Final Report

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MICROBOTS FOR LARGE-SCALE PLANETARY SURFACE AND SUBSURFACE EXPLORATION

Prepared for:

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ABSTRACT

This report presents a new mission concept for planetary exploration, based on the deployment of a large number of small spherical mobile robots ("microbots") over vast areas of a planet's surface and subsurface, including structures such as caves and near-surface crevasses (see Figure 1). This would allow extremely large-scale in situ analysis of terrain composition and history. This approach represents an alternative to rover and lander-based planetary exploration, which is limited to studying small areas of a planet's surface at a small number of sites. The proposed approach is also distinct from balloon or aerial vehicle-based missions, in that it would allow direct in situ measurement.

In the proposed mission, a large number (i.e. hundreds or thousands) of cm-scale, sub-kilogram microbots would be distributed over a planet's surface by an orbital craft and would employ hopping, bouncing and rolling as a locomotion mode to reach scientifically interesting artifacts in very rugged terrain. They would be powered by high energy-density polymer "muscle" actuators, and equipped with a suite of miniaturized imagers, spectrometers, sampling devices, and chemical detection sensors to conduct in situ measurements of terrain and rock composition, structure, etc. Multiple microbots would coordinate to share information, cooperatively analyze large portions of a planet's surface or subsurface, and provide context for scientific measurements.

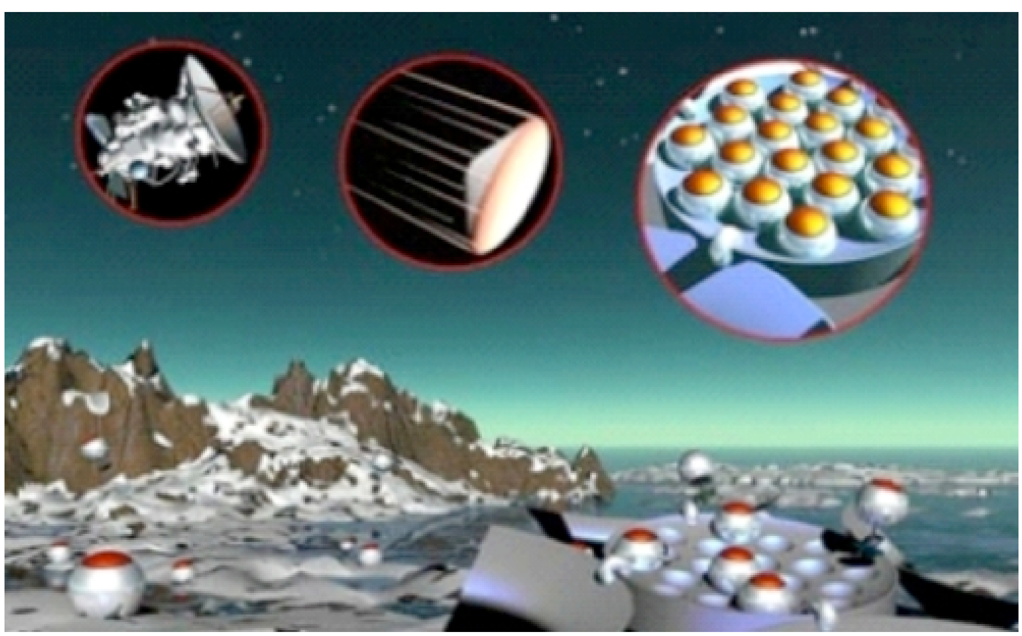


Figure 1. Microbot planetary surface and subsurface exploration concept

1. ADVANCED CONCEPT DESCRIPTION

1.1 Motivation and System Overview

1.1.1 *Motivation*

Scientific Rationale

Scientific study of many interesting extraterrestrial rocky and icy objects (planets, moons, and small bodies) requires access to rough terrain. Present wheeled rovers such as JPL's Sojourner, MER, and the planned MSL are not well suited to extremely rough terrain, since each rover is too precious to risk entrapment, and since the rovers are not designed to access highly sloped or uneven surfaces. The development of a system of small, hopping microrobotic units proposed here would allow access to very cluttered, sloped, and rough terrain. Such a system would enable a new systematic program of Solar System-wide exploration, mapping, and scientific study of geological, geomorphological, and potentially biologically significant sites. Such a system would be useful in many extraterrestrial environments. Planetary targets would include Mars, icy moons, rocky moons (including Earth's natural satellite), high temperature bodies such as Venus and Io, and asteroids. Our report will focus on a few representative challenging environments that are of high scientific interest among the planetary and astrobiology communities [1]. These include icy terrains on polar Mars and various gas giant moons, rough and high vertical relief landscape, and caves or other subsurface access [2].

Terrains of Scientific Interest

The ability of microbots to access rugged and subsurface terrain opens a wide spectrum of potential mission targets. Described below are some of the most scientifically significant of these targets and the extraterrestrial bodies that are known to possess such features (or for which there is reason to believe that such features may be found).

- *Surface Targets (i.e. rough and large vertical relief terrains)*

  Such targets include lava flows, chaotic or fractured terrain, cliffs, rock overhangs, tafoni, impact fracture fields, and dunes. Extraterrestrial bodies containing these targets include Mars, the Moon, Venus, and various asteroids. Such targets are valuable since rough terrain can trap drift materials, provide potential protected microhabitats for possible microbial life, and provide information on the geomorphological, volcanic, tectonic and hydrological history of the area. A selection of these terrains on Earth and other planets can be seen in Figure 2.

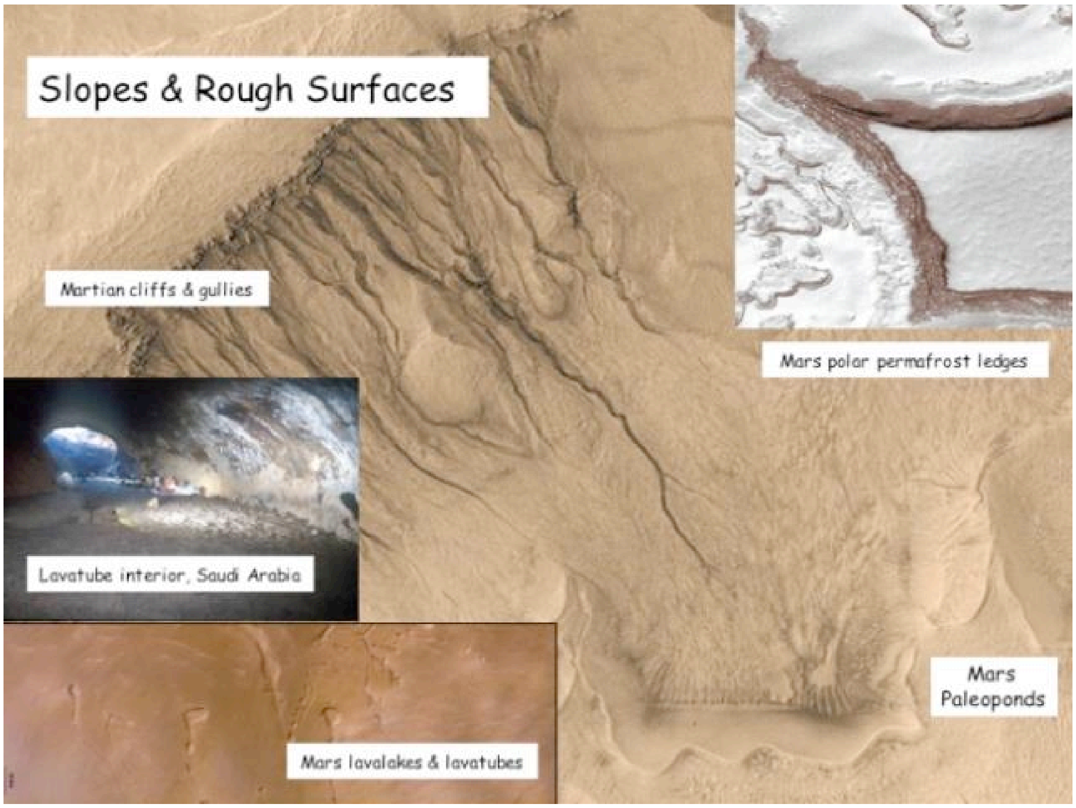


Figure 2. Background image of "weeping slope" and ponds at the base of Newton Crater, Mars (Malin Space Sciences image). Upper right shows steeply layered Martian polar lobes of possible permafrost (Malin Space Sciences image). Central left shows view of interior of Hibashi Cave, a lavatube in Saudi Arabia (image by John Pint). Lower left image acquired by the European Space Administration's Mars Express mission provides clear evidence of large lavatubes flowing from lavalakes on Martian volcanic flanks.

- *Subsurface Targets (i.e. caves and down-borehole deployments)*

Such targets include lavatubes, ice caves, and artificially drilled boreholes. Extraterrestrial bodies containing these targets include Mars, the Moon, Venus, and Io (for lavatubes), icy caves in Martian poles, icy moons, and possibly comet interiors (for ice caves). Boreholes might be drilled on any planet or moon.

These targets are valuable since natural caves and other subsurface voids can provide a radically different set of conditions than the overlying surface [3]. Such areas can serve as a repository for trapped materials from a planet's past (see Figure 3), and can yield materials that may shed light on past climate history [4,5] and past solar activity [6].

They can also provide a suite of environments for an enormous diversity of extremophile organisms [7], and have been suggested as the last refuge of life on planets like Mars where surface conditions have become significantly less hospitable to life over geological time [8]. As mineralogical "factories," the minerals whose formation they nurture are unparalleled in abundance and variety [9].

We have clear evidence of lavatube caves on the Moon, Mars, Venus and the Jovian moon Io (see Figure 4) [2,10]. In addition, consideration of the basic physics, chemistry, and temperature regimes of different bodies enables us to predict likely cave types and novel void-creating mechanisms that remain to be discovered elsewhere in the Solar System [2].

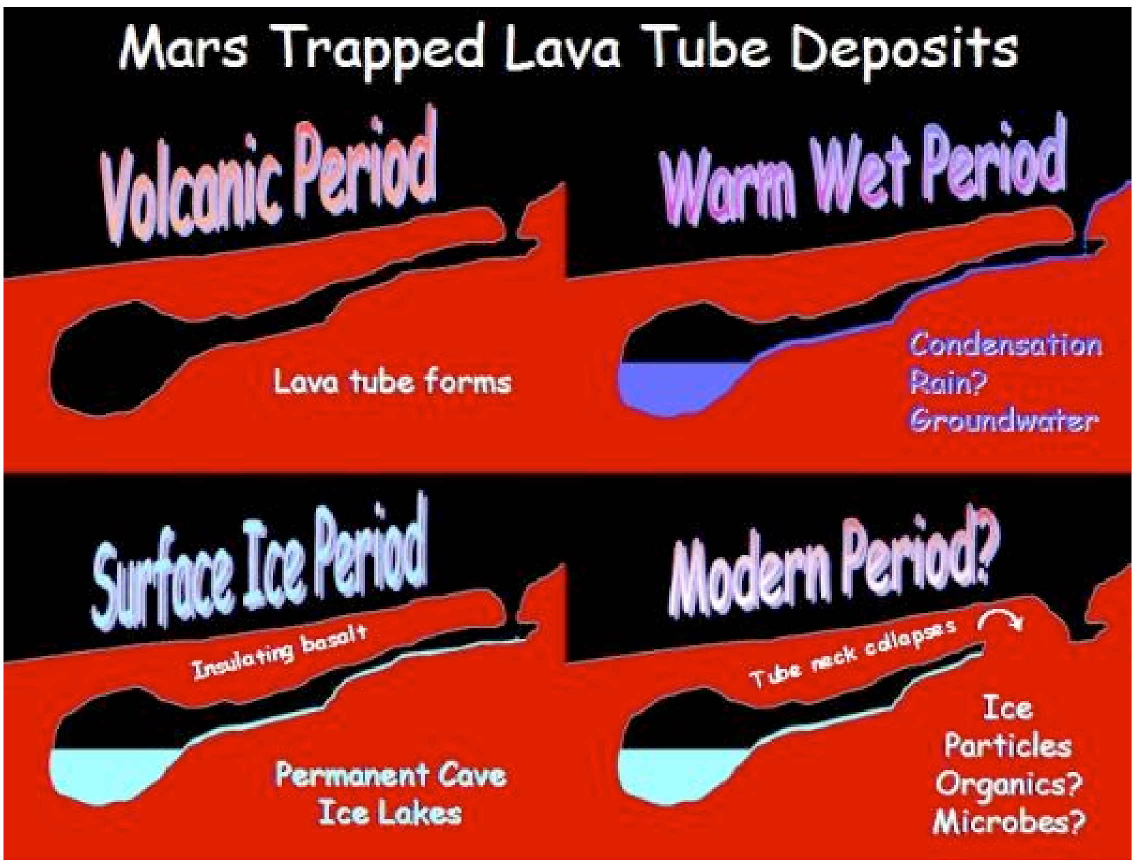


Figure 3. It is plausible that some of the tremendous number of lavatubes evident on the Martian surface are serving as time capsules for ices, trapped particles, organic compounds, and perhaps evidence of organisms from the earlier, more hospitable era of Mars' past [11]. A few billion years ago, during the most active shield volcano period, tubes formed which might have collected groundwater or precipitation. During the following several billion years of gradual cooling and drying, permanent ices may have formed and been trapped by subsequent collapse of entrance features, a common occurrence

in terrestrial lava tubes. Such sealed tubes might contain a wealth of scientifically important material.

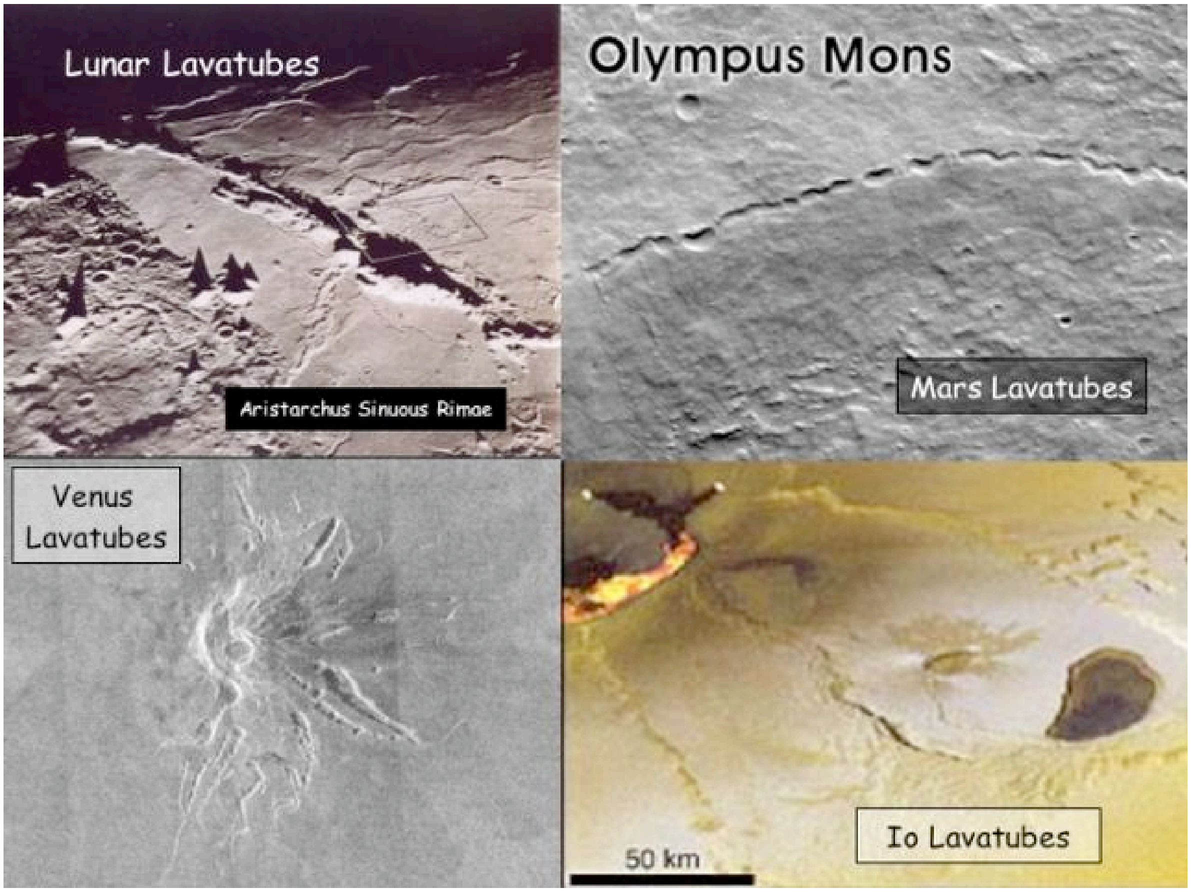


Figure 4: The identity of lunar features as ancient lavatubes was recognized during the Apollo era [10]. Viking images from the mid 1970's and the recent series of imaging missions around Mars reveal that Mars has abundant tubes distributed everywhere on the flanks of its volcanoes [2]. An examination of radar images from Venus is also showing us the numerous features that appear to be lavatubes on that planet (Boston et al., unpublished data). The Galileo Mission images from the moon Io, currently the most volcanically active body in the Solar System, also show probable tubes formed from the rapid resurfacing and active sulfur-rich volcanic activity.

- *Icy Surface Targets*

  Such targets include polygons, cryoconites, non-thermal meltwaters, and fissures. Because icy moons are so prevalent in the Solar System, this major class of objects is of great scientific interest. Icy surfaces on Earth exhibit unique and complex three-dimensional structures often collectively called "periglacial terrain" [12]. This landscape type is composed of ice features, compacted snows, and permafrost (permanently frozen soils). At Earth's poles and at the flanks and advancing glacier fronts, there are examples of permanent and transient ice caves. Examination of the rugged surface terrain of the Jovian moon Europa and Ganymede shows the challenges to be faced in surface exploration of these bodies (see Figure 5). Microbot teams can provide access to these terrains for exploration and science that will be difficult to achieve by other methods.

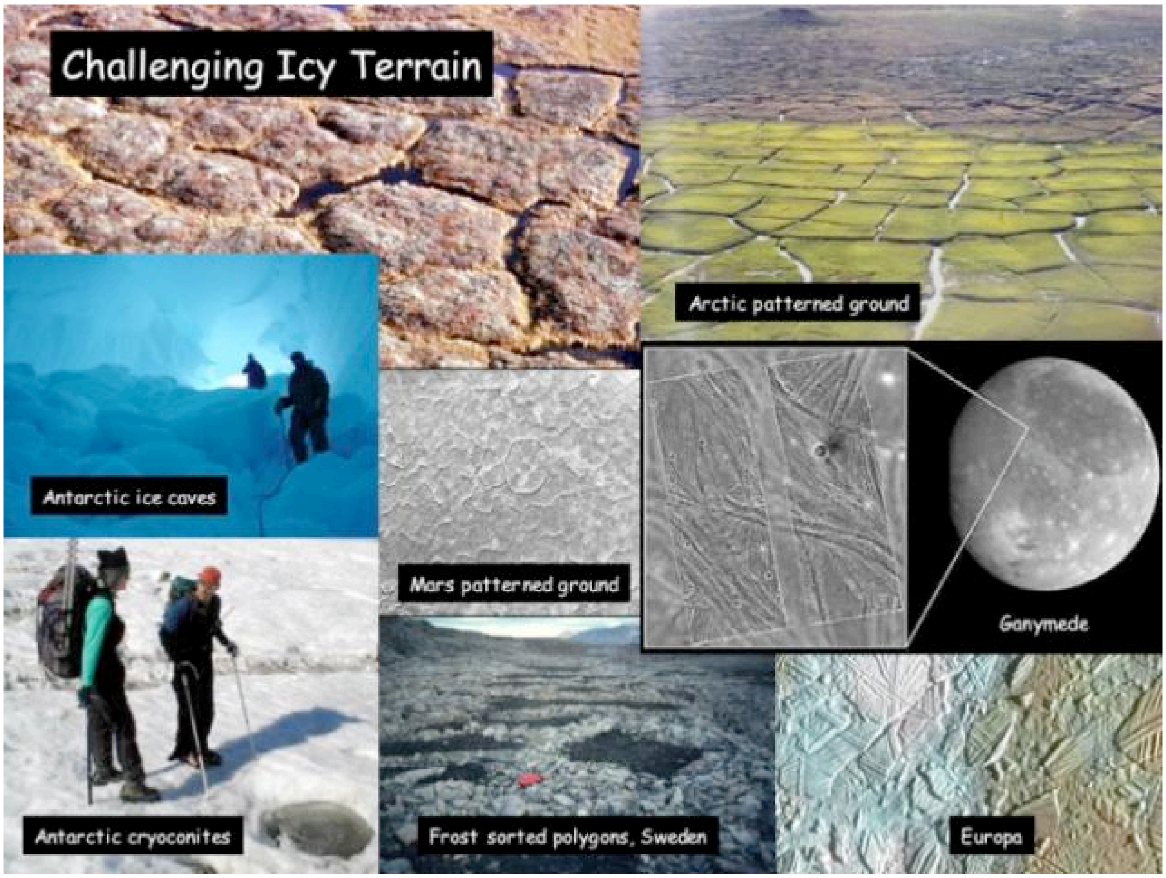


Figure 5. Ice (both water, CO2, and possibly others) appears to be a common building material for bodies in the outer Solar System. Patterned ground, produced by freeze/thaw cycles and frost-heaving is well known on Earth (top two images), and clearly visible on Mars (center image). In the cracks of this terrain, blown in materials accumulate and transient melting of water provides a biologically rich and protected environment in these small fissure features. Permanent ice caves in Antarctica and fumarole pillars recently discovered (P. Kyle, pers. comm.) are also inhabited by various cyanobacteria and other microorganisms. Cryoconites (shown in lower left image) are meltwater holes caused by selective solar heating of dark albedo particles or small objects on ice surfaces [13]. These features become oases for many types of microscopic and microinvertebrate life [14]. Their dark color enables them to be self-perpetuating habitats over long periods of time. Such features are currently below the resolution of imaging on orbital planetary missions but would be prime targets for microbot exploration.

1.2 System Overview

The proposed mission concept is based on the deployment of a large number (hundreds to thousands) of cm-scale mobile robots ("microbots") over very large areas of a planet's surface and subsurface. A microbot is a self-contained spherical robot equipped with power and communication systems, a mobility system that enables it to move via hopping, rolling, and bouncing, and a suite of miniaturized sensors such as imagers, spectrometers, and sensors for chemical analysis (see Figures 6 and 7). With advanced power, locomotion, sensing, and computation technology, we expect that microbots would be on the order of 10 cm in diameter and approximately 100 g or less in 10 to 40 years.

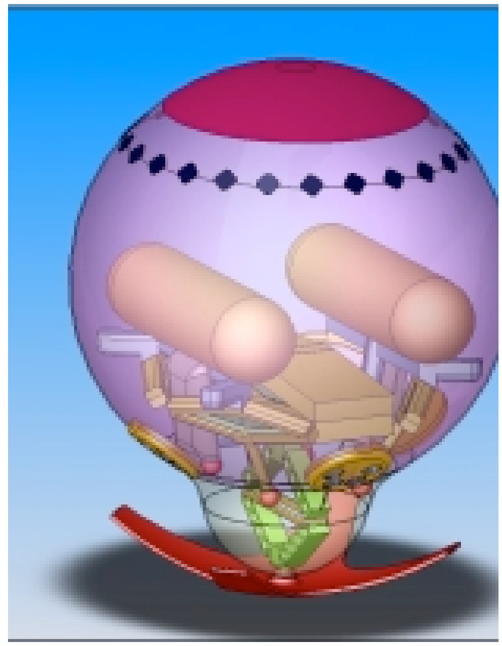


Figure 6: Microbot conceptual design

Multiple "teams" of hundreds to thousands of microbots would be distributed over a planet's surface by a landing craft (see Figure 1) or aerial vehicle, such as a balloon. Microbot teams could also enter caves through surface vents. They would move by a combination of hopping, rolling, and bouncing, an effective method for small devices in low gravity [15]. This locomotion mode would allow microbots to travel through extremely rough terrain and access sites of interest that are beyond the reach of ordinary rovers and orbital or aerial platforms.

Figure 7. Artist's concept showing potential microbot scale

They would transmit science data via low-power communication to their lander platform or to an orbiting spacecraft, which would then relay the data to Earth. This approach would allow large-scale in situ analysis of surface and subsurface characteristics. Individual microbots would cooperate autonomously to share information, collaboratively explore science targets, and relay commands and data in caves. Since many microbots would be deployed, the overall system would be highly redundant and robust. The resulting mission would allow planetary scientists to gather detailed data about surface and subsurface properties that span large geographical areas.

1.2.1 *Reference Mission Description*

The microbot system concept is designed for surface and subsurface exploration. Here, a Surface Reference Mission and a Subsurface Reference Mission are described. These reference missions are intended as representative, realistic scenarios that can be used to study the potential feasibility of the microbot concept.

• *Surface Reference Mission*

The Surface Reference Mission assumes exploration of a body having solid terrain (i.e. not watery or with a vaporous atmosphere). The terrain is assumed to be very rough, consisting of dense rock distributions, steeply sloped terrain features such as gullies and escarpments, loose drift material with hazardous mobility characteristics, and small-scale unevenness caused by small rocks, pebbles, etc. Such terrain is often of primary interest to planetary scientists, as described in Section 2.1.1, due to the possibility of exposed volatiles in the wind or water-formed geological features. The range of conditions for this reference mission are:

- Effective terrain coefficient of restitution ranging from 0.1 to 0.5. This range roughly corresponds to highly deformable terrain (such as sandy soil) to rigid terrain (such as rock);
- Effective terrain traction coefficient ranging from 0.1 to 0.4. This range roughly corresponds to soft, slick terrain to high-friction terrain;
- Obstacle density of 20 obstacles/m^2 [23], with an obstacle defined as an object (such as a rock) greater than 1.5 m in maximum elevation.

Tge target for the Surface Reference Mission for a team of 1000 microbots are a 30 day average microbot life span and a 135 km^2 (50 square mile) coverage for each team.

• *Subsurface Reference Mission*

The Subsurface Reference Mission assumes exploration of a cave-like subterranean region formed by volcanic action (i.e. a lava tube cave). The cave floor is assumed to be relatively flat in its interior due to the nature of its volcanic formation. Near surface entrances, rubble from collapsed rock formations that created the entrances would have been leveled by layers of sediment that might have accumulated over million (or even billions) of years [15]. The cave profile will contain both inclined and declined slopes that the microbots will be required to traverse. The Hibashi cave in Saudi Arabia has been identified as an Earth cave that possesses similar qualities to caves on bodies such as Mars [17] (See Figures 8 and 9).

Figure 8. View of Hibashi cave looking outward toward an entrance

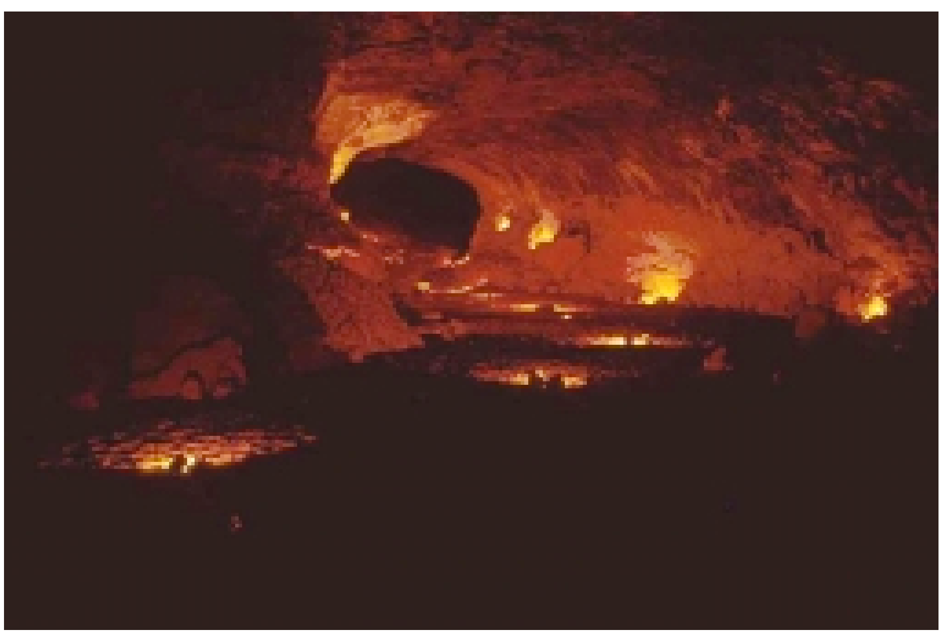


Figure 9. Hibashi by candlelight showing the cave's relatively uniform cross-section

The following range of conditions for this reference mission are:

- Terrain coefficients of restitution and traction similar to the ranges defined for the Surface Reference Mission (see above) with a maximum cave floor slope of ±45°.

System design targets for the Subsurface Reference Mission for a team of 100 microbots are a 20 day average microbot life span and a 1 km maximum microbot penetration into the cave, while maintaining communication with the surface.

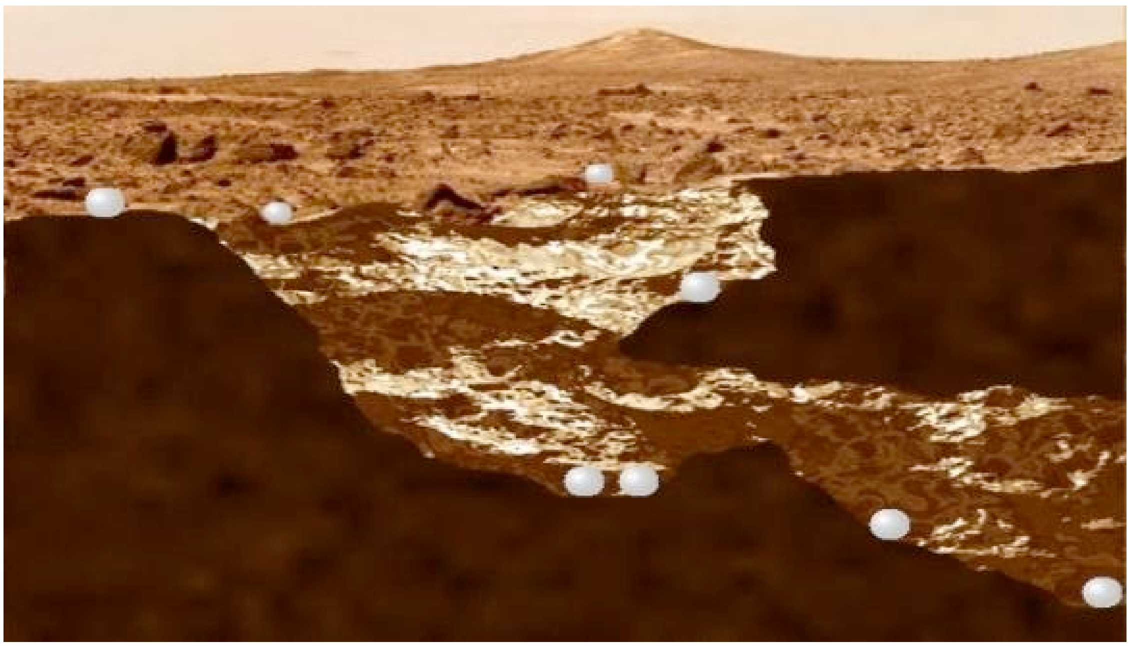


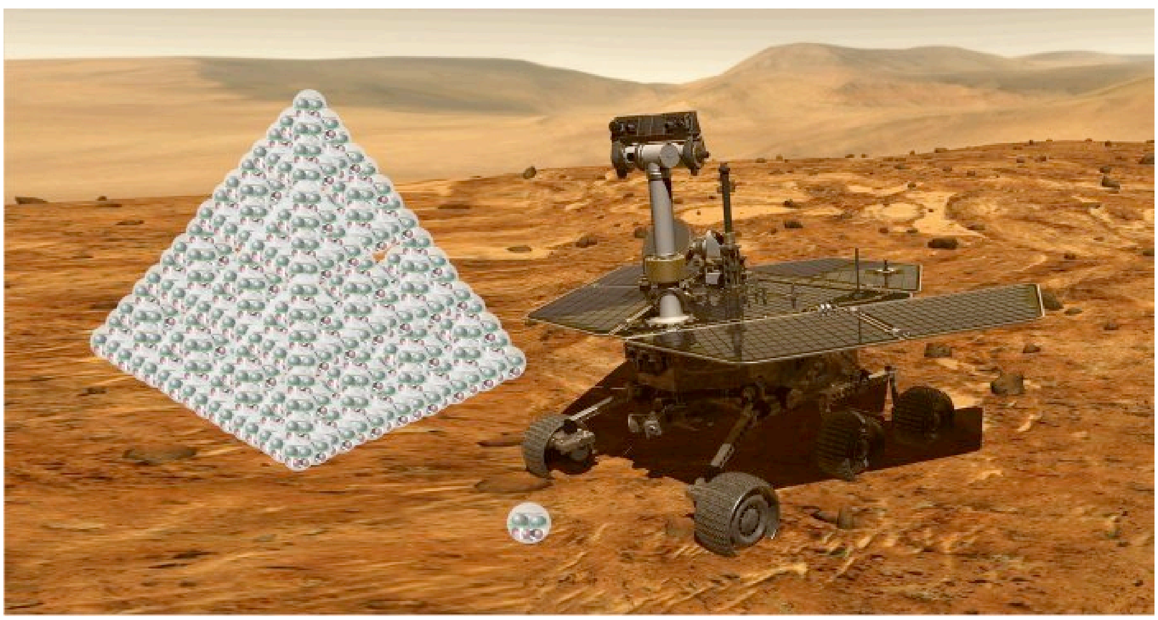
Figure 10. Illustration of microbots (shown in white, with scale exaggerated) entering a lavatube-like cave.

1.2.2 *Microbot Landing and Deployment Systems*

The mode of microbot delivery to a planetary surface is important, since it determines the initial distribution of both microbot teams and individual units. Three strategies deserve consideration.

The first strategy uses a landing mode similar to that employed in the Mars Pathfinder and Mars Exploration Rover missions [18]. This approach has been successfully demonstrated on Mars. For a microbot mission the specifications for parachute deceleration and airbag cushioning could be relaxed since microbot's shells could be designed to be moderately impact resistant. Tolerance to impact velocities would allow landings at higher planetary elevations for parachute-based entry methods, since for high-elevation landings there is less entry vehicle deceleration due to atmospheric drag, and thus impact velocities may be higher. The ability to land at high elevations would allow access to a higher percentage of the planet's surface. In this landing approach, many microbots would be deployed from a single landing platform.

A second strategy is similar to the one described above, but with multiple, small entry vehicles. This would permit a single mission to either investigate several widely-spaced target sites simultaneously, or deploy multiple teams over several kilometers at a single site. The optimal team size for maximum scientific return is likely to be on the order of hundreds of microbots per site. Roughly one thousand microbots could be launched in the same volume and mass as a MER rover [18] (see Figure 11). This group could be split into several teams of optimal size that land separately and thereby study several diverse regions during a single mission.



1000 Microbot Team - Height 1.5 m, mass 150kg
Exploration area: 50 km^2 with dense coverage

MER Sprit - Height 1.5 m, mass 174kg
Exploration area: less than 1 km^2 – with single path coverage

Figure 11: Comparison of MER rover and a 1000-member microbot team.

A third landing approach was inspired by Kerzhanovich and Cutts' analysis of the potential use of aerial robots for planetary exploration [19]. Studies have shown that a balloon-borne mission could last long enough in the Martian atmosphere to travel hundreds of kilometers. By eliminating a landing platform and instead dropping the microbots directly from a balloon, a wide initial distribution could be achieved (see Figure 12). This approach would also allow mission planners to select initial drop sites using aerial images taken by the balloon system. This could be a significant advantage for subsurface missions, where the team might otherwise have to travel considerable distances to locate a promising cave entrance. The main disadvantage to using a balloon as a final-stage entry vehicle is its susceptibility to wind. Wind not only affects the trajectory of the balloon, but might also increase the impact velocity of the microbots during drop. Clearly, balloons could not be used on bodies that have no significant atmospheres, such as the Moon.

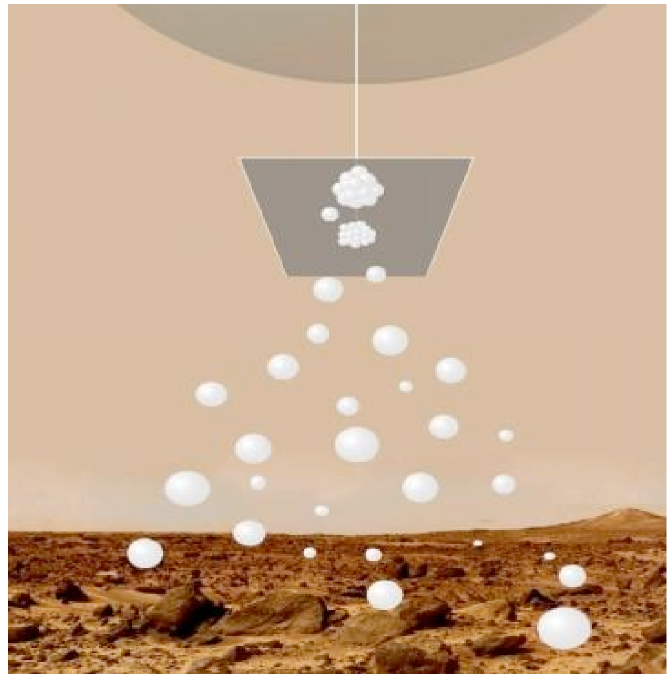


Figure 12: Microbot dispersal from an aerial platform

1.2.3 *Planetary Protection Protocol Issues*

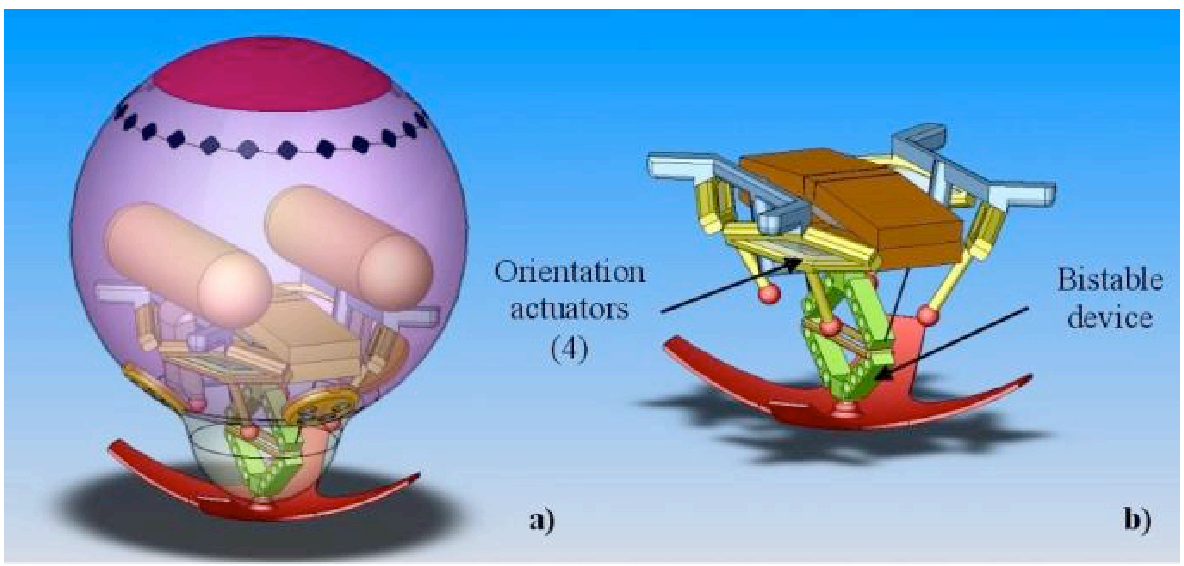
Protecting possible extraterrestrial biospheres from inadvertent contamination by Earth microorganisms is a major challenge facing exploration [20]. Large, complex landing devices are very difficult to sterilize. Since the Viking landers, where whole vehicle sterilization was accomplished, a reduced bioload of organisms is now achieved using clean-room techniques rather than absolute sterilization. Thus, on each of the recent MER landers sent to Mars the estimated buried bioload is about 200,000 microbial spores (R. Kern, JPL, pers. comm.) These spores are likely to remain dormant or be killed by the harsh Martian surface conditions; however, should this material gain access to the subsurface where conditions may be significantly more benign, they could constitute a contamination risk. The small and relatively simple structure of individual microbots units will facilitate more thorough efforts to reduce or eliminate the buried bioburden. Indeed, even envisioning future human missions to Mars, microbot units can be used for reconnaissance and data gathering in areas perceived to be potentially biologically sensitive, thus reducing human associated contamination threats to such sites.

2. DETAILED MICROBOT SYSTEM DESCRIPTION

Microbots are self-contained units, each with their own sensor suites, mobility mechanisms, power supplies, and communication systems enclosed in a lightweight polymer spherical shell.

2.1 Microbot Mobility

Basic microbot mobility is provided by a bi-stable mechanism activated by dielectric elastomer actuators. This mechanism enables the microbot to achieve mobility via directed hopping (see Figures 13 and 14). The microbot can also move by bouncing and rolling. In our current concept, the mobility mechanism is constructed of lightweight polymer materials. The microbot is weighted so that after one locomotion cycle of rolling and bouncing, it will return to a posture with its "foot" on the ground. A working prototype of the bi-stable jumping mechanism has been developed by our group at MIT. This is described in detail in Section 2.1.3.



a. Overview *b. Mobility Components*
Figure 13. A directional hopping mechanism

Microbots would be powered by a unique micro fuel cell concept developed in connection with researchers at Stanford University [21]. The low weight, high elastic energy storage capabilities of the bi-stable polymer actuators combined with the high energy/low weight of the micro fuel cells results in a mobility system with outstanding characteristics for this application. Estimates of the anticipated parameters for a microbot are given in Table 1.

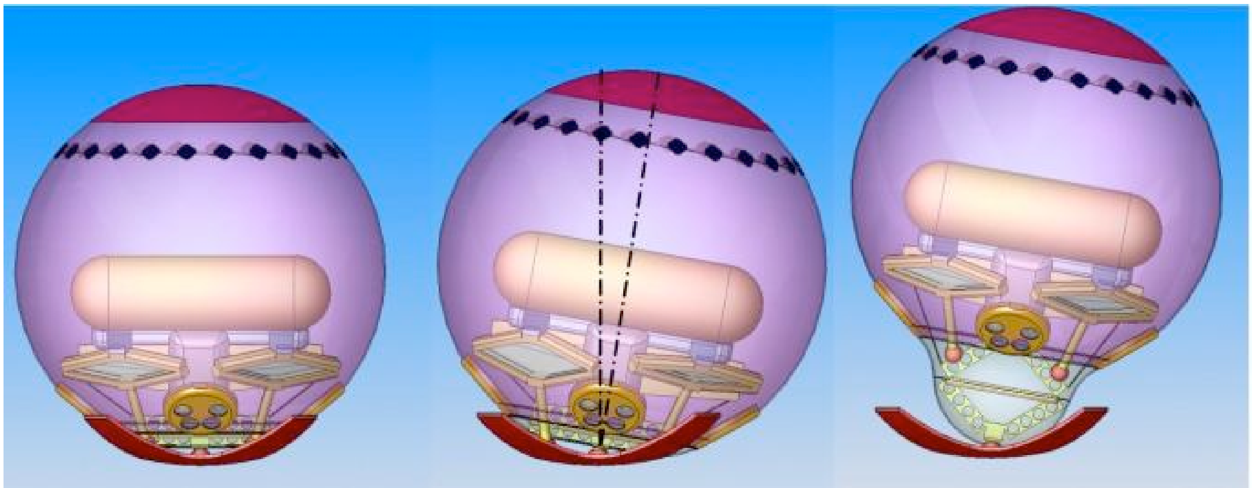


Figure 14. Changing the attitude of the microbot using the directional hopping mechanism concept.

Table 1. Anticipated Microbot Parameters

Mass (total)	100 g
Diameter	10 cm
Hop height (Mars)	1.5 m
Distance per hop (Mars)	1.5 m
Average hop rate	6 hops/hour
Maximum hop rate	60 hops/hour
Fuel use	1.5 mg/hop
Peak power supply output	1.5 Watt

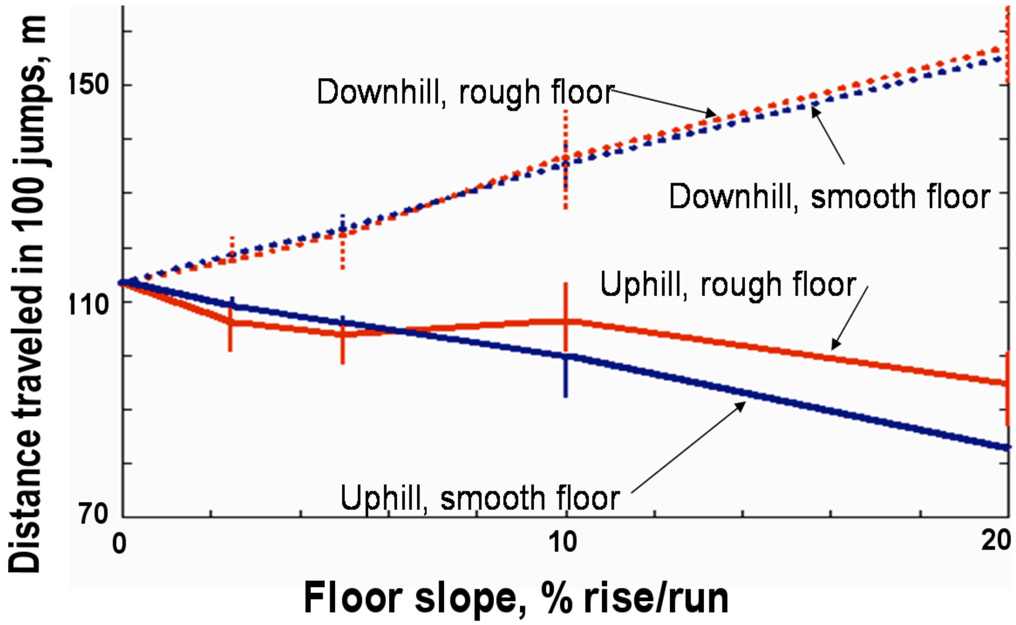
2.1.1 *Surface Mobility Analysis*

Microbots have the ability to quickly traverse rough terrain using a combination of hopping, bouncing, and rolling. This type of locomotion would allow a microbot to hop over obstacles many times its own diameter. This concept has been considered for robot mobility in the past [22]. However the proposed fuel cell/polymer actuator mobility system has an energy-to-weight ratio sufficiently high to provide a new perspective on the concept. Although the path traveled by a microbot is uncertain in nature due to the unpredictability of bouncing, the method is very energy efficient in obstacle-dense terrains that preclude straight-line paths. Thus general surface motion would appear somewhat random (i.e. Brownian) in nature.

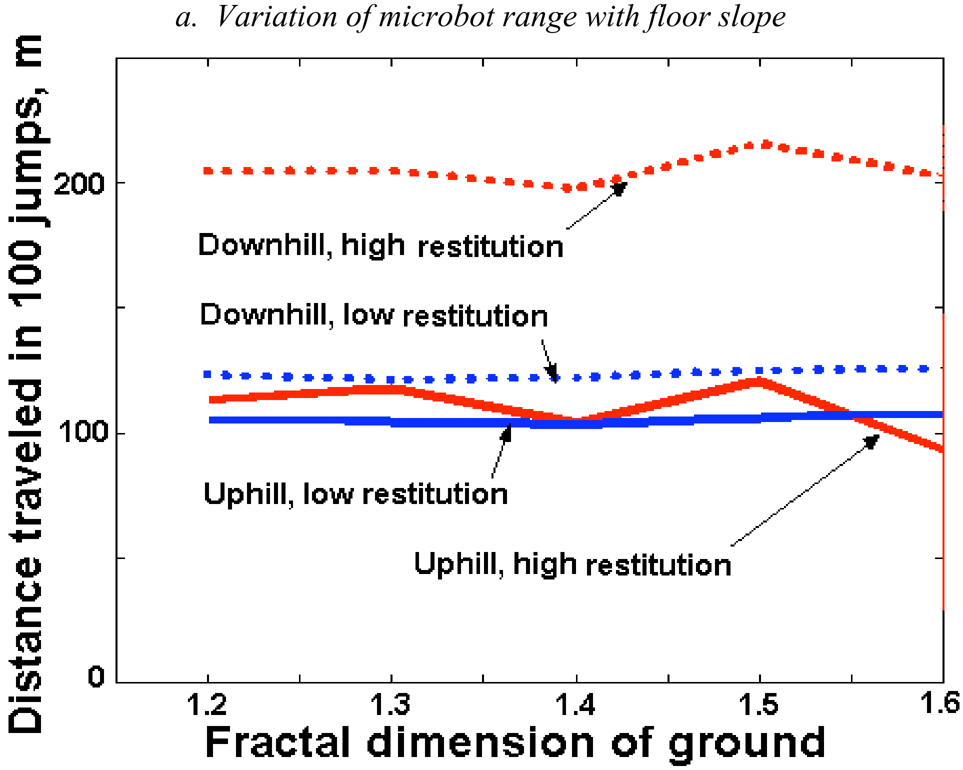
Fundamental microbot locomotion characteristics have been studied using simple models of microbot dynamics and microbot-terrain interaction. Preliminary analysis shows that a microbot should be able to leap up to 1.5 m high and 1.0 m horizontally under Martian gravity, sufficient to surmount an obstacle of one meter in diameter (see Table 1). Analyses of the Viking and Pathfinder landing sites by Golombeck and Rapp [23] indicate that boulders on Mars larger than 1 m diameter are rare. Thus a jumping microbot could overcome all but the largest obstacles on the Martian surface without the need for complex route planning. This would permit the exploration of challenging or obstacle-filled terrains that would be difficult or impossible for a conventional rover, including caves and other subsurface features.

Simulations and experiments have shown that microbots can climb slopes covered in sand or loose gravel up to the material's natural angle of repose. Figure 15a shows a plot of the predicted distance traveled uphill and downhill by a microbot team on terrain with average slopes up to twelve degrees. Note that the microbot maintains stability on sloped terrain by "digging in" to the deformable terrain surface. Very steep inclines or rock shelves would be treated as obstacles, and leaped over if sufficiently small. For a conventional rover with wheels or legs, the limiting factor determining the maximum traversable slope is either the initiation of tip-over or soil failure. The low center of gravity of the microbot makes it resistant to tip-over, and its spherical geometry ensures that even if tip-over occurs the microbot will merely roll a short distance and naturally right itself. In addition, many surfaces on Mars are covered with extensive deposits of sand or dust. Simulations suggest that a microbot could climb steeper slopes in this type of terrain than it could on bare rock (this is captured in the "smooth floor" vs. "rough floor" comparison).

Monte Carlo simulations have been performed to study the influence of other terrain conditions on microbot mobility. Expected surface properties are described in our Surface Reference Mission (see Section 1.2.1). Surface coefficients of restitution, traction parameters, slope, and obstacle density were observed to have a moderate influence on rate of travel (±40 % over the baseline 1.0 m per jump), with slope having by far the largest influence..



a. Variation of microbot range with floor slope



b. Comparison of microbot range with high and low coefficients of restitution versus terrain roughness

Figure 15. Variation of microbot range with environmental parameters

Figure 15b shows that surfaces with high coefficient of restitution (corresponding to solid rock or packed soil) increases the distance traveled via bouncing. For example, on a modest slope of five degrees, the average rate of travel downhill on a rock-like surface was 2.1 m per jump compared to 1.1 m per jump for a sand-like surface, but the uphill rate of travel varied from 0.5 to 1.5 m per jump on rock versus 1.0 m per jump on sand, depending on the slope. Figure 15b shows that microbot travel is relatively insensitive to terrain roughness (indicated by the fractal dimension) due to its hopping mode of locomotion. Variations in the soil traction characteristics had little noticeable effect on bouncing, but low traction led to some energy loss during the jumping process and reduced directional control. The main difficulty posed by steep slopes is the possibility of rolling downhill, which is relatively unlikely on deformable materials such as sand, but can retard uphill travel on bare rock

The effect of large obstacles on microbot mobility is another area of concern. It was found that if rocky obstacles are widely spaced a microbot would be able to travel normally by leaping around or over the obstacles. However, if rocks are close enough to touch and form small crevasses and gaps, there is a chance the microbot will become wedged or stuck between rocks. Such a scenario requires an obstacle density greater than that seen at the Viking 2 site, currently believed to have one of the highest rock densities on Mars [23].

Simulations of the potential area coverage of a microbot team showed that a team of microbots moving over representative surface terrain would spread over an area of nearly 50 square miles within 5000 hops. While these simulations are based on relatively simple models they suggest the feasibility of the microbot concept for large area surface exploration. The notion of “obstacle” is unique with respect to the innovative mobility of microbots. For a microbot, obstacles might be wedging points or a slope that would cause uncontrolled rolling, rather than a boulder (which would be an obstacle for a conventional rover).

Mission-planning algorithms that consider the random nature of a microbot’s rolling, hopping, and bouncing would be important for missions where it is necessary to reach a precise target area, such as the entrances to a system of caves. One conceptual microbot design (see Figures 13 and 14) would provide some directional control of the system’s hopping motion. There is a tradeoff in terms of “returned science” of providing the system with a higher degree of mobility and intelligence (i.e. obstacle detection and path planning) versus the penalties inherent in additional sensors and system complexity.

2.1.2 *Subsurface Mobility Analysis*

Microbots are designed to access subsurface terrain features such as lava tubes. The lava tubes selected as the Subsurface Reference Mission are expected to have entrances with diameters of several meters, leading to long caves with relatively flat, gently sloping floors with three types of surfaces: bare rock, accumulated wind-blown sediment, and "breakdown piles" of boulders that have fallen from the cave ceiling. A microbot team could travel freely on rock or sediment, advancing one to two meters per jump cycle as on surface terrain.

Mobility over breakdown piles is more challenging. Field studies have been performed in a lavatube cave system near Grants, New Mexico with physical microbot analogs to study mobility over breakdown piles (see Figure 16). These studies showed that the gaps between boulders in breakdown piles can lead to wedging and entrapment of some microbots. However, breakdown piles are features of relatively young lava caves, and it is believed that billions of years of dust deposition in planets such as Mars have buried the features that would be a serious hindrance to microbot travel [15].

As with the Surface Reference Mission, simulations have been performed to study microbot subsurface mobility over a wide variety of cave geometries and surface parameters (see an example in Figure 17). These simulation studies suggest that microbots would be able to move quite effectively in extraterrestrial lava tubes. In most cases a relatively small team of 50 to 100 microbots could penetrate the 1 km reference distance into the caves in 10-20 days, with the loss of relatively few team members. Sufficiently many members survived to establish the LAN network required to communicate with the surface.

While subsurface missions may initially appear more challenging than surface missions from a mobility point of view, our simulations have suggested that the defined structure of the expected caves makes the problems similar. For caves, communication issues (discussed in Section 2.2.3) are a more significant challenge.

Figure 16. MIT/NMT Team Field studies in lavatube cave

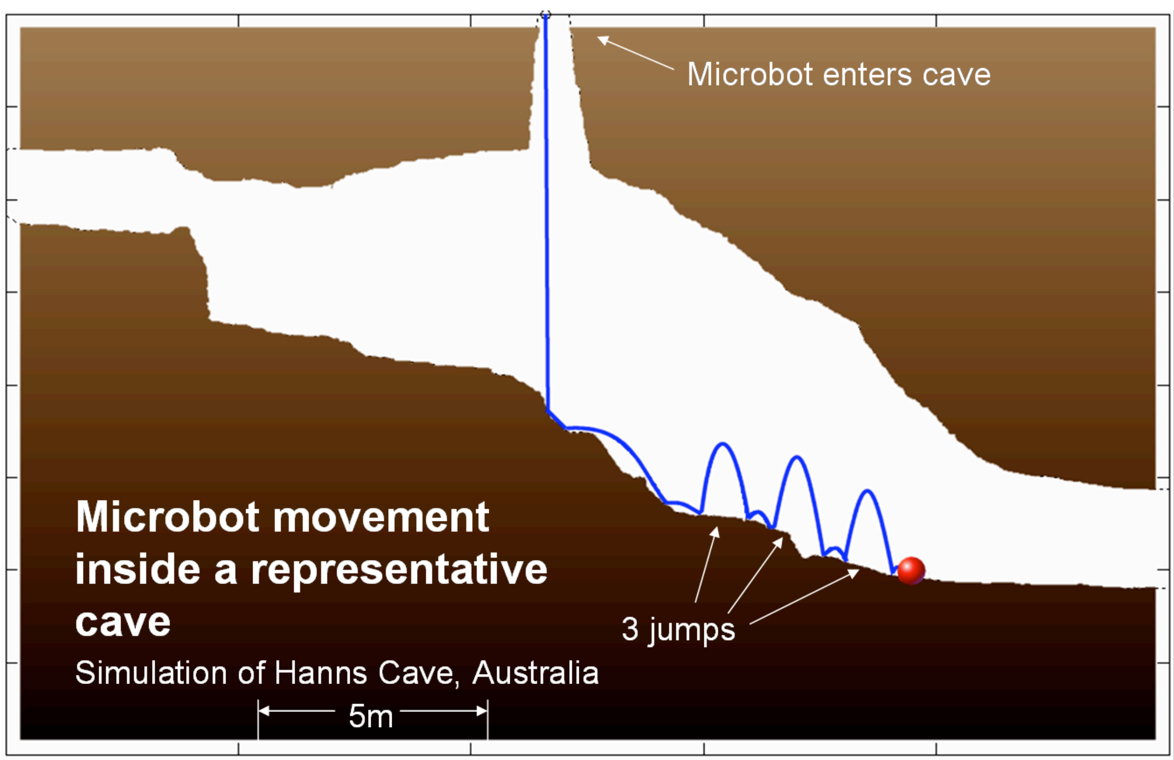


Figure 17. Subsurface simulation (microbot enlarged for clarity)

2.1.3 *Microbot Mobility Mechanism Design*

The microbot mobility mechanism will need to be simple, power efficient, robust, durable, reliable, and lightweight. It would be difficult to achieve such design objectives using conventional technologies such as motors, bearings, gear trains, and encoders, which can be heavy, complex, and unreliable. We propose a novel mobility mechanism based on dielectric elastomer actuators powered by hydrogen/oxygen fuel cells. Here the fundamental technologies related to microbot mobility are described.

Electroactive Polymer Artificial Muscles (EPAMs)

Electroactive polymer artificial muscles (EPAMs) have been shown to be potentially highly efficient, low cost, light weight, and inherently simple [24, 25, 26]. The operating principle of these actuators is based on the Maxwell (electrostatic) pressure generated by a strong electric field applied across a soft elastomeric material (see Figure 18). The compressive Maxwell pressure tends to generate expansion in the orthogonal directions in the film. Compliant electrodes are used to permit this motion. With current state of the art elastomers, the electrode area can expand up to 2.8 times its initial size during actuation [27].

If the film is incorporated into a compliant frame with appropriate preloading, as in Figure 19, the orthogonal expansion is converted into useful mechanical work. Linear strains of approximately 200 percent are possible with such a design [27]. When compared to

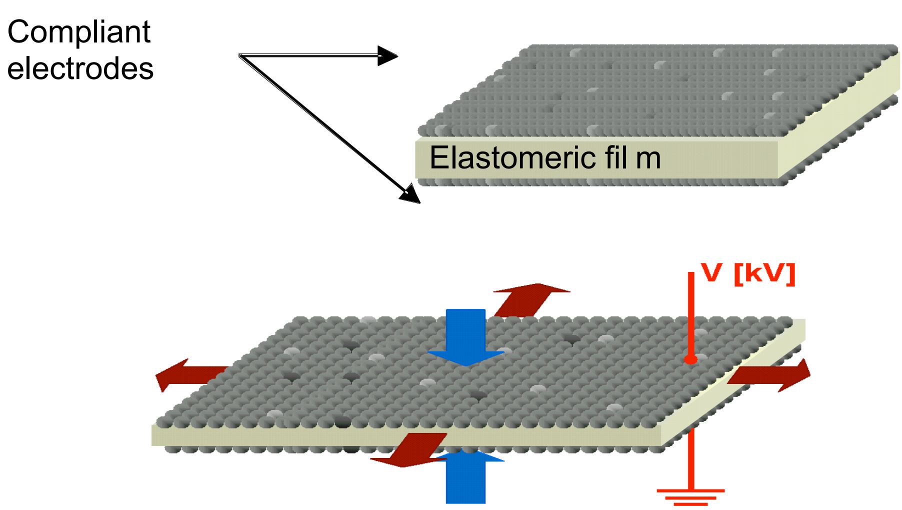


Figure 18:Dielectric elastomer actuator Operating principle

conventional DC motor/gearhead combinations, dielectric elastomer actuators contain 10 to 100 times fewer parts. Since they are all plastic, they are also much lighter than conventional actuators. Finally, since an EPAM's motion involves material deformation rather than sliding and rolling mechanical surfaces, close tolerances and lubrication are not required for good performance and durability. Hence, they are attractive potential actuators for the microbot mobility mechanisms.

Figure 19: Experimental dielectric elastomer actuator showing 200 percent strain.

One drawback of EPAMs is their relatively slow actuation time. To generate a hopping motion, energy must be released quickly [27]. In our work we have developed bi-stable EPAM actuators that allow energy to be stored ("charged") over time, then quickly released [28]. A schematic of the proposed mobility system is illustrated on Figure 20. In the charging phase (between states 1 and 2), the diamond-shaped EPAM actuator extends and stores energy in an over-the-center bi-stable mechanism. This bi-stable mechanism is composed of two beams that pivot about a common axis, and an extension spring. The mechanism reaches a stable configuration as the actuator nears the end of its stroke (state 3). Backlash in the interface between actuator and bi-stable mechanism allows the actuator to return most of the way to its initial position. Finally, at the end of its return stroke, the actuator delatches the bi-stable mechanism from its stable configuration, resulting in a rapid energy release suitable for hopping. A prototype microbot jumping mechanism based on bi-stable EPAMS has been developed. Figure 21 shows a series of photographs of one of these actuators jumping.

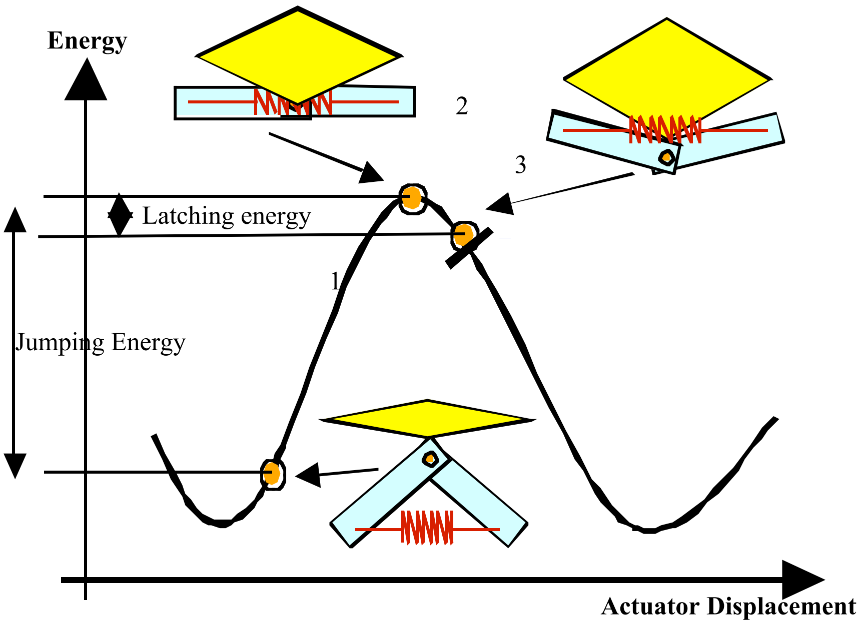


Figure 20. Indexing actuator mobility system concept. (The diamond actuator opening indexes the mobility system events).

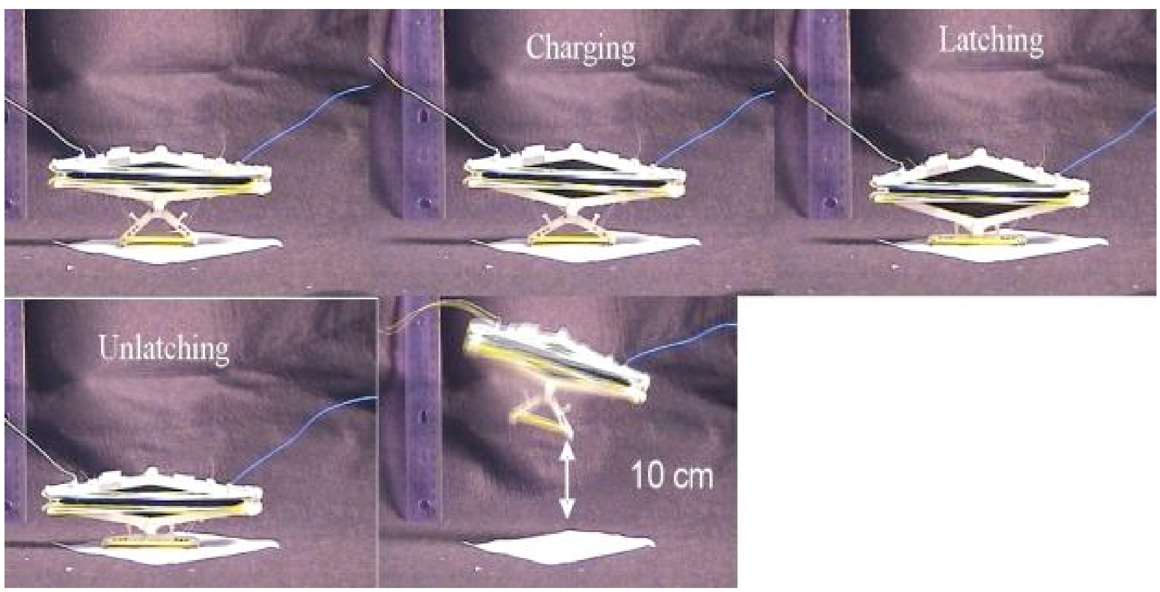


Figure 21: Sequence of images of the indexing actuator prototype performing a jump. The total cycle time is about 20 seconds.

Micro fuel cells are promising energy sources to power EPAMs. Fuel cells will produce large amounts of energy, but slowly (i.e. at low power rates). The EPAM would store this energy in its elastic elements as it "charges" its hopping mechanism. The mechanism can then release this energy quickly during the hop. Since the required hopping rate of the microbot (as defined by the two reference mission requirements) is roughly one hop per minute, the fuel cell is able to meet the energy requirements without requiring high power rates.

2.2 Communication and Control

2.2.1 *Communication*

Both surface and subsurface exploration missions will require microbot teams to establish a robust communications network. For example, each microbot will need to communicate science data to a central unit, such as the lander, for relay to orbit or earth. Microbots will also need to transmit information regarding their position and surrounding environment either to the surrounding team, or to a central unit so that mission targets can be updated (see Figure 22). Neighboring microbots might also need to share navigational information such as obstacles or terrain features. From a communications perspective, microbots that are trapped in a terrain feature may still perform useful roles as information relays and repositories.

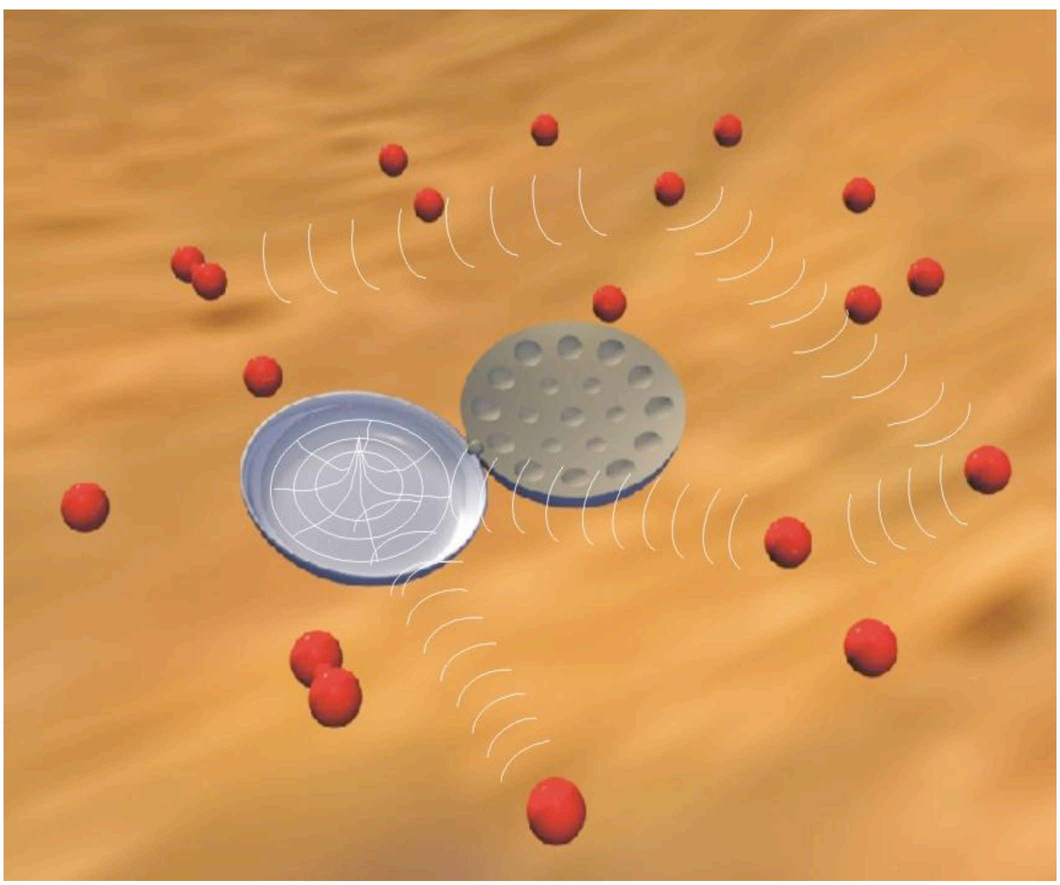


Figure 22. Illustration of surface communication scenario.

In the case of subsurface exploration, non-line-of-sight communication is difficult due to rock absorption of radio signals. Here individual units could be used to create a "trail of breadcrumbs" LAN to allow communication back to the surface. In order to achieve such communications, each microbot would need to be equipped with a reliable and relatively low power transmission/receiver system, with the transmission band appropriately selected based on the mission.

2.2.2 *Surface Communications*

The Surface Reference Mission requires an exploration area of 135 square kilometers (50 square miles) by a team of 1,000 microbots. In this scenario, the average communications distance between microbots is approximately 6.5 km. A high frequency radio (in the GHz range) would meet this mission's requirements, with the benefits of a small transmitter/receiver size and low power consumption. Typical cellular phones utilizing bandwidths between 0.9 and 1.8 GHz can communicate within cell sizes of 1 to 5 km [29], with output power of 100mW and antenna gain of 45.5 dB. Alternately, communications systems at 31 GHz with transmitted power of 50 mW and antenna gain of 35 dB have been demonstrated in a 9 km point-to-point (i.e. line-of-sight) communication system [29]. However, these high frequency signals are more susceptible to attenuation from the atmosphere and intervening terrain features such as mountains, boulders, etc. A tradeoff between miniaturized dimensions and transmission range can be obtained if the bandwidth is chosen in the range between 1 and 35 GHz. Greater frequencies might be used to meet specific mission needs or particular terrain conditions.

A substantial percentage of the power consumption of high frequency radio transmitters/receivers is used by atomic clocks necessary to tune their RF frequency. MEMS-based atomic clocks with mechanical resonators are currently under development, and are expected to reduce power consumption by one order of magnitude, and size by two orders of magnitude [30]. This would make such communications hardware well within the requirements for the microbot concept in the NIAC 10 to 40-year time frame.

Other important issues in microbot communications are antenna type and size, and signal frequency. Miniaturized phased array antennas have been developed with approximate dimensions of 10 cm × 10 cm × 0.08 cm [31]. The antenna might be printed on the microbot shell with little increase to system weight and volume. Signal frequency determines the maximum data rate of the communications network. For the frequency range discussed above, the maximum data rate that can be achieved using current technology with mW order power outputs is approximately 10 Mbps [29]. This would be more than adequate for the proposed reference missions, if it is compared with current rover missions where communication of approximately 0.1Mbps is established with an orbiting craft.

2.2.3 *Subsurface Communications*

The main challenge in communications for a subsurface mission is establishing reliable communications from subsurface to surface. Due to radio wave absorption by rock, high power and very low frequency is required to communicate directly from subsurface to surface. A very large antenna would be needed for low frequencies, which makes this solution impractical.

At high frequencies the distance for reliable non-line-of-sight communication is small, preventing direct subsurface-to-surface communications via the cave entrance. A solution to this problem is to use the microbot units as communications network to relay communications back to a central unit on the surface via the cave entrance, where it could be relayed back to Earth or to orbit (see Figure 23). Some of the microbots would be programmed to stop at various penetration distances into the cave. These microbots would act as relay communications nodes of the network. Based on experimental results in terrestrial caves, non-line-of-sight wireless communication at a bandwidth of 2.4 GHz is possible up to distances of approximately 20 meters [32]. A simulation-based analysis of microbot subsurface communications showed that approximately 50 microbots acting as relay nodes could gain 1 km penetration distance, while establishing a communication network with the surface.

2.2.4 *On-Board Data Processing*

Each microbot will gather scientific data that needs to be ultimately returned to Earth. It is expected that each microbot could gather several Mbits of data per day. In addition, microbots will need to relay data and command information from other team members. Considering an entire team of microbots, this could become a very large volume of information. Therefore, it is crucial for microbots to possess on-board data processing and data reduction capabilities to minimize the amount of information exchanged. An example of current miniaturized on-board data processing systems indicates that several Mbps of data can be processed within a volume of 12 cm^3, mass of 10 g, and power of 500 mW [29] (Figure 24a). It is reasonable to believe that next generation devices could improve further these numbers.

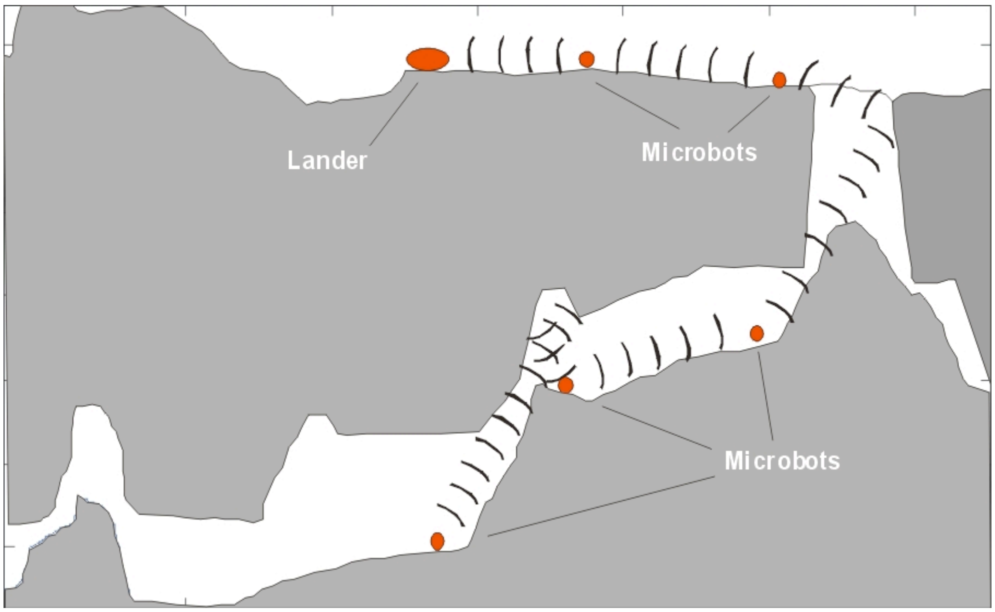
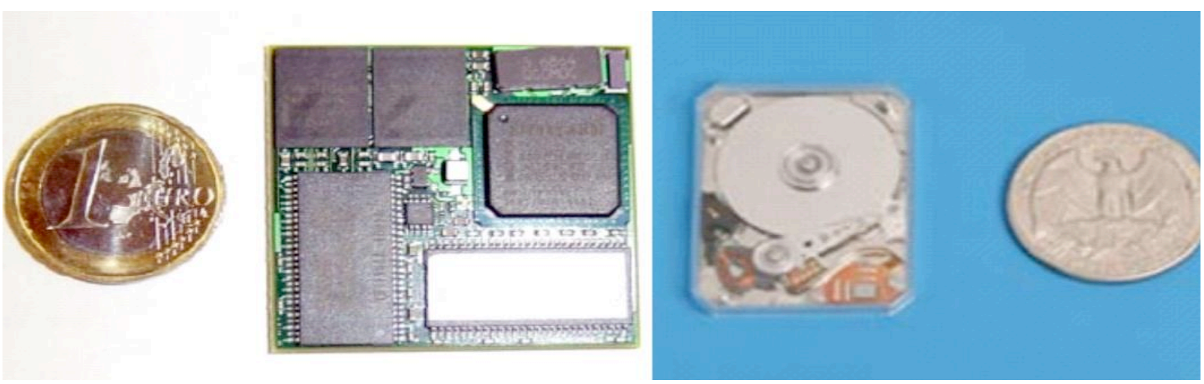


Figure 23: Illustration of cave communication network - profile of Weebubbie cave (Australia)



a. An integrated data processing unit (U. of Braunschweig) *b. 4GB disk for data buffering and storage (Toshiba)*

Figure 24. Current miniature data processing and storage devices

2.3 Coordinated Control of Microbot Teams

In the microbot concept, a mission might employ several teams at widely spaced sites on a planet's surface or subsurface, with each team composed of tens or hundreds (or even thousands) of microbots. These teams will possess two important qualities. First, they may be homogeneous or heterogeneous. This means that they may have identical or different capabilities (for example, some microbots might have specific functions, such as carrying large sensors). Second, microbots may need to be capable of both centralized and decentralized planning, navigation, and control functions. That is, microbots will need to be able to adjust their overall mission objectives based on information and directives from a central unit or other team members. In addition, each microbot will need to be able function independently to increase overall team robustness to single-point failure.

For example, to efficiently explore a terrain region, these teams will need to coordinate their motion, information sharing, computation, and communication. Effective coordination of microbot teams is challenging for several reasons. First, the large team size makes classical control methods (such as those based on overall system optimization) impractical due to overwhelming computational requirements. Second, effective control of large, decentralized multi-agent systems is inherently difficult and is a current frontier of robotics research [33, 34, 35]. Third, a heterogeneous team may require strategic allocation of resources, so that appropriately equipped microbots are available to analyze a given science target. Finally, subsurface exploration requires intelligent establishment of a "trail of breadcrumbs" LAN to ensure communication among microbots and to the surface.

Methods for coordinated control of large, distributed, homogeneous and heterogeneous microbot teams would leverage recent work in the robotics community that has studied the emergence of complex behaviors for decentralized systems [33]. Other promising work has been based on biological models (i.e. "virtual pheromones") for control of large number of mobile robots, modeled on the behavior of ants and termites [35]. Such an approach would not require unique identities for each robot, explicit message routing, or centralized representations of the team, all of which can be detrimental for large systems. Other research has studied flocking, herding, and schooling behaviors observed in nature [36].

A potential exploration scenario might begin by identifying potentially interesting science sites from aerial imagery (described in Section 1.2.2), individual microbot imagers, or both. Here, microbots might share monocular vision data to construct "synthetic" stereo (i.e. range) data (see Figure 25) [37]. On-board microbot intelligence might range from simple "goal seeking" navigation behavior, in which a unit would simply follow directions from a central control agent (such as ground-based operators), to more advanced "autonomous science" behavior, in which a unit would identify imagery and sensor data to detect potentially significant sites, and autonomously investigate them [38]. When a microbot or operator identifies a science target, the microbot could broadcast a cue or message identifying the target location, type, and potential value. Neighboring microbots could then determine the value of their assistance, based on the distance to the target, the appropriateness of their scientific suite, and potential science value of the target. If the value of their assistance is high, the microbot could move toward the target to assist in scientific analysis. The result would be collective analysis of the target by multiple microbots from various locations, distances (i.e. scales), and with various instruments. Context information for the science data would be gained from images of the surrounding terrain, possibly supplied by other team members, and knowledge of the relative locations of microbot team members. Vision-based and radio signal-based localization methods appear promising for microbot localization [31, 39].

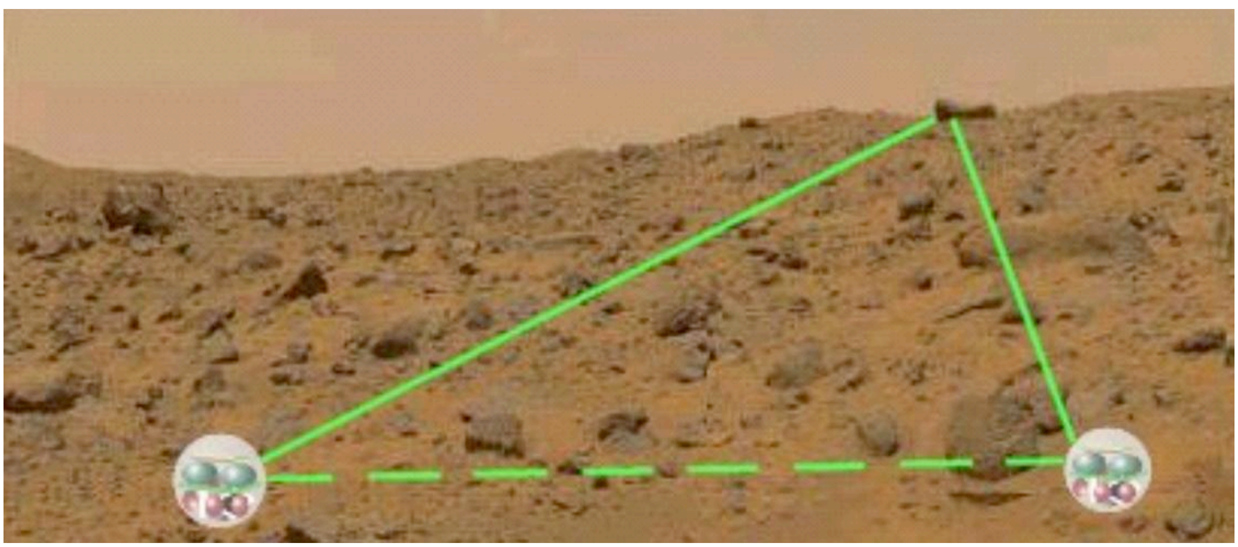


Figure 25: Synthetic stereo vision via microbot data sharing

2.4 Power

Power plays a critical role in a microbot planetary exploration mission. Microbots lack the large surface area necessary to use conventional solar-voltaic cells; also, such cells would clearly not work in subsurface missions or in shadowed areas. The power concept developed for our design uses miniature fuel cells such as those shown in Figure 26 [21].

This work was performed in cooperation with Professor Fritz Prinz at Stanford University. The use of bi-stable mechanisms for the EPAM actuators lowers the peak power consumption necessary for hopping, which in turn enables the use of high efficiency/low power devices such as fuel cells. Analyses have shown that fuel cell powered robots offer significant mass reduction for long range missions over similar battery powered units.

Figure 27 shows the ratio between the mass of a fuel cell system and the mass of a battery system as a function of microbot lifetime. Lifetime here is expressed in the total number of hops a microbot can make before depleting its energy reserves. This comparison is part of a larger power system analysis which determined that only a few grams of fuel will be required to meet reference mission requirements (see Section 1.2.1 and Table 1). The results show that for lifetimes of less than 200 jumps, the weight ratio is greater than one, indicating that batteries would be a lighter energy storage mode for a short mission. However, in the proposed reference mission, microbots are required to make roughly 5000 jumps, a lifetime for which a fuel cell power system would have considerably lower weight than batteries. This is due to the fact that a fuel cell system has a power extraction module of fixed weight, but additional fuel (H_2 and O_2) has negligible weight. Fuel cells are therefore considered highly promising for long-duration missions.

The mobility mechanism, sensor suites, communications electronics, and system microcomputers will all draw significant power. The mobility mechanism is estimated to draw a peak power of 0.2 W, and we estimate that the power draw of the other subsystems will be on the same order of magnitude. Thus a power supply with peak output of 1.5 W could run these systems with intelligent power management (i.e. not all systems would run simultaneously). Current state-of-the art miniature fuel cells (see Figure 26) can generate 450 mW/cm^3 of power continuously [21]. A fuel cell with power density of 2000 mW/cm^3 was assumed for our mission, and was shown to be capable of providing sufficient system power. It is reasonable to assume that a power density of 2000 mW/cm^3 would be achieved in the 10-40 year time frame, since such a power density does not violate the governing physics of fuel cell technology, and is likely achievable through continued advancements in manufacturing and materials engineering.

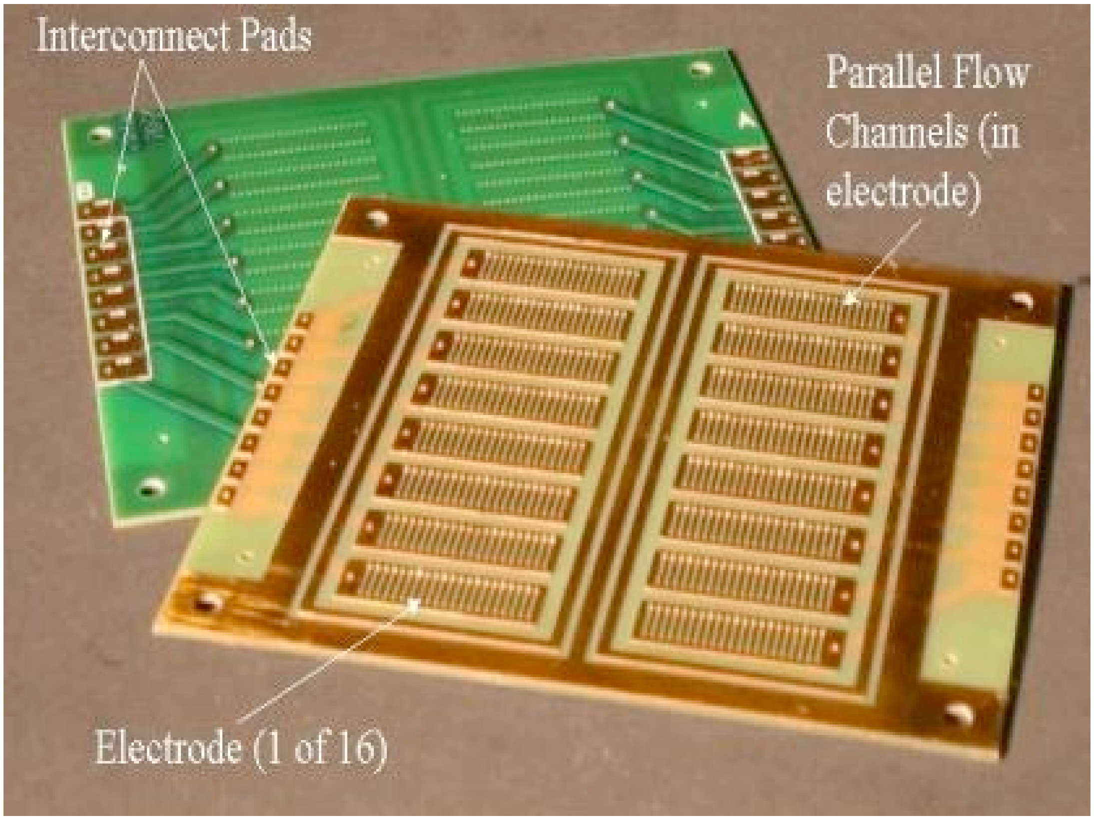


Figure 26. Current miniaturized fuel cell technology [21]

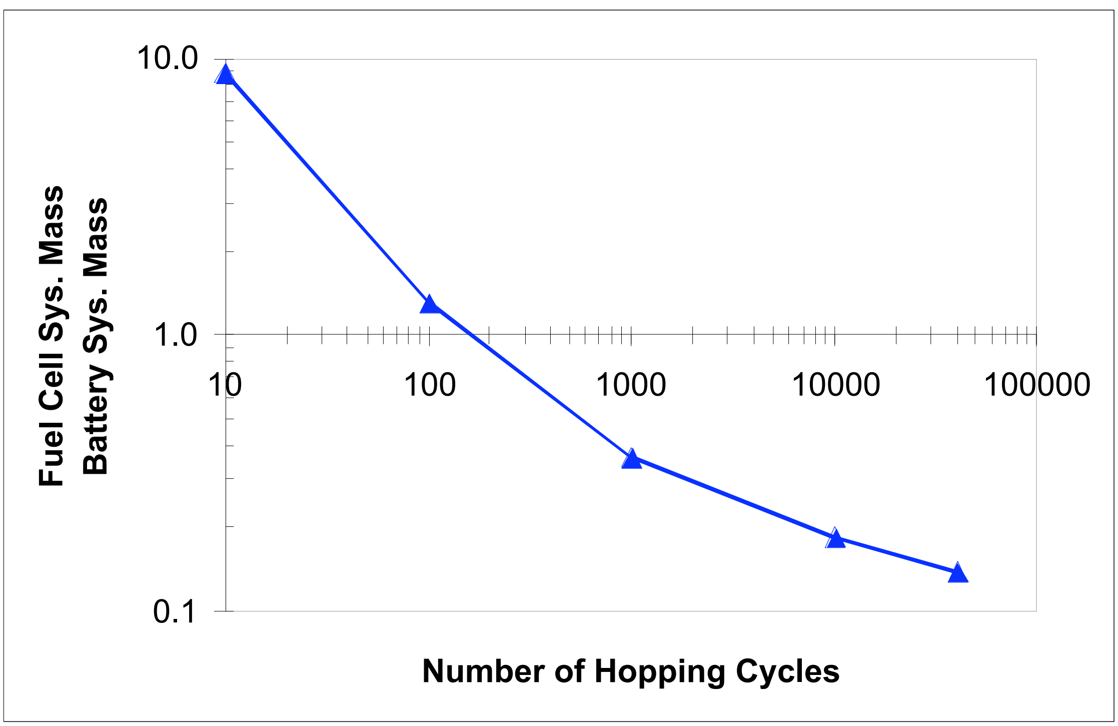


Figure 27 Comparison of fuel cell system mass and battery system mass versus total mission hopping cycles

3. Sensors and Computation

3.1 Sensors

Sensors are the heart of a microbot system, since they are critical elements for scientific exploration of the bodies of the solar system. To be useful, microbots will need to perform in-situ geochemical analysis in diverse terrains. These tasks will require basic chemical characterization (to search for organic and inorganic materials, isotopic fractionation, etc.) as well as geophysical terrain analysis related to geothermal activity, climate history from ice-soil strata, investigations of trapped particles, sedimentary rocks, mineral recrystallization, organic residues, etc. Missions might require the detection of methane, bio-benign environments at bottoms of fissures, microbiota in microniches, organic molecules, sulfur compounds, signs of water, etc. Microbots might also need to carry environmental sensors to measure pressure, temperature, etc. Finally, microbots would require sensors related to navigation, localization, and locomotion, such as accelerometers, gyroscopes, etc. Microbot sensors suites might also vary according to their mission. A typical basic sensor suite is given Table 2.

Many appropriate sensors already exist in micro-size. The development of a wide range of others is well underway. Some results of a study of microsensor performance are summarized below.

Table 2. Typical Basic Microbot Sensor Suite

Science sensors	- Panoramic cameras, microscopes - Mass spectrometers, gas analyzers - X/Alpha-Ray, Mössbauer spectrometers
Environmental and physical sensors	-Pressure, temperature, dust sensors, and UV detectors
Mobility sensors	- Accelerometers, IMU packages, panoramic cameras

3.1.1 *Panoramic Imagers*

A panoramic imager would be used principally for navigation, for the identification of interesting sites, and for providing geographic context. They would cover the range of visible to near infrared spectra (approx 400nm to 1100nm) with appropriate filters. Miniaturized prototypes of such cameras already exist. An example is shown in Figure 28. CMOS image sensors have achieved a volume of 0.27 cm^3, power consumption of 30 mW and weight of approximately 0.3 grams. Further advancements should lead to improved pixel resolution. The microbot concept might accommodate two such cameras mounted with a baseline spacing in the range of 70 mm to 90 mm (approximate human interocular distance = 70 mm) to yield stereo-based range images. This baseline spacing would be useful for close-range navigation. Long-range stereo for navigation and localization could be accomplished by combining images from several microbots (see Section 2.3).

3.1.2 *Microscopic Imagers*

Microscopic imagers allow close examinations of rocks, microbiota in microniches, etc. The challenge for miniaturization is to yield acceptable optical resolution [40]. The resolution of conventional-sized microscopes (approximately 300 nm) is sufficient for planetary missions [40]. To date, miniaturized microscopes have optical resolution in the range of 10μm [41]. Such microscopes work in the infrared range with LED light sources.

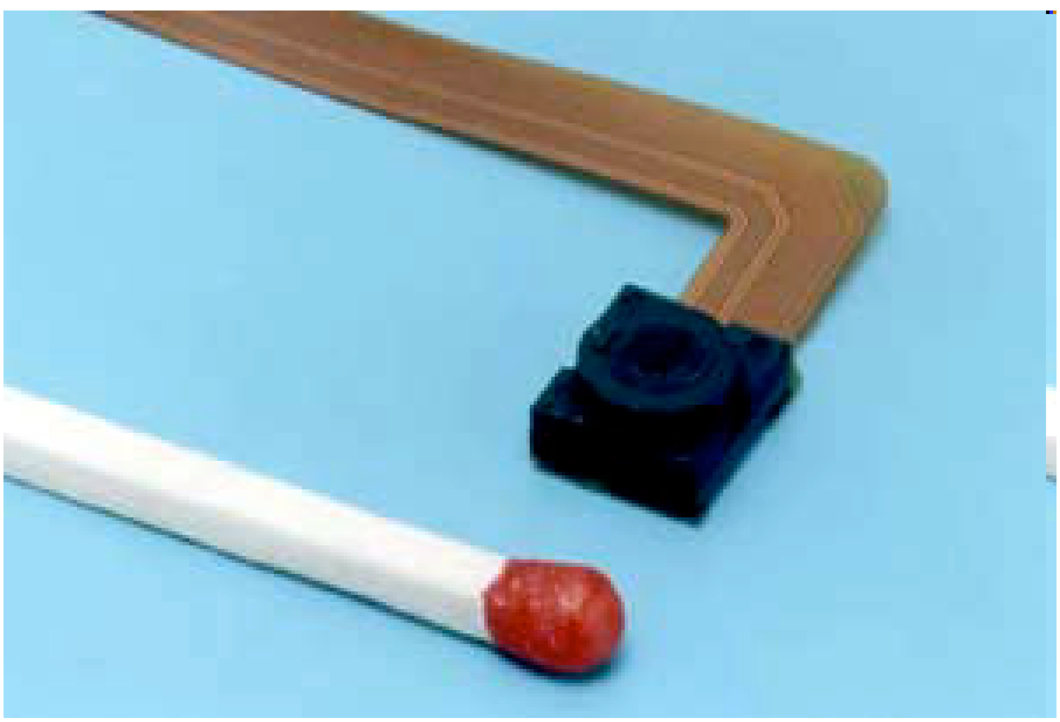


Figure 28. A CMOS micro-camera module by Fujitsu [42]

3.1.3 *Mass Spectrometers / Gas Analyzers*

Mass spectrometers are primary instruments for chemical characterizations. Conventional mass spectrometers use both magnetic and electric field properties, as function of the mass, to identify ionized molecules. The precision of these instruments relies on the measurements accuracy and stability of these fields. Conventional laboratory spectrometers characterize both solid and gaseous compounds with high precision. For a miniaturized system, spectrometers that use a radiation source to create the electric field (an ion mobility spectrometer – IMS) are most promising [43] (see Figure 29). The spectrometer total volume is 0.6 cm^3 and achieves the precision of parts per billion. The use of this type of instrument is not simple. It requires sample preparation, such as a laser source to vaporize the sample, and a means to ingest the resulting gases. Research is currently underway to develop lab-on-chip Micro Gas Analyzers with MEMS size dimensions and power consumption in the order of few mW [30].

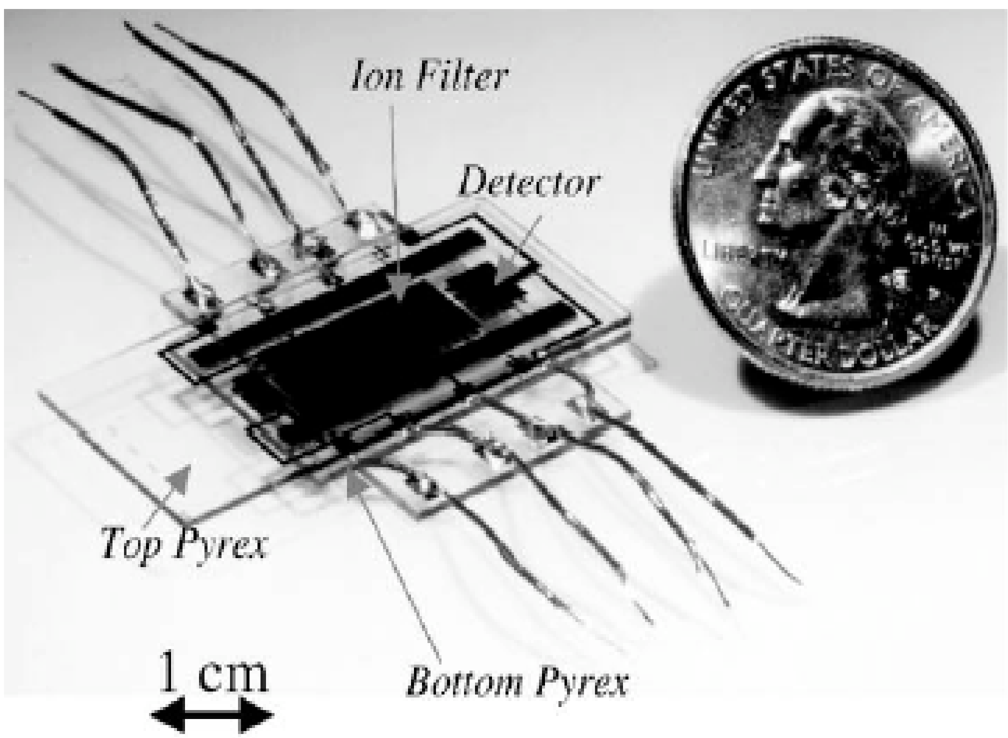


Figure 29. A MEMS IMS spectrometer for chemical vapor detection [43]

3.1.4 *X/Alpha-Ray and Mössbauer Spectrometers*

X-ray and Mössbauer spectrometers are fundamental instruments for the chemical and mineralogical analyses of rocks and soil. They expose materials to collimated radiation beams and analyze the energy spectra of backscattered and emitted rays to determine the material atomic structure. The devices must be in close proximity to specimens to reduce power consumption. Spectrometers used on current planetary missions have mass of approximately 300 g and require approximately 3 W of energy [40]. Spectrometer miniaturization depends on ray-collimator size that also affects resolution. Next generation spectrometers are anticipated to achieve an order of magnitude improvement in performance [44]. Therefore it is expected that both size and weight will decrease considerably.

Mössbauer spectrometers use a radioactive source to illuminate the target and measure the backscattered gamma signal. The target specimen needs to be in contact with the source head to minimize measurement errors. The acquired spectra are temperature dependent and measurements are taken in different conditions to establish the compound characteristics. Current miniaturized instruments have volumes of approximately 250 cm^3, mass < 300 g and power consumption of 0.4 W [45]. Miniaturized versions of this type of instrument could be limited by both the size of the electro-mechanic vibrator and the radiation shield. Therefore, even if new materials and new packaging technologies are developed, these devices may remain close to their current size. However their size and power consumption could be accommodated by a microbot, assuming that it did not carry substantial other instrumentation. Thus some members of a heterogeneous microbot team might be devoted to carrying only spectrometers.

3.1.5 *Accelerometers, Gyroscopes, Temperature Sensors, etc.*

Current technologies for miniaturized accelerometers, gyroscopes, and temperature sensors allow dimensions in the size of microns and power consumptions in the order of approximately 1mW [46]. Next generations of some of these sensors are targeted at dimensions less than a micron [46] with power consumption of microwatts. Since this sensor technology is moving at such as rapid pace it is expected that this technology will not be a serious constraint to the microbot concept in the 10 to 40 year time frame.

3.2 Computation

Each microbots would have computational demands for navigation and control, data processing and data reduction, and communications. Current computing power for MER mission is in the order of 20 MIP and is expected to increase one order of magnitude for the MSL mission in 2009 [47]. It is reasonable to believe that in 10 to 40 year time frame, computing power would increase several orders of magnitude, and that computing ability would not be a critical issue for our proposed mission.

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