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GNC OF SHAPE MORPHING MICROBOTS FOR PLANETARY EXPLORATION

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In this paper we analyze the feasibility of inflatable microbots that can roll, crawl, hop and hover. Guidance, Navigation and Control is critical to the success of the microbot concept. Each microbot will have a mass of 0.25 kg, a stowed volume of 10 cm × 3 cm × 1 cm and consists of a compact system on a board, comparable to a smartphone. For this size and volume, thousands can dispersed on a planetary surface. These microbots can operate as swarm, with the advantage of concurrently covering the ground and atmosphere. The small footprint of these platforms could make them ideal secondary or tertiary payload on large rovers and landers. This main board would contain solar photovoltaics for power generation, an onboard computer, IMU, camera, a series motors and actuators, a MEMS powder or gas pump and MEMS vacuum pump. Importantly the robot would contain a set of inflatable bladders. The system would not use a battery due to its inherent vulnerability to temperature. Depending on their application, these bladders would be filled with CO_2 or filled with Martian regolith that would be vacuumed thus rigidizing into a solid structure or filled with hydrogen. The hydrogen filled microbots would float and hop over areas of interest. The bladder will be loosing some of the hydrogen over time and hence more hydrogen will be produced on demand to maintain a set average altitude. The ground based microbots by turning soft or rigid on demand, can crawl over obstacles or even sloped surfaces. Surfaces with very few rocky obstacles would benefits from having wheels. Here the wheels would consist of the inflatable bladder filled and rigidized with Martian regolith. When it is flat ground, with few obstacles, options include inflating sphere-shaped bladder with CO_2 that can be blown by the Martian wind.

INTRODUCTION

One of NASA's key goals is the search for past habitable environments and possibly past life on Mars, as outlined by NRC Planetary Science Decadal Survey [1]. NASA identified a critical need for new robotics technology to explore extreme environments [2]. Evidence of life having adapted to isolated environments on Earth strengthens the case for such environments to exist on Mars [3]. Orbital imagery and exploration using one or few rovers may lack the area coverage to identify these hidden environments. In this proposal, we present a low-cost, distributed network of shape-morphing robots that can perform surface exploration of

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rugged environments. These robots utilize inflatables filled with regolith and can vary their softness enabling them to crawl/grasp over obstacles including slopes, ridges and cliffs.

In this concept (**Figure 1**), each robot would have a mass of 0.25 kg, a stowed volume of 9 cm × 3 cm × 1 cm (similar to a chocolate bar) and consists of a compact system on a board, comparable to a smartphone. For this size and volume, thousands can dispersed on a planetary surface and atmosphere. This main board would contain solar photovoltaics for power generation, an onboard computer, IMU, camera, a series motors and actuators, a MEMS powder or gas pump and MEMS vacuum pump. Importantly the robot would contain a set of inflatable bladders. The system would not use a battery due to its inherent vulnerability to temperature. Depending on their application, these bladders would be filled with CO_2, filled with Martian regolith that would be vacuumed thus rigidizing into a solid structure or even H_2 to float in the atmosphere. The hydrogen filled microbots would operate as aero-bots that would slowly traverse the atmosphere and take overhead images of hard to reach terrain on Mars. Some of hydrogen will leak from the bladders over time and hence hydrogen will need to be produced on demand. By turning soft or rigid on demand, the robots can crawl over obstacles or even sloped surfaces [4-5]. This rigidizing process would be used to produce robots of various preset shapes depending on the surface environment. Surfaces with very few rocky obstacles would benefits from having wheels. Here the wheels would consist of the inflatable bladder filled and rigidized with Martian regolith. When it is flat ground, with few obstacles, options include inflating sphere shaped bladder with CO_2 that can be blown by the Martian wind.

The primary technical challenge for this concept lies with overall miniaturization and integration of the system components such as the inflatables into a small package suited for a planetary environment. A secondary challenge is thermal control to ensure all critical electronic components remain within a temperature of -40 ^{o}C to +60 ^{o}C. Control of tens to hundreds of robots to perform exploration have already been demonstrated in a laboratory setting [10-11, 20]. The potential for scaling up to thousands of robots is possible with a new of class of robust, decentralized, neuromorphic algorithms that require minimal computer hardware. The big advantage is the mass and volume savings possible by utilizing Martian resources either regolith, the atmospheric CO_2 in-situ or production of H_2 in-situ. The flying/floating microbots are naturally positioned to have low mass.

Our preliminary studies suggest 70 % launch mass savings if regolith were utilized. While this is not significant for a single miniature 0.25 kg robot, this can lead to 4-fold launch cost savings when scaled to 1,000 robots. Even more impressive is the new capabilities it can bring, enabling these robots to climb, crawl and fly. This is an important advantage for long duration mission, where there is significant need to have improvised tools and capabilities to address unexpected conditions. Knowing the rock distribution and obstacles in a particular area, it may be possible to inflate into place the right sized wheels or sphere to traverse these obstacles. When the rock field is too dense, it may make sense to fly over the obstacle field to get to the next terrain. Even more interesting is the possibility of inflating a spare wheel, a spare flying bladder or spare part when a critical component is damaged or destroyed.

In the following paper we analyze the initial feasibility of the microbot concept, particularly Guidance, Navigation and Control (GNC) and the potential for networks of tens or hundreds of robots for performing area coverage and exploration. In the next section we report on related work on inflatables and their use in space exploration. In the following section, we present the system concept of a chocolate bar-sized robot deploying into a ground robot with wheels, a spherical robot or a flying aerobot. This is followed by a section analyzing subsystem feasibility and discussion of the concept followed by conclusions.

RELATED WORK

Advancing inflatable robots enable shape morphing capabilities that can position these systems to operate on the ground and atmosphere of an off-world environment. Aside from traditional wheel-based designs, dynamic hopping designs have also been explored recently. Some of these hopping rovers use mechanical hopping, which utilizes a spring mechanism, creating a direct reactive force to push the robot from the surface. However, even with a spring-loaded mechanism, it is difficult for the robots to maneuver accurately around objects. The inflatable shape morphing bots currently being developed will be able to use a regulated amount of regolith to fill the

Figure 1: JPL's Inflatable rover concept traversing rugged planetary environment.

inflatable hemispheres to maneuver around obstacles and rugged terrain environments. The inflatables can also use lighter than atmosphere gases such as hydrogen to simply fly/float over large obstacles fields. There is also the potential for the robots to use the combination of ballast and lighter than atmosphere gases to perform long duration hops.

These proposed inflatable, shape-morphing microbots follow an illustrious history of other inflatable systems playing critical parts in off-world exploration. For example, the first planetary balloon flew on the Soviet Vega mission in December of 1984 [14]. Each spacecraft deployed a 1500 kg descent module towards Venus, and the main spacecraft were retargeted toward Comet Halley, in June of 1985. The descent modules separated into two parts, the lander and the balloon package. The Vega 1 balloon lasted about 56 minutes and the Vega 2 balloon transmitted data for 46.5 hours. However, both landers reached the surface and successfully returned data about the Venusian atmosphere and soil composition.

Since then, several other inflatable robots have been proposed and/or developed for planetary and asteroid exploration. One of these being the AMIGO (Asteroid Mobile Imager and Geologic Observer) designed by UA SpaceTREx. AMIGO [15] is a low-cost version of the SphereX spherical robot [13]. The Hedgehog robot is another concept intended to explore low-gravity environments and uses reaction wheels to hop [16]. AMIGO uses low-cost electronics and importantly an inflatable for mobility, communications [17] and tracking. AMIGO is a semi-inflatable robot designed to operate in a swarm to characterize an asteroid surface. Upon descent, the robot inflates from its 1U state. The inflatable component of the AMIGO design is pivotal to the multi-functionality of the robot since it also addresses the issue of tracking a small lander of the surface of an asteroid and allows for a 1U stowed state within a mother spacecraft.

Other examples of inflatables robots include the 3-wheeled JPL inflatable rover. The rover can attain a large size relative to this stowed volume, enabling it to roll over obstacle fields [18]. In addition, it has a large inflatable communications antenna for transmitting high-resolution images and sensor data. It is unclear how much control authority was possible with the three wheeled inflatable rover. Another robot is the tumbleweed robot that consist of a single inflated sphere, with a system to dynamically move the center of mass. This permits controlled rolling. It is important to note that the inflatable rovers have the potential traverse over obstacle fields and explore high-priority targets on Mars for very little payload footprint. In our concept, we exploit the swarm collective organization to deploy tens to thousands of inflatable robots that can cover wide swathes of the surface of an off-world environment for low-cost.

THE MICROBOT SYSTEM - ROVER

In this concept (Figure 2), each robot would have a mass of 0.25 kg, a stowed volume of 9 cm × 3 cm × 1 cm and consists of a compact system on a board, comparable to a smartphone. Earlier concepts of a microbot was rigid and lacks some of the advantages described here [7, 8]. Up to 27 of these microbots are stowed into vertical racks inside a 1U CubeSat sized deployer. For this size and volume, hundreds can be dispersed on a planetary surface.

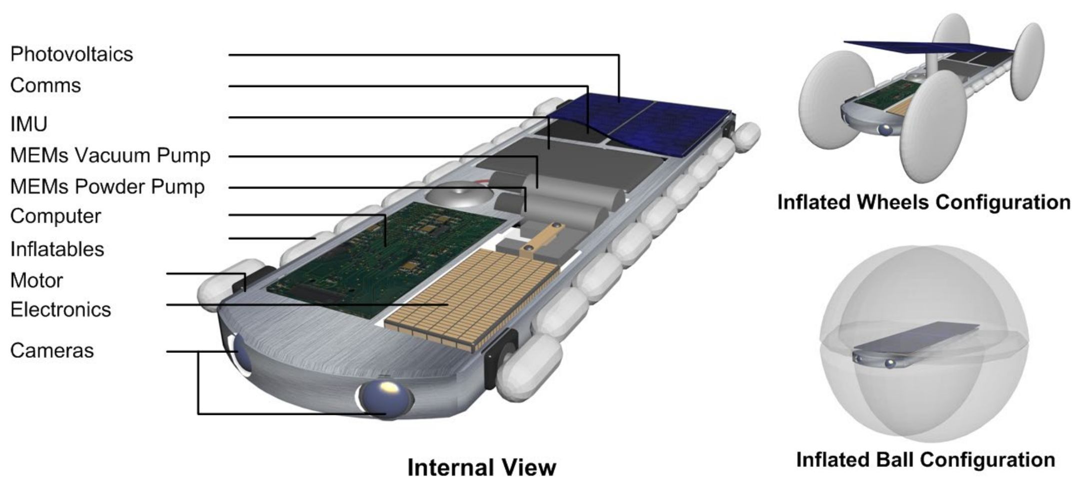

Figure 2. (Left) Microbot Stowed Configuration. (Right) Deployed configurations.

Swarms of these robots could form large structures including communication antennas [11], weather networks and seismic stations. This main board would contain solar photovoltaics for power generation, an onboard computer, IMU, camera, a series motors and actuators, a MEMS powder or gas pump and MEMS vacuum pump. Importantly the robot would contain a set of inflatable bladders.

The system would not use a battery due to its inherent vulnerability to temperature. Depending on their application, these bladders would be filled with lunar regolith that would be vacuumed thus rigidizing into a solid structure. By turning soft or rigid on demand, the robots can crawl over obstacles or even sloped surfaces [4-5]. Surfaces with very few rocky obstacles would benefits from having spherical body. Here the spherical body would consist of the inflatable bladder filled and rigidized with lunar regolith.

The primary technical challenge for this concept lies with overall miniaturization and integration of the system components such as the inflatables into a small package suited for a planetary environment. A secondary challenge is thermal control to ensure all critical electronic components remain within a temperature of -150 °C to +120 °C. Control of tens to hundreds of robots to perform exploration have already been demonstrated in a laboratory setting [10-11]. The big advantage is the mass and volume savings possible by utilizing lunar resources such as regolith. Our preliminary studies suggest 70 % launch mass savings if regolith were utilized. While this is not significant for a single robot, this can lead significant saving when scaling to 100s of robots (Table 1).

Even more impressive is the new capabilities it can bring, enabling these robots to climb and crawl. This is an important advantage for long duration mission, where there is significant need to have improvised tools and capabilities to address unexpected conditions. Knowing the rock distribution and obstacles in a particular area, it may be possible to inflate into place the right sized sphere to traverse these obstacles. Thanks to this inflation system, significant launch costs could be reduced at the end of a mission. It is presumed launch cost to the lunar surface is $1,000,000/kg.

Table 1. Cost Savings from Inflatable Deployment of Ground Robots

Configuration	Stowed Mass [kg]	Deployed Mass [kg]	#	Launch Cost Savings
Inflatable System	0.44	1.35	100	$100 million
Rigid System	1.35	1.35	100	-

THE MICROBOT SYSTEM - HOVERING AEROBOT

A second configuration of microbots considered is an aerobot. Each aerobot is 0.25 kg and has a stowed volume of 9 cm × 3 cm × 1 cm would contain nearly 8 grams of H_2 to inflate a balloon that would enable the microbot to hover/float above ground. The hydrogen is stored in the form of lithium hydride (LiH) and water (H2O). When mixed together, the reaction releases hydrogen gas:

$$LiH + H_2O \rightarrow H_2 + LiOH \qquad (1)$$

The aerobot would inflate to 13 m^3 in the Martian atmosphere sufficient to lift the full 0.25 kg mass of the system. Presuming 10% of the hydrogen is lost through permeation from the bladder membrane, there is sufficient H_2 to allow the vehicle to float continuously for 90+ sols.

The aerobot will be powered using solar power, receiving up to 0.5 W during daytime and approximately 5 Whr of electrical energy per sol. Electrical energy will be required to power all the onboard electronics, sensors and UHF communications. In addition, the aerobot will power an onboard pump that will regulate control of H_2 volume within the bladder. The regulation of H_2 volume will be used to control altitude of the aerobot in the Martian atmosphere. Additionally, the H_2 gas can be heated using sunlight. The inflatable membrane will consist of Mylar which is resistant to hydrogen leakage and carbon nano-particles that collect sunlight and turn it into heat at 99% efficiency [19].

When the aerobot needs to gently land or lower altitude just above ground, it will pump some of the H_2 gas back into an aluminum storage tank. Furthermore, the aerobot could perform gentle hopping maneuvers and pitch maneuvers by constantly controlling volume of H_2 in its inflatable bladder using an onboard pump. Roll and yaw control will be possible using a single thrust vectored electrical propeller system.

Table 2. System Specifications of the Aerobot

Mass	0.25 kg
Stowed Volume	9 cm × 3 cm × 1 cm
Deployed Volume	13 m^3
Power In (Solar)	0.5 W (daytime)
Flight	Buoyant Gas
Buoyant Gas	H_2
Mission Life	90+ sols
Buoyant Gas Lost /Sol	10%
Gas Storage	LiH, H_2O – 100 g
Max velocity	1 m/s

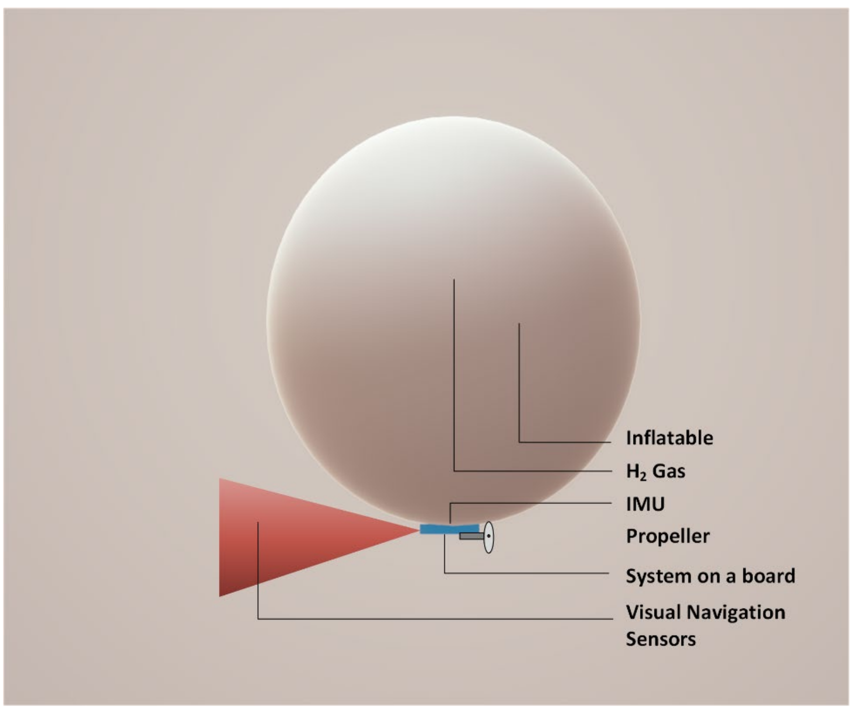

Figure 3. Aerobot Sketch

NETWORK EXPLORATION

In this following section we describe strategies to enable network exploration using a swarm of microbots [12]. The lunar and Martian surface is scattered with fragments of rocks and large boulders. These objects maybe dangerous obstacles for the microbots. A key requirement is to avoid them. So, the system of multiple microbots deployed on the lunar or Martian surface are required to avoid obstacles, while maximizing area coverage. A third requirement is that the microbots maintain multiple communication links so that acquired science data may be communicated effectively to a mothership.

In this section, we describe an algorithm developed to distribute a fleet of N Microbots on the lunar surface and Martian surface (Table 3). For the lunar surface it is possible to use the ground robot configurations. While on Mars it is possible to use the ground robots and aerobots. We use the concept of virtual forces to repel each lander from the rest of the fleet.

Table 3. Pseudo-code for area coverage maximization using a fleet of lander.

Algorithm: Maximize coverage for multiple landers

Require: Initial position, orientation for all landers $i = 1 \text{ to } N$;

1. Compute the Euclidean distance between each lander;
2. Compute the degree D for each lander based on the communication range (R_c);
3. Compute the Euclidean distance between each lander and its neighboring obstacle;
4. **for** $k = 0$ to K **do**
5.   **for** $i = 1$ to N **do**
6.   Compute the net force on lander i,
      according to (8) - (11);
7.   **end for**
8.   **for** $i = 1$ to N **do**
9.   **for** $t = 0$ to $k+1$ **do**
       Move each lander i according to (12)
      end for
10.   At $t = k+1$, compute the new
11.   Euclidean distances and degree D;
   end for
12. **end for**

The microbots are all identical and operate in a distributed fashion without relying on a single surface asset. They have equal sensing range (R_s) and equal communication range (R_c). Each robot can communicate its location and orientation to its neighbors and has navigation sensors to locate and characterize obstacles.

In our area coverage algorithm [12], the microbots interact with each other through a combination of global repulsion combined with local, limited attraction. The repulsion and attraction are achieved using a concept called *virtual forces* that we simulate to enable collective control over the microbots. The modelled *virtual forces* used to position the microbots are of three kinds: F_{cov}, F_{com} and F_{obs}. F_{cov} causes the microbots to repel each other to maximize the sensing range of the target area, F_{coms} constrains the degree of communication links for each lander by attracting microbots (locally) when they are on the verge of losing connection. F_{obs} causes the microbots to move away from neighboring obstacles [12]. Considering a network of N

microbots *1, 2, 3… N* with positions $r_1, r_2, r… r_N$ respectively and $||r_{ij}||$ representing the Euclidean distance between microbots *i* and *j*, F_{cov} and F_{coms} are defined in (2) and (3) respectively:

$$F_{cov}(i,j) = \left(\frac{C_{cov}}{\|r_{ij}\|}\right)\left(\frac{r_i - r_j}{\|r_{ij}\|}\right) \tag{2}$$

$$F_{com}(i,j) = \begin{cases} \left(-C_{com}\|r_{ij}\|\right)\left(\frac{r_i - r_j}{\|r_{ij}\|}\right) & if\ degree < D \\ 0 & otherwise \end{cases} \tag{3}$$

Similarly, for *L* obstacles *1, 2, 3… L* with positions $r_1, r_2, r_3… r_L$ respectively and $||r_{il}||$ representing the Euclidean distance between lander *i* and obstacle *l*, F_{obs} is defined as follows.

$$F_{obs}(i,l) = \left(\frac{C_{obs}}{\|r_{il}\|}\right)\left(\frac{r_i - r_l}{\|r_{il}\|}\right) \tag{4}$$

Where, C_{cov}, C_{com} and C_{obs} are the force constants and the net force experienced by lander *i* can be expressed as follows:

$$F(i) = \sum_{j=1, j\neq i}^{N}(F_{cov}(i,j) + F_{com}(i,j)) + \sum_{k=1}^{L} F_{obs}(i,k) \tag{5}$$

The equation of motion for lander *i* can then be formulated as:

$$m_i \frac{d^2 r_i}{dt^2} + \mu_i \frac{dr_i}{dt} = F(i) \tag{6}$$

Where, m_i is the mass and μ_i is the damping factor of lander *i*. When the distance between two microbots tends to zero, $||F_{cov}|| \rightarrow \infty$ to avoid collisions. When the degrees of connection between a lander and neighbor is less than *D*, $||F_{com}|| > 0$ to prevent loss of connection. Similarly, $||F_{obs}|| \rightarrow \infty$ when the distance between a lander and an obstacle tends to zero to avoid collisions.

For simulation of the stated algorithm, we considered 40 microbots deployed at random positions inside a square test area. Each lander has a communication range, R_c = 5 units and sensor range, R_s = 2.5 units. The target area consists of obstacles of random sizes at random positions. The 40 microbots must move in the 2-D space in such a way that it maximizes the coverage area, avoiding collision with each other and the obstacles and maintaining a degree of communication links, *D* = 3. Figure 4 shows the lander positions at different times. The microbots disperse to maximize distance while maintaining a communication link between two neighbors. The red dots are the obstacles, black dots the microbots and the lines connecting them are the active communication links

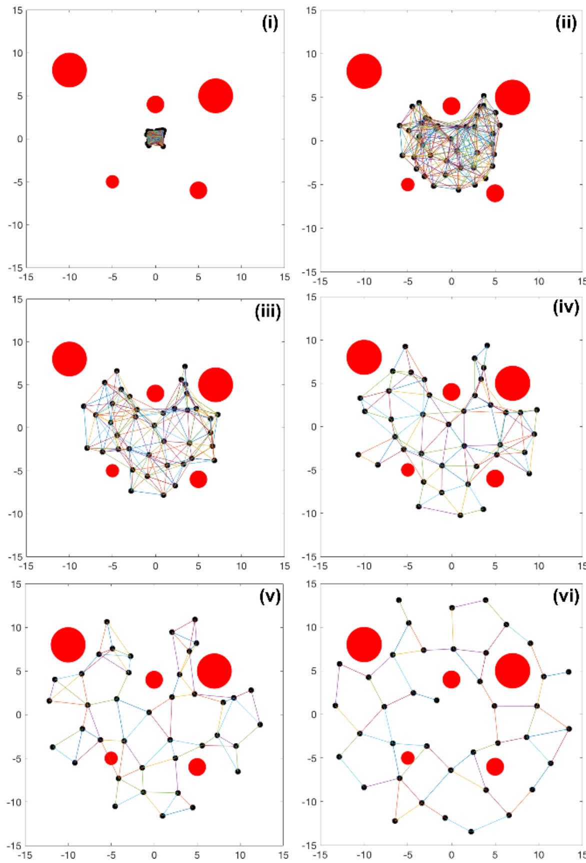

Figure 4. Simulation of a system of 40 Microbots at timestep 0, 15, 30, 60, 100 and 200.

Figure 5 shows the variation of the coverage area with time for different values of D = 2,3,4,5, and 6. The swarm of microbots can provide unique and very detailed measurements of a spacecraft impacting onto the asteroid surface. Figure 6 shows a second simulation of a swarm of robots being simulated to repel a target area and form 'donut' around the area. This will enable the swarm to track and record the impact event and collect data from multiple viewpoints. The red dots are the obstacles and the black dots are the microbots. The microbots were placed randomly on the target area and the impact event is supposed to take place at coordinates (3, -1). Each lander positions itself to be at a safe distance from the target impact site, while avoiding obstacles.

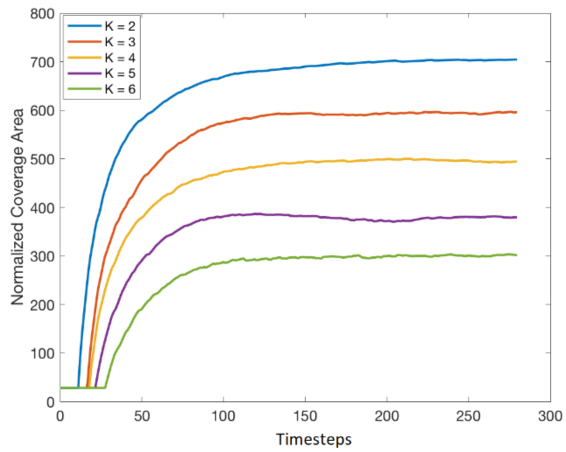

Figure 5. Area coverage by a swarm of 40 robots with respect to settling timesteps.

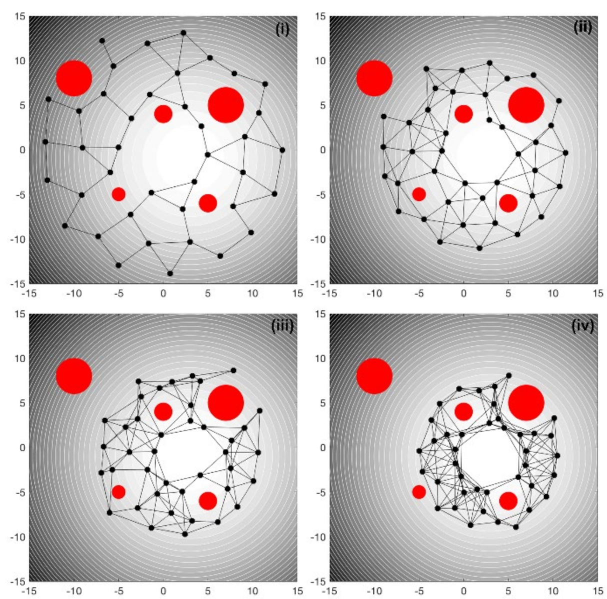

Figure 6. Simulation of a system of 40 microbots commanded to avoid a target impact site at 0, 50, 100 and 150 timesteps.

These results show that we can organize swarms of microbots into predetermined patterns (such as donuts) to monitor ground events. In addition, we can use this technique enable maximum area coverage taking into account constraints of multiple communication links.

As depicted in Figure 4, 5 and 6 these inflatable shape morphing bots can deploy in multiples from a CubeSat, creating a swarm which will maximize their return and minimize cost. Our future analysis, points towards the feasibility of such systems being distributed in large numbers on planetary surfaces while conforming to CubeSat design specifications. The results of our present work will provide insight into the structural dependability and lead to prototype development.

CONCLUSION

In this work we analyze the preliminary feasibility of deploying microbots that utilize in-situ or stored resources to attain a deployed configuration. The microbots are packaged as a 'systems on a board' the size of a typical smartphone. Upt o 27 of these microbots are stowed into vertical racks inside a 1U CubeSat sized deployer. The microbots can deploy into ground robots with wheels, a spherical rolling/hopping robot or into hovering aerobots. The hovering aerobots would generate hydrogen on demand to inflate and hover/fly-over obstacle fields. The system will use visual cameras for navigation. Our initial studies these aerobots can travel up to 1 m/s and remaining floating for 3 months or more. Utilizing scores of these microbots it maybe possible to systematically explore a region while maintaining one or more communication links with each node. We show it is possible to attain maximum area coverage using these swarms. Furthermore, we show the robots can arrange themselves into desired configurations for on the ground event observation from multiple views. Overall, we show a promising low-cost pathway to deploys hundreds if not thousands of microbots to perform large scale surface and near-surface exploration.

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