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Mobility and Power Feasibility of a Microbot Team System for Extraterrestrial Cave Exploration

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Abstract—**Planetary scientists are greatly interested in the caves present on the Moon and Mars, however these areas present major challenges to current space robots. A new space robotics concept, Microbots, is presented and a possible reference mission to Mars is discussed. The feasibility of the mobility and power systems of the Microbot are analyzed within the context of the reference mission. The results of this analysis are that the Microbot system is a feasible concept for a development timeline of approximately 10 years.**

I. Introduction

There is an important scientific motivation to explore the extraterrestrial (ET) caves of the solar system, including the Moon and Mars [1]. These caves possibly contain water deposits, biological materials, as well as significant geological and geomorphologic information. Hence, there is significant interest in exploring extraterrestrial caves in future space missions [2]. Figure 1 shows a Martian lava tube cave with collapsed roof sections known as skylights.

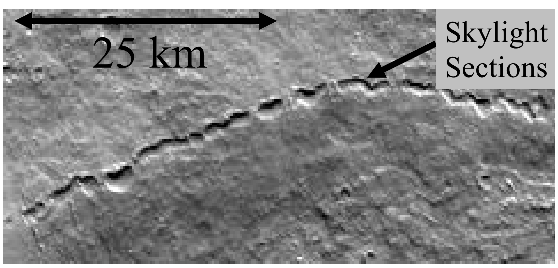

Fig. 1. An orbiter view of a lava tube cave with skylights on Mars.

Astronaut exploration of ET caves would be exceedingly dangerous and therefore such missions are a strong candidate for robotic or combined astronaut-robot exploration. Current exploration robot designs, such as the Mars Exploration Rover (MER) and the Mobile Science Laboratory (MSL) are not well suited for subsurface exploration. These robots are unable to traverse extremely rough terrain, navigate over large obstacles, or ascend and descend very steep slopes. Rough terrain entrapment of such systems would result in single point mission failure. Hence, mission planners are unlikely to risk a rover in unknown subsurface area such as a cave.

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This paper describes a robotic ET exploration concept to deploy hundreds or thousand of small and sacrificial ball-like robots onto the surface of Mars. These robots would explore subsurface lava tubes, entering through cave skylights. They could be deployed from an orbiter with a balloon landing, such as were used by the MER rovers Spirit and Opportunity (see Figure 2). They could also be dropped or thrown into cave openings by astronauts or carried by conventional rovers. These mobile robots, or "Microbots," would be self-contained spherical devices approximately 100 millimeters in diameter with a mass of approximately 100 grams (see Figure 3).

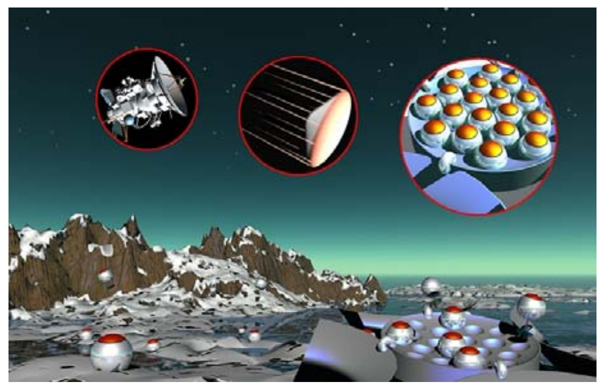


Fig. 2. The Microbot exploration concept showing orbiter deployment.

Microbot would contain a micro fuel cell power system, communication and data processing equipment, a payload of scientific and navigation sensors, and a Dielectric Elastomer Actuator (DEA) mobility system that produces a combination of hopping, bouncing, and rolling. Preliminary analysis has shown that a mission of two thousand Microbots would have the same launch weight and volume as a single MER rover.

This paper presents a feasibility analysis of the Microbot system design for a 10 year development timeframe. The system performance is evaluated in the context of a reference mission to Mars. The operation and efficiencies of the Microbot subsystems are discussed, focusing on the power and the mobility subsystems.

II. System Concept

The Microbot system is an exploration robot designed to traverse very rough terrain while being robust to single point failures. After deployment, the Microbots would use their mobility systems to hop, bounce, and roll over the planet's surface in the direction of a feature of interest, such as a cave entrance, a deep ravine, or a canyon. This mobility strategy is an effective option for low gravity environments, such as Mars and the Moon [3].

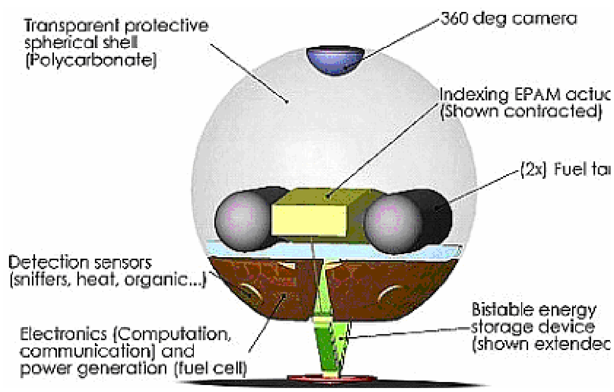


Fig. 3. The Microbot system concept and major modules.

Upon reaching the feature, the Microbots would use their mobility system to descend into and explore the feature's interior while taking scientific measurements, a task currently infeasible with today's rover technology. The Microbots would then transmit the data to a surface lander or orbiting spacecraft via a low power local area communication network established between the members of the team.

The individual Microbots would work collaboratively to navigate on the surface, take scientific measurements, and transmit the data to the surface. This highly redundant approach to ET exploration allows the overall robotic system to be robust to failure or entrapment of any number of the team members.

III. Subsystem Descriptions

The individual Microbots consist of four major subsystems: a mobility system, a fuel cell power generation system, an integrated electronics package, and a scientific sensor payload.

A. Power Generation System

The Microbot system would use small-scale hydrogen fuel cells to generate power. Fuel cells were selected as the power source because they outperform battery power supplies in terms of energy density (energy per unit mass) for long duration missions [4], [5]. Fuel cells were also selected because they are high-efficiency but low-power devices. They will perform well with the low peak power characteristic of the mobility system's DEA actuators [5].

Proton exchange membrane (PEM) hydrogen fuel cells were selected for the Microbot system. These fuel cells convert the chemical energy of hydrogen and oxygen into electrical energy, water and waste heat. PEM fuel cells offer the advantages of being very efficient and operating at low temperatures [6]. The small water byproduct can be captured and held within the Microbot, keeping the mass of the system constant and avoiding any contamination of the environment.

B. Mobility System

The main component of the Microbot mobility system is a DEA coupled with a bi-stable device (see Figure 3). The DEA works by using the Maxwell (electrostatic) pressure generated by a strong electric field to compress a soft elastomeric film, thus generating an expansion in the directions orthogonal to the film [7]. The current state-of-the-art actuators allow for the film area to expand up to several times its initial size during actuation (see Figure 4)

Fig. 4. The MIT experimental diamond Dielectric Elastomer Actuator [8], [9].

In order to initiate a hop, electrical energy is slowly pumped into the DEA, causing it to in turn expand the bi-stable device. When the bi-stable mechanism has been deformed sufficiently, it switches states and quickly releases its stored mechanical energy in the form of a hop. The fact that the energy required to hop the Microbot is accumulated over a relatively long period of time decreases the peak power requirement from the fuel cell power supply. A proof-of-concept of this bi-stable hopping mechanism has been demonstrated [8].

The Microbot travels by hopping followed by bouncing and rolling. The directionality of this mobility system is controlled by the hopping angle of the device. Changing the orientation of the bi-stable device varies the direction in which the hopping energy is released. The Microbot is weighted so that after the rolling and bouncing motion is complete, it will return to an upright position [9]. If the environment prevents this from happening, the Microbot will use the actuator to right itself.

C. Sensors

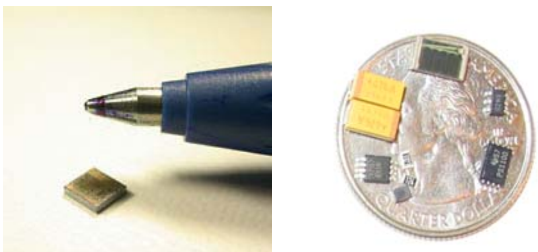
The Microbot requires sensors to navigate and make the mission specific scientific measurements. To control its mobility and navigate, the Microbot would use sensors such as accelerometers and inertial measurement unit (IMU) and a vision system.

The scientific sensor suite would be selected to meet the mission objectives. Possible sensors include microscopes, panoramic cameras, mass spectrometers, gas analyzers, chemical sensors, and X or Alpha-Ray sensors. The sensor selection would take advantage of the large number of Microbots in a team by allocating different sensors to each robot, resulting in a diverse range of scientific measurements.

D. Communications and Electronics

The Microbot concept requires a number of different electronics subsystems, including subsystems for communication, computation and data storage, and power regulation. The Microbots need to communicate with each other and to transmit scientific data to a landing or orbiting craft. High frequency radio communication would allow for low power communication over long distances as well as the benefit of a small transmitter and receiver size [11]. This type of ultra-low power and ultra-compact communication technology has been developed, such as the chip show in Figure 5(a) that can send and receive wireless communication with minimal external components [12].

Communication from a subsurface location would be possible with the use of a local area network (LAN) where each of the Microbots operate as a node in the network. The Microbots could be instructed to stop at various penetration depths in order to maintain a communication link with the surface [5]. Non-line-of-sight communication has been shown to be possible in terrestrial caves at distances up to 20 meters [1].



(a) (b)

Fig. 5. (a) A single chip mote developed at UC Berkeley. (b) The off-the-shelf components required to regulate the power system.

The Microbots also require data processing, data storage and power regulation electronics. The current states of electronics in these areas are close to meeting the requirements of the Microbot system. Miniaturized computer systems can process Mbps of data in a very small volume at low power [11]. Highly efficient miniaturized electronics are available to regulate the electrical power generated by the fuel cell system (see Figure 5(b)).

IV. System Feasibility

The feasibility analysis presented in this paper focuses on the mobility and power systems of the Microbots. Other issues, such as the sensors, team navigation and thermal regulation present important technical challenges [4]. However, these are beyond the scope of this paper.

A. Reference Mission

To evaluate the feasibility of the Microbot system concept, a sample reference mission for lava tube cave exploration on Mars is considered. In this mission, the Microbots would be deployed on the surface of Mars, travel a kilometer over rough terrain, and then penetrate into a cave 500 meters while collecting scientific data (see Figure 6). It is assumed that to perform this mission, the Microbots must be able to execute 2000 one meter high hops on Mars. The mission duration is selected based on the desired hopping rate and the amount of time required to take sensor readings. For this study, it is assumed that this mission would be accomplished in 7 earth days, or about 6.8 sols (Martian days).

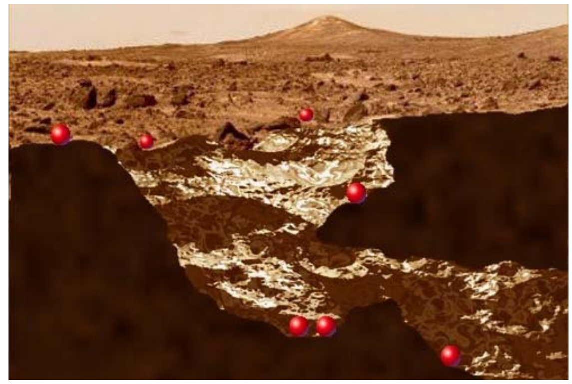


Fig. 6. A concept drawing of a team of Microbots entering a lava tube cave on Mars.

B. Feasibility Analysis

The two key questions addressed here are whether the system can provide enough power to successfully complete the mission and can the Microbot carry enough fuel to travel the required distance without exceeding the design constraints of size and weight? For this analysis, the desired Microbot mass is 100 grams and diameter is 100 millimeters. Table 1 summarizes these requirements.

TABLE 1

THE FEASIBILITY STUDY SYSTEM REQUIREMENTS

Mass	100 grams
Diameter	100 millimeters
Number of Hops	2000
Hop Height on Mars	1 meter
Travel Distance	1.5 kilometer

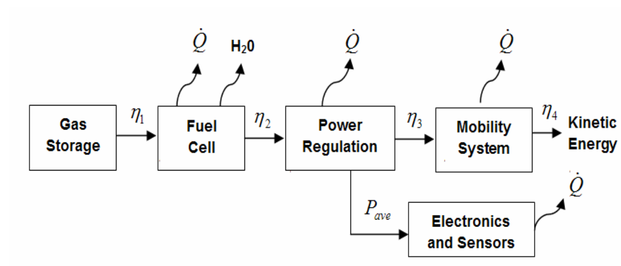


Fig. 7. The energy and power model of the Microbot system.

Figure 7 illustrates the energy conversion model used in this analysis.

In Figure 7, the symbols are:

1. η_1 is the efficiency of the fuel storage system, the ratio of mass of fuel divided by mass of the fuel storage system.
2. η_2 is the efficiency of the fuel cell, expressed as the percent of the lower heating value (LHV) of hydrogen that is converted into electrical energy, where the LHV is approximately 120,000 joules per gram of hydrogen.
3. η_3 is the electrical efficiency of the power regulation subsystem.
4. η_4 is the energy conversion efficiency of the

mobility system to produce kinetic energy.

5. P_{ave} is the average power draw of the electronics.

6. $\dot{Q}$ is the heat generated in each energy conversion process in the system. This generated heat is necessary for the thermal viability of the Microbot system in the cold Martian environment [4].

The following section analyzes these model parameters in greater detail.

C. *Efficiencies*

1) *Fuel Storage*

The efficiency of a fuel storage system, η_1, is equal to the percent of the fuel storage weight that is fuel. This dimensionless number is a useful metric for comparing different types of fuel storage systems. Here, the fuel and oxidizer are hydrogen and oxygen, which react in a 1:8 mass ratio.

Hydrogen is not as simple to store as oxygen due to its extremely low atomic weight. The current best methods for storing hydrogen are in chemical or metal hydrides or as liquid hydrogen [16]. Since using liquid hydrogen and chemical hydrides would add substantial system complexity, a metal hydride was chosen as the storage media. Currently the best metal hydride technology is sodium alanate, which stores hydrogen with a weight efficiency of 5.5%[16]. As additional packaging and regulation will be required, a conservative estimate for the overall hydrogen storage percent weight of 3.5% is used here.

Oxygen has a considerably larger atomic weight and can be stored as a compressed gas. The oxygen can be stored at high pressures using high-strength carbon fiber composites. Considering the weight of the container and pressure regulation required, a storage efficiency estimate is 35%.

2) *Fuel Cells*

The PEM fuel cell was selected because of its low operating temperature of 0-120ºC and efficiency as high as 70% [6]. Given the volume and mass constraints of the system, a conservative energy efficiency (η_2) of 60% is assumed for the fuel cell system. See Figure 8 for an example of miniature PEM fuel cells.

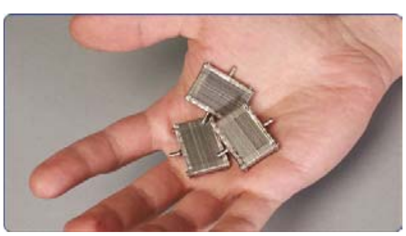


Fig. 8. Micro PEM fuel cells [15]

3) *Power Regulation*

The Microbot system requires 3-5 volts for its electronics and communication and 1-10 kilovolts for the DEA mobility elements. Using current technology, the low voltage regulator could have conversion efficiency as high as 96% [14]. A miniature high voltage converter could have efficiency as high as 85% at 10,000 volts (see Figure 9) [17]. Because these regulators might not always be operating at their optimal point, more conservative efficiencies are used: 90% for the low voltage regulator and 60% for the high voltage converter.

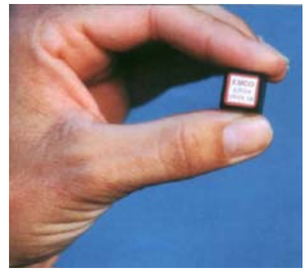


Fig. 9. A miniature high voltage DC-DC converter [18]

4) *Mobility System*

The efficiency of the mobility system is broken down into three components: the DEA, the bi-stable mechanism, and the mobility action. The main energy losses in the DEA are electrical current leakage through the elastomeric film and viscoelastic effects [8]. Current efficiency of the DEA to convert electrical power into mechanical work is on the order of 5% [20]. This value will be substantially increased as new materials are developed. For the purpose of this analysis, it is assumed that a DEA efficiency of 20% is a reasonable performance goal for the 10-year development timeframe. See Figure 10 for a demonstration of the capabilities of current Microbot laboratory prototypes.

The bi-stable energy storage mechanism has estimated efficiency of approximately 90%. The final element in the mobility system efficiency is the amount of energy that is lost during the hop, principally to soil deformation. Based on preliminary estimations, a thrust efficiency of 70% is selected [17]. The product of these three values, η_4, gives an overall mobility system efficiency of 12.6%.

Another performance metric of the mobility system is the specific energy, e_{DEA}, the work output per actuation cycle as a function of the DEA mass. Assuming space-quality DEA fabrication and development, this value is estimated to be on the order of 0.1 J/g [20]. This number is used to determine the mass of the mobility system.

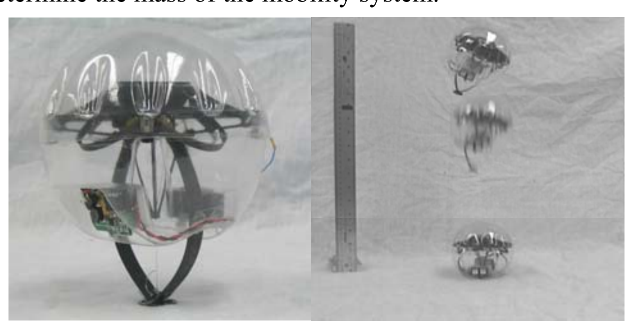


Fig. 10. A current prototype of the Microbot system composed of a DEA actuator, onboard energy storage, and integrated electronics.

5) *Electronics and Sensors*

Using MEMS sensors, ultra-high efficiency components, and distributed computation, the power demand of the electronics will be very low. For example, currently available commercial off the shelf (COTS) wireless sensor platforms are able to receive, process, and transmit data over high frequency radio communication with less than 50 mW of power [19], [5].

Since the largest power consumption in the electronics system is assumed to be the communication subsystem, and neither the sensors nor the communication systems must be on at all times, a duty cycled can be implemented that minimizes power consumption. Assuming a communications power consumption of 50 mW operating with a light duty cycle and the use of MEMS sensors and high efficiency integrated electronics, an average power demand of 0.1 watts was estimated.

The efficiency values discussed above are summarized in Table 2.

TABLE 2
THE SUBSYSTEM EFFICIENCIES USED IN THIS SYSTEM STUDY

	Efficiency
Hydrogen Storage	3.5%
Oxygen Storage	35%
Fuel Cell	60%
Low Voltage Regulation	90%
High Voltage Regulation	60%
DEA Actuator	20%
Bi-stable Mechanism	90%
Hopping	70%

D. Integrated System Feasibility

Given the efficiency values in Table 2 and system model in Figure 7, the goal of the feasibility analysis is to determine if a 100-gram Microbot can successfully perform the reference mission. The mass of the Microbot consists of several components. The first is the mass of the electronics and sensors, the Microbot shell and structure, and the fuel cells. The mass of these items is essentially a constant as it is not a strong function of the mission range and duration. Here a value of 35 grams is used. This number is based on current lab prototypes [5].

The other major mass elements are the mobility mechanism including its actuator and the fuel and fuel storage elements. The amount of fuel (hydrogen and oxygen) required is a function of the amount of energy required for the mission. The total energy, E_{total}, required from the fuel cell and power regulation systems is:

$$E_{total} = E_{electonic} + E_{KE} \tag{1}$$

where $E_{electric}$ is the energy consumed by the electronics and communications systems and E_{KE} is the mobility energy required to perform the mission. The energy required for the electronics is:

$$E_{electonic} = P_{ave} t_{mission} \tag{2}$$

where P_{ave} is the average power requirements of the electronics and $t_{mission}$ is the length of the reference mission.

Assuming the Microbot does not bounce or roll, the kinetic energy required for a N_{hops} hops mission is a function of total system mass (in this case 100 grams) and the assumed the hop-height (one meter):

$$E_{KE} = \eta_4 N_{hops} mgh \tag{3}$$

where m is the mass of the Microbot, g is gravitational acceleration, 3.69 m/s^2 on Mars, and h is the hop height. Note that energy required to orient the Microbot hopping foot is not considered here because it is less than 1% of the total hopping energy.

Referring to Figure 7, the fuel mass consumed to produce a given amount of electrical energy (E_{total}) is given by:

$$m_{H_2} = \frac{E_{total}}{\eta_2 \eta_3 LHV_{H_2}} \tag{4}$$

where m_{H_2} is the unconsumed mass of the hydrogen in the fuel storage device and LHV_{H_2} is the LHV for hydrogen at the Microbot operating temperature (120 kJ/gram).

The actuator mass is determined by the mobility system performance, the Microbot total mass, and the jump height:

$$m_{DEA} = \frac{mgh}{\eta_{Estorage} \eta_{hop} e_{DEA}} \tag{5}$$

where m_{DEA} is the mass of the DEA mobility actuator, $\eta_{Estorage}$ is the efficiency of the mechanical energy storage device, η_{hop} is the hopping thrust efficiency, and e_{DEA} is the specific energy output of the DEA per actuation. The mass of the Microbot (m) includes the mass of the DEA mobility system (m_{DEA}).

The number of possible hops, N_{hops}, can be calculated for a given kinetic energy and Microbot mass value:

$$N_{hops} = \frac{E_{KE}}{mgh} \tag{6}$$

IV. RESULTS

Figure 11 shows the number of hops as a function of total Microbot mass. These numbers assume a mission of 7 earth days and a constant power consumption of 100 mW for the electronics and sensors. Note that the total number of hops ignores the additional distance traveled by any bouncing or rolling.

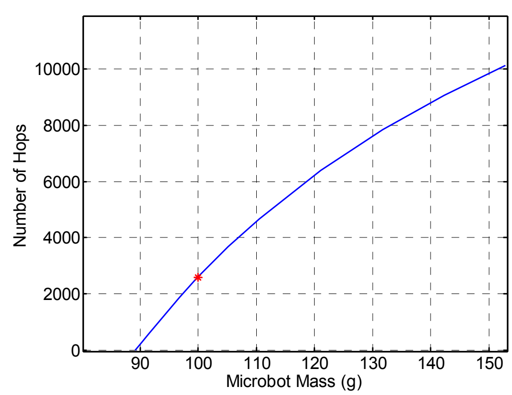


Fig. 11. A plot of the number of hop on Mars during a 7 earth-day mission as a function of the Microbot mass.

The results of the above calculations for a 100 gram Microbot are show in Table 3. A significant amount of the energy produced by the fuel cells is consumed by the electronics during the course of the 7 earth day mission. The fraction of the total energy consumed decreases as the total Microbot's mass increases. Thus, the fraction of the energy consumed by the mobility system increases with the mass. This information is summarized in Figure 12.

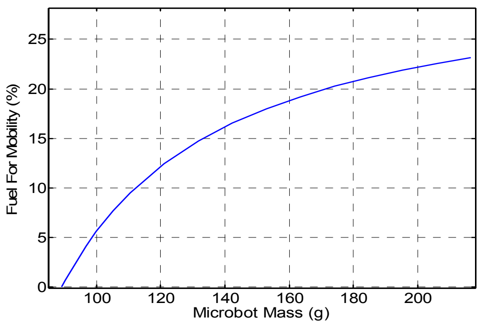


Fig. 12. The percent of the fuel that is consumed by the mobility system during a 7 earth-day mission to Mars.

The Microbot concept is able to successfully meet the design requirements and the reference mission specification. The heat generated by the Microbot system, $\dot{Q}$, is 0.22 watts. This is a sufficiently high value to ensure that the Microbot maintains an acceptable temperature in the cold Martian environment [4].

TABLE 3
THE RESULT OF THE FEASIBILITY STUDY FOR THE MICROBOT DESIGN

Total Oxygen Storage Mass	26 g
Total Hydrogen Storage Mass	32 g
DEA Actuator Mass	5.8 g
Fixed Mass Items	35 g
Total Mass	100 g
Number of Hops	2585
Mission Length	7 earth days
$\dot{Q}$	0.22 W

V. CONCLUSIONS

The integrated Microbot power and mobility systems discussed in this paper are shown to be feasible for the assumed reference mission. The feasibility analysis presented in this paper applies system efficiency values to the integrated Microbot system illustrated in Figure 7 and modeled in (1) – (6).

Using conservative values, the feasibility analysis has indicated that a 100 gram Microbot will be able to successfully complete the Martian reference mission, performing over 2000 hops. The feasibility analysis used conservative subsystem efficiencies values based on a 10 years design timeframe.

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