A Concept Mission: Microbots for Large-Scale Planetary Surface and Subsurface Exploration

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Abstract. This paper 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.

INTRODUCTION

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 microrobot 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. In this paper we focus on a few

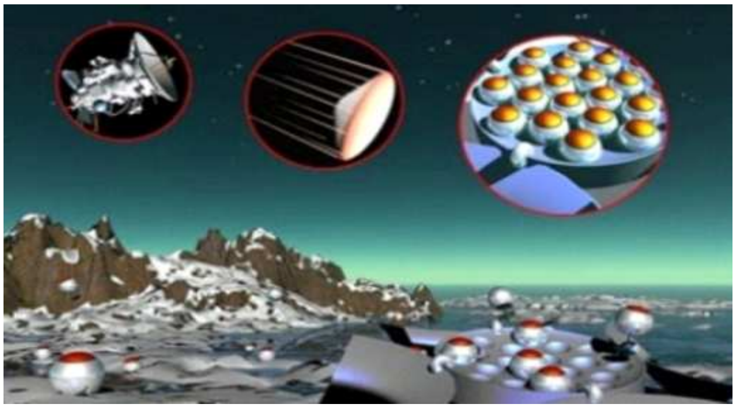

Figure 1. Microbot Planetary Surface and Subsurface Exploration Concept.

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challenging environments that are of high scientific interest to the planetary and astrobiology communities (NASA, 2003). These include icy terrains on polar Mars and various gas giant moons, rough and high vertical relief landscape, and caves or other subsurface access, as discussed below (Boston, 2003).

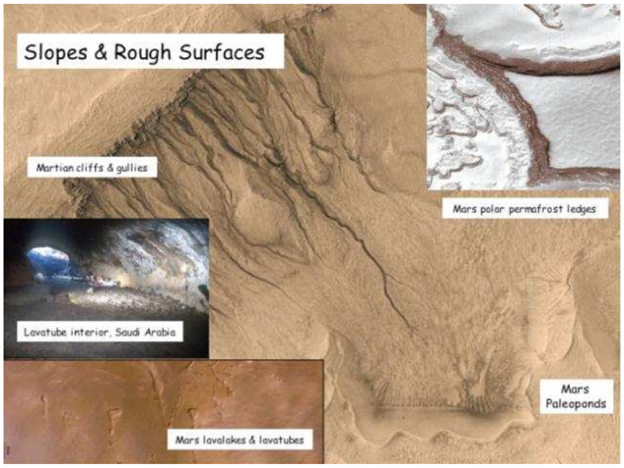


FIGURE 2. Background Image of "Weeping Slope" and Ponds at the Base of Newton Crater, Mars (Malin Space Sciences Image). Upper Right Shows Steeply Layered Martian Polar Lobes of Possible Permafrost (Malin Space Sciences Image). Central Left Shows View of Interior of Hibashi Lava Tube Cave, in Saudi Arabia (by J. Pint). Lower Left Image Acquired by the ESA's Mars Express Mission Shows Evidence of Large Lava Tubes.

Rough and large vertical relief terrains hold important scientific information. 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 are shown in Figure 2. Icy surface targets have high scientific value. 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" (Clark, 1988). 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. Microbot teams can provide access to these terrains for exploration and science that will be difficult to achieve by other methods.

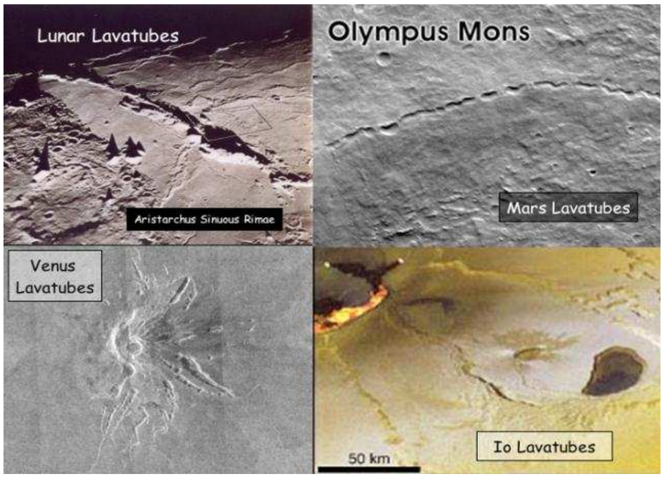
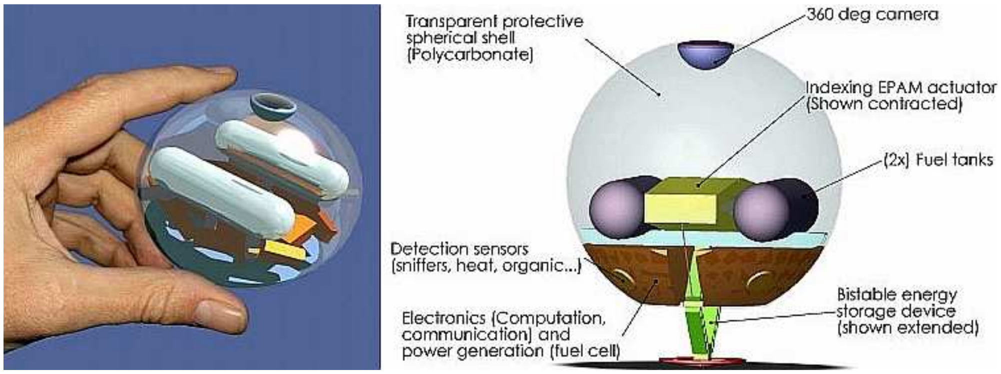


FIGURE 3. The Identification of Lunar Features as Lava Tubes was Made During the Apollo era (Oberbeck et al. 1969). Viking Images and More Recent Mars Missions Show Mars has Abundant Lava Tube Caves (Boston, 2003). Radar Images from Venus Show Numerous Lava Tube Like Features (Boston et al., communicative data). The Galileo Mission Images of Io, Also Suggest Lava Tube Structures.

Subsurface targets include lava tubes, ice caves, and artificially drilled boreholes. Extraterrestrial bodies containing these targets include Mars, the Moon, Venus, and Io (for lava tubes); 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 (Boston, 2000). Such areas can serve as a repository for trapped materials from a planet's past, and can yield materials that may shed light on past climate history (Polyak et al., 1998, 2001) and past solar activity (Shopov et al., 1994). They can also provide a suite of environments for an enormous diversity of extremophile organisms (Boston et al., 2001), 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 (Boston et al., 1992). As mineralogical "factories," the minerals whose formation they nurture are unparalleled in abundance and variety (Hill and Forti, 1997).

This is clear evidence of lava tube caves on the Moon, Mars, Venus and the Jovian moon Io (see Figure 3) (Boston, 2003; Oberbeck et al., 1969). 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 (Boston, 2003). It is plausible that some of the tremendous number of lava tubes 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 (Oberbeck et al. 1969). 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.

System Overview



a) b)

FIGURE 4. Microbot Explorer Concept. (a) Sketch Showing Microbot Approximate Size. (b) Major Components.

The proposed mission 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 (see Figure 4). 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, chemical analysis sensors. With advanced power, locomotion, sensing, and computation technology, we expect microbots to be on the order of 10 cm in diameter and approximately 100 gm in mass.

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 (Fiorini et al., 1999). 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. 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 gather detailed data about surface and subsurface properties that span large geographical areas.

FIGURE 5. View of Hibashi Cave Looking Outward Toward an Entrance.

Reference Mission

To evaluate the feasibility of the microbot concept two reference missions were considered, a surface and a subsurface mission. The surface reference mission assumes exploration of a body having solid terrain (i.e. not watery or with a vaporous atmosphere). The terrain for the surface mission 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. An obstacle density of 20 obstacles/m^2 is assumed (Golombeck and Rapp, 1997). The target mission assumed a team of 1000 microbots, a 30 day average microbot life span, and a 135 km^2 (50 square mile) desired coverage.

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 billions) of years (Boston and Pint, unpublished data). The cave profile will contain both inclined and declined slopes that 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 (Pint, 2003) (See Figure 5). Goals for the subsurface mission are for a team of 100 microbots to penetrate up to 1 km into a cave in 20 days, while maintaining communication with the surface.

Landing and Deployment System

The mode of microbot delivery to a planetary surface determines the initial distribution of both microbot teams and individual units. Three strategies for landing and deployment were considered in this study. The first uses a landing mode similar to that employed in the Mars Pathfinder and Mars Exploration Rover missions (Mars Exploration Rover, 2004). Here a parachute-based decent and airbag cushioned landing is used. Microbot shells could be designed to be somewhat impact resistant which would allow landings at higher planetary elevations than has been possible in the past, permitting access to a higher percentage of the planet's surface. In this landing approach, many microbots would be deployed from a single landing platform. Roughly one thousand microbots could be launched in the same volume and mass as a MER rover (Mars Exploration Rover, 2004).

The 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. This group could be split into several teams of optimal size that land separately and thereby study several diverse regions during a single mission.

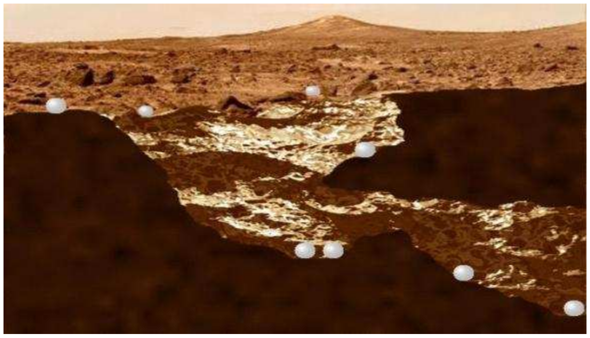


FIGURE 6. A Concept Drawing of Microbots (in White) Entering a Lava Tube Cave.

The third strategy was inspired by an analysis of the potential use of aerial robots for planetary exploration (Kerzhanovich and Cutts, 2000). 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 low-flying balloon, a wide initial distribution could be achieved. This approach would also allow mission planners to select initial drop sites using aerial images taken by the balloon system.

MICROBOT SYSTEM DESCRIPTION

A microbot system is composed of four fundamental subsystems: 1) Mobility, 2) Power, 3) Communication, Control and Computation, and 4) Sensors. Each of these systems plays an important role for the mission and requires detailed analysis. A description of these concepts is provided here.

Microbot Mobility

Microbot mobility is provided by a bi-stable mechanism activated by dielectric elastomer actuators. This mechanism enables the microbot to move by directed hopping (see Figures 7 and 8), followed 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 demonstrated.

TABLE 1. Anticipated Microbot Performance.

Mass (total) (g)	100
Diameter (cm)	10
Hop height (Mars) (m)	1.5
Distance per hop (Mars) (m)	1.0
Average hop rate (hops/hour)	6
Maximum hop rate (hops/hour)	60
Fuel use (mg/hop)	1.5
Peak power supply output (watt)	1.5

Microbots would be powered by a micro fuel cell concept developed in connection with this study by researchers at Stanford University (O’Hayre et al., 2003). 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.

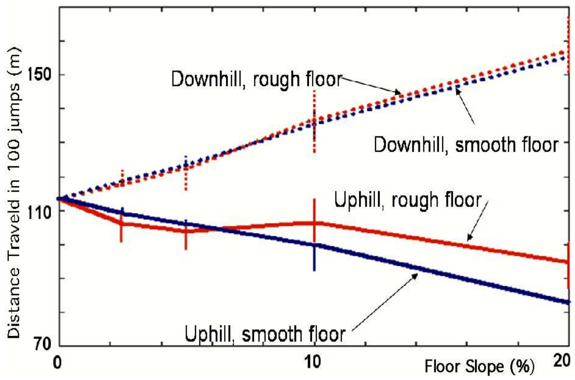


FIGURE 7. Variation of Microbot Range with Floor Slope

A microbot’s ability to hop, bounce, and roll combined with its high energy to weight ratio fuel cell/polymer actuator system allow it to traverse very rough terrain for long distances. In this study microbot locomotion has been studied and simulated. This 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). Studies have suggested that boulders on Mars larger than 1 m diameter are rare (Golombeck and Rapp, 1997). 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 7 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 on impact. Very steep inclines or rock shelves would be treated as obstacles, and leaped over if sufficiently small. For a 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 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. 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

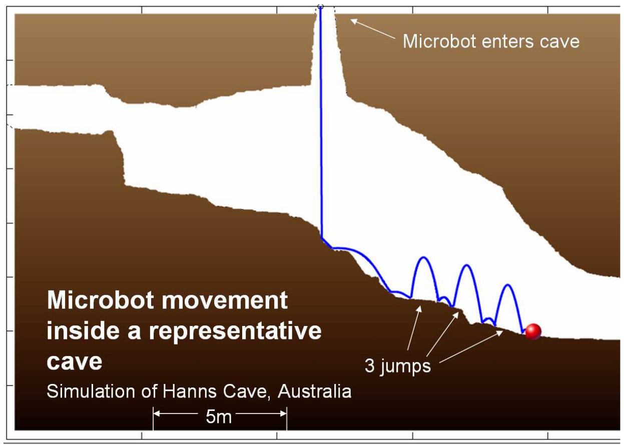


FIGURE 8. Subsurface Simulation (Microbot Enlarged for Clarity).

largest influence. Simulations of the potential area coverage of a microbot team have shown 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.

Microbots' mobility mechanism would permit the exploration of 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 near cave entrances is more challenging. Field studies in lava cave systems near Grants, New Mexico have shown 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 on planets such as Mars have buried the features that would be a serious hindrance to microbot travel.

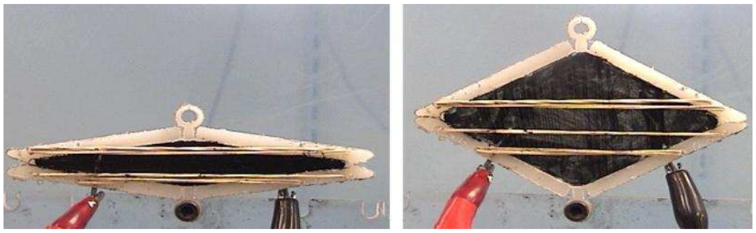


FIGURE 9. Experimental Dielectric Elastomer Actuator with 200 Percent Strain.

Simulations have been performed to study microbot mobility over a wide variety of cave geometries and parameters (see Figure 8). 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 a 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, simulations have suggested that the defined structure of the expected caves makes the problems similar. For caves, communication issues (discussed below) are a more significant challenge.

The microbot mobility mechanism is simple, power efficient, robust, durable, reliable, and lightweight. It is based on dielectric elastomer actuators powered by hydrogen/oxygen fuel cells. Electroactive polymer artificial muscles (EPAMs) have shown potential to be highly efficient, low cost, light weight, and inherently simple (Kornbluh et al., 2000; Wingert et al., 2002; Vogan et al., 2004). 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. 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 (Vogan et al., 2004).

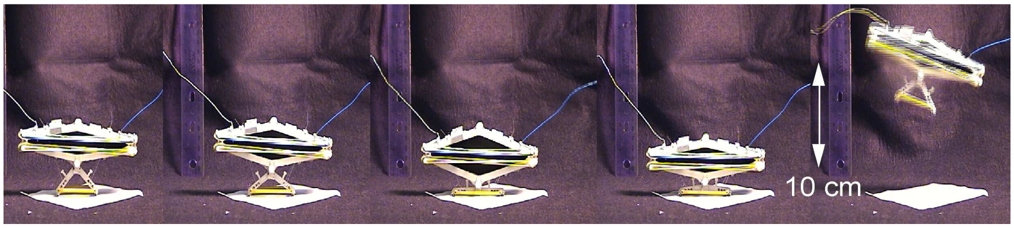


FIGURE 10. Sequence of Images of the Indexing Actuator Prototype Performing a Jump

If the film is incorporated into a compliant frame with appropriate preloading, as in Figure 9, the orthogonal expansion is converted into useful mechanical work. Linear strains of approximately 200 percent are possible with such a design (Vogan et al., 2004). When compared to 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 microbot mobility mechanisms.

A drawback of EPAMs is their relatively slow actuation time. To generate a hopping motion, energy must be released quickly (Vogan et al., 2004). In this study a bi-stable EPAM actuator that allows energy to be stored over time then quickly released has been developed (Vogan et al., 2004). A prototype jumping mechanism based on bi-stable EPAMS has been developed. Figure 10 shows a series of photographs of one of these actuators jumping.

Micro fuel cells are promising energy sources to power EPAMs. Fuel cells 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.

Power

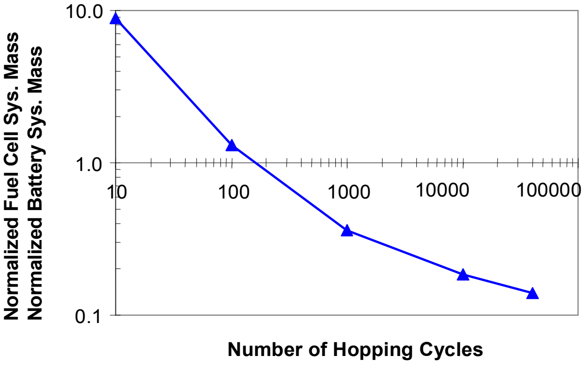


FIGURE 11. Comparison of Fuel Cell System Mass and Battery System Mass Versus Total Mission Hopping Cycles.

The power concept developed for the microbot uses miniature fuel cells such as those shown in (O'Hayre et al., 2003). 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. Figure 11 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. Analysis also showed that only a few grams of fuel would be required to meet reference mission requirements. For reference missions, 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 because a fuel cell system has a power extraction module of fixed weight, but additional fuel (H_2 and O_2) has negligible weight.

The mobility mechanism, sensor suites, communications electronics, and system microcomputers all draw significant power. The mobility mechanism is estimated to draw a peak power of 0.2 W, and power draw of other subsystems is estimated to 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 can generate 450 mW/cm^3 of power continuously (O'Hayre et al., 2003). 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 expected that a power density of 2000 mW/cm^3 will be achieved in the future.

Communication, Control and Computation

Both surface and subsurface exploration missions require the microbot teams to establish a robust communications network, to communicate science data to a central unit, such as the lander, for relay to orbit or earth. Microbots will also need to share information regarding their position and surrounding environment either to the team or to a central unit so that mission targets can be updated. 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 positioned to create a "trail of breadcrumbs" LAN allowing communication to the surface. To achieve such communication, each microbot would be equipped with a reliable and low power transmission/receiver system.

The surface reference mission requires an exploration area of 135 square kilometers by a team of 1,000 microbots; 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. A communications system at 31 GHz with transmitted power of 50 mW and antenna gain of 35 dB has been demonstrated in a 9 km point-to-point (i.e. line-of-sight) communication system (Meinel, 1995). Such high frequency signals are susceptible to attenuation from the atmosphere and intervening terrain features. Hence microbots might be required to establish a local area network for some surface missions. Miniaturized phased array antennas have been developed with approximate dimensions of 10 cm × 10 cm × 0.08 cm (Edwards). The antenna might be printed on the microbot shell with little increase to system weight and volume. For the frequency ranges discussed above, the maximum data rate that can be achieved using current technology with mW order power output would be adequate for the proposed reference missions (Dubowsky et al., 2004).

Communication in a subsurface mission is difficult because of the short range of radio transmissions in caves due to radio wave absorption by rock. The solution to this problem considered in this study is to use the microbot units as a communications network to relay information back to a central unit on the surface at the cave entrance, where it could be sent to Earth or to orbit. Some microbots would be programmed to stop at various penetration distances into the cave. These microbots would act as relay nodes of the communication 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 (Boston et al., 2003). 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.

To efficiently explore a terrain region, microbot teams will need to coordinate their motion, information sharing, computation, and communication. Effective coordination of microbot teams is challenging. However, recent research has suggested methods that could be applied to the proposed concept. Recent work in the robotics community has studied the emergence of complex behaviors for decentralized systems (Arkin and Bekey, 1997). 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 (Payton et al., 2003). 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 (Reynolds, 1987). Preliminary studies have suggested that these methods are applicable to microbot control. Additional studies are required to fully explore their effectiveness given the limited computation, communication bandwidth and sensor information of the microbots.

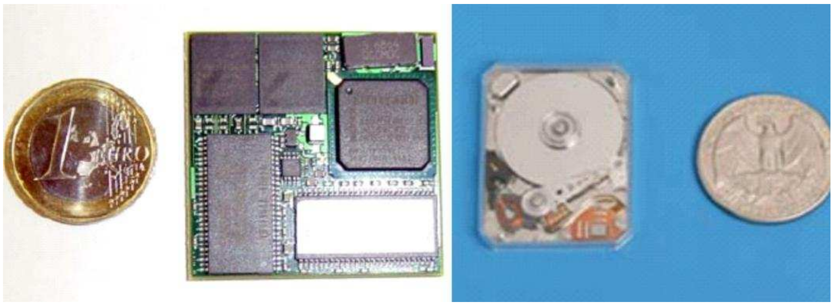

(a) (b)

FIGURE 12. Current Miniature Data Processing and Storage Devices. (a) Miniature Data Processing Unit (Buschmann et al. 2003). (b) 4 GB Disk for Data Buffering and Storage (Toshiba).

Each microbot will gather scientific data that ultimately needs to be returned to Earth. It is expected that each microbot could gather several megabits of data per day. In addition, microbots will need to relay data and command information from other team members. For a team of microbots, this could be a large volume of information. Therefore, microbots will need to perform on-board data processing. Current miniaturized data systems can process several Mbps of data in a volume of 12 cm^3, mass of 10 g, and power of 500 mW (Buschmann et al., 2003) (Figure 12a). It is reasonable to believe that in foreseeable future computing power would increase several orders of magnitude, and that computing ability would not be a critical issue for our proposed mission.

Sensors

Microbots will need to perform in-situ geochemical analysis in diverse terrains. These tasks will require basic chemical characterization as well as geophysical terrain analysis related to geothermal activity, climate history, 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 sensor 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.

A panoramic imager would be used principally for navigation, identification of interesting sites, and providing geographic context. CMOS image sensors have achieved a volume of 0.27 cm^3, power consumption of 30 mW and weight of 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 to yield stereo-based range images. Microscopic imagers would allow close examinations of microbiota. The challenge for miniaturization is to yield acceptable optical resolution (Sims et al., 1999).

Mass spectrometers are primary instruments for chemical characterization. The precision of these instruments relies on the accuracy and stability of their magnetic or electric fields. For a miniaturized system, spectrometers that use a radiation source to create the electric field (an ion mobility spectrometer – IMS) are most promising (Miller et al., 2001). The spectrometer total volume is 0.6 cm^3 and it achieves a 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 (Nguyen, 2004).

TABLE 2. Typical Basic Microbot Sensor Suite.

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

X-ray and Mössbauer spectrometers are fundamental instruments for chemical and mineralogical analyses of rocks and soil. The devices must be in close proximity to specimens to reduce power consumption. X-ray spectrometers used on current planetary missions have mass of approximately 300 g and require approximately 3 W of energy (Sims et al., 1999). X-ray 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 (Alp, 2001). Therefore it is expected that both size and weight will decrease considerably. Future miniaturized versions of Mössbauer spectrometers could be limited by the size of the electro-mechanical vibrator and the radiation shield. Their size and power consumption could be accommodated by a microbot, assuming it did not carry other instrumentation. Some members of a microbot team might therefore be devoted to carrying only spectrometers.

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. Next generations of some of these sensors are targeted at dimensions less than a micron (Ekinci et al. 2004) 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 foreseeable future.

CONCLUSIONS

This paper has presented a new mission concept for planetary exploration, based on the deployment of a large number of small spherical mobile robots over vast areas of a planet's surface and subsurface. The proposed concept would allow extremely large-scale in situ analysis of terrain composition and history. A system overview and a pair of reference missions have been presented, along with brief summaries of potential landing and deployment systems. Enabling technologies for the microbot mission concept have been discussed, and it has been shown that much of the technology required by the concept is either currently available or expected to be developed in the near future. The proposed concept therefore represents a practical and promising approach to Solar System exploration.

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REFERENCES

Alp, E.E., et al., “Source and optics considerations for new generation high-resolution inelastic X-ray spectrometers,” *Nuclear Instrumentations and Methods in Physics Research*, 2001, p. 617-622.

Arkin, R. and Bekey, G., *Robot Colonies,* Kluwer Academic Publishers, 1997.

Boston, P.J. Extraterrestrial Caves. Encyclopedia of Cave and Karst Science. Fitzroy-Dearborn Publishers, London, 2003.

Boston, P.J., “Life Below and Life 'Out There'.” *Geotimes,* **45**(8), 2000, pp. 14-17.

Boston, P.J., et al., “Cave biosignature suites: Microbes, minerals and Mars,” *Astrobiology Journal* **1**(1), 2001, pp. 25-55.

Boston, P.J., Ivanov, M.V., and McKay, C.P., “On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars,” *Icarus,* **95**, 1992, pp. 300-308.

Boston, P.J., Pint, J., private communications.

Boston, P.J., et al., “ Extraterrestrial subsurface technology test bed: Human use and scientific value of Martian caves,” Proc. of *Space Tech. & Applic.* Forum 2003. Amer. Inst. of Physics, College Park, MD.

Buschmann, M., Winkler, S., Kordes, T., Schulz, H., Vörsmann, P., “ Development of a fully autonomous Micro Aerial Vehicle (MAV) for Ground Traffic Surveillance,” 10th IFAC Symposium on *Control in Transportation Systems*, CTS 2003.

Clark. M.J., “ Advances in Periglacial Geomorphology,” Chichester, 1988, Wiley, NY.

Dubowsky, S. et al., NIAC (NASA Institute for Advanced Concept) Phase I report, April 2004.

Edwards, D.J., “Department of Engineering, University of Oxford, Oxford, UK,” http://www.eng.ox.ac.uk~comwww/ radar/xant.html.

Ekinci, K.L.; Yang, Y.T.; Roukes, M.L., “Ultimate limits to inertial mass sensing based upon nanoelectromechanical systems,” *Journal of Applied Physics*, **95**, n 5, 1 March 2004, p 2682-9.

Fiorini, P., Hayati, S., Heverly, M., anad Gensler, J., "A Hopping Robot for Planetary Exploration," Proceedings of IEEE Aerospace Conference, 1999.

Golombeck, M. and Rapp, D., "Size Frequency Distributions of Rocks on Mars and Earth Analog Sites" Journal of Geophysical Research, **102**, 1997, No. E2, pp. 4117-4129.

Hill, C.A. and Forti, P., “Cave Minerals of the World, 2nd Edition,” National Speleological Society, Huntsville, AL, 1997.

Kerzhanovich, V. and Cutts, J, "Aerobots in Planetary Exploration,” Proc. IEEE Aerospace Conference, 2000, Vol. 7, 547-555.

Kornbluh R ., Pelrine R., Joseph J, “Elastomeric Dielectric Artificial Muscle Actuators for Small Robots,” Proceedings of the Materials Research Society Symposium, vol. 600, 2000, pp. 119-130.

Mars Exporation Rover, 2004, press kit at: http://marsrovers.jpl.nasa.gov/newsroom/merlandings.pdf.

Meinel, H.H., “ Commercial applications of millimeter waves: history, present status, and future trends,” *IEEE Transactions on Microwave Theory and Techniques*, v 43, n 7 pt 2, July 1995, p 1639-1653.

Miller, R., E.; Nazarov, E., G.; Eiceman, G., A. and King, T., A., “A MEMS radio-frequency ion mobility spectrometer for chemical vapor detection,” *Sensors and Actuators,* **A 91**, 2001, pp. 301-312.

NASA Astrobiology Roadmap, Final Version. Sept. 2003. http://astrobiology.arc.nasa.gov/roadmap.

Nguyen, C., “Micro-Electro Mechanical Systems: Scaling Beyond the Electrical Domain,” DARPATech 2004 Symposium, March 2004. http://www.darpa.mil/ DARPATech2004/pdf/ scripts/NguyenScript.pdf.

Oberbeck, V., Quaide, W.L. and Greeley, R., “On the Origin of Lunar Sinuous Rilles,” *Mod. Geol.* **1**, 1969, pp. 75-80.

O'Hayre, R., et. al, “Development of portable fuel cell arrays with printed-circuit technology, ” Journal of Power Sources, v. 124, 2003, pp. 459-472.

Payton, D., Estkowski, R. and Howard, M., “Compound Behaviors in Pheromone Robotics,” *Journal of Robotics and Autonomous Systems,* 44, pp. 229:240, 2003.

Pint, J., “The Desert Caves Project: Hibashi Cave,” 2003. http://www.saudicaves.com/hibashi.

Polyak, V.J., Cokendolpher, J.C., Norton, R.A., and Asmerom, Y., “Wetter and cooler late Holocene climate in the southwestern United States from mites preserved in stalagmites,” *Geology,* **29**, 2001, pp. 643-646.

Polyak, V.J., McIntosh, W.C., Provencio, P., and Güven, N., “Age and Origin of Carlsbad Caverns and related caves from 40 Ar/ 39 Ar of alunite," *Science,* **279**, 1998, pp. 1919-1922.

Reynolds, C., “Flocks, Herds, and Schools: A Distributed Behavioral Model,” Proc. of *SIGGRAPH*,” 21(4), 1987, pp. 25-34.

Shopov, Y.Y., Ford D.C. & Schwarcz H.P., “Luminescent Microbanding in speleothems: High resolution chronology and paleoclimate,” *Geology,* **22**, 1994, pp. 407-410.

Sims, M.R.; et. al., “Beagle 2: The Exo-Biology Lander on ESA's 2003 Mars Express Mission,” SPIE Conference on Instruments, Methods, and Missions for Astrobiology II, 10 Denver, CO. July 1999.

Vogan, J., et al , F. “Manipulation in MRI Devices Using Electrostrictive Polymer Actuators: with an application to Reconfigurable Imaging Coils,” IEEE International Conference on Robotics and Automation, 2004.

Vogan, J., *Development of Dialectric Elastomer Actuators for MRI Applications,* M.S. Thesis, Massachusetts Institute of Technology, 2004

Wingert, A., Lichter, M., Dubowsky, S., and Hafez, M. "Hyper-Redundant Robot Manipulators Actuated by Optimized Binary Dielectric Polymers," Proc. SPIE Smart Structures and Materials Symposium 2002, San Diego, CA, vol. 4695, March 2002.