Shape Morphing Microbots for Planetary Exploration

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Abstract— **NASA has expressed a demand for new explorative robotic technology as the search for previously habitable environments progresses. Exploration, utilizing one or few rovers may restrict the scouting range causing a lack of discovery of hidden environments. Current planetary robotic systems contain single robots that have rigid and prebuilt components. All of which have high launch costs and are incapable of exploring extremely rugged environments. Utilizing innovative and low-cost inflatable robot technologies it is possible to conceive short, low-cost, high-risk, high-reward missions.**

Our current work focuses on networks of cost efficient inflatable Microbots with the intent of rugged environment exploration. These robots deploy inflatables filled with regolith which vary softness allowing them to crawl over obstacles. The generic architecture of these shape-morphing Microbots has been developed and is suitable as a payload on board satellites of size 1U and above. 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, lead to prototype development, texting, and improvement.

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1. INTRODUCTION

The ability to explore new planetary environments will provide answers to major questions regarding sources of matter, environmental conditions and potential sites for a base. Although portions of the lunar surface have been explored in the past, most of it is still unexamined. There are also several lava tubes on the moon that may lead to tunnels beneath the surface. Many of these have not yet been traversed due to the size and mobility constraints of most rigid lunar rovers. Several concepts currently being studied utilize small disposable robots to explore these environments [1]. This includes inflatable shape-morphing Microbots. These Microbots have the potential to overcome obstacles in rough terrain and enable more in-depth planetary ventures with their miniature sizing. The soft body of the Microbots could enable them to traverse tight gaps and withstand hard impacts.

The miniaturization of electronics, sensors and actuators, and wide-availability of high-reliability COTS components has made the small satellite revolution possible. In addition, the CubeSat approach has provided standard that has enabled a commercial marketplace of modular components. Utilizing these low-cost technologies, it is possible to conceive short, low-cost, high-risk, high-reward missions. To date, CubeSats have been proposed as Earth-orbiting and planetary spacecraft on flyby missions. A few have been proposed for orbital missions. By utilizing CubeSat landers, multiple inflatable Microbots could be deployed in swarms, maximizing return.

Our current work focuses on networks of cost efficient inflatable Microbots with the intent of rugged environment investigation. These robots deploy inflatables filled with regolith which vary softness allowing them to crawl over obstacles. Unlike other robots in the past, these Microbots are designed to utilize in-situ regolith to attain their mass and strength, and to shift their center of mass, resulting in their motion. Previous robots would use a reaction wheel within them, whereas these do not necessarily need one to generate their motion. The generic architecture of these shape morphing Microbots has been developed using SolidWorks and is suitable as sub-payloads on board satellites of size 1U and above. We compare the potential launch cost saving of rigid Microbots vs the proposed inflatable design. Each Microbot is packaged into the size of a chocolate bar, 9 cm × 3 cm × 1 cm. A single 1U CubeSat can deploy 27 of these Microbots and a 3U can deploy 81 Microbots. These Microbots utilize in-situ sand to inflate into a sphere of 10 cm diameter. There are many methods of mobility across rugged planetary terrain. Most previous designs have been traditional rovers, well suited for small obstacles. However, in rugged terrain environments, caves and lava tubes, traditional rigid and wheel-based rovers tend to fall short with obstacle avoidance and conquering.

In Section 2.0 we analyze past and related work, followed by presentation of the Microbot in Section 3.0. In Section 4.0 we extend the Microbot concept to network exploration. In Section 5.0 we present Conclusions and Future Work.

2. RELATED WORK

Advancing shape-morphing technologies enable the possibility of down-sizing traditional rovers while improving mobility on planetary surfaces. 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 inflatable hemispheres to maneuver around obstacles and rugged terrain environments.

The first planetary balloon flew on the Soviet Vega mission in December of 1984 [2]. 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.

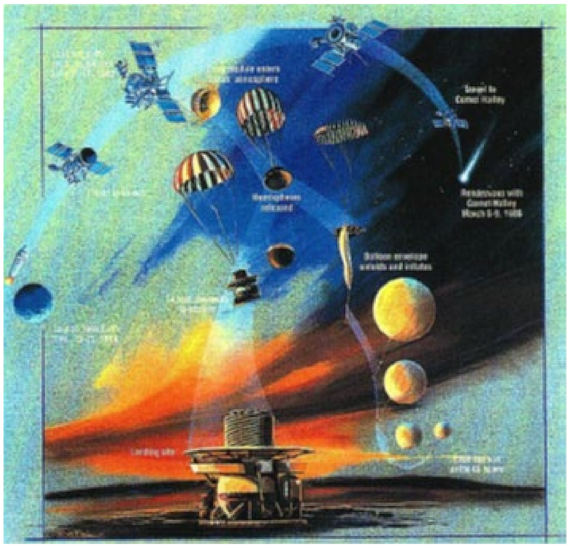

Figure 1. Soviet Vega mission depiction

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, shown in Figure 2. AMIGO [4] is a low-cost version of the SphereX spherical robot [3]. The Hedgehog robot is another concept intended to explore low-gravity environments and uses reaction wheels to hop [9]. AMIGO uses low-cost electronics and importantly an inflatable for mobility, communications [10] 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.

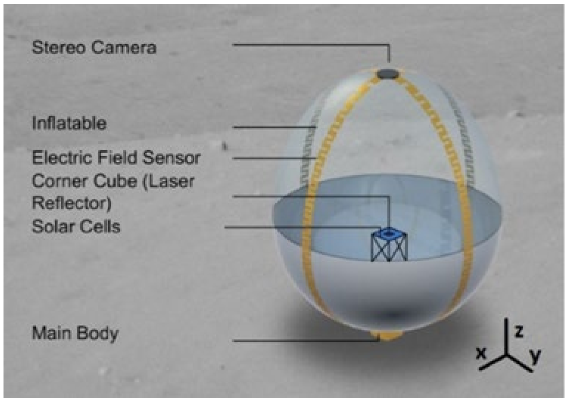

Figure 2. AMIGO Design Overview [4]

3. THE MICROBOT

In this concept (Figure 3), each robot would have a mass of 0.44 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]. For this size and volume, hundreds can be dispersed on a planetary surface.

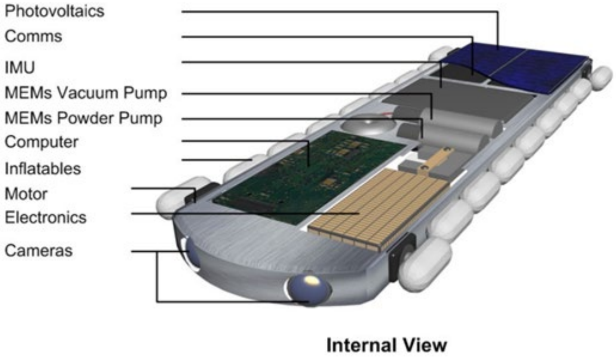

Figure 3. Microbot System Layout

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 ºC to +120 ºC. 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

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	-

Designing and developing an inflatable design to fit within a 3U CubeSat while still providing excellent camera images and housing miniature science instruments is the main objective of our current work. CubeSat are now widely adopted as secondary payload on rockets, orbiting spacecraft and landers. Figure 4 shows the Microbots being dispersed from a 3U CubeSat deployed on the Moon. The CubeSat chassis ejects a series chocolate-bar-sized robot that then inflate and gain 1 kg of mass.

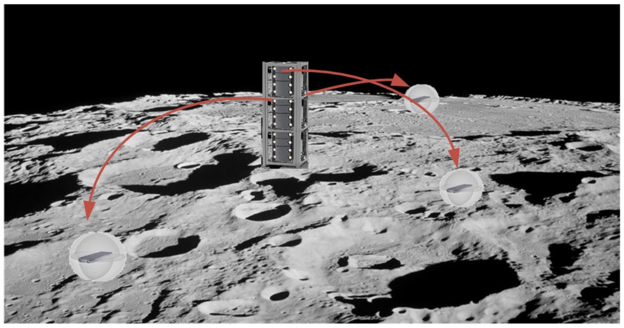

Figure 4. Inflatable Microbot Deployment from 3U CubeSat

3.1 System Architecture

The Microbot utilizes an ARM 11 microprocessor (Figure 5) equipped with 512 MB ram and 4 GB of flash for computing. Erasable data are two 16 GB solid state storage for storing the OS, computer programs and collected data. The robot has separate modules for electrical power system, thermal management, inflation system, IMU, UHF radio, mobility system that are based on the TinyCircuits size and dimensions. The main sensors are a stereo camera and temperature sensors.

The stereo cameras and IMU will be used to perform localization and compute direction. Another major subsystem is the thermal control system. As the surface of the Moon can undergo severe temperature change from -150º C to 120 ºC. thermal management system will be kick into operation to retain the generated heat from the electronics. The use of sand to fill-up the wheels makes the spherical rover well insulated and a form of ballast.

3.2 Mass Budget

The preliminary mass budget for each Microbot is given below (Table 2). The components for the inflatable and

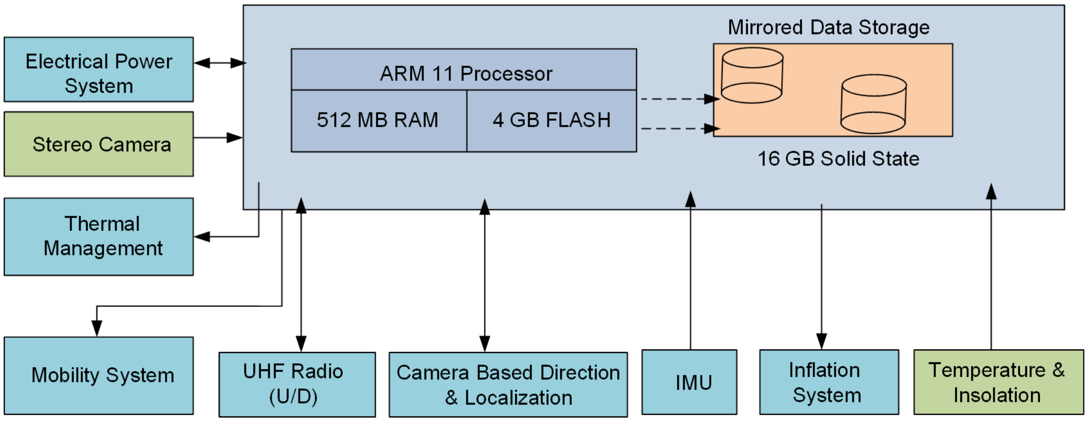

Figure 5. Microbot Computer System Architecture.

structural subsystem take up 135 g. The next major components are the stereo camera, 73 g and avionics which is 64 g while the power system including the battery, solar panel and power electronics take up 61 g. Overall, we also include a 25% mass margin sufficient to account for uncertainties in the system design.

Table 2. Microbot Mass Budget

Item	Mass (g)
Avionics, IMU & Computer	64.2
Power Subsystem	60.5
Communication Subsystem	7.0
Thermal Subsystem	15.0
Structure & Inflatable	60.0
Inflatable Pump	75.0
Stereo Camera System	73.0
Margin (25 %)	89.0
Total	444.0

3.3 Regolith Pump

One major step in the improvement of the Microbot design is creating a dual-purpose pump that will take in regolith but also be able to remove air when needed. Another hurdle encountered is creating the dual-purpose pump small enough to fit within the given size constraints. For this, a 3-D printed part will most likely be used in the prototyping of the pump. Once a design is finalized and tested to withstand the given pressure, volume, and power requirements a 3-D model will be generated and tested to ensure the functionality. The proposed pump is based on the De Dietrich powder handling system (Figure 6).

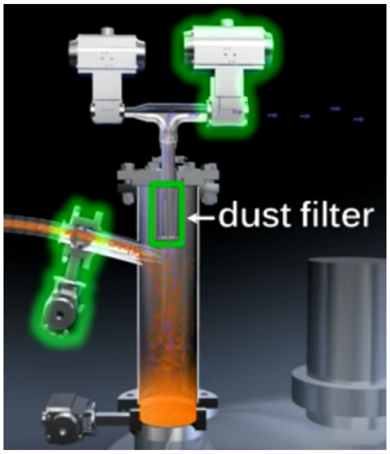

Figure 6. De Dietrich powder pump system [5].

The design for this custom regolith pump will be based off a model similar to a small-scale component of the De Dietrich powder handling system [5]. The De Dietrich powder handling system is comprised of a vacuum source, to remove air from the pump body. From a powder inlet valve, powder enters the pump body while dust and debris are carried through a dust filter and out the vacuum source. A system layout is shown in Figure 7 and it show prototype stowed configuration and deployed configuration. This system contains multiple parts that will not be needed on the miniaturized pump for the Microbot design. However, a similar concept will be investigated and implemented for the prototyping procedure.

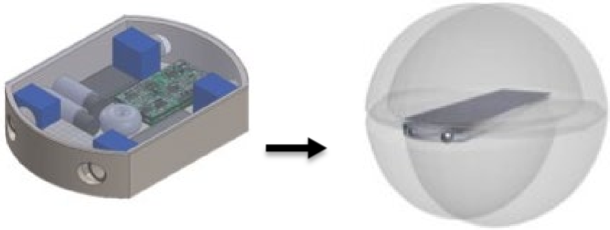

Figure 7. Robot deployment through inflation of bladders using regolith,

3.4 System Level Prototyping and Testing

Future work will consist of testing the integrity of the inflatable and creating a prototype, testing, and verifying data through calculation and analysis software to confirm compliance with the system requirements. In order to verify the systems structural integrity, ANSYS will be used to simulate the forces, stresses and strains that are expected for the system to encounter throughout its mission. Along with the simulation will be a thermal mapping of the system to provide evidence that all components shall survive for the expected time frame.

As has been determined [6], the grain size of mature lunar soil varies from about 10 % being greater than 1 mm, 50% being greater than 100 microns, and 90% being greater than 10 microns. Using this data, as shown in Figure 8, the power required from the pump components will be calculated and tested within the prototyping stages.

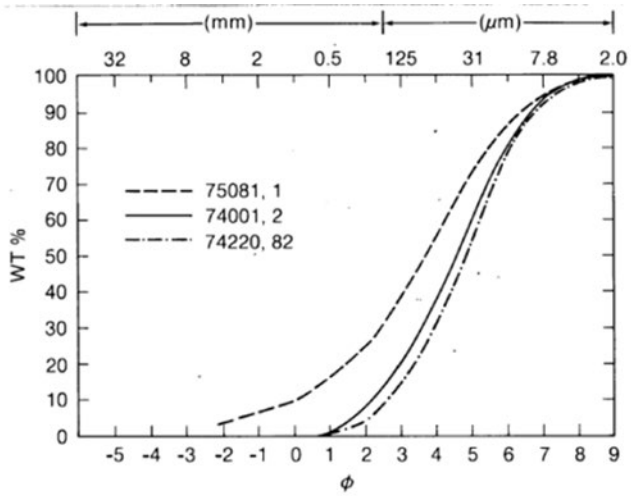

Figure 8. Grain Size of Lunar Regolith [6]

4. NETWORK EXPLORATION

In this following section we describe strategies to enable network exploration using a swarm of Microbots. The lunar 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 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 (Table 3). 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 $i$= $1$ to $N$;
Compute the Euclidean distance between each lander;
Compute the degree $D$ for each lander based on the communication range ($R_c$);
Compute the Euclidean distance between each lander and its neighboring obstacle;
for $k$ = 0 to $K$ do
    for $i$ = 1 to $N$ do
        Compute the net force on lander $i$, according to (8) - (11);
    end for
    for $i$ = 1 to $N$ do
        for $t$ = 0 to $k+1$ do
            Move each lander $i$ according to (12)
        end for
        At $t = k+1$, compute the new
        Euclidean distances and degree $D$;
    end for
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 lander can communicate its location and orientation to its neighbors and has a laser rangefinder to locate and characterize obstacles.

In our area coverage algorithm, 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 nano-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 [15]. Considering a network of N Microbots $1, 2, 3 \ldots N$ with positions $r_1, r_2, r \ldots r_N$ respectively and $\|r_{ij}\|$ representing the Euclidean distance between Microbots i and j, F_{cov} and F_{coms} are defined in (8) and (9) respectively:

$$F_{cov}(i,j) = \left(\frac{C_{cov}}{\|r_{ij}\|}\right)\left(\frac{r_i - r_j}{\|r_{ij}\|}\right) \quad (1)$$

$$F_{com}(i,j) = \begin{cases} \left(-C_{com}\|r_{ij}\|\right)\left(\frac{r_i - r_j}{\|r_{ij}\|}\right) & if\ degree < D \\ 0 & otherwise \end{cases} \quad (2)$$

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

$$F_{obs}(i,l) = \left(\frac{C_{obs}}{\|r_{il}\|}\right)\left(\frac{r_i - r_l}{\|r_{il}\|}\right) \quad (3)$$

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:

$$F(i) = \sum_{j=1, j\neq i}^{N}\left(F_{cov}(i,j) + F_{com}(i,j)\right) + \sum_{k=1}^{L} F_{obs}(i,k) \quad (4)$$

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

$$m_i \frac{d^2 r_i}{dt^2} + \mu_i \frac{dr_i}{dt} = F(i) \quad (5)$$

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 9 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

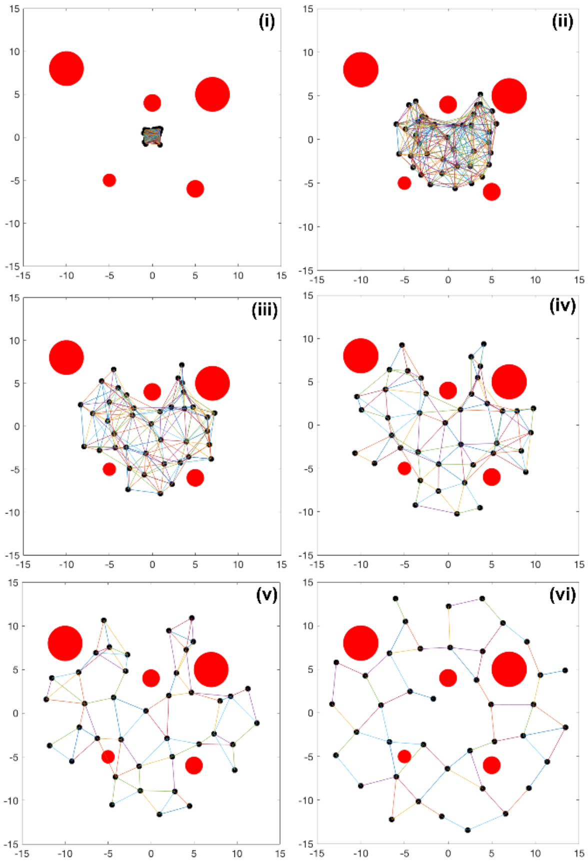

Figure 9. Simulation of a system of 40 Microbots at timestep 0, 15, 30, 60, 100 and 200.

Figure 10. shows the variation of the coverage area with time for different values of $D = 2,3,4,5$, and 6. The swarm of nano-Microbots can provide unique and very detailed measurements of a spacecraft impacting onto the asteroid surface. Figure 11 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.

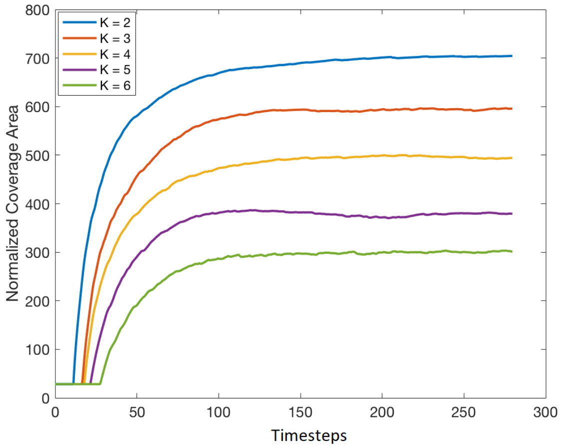

Figure 10. Area coverage by a swarm of 40 robots with respect to settling timesteps.

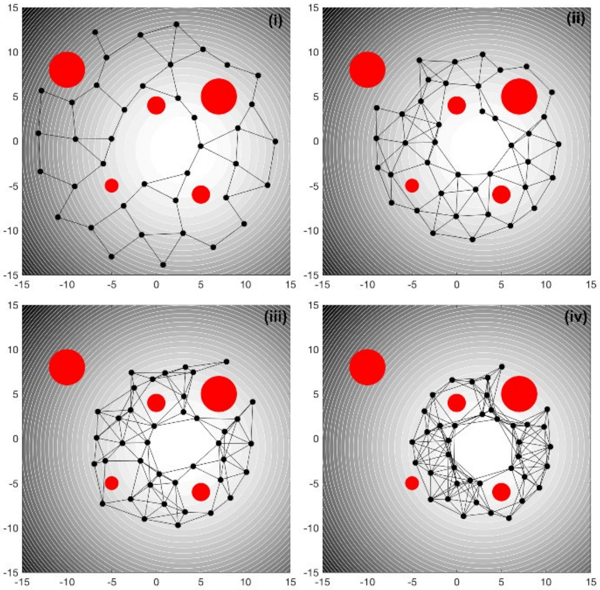

Figure 11. Simulation of a system of 40 Microbots commanded to avoid a target impact site at 0, 50, 100 and 150 timesteps.

These results show that we can organize swarms of microbots into predetermined patterns (such as donuts) to monitor impact 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, 9 and 11 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.

5. CONCLUSIONS

The next major phase of lunar exploration will benefit from sending hundreds or thousands of surface explorers such as the presented Microbots. These Microbots could provide in-situ pictures and measurements and provide "Google Streetview" coverage of the surface of the moon. We have analysed the preliminary feasibility of operating scores of Microbots, each 1.35 kg in mass. These Microbots would hop and roll over the lunar surface. Hopping will be achieved by rolling at high speeds and climbing over inclines. The Microbots would include science instruments such as stereo cameras and accelerometer to perform geological characterization of the surface. A network of Microbots situated on the surface of the moon can provide unique and detailed in-situ measurements of a spacecraft impacting nearby. In this work, we demonstrate an algorithm that utilizes the concept of *virtual forces* to enable a decentralized swarm of Microbots to effectively attain maximum area coverage for exploration and to position themselves to witness an impact event from multiple viewpoints. The results show a promising pathway towards field study in a more detailed, simulated lunar surface environment.

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BIOGRAPHY

Rachel Moses *is currently an undergraduate student at the University of Arizona department of Aerospace and Mechanical Engineering. Her research interests include shape morphing planetary exploration robotics, structural dynamics, and multidisciplinary design optimization. Rachel has worked on multiple systems for proposed CubeSat missions.*

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