2007 IEEE International Conference on
Robotics and Automation
Roma, Italy, 10-14 April 2007

Exploring Mars Using a Group of Tumbleweed Rovers

Lori Southard, Thomas M. Hoeg, Daniel W. Palmer, Jeffrey Antol, Richard M. Kolacinski, and Roger D. Quinn, *Member, IEEE*

Abstract **–Current Mars exploration and science is limited to orbiters and areas close to original rover landing sites. Most of the places of geological interest lay many kilometers outside of suitable landing sites. *In-situ* resources such as wind can enable rovers to travel great distances on Mars while using little internal power. In this paper, a dynamic model of an individual wind driven rover is used to enhance a stochastic simulation of multiple rovers traversing the Martian environment. The results from this simulation support the claim that a group of rovers equipped with minimal control mechanisms or internal energy sources can autonomously disperse and explore Mars.**

Index terms – group behavior, Mars rover, wind-driven locomotion, biologically-inspired robotics

I. INTRODUCTION

The exploration of space is an especially difficult task that requires a unique solution to maximize effectiveness, adaptability, and robustness of design while staying within a strict set of criteria for weight, size, and operational envelopes. Robotic planetary exploration places additional design restrictions due to environmental effects such as dust, radiation, and corrosive elements. A Martian rover design must be able to accommodate these and other challenges as well as navigate rugged landscape in places of interest such as *Dao Vallis* - a 1200 km long valley with gulley features that are believed to have been formed relatively recently by water [1]. Novel robotic rovers that take advantage of *in-situ* resources would enable vast expanses of Mars to be explored at low cost. Wind powered movement is a prime candidate for an alternate mode of transportation because there is sufficient wind on Mars [2] and the rover power and drive train systems could be significantly smaller, less massive, and require less energy than conventional rovers [3,4,5]. Even limited locomotion control and communication capabilities could enable a group of rovers to travel long distances in loose formation for coordinated exploration.

Nature provides solutions to many engineering problems. One example is the Tumbleweed, or Russian thistle (*Salsola Tragus*), which travels long distances over irregular terrain using the wind. Although a Mars rover would have a different goal, the ability to travel long distances using wind power is beneficial in both cases.

Manuscript received January 31, 2007. This work was funded by NNL04AA71G from NASA Langley Research Center.
Lori Southard is with Case Western Reserve University Cleveland, OH 44106 USA (216-368-5216, e-mail: lxs97@case.edu).
Thomas M. Hoeg., is also from Case Western Reserve University, Cleveland, OH 44106 USA. (email: Thomas.hoeg@case.edu)
Daniel Palmer is with John Carroll University, University Heights, OH 44118 (email: dpalmer@jcu.edu)
Jeffrey Antol is with NASA/Langley Research Center, Hampton, VA 23681. (email: Jeffrey.Antol-1@nasa.gov)
Richard Kolacinski is with C.S. Draper Laboratory, Inc., in Cambridge, MA 02139. (email: rkolacinski@draper.com)
R. D. Quinn is with Case Reserve University, Cleveland, OH 44106 USA. (e-mail: rdq@case.edu).

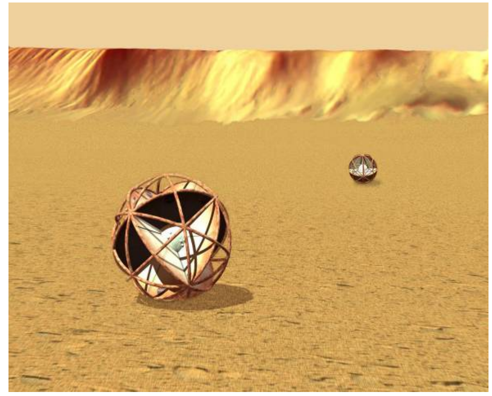

Fig. 1 Group of Tumbleweeds in Dao Vallis

Previous work included a quasi-static analysis to predict the minimum diameter of a spherical rover given a drag coefficient that would enable the rover to travel over a rock field [3] and a two dimensional dynamic analysis to predict the maximum obstacle height a spherical rover of a specific diameter can surmount in the Martian environment [6,7]. A 3-D analysis predicted obstacle navigation, stopping and turning performance using simple control mechanisms [8].

Another problem that must be further addressed is the control of a group of cooperating tumbleweed robots for the purpose of exploration [6]. A group that can communicate with each other or even just with their nearest neighbors can work together to explore larger expanses. Much work has been done on swarming-intelligence and algorithms for guidance of micro-robot swarms [9] control of unmanned ground vehicles (UGV's) [10], "super-entity" formation [11], and micro-satellite swarms [12]. This paper addresses the problem of tumbleweed rover group dispersion and goal seeking tasks using a simulation.

II. CONCEPTUAL ROVER DESIGN

A. Design

The following design is an initial subsystem configuration for the Tumbleweed rover [13]. It compromises between cost, weight, performance, and current technological readiness.

Radioisotope Thermophotovaltaic (RPTV) systems could supply sufficient energy over a long duration and with low mass requirements when the technology is ready. Deployment could be accomplished by a separate battery which does not need to be carried when the rovers are exploring [12].

Traditional sensors can take measurements required by a mission to Dao Vallis. These include gas chromatograph/mass spectrometer (GC/MS), x-ray diffraction/x-ray fluorescence (XRD/XRF), as well as separate sensor package vehicles capable of localized sensing while the tumbleweed moves on to other locations[13]. The advantage of sending multiple rovers is the sensor packages can be divided among many rovers, allowing the rovers to be more light weight.

Lightweight radio equipment equipped with the Proximity-1 link protocol would be capable of communicating with assets orbiting Mars and is already under development. Radiometric ranging techniques have been successfully field-tested on the Mars Exploration Rover missions and by combining them with state estimations from MEMS IMUs between radiometric updates it should be possible to accurately predict the tumbleweed's position over a long-duration mission[14].

Cruise stage deployment allows some flexibility for deployment to a different location from the primary mission and is much less expensive than having a dedicated tumbleweed mission [12].

The structural design was made by NASA LaRC based on analysis by the Jet Propulsion Laboratory. That design has the following characteristics [15]:

- The baseline choice for all solid structural materials (*e.g.*, three orthogonal hoops) is titanium alloy spring steel tubing (5 mm outside diameter) and 1 mm wall thickness – a total mass of 3.4 kg)
- All membrane materials are preferably woven PBO (polybenzoxazole) fabric (1 kg total membrane mass)
- All titanium in contact with the ground would be covered with a PBO fibrous tread to help reduce abrasion

TABLE I
TUMBLEWEED DESIGN[13]

Power	RTPV systems w/ primary batteries to aid in initial deployment[12]
Sensors	Conventional sensor suite (GC/MS, XRD/XRF, and imager) distributed among multiple tumbleweeds (possibly deployable)[13]
Communication	Radio equipment compatible with the Proximity-1 link protocol[14]
Navigation	Radiometric module in conjunction with MEMS IMUs[14]
Deployment	Secondary payload on the cruise stage[12]
Structure	Titanium alloy spring steel tubing covered with a PBO fibrous tread, membrane materials are woven PBO[15]

B. Mission

This section is a summary of a proposed mission to Dao Vallis [13,16]. A mission scenario to explore gullies could be accomplished by first deploying a group of Tumbleweed rovers on the upslope plateau behind a crater or canyon with known gullies, see Figure 2 part (1). Blown by the wind, the Tumbleweeds would first characterize the plateau, obtaining elevation data to determine the horizontal extent of it. Subsurface sounding of the plateau would be conducted to search for an aquifer and the overburden composition would be examined to estimate its thermal conductivity. After completion of the plateau investigation, two proposed options exist for directing the Tumbleweeds toward the gullies. However, in regions where the winds are uncertain, if a Tumbleweed could be equipped with the simple ability to stop and start (e.g., changing shape of the structure), Tumbleweed could be made to stop on the plateau and wait for a favourable wind direction toward the gullies.

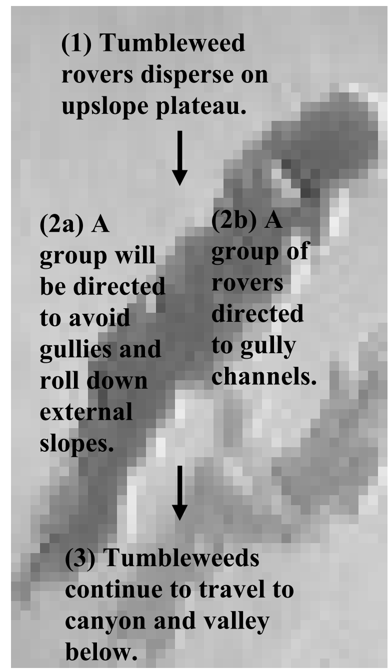

Fig 2. Depiction of Rover mission in Dao Vallis.

Moving down the slope, the next goal of the Tumbleweeds would be to search for evidence of a shallow aquifer, which would take the form of an ice plug beneath the overlying plateau, but close to the cliff face surface. As the Tumbleweed rolls down the slope, evidence of liquid water would be searched for on the exposed portions of the rock layers (i.e., a test for chemical signatures), see Figure 2 part (2a). A subset of the Tumbleweeds could also be deployed so as to avoid the gullies and roll down external slopes to gather data on the surrounding soils for comparative data, see Figure 2 part (2b). As the Tumbleweeds proceed down the gully channels, the interior would be examined to provide improved measurements regarding channel bed shape, depth, path (i.e., deflection around obstacles), etc. These measurements will present several challenges for the Tumbleweeds, as some instruments will require a stationary period to allow proper integration time. One method would be to deploy an instrument package that could be dropped from the Tumbleweed as it rolls down the gully [8].

The Tumbleweeds would complete the mission by examining the debris apron to determine the size of particles being transported down-slope and the composition of the soil in the debris apron, see Figure 2 part (3). At this point, depending on the condition of the vehicles, the mission could be extended by allowing the Tumbleweeds to continue taking measurements as they are blown about by the winds within the canyon or valley below.

III. Dynamic Simulation

A Tumbleweed should have a large drag coefficient and the ability to navigate obstacles. In previous studies, the box-kite model with three orthogonal circular sails was found to have the highest coefficient of drag [17,18,19], however models with a higher number of circular sails had not been tested. We tested three, six, and nine sails to determine which design had the highest drag coefficient [16]. The model with three compliant fabric sails had the highest drag coefficient (1.4) and the design was modified with interconnecting circular rings so that the shape would remain relatively spherical allowing the tumbleweed to roll effectively. Figure 1 shows the three sailed model design.

A computer model of the three-sail design was created in

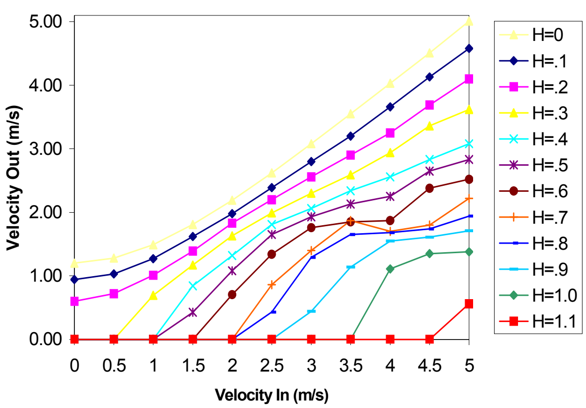

Fig 3. Velocity after impact as a function of initial impact velocity and obstacle height

ProEngineer and then imported into VisualNastran 4D for simulation. The simulation parameters (shown in Table II) were based on guidelines from NASA Langley Research Center (mass, diameter, air density, gravity, and wind speed), general estimates (coefficients of restitution and friction), and experimental results (drag coefficient).

TABLE II
Dynamic Parameters

Mass	20 kg
Coefficient of Drag	1.4
Coefficient of Restitution	0.5
Coefficient of Friction	0.5
Diameter	5 m
Air Density	1.55 kg/m^3
Gravity	3.69 m/s^2

Drag was modeled as a linear force acting on the geometric center of the Tumbleweed in the direction of the wind:

$$F_{drag} = \frac{1}{2}\rho_{air} v_{rel}^{\;2} C_d A. \quad (1)$$

Where ρ is the air density, v_{rel} is wind's velocity relative to the rover, C_d is the drag coefficient and A is the projected area of the rover normal to the wind. A three dimensional simulation was used to quantify the dynamics of rover acceleration and obstacle navigation [21]. These relatively high fidelity simulations were used to help us understand the rover's dynamics so that we could approximate them in a stochastic simulation for group behaviour experiments.

A. Obstacle Navigation

To quantify the effect of velocity on obstacle navigation a set of simulations was run at a variety of rover velocities (0 to 5 m/s at 0.5 m/s intervals) and a variety of obstacle heights (0 m to 1.1 m at 0.1 m intervals) [21]. The simulations were set up with a rectangular prism representing the obstacle and the rover was placed with its leading edge touching the plane representing the face of the obstacle and the initial velocity was varied.

The simulations were run from this starting situation until either: a) the rover's center of mass had cleared the obstacle (successful navigation) or b) the rover fell back off the obstacle and stopped (unsuccessful navigation). The results of those simulations are shown in Figure 3, which shows the velocity after impact as a function of obstacle height and the rover's initial velocity. A velocity of 0 m/s indicates unsuccessful obstacle navigation and everything else can be considered successful although high velocity losses will cause difficulties in navigating future obstacles. The rover's center of mass clears the obstacle plan at 2.5 meters, so the velocity out at H=0.0 represents the Tumbleweed rover travelling 2.5 meters on a flat surface

B. Path Deflection

Rocks are complex shapes with random geometries and it is unlikely the rover would hit a rock face directly like a rectangular prism. To quantify this effect, simulations were run with the same rectangular prism, but this time at a variety of heights, velocities, and different obstacle orientations. Since it is safe to assume that the rock orientations are randomly distributed, the results focus on the overall effects of velocity and obstacle size on rover direction. It was determined that the height of the obstacle is the important factor in determining the angular deflection of the rover.

C. Steering Control

Passive rovers could be deployed to wander Mars, but group behavior strategies using even weak control authority can be used to more rapidly disperse the vehicles and to guide them toward particular targets. The rover is steered by producing a moment using an offset mass. How well the rover can be turned is affected by a number of conditions such as the rover's current direction, orientation, speed, etc. To quantify these effects a number of simulations with different initial rover velocities (0 m/s to 5 m/s in 1 m/s increments) and initial directions ($-\pi/4$ radians to $+\pi/4$ radians in $\pi/16$ radians increments), with changes in rover direction being recorded. Each simulation was run with a 1 kg mass laterally offset 1 m from the center of the rover and was run until the rover had traveled 5 m downwind. It was found that the rover's direction can be effectively changed using this strategy.

D. Deceleration Control

By lowering its sails and effectively eliminating the drag force the Tumbleweed's forward momentum will begin to dissipate. Also, the small masses used for turning can be used to slow the rover by placing the masses at positions which are unfavorable to the Tumbleweed's forward rotation (by making the rover expend energy lifting the masses past its geometric center). A simulation was used to analyze these mechanisms. This simulation had a rover starting at a speed of 5 m/s with two 1 kg masses that could move along a set of perpendicular axes into positions unfavorable to rotation. It is relatively easy to begin decelerating, but coming to a complete stop on a smooth plane takes time, however obstacle impacts should help to encourage stopping behavior. The major drawback to this method is that it is energy intensive.

Another method that could accomplish stopping is to lower the sails of the Tumbleweed. This would lower the drag coefficient slowing the rover and making it more likely to be stopped by rocks of a much lower height. This was assumed as the method of deceleration in this version of the group behavior simulation described below.

The proposed control methods are in the early stages of development, the simulation phase. Eventually, these methods will need to be experimentally tested. Until this future work is completed, assumptions based on simulation and expected behaviors were incorporated into a group behavior simulation.

IV. GROUP BEHAVIOR SIMULATION

A rover simulation was developed according to the rock field data, wind models, and altitude data of Dao Vallis.

A. Martian Rock Field

A Mars Tumbleweed will be interacting with various, different conditions on Mars. This stochastic simulation models a group of Tumbleweeds interacting on a flat rock field. The size-frequency distribution of rocks on Mars was taken from the previous missions of *Viking I, Viking II, and Pathfinder*. A conservative estimate of the height/diameter ratio of the rock field is 0.5 [20,21]. An exponential model of the size-frequency distributions of the rocks from *Viking I* with respect to the diameter of the rocks was developed by Golombek and Rapp [22].

$$N(D) = Le^{-sD} \tag{2}$$

N(D) is the cumulative number of rocks per square meter with a diameter greater than or equal to a given diameter *D*. *L* is 3.82 and *s* is 3.38 and those values are exponential fit parameters obtained by using the image data. The exponential curve drops off more slowly for larger diameter rocks than actual data so this model gives a conservative model of a Martian rock field. A distribution function was derived by Antol et al. [3] and the function is

$$F(D) = \int_0^D f(\xi)d\xi = 1 - e^{-sD}. \tag{3}$$

A rock height generator was developed to determine normalized random rock diameters. The absolute value of the diameter would then be halved according to the height/diameter ratio to obtain the height of the rocks in the Martian rock field. Every square meter a Tumbleweed rover enters has this statistical maximum height associated with it, which could dominate the Tumbleweeds motions.

B. Dao Vallis Geography

For the stochastic simulation, the general topography of the Martian surface was taken from the Mars Orbiter Laser Altimeter (MOLA) mission data of *Dao Vallis*[23]. From the data points a general slope or elevation gradient for a particular region could be calculated. A Gaussian randomization of the entire surface was used to simulate valleys and other geological obstacles. With the gradient of points on the surface known, the acceleration of a Tumbleweed rover was calculated due to the slope.

C. Wind Model

The Martian wind speed varies depending on the season: 2-7 m/s (summer), 5-10 m/s (fall), 17-30 m/s (dust storm) (Viking Lander sites). From the *Pathfinder* mission results, winds were strongest in early morning hours and remained strong around noon and were relatively light during late afternoon and early evening [24]. Wind direction rotates throughout the day: south at night, westward in the mornings, north in the afternoon, and east during the evening. The average wind speed for these 30 days was 6.975 +/- 2.57 m/s and the wind direction 180.2 +/ 78.6 degrees where 0 degrees is the wind blowing northward. A Gaussian distribution was used to model the wind speed.

D. Group Behaviour Simulation

The stochastic group behavior simulation dynamics are taken from the results of the Dynamics Simulation in Section III. It is an event based simulation. For every five meters travelled, a Gaussian-based result is calculated for changes in velocity, path deflection, time for the expected rock height, angle, slope, control input, wind direction, and wind velocity for that area travelled.

E. Dispersion Algorithm

Due to the lightweight and low cost nature of Tumbleweed rovers it would be practical and advantageous to use a group of rovers to explore the Martian environment, especially when exploring regions such as *Dao Vallis*, which has a large array of canyons [17]. Although for specific geological exploration a global position determining method such as radiometric ranging with Mars' orbiting satellites [18] is desired, it would be advantageous to have specialized positioning rovers which could compute absolute positioning during down times. However the relative communication relying on inter-tumbleweed communication would be desirable for short ranges and times and allow for

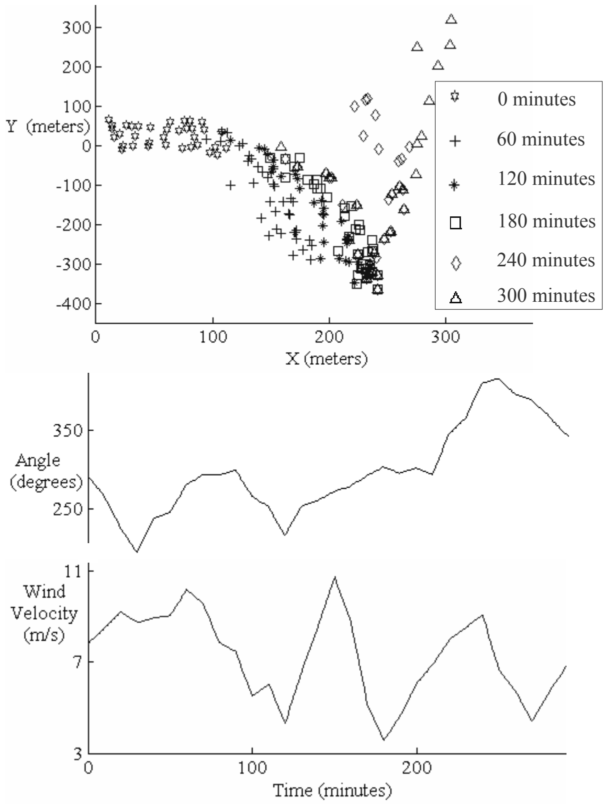

Fig 4. (a) Dispersion of thirty-five rovers in plateau of Dao Vallis (b) Wind direction is directed to the southwest. At 0 degrees the wind is directed east (c) Wind speed varies between 3.5 to 11 m/s

an exploration specialized rover [6] to carry more weight in scientific instruments than global positioning equipment. The swarming algorithm assumes using the strength of signals to determine relative distances from each other for positioning techniques and the algorithm allows for systematic opportunistic exploration of a given site.

The swarming algorithm is a multipurpose algorithm that can be slightly altered for different purposes such as dispersion, exploration, and formation maintenance. It is based on the dispersion algorithm pseudo-code from Kolacinski et al. [6]. Rover control is based on the stopping/starting and steering performance predicted by the dynamic simulation. The target density is the amount of rovers in a particular area. The goal of the strategy is to disperse the rovers to make the inner desirable distance less than or equal to the target density while the target density in the outer communication limit is greater than or equal to the target density. The dispersion algorithm runs until all rovers are spaced properly, and then the exploring algorithm runs for a given time. The deceleration and steering parameters determined by the dynamic simulation are input into the kinematics of the event algorithm.

F. Traveling to a desired location

Can the Tumbleweed start from a point and reach a target using realistic and limited control? The basic assumptions in this investigation are: that the target is physically reachable and the Tumbleweed can determine the direction it is headed. The rovers will use the dispersion algorithm to maximize the distance covered as they head to their goal location. The algorithm works by averaging the two directions together: the desired dispersion direction and the desired goal direction. This is then compared to the current direction of travel which is the direction of the wind. From this each rover decides whether to stop, steer, or do nothing.

V. Results

A. Dispersion Results

The first algorithm implemented was the dispersion algorithm to see if once landed the rovers would be able to spread out in order to maximize the area explored. Wind direction and speed have an effect on dispersion of the rovers and taking this into account in the control algorithm improves the results. With no changes in the wind direction the rovers have to rely solely on their limited steering capability. Fig 4 shows snapshots of a sample run of thirty-five rovers starting out in a one hundred meter landing site on a plateau of Dao Vallis and dispersing as time passes while the wind changes directions. This figure clearly shows the density of the rovers decreasing with time.

B. Traveling to a Desired Location

An algorithm was developed to cause the rovers to move in a certain direction. This meant averaging the two desired directions, desired dispersion direction and desired path direction, to choose a direction of travel. Fig 5 shows a sample run of this algorithm for a nearby goal. The control algorithm causes them to disperse regularly throughout the run. However without control, the rovers move in the direction of the wind. With control, the rovers can stop and steer slightly when headed in the wrong direction or can adjust to the desired angle.

VI. Discussion and Future Work

Through the use of three-dimensional dynamic modeling, the rover dynamics and control mechanisms have been sufficiently quantified for individual rovers on simplified terrain. These results were used as inputs to a stochastic simulation supported by more accurate physical data than had been used in the past. The results from the swarming simulation show that dispersion and exploration with Tumbleweed rovers is feasible.

Future work will include examining different group behavior algorithms. Changing different parameters while a rover travels to a desired location will be one of the steps. A likely mission scenario involves an organized search for geologically interesting features using a group of rovers with heterogeneous sensor packages. An overall goal is to quantify the desired number of rovers for a given mission. The work also needs to be implemented in hardware and experimentation performed for further investigation into the implementation of the Tumbleweed rovers in an exploration mission to Mars.

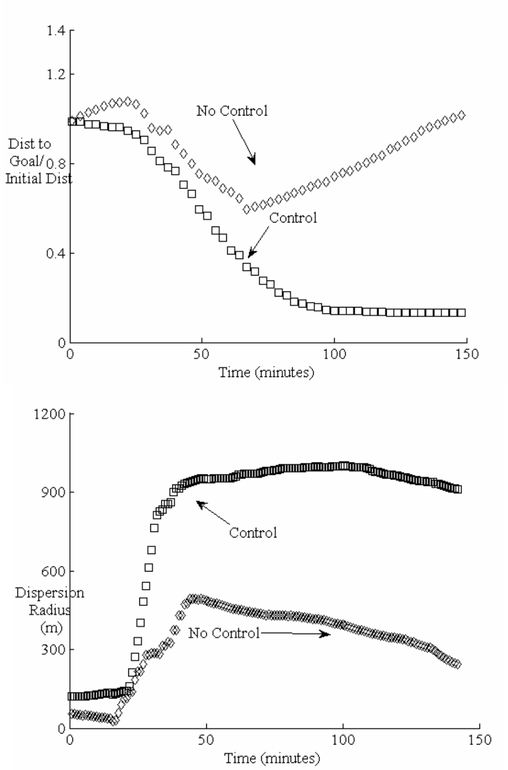

Fig 5. (a) Distance to goal location (Current distance / Original Distance). Original distance was set as 1 km at a direction of 300 degrees east (b) Dispersion diameter taking from mean center of the group and the diameter is the standard deviation of the group.

REFERENCES

[1] Heldmann, J.L. and Mellon, M.T., "Observations of Martian gullies and constraints on potential formation mechanisms," *Icarus,* v. 168, 2004, pp. 285-304.

[2] Lorenz, R.D. (1996) "Martian Surface Windspeeds, described by the Weibull distribution", In J. Spacecraft and Rockets, Vol. 33, pp.754-756.

[3] Antol J., Calhoun P., Flick, Hajos G., Kolacinski R., Minton, Owens R., Parker, (2003) "Low Cost Mars Surface Exploration: The Mars Tumbleweed", NASA Technical Report, NASA/TM-2003.

[4] Jones, J., "Inflatable Robotics for Planetary Applications," In Proc. 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space (I-SAIRAS), Montreal, Canada, June, 2001.

[5] Hanrahan, D. H., Minton, C. A., DeJarnette , F. R., Camelier, I. A., and Fleming , M. H. "", Portugal 6-9 October 2003, Lisbon Portugal, Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science Workshop.

[6] Kolacinski, R.M., Palme, D.W., Cloutier, P.M., and Schatz, J.E. (2003) "Biologically Inspired Design for Low Cost Exploration of Space: Swarms of Martian Rovers Based upon the Russian Thistle," 7th World Multiconference on Systemics, Cybernetics and Inofrmatics (SCI03), Orlando, FL, July 27-30.

[7] Kolacinski, R.M., Quinn R.D. (2004) Design of a Biologically Inspired Martian Rover Based upon the Russian Thistle (Salsola Tragus), Dynamics and Control of Space Structures Symposium (DCSSS04), July 19-22, 2004, Italy.

[8] Hoeg, T., Southard, L. Boxerbau, A. Reis, L. Antol, J., Heldmann, J. Quinn, R. "Tumbleweed Rover Science Mission to Dao Vallis". AIAA 2006 Reno,Nevada.

[9] Dohner, J.L., "A guidance and Control Algorithm for Scent Tracking Micro-Robotic Vehicle Swarms", J. of Dynamic Systems, Measurement, and Control, V 120, 1998.

[10] Balch, T., Arkin, R.C., "Behavior-based Formation Control for Multi-robot Teams", IEEE Transactions on Robotics and Automation, in press, 1999.

[11] Palmer, D.W., Hantak, C.M., Kovacina, M.A., "Impact of Behavior Influence on Decentralized Control Strategies for Swarms of Simple, Autonomous Mobile Agents", in Workshop: Biomechanics Meets Robotics Modeling and Simulation of Motion, Heidelberg, Germany , 1999.

[12] Vaidyanathan, R., "Auto-adaptive Fuzzy Rule Base Control of Autonomous Satellite Swarms", Research Grant supported by Kirtland AFB Space Vehicles Directorate, Orbital Research, 1999.

[13] Hoeg, Thomas. "The Martian Tumbleweed: Conceptual Design to Practical Application. 2005 Thesis (Master's)-Case Western Reserve University, Cleveland.

[14] Antol, J., Calhoun, P. C., Flick, J. J., Hajos, G. A., Keyes, J. P., Stillwagen, F. H., Krizan, S. A., Strickland, C. V., Owens, R., and Wisniewski, M. "Mars Tumbleweed: FY2003 Conceptual Design Assessment", *NASA Technical Report, NASA/TM-2005-213527*

[15] Antol, J., Woodward, S., Hajos, G., Heldmann, J., Taylor, B. "Using Wind Driven Tumbleweed Rovers to Explore Martian Gully Features." AIAA-2005-0245.

[16] Schwarz, Jordan. "Navigation and Localization of the Mars Tumbleweed Surface Exploration Vehicle." North Carolina State University, Aug 11, 2004. (http://centauri.larc.nasa.gov/tumbleweed/)

[17] Antol, J., "A New Vehicle for Planetary Surface Exploration: The Mars Tumbleweed", *1st Space Exploration Conference: Continuing the Voyage of Discovery*, AIAA-2005-2520.

[18] Rose, S., Moody, C., James, D., and Barhorst, A. "Drag Measurement and Dynamic Simulation of Martian Wind Driven Sensor Platform Concepts." AIAA-2005-249.

[19] Strickland, C. and Keyes, J. "Wind Tunnel Tests to Determine Drag Coefficients for the Mars Tumbleweed." AIAA-2005-248.

[20] Rose, S. E., Moody, C. B., James, D. L., and Barhorst, A. A. (2005). Drag Measurement and Dynamic Simulation of Martian Wind Driven Sensor Platform Concepts. Accepted for publication, Journal of Fluids and Structures, to appear in Vol. 21, No. 7

[21] Southard, L., Hoeg, T., Kolacinski, R., Quinn, R., "Dynamic Simulations and Control of a Group of Wind Driven Martian Rovers," Infotech@Aerospace, AIAA, Washington, DC, 2005.

[22] Hauber, E., Jaumann, R., Mosangani, N., Russ, F., Trauthan, K., Matz, D., Fabel, O. "Rocks at the Pathfinder Landing Site, Mars: Identification and Size Distribution." URL:http://mpfwww.jpl.nasa.gov/MPF/science/lpsc98/1607.pdf. August 1, 2005.

[23] Golombek, M. "Extreme Rock Distributions on Mars". Lunar and Planetary Science XXXIII (2001)-1116.

[24] Golombek, M., Rapp, D. (1997). "Size-frequency distributions of rocks on Mars and Earth analog sites: implications for future landedmissions," In J. Geophys. Res., Vol. 102, No. E2, pp 4117-4119

[25] Smith, D., Neumann, G., Arvidson, R. E., Guinness, E. A., and Slavney, S., "Mars Global Surveyor Laser Altimeter Mission Experiment Gridded Data Record", NASA Planetary Data System, MGS-M-MOLA-5-MEGDR-L3-V1.0, 2003.

[26] Mars Pathfinder Historical Weather Data. http://mars.sgi.com/ops/asimet.html Accessed January 2006.