in agency programmatics.

A number of alternative concepts are tested for planetary exploration, which include surface explorers based on legged locomotion [14], [15], the exploitation of swarm capabilities [16], [17], or flying systems [18]. However, no such working prototype that has operated in space exists currently. Planetary orbital explorers, such as the Mars Odyssey, are examples of relatively small autonomous systems [19]. Other interesting concepts in this category include those that release a landing probe (to a planet, asteroid or comet) like Cassini-Huygens [20], Deep Impact–EPOXI [21] and Rosetta [22], or that land themselves, such as NEAR Shoemaker [23] and Hayabusa [24].

From the above examples, a trend is observed, from the large and massive systems to the small and lightweight ones and again towards larger exploration rovers, the difference in mass is obvious; Table 5.1 and Fig. 5.1 show clearly this trend as exhibited by NASA's rovers. The first rovers were large because of the then available technology. The development of microtechnology enabled miniaturization and development of designs that could be accommodated in a launcher. At the same time, the requirements of the scientific community were the main design consideration for the development of larger systems. The size of the MSL is comparable to that of the Rocky I; however, earlier designs had almost no space for scientific payloads.

Table 5.1 - Characteristics of different rover generations from JPL.

Rover	Mass (kg)	Instrument Mass (kg)	Average Speed (m/h)	Distance Travelled (km)	Largest Object Over (m)	Approx. Volume (m^3)
Sojourner (1996)	10.6	< 4.5	3.5	≈ 0.1	N/A	0.7x0.5x0.3
MER (2003)	176.5	6.8	34.0	Spirit ≈ 8, Opportunity >28	0.26	1.5x1.6x2.3
MSL (2011)	900.0	80.0	30.0	N/A	0.75	2.7x2.9x2.2

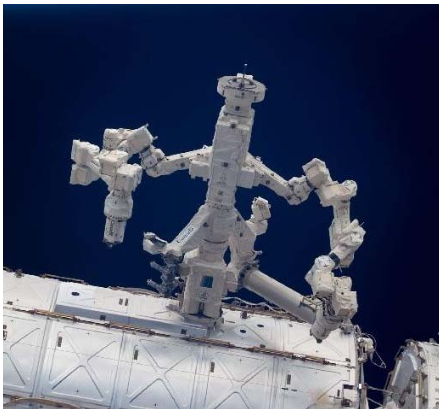
Fig. 5.1 - Full-scale models of three generations of exploration rovers. Sojourner (centre), MER (left) and MSL (right). (*Courtesy of NASA/ JPL-Caltech*).

5.2.2 Servicing

To sustain a constant presence in space and to enable longer exploration missions, it is necessary to develop servicing systems. Such systems are used in servicing or removal of malfunctioning satellites, removal of space debris, inspection and construction of space structures, or, in the future, in astronaut assistance at planetary outposts. These robotic systems must be able to manipulate objects with various characteristics, making them more complex.

Currently, the most successful space robots, such as the Shuttle Remote Manipulator System (SMRM) or “Canadarm”, the Space Station Remote Manipulator System (SSMRM) or “Canadarm 2” and the Special Purpose Dexterous Manipulator (SPDM) or “Dextre” on ISS [1], Fig. 5.2a, are mainly teleoperated via dedicated remote interfaces. The European Robotic Arm (ERA) [25] (est. launch in 2012) and the Japanese Experiment Module Remote Manipulator System (JEMRMS) [26], currently at the ISS, have a greater level of autonomy but still require a human operator.

To overcome the increasingly important problem of space debris and malfunctioning satellites, a greater level of autonomy is required. The first mission that demonstrated autonomous in space servicing was JAXA’s ETS-VII; Fig. 5.2b [27]. NASA and DARPA extended the concept, initially with the unsuccessful DART mission and later with the successful Orbital Express mission [28]. ESA and others pursue similar designs for on-orbit servicing, like the TECSAS and the DEOS [29]. Additionally, ESA and JAXA have developed fully autonomous human-class systems for logistic purposes for the ISS. Both the Automated Transfer Vehicle (ATV) [30] and the H-II Transfer vehicle operated smoothly [31].



(a)

(b)

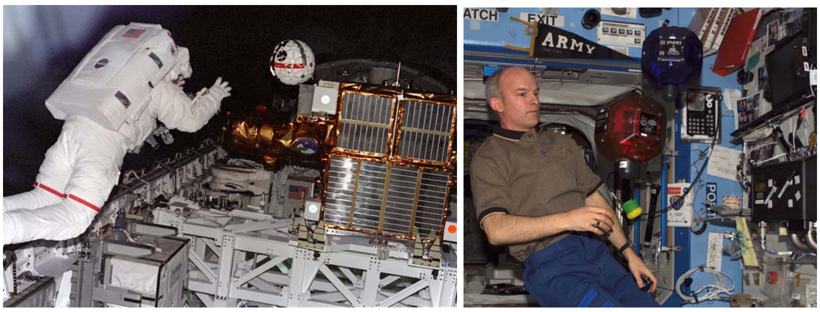
Fig. 5.2 - (a) Dextre on ISS (*Courtesy of NASA*) and (b) ETS-VII prior to launch (*Courtesy of JAXA*).

5.2.3 Experimental Systems

Space agencies, R&D institutes, universities and companies have developed a number of designs to test future space robotic systems and enabling technologies. The systems that have been tested in space are presented here.

During the STS – 55 mission (1993), various control modes in space were tested using DLR's ROTEX [32], a small, six-axis robot equipped with a gripper and mounted inside a space-lab rack. On behalf of DLR, the Robotic Components Verification on the ISS (ROKVISS) was installed in 2005, and removed in 2010. Its main purpose was to update and validate space robot dynamic models, to verify DLR's proprietary modular joints and to verify telepresence methods [33]. The most recent experimental system in space is the Robonaut 2 by NASA and GM [34], which will test the performance of an anthropomorphic robot, resembling future robots that can replace astronauts, while retaining at the same time the dexterity of the human body.

The need for miniature robotic systems to assist the astronauts and capable of performing a number of tasks, lead to the development of the AERCam Sprint [35] and the MIT SPHERES [36], Fig. 5.3. Their performance proved that small autonomous robots could indeed assist humans. Various small robots have been proposed since then, but few designs have been tested. An interesting example is Robyspace [37], which was developed to examine the capabilities of small robotic systems operating in specialized nets. The integration of a large number of electronics for sensing and actuation in a small volume enabled the development of all these experimental systems. However, a greater degree of integration is necessary in order to increase redundancy and functionality.



(a) (b)

Fig. 5.3 - (a) AERCam Sprint, (b) SPHERES in on-orbit experiments. (*Courtesy of NASA*).

5.3 Robotics Miniaturization in Space

5.3.1 Motivation

The wealth of available micro and nanotechnologies (MNT), such as MEMS and microelectronics, the exciting and innovative prospects they present combined with the importance of space robotics for space exploration, leads us to the conclusion that the introduction of micro and nanotechnologies in space robotics will significantly augment the capabilities of space robotics and will pave the way for further space robotic exploration missions. Space robotics is an area of particular importance to future missions; the introduction of MNT, either sourced from terrestrial applications (spinning-in) or specifically designed for space robotics, results in their overall miniaturization. However, as noted earlier, the term miniaturization when applied to space robotics has a somewhat different meaning than the traditional one. Therefore, for such systems the miniaturization process refers to (a) reduction of component size and mass, with increased functionality and unchanged total size and (b) reduction in overall size, while maintaining capabilities.

The terms MNT and microsystems are used in the present chapter with a broader meaning; they encompass MEMS technologies, nanotechnologies and miniature or microrobotic technologies, collectively referred as MNT or microsystems. Electronic devices (e.g. processors) are not generally recognized as examples of microsystems, however, in order to benefit from the reductions achieved with microsystems and from the integration of devices and electronics, they are considered here as microsystems. Additionally, any enabling technologies that allow for the miniaturization of space robotics are also of interest. Further clarification on the terms MEMS and microsystems can be found at [38].

There are several reasons why the miniaturization of space robotics is desirable. An important motivation for the systematic miniaturization of robotic systems is that launch vehicles have tight constraints with respect to the payload's mass and volume characteristics and therefore successful miniaturization directly results in an improved, more compact and less expensive system. The cost to place one kg in Low Earth Orbit is approximately $10K and can rise up to $20K; this cost is significantly increased for long space exploration missions (e.g. Moon, Mars, asteroids, etc.), therefore any weight and volume reduction would significantly decrease the launch cost. Another benefit of the miniaturization process is that the total resources required for space systems (e.g. mass, volume, power) are substantially reduced. Furthermore, systems such as proprioceptive and exteroceptive sensors, wireless communications, control units, power generation and transmission units can be integrated into small packages at a system level, thus allowing for a substantial increase in payload, reduction in power losses and more efficient thermal management. Integrating several microsystems into a silicon wafer and introducing redundancy by design, results in increased reliability and flexibility, lower risk and greater functionality compared to conventional robotic space systems. Silicon wafer microsystems are subject to economies of scale and therefore reduce the overall cost. Additional benefits of terrestrial microtechnologies in particular often include better performance compared to those in space, significantly smaller development costs since investments on non space technology exceed by orders of magnitude those of space, and sustainability of capabilities, reliability and strict quality procedures due to the presence of strong markets.

A successful miniaturization (i) results in a compact system, (ii) reduces the required power budget, (iii) reduces the development cost, (iv) requires fewer resources and smaller testing facilities, (iv) lessens complexity and improves overall performance. These benefits are particularly important for space applications, therefore the adaptation and implementation of micro technologies in space robotics is of great interest and expected to yield substantial benefits.

The field of MEMS is the most important in terms of commercialisation, range of applications and technological maturity. The worldwide market for MEMS, boosted by automotive applications and by mobile handsets, gaming controllers, digital cameras and other consumer electronics devices, exhibits nowadays an increasing growth and has expanded to cover nearly all critical technological domains. The MEMS market reached $6.9B in 2009, approximately $8B in 2010, and is expected to be $9B in 2011, with an expected Compound Annual Growth Rate (CAGR) for the next five years equal to 13% [39]. The MEMS accelerometer, gyroscope and inertial measurement unit (IMU) market and in general the motion sensing industry is especially robust. For 2011, the MEMS gyroscope market is estimated at $1B and the MEMS accelerometer market at $1.3B [40]. This growth will be mostly driven by the deployment of more motion control user interfaces on consumer electronics and drop detection and protection features in portable systems. Table 5.2 shows the MEMS market volume in millions of units.

Table 5.2 - MEMS Market Forecast 2011 – 2015 in Millions of Units [39].

MEMS Device	2011	2012	2013	2014	2015
Accelerometers	1362	1630	1838	2002	2194
RF MEMS	805	987	1190	1551	2023
Inkjet Heads	673	683	691	706	719
Microphones	579	816	995	1186	1381
Pressure Sensors	389	488	571	633	689
Digital Compass	340	441	542	652	770
Gyroscopes	325	402	510	587	722
Microfluidics for IVD (In Vitro Diagnostics)	312	394	493	621	785
Oscillators	72	138	248	421	674
Microdispensers	55	68	118	141	168

Projection Systems	9	21	44	79	136
Optical MEMS	2.2	3.7	6.6	12.8	18.3
Micro displays	2	5	10	15	20
Microbolometers	0.3	0.4	0.4	0.6	0.7
Other (Microstructures, microtips, flow meters, micro speakers, microfluidics for research)	6	15	43	112	209

The major terrestrial technological areas that employ MEMS are automotive, aerospace, defence, industrial processes, consumer products, biotechnology and telecommunications. Solutions provided by MEMS are finding their way into an increasing number of automation and robotics applications, such as motion sensing, impact detection, and rollover prevention. Commercial microsystem industries provide reliability procedures and yield management systems for microsystems and microsensor systems that offer excellent data return performance, redundancy and reduced power budget integrated in a very small package. A good example are inertial navigation systems, where inertial measurement sensors from the automotive industry and complete inertial measurement units from oil drilling, offer increased performance, and reduced power and space requirements. MEMS and microsystems have a large and diverse market that enables cost reduction and sustainability of available resources. It is also worth noting that the fraction of the MEMS market solely dedicated to space applications is very small, often the MEMS that have been used in space have been developed exclusively for the targeted application; the situation is directly opposite to the case of solar cells, where solar technology was first used in space and then on terrestrial applications.

5.3.2 State-of-the-Art

Microtechnologies for space systems in general and robotics in particular, have attracted the interest of the scientific community during the past decade. The Jet Propulsion Laboratory (JPL) discussed the role of MEMS in the development of smaller robotic systems in 1999 [41] and the MEMS technology developments at JPL, such as LIGA based devices, micro-propulsion, microvalves, optics, microactuators, system on a chip, microinstruments, biomedical devices and packaging were analyzed in [42]. A 1998 work also discusses the use of MEMS and microtechnologies in propulsion, inertial navigation and wireless sensors in space systems [43]. More recently, the use of microrobotics in space, and the use of MEMS, NEMS (Nano Electro Mechanical Systems) and microtechnologies towards a miniaturized robot in terms of mass and volume has attracted a lot of interest [44]. While not strictly related to the use of microtechnologies [45] discusses the use of length scaling in space dynamics; a method for simulating the orbit and attitude of small objects and therefore provide insights for the dynamics of very small spacecrafts ESA has organized several roundtables on MNT for Space applications [46]. Finally, the results of a recent ESA initiative for the introduction of terrestrial MNT to space robotics can be found at [47]. In addition to the small exploration systems, several studies exist on the design of miniaturized space systems, such as: the mobile micro-robot Alice [48] developed at École Polytechnique Fédérale de Lausanne (EPFL), ESA's Nanokhod exploration rover [49] and the spider inspired climbing robot (Abigaille-I) for space at [50].

Despite these reports and studies and the benefits highlighted in the above section, microtechnology is still sporadically used in space robotics. An overview of the more developed areas of microtechnology in space is at [51] and [52] provides a thorough review of the current and future use of MEMS and microsystems in space systems. The most developed areas of use in space are inertial navigation, where accelerometers and gyroscopes (e.g in the current Mars rovers) are sourced from commercial and military applications, atomic force microscopes and propulsion. MEMS based propulsion that produces small thrusts in the order of μN to 1N (micropropulsion), especially cold gas thrusters and ion thrusters (colloid and FEEP thrusters), is particularly suitable for fine control, positioning formation flying applications and for primary acceleration of small spacecrafts [53-58]. NASA has used miniature science instruments for the Phoenix Mars Mission (2008) and for the Mars Science Laboratory (MSL) mission, which will land and operate the Curiosity rover and was launched in November 2011 [59]. Finally, the James Webb Space Telescope (est. launch 2014) will use a MEMS based microshutter array for the Near InfraRed Spectrometer (NIRSpec) of the telescope [60, 61]. Table 5.3 provides a summary of the MEMS technologies flown in space and their technology readiness levels (TRL) [51]. Devices that were used in satellites (CubeSats, ST5, Delfi C3) are discussed in Section 4.

Table 5.3 - MEMS in space applications and estimated TRL [51].

MEMS Device	Flown in space?	Estimated TRL
Inertial Navigation	Yes	High
Pressure Sensors	Yes (Launch vehicles, propulsion)	High
Magnetometer	Yes (CubeSats)	High
Atomic Force Microscope	Yes (Phoenix mission)	Medium – High
Sun sensor	Yes (Delfi C3)	Medium – High
Micro-fluidics	Yes (Space shuttle, satellites)	Medium
Bolometer	Yes (Planck 2009)	Medium – High
Optical Switching	No	Medium – High
Propulsion: ion, cold gas, colloid, solid	Yes (ST5, small satellites)	Medium
Thermal Control	Yes	Medium
RF switch and variable capacitor	Yes (2000, OPAL picosatellites)	Low – Medium
Adaptive Optics & MOEMS instruments	James Webb Telescope (est. 2014)	Low – Medium
MEMS Oscillator	No	Low – Medium

5.3.3 Miniaturization Challenges

In order to assess the areas where the introduction of miniaturization in space robots is essential, it is necessary to identify the main challenges during design and operation. The candidate areas for miniaturization in space robotics should be searched within their subsystems' components. The difference between the target applications for microrobotics on Earth and space robotics must be stressed again; a robot cannot be miniaturized if this negatively affects its objectives, e.g. a rover should be able to travel for kilometers and gather samples, this is not possible with a microrover. The miniaturization challenges interest greatly the space agencies, such as the work presented in [47].

Space systems in general and space robotics in particular have the following sub-systems: Power, Propulsion, Structure, Attitude and Orbital Control (AOCS), On Board Data Handling (OBDH), Locomotion, Guidance, Navigation and Control (GNC), Communication, Thermal, Manipulators and End - Effectors [62]. Depending on the application of each space robot, a subsystem might not be applicable, for example a rover requires no propulsion; however this categorization is standard for all space systems. The subsystems that have the greatest demands (i) in terms of mass and volume are Power, Propulsion and Structure, (ii) in terms of required computational power are OBDH, AOCS, GNC and the motion of manipulators, and (iii) in terms of power demands from the Power subsystem are Thermal, Locomotion and Propulsion. Therefore, the focus of R&D in Micro & Nanotechnology (MNT) should be given in these areas to efficiently address the current challenges. Table 5.4 presents the main challenges per space robot class and where the introduction of MNT is expected to have the highest impact.

Table 5.4 - Challenges for MNT R&D per space robot class.

Class	Subsystem	Challenges for Micro- & Nano- Technology
1. Rovers/ Other Means of Locomotion	Power	• Solution for solar cell efficiency decrease by dust • Large and heavy batteries: higher density required
	OBDH	• Low computational power: More efficient electronics, decentralized architectures
	Thermal	• Improved materials, spot cooling/ heating
	Actuation	• Low eff. DC motors: Better materials required • Low integration of electronics
	Navigation	• Slow in rough terrains due to computational restrictions
2. Stationary Planetary Explorers	Power	• See Class 1 above
	Propulsion	• Landing with retros has mass and volume penalty: Better properties for fuels
	Mechanisms	• See Class 6 below
	Thermal	• See Class 1 above
3.Orbital Planetary Explorers	Power and OBDH	• See Class 1 above
	AOCS	• High electrical power consumption: better electronics required

		• More efficient and smaller sensors required
	Comms	• High power consumption: better electronics req.
	Propulsion	• ≈ 50% of mass & volume of the system: better fuel properties • Electrical propulsion requires high power reqs.
	Structure	• ≈ 20% of total mass: lightweight materials • Enhanced properties required: active materials
4.Aerobots/ Balloons	Power	• No efficient flexible solar cells • Large Batteries: See Class 1
	Structure	• Restrictive space for all the necessary subsystems • Corrosive environments: protection required
	AOCS, OBDH, Comms, Thermal	• High integration needed: better electronics required • High efficiency required: better sensors required
	Propulsion	• Use mainly of propellers: See Actuation of Class 1
	Power	• Highly efficient flexible cells required
5.Orbital Servicers	AOCS	• See Class 3 above • Reqs. during rendez-vous, docking and manipulation
	Comms	• See Class 3 above
	OBDH	• See Class 1 • Reqs. during rendez-vous, docking and manipulation
	Propulsion	• See Class 3 above
	Structure	• See Class 3 above
	GNC	• Massive sensors • High power consumption
	Manipulators	• See Class 6 below • Computational intensive: complex dynamics
6. Manipulators	Sensors	• Integration of more sensors for high autonomy
	Structure	• Large mass • Massive and confusing cabling • Increased stiffness of cabling affects movement
	Actuation	• See Class 1 above
	End Effector	• End effectors designed for specific tasks • Higher dexterity and sensory information required

5.3.4 General Selection Criteria

Not all MNT components can be used in miniaturizing space robotic devices, as their reliability in space condition varies. This is especially pertinent to those systems that are sourced from terrestrial applications. A set of criteria for the selection of microsystems (MEMS, micro and nanotechnologies, etc.) is presented here.

To access the compatibility of the selected MNT components with the space environment and functionality requirements of space robotics the following criteria are proposed: (i) applicability to space robotics, (ii) launch conditions, (iii) external space environment requirements (LEO, GEO, Mars, Moon, Near Earth Asteroid), (iv) required technical lifetime. Additionally, microsystems that are part of the scientific payload must also comply with the scientific objectives of the experiment. Each component should be able to withstand mechanical shocks of 6000 to 10000g and be able to at least operate in a temperature range of -50°C to +80°C. A study on the reliability of MEMS under vibration and shock can be found at [63]. Vacuum conditions are detrimental to MEMS performance and out-gassing in a vacuum environment has also adverse effects on a device's performance; however, it has been observed that a nitrogen atmosphere inside the MEMS packaging has a positive effect on the device's performance and reduces drift. An additional criterion is the maximum operating voltage, which is limited at approximately 2 kV for space applications due to electrical insulation specifications. Space radiation is an important problem that is experienced by all structures operating in space. The high energy particles present in space radiation can trigger single-event effects (SEE) in all digital electronics. MEMS based on capacitive sensors (accelerometers, gyroscopes, proximity sensors) exhibit certain problems when exposed to radiation, due to their operating principle; radiation effects result in creating output drifts and generate noise; packaging is not always a sufficient solution, especially when volume and mass limitations are imposed. The effect of radiation on devices in space is a subject of great interest [52, 64]. Reference [64] provides also a list of radiation tested MEMS and microsystem devices.

For each microsystem, it is important to consider the development risk, time, and cost required to reach the maturity necessary for use in space. Currently, there is no general qualification process for space MNT, it is done on a case by case basis and usually there is no volume production of those devices that are space compliant. The general standards for European space activities can be found at [65], while a study on the reliability of MEMS in space can be found at [66]. Problems are usually addressed by correct design while the applicability of packaging techniques of MEMS devices for space is limited; for example the packaging of heterogeneous MEMS is problematic because the metallic parts cannot withstand the high temperatures of the packaging process. The reliability of MEMS is discussed in [67]. As a final guideline, a terrestrial component that has been tested and verified by being used in the industrial or commercial sector would require an additional 10% cost to be made space compliant. If the terrestrial component or technology has not been extensively tested, the cost of technology transfer to space increases above this 10% figure, and in proportion to the number of tests required.

The proposed set of criteria will aid in the selection of MNT components for space robotics, however ideally a streamlined selection process would enable the miniaturization of space robotics to a significantly greater degree.

5.3.5 Enabling Technologies

MNT can greatly benefit space robotics; the miniaturization of critical components of the subsystems provide to the designers more solutions and flexibility during development. The efficient, systematic introduction of MNT to space robotics requires the fusion of the challenges and requirements of the future robotic systems. The most important technologies and how they will affect space robots and their subsystems are outlined here.

Sensor Islands: Sensor Islands are known as Power and Computational Autonomous Remote Sensors, a research area highly pursued and MNT dependent. This concept is very important because it can increase the autonomy and flexibility of space systems. A sensor island should be able to: (a) receive or harvest power with minimal cabling, (b) have high electronics integration, (c) be computational autonomous and perform data fusion and signal processing, without need to send or receive any data, except for the final data packages, (d) wirelessly communicate with a central computer for the overall control and (e) integrate sensors of different functionalities. In this way, the computational architecture becomes completely decentralized and the overall system more compact and robust.

Power: The upgrade of current power subsystems is strongly related to the advances in power density for batteries (Ah/kg) and higher efficiency for solar cells. Nanomaterials and microelectronics can harvest and exploit more energy than current technological solutions, reducing the mass and weight of current power production and storage systems. Efficient electronics reduce the power requirements and have positive impact in power management.

Structure: The target technology is the development of structural elements with advanced capabilities. Robust but lightweight materials like carbon fiber reinforced plastics (CFRP) are already available and in production; however their capabilities should be augmented by ejecting specialised nanoparticles and general use of nanotechnology and nanomaterials. These new structural elements can be combined with techniques for embedding sensors, cables and piping inside the structure, thus lowering mass penalties and thermal losses and increasing flexibility and environmental protection. The technology of electroactive polymers (EAP) and piezoelectric elements can also be used as sensors and/ or actuators (e.g. as vibration suppressors).

OBDH & GNC: Developments here should be aimed towards a decentralized architecture; therefore the enabling technologies are based on those for Sensor Islands. Dedicated image processors would lower the computational burden, and miniaturized cameras and optics would render the navigation capabilities more efficient. There are MNT systems with small footprints and low consumption offering superior functionalities for commonly used sensors, such as GPS, gyroscopes and IMUs. Additionally, for electronics and microcontrollers 64 bit solutions would increase the overall computational power.

Actuators: Reduction of motor volume and mass require advanced materials enhanced with nanoparticles. They new materials could lower the power losses and increase the magnetic flux and therefore the produced torque and/ or speed. Additionally, higher integration would minimize the essential electronics volume.

All subsystems could benefit by the introduction of MNT and terrestrial MNTs exhibit a significant potential for use in space systems. In general MNTs can lead to smaller, lighter, less power consuming and with higher functionality parts, which in turn means: (a) lighter and more compact systems (without affecting capabilities), (b) more space for payload (e.g. scientific instrumentation, cargo, etc.), (c) higher autonomy capabilities, (d) higher security, operational flexibility, greater redundancy, (e) lower development costs and time and (f) lower launch costs.

5.4 Micro/ Nano Satellites

5.4.1 State of the Art

MNTs and miniaturization in terms of weight and volume also have been introduced in satellites. Although satellites are not strictly considered as robotics systems, they are automated space systems, and therefore pertinent to this chapter. The satellite market is the most mature and well-known segment of space systems. Since the launch of Sputnik 1 in 1957, more than 4900 launches have placed approximately 6000 satellites into orbit, of which, as of April 2011, about 957 are operational per the latest available satellite database available at [68]. Of those operational, 463 (49%) are in Low Earth Orbit, (LEO, 160 – 2000 km), 397 (41%) are in Geostationary Orbit, (GEO, 36000 km), 63 (6%) are in Medium Earth Orbit, (MEO, 2000 – 36000 km) and 34 (4%) are in Elliptical Orbits. These satellites are of government, military, commercial or civil nature. Their uses in orbit are shown in Table 5.5, using data from [68]. The majority (93%) of commercial satellites are communication satellites, 4% are Earth Observation/Remote Sensing satellites, 2% are Technology Development, and 1% are for Navigation Demonstration (prototype satellites for the Galileo system).

Table 5.5 - Function of satellites on orbit.

Function	Percentage
Communication	59%
Earth Observation/ Remote Sensing	9%
Navigation	8%
Military Surveillance	7%
Astrophysics / Space Science	5%
Earth Science/ Meteorology	4%
Other	7%

For the next decade, there will be an average of 122 satellites launches per year, a 60% increase compared to the average annual rate of 77 per year in the 2000s, with a total of 1220 satellites build in the decade 2010 – 2020. The total revenue from the manufacturing and launch of these 1220 satellites will reach $194 billion worldwide for the decade 2010-2020, while currently 60% of the total €5B annual revenue of the European space industry comes from the manufacture and launch of communications satellites. The average satellite mass is estimated to be 1890 kg in the coming decade [69, 70]. For the satellites currently in orbit, the average wet mass at launch (mass including fuel at launch) is 2139 kg and the average dry mass (mass in orbit) is 1190 kg. Table 5.6 shows the mass (wet mass) distribution of the satellites in orbit using data from [68].

Table 5.6 - Mass distribution of satellites on orbit.

Weight (kg) (wet mass)	Percentage
<500	26.40%
500 - 1000	13.69%
1000 - 1500	8.98%
1500 - 2000	5.37%
2000 - 2500	9.75%
2500 - 4000	18.07%
4000 -5000	11.39%
>5000	6.35%

5.4.2 Miniaturization efforts in satellites

It is clear from the above statistics that the satellite market is growing fast and the average mass is quite high. Similarly to space robotic systems, the cost/ launch is proportional to the wet mass of each satellite and higher mass means higher systems and development complexity. It is clear that any mass and volume reduction would significantly decrease the launch cost. Within this context, the term miniaturization of satellites in terms of mass and volume and has a different meaning compared to the traditional one, used in terrestrial applications.

The miniaturization in satellites is achieved in three ways: (a) by scaling down the satellite's mass and volume while retaining functionality (small satellites), (b) by implementing micro/ nano technologies for the subsystems, mostly in the form of microelectronics and MEMS and (c) by combining (a) and (b). A small satellite is defined as a satellite of wet mass of less than 500 kg. Within this range, a microsatellite has a wet mass between 10 and 100 kg, a nanosatellite between 1 and 10 kg and a picosatellite between 0.1 and 1 kg. Compared to the average wet mass of 2139 kg or with an average telecommunication satellite with a mass of 1000-5000 kg, a 100 kg satellite is at 10 to 50 times smaller, a significant weight decrease. The development of nano, micro and picosatellites requires decreased infrastructures and cost, making them ideal candidates for academic institutions and research centres that have a limited budget for space activities, and for novel technology demonstrations which would be otherwise difficult and costly to put in orbit. The importance of small satellites, especially in the weight range of 1 to 30 kg, is also recognised by the United Nations, which led to the establishment in 2009 of the Basic Space Technology Initiative, a new area of activity of the United Nations Programme on Space Applications [71].

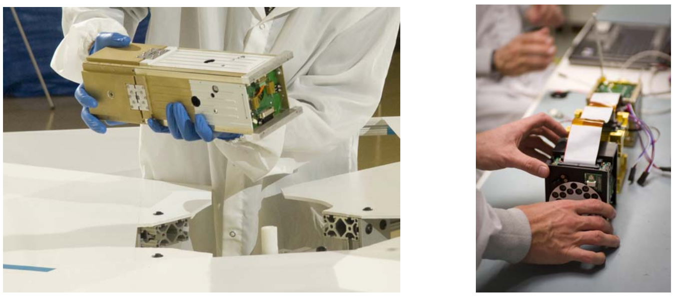
The majority of the miniaturization efforts have been concentrated in case (a), where MEMS and microelectronics are mostly used. In general the implementation of MNT is still sporadic and mostly occurs at small satellites. A review of MEMS used in pico to microsatellites can be found at [51]. A successful example of the miniaturization of satellites is the CubeSat standard [72, 73]. A CubeSat is a miniaturized satellite that weighs no more than 1.33 kg, therefore it is classified as a nanosatellite; its dimensions are 10x10x10 cm and usually uses commercial off-the-shelf (COTS) electronics components. CubeSats are scalable in 1U increments; a 2U CubeSat is 20×10×10 cm and a 3U CubeSat is 30×10×10 cm. The CubeSat standard was developed in 1999 by the California Polytechnic State University (Cal Poly) and Stanford University, with the aim of providing a standard design for picosatellites, while reducing cost and development time, increasing accessibility to space and sustaining frequent launches. CubeSats are used for educational purposes and technology demonstrations, such as testing microtechnologies in space, earth remote sensing, tethers and biological experiments.

CubeSats are launched and deployed using a common deployment system, the Poly-PicoSatellite Orbital Deployer (P-POD). The P-PODs are mounted on the launch vehicle and carry a maximum of three CubeSats into orbit. Additionally, CubeSats are usually “piggy-back” launches; the launch vehicle is used for another purpose (e.g. for a commercial, full-size satellite) and the CubeSats are put into orbit once the main spacecraft has been deployed. The minimized mass and volume, in conjunction to the use of COTS components and the “piggy-back” launch, results in a significantly less expensive system that is developed much faster compared to bigger satellites. As a guideline, a CubeSat costs approximately $40K, including launch costs and has an average development time of 1-2 years, whereas a 500 kg satellite requires 3 years and bigger ones require 5 and more years. However, CubeSats have a smaller lifetime compared to that of bigger satellites (weight > 500 kg), since they use COTS that have not been fully tested and qualified for the harsh space environment (vacuum, radiations, extreme thermal conditions); for example the typical lifetime of a telecommunications satellite is 15 years, whereas CubeSats have a lifetime of months to 3 years. It should be noted, that the benefits of CubeSats are also applicable to micro and nanosatellites.

From 2003 to 2009, more than 45 CubeSat missions have been successfully launched, such as ESA’S SSETI Express [74] and the SwissCube. The EPFL developed and successfully launched in 2009 the SwissCube, with the aim of taking pictures of the atmospheric airglow using a small low cost earth sensor [75]. The earth sensor weighted less than 50 gr, the optics volume was 30x30x65 mm^3, and the payload board was 80x35x15 mm^3. To acquire quality airglow images, the required attitude determination accuracy was better than 1°.

There are several small satellite missions that employ microtechnologies. MEMS are mostly used in the CubeSat attitude determination subsystem, such as inertial sensors (gyroscopes), magnetometers, and optical sensors (sun sensors, star trackers). Magnetometers and gyroscopes are typically COTS devices, while sun sensors and star trackers are space specific. The SwissCube-1 mission used the MEMS gyroscope ADXRS614 manufactured by Analog Device and the 3 axis Honeywell magnetometer HMC1053. Another example is the AAUSAT-II Cubesat developed at Aalborg University, Denmark (2008), which used 6 Analog Devices single chip yaw rate gyroscopes (model ADXRS401), and one 3 axis magnetometer (model HMC1053) from Honeywell as part of the attitude determination system [51]. In both cases, the sensors operated satisfactorily in orbit. MEMS based propulsion that produces small thrusts in the order of μN to 1N (micropropulsion) has also been used in pico to nanosatellites.

The PRISMA mission (2010) used a MEMS micropropulsion system. The mission consisted of two satellites, Mango (140 kg) and Tango (40 kg), with the aim of demonstrating autonomous satellite formation flying. Mango was equipped with a hydrazine propulsion system, a high performance green propellant (HPGP) system and a MEMS cold gas micropropulsion system manufactured by Nanospace. The system consisted of a four thruster array, orthogonally distributed in the equator plane of the golf ball sized thruster module, with a thrust range of 10 μN to 1 mN and used nitrogen as propellant. The micropropulsion system was used successfully during the mission and is candidate for future missions where extremely low and accurate thrust is required [76]. The Delft University of Technology in the Netherlands launched Delfi-C3, a 3 unit CubeSat in 2008 and its follow up will be Delfi-n3Xt, which test several innovative technologies, including a micropropulsion system and micro sun sensors [77]. The University of Toronto's Institute of Aerospace Studies Space Flight Laboratory has successfully launched a number of nanosatellites, such as MOST (2003) [78]. MOST incorporated a small optical telescope (15 cm aperture) equipped with a CCD photometer designed to return high photometric precision and frequency on stars other than the Sun and successfully demonstrated the capabilities of a significantly smaller telescope. NASA's Space Technology 5 mission (2006) demonstrated the operation of three 25kg, fully functional spacecrafts that functioned as a single constellation and implemented multiple new technologies and miniaturized components [79]. The miniaturized technologies that were successfully validated include the following: cold gas microthrusters (CGMT), designed by Marotta Scientific Controls, Inc., variable emittance coatings for thermal control, which consisted of an electrically tuneable coating that could change properties (absorbing heat when cool to reflecting or emitting heat when in the Sun) [80] and CULPRiT, a microelectronic device that allows circuits to operate at 0.5 Volts, a technology that is expected to reduce power consumption while achieving a high radiation and latch-up immunity. Recent examples of successful nanosatellite missions are NASA's NanoSail-D (2010), Fig. 5.4a, and the O/OREOS (2010), Fig. 5.4b, [81, 82]. NanoSail-D's objective was the experimental validation of solar sail capabilities, with the sail packed in-side the 9.9x9.9x37.9 cm^3 satellite. NanoSail-D successfully deployed the 100 square feet polymer sail in January 2011. O/OREOS is the first nanosatellite to operate in the exosphere, conducting autonomous biological and chemical measurements, weighs 5.5 kg and will use a propellant-less mechanism for de-orbiting.



(a) (b)

Fig.5.4 – (a) Nanosail – D stowed and ready for deployment test and (b) test of an early prototype of O/OREOS bus (*Courtesy of NASA*).

5.5 Future Trends

As discussed above, the design of robotic devices for space applications is in general affected by the ongoing miniaturization efforts in two ways. Those systems that must be of certain size become more capable, while the rest shrink in size. However, the size of all space systems remains much larger from that of the terrestrial systems, due to the different scale of the actual space tasks, the conservatism of the space industry [76] (it may lag ten years with respect to the same technologies on earth), the need for extreme reliability and the inability for in-situ repairs, and the requirement for survivability in extreme space conditions (radiation, atomic oxygen, extreme atmospheres).

It is expected though that a number of drastically smaller devices will be considered and employed in space applications. For these to be adopted, the operating scenarios will have to exploit the capabilities of micro and nanotechnologies in innovative ways. For example, an alternative to some functions provided by lander-deployed rovers can be the deployment of a large number of microrobotic planet monitoring modules with low flying balloons. These can cover great areas, establish a redundant communications network, transmit temperature, seismic or other data, and even change their position periodically using spring loaded mechanisms, with all their functions powered by harvesting solar energy. A similar scenario includes a parachute-deployed network of interconnected channels, covering vast planetary areas and containing sensing bionano robots [83]. Micro or nanorobots can also be envisioned to act as rover or mother station linked disposable "scouts," exploring hazardous zones in "one-shot" missions [44]. Another possibility is using swarm nanorobots for inspection and repair of space structures on orbit or on planets, or for checking the status of spacecraft thermal shielding before reentry. Researchers also envision applications such as spacesuit repairs by suit embedded nanorobots [84].

The driving forces that will further strengthen the trend towards miniaturization of robotic devices for space applications are many. The demand for small volume and mass of space systems will continue to be important, due to launch volume and mass technology constraints. As mentioned earlier, the cost of launching a kilogram exceeds $10K, reaching even twice as more. Clearly, adding mass increases the cost. Miniaturization will continue occurring also due to component size reduction and to higher level of integration between platforms providing mobility (such as spacecrafts or rovers) and instruments or sensors [85]. Downscaling of systems and components has some interesting properties. For example, the inertia forces on a component are proportional to the cube of its characteristic length (size), while its stiffness is inversely proportional to it. Therefore, a decrease in size reduces the inertial forces and increases its rigidity, with an obvious benefit to its overall robustness to shocks [44]. Also, since the ratio of area to volume is inversely proportional to length, smaller systems can have higher power densities and can dissipate power more effectively [86]. It is also important to note that a large number of inexpensive robotic devices are obviously more effective against failures versus a single large and expensive one, as the failure of a few of the miniature devices will not jeopardize the entire mission.

Miniaturization will have to overcome formidable technological obstacles. For example, it is very difficult to have high voltages required in electron spectrometry in a very confined space [85], to produce radiation hardened chips with the same capabilities as those for terrestrial applications, or to cover great distances at reasonable times with millimeter size rovers. Despite factors that hinder the proliferation of miniaturized robotic devices in space, the trend is clear and will continue for many years to come.

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