SPACE APPLICATIONS OF *MICRO*-ROBOTICS: A PRELIMINARY INVESTIGATION OF TECHNOLOGICAL CHALLENGES AND SCENARIOS

P. Corradi, A. Menciassi, P. Dario
Scuola Superiore Sant'Anna
CRIM - Center for Research In Microengineering
Viale R. Piaggio 34, 56025 Pontedera (Pisa), Italy
Email: p.corradi@crim.sssup.it

ABSTRACT

In the field of robotics, a microrobot is defined as a miniaturized robotic system, making use of micro- and, possibly, nanotechnologies. Generally speaking, many terms such as micromechanisms, micromachines and microrobots are used to indicate a wide range of devices whose function is related to the concept of "operating at a small scale".
In space terminology, however, the term "micro" (and "nano") rover, probe or satellite currently addresses a category of relatively small systems, with a size ranging from a few to several tens of centimetres, not necessarily including micro- and nanotechnologies (except for microelectronics).
The prefix "micro" will be used in this paper in (almost) its strict sense, in order to address components, modules and systems with sizes in the order of *micrometers up to few millimetres*. Therefore, with the term *microrobot* it will be considered a robot with a size up to few millimetres, where typical integrated components and modules have features in the order of micrometers and have been entirely produced through micromechanical and microelectronic mass-fabrication and mass-assembly processes. Hence, the entire robot is completely integrated in a stack of assembled chips.
Due to its size, the capabilities of the single unit are limited and, consequently, microrobots need to work in very large groups, or swarms, to significantly sense or affect the environment. Main inspiration for the swarm concept is biomimetic: nature offers plenty of examples of swarms (e.g., insects) capable of efficiently accomplish tasks, as surface exploration looking for food, for example.
This paper gives an overview of some technological problems in the development of microrobots, while trying to take into consideration space environment requirements. Possible solutions based on state-of-the art technologies will be proposed and some possible scenarios of application in space (e.g., planetary exploration) will be introduced.

INTRODUCTION

One of the main goals of the design of a space system is the reduction of costs for a given performance. Miniaturization allows a reduction of the required resources and, potentially, even better performances. Micro- and nanotechnologies have demonstrated the capability to fabricate and assembly different types of micro and nano-devices in microsystems, creating advanced micro-instruments for specific applications. The concept of miniaturization and integration of devices and systems brings mainly to the following advantages [1], [2]:

- Required resources (mass, volume, power, etc.) are dramatically reduced.
- Integrated Micro-Electro-Mechanical-Systems (MEMS) and Nano-Electro-Mechanical-Systems (NEMS) can substitute many discrete components and devices.
- The system is produced with "batch" processes, and so with mass fabrication; this implies costs reduction and possible redundancy of critical parts in order to achieve higher reliability during operation.
- Performances for cost and mass unit are higher, that means it is possible to decrease the cost of the whole system, or at given overall costs, increasing performances.
- Small "facilities" are requested to test the system.

All these advantages are particularly relevant in the space field. Miniaturization can play a critical role in the development of next generations of satellites, planetary probes, spacecrafts and on-board instruments. Several MEMS have been and are currently investigated for space applications and employed in space endeavours [3][4].
However, as new and emerging fields, micro- and nanotechnologies still need to solve several problems, e.g., life time, especially for micro-mechanical parts; development of test systems and techniques for devices with dimensions ranging from micrometers to nanometers; packaging and interconnections [5]. Moreover, in space applications, the impact of high levels of radiation [6], extreme temperatures and other interactions with the space environments [7] can considerably affect the performances of devices.

Micro- and nanotechnologies represent a point of convergence of several disciplines that are currently growing very rapidly, like biotechnologies, nanosciences and information technologies. Several research fields are affected by this trend, like Robotics, and more specifically, *Microrobotics*.
In the robotic community, Microrobotics represents the last frontier for the development of autonomous (or semi-autonomous) miniaturized artificial machines, still following a traditional *top-down* approach in the fabrication. Beyond this, a completely new technological approach arises, that is the *bottom-up* fabrication based nanotechnology (or molecular engineering [8]).
Before proceeding, it is worth here to specify some definitions. In space terminology, a large mismatch between dimensional definitions used for space systems and their strict dimensional meanings exists. For examples, literature reports the term "picosatellite" for satellite with roughly 1 dm^3 volume and about 1 kg weight (e.g., the Cubesat standard devised from Stanford University [9]), and "nanorover" for robotic probes with a minimum size of several centimetres, e.g., Minerva hopper [10], currently onboard Hayabusa spacecraft (formerly called "MUSES-C"), MUSES-CN [11] and LAMAlice [12]. Finally, with the term of microrobots or microrover, several tens of centimetres large robotic system are currently addressed, e.g., all the Rocky series and Mars Pathfinder Sojourner Rover, Nanokhod [13], MicroRosa2 [14], Solero [15].
In the field of terrestrial robotics a more rigorous use of the term is adopted, as it will be outlined later.
Bearing in mind the above mentioned considerations, the lessons learned during past activities on Microrobotics (e.g., MICRoN [16]) and, in particular, the first research activity related to a large European project on swarm Microrobotics (I-SWARM [17]), the authors have focused their interest on the possible application of mm-sized robots in space and the major technological challenges that emerge. Rather than presenting technical solutions, the main purpose of this paper is to preliminarily investigate the limit and usefulness of the miniaturization of robots for space exploration and applications, which could be feasible with the state of the art technology, before changing completely approach, i.e. converging efforts on advanced concepts based purely on nanotechnology and molecular engineering. A first approach to space Microrobotics has already been presented sixteen years ago [18][19]. Based on the tremendous developments of micro and nanotechnologies in the last decade, the paper gives an updated contribution on the feasibility study of these "chip robots".

RATIONALE OF SPACE MICROROBOTICS

Mass fabricated autonomous mobile robots of few millimetres are supposed to profoundly demonstrate, in space applications, the advantages mentioned in the previous paragraph as regards micro- and nanotechnologies.
In the space field, Microrobotics can actually be seen as the furthest step towards mass, complexity and cost reduction in space robotic systems, still following a top-down fabrication approach (i.e., not following nanotechnological bottom-up processes). First of all, microrobots meet the space system demand for small volumes and low weight. As well known, space payload costs are about 20 k€/kg; if, for example, a 3 mm on-a-side cube chip-robot is considered (2-3 mm on-a-side microrobot is currently under development [17]), and considering an average density of about 2.5 g/cm^3 (between Silicon and Aluminium), each single microrobot would weigh in the average about 70 mg. Consequently for 20 k€ it would theoretically be possible to pack more than 14.000 microrobots. Up to 30.000 of them could be packed in the same volume of a CubeSat. They would form a set of redundant multifunctional modules able to sense and performing tasks: consequently a robust and reliable system.
Some important advantages of microrobots for space missions deal also with mechanical robustness. For example, when linear dimensions of a cantilever beam structure are scaled by a factor of k, its volume and hence the mass is reduced by a factor of k^3. But at the same time the mechanical stiffness is just decreased by a factor of k. As a conclusion, mechanical strength of an object is decreased much more slowly than the inertial force it can generate (i.e., k versus k^3, for the cantilever beam). That's why, in part, small insects can survive falls from a large height and they are also capable of manipulating objects many times larger than their size or weight. Hence, a first consequence of scaling is that microdevices and microrobots can withstand much larger acceleration than their "macro" counterparts (e.g., a micromechanical accelerometer survived being fired from a tank, which means experiencing roughly a 10^5 g acceleration). Consequently, microrobots could survive rough impacts on planetary surfaces much better than large robotic probes, nowadays used in space missions. This means basically that less efforts should be devoted to the landing systems, and therefore less money and developing time are requested.
Another contribution to increase the system reliability is due to the eventual absence of (wire-)connectors in microrobots, which often represent a critical aspect in larger robots.
Space Microrobotics potentially offers new capabilities and opportunities in space missions, in particular for planetary exploration where a huge number (or swarms) of microrobots could be spread over a region of interest, increasing the mission reliability, and using mass production of multiple identical robots for one mission or for a number of missions (in the same region or in regions with similar characteristics). Swarm Intelligence algorithms [20] could also be

investigated for space missions, in particular for planetary explorations. As an alternative to advanced Artificial Intelligence, similar bio-inspired strategies can bring adaptability and flexibility in the exploration system and consequently, they can particularly benefit missions on far celestial bodies, where remote control of the probes can be absolutely useless or unacceptably slow, especially for urgent actions. The deployment of large quantities of microrobots on the target to be explored, e.g. a planet, a satellite or an asteroid, would also allow the creation of a distributed network of sensing probes (e.g., for climate and seismic monitoring). Finally low-cost mass-fabricated microrobots could also be used as disposable units for exploration in extremely hazardous environment.
Nevertheless, the development of "chip-robots" and their application in space exploration is still a great technological challenge.

STATE OF THE ART OF MICROROBOTICS

In literature, the term "Microrobotics" covers (often improperly) several different types of small robotic devices and systems. Three different microrobots subcategories can be better defined [21]:

- Miniature robots or minirobots: size in the order of a few cubic centimeters and fabricated by assembling conventional miniature components (electronic surface mounted devices, small motors and wheels, commercial coin batteries, plastic chassis, etc.);
- MEMS-based microrobots: a sort of "modified chip(s)" fabricated by silicon MEMS-based technologies having features in the micrometer range;
- Nanorobots: scale comparable to the biological cell (in the range of a few hundreds of nanometers up to few micrometers) and fabricated by molecular engineering.

There are many examples in literature of the first category. Their size ranges from roughly one cubic cm to one cubic inch (1 inch = 2.54 cm). They are often devised to be (manually) produced in large quantities and to emulate large colonies of interacting agents, following bio-inspiration, in order to mimic some natural behaviors shown by biological swarms, like ants. Some of the most important examples of this trend are completely autonomous car-like robots, with wheels and chassis, e.g., Ants [22], Alice [23], Mini-Robot [24], Jasmine [25]. Other prototypes are rather thought for microassembly tasks (in microfactories [26]) and present different locomotion solutions, e.g. Nanowalker [27] and Micron [28]. Finally, also flying [29] and swimming [30] minirobots have been developed or are currently under study.
It is possible to find just few examples of the second group, which is the category of interest within the aim of this paper. More precisely, integration of only few modules that should be assembled to form a complete microrobot have been so far developed. Systems are developed through (Si-based) microfabrication processes. University of Berkeley, USA, developed the Crawling Robot [31], and Silicon Robot [32], which are basically locomotion modules (or conveyors), and the Smart Dust [33], which is so far conceived to be a communication module, more than a robot. One of the most spectacular demonstrators of conveyor made is the "silicon microrobot" with legs actuated by lithographically defined thermal polymer actuators [34]. Finally, very recently, a sub-mm locomotion system has been developed by the Darthmout University, USA, although it needs an active floor (or arena) to move. For a complete state of the art on MEMS-based Microrobotics, please refer to [35].

TECHNOLOGICAL CHALLENGES FOR MICROROBOTICS AND SPACE MICROROBOTICS

Technological issues associated with the fabrication of a complete robot, i.e. a moving unit capable to interact with the environment with sensors and tools, wireless powered, autonomous, and able to communicate, have been considered. Space exploration missions, in fact, require all these capabilities.
The following topics should be investigated in order to devise a complete (micro-)robot for space application: Power, Communication, Electronics, Control Software, Tools, Sensors, Locomotion and final Module Assembly Techniques. On the other hand, dealing exhaustively with all these topics is certainly not feasible within the frame of a single paper. Consequently the investigation of only three major issues will be here reported: power (in more details), communication and a brief introduction to locomotion.
The preliminary design of the I-SWARM microrobot, currently under development in its sub-modules, will be considered as case study (Fig. 1). As a preliminary requirement, I-SWARM microrobots should be 2×2 mm^2 large and possibly less than 2 mm high. The project goal is to study the design and programming of a relatively large number (up to one thousand) or swarm of simple physical microrobots such that a desired collective behaviour emerges from the inter-robot interactions and the interactions of the robots with the environment inspired by - but not limited to - the emergent behaviours observed in social insect colonies.

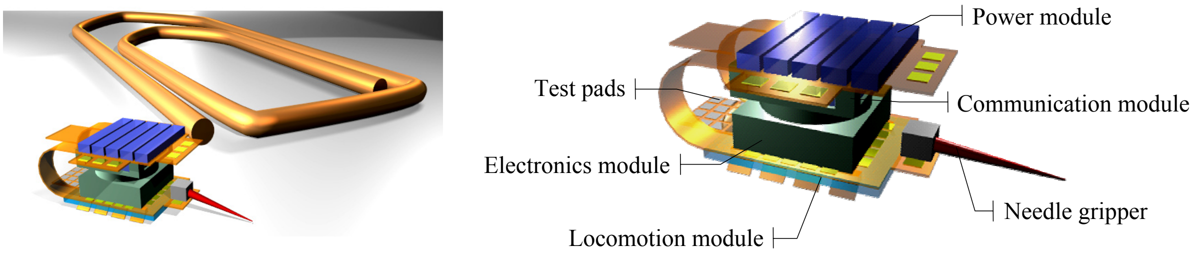


Fig. 1. Preliminary concept of the I-SWARM microrobot

Power

Power represents probably the most critical aspect in the development of wireless microrobots. In fact, not only it is difficult to integrate a complete power system in few mm^3, but the miniaturization is a dramatic limit to the on-board available power, and consequently, to all the capabilities of the microrobot. The overall powering system should include a full independent storage battery, which supplies energy to the microrobots, and a wireless unit that scavenges energy from an external energy source (e.g., sun) and converts it to electrical power for the robotic system.
The requirements of power sources for space Microrobotics applications are high energy density, robustness to temperature extremes and mechanical shock, long cycle life and long storage lifetime [36]. The required operational conditions would obviously depend from the target of the mission, e.g., which celestial body has to be explored.
Referring to the I-SWARM microrobots, the overall power unit must be roughly large 2 × 2 mm^2. As a preliminary requirement, the conceived thickness of the power unit should be far less than 1mm and it should be able to supply a continuous power of at least 150 µW with an output voltage of about 3 V.
It is hard to find power sources capable to be integrated in few mm^3 and to furnish enough power. At present, some independent battery systems based on different principles are being used as miniaturised power supplies, including coin chemical type batteries [37], super capacitors [38], miniaturised fuel cells [39], thin film [40] and thick film [41] batteries. Main characteristics are reported in Table 1.
Among them, the former three types seems not suitable for the application in Microrobotics because of their present too large size and difficulty of miniaturization. Thin and thick film batteries are suitable for miniaturization. Commercial thin film batteries have superior features compared to commercial thick film batteries, and they are thinner. Advanced rechargeable thick film batteries have been developed at laboratory level, with size and performances comparable to the thin film batteries [42]. However, to date, thin film batteries can still be considered the best candidate as independent storage battery for microrobots.
A 4 mm^2 single layer thin film battery can storage about 60 µWh and it is able to output up to 720 µW [40] continuous power (for just few minutes). Typically, the cell thickness is 5-25 µm with a substrate of about 130 µm. Thin film lithium batteries can be integrated into Multi-Chip Modules (MCMs) for possible use with microrobots for space exploration. Five batteries stacked together could have a thickness of less than 300 µm guaranteeing about 300 µWh. Temperature survivability of thin film batteries is in the range -50°/+180° C, while they are operational in the range -50°/+120° C. The charge loss per year can be less than 1%.
Thin film batteries most fully meets the above mentioned requirements for space applications. A relatively simple process for the fabrication of polymer-based thin-film lithium ion batteries for space applications has been developed at the NASA Glenn Research Center [43]. Kapton® Polyimide film (by DuPont), is used as substrate. It is a space-qualified polymer that is lightweight, flexible, and performs well under the rigors of the near-Earth space environment.

Table 1. Batteries

	Coin Battery	**Micro Super Capacitor**	**Micro Fuel Cell**	**Thin film Battery**	**Thick film Battery**
Diameter (mm)	4.8	6.8	-	-	(55)
Length (mm)	-	-	12.5	> 0.001	-
Width (mm)	-	-	12.5	> 0.001	-
Thickness (mm)	1	1.8	1	0.005-0.025	0.65
Voltage (V)	1.55	2.5	0.2-1.0	3.6	1.5
Power density (µW/mm^3)	0.9	77	500	900	970
Energy density (µWh/mm^3)	340	2.8	16	1000	29

It is worth here to mention three interesting novel battery technologies, whose progresses should be monitored.
A novel approach to electrochemical energy production is currently pursed by mPhase Technologies Inc. and Bell Labs (Lucent Technologies), which are going to commercialize soon a nanotechnology based chemical battery, under the name of Nanobattery®, easy to miniaturize and compatible with semiconductor processes, very long shelf life (more than 25 years) with no maintenance and inexpensive to mass production. A trigger stimulus (e.g., voltage, acceleration, temperature) is needed to activate the battery. These are all very attractive properties for space applications. Preliminary characteristics are: supplied voltage of 1.65 V (open circuit), thickness of 600 μm, power density of 130 $\mu W/mm^3$, energy density of 120 $\mu Wh/mm^3$. The main drawback is that, so far, it is not rechargeable, so the battery could eventually be used for "one-shot" missions or tasks.
Another very interesting non-conventional battery technology, is addressed by radioisotope microbatteries. Radioactive materials contain extremely high energy densities (approximately 10^5 J/mm^3). This energy has been used on a much larger scale for decades in deep space missions (e.g., Pioneer 10 and 11, Voyager 1 and 2, Galileo, Ulysses and Cassini), with Radioactive Thermoelectric Generators (RTGs), where the generated heat is converted into electricity using thermoelectric conversion mechanisms. However, it must be remembered that in most cases the energy is being emitted from the radioactive source over a very long period of time (depending from the half-life of the source, it can range from few seconds up to hundreds of years). And, unfortunately, efficient methods of converting this power to electricity at small scales do not exist. Therefore, efficiencies obtained are extremely low (< 2-3%). As a consequence, radioisotope power microbatteries cannot be considered, at present, primary batteries for microrobots.
Two approaches are interesting for utilization in microrobots for space missions, mainly due to their high integration and miniaturization capability. The first is based on the betavoltaic effect [44]. Betavoltaic cells tend to be low-power devices operating at low efficiencies (< 0.5%). The second approach is based on a nuclear-mechanical-electrical conversion and is represented by the Radioisotope Micropower Generator for MEMS based on Piezoelectric Direct Charging [45]. Best demonstrated efficiency is very low, around 2.5% and power obtained for micro prototypes is still very low (typically in the order of nW), even if it depends from the type and amount of radioactive thin film used. Radioisotope microbatteries could be considered as on-board energy supplies for thin film batteries when temporary lacks of primary external energy sources (e.g., sun light) occur, in order to keep the microrobot in quiescent state or to let it perform very low power tasks (e.g., sensing). Finally, radioisotope microbatteries could function in harsh environments. For example the components of the Radioisotope Micropower Generator could withstand extremely high temperature environments, as they are present on Venus, for instance, considering to use higher Curie temperature piezoelectric materials (e.g., pseudo-ilmenite-type $LiTaO_3$, T_{Curie} = 615° C) in place of the lead zirconate titanate (PZT) plate used.
As a last microbattery category to mention, there are currently large efforts in the field of Power MEMS, i.e. Micro Electro-Mechanical Systems able to exploit combustion for mechanical and electrical power generation [46]. However, micro-engines are not expected to reduce further in size (than about 1 cm^3) due to manufacturing and efficiency constraints. At small scales, viscous drag on moving parts and heat transfer to the ambient and between components increase, decreasing the efficiency. Furthermore, it is hard to think possible in space any refilling of fuel of such batteries, so they would just be disposable systems. Finally, it would also be necessary to consider the composition of the atmosphere in which the micro-engines has to operate, since they need a combustive agent (oxygen).

Regarding wireless power scavenging units, the available technologies include inductive coupling, where energy is transferred between coils [47], microwave energy transmission [48], and Photo-Voltaic (PV) cells. The first two technologies could be employed in a space scenario, by considering the presence of a large lander capable to irradiate electromagnetic fields with enough power. However both the technologies require too large hardware to be integrated in a microrobot. For instance, in order to generate a reasonable coupling voltage in the coil for inductive coupling, either the integrated coil must have too many turns, which is difficult to be realised using the normal microfabrication technology, or the external magnetic field must be so strong that it is not only probably unfeasible, but the induced thermal and magnetic interference could also be serious. Besides, the rectifying and filtering stage necessary to convert the ac voltage generated in the coil to dc voltage, which is required by the electronics, would make the power unit exceed the required size. The system for microwave energy transmission would require cumbersome hardware as well, like the antenna and rectifying and filtering electronics, and it could also cause interference to the electronics too. Main drawbacks of these technologies are resumed in Table 2.
Solar cells definitely seem, at present, the only technical solution for energy scavenging in autonomous space robots, especially for microrobots aimed at missions on near-Earth celestial bodies. Since the output voltage of a single solar cell is typically around 0.5 V, the required voltage for the microrobot can be achieved by either connecting several solar cells in series or by integrating a voltage booster. A great advantage is that it is easy to fabricate micro PV cells using the normal microelectronic technology. Furthermore, advanced techniques allow to reduce the size of the device already down to 3 × 3 mm^2 without performance degradation, a problem usually encountered when cells are cut in small chips.

Table 2. Energy Scavenging Units

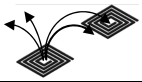
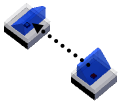
	Scavenged energy form	Drawbacks
Inductive coupling	Oscillating magnetic flux	- Coils must have too many turns - External magnetic field should be too strong - Too large conditioning electronics
Microwave energy transmission	Microwaves	- Too large antenna - Too large conditioning electronics
PV cells	Light	If based on solar light, PV cells would be useless for: - deep space probes - submarine applications (e.g., on Europa) - cloudy and dense planetary atmosphere (e.g., on Venus)

Solar cells output direct current, which avoids the use of complex and space-consuming conversion circuitry to be integrated. The dc output voltage from a solar cell could then be directly used to supply power for the robots, and the remaining power can be used to charge an integrated thin film battery, for example. However, critical aspects arise with the use of PV cells. They obviously need the direct exposition to the Sun (or artificial light sources). PV cells are practically useless for submarine applications, for deep space probes, or for exploration of planets with cloudy and dense atmosphere as Venus, for example. The obscuration by suspended dust, as it happens in the atmosphere of Mars, could represent a further problem. Several dust-removal techniques have been devised [49], but their integration on microrobots could be very challenging or unfeasible. However, phenomena like the "dust devils" on Mars have already demonstrated on large planetary rovers that dust would not represent the critical aspect it was supposed to be, regarding solar cells obscuration.
Basically three types of high-efficiency and compact PV generators exist: multi-junction PV cells, monocristalline silicon cells, and chalcogenide PV cells, such as copper indium gallium diselenide, $Cu(In,Ga)Se_2$ (called CIGS). High-efficiency PV cells directly fabricated on lightweight, space-qualified durable substrate (e.g., Kapton®) have been developed for space applications [43] using CIGS based materials. CIGS PV cells are highly appealing for space: wavelength band-gaps are, in fact, near optimum for absorption of the solar spectrum in space and on the surface of Earth and they are also very promising because of their tolerance against high energy irradiation (present in several space environments). Typical efficiency of about 15-20% can be achieved [50]: a 4 mm^2 solar cell under 1000 W/m^2 (i.e., sunshine on Earth) would furnish 600-800 μW to the microrobots.

Communication

Communication between microrobots and between microrobots and the spacecraft is fundamental. Due to the limited on-board power and, secondary, the small size of the microrobots, long range communication is practically impossible. From preliminary estimations done in the frame of the I-SWARM project, it is hard to expect a communication range better than few centimetres. As a first consequence, the microrobotic swarm should remain quite compact and quite close to the lander, which would work as antenna tower to send data back to the orbiter or directly to Earth. The ability to communicate is also of paramount importance for swarm systems in which continuous interaction with the environment and neighbours is necessary, in order to explore, perform collective tasks and share information. This last aspect is a capital element both in natural and robotic swarms, where inter-robot communication (direct or indirect) is the base of emergent behaviours [20].
Three main communication systems have been considered, whose properties and drawbacks are resumed in Table 3.
From a dimensional viewpoint, the integration of a communication system in 4 mm^2 can be achieved with optical devices or micro-coils for magnetic induction-based communication, for example. However, the second solution would require too high power at the receiver stage and, in any case, the communication range has been estimated less than 10 mm for the available power. Size issues are probably more important considering radio-frequency (RF) based systems. RF communication has been extensively used, even in miniature robotics [23], in a frequency band ranging from 30 MHz to 3 GHz. RF communication could be based on the technique used in the RF identification systems (RFID), that means the microrobots could use back-scattering effects to transmit their information to the lander, which actually generates the microwaves. However, as in the case of the microwave energy transmission, one of the main problems related to the integration of RF communication systems on microrobots regards the required antenna size. Antenna must be at least quarter of the RF wavelength. Consequently, at 3 GHz the antenna should be around 2-3 cm.

Table 3. Communication Technologies

	Properties	Drawbacks
RF 	- Long distance communication - 2 GHz ASIC can be integrated in $4mm^2$	- Large antenna for microwaves based communication - Higher frequencies (EHF for mm-sized antenna) require advanced electronics
Coil induction 	- High degree of integration: few tens of turns in $4mm^2$ possible - MHz based communication	- High power requested at the receiver stage - Short communication range (< 10mm) for the available power
Optics 	- High degree of integration - Low power consumption - Directionality - Devices suit aerospace requirements	- Need for line-of-sight - Troubles with dust - Need for a mirror architecture - Proper packaging to avoid photodiode saturation

In order to reduce antenna size in the millimeter range, e.g., 2-3 mm, RF transmission around 30 GHz would be required, consequently moving into the Extremely High Frequency (EHF) band (30-300 GHz) of millimeter-waves. Some examples of small millimeter-wave transceiver chips can be found in literature [51]. However, any attempts to adapt, in such a small volume, the existing IC technology used for the electronic module to the required monolithic microwave integrated circuits (MMICs), based on gallium arsenide (GaAs) technology, needs carefully investigation, both from compatibility and size viewpoint. Another issue would be the interferences between the microrobots.
As advanced concept, if microrobots could self-connect each other in order to form a few centimetres long antenna and gather more power, they could be able to communicate with the spacecraft through microwaves and at higher distances.
Optical communication seems the most viable solution for microrobotics, both from a dimensional and a power viewpoint. A highly integrated 2×2 mm^2 optical mirrored chip, based on Infra-Red (IR) Light Emitting Diodes (LEDs) and photodiodes, is currently in development in the frame of the I-SWARM project [52]. Optical communication is highly directive, a very important feature for the robotic swarm coordination, even if, as a drawback, it needs line-of sight, a condition requiring flat and clear surfaces, which is improbable to be satisfied in space applications, as planetary exploration. Anyway, suitability of optical devices, as LEDs and photodiodes, to space applications is achieved in the optoelectronic industry. Space radiation (UV and charged particles) resistant transparent polymeric materials to fabricate optical structures (e.g., micro-lenses) and packaging have been addressed by a long time [53] and effects on the optical properties of selected transparent polymers in space environments have been investigated [54].

Locomotion

While power and communication systems in a microrobot can be preliminary conceived by miniaturizing and highly integrating existent technologies, locomotion requires a totally different approach.
Depending on the application and the environment of the mission, the microrobots would need to walk, crawl, swimming or flying. No working flying microrobot has been so far developed and flying capabilities under gravity conditions would probably require more than few lines to be properly addressed. Thus, in the following, only walking and crawling and, afterwards, swimming capabilities will be briefly investigated.
Any attempts to miniaturize efficient macroscopic locomotion solutions to be integrated in such a small volume is yet unfeasible. In order to realize a module of less than $2 \times 2 \times 1$ mm^3 no wheel-based or complex mechanisms can be considered: the system needs to be extremely simple, mainly because it needs to be batch fabricated through microfabrication processes. By considering terrain microrovers, it seems unrealistic that such small vehicles could ever traverse as rough terrains as large vehicles. However, on Earth, ants can traverse much more varieties of terrain than humans or machines, and we could argue that an ant could quite easily manage a walk on a Martian-like surface. This is just to say that size is not by itself an obstacle to locomotion on rough surfaces. In addition, the small size of a microrobot would allow exploration in regions where larger robots could not move at all (presence of high rocks close to each other) or where larger robots can not go (like small caves).
Microrobotic locomotion often tries to take inspiration form nature (i.e., to be biomimetic): there is plenty of examples in nature of efficient walking or crawling systems in mm-sized insects, for example. However, nowadays microrobotic technology is stressing the concept of top-down fabrication in this kind of systems, and it is hard to think that it will ever possible to properly emulate the capability of biological locomotion microsystems with an approach based on the development of homogeneous parts in silicon and smart materials. It seems we are at a transition border between the

two worlds: “silicon” and “biology”. All the technical attempts to top-down fabricate similar systems seem more engineering exercises than practical solutions.

Locomotion capability in Microrobotics has been so far based on microconveyance modules, working on electrostatic or electrical actuation of vibrating micro-leg arrays [35]. Walking microrobots are often helped by active surfaces (electric or magnetic driving) or they are operative on perfectly smooth and clean surfaces, which cannot obviously be found in space planetary missions. At present, it seems there are no suitable walking locomotion systems for microrobots that look capable to work on sandy Mars-like surfaces. Crawling techniques (e.g., inchworm locomotion) seems to have better hopes [55], but, at this small scale, there are no efficient demonstrations in literature. Another interesting solution of locomotion on rough terrains, would be represented by hopping microrobots [56], especially in low gravity environments. Several space rovers have been conceived as hoppers, e.g. Minerva [10]. Spring mechanism-based microsystems, loaded by electrostatic fields, and able to make jump the microrobots, even randomly, would possibly represent an efficient system for random exploration of an area with swarms of robots. As a preliminary conclusion, swarms of microrobotic worms or hoppers could eventually be the main locomotion solutions on which devise microrobotic systems for planetary surface exploration.

Swimming could be an easier task, since the uniformity of the environment allows simple actuators, like simple oscillating wet Electro-Active-Polymer (EAP) cantilevers, acting as fins [30], or novel technologies like Synthetic or Pulsed Jets [57], even if miniaturization has to be investigated. Similar systems could be realistically used in medium terms for applications in microgravity, e.g., on space stations or orbiting spacecrafts, where atmosphere is present.

Table 4 reports a list of the main technologies and techniques for microrobotic locomotion.

INTRODUCTION TO SCENARIOS FOR SPACE MICROROBOTICS

Some preliminary ideas about possible scenarios of microrobot applications in space will be introduced. In no way the authors mean to describe feasible scenarios, being well aware of the complexity of the definition of a space exploration mission. The following is just an overview of some of the opportunities that could be explored.

Basically, two typologies of space application for microrobots can be addressed:

- Microrobots for exploration and scientific survey of celestial bodies (and outer space);
- Microrobots for future use inside and outside the International Space Station (ISS).

Considering planetary exploration, a small spacecraft lander could spread around crawling microrobots on the planetary surface, in order to perform simultaneous and detailed exploration and analysis of the area. The system would be theoretically robust thanks to the large number of units involved, fault-tolerant (failure or loss of a certain percentage of the units is acceptable) and, if controlled by swarm intelligence algorithms, it could even be able to adapt and be flexible to unforeseen situations.

Submarine space missions could be conceived on Europa, the second Galilean satellite. From the images and data collected by the Galileo spacecraft, scientists believe that a subsurface water “ocean” roughly existed in relative recent history and may still be present beneath a 3-5 km thick icy crust. A scenario involving the microrobots on Europa could consider a robust drilling probe (there are yet several concepts about this) deployed by the orbiter and containing the microrobots. It should perforate the icy crust entering the underneath submarine environment, where it would release thousands of swimming microrobots, in order to collect data. The microrobots would probably survive few minutes, due to the harsh environment and absence of power source (sun). Communication would also be a major critical issue.

It is also possible to conceive hybrid missions with larger robotic rovers. A large and simple rover equipped with camera could spread or release microrobots around to sense the environment in order to safely move, perform a detailed environmental analysis, and also to have a feedback about the most interesting regions to explore (from this viewpoint, microrobots could be even seen as an upgrade of the current large rovers for planetary exploration).

Table 4. Main Actuation Technologies and Techniques for Locomotion

	Technology/Techniques	**Remarks**
Walking/Crawling	Ceramic (PZT) actuators	Mass production difficult in the present sizes, high voltages
	Dry EAP (PVDF) actuators	Limited temp. range, poor chem. stability in harsh environments
	Shape Memory Alloy (SMA) actuators	High power requirements
	Hopping mechanism	Miniaturization feasibility to be investigated
	Wind dragging (e.g., on Mars)	Not under control
Swimming	Wet EAP (IPMC) fins	Short life, low actuation force
	Synthetic (or Pulsed) Jet	Miniaturization feasibility to be investigated
Flying	PZT, dry EAP	No working prototypes in the state of the art
	Wind dragging (e.g., on Venus)	Not under control

The microrobots (or some of them) could be recovered on-board the main rover. In the case of crawling microrobots, they could be recovered by the rover when it passes over them and magnetically attracted, for instance. In this way, soil grain samples, which have been selected by the microrobots, could be chemically analyzed also on-board the rover, which could be equipped with some more advanced and more power consuming instruments. Finally, microrobots could be employed as disposable units for analysis of hazardous zones, accomplishing short "one-shot" missions, which would also allow the use of not-rechargeable batteries on-board the microrobots, avoiding the integration of energy scavenging systems. The microrobots would be helpful in performing more advanced tasks, as exploring small holes or narrow passages, which large rovers cannot accomplish.
The "ejection" or releasing of microrobots from the main lander or the rover could be conceived as focused towards a specific direction or diffused all around. In this last case, considering that with 1 kg payload more than 10.000 microrobots can be stored inside the rover or the lander and, thinking to achieve the challenging goal to make possible communication between the microrobots up to 3-5 cm distance, an area up to about 5×5 m^2 could be completely covered and explored with the microrobots.
Microrobots could also be employed for inspection and surveillance tasks on the ISS. The microgravity environment presents on the ISS offers the possibility to use novel flying microrobotic systems propelled by synthetic jets or dry EAP fins. They could be continuously operative and devoted to pervasively monitor environmental conditions. Power could be scavenged through internal ISS illumination. With a proper locomotion capability, swarms of sun-powered microrobots could be spread on the whole external ISS surface for general monitoring (e.g., debris impacts, Environmental Control and Life Support System -ECLSS- valves, etc.). Swarms of microrobots could check thermal shield status of docked ships for safe Earth re-entry. Walking on external module surface of ISS would require some reliable stick capabilities of the microrobot feet. Magnetic attraction techniques can not be used, since the main material used for ISS structure is Aluminium. Gecko-like adhesive properties would be a an amazing and winning solution, which is currently under study [58].

CONCLUSIONS

Microrobotics could represent the furthest step towards cost, volume and weight reduction for space robotic probes and a totally different approach in their fabrication. It could represent a revolutionary strategy for space exploration. However, huge technological problems still need to be solved. Power, communication and locomotion represents three of the major issues in Microrobotics. The size restriction forces to dramatic limitations in the available power, and, consequently, also in the capability to drive core systems like communication, fundamental for both inter-robots and robots-spacecraft data exchange, and locomotion, which, in addition, presents serious problems due to the necessity of moving micro-parts. The other technical issues, like sensors, tools, and module assembly techniques will be possible issues of next articles.

ACKNOWLEDGEMENTS

The authors wish to thank the I-SWARM project Consortium for contributions in the state-of-the-art technology and in the preliminary definition of the microrobot modules. Special thanks go to Dr. Jörg Seyfried from Universität Karlsruhe (TH), IPR, Germany, for kind permission of using pictures of the I-SWARM microrobot concept.

REFERENCES

[1] A.M. de Aragón, "Future Applications of Micro/Nano-Technologies in Space Systems," Technical Directorate, Systems and Programmatics Department, System Studies Division, ESTEC, Noordwijk, The Netherlands, 1996.
[2] P. Dario, and M.C. Carrozza, "The Trends towards Miniaturisation," *Proc. of the International Workshop on Innovations for Competitiveness*, ESA-ESTEC, Noordwijk, The Netherlands, March 19-21, 1997, pp. 301-306.
[3] S.W. Janson, H. Helvajian, K. Breuer, "MEMS, Microengineering and Aerospace Systems," *AIAA Journal*, 1999.
[4] L. Muller, "Microelectromechanical Systems (MEMS) Technology Integration Into Microspacecraft," *JPL Technical Report*, 1996.
[5] S. Barthe, F. Pressecq, and L. Marchand, "MEMS for space applications: a reliability study," *4th Round table on MNT for Space*, 2003.
[6] L. D. Edmond, G. M. Swift, C. I. Lee, "Radiation response of a MEMS accelerometer: an electrostatic force," *IEEE Transaction on Nuclear Science*, Vol. 45, pp. 2779-2788, 1998.
[7] D. C. Ferguson, "Interactions between spacecraft and their environments," *AIAA Journal*, 1993.
[8] K. E. Drexler, *Engines of Creation*, Anchor Books, 1986.

[9] http://www.cubesat.org
[10] T. Yoshimitsu, T. Kubota, I. Nakatani, T. Adachi, and H. Saito, "Micro Hopping Robot for Asteroid Exploration," *Acta Astronautica*, Vol.52, No.26, pp. 441-446, 2003.
[11] B.H. Wilcox and R.M. Jones, "The MUSES-CN nanorover mission and related technology," *IEEE Aerospace Conference Proceedings*, 2000.
[12] M. Freese, M. Kaelin, J.-M. Lehky, G. Caprari, T. Estier, and R. Siegwart, "LAMAlice : A nanorover for planetary exploration," *Proceedings of 1999 International Symposium on Micromechatronics and Human Science (MHS)*, pp. 129-133, Nagoya, Japan, 1999.
[13] M. Van Winnendael and G. Visentin, "Nanokhod Microrover Heading Towards Mars," *Fifth international Symposium on Artificial Intelligence and Automation in Space, I-Sairas '99*, ESA SP-440, August 1999.
[14] A. Matti, S. Jussi and S. Jari, "The Micro Rosa2 activity – conclusion and future plans," *Proceedings of the 7th ESA Workshop ASTRA 2002*, ESTEC, Noordwijk, The Netherlands, November 19 - 21, 2002.
[15] S. Michaud, A. Schneider, R. Bertrand, P. Lamon, R. Siegwart, M. Van Winnendael, and A. Schiele, "SOLERO: Solar Powered Exploration Rover," *Proceedings of the 7th ESA Workshop ASTRA 2002*, November 2002.
[16] MICRoN: Miniaturised Co-operative Robots advancing towards the Nano range, IST-2001. European Community, 2002-2005 - Contract # 33567. http://wwwipr.ira.uka.de/~micron/
[17] I-Swarm: Intelligent Small World Autonomous Robots for Micro-manipulation, 6th Framework Programme Project No FP6-2002-IST-1. European Communities, 2003-2007 - Contract #507006. http://www.i-swarm.org
[18] R.A. Brooks, A.M. Flynn, "Fast, cheap and out of control: a robot invasion of the solar system," *Journal of The British Interplanetary Society*, Vol. 42, pp 478-485, 1989.
[19] A.M. Flynn, R.A. Brooks, and L.S. Tavrow, "Twilight Zones and Cornerstones: A Gnat Robot Double Feature," *MIT A.I. Memo 1126*, July 1989.
[20] E. Bonabeau, M. Dorigo, G. Theraulaz, *Swarm intelligence: from natural to artificial systems*, Oxford University Press, New York , NY, 1999.
[21] P. Dario, R. Valleggi, M.C. Carrozza, M.C. Montesi, and M. Cocco, "Review - Microactuators for Microrobots: A Critical Survey," *J. Micromech. Microeng.* 2(3), pp. 141–157, 1992.
[22] J. McLurkin, "The Ants: A Community of Microrobots," *S.B., M.I.T.,* 1995.
[23] G. Caprari, P. Balmer, R. Piguet, and R. Siegwart, "The Autonomous Micro Robot "Alice": a platform for scientific and commercial applications", *Proceedings of 1998 International Symposium on Micromechatronics and Human Science (MHS)*, Nagoya, Japan, November 25 -28, 1998.
[24] http://www.sandia.gov/media/NewsRel/NR2001/minirobot.htm
[25] S. Kornienko, O. Kornienko, and P. Levi, "Minimalistic approach towards communication and perception in microrobotic swarms," *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 4005-4001, 2005.
[26] J.-M. Breguet, C. Schmitt, R. Clavel, "Micro/Nanofactory: Concept and state of the art," Microrobotics and Microassembly," *SPIE's Photonics East*, Boston, vol. 4194, pp. 1-12, 5-6 November, 2000.
[27] S. Martel, L. Cervera Olague, J.B. Coves Ferrando, S. Riebel, T. Koker, J. Suurkivi, T. Fofonoff, M. Sherwood, R. Dyer, and I. Hunter, "General description of the wireless miniature NanoWalker robot designed for atomic-scale operations," *Proceedings of SPIE: Microrobotics and Microassembly*, Vol. 4568, pp. 231-240, October 29-31, 2001.
[28] J. Brufau, M. Puig-Vidal, J. López-Sánchez, J. Samitier, J. Seyfried, R. Estaña, and H. Woern et al. "MICRON: Small Autonomous Robot for Cell Manipulation Applications," *Proceedings of the 2005 IEEE Int. Conf. on Robotics and Automation (ICRA)*, pp. 856-861, 2005.
[29] J. Yan, R.J. Wood, S. Avadhanula, M. Sitti, and R.S. Fearing, "Towards flapping wing control for a micromechanical flying insect," *IEEE Intl. Conf on Robotics and Automation*, Seoul, Korea, May 2001.
[30] S. Guo, T. Fukuda, and K. Asaka, "A New Type of Fish-Like Underwater Microrobot," *IEEE/ASME Transactions on Mechatronics*, Vol. 8, no. 1, March 2003.
[31] R. Yeh, and K. Pister, "Design of Low-Power Articulated Microrobots," *in Proc. Int. Conf. on Robotics and Automation Workshop on Mobile Micro-Robots*, pp. 21–28, April 23–28, San Francisco, CA, USA.
[32] S. Hollar, A. Flynn, C. Bellew, and K. Pister, "Solar Powered 10mg Silicon Robot," *MEMS 2003*, Kyoto, Japan, January 19-23, 2003.
[33] B.A. Warneke, M. D. Scott, B. S. Leibowitz, L. Zhou, C. L. Bellew, J. A. Chediak, J. M. Kahn, B. E. Boser, and K. Pister, "An autonomous 16 mm solar-powered node for distributed wireless sensor networks," *in Proc. Sensor 2002*, Orlando, FL, June, 12–14 2002.
[34] T. Ebefors, "Polyimide V-groove joints for three-dimensional silicon transducers," Royal Institute of Technology, Sweden, 2000.
[35] M. Gad-el-Hak, ed., *The MEMS handbook*, CRC Press LLC 2002, chapter 28.

[36] W.C. West, J. F. Whitacre, B. V. Ratnakumar, E. J. Brandon, and G. Studor, "Micro-Power Sources Enabling Robotic Outpost Based Deep Space Exploration," *Forum On Innovative Approaches To Outer Planetary Exploration 2001–2020*, February 21–22, 2001 Lunar And Planetary Institute, Houston, Texas.
[37] Sony Inc. watch MicroBattery, Type: SR410SW.
[38] Panasonic Inc. Electric double layer capacitors (Gold capacitor), Type: EECEN0F204.
[39] J.D. Holloday, E. O. Jones, M. Phelps, J. Hu, "Microfuel processor for use in a miniature power supply," *Journal of Power Sources*, June 2002, 108, pp. 21–27.
[40] Cymbet™ Corporation, lithium ion thin film battery, Type: POWER FAB™.
[41] Power Paper Ltd., Power Paper® battery, Type: STD-2.
[42] P.H. Humble, J.N. Harb, and R.M. LaFollette, "Microscopic Nickel-Zinc Batteries for Use in Autonomous Microsystems," *The Journal of the Electrochemical Society*, Vol. 148, (2001), p. A1357.
[43] http://powerweb.grc.nasa.gov/pvsee/programs/thinfilm/tfg_thinfilm.html
[44] H. Guo and A. Lal, "Nanopower Betavoltaic Microbatteries," *Digest of Technical Papers, Transducer 03*, Vol. 1, pp. 36–39, 2003.
[45] A. Lal, R. Duggirala, and H. Li, "Pervasive Power: A Radioisotope-Powered Piezoelectric Generator," *IEEE Pervasive Computing*, Vol. 04, no. 1, pp. 53-61, January-March 2005.
[46] http://www.vimpa.org
[47] G. Vandevoorde and C. Puers, "Wireless energy transmission for stand-alone systems: a comparison between low and high power applicability," *Sensors and actuators*, A 92 (2001), 305 – 311.
[48] T. Shibata, Y. Aoki, M. Otsuka, T. Idogaki, and T. Hattori, "Microwave Energy Transmission System for Microrobot," *IEICE Trans. Electron*., Vol. E80-C, no.2, p. 303, February1997.
[49] G.A. Landis, "Mars Dust Removal Technology," *AIAA Journal of Propulsion and Power*, Vol. 14, No. 1, 126-128, January 1998.
[50] K. Ramanathan, J. Keane, and R. Noufi, "Properties of High-Efficiency CIGS Thin-Film Solar Cells," *31st IEEE Photovoltaics Specialists Conference and Exhibition*, Lake Buena Vista, Florida, USA, January 3-7, 2005.
[51] K. Ohata, K. Maruhashi, M. Ito, and T. Nishiumi, "Millimeter-Wave Broadband Transceivers," *NEC Journal of Advanced Technology*, Vol. 2, No. 3, 2005.
[52] P. Valdastri, P. Corradi, A. Menciassi, J. Seyfried, and P. Dario, "Micromanipulation and Communication Issues in a Swarm Microrobotic Platform," unpublished.
[53] C. Giori and T. Yamauchi, "Space radiation resistant transparent polymeric materials," *NASA contractor report CR-2930*, December 1977.
[54] D.L. Edwards, W.C. Hubbs, D.J. Willowby, M.F., Piszczor, and M.L. Bowden, "Space Environmental Effects on the Optical Properties of Selected Transparent Polymers," *1997 ASME International Solar Energy Conference,* ASME G01050, pp. 199-204, April 25-30, 1997.
[55] D.P. Tsakiris, M. Sfakiotakis, A. Menciassi, G. La Spina and P. Dario, "Polychaete-like Undulatory Robotic Locomotion," *Proceedings of the 2005 IEEE International Conference on Robotics and Automation (ICRA 2005)*, pp. 3029-3034, Barcelona, Spain, April 18 - 22, 2005.
[56] M. Confente, C. Cosma, P. Fiorini, and J. Burdick, "Planetary Exploration Using Hopping Robots," *Proceedings of the 7th ESA Workshop ASTRA 2002,* ESTEC, Noordwijk, The Netherlands, November 19 - 21, 2002.
[57] D.J. Coe, M.G. Allen, B.L. Smith, and A. Glezer, "Addressable micromachined jet arrays," *Technical Digest: TRANSDUCERS 95*, Stockholm, Sweden, 1995.
[58] G. Shah and M. Sitti, "Modeling and Design of Biomimetic Adhesives Inspired by Gecko Foot-Hairs," *IEEE International Conference on Robotics and Biomimetics (ROBIO)*, Shenyang, China, August 2004.