NASA/TM-2003-212411

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August 2003

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

August 2003

Acknowledgments

Special thanks to the LaRC researchers who took time to provide information and recommendations: Keith Belvin, Paul Brewster, John Connell, Pete Covell, Juan Cruz, David Dress, Alicia Dwyer (ICASE), Jil Hallenberg (Montana State University), Nancy Holloway, Luther Jenkins, Jerry Kegelman, Drew Landman (ODU), Joel Levine, Ken Lodding, Harry Morgan, John Quagliano, Frank Quinto, Kurt Severance, Walt Silva, Ralph Stevens, Fred Stillwagen, Ji Su, Butch Watkins, Judith Watson, Rich White, and Tom Yager.

Special thanks are due to the Library and Media Services Branch of the Langley Research Center who published this document, with special acknowledgment to the NCI Technical Publications Support Group at Langley: Denise Stefula, editing; Dee Bullock, illustration and image preparation; Patricia Gottschall, desktop publishing; and Mary Edwards, proofing.

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1. Introduction

1.1. Background

Many people throughout time have been fascinated with the planet Mars, from the early Greek and Roman civilizations who were intrigued by its unique reddish color to Galileo and Huygens who first observed Mars' surface features by telescope in the 1600s. The Italian astronomer Schiaparelli sketched these surface features in the late 1800s, calling them "canals," and Percival Lowell studied them extensively by telescope in the early 1900s. With the development of spaceflight capability in the mid-20th century, the opportunity for direct exploration of Mars became a reality. The first spacecraft to visit Mars was the NASA Mariner 4 probe, conducting a flyby mission in 1965, followed by Mariners 6 and 7 in 1969. The project culminated with Mariner 9 achieving an orbit around Mars in 1971 and completing a global photographic survey that ultimately dispelled the notion of Martian canals (ref. 1).

In 1976 the Viking project achieved the first successful soft landing on the surface with two landers that, in conjunction with two Viking orbiters, provided the first detailed scientific investigation of the surface and atmosphere over a period of 6 years. The next successful mission to Mars would not be accomplished until 1997 when Mars Pathfinder landed on the surface and deployed the Sojourner rover. This highly successful mission was followed by the Mars Surveyor orbiter, which is currently providing detailed images of the surface, and the Mars Odyssey orbiter, which is currently conducting scientific investigations that indicate large volumes of frozen water may exist just below the surface.

Several missions to the surface of Mars are planned in the near future, beginning in the summer of 2003 when NASA will launch a pair of Mars Exploration Rovers (MERs), as discussed in reference 2. The MERs are the first in what will be a series of advanced landers and rovers that will explore the Red Planet throughout the decade (fig. 1). Each MER will weigh approximately 180 kg and carry a suite of scientific instruments, including cameras. The MERs are solar powered and can travel up to 100 m in a single Martian day, or sol, and are expected to survive for at least 90 sols, traveling approximately 9 km. While this 9-km total range is impressive compared with the several meters that the Sojourner rover traveled in 1997, it reflects only a small portion of the Martian surface.

Figure 1. Cornell University artist depiction of a Mars Exploration Rover during surface operations.

Figure 2. JPL artist depiction of Mars Pathfinder bouncing across the surface of Mars inside air bag landing system.

Wheeled rovers are very complex and expensive, with limited ability to traverse rough terrain. Landing sites must be chosen that will ensure the safety of the rover and its ability to carry out a mission. Therefore, many scientifically interesting sites are inaccessible by current rover designs; the vast majority of our knowledge of the Red Planet is from data obtained by orbiting spacecraft. To gain a better understanding of the global picture of Mars from an up-close surface perspective, a new capability is needed that can transport scientific instruments across hundreds or even thousands of kilometers of varied Martian terrain.

1.2. Overview of the Concept

It began as a humorous conversation. Several engineers at NASA Langley Research Center (LaRC) were discussing the Mars Pathfinder mission, which utilized a novel landing and deployment system of air bags (fig. 2). The air bags cushioned the Pathfinder lander and its accompanying Sojourner rover after its fiery atmospheric entry and subsequent impact with the ground (ref. 3). The engineers joked that the air bag system allowed Pathfinder to travel a significant distance across the surface of Mars, much farther than the tiny, wheeled Sojourner rover ultimately would accomplish on its own. However, a number of serious questions were posed: *What if the air bag were never deflated and Pathfinder were allowed to keep rolling? How could rolling be maintained? Could the wind be used to keep it rolling, like a tumbleweed plant?*

Over the weeks that followed the initial discussion, many ideas were generated on how wind-driven mobility might be accomplished on Mars. It became evident from the follow-up conversations that a "Mars Tumbleweed," a rover whose mobility would be derived by the surface winds on Mars, would be an interesting concept to study. The Tumbleweed concept is unique in that it would be the first vehicle to take advantage of a powerful natural resource on Mars for mobility, the wind, which has shaped the surface geology of Mars as much as water, volcanism, and meteor impacts. Taking advantage of this resource is a great way to both improve the mobility of a science platform and reduce the complexity of the vehicle needed to transport it. It was recognized as a concept that may one day offer an efficient, cost-effective means of moving lightweight science payloads across vast distances. Mobility was defined by the Space Studies Board of the National Research Council as essential for future exploration of the solar system (ref. 4).

However, achieving Mars wind-driven mobility is not a minor task. The density of the atmosphere on Mars is approximately 60 to 80 times less than that on Earth. The static pressure is 1 percent that of Earth at sea level. Average Martian temperatures are −63 °C (the equivalent of a 35-km Earth altitude). Wind speeds are typically around 2 to 5 m/s during the day, with gusting periods of 10 to 20 m/s and seasonal dust storms wherein wind speeds exceed 25 m/s. But because of the low density of the Martian atmosphere, even the strongest winds on Mars develop low dynamic pressures that equate to just a gentle breeze on Earth. A Mars Tumbleweed rover would therefore have to be extremely lightweight and equipped with lightweight, low-power instruments. If the Tumbleweed rover design could be kept simple and inexpensive, it would allow relatively large numbers to be deployed for regional or perhaps global coverage of the Martian surface, gathering scientific data to complement missions such as those carried out by the MERs.

Because the Mars Tumbleweed concept appeared very promising, an additional question was posed: *Had the concept previously been investigated?* A brief literature search revealed that an idea for wind-driven rovers was developed in the late 1970s (ref. 5) by Jacques Blamont of the National Center for Space Studies (CNES, or Centre National d'Etudes Spatiales in France). His idea evolved into the University of Arizona Mars Ball concept, an inflatable rover whose mobility was produced through sequenced inflation and deflation of air bags. Models were developed to test the Mars Ball concept; however, research into wind-driven rovers was not conducted because the idea did not appear feasible at the time.

A study was therefore proposed to the LaRC Creativity and Innovation (C&I) initiative to research the current feasibility of a Mars Tumbleweed rover. In the process of planning the C&I research activity, several other organizations were discovered that are also exploring Mars Tumbleweed concepts, including the Jet Propulsion Laboratory (JPL) (ref. 6) and Texas Technical University (TTU) (ref. 7). An additional Mars Tumbleweed effort by researchers at the Swiss Federal Institute of Technology was also recently identified (ref. 8). More information on these concepts can be found in section 5.3.

1.3. Goals for the Study

Those goals established for the first-year C&I effort were modest. No funding was requested, only time to further explore the concept. Three goals would define the study's focus: brainstorming sessions with local experts, basic analyses to examine the feasibility of wind-driven mobility on Mars, and definition of science investigations that could be conducted using a Mars Tumbleweed rover.

- Brainstorming Sessions**:** Discuss concept with LaRC structures, materials, and aerodynamics experts. Enlist particular experts as consultants.

- Feasibility Study**:** Determine aerodynamic and structural characteristics that will allow Mars wind-driven mobility. Complete a literature search on similar research.

- Science Objectives**:** Define applicable science goals, associated science requirements, and instrument complements.

2. Brainstorming Sessions

The first goal of this study was to discuss the concept with various engineers and researchers, primarily at LaRC and particularly those with expertise in structures/materials, aerodynamics, and dynamics. Feedback was sought on the validity of the concept, applicable technologies, and recommendations for future testing and analysis. Additionally, brainstorming discussions were held among core team members to discuss the areas mentioned above as well as to define notional design concepts. The following are primary areas that were investigated and the individuals contacted:

Structures and Materials

Ultralightweight structures—Keith Belvin

Inflatable rigidizable structures—Judith Watson, Bill Grahm, and Carl Knoll (ILC Dover, Inc.)

Thin films—John Connell

Active materials and structures—Nancy Holloway and Ji Su

Aerodynamics

Computational fluid dynamics—Harry Morgan

LaRC wind tunnels—Jerry Kegelman

Full-Scale Tunnel—Drew Landman (Old Dominion Univ.)

Low-Turbulence Pressure Tunnel—Frank Quinto

14- by 22-Foot Tunnel—David Dress

Transonic Dynamics Tunnel—Walter Silva

Basic Aerodynamic Research Tunnel—Luther Jenkins and Richard White

Low Reynolds number aerodynamics—Thomas J. Mueller (Univ. of Notre Dame)

Dynamics

Rolling resistance—Tom Yager

Several key results from the brainstorming discussions included:

- Developing several notional concepts of Mars Tumbleweed rovers in addition to the concepts that resulted from initial discussions.

- Identifying a need to conduct aerodynamic analysis and/or wind-tunnel testing, at the appropriate Reynolds numbers, to examine the aerodynamic characteristics of proposed Mars Tumbleweed concepts.

- Identifying an interest in studying the rolling characteristics and drag properties of the tumbleweed plant to determine characteristics that could potentially be incorporated into the Mars Tumbleweed rover design.

- Considering biologically inspired “swarming” strategies for coordinating multiple Tumbleweed rovers in order to maximize science return.

- Identifying lightweight materials and structures that could be applied to a Mars Tumbleweed rover.

3. Feasibility Study

The second goal of the study was to examine the basic feasibility of wind-driven mobility on the surface of Mars. The resulting analysis effort was divided into three areas: quasi-static analysis of a Mars Tumbleweed rolling on a smooth flat surface, quasi-static analysis of a Mars Tumbleweed rolling through a typical Martian rock field, and dynamic analysis of a Mars Tumbleweed on a slope.

A literature search for information on related wind-driven rover research was also conducted as part of this goal, the results of which can be found in section 5.3.

3.1. Mars Atmosphere Data

A set of Mars environment data was collected in order to conduct consistent analyses. The following assumptions on the Mars atmosphere were derived from the references indicated:

- Surface atmospheric density: 0.0155 kg/m^3 (ref. 9)

- Mars surface wind speeds (ref. 10):

    - Viking 1: 2 to 7 m/s (summer); 5 to 10 m/s (fall); 17 to 30 m/s (dust storm) (ref. 11)

- Dynamic pressure (calculated):

    - 0.03 Newtons per square meter (N/m^2) for wind speed of 2 m/s

    - 0.8 N/m^2 for wind speed of 10 m/s

- Mean surface atmospheric pressure: 636 N/m^2 (6.4 mbars) (ref. 9)

- Kinematic viscosity estimate: 8.0×10^{-4} m^2/s (refs. 9 and 12)

- Speed of sound estimate: 250 m/s (ref. 9)

- Diurnal temperature range (Viking 1 landing site): 184 to 242 K (ref. 10)

3.2. Quasi-static Analysis of a Tumbleweed Rolling on a Smooth Flat Surface

Given the above Mars atmospheric assumptions and initial ballpark estimates of the rover mass and drag coefficient, listed below, a simple spherical Mars Tumbleweed rover was analyzed to obtain a first-order approximation of the required rover size and the associated required minimum wind speeds.

- Mars Tumbleweed mass: 5 kg (including instruments)

- Mars wind speeds: typical wind speeds of 2 m/s with periods of higher winds and gusts at 10 m/s were assumed

- Reynolds number: 14000 to 71000 (for a 6-m Tumbleweed in wind speeds ranging from 2 to 10 m/s)

- Drag coefficient: 0.5 (typical for a sphere at the given Reynolds numbers) (ref. 13)

For this initial analysis, the Tumbleweed rover was assumed to be a nonrigid sphere in pure planar rolling motion (no sliding) on a flat, solid, rock-free surface (fig. 3).

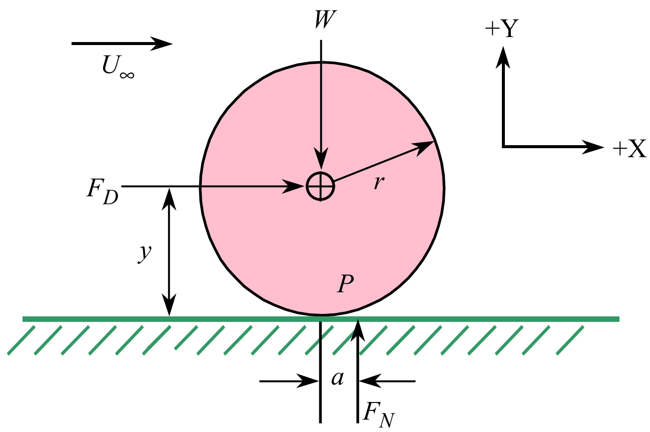


Figure 3. Forces acting on a Mars Tumbleweed.

Note that a friction force is not defined in figure 3 because only rolling motion is occurring with no sliding. However, there is a rolling resistance effect due to a slight deformation that would occur between the nonrigid rolling body and the surface at point P. This is accounted for by offsetting the normal force (F_N) from the Tumbleweed's center of mass at a distance a (ref. 14). Assuming a simple moment balance about point P,

$$\sum M_P = 0 \Rightarrow Wa - F_D y = 0 \tag{1}$$

where W is the weight of the Tumbleweed rover, a is the offset distance of the normal force (F_N), F_D is the drag force assumed to act through the center of mass, and y is the distance from the ground to the point where F_D acts. The drag force is defined as

$$F_D = C_D A_{\text{ref}} \bar{q} \tag{2}$$

where C_D is the drag coefficient of a given Tumbleweed vehicle, A_{ref} is the cross-sectional area of the Tumbleweed, and $\bar{q}$ is the dynamic pressure, given by the equation $\frac{1}{2}\rho U_\infty^2$, with ρ being the atmospheric density and U_∞ the free-stream velocity.

In order for the Mars Tumbleweed to begin moving from rest, the force due to wind must exceed the rolling resistance. Solving equation (1) for F_D and assuming that $y \cong r$, where r is the Tumbleweed radius, yields a simple expression for the minimum force needed to initiate motion of the Tumbleweed rover (ref. 14):

$$F_D = \frac{Wa}{r} \tag{3}$$

The Mars Tumbleweed weight (W) is given by

$$W = m g_{\text{mars}} \tag{4}$$

where m is the Tumbleweed mass and g_{mars} is acceleration due to gravity on Mars (3.69 m/s^2).

The ratio a/r, defined as the *coefficient of rolling resistance*, or μ_r, which typically ranges from 0.02 to 0.12 for automobile tires on hard surfaces (ref. 15) with 0.06 being the maximum for tires on dry pavement (ref. 16). Because specific data were not available for a Tumbleweed structure rolling across a Martian surface, the coefficient of rolling resistance was assumed to be the tire maximum value of 0.06 in order to approximate a Tumbleweed on a solid, rock-free surface.

For the typical wind speed of 2 m/s, a 5-kg Tumbleweed rover with a drag coefficient of 0.5 would need a radius of almost 5 m in order to achieve mobility on Mars (fig. 4).

However, the same Mars Tumbleweed is greatly reduced to a radius of approximately 1 m for the higher gusting wind speed of 10 m/s (fig. 5).

If the drag coefficient is increased beyond the 0.5 of a simple smooth sphere to 1.0, the 5-kg Mars Tumbleweed could operate at the lower typical wind speed of 2 m/s with a radius of approximately 3.5 m (fig. 6).

In summary, a 5-kg Tumbleweed rover having a drag coefficient of 0.5 would require a radius of 1 to 5 m in order to initiate rolling on a smooth, flat Martian surface in winds from 10 m/s down to 2 m/s. This size appears feasible, because the Mars Pathfinder air bag system was approximately a 3-m radius when inflated. If the mission can be accomplished by waiting for higher wind speeds, then the smaller radius Tumbleweed could be utilized. Or, a larger radius Tumbleweed could have an increased mass capability if used in higher winds, accommodating a larger payload. Likewise, the results show that increasing the drag coefficient to 1.0 or greater would have similar benefits.

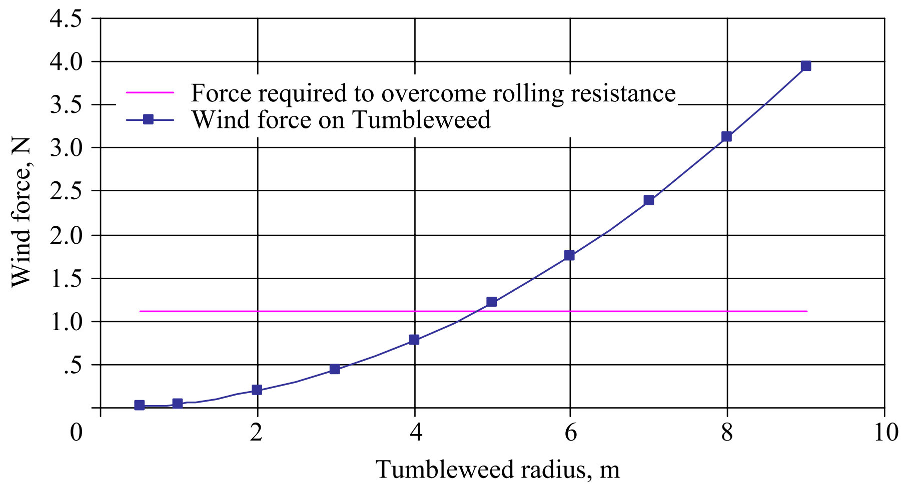


Figure 4. Wind force versus Tumbleweed radius (U_∞ = 2 m/s, C_D = 0.5, m = 5 kg).

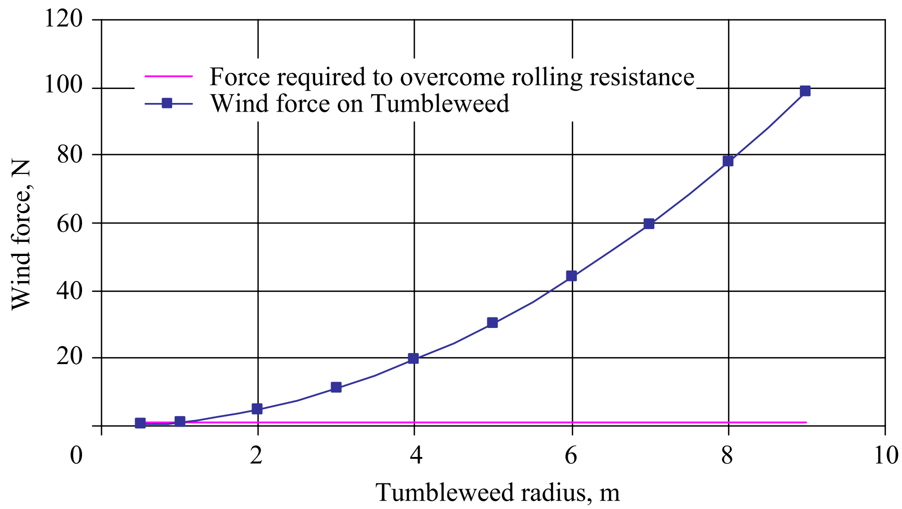


Figure 5. Wind force versus Tumbleweed radius (U_∞ = 10 m/s, C_D = 0.5, m = 5 kg).

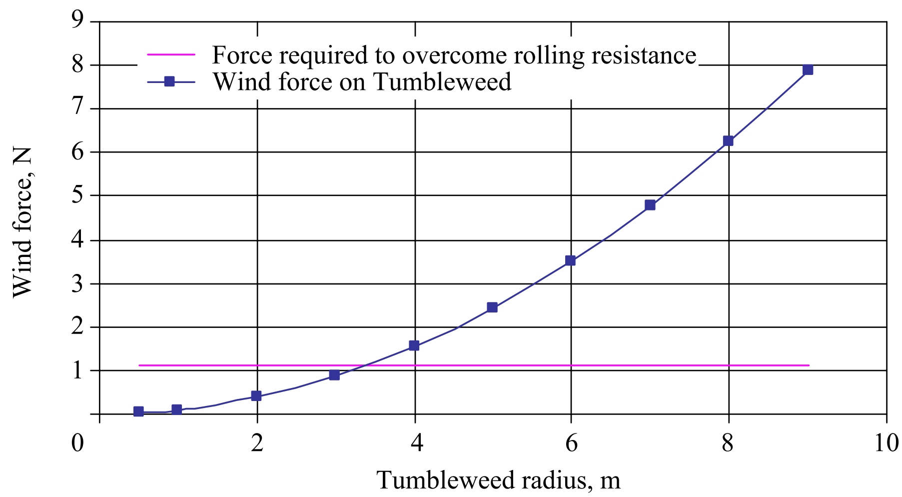


Figure 6. Wind force versus Tumbleweed radius (U_∞ = 2 m/s, C_D = 1.0, m = 5 kg).

These results are based on a highly simplified model, however, with assumptions (e.g., a smooth, flat surface) that would not be valid in a majority of regions on Mars. In particular, the μ_r requires further investigation, perhaps laboratory testing, to obtain specific coefficients of rolling resistance for particular Tumbleweed designs on various Martian terrains. Additional analyses to examine the effects of a Tumbleweed rolling through a Martian rock field are also needed and are addressed in part subsequently.

3.3. Quasi-static Analysis of a Tumbleweed Rolling Through a Typical Martian Rock Field

Recognizing that the Tumbleweed rover will have to navigate varied Martian terrain, an analysis of a simple Tumbleweed's ability to negotiate obstacles was performed. To this end, a typical Martian rock field was modeled and used to perform feasibility and trade studies on Tumbleweed design parameters (e.g., radius and drag coefficient). Specifically, a simple, quasi-static model of an idealized Mars Tumbleweed rolling over an obstacle was constructed and used to determine the maximum navigable rock size for a given set of design parameters. Monte Carlo simulations that combined this model with a statistical model of Martian rock field distributions were then performed to gauge the effectiveness of various Tumbleweed configurations.

The computational costs associated with Monte Carlo simulation necessitate simplifying assumptions in the model of the Tumbleweed's behavior. In particular, numerical simulation of intermittent contact between two bodies (i.e., a bouncing Tumbleweed and the ground) and accurate modeling of the slip-stick friction that governs the sliding/rolling behavior of the Tumbleweed are described by coupled differential algebraic equations (DAEs) and are very intense computationally. A simple, quasi-static model that produces conservative estimates with little computational overhead was therefore developed (fig. 7).

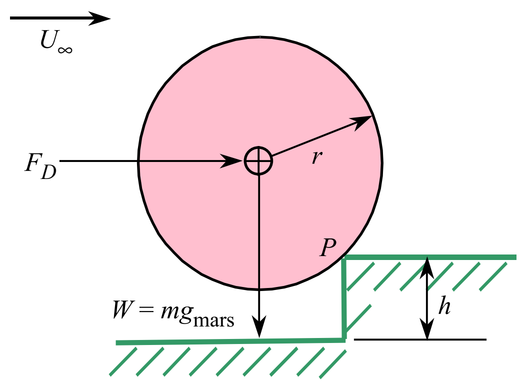


Figure 7. Tumbleweed maneuvering over obstacle.

The Tumbleweed is assumed to be a perfect, inelastic, homogeneous sphere that rolls without slip. It is further assumed that the Tumbleweed contacts the obstacle at a single point and that the motive force due to drag acts through the sphere's center of mass. A quasi-static analysis is used to determine the maximum obstacle height for which the rolling moment induced by the motive force exceeds or balances the oppositely signed rolling moment induced by the body gravity force. While this model neglects crucial dynamics, the neglected dynamics would be expected to improve the Tumbleweed's ability to navigate obstacles. For instance, the quasi-static model neglects the kinetic energy of a rolling sphere that can be used to perform some work necessary to raise the Tumbleweed's center of mass. The neglect of bouncing places severe limits on the size of the obstacle that can be navigated.

Assuming a simple moment balance (M_P) about point P yields an expression for deriving the maximum navigable rock size:

$$\sum M_P = 0 \;\Rightarrow\; \xi_{\max} = 1 - \sqrt{\frac{1}{Q^2 + 1}} \tag{5}$$

where ξ is the ratio of obstacle height to Tumbleweed radius and Q is the ratio of motive force to body gravity force:

$$\xi \equiv \frac{h}{r}$$

$$Q \equiv \frac{F_D}{mg}$$

where h is the obstacle height, r is the Tumbleweed radius, F_D is the drag force, m is the Tumbleweed mass, and g is the acceleration due to gravity. Inspection of equation (5) reveals that the maximum navigable rock size increases with the available motive force acting upon the Tumbleweed. The ratio of navigable rock size to Tumbleweed radius, ξ_{max}, approaches unity asymptotically as the Q approaches infinity. Furthermore, ξ_{max} increases monotonically with Q. This implies that the maximum navigable rock size increases supralinearly with increasing Q, but the asymptotic behavior suggests the existence of a point of diminishing return.

Equation (5) can be used to construct a relationship between the drag force acting upon the Mars Tumbleweed and the maximum navigable rock size. The drag force F_D is given by equation (2), $F_D = C_D A_{ref} \bar{q}$. It should be noted that this model of the drag force neglects boundary layer effects between the Martian surface and the atmosphere.

Inspection of equation (2) shows that the drag force is a function of Tumbleweed radius, drag coefficient, and wind speed. Two of these parameters, Tumbleweed radius and drag coefficient, are tunable and form the parameter space used for the trade studies performed. Using the assumptions from section 3.1, in which Martian winds vary from 2 to 10 m/s (2 to 7 m/s during the summer and 5 to 10 m/s during the winter), a nominal free-stream velocity, V_{nom} = 7 m/s, was chosen for use in this particular analysis. With Reynolds numbers in the same regime as those defined in section 3.2, the drag coefficient of C_D = 0.5 is also valid for this analysis (ref. 13). Rewriting equation (5) as an explicit expression for maximum navigable rock height (h_{max}) in terms of Tumbleweed radius and drag coefficient produces

$$h_{max} = r\left\{1 - \sqrt{\frac{(mg_{mars})^2}{\left[C_D(\pi r^2)\left(\frac{1}{2}\rho V_{nom}^2\right)\right]^2 + (mg_{mars})^2}}\right\} \tag{6}$$

where the nominal free-stream velocity, V_{nom}, is used; the Tumbleweed mass, m, is 5 kg and g_{mars} is the acceleration due to gravity on Mars (g_{mars} = 3.69 m/s^2). Using this expression, the relationship between the maximum navigable rock size and Tumbleweed radii and drag coefficients was plotted for different drag coefficients over a range of radii (fig. 8).

As can be seen, increases in radius produce the most effect on maximum navigable rock size for radius values over 5 m. Increases in drag coefficient greatly increase the maximum navigable rock size. *These results show that a smooth, spherical rover may not be the best design for negotiating obstacles. A significant benefit can be achieved by designing the Mars Tumbleweed to maximize drag in this situation.*

Similarly, it can be seen that increasing the radius of the Tumbleweed has a significant impact upon maximum navigable rock size. However, space and weight constraints would place strict limitations upon the size of the rover. *Because of these limitations, preliminary results indicate that a candidate design procedure may be to maximize the drag coefficient of the Tumbleweed rover and then determine an appropriate radius corresponding to that drag coefficient.*

In order to determine appropriate Mars Tumbleweed radii, the maximum navigable rock size must be determined as well as a relationship between the maximum rock size and the composition of Martian rock

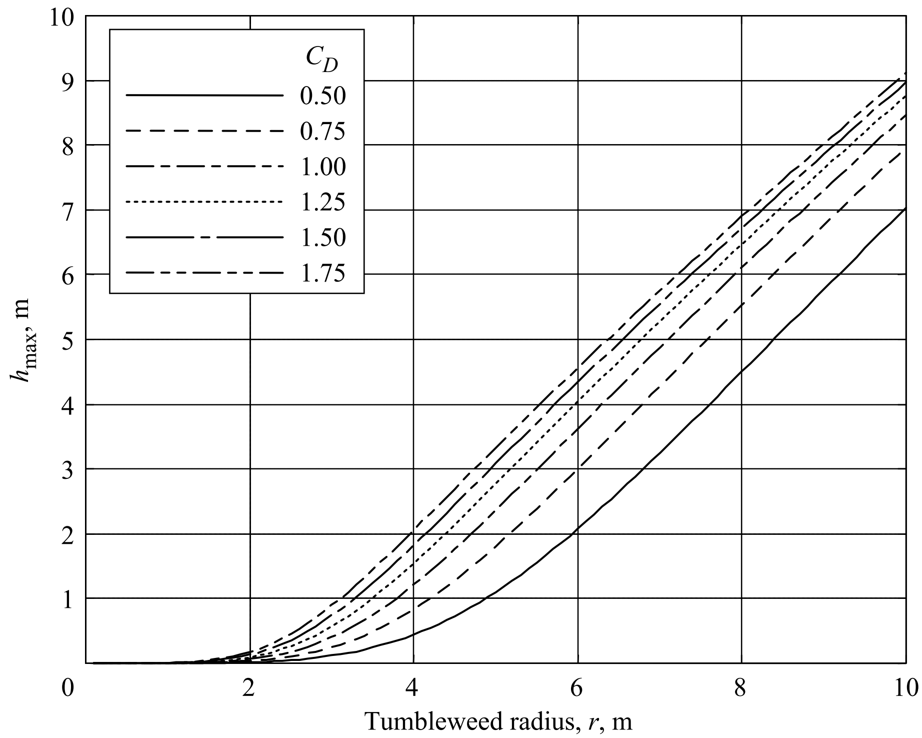


Figure 8. Effect of drag coefficient on maximum navigable rock size (h_{max} versus r and C_D).

fields. Once a realistic relationship has been constructed, the likelihood that a particular Tumbleweed design can traverse a Martian rock field under the motive power of the wind can be estimated via Monte Carlo simulation.

Several models of Martian rock fields exist in the literature. An exponential fit of the size-frequency distribution of rocks in the vicinity of the Viking 1 lander proposed by Golombek and Rapp (ref. 17) at JPL was chosen for the rock field model in the Monte Carlo simulation. This distribution is given by the expression

$$N(D) = Le^{-sD} \tag{7}$$

where $N(D)$ is the cumulative number of rocks per square meter with a diameter greater than or equal to a given diameter, D. Parameters L and s are determined via a least square estimation using Viking image data. For rocks observed in the image near and far field but neglecting those in the vicinity of a crater rim, the parameters are

$$L = 3.82$$

$$s = 3.38$$

Comparison of the exponential curves with the actual data shows that the fit curves actually drop off more slowly for large rock sizes than the actual data and therefore slightly overpredict the area covered by large rocks. By using the fit that neglects the rocks in the vicinity of a crater rim, we obtain a conservative model of a Martian rock field in the absence of geologic disturbances.

Using this size-frequency distribution, a probability distribution function that describes the probability of encountering a rock of a particular size, D, in a 1-m^2 area can be constructed. Examining the frequency interpretation of the probability density function,

$$f(x)\,\Delta x \cong \frac{\Delta n_x}{n} \tag{8}$$

where Δn_x is the number of trials such that $x \le x(\xi) < x + \Delta x$, and taking the limit as $\Delta x \to 0$, we obtain the following relationship between the size frequency distribution ($f(D)$) and the probability density function:

$$f(D) = \lim_{\Delta D \to 0} \frac{N(D) - N(D + \Delta D)}{N \Delta D} \tag{9}$$

N is the total number of rocks present in a 1-m^2 area and is determined from equation (7) with $D = 0$:

$$N = N(0) = Le^{-s(0)} = L$$

Substituting equation (7) into equation (9) and invoking L'Hospital's rule yields

$$f(D) = se^{-sD} \tag{10}$$

The probability distribution function is related to the density function by the relationship

$$f(D) = \frac{dF(D)}{dD} \tag{11}$$

Therefore,

$$F(D) = \int_0^D f(\xi)\,d\xi = 1 - e^{-sD} \tag{12}$$

where the probability distribution function $F(D)$ is defined as the likelihood that a rock encountered will have a diameter, d, less than or equal to D or $F(D) \equiv P(d \le D)$.

For the Monte Carlo simulation, a Cartesian grid was constructed. A constant wind velocity of 7 m/s over the grid was assumed. The Mars Tumbleweed was then allowed to traverse the grid under the motive force of the wind. At each point on the grid, representing 1 m^2, it is assumed that the Tumbleweed encounters a rock. Four different ranges of rock size were identified:

1. Very small rocks ($d \le h_{max}/10$) that will not affect the Tumbleweed's progress.

2. Fully navigable rocks ($h_{max}/10 < d \le h_{max}$) that the Tumbleweed can negotiate but rocks that may alter the course of the Tumbleweed by inducing a lateral excursion and that do not prevent forward motion in the direction of the wind.

3. Larger, partially navigable rocks ($h_{max} < d \le 1.5\ h_{max}$) that the Tumbleweed cannot roll over but may be able to roll around.

4. Unnavigable rocks ($1.5\ h_{max} < d$) that the Tumbleweed cannot navigate over or around.

A random number is generated and, using equation (12), the size range of the rock encountered is determined. If the rock size is very small, the Tumbleweed is advanced in the direction of the wind to the next grid point; if the rock is completely unnavigable, the Tumbleweed is assumed to be stopped and the run is terminated. The two remaining cases both allow advancement in the direction of the wind, but lateral excursions (normal to the wind direction) are also possible. If the rock is fully navigable, the Tumbleweed is advanced to the next rank on the grid and a normally distributed random number is used to determine the lateral excursion, if any. If the random number generated is less than one in magnitude, the Tumbleweed advances in the direction of the wind; if it is greater than one, a lateral excursion to an adjacent file occurs with the direction of the excursion determined by the sign of the random number. In the case of a partially navigable rock, a uniformly distributed random number between –0.5 and 0.5 is used to determine the appropriate motion. For values in a small neighborhood of zero, no motion is permitted and the run is terminated; otherwise, the Mars Tumbleweed is advanced to the next rank and to an adjacent file where the lateral excursion is again determined by the sign of the random number. Note that the normal distribution, $N(0,1)$, used to model the lateral excursions has a zero mean by definition and a standard deviation of one, hence the case where the random value having a magnitude greater than one is a one sigma case.

Each rover configuration (drag coefficient and radius) was run 10 000 times with each run continuing until the Tumbleweed encountered a rock that it could not negotiate or until the distance made good (distance traveled in the direction of the wind) exceeded 10 km. The simulations were run for a range of radii from 0.1 to 7 m and drag coefficients of 0.5 (the baseline case of a sphere), 1.0, 1.5, and 2.0 (a 2-D plate). The Monte Carlo results, shown in figure 9, are the mean distances traveled by the Mars Tumbleweed in the direction of the wind for each configuration.

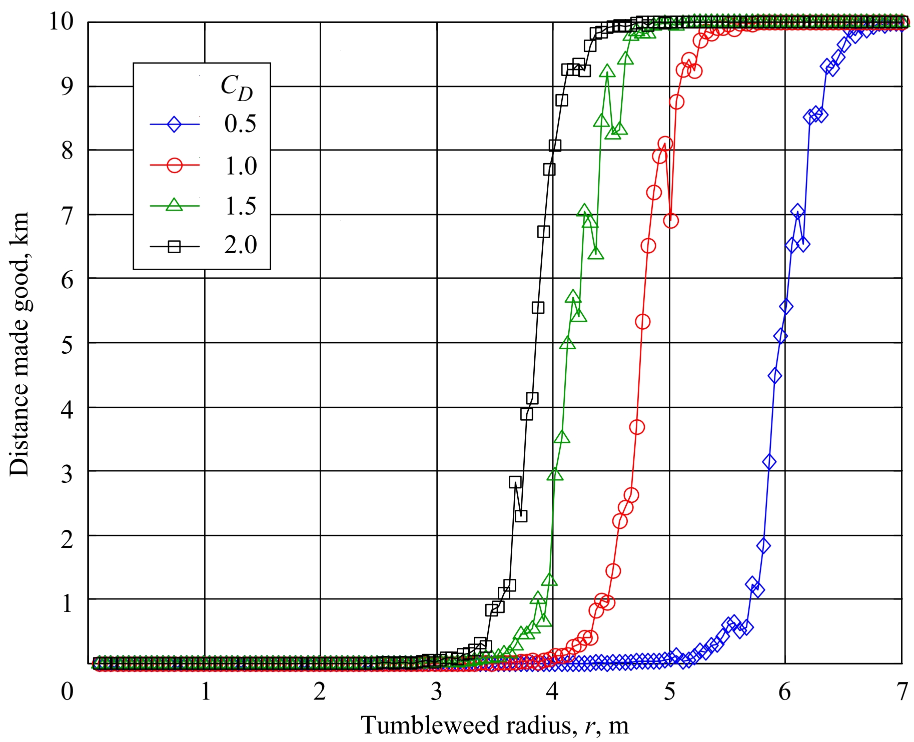


Figure 9. Mean distance made good versus radius.

The results demonstrate that an increased drag coefficient will significantly improve the ability of the Tumbleweed to negotiate a Martian rock field. A Mars Tumbleweed with a drag coefficient of 0.5 would require a radius of approximately 7 m or greater to negotiate the typical rock field whereas the radius necessary to negotiate a typical rock field falls to approximately 5 m for a drag coefficient of 1.0 and to approximately 4 m for a drag coefficient of 1.5. The effectiveness of increasing the drag coefficient decreases as the drag coefficient increases; however, in the range of drag coefficients that could reasonably be affected ($1.25 \leq C_D \leq 1.75$), the increases still correspond to significant increases in performance. Assuming that the median value of this range, $C_D = 1.5$ (approximately the drag of a low porosity parachute), is achievable, it can be seen that the Tumbleweed concept is feasible with a radius of less than 5 m.

The model used to construct the Monte Carlo results is simple and neglects many important dynamics—such as surface friction, rolling resistance, deformation of the Tumbleweed, and bouncing—requiring consideration to provide a realistic model of a rolling Tumbleweed. The assumptions made in the development of the model are conservative and should underpredict the efficacy of the tumbleweed concept. The validity of assuming that these simplifications are conservative needs to be addressed by examining the neglected dynamics.

3.4. Dynamic Analysis of a Tumbleweed on a Slope

A simplified mathematical model of the Tumbleweed dynamics was created in order to assess the feasibility of the Tumbleweed concept and to derive basic sizing parameters. The approach was to develop a planar model assuming rolling motion from a rest condition. This technique yields a size/weight relationship necessary for wind-propelled rolling motion as a function of wind speed. As discussed in section 3.2, the wind force must exceed the rolling resistance for motion to initiate from rest. The rolling resistance is a function of normal force distribution, which arises from compression of the Tumbleweed structure and/or deformation of the ground surface under the Tumbleweed's weight. This analysis assumes that the rolling resistance is dominated by the compression of the Tumbleweed structure. This seems to be an appropriate assumption because the size/weight ratio of the Tumbleweed will be large and the resulting structural stiffness small when compared with the compliance of Mars surface. Because ground speed is near zero for impending motion, viscous effects of the ground contact were neglected in this preliminary analysis.

The first step in creating the initial model was to develop the planar rolling equation of motion. This model will be developed with the following assumptions:

- Tumbleweed is constrained to simple planar rolling motion along an arbitrary ground slope.
- Tumbleweed motion is along smooth surface with no obstacles to maneuver (i.e., no rocks).
- Tumbleweed has rolling resistance due to nonpoint contact with the ground (i.e., Tumbleweed is nonrigid).

We begin with the translational and rotational equations of motion given by equations (13) and (14):

$$F = ma \tag{13}$$

$$T = I\alpha \tag{14}$$

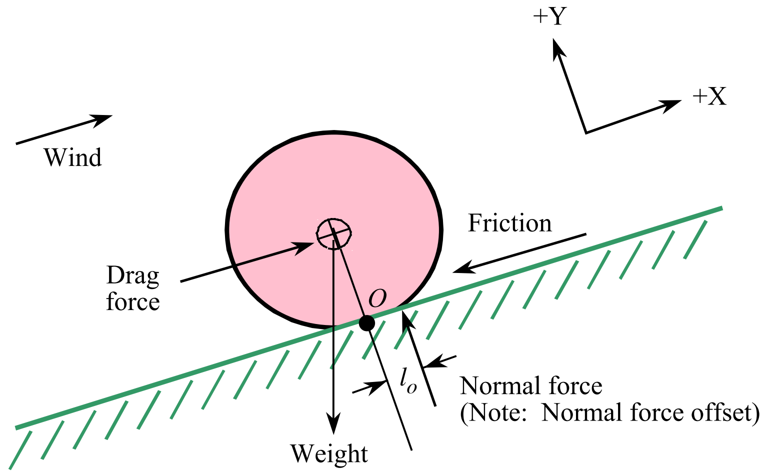


Figure 10. Tumbleweed model.

where F is the total force on the Tumbleweed, m is the mass, a is the translational acceleration, T is the total moment on the Tumbleweed about the mass center, I is the moment of inertia about the mass center, and α is the rotational acceleration. Applying a rolling constraint, given in equation (15), results in an instantaneous center of rotation about the contact point O.

$$V = r\omega \tag{15}$$

where V is the velocity of the mass center, r is the Tumbleweed radius, and ω is the angular velocity of the Tumbleweed. Because the contact point O is assumed to be an instant center, the Tumbleweed rolling dynamics can be formulated by summing moments about the point O:

$$T_O = I_O\alpha \tag{16}$$

where T_O is the total moment on the Tumbleweed about the contact point, and I_O is the moment of inertia about the contact point. Assuming an arbitrary ground slope and no obstacles to maneuver (i.e., no rocks), the total moment about the contact point may be expressed as the summation of torque due to aerodynamic drag, T_D, gravity, T_g, and rolling resistance, T_r. Figure 10 shows a free body diagram of the forces acting on the Tumbleweed.

$$T_O = T_D + T_g + T_r \tag{17}$$

The aerodynamic drag torque about the contact point can be expressed as a function of the deformation of the Tumbleweed, δ, caused by interaction with the ground and measured along a line perpendicular to the ground slope.

$$T_D = F_D(r + c_p - \delta) \tag{18}$$

where F_D is the drag force and c_p is the distance from the Tumbleweed center of mass to the center of pressure measured along a line perpendicular to the ground slope. The center of pressure of the Tumbleweed may not be coincident with the geometric center because there is a wind boundary layer at the Mars surface with an estimated height of approximately 5 m (ref. 18). However, the effects of the boundary layer on drag force magnitude and center of pressure are considered secondary effects and thus neglected in this simplified analysis. As the model is developed further, additional fidelity will be added and this assumption will be addressed in a more complete dynamic analysis. The drag force is given in equation (19):

$$F_D = C_D A_{\mathrm{ref}} \left(\frac{1}{2} \rho V_{\mathrm{tw}}^2 \right) \tag{19}$$

where, similar to equation (2), C_D is drag coefficient, A_{ref} is the cross-sectional area, and $\left(\frac{1}{2} \rho V_{\mathrm{tw}}^2 \right)$ is the equation for dynamic pressure, where ρ is the atmospheric density and V_{tw} is the velocity of the Tumbleweed relative to the wind.

Given a Mars surface slope relative to the gravity vector, θ_S, the torque due to gravity about the contact point can be expressed as

$$T_g = m g_{\mathrm{mars}} \, (r - \delta) \sin(\theta_S) \tag{20}$$

where m is the mass of the Tumbleweed and g_{mars} is the acceleration due to gravity on Mars. The torque due to rolling resistance can be determined by assuming some effective normal force offset, l_O.

$$T_r = F_N \, l_O \tag{21}$$

where F_N is the normal force, which can be expressed in terms of the Tumbleweed weight as

$$T_r = mg \cos(\theta_S) \, l_O \tag{22}$$

The offset, l_O, arises from the shift in the normal force center of pressure as the Tumbleweed lifts up along the downwind region of the ground contact footprint at the onset of rolling. As discussed in section 3.2, the offset can be approximately determined by assuming some rolling resistance coefficient, μ_r, which is defined as the ratio of l_O to the Tumbleweed radius. Thus we have

$$\mu_r = l_O / r \tag{23}$$

Typical values of rolling resistance range from 0.02 to 0.06 for tires on concrete, 0.06 to 0.12 for tires on a medium hard surface, and 0.16 to 0.3 for tires on sand (ref. 15). An alternative approach for approximately determining rolling resistance is to assume some deformation of the Tumbleweed under its own weight. Equation (24) provides an expression of the length of the Tumbleweed surface in contact with the ground. This equation assumes a circular surface geometry with deformation as shown in figure 10.

$$l_c = [4\delta \, (2r - \delta)]^{1/2} \tag{24}$$

where δ is the deformation of the Tumbleweed measured along the radius and l_c is the length of the surface in contact with the ground (note: l_c is a sector length, assuming a circular shape for the Tumbleweed outer surface). Assuming that the normal force acts at a point 50 percent offset from the center of the contact patch yields

$$l_O = \left(\frac{1}{4} \right) l_c = \left[\left(\frac{1}{4} \right) \delta \, (2r - \delta) \right]^{1/2} \tag{25}$$

or

$$l_O = r[p_\delta(1 - p_\delta)]^{1/2} \tag{26}$$

where p_δ is the ratio of the Tumbleweed deformation (δ) to the diameter. Substituting equation (26) into equation (23) results in an expression of the rolling resistance as a function of p_δ.

$$\mu_r = [p_\delta(1 - p_\delta)]^{1/2} \tag{27}$$

which, for small values of p_δ, becomes

$$\mu_r = (p_\delta)^{1/2} \tag{28}$$

Equation (28) can be used to determine approximate values of rolling resistance assuming some deformation of the Tumbleweed under its own weight. For example, a deformation of 1 percent of the diameter ($p_\delta = 0.01$) results in a rolling resistance equal to 0.10.

The structural stiffness can be determined by the following procedure: express the compressive force, F_c, as a linear stiffness constant, K_s, multiplied by the deformation

$$F_c = K_s\delta \tag{29}$$

Assuming that the Tumbleweed is deformed under its own weight, W, and expressing δ in terms of p_δ yields

$$W = K_s(2rp_\delta) \tag{30}$$

Equation (30) can then be used to determine the stiffness of a Tumbleweed rover as a function of weight and to determine size given a percentage deformation. This relation will be useful in deriving structural sizing parameters given candidate materials and geometric configurations.

Equations (13) through (30) provide a basis for a simplified planar rolling dynamics model of a Mars Tumbleweed on an arbitrary slope. Referring to figure 10, rolling motion from a rest state is initiated as the drag force increases to the point where the drag torque on the Tumbleweed exceeds the combination of torque from gravity and rolling resistance. At this point a torque balance is achieved. As drag force increases beyond this point the Tumbleweed undergoes positive acceleration and gains forward speed. The Tumbleweed moves with the wind and a new equilibrium rolling rate is reached as the drag force lessens. Thus, performing a torque balance will provide the minimum conditions for impending motion from rest. Substituting the equations for torques acting on the Tumbleweed—equations (18), (20), and (22) into equation (17)—then setting this new expression equal to zero yields the conditions for torque balance. Given a positive torque convention of positive rolling motion in the X direction yields the following:

$$T_O = F_D(r + c_p) - mg\,r\sin(\theta_S) - mg\cos(\theta_S)\,r\,\mu_r = 0 \tag{31}$$

or

$$C_D A_{\text{ref}}\left(\frac{1}{2}\rho V_{\text{tw}}^2\right)(r + c_p) - mg\,r\sin(\theta_S) - mg\cos(\theta_S)\,r\,\mu_r = 0 \tag{32}$$

The friction force shown in figure 10 performs no work on the system undergoing rolling motion and therefore is not included in this analysis. The velocity of the Mars Tumbleweed relative to the wind, V_{tw}, will be assumed to be equal to an effective free-stream velocity, and c_p will be set equal to zero for the purpose of this initial analysis. These assumptions will most certainly need to be revisited as the analysis matures because the boundary layer of the wind blowing across the Martian surface is significant as compared with the estimated Tumbleweed size.

A torque balance was conducted using equation (32) for a range of values for rolling resistance, drag force coefficient, mass, radius, wind speed, and slope. Figures 11 through 13 show the maximum ground slope that the Tumbleweed can traverse as a function of effective free-stream wind speed assuming the drag coefficient of a smooth sphere (0.5) and a mass of 5 kg. The rolling resistance is varied from 0.0, for a rigid Tumbleweed in rolling contact, to 0.2, which is within the range of a low-pressure tire rolling on a sand surface. As the rolling resistance is increased the wind speed threshold necessary to initiate forward motion increases. However, as the wind speed increases above this threshold the maximum attainable slope rapidly approaches 90°, especially for the larger radii. This effect is due to diminished rolling resistance as the normal force goes to zero when the slope approaches 90°. *When the radius is large in combination with high wind the Tumbleweed can climb a near vertical slope. This should remain true if the rate of slope change is gradual enough that the wind boundary layer assumptions are valid for upslope conditions, that is, the wind is always flowing parallel to the slope.* This assumption will be revisited for particular steep slope conditions with reduced boundary layer thickness. Increased rolling resistance may occur for steep slopes for which there is a significant free-stream wind component nonparallel to the local slope. However, the assumption of wind parallel to the slope should approximate a wide range of moderate slope conditions and provides a simple design requirement for traversing nonrocky terrain.

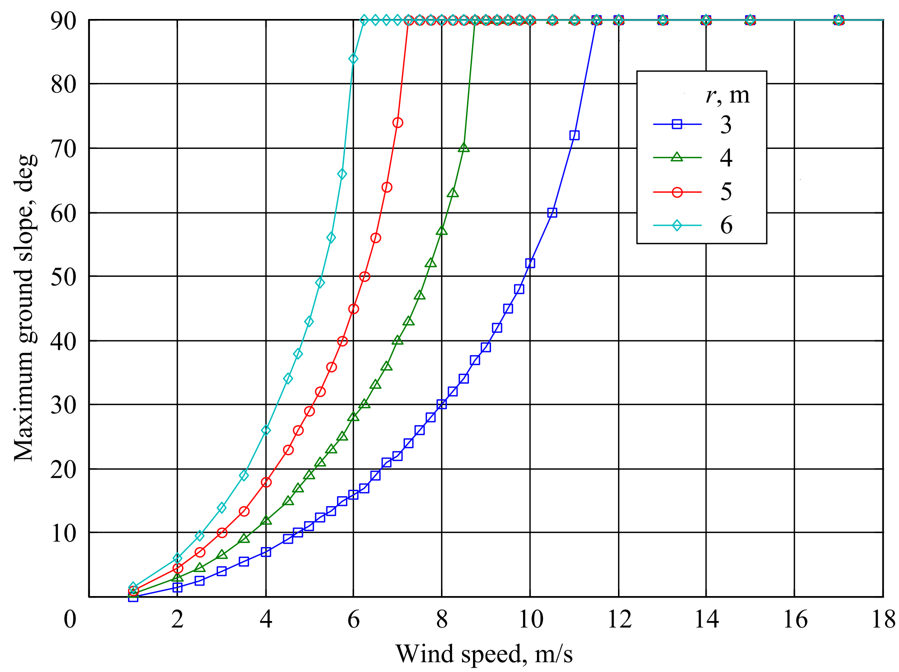


Figure 11. Maximum slope versus wind speed (m = 5 kg, C_D = 0.5, μ_r = 0.0).

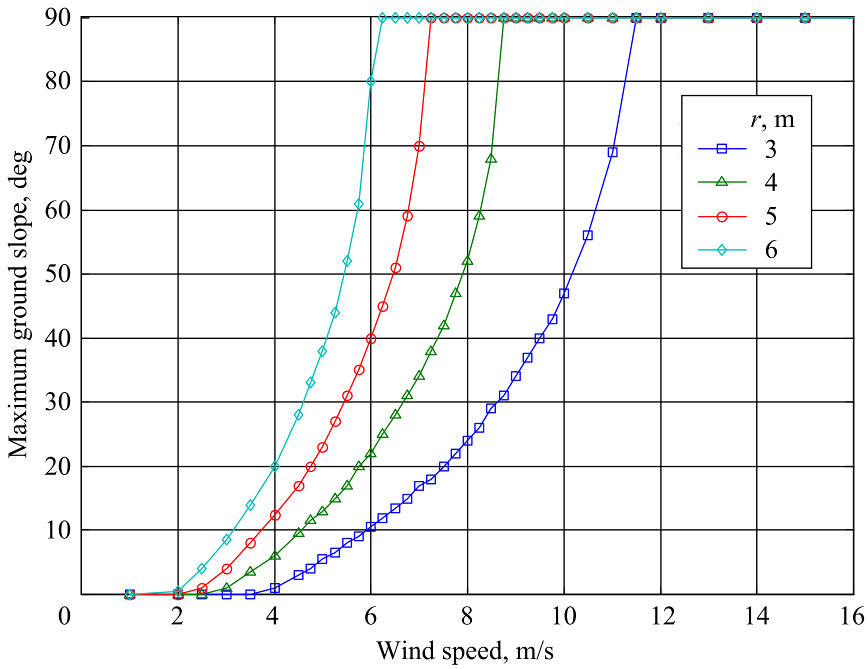


Figure 12. Maximum slope versus wind speed (m = 5 kg, C_D = 0.5, μ_r = 0.1).

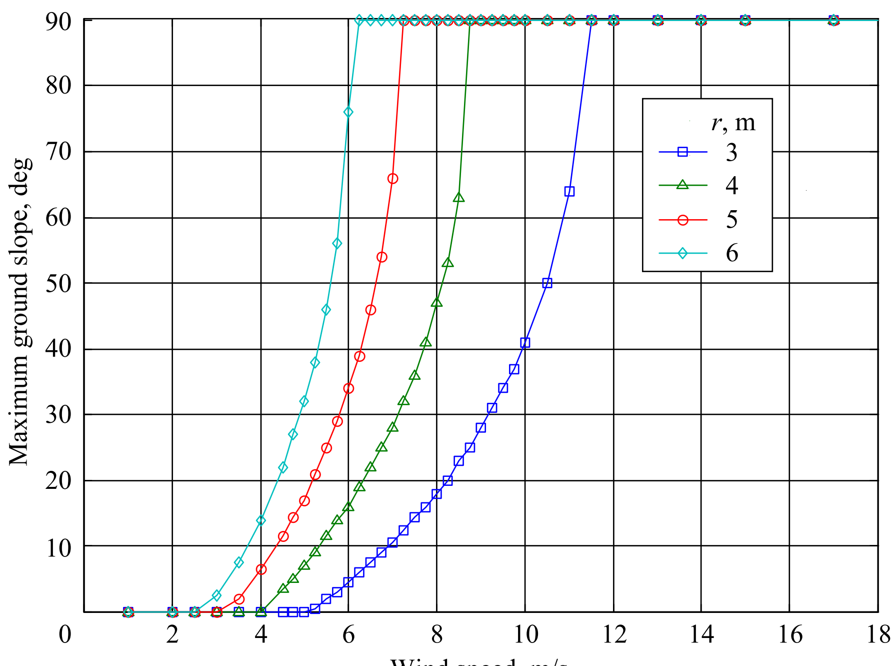


Figure 13. Maximum slope versus wind speed (m = 5 kg, C_D = 0.5, μ_r = 0.2).

Using a value of rolling resistance of about 0.1, which is within the range for a low inflation-pressure tire rolling on a medium hard surface, yields the following design sizing for a Tumbleweed with smooth spherical geometry. A radius of about 6 m is required to traverse a 30° slope with wind speed of 4.5 m/s (average summer wind, see section 3.1). A radius of about 3.5 m is required to traverse a 30° slope with wind speed of 7.5 m/s (average winter wind, see section 3.1). Figures 14 and 15 demonstrate the effects of increasing drag coefficient and mass, respectively. *As the drag coefficient is doubled, the radius required to traverse a 30° slope is reduced to 4 m in average summer winds and to below 3 m in average winter winds. If the mass and the drag coefficient are doubled the resulting slope traversed for a given radius and wind speed remains the same.* When comparing figures 12 and 15 this equivalence is evident. Upon examination of equation (32), one notices that doubling of both mass and drag coefficient does not affect the torque balance.

The analysis results in this section can be used to perform preliminary Tumbleweed rover sizing necessary to maneuver smooth terrain of a given slope. *Tumbleweeds with radii of 3 to 6 m can climb the terrain of a 30° slope for reasonable ranges of mass, drag coefficient, wind speed, and rolling resistance.* An approximate relationship among deformation, rolling resistance, and structural stiffness has been established in equations (23) through (30). The equations in this section can thus be used as a basis for performing design trades of stiffness, weight, and drag coefficient for a range of selected materials and Tumbleweed geometries. Future work will continue the development of this methodology by considering improved modeling of the wind boundary layer and the addition of a rock model for the evaluation of motion along a nonsmooth surface. The complete model will be used to update the rock field analysis contained in section 3.3, allowing consideration of slope and Tumbleweed deformation in that analysis. The force and torque models developed will be used as the basis for a dynamics simulation that will be used to study start/stop, speed control, and coordinated motion for the purpose of controlled maneuvering of a single Mars Tumbleweed or group of Tumbleweeds (see sections 4.1 and 5.4 for descriptions of these capabilities).

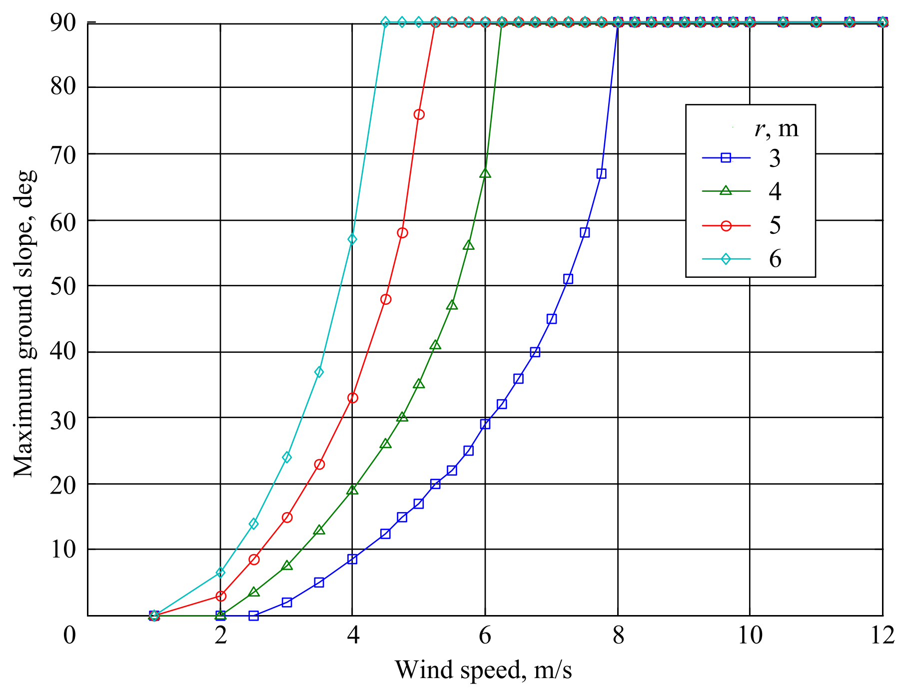


Figure 14. Maximum slope versus wind speed (m = 5 kg, C_D = 1.0, μ_r = 0.1).

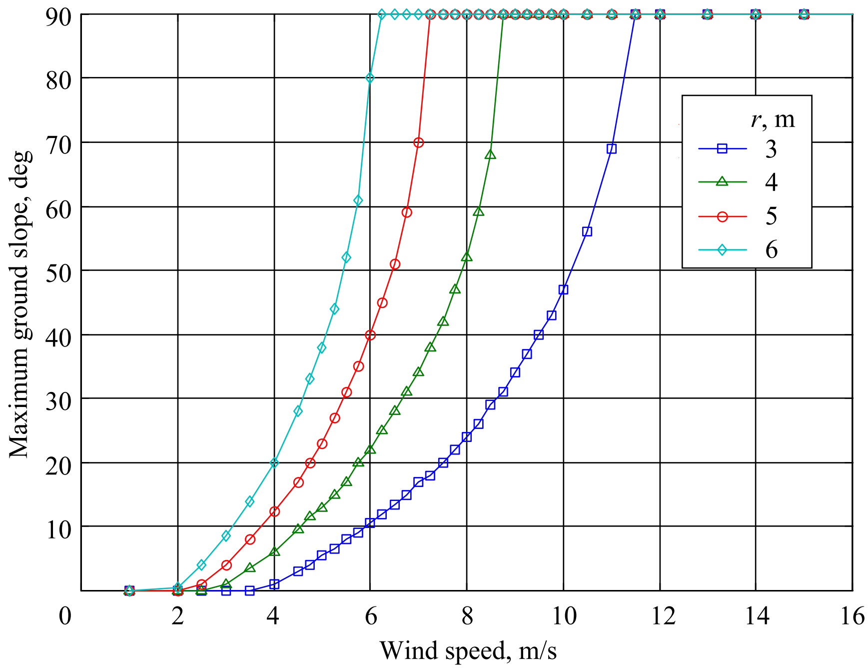


Figure 15. Maximum slope versus wind speed (m = 10 kg, C_D = 1.0, μ_r = 0.1).

3.5. Summary

Based on the preliminary analysis results presented in sections 3.2 to 3.4, wind-driven Tumbleweed rovers appear feasible for application on the surface of Mars. However, the Tumbleweeds would need to be lightweight (5 to 10 kg) and relatively large, with radii ranging from 3 to 6 m. The mathematical models presented here will be enhanced in the second year of this study effort and additional analyses conducted to refine the results.

4. Science Objectives

4.1. Preliminary Science Objectives

The third and final goal of this study was to define a preliminary set of science objectives and associated instruments applicable to the Tumbleweed rover concept. In general, *what type of science could be conducted on Mars with a Tumbleweed rover?*

The first step in answering this question was an examination of the Mars Exploration Program scientific goals and objectives, as defined by the Mars Exploration Program Advisory Group (MEPAG) in March 2001 (ref. 19). The MEPAG has defined four overarching program goals for Mars exploration.

- Determine if life ever arose on Mars.
- Investigate the climate on Mars.
- Determine the evolution of the surface and interior of Mars (geology).
- Prepare for human exploration.

The MEPAG also defined associated objectives within each of the above goals and corresponding investigations to accomplish those objectives. These objectives and investigations were reviewed and a subset identified as being potentially applicable to Tumbleweed rovers (the detailed subset of MEPAG objectives/investigations can be found in the appendix). In particular, those investigations that require multiple vehicles and/or widespread coverage were considered primary candidates. *The most promising science missions for the Mars Tumbleweed appear to be within the "search for life" and "climate" investigations.*

The next step was to identify the types of scientific instruments needed to perform the investigations (see section 4.2 for a brief discussion of specific instrument technologies). Water sensors and biomarker detectors (such as mass spectrometers) are needed to search for signs of life, while microweather sensors are needed for climate monitoring missions.

For certain scientific instrumentation, a Tumbleweed rover may need to remain stationary for a period of time, perhaps for weeks or even months, in order to take particular measurements in sufficient numbers. Therefore, a "control capability" may be needed to "command" a Tumbleweed to stop in locations of interest, take data for a period of time, and begin moving again once the measurements are complete and the winds are favorable. This "start/stop" capability is most likely needed if the instrument is integrated with the rover. There are cases where a control capability may not be necessary; for example, a simple Tumbleweed with no instrumentation that is used only to track wind direction would need to be entirely at the mercy of the winds. A control capability may not be needed for a Tumbleweed rover whose mission is to drop sensor packages and establish a sensor net as it is rolling.

A summary of the preliminary science goals and objectives for Tumbleweed rovers, the associated instrument types, and the control capability requirements is presented in table 1. The MEPAG science

Table 1. Preliminary Science Objectives

Science goal	Objective/investigation	Associated instrument	Control capability
Climate	Measure wind speed and direction	None or tracking beacon	None
Climate	Measure temperature, pressure, wind speed	Microweather sensors (dropped from rover)	None
Climate, life	Measure temperature, pressure, wind speed Search for water and complex organic molecules	Microweather sensors Microwater sensors/ spectrometers (integrated with rover)	Simple (ability to stop/start)
Geology	Mineralogy, geochemistry Global seismic monitoring	Alpha proton or mass spectrometer Seismometers	Moderate (ability to stop/start, maneuver)
Climate, geology, life	Visual observations	Camera	Complex (ability to stop/start, maneuver, point at targets)

goals and associated objectives/investigations are listed in the first and second columns, respectively. The third column identifies corresponding types of instruments, and the fourth column defines the extent of controllability that may be needed by the instruments to accomplish the measurements.

The identified goals and objectives are listed in table 1 by increasing complexity of the control capability that may be required. The simplest mission, as discussed previously, could involve a Tumbleweed with no instrumentation that is used only to track wind direction (see row 1 of table 1). This would be a first generation Tumbleweed design that could also serve as a proof-of-concept mission and would require an orbiting vehicle to track the Tumbleweed using radar, visual observations, or through monitoring of a tracking signal radiating from the Tumbleweed.

A second generation Tumbleweed mission (rows 2 and 3 of table 1) may utilize sensors to monitor the weather or search for biomarkers and thus will require supporting power, data, and communication subsystems. The instruments could be microsensor packages integrated with the rover or dropped from the rover in order to establish a sensor net on the surface. In the case of the dropped microsensor packages, a control capability may not be necessary whereas with the integrated sensors, a simple control capability may be needed in order to stop and start the Tumbleweed to acquire science data at particular locations and then to allow the Tumbleweed to be blown to new locations.

The third and fourth generation Tumbleweed rovers (rows 4 and 5, respectively, of table 1) would require more complexity in the control system, allowing science data to be taken at specific locations and perhaps at specific targets (e.g., rocks, land formations, etc.). The control capability would be more than a simple start/stop and could involve the use of smart materials, such as electroactive polymers, to provide an actuation capability for steering or maneuvering of the vehicle. Swarming algorithms may also be used to coordinate the data collection of multiple Tumbleweed rovers in order to maximize the science return.

In summary, the science requirements will be a strong driver of the Tumbleweed design, not only in the areas of system power, data, communications, and structural configuration, but also in aspects of vehicle controllability. In the second year of this C&I study, the science objectives will be refined and specific missions identified through discussions with Mars program scientists.

4.2. Microinstrument Technologies

The final step in the definition of the preliminary science objectives was an identification of existing, as well as planned, microinstrument technologies that could be used to accomplish the identified investigations. These technologies include:

- Existing microinstruments/sensors
    - subsurface sample/water detection experiment (Deep Space 2, JPL)
    - pressure, temperature, humidity and dust-loading sensors for network climatology (Pascal probes, Ames Research Center)
    - Mars microphone (Mars Polar Lander, Univ. of California Berkeley)
    - Alpha Proton X-Ray Spectrometer (APXS) (Mars Pathfinder, JPL)
    - Imager for Mars Pathfinder (IMP) (Mars Pathfinder, Univ. of Arizona)

- Advanced microinstruments/sensors
  - Surface-penetrating radar for water detection (Johns Hopkins Univ.)
  - Microweather station, Microseismometer, Microaccelerometers (JPL)
  - “Sensitive Skin” flexible sensor array (Rensselaer Polytechnic Institute)
  - Smart Dust (Univ. of California Berkeley)
  - Lab-on-a-Chip (TTU)
  - Sensor Web (JPL)

The instruments and sensors for Tumbleweed missions will not be limited to the above preliminary list of technologies. The mass, power, and data requirements of these and other sensors will be investigated further in the second year of this C&I study effort to provide the requirements for trade studies of supporting subsystems.

5. Tumbleweed Concepts

5.1. NASA LaRC Design Concepts

Several notional design configurations of Tumbleweed rovers have been developed, consisting of inflatable structures, kite-like structures, and those inspired by the tumbleweed plant. Simple models of these concepts have also been developed and preliminary tests using fans to propel them were conducted to examine basic rolling characteristics. An overview of each concept is presented herein.

The “Wedges” concept uses inflatable sphere sections to increase the apparent diameter of the system (fig. 16). Instead of using a single inflated sphere, the separate wedge sections are used to form a spherical shape (a variation of this concept would use small spheres rather than wedges in order to simplify the design). The primary driver of the Wedges concept is to allow an instrument package, represented by the box in the center, access to the Martian environment, whereas a single sphere may require protrusions through the wall of the sphere to allow instrument access. While an inflatable design offers a simplistic and proven deployment system, the long-term survivability of an inflated object rolling and bouncing over the sharp, jagged rocks of the Martian landscape is questionable. However, in the case of the Wedges concept, the use of numerous inflated sections may provide a level of redundancy over that of a single inflated sphere.

The “Box Kite” concept employs fabric sails stretched around spring hoops in the manner used in tents, automobile sunscreens, and children’s toys (fig. 17). This concept originated because of the concern for long-term survivability of inflatable structures. Fabric stretched over hoops may provide longer term durability than inflatable structures. Packaging and deployment methods appear relatively simple to accomplish; however, tearing of the fabric by dust during wind storms or by scraping against rocks during rolling is a primary concern. Another equally important concern is the potential for this structure to become wedged on rocks because of the numerous open segments of the design.

The “Dandelion” concept (fig. 18) uses a spherically symmetric array of struts, legs, and spines to increase the apparent diameter of the instrument pod. The concept arose from the idea to create a

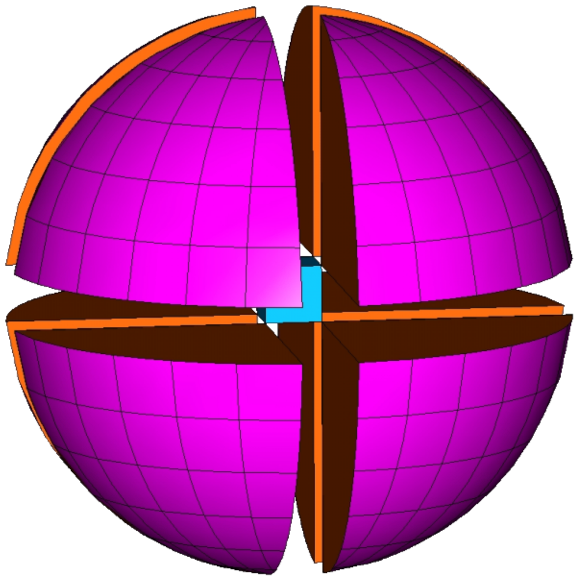


Figure 16. “Wedges” concept.

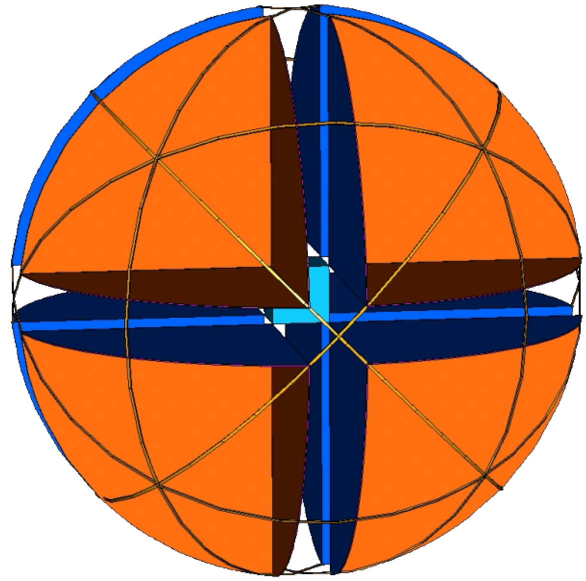


Figure 17. “Box Kite” concept.

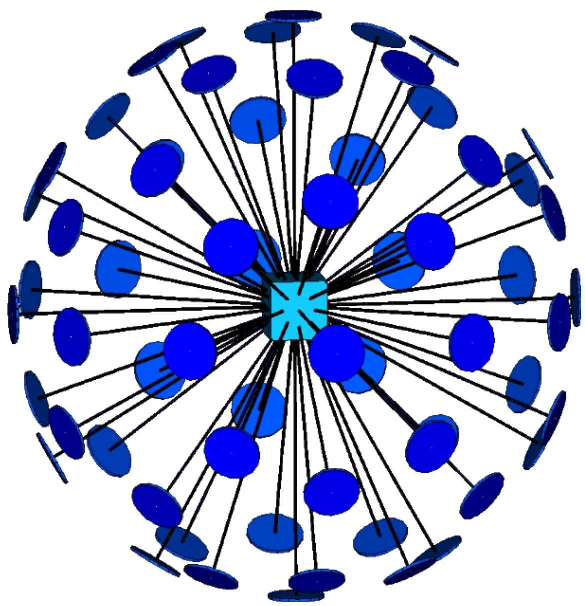


Figure 18. “Dandelion” concept.

structure that increases drag in the same manner as an actual tumbleweed plant (Russian thistle), which has developed the capability to harness the wind for movement using an intricate, lightweight branch structure. The Dandelion concept, with its deployable “branches,” was first conceived as an instrument box with numerous branches protruding from it; pads were later added to the ends to prevent sinking into soft dust or sand. The pads could also house sensors, perhaps being dropped as the Mars Tumbleweed rolls along the ground. The result is a structure that resembles a dandelion more than a tumbleweed plant. This concept does not have the material drawbacks of the Wedge or Box Kite; however, the potential exists for this structure to also become wedged on or between rocks.

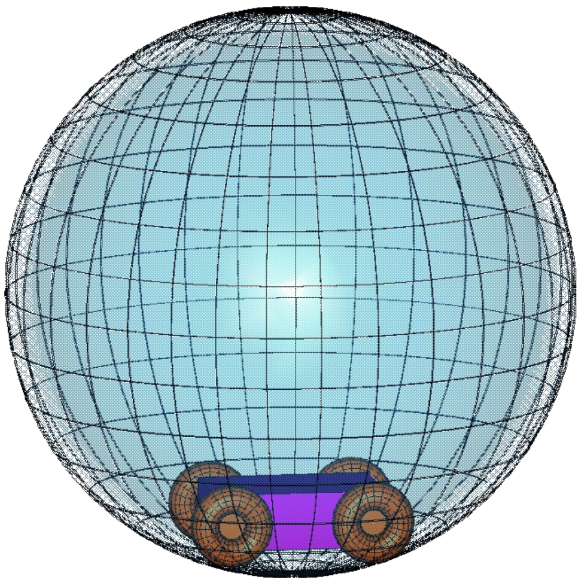


Figure 19. "Hamster Ball" concept.

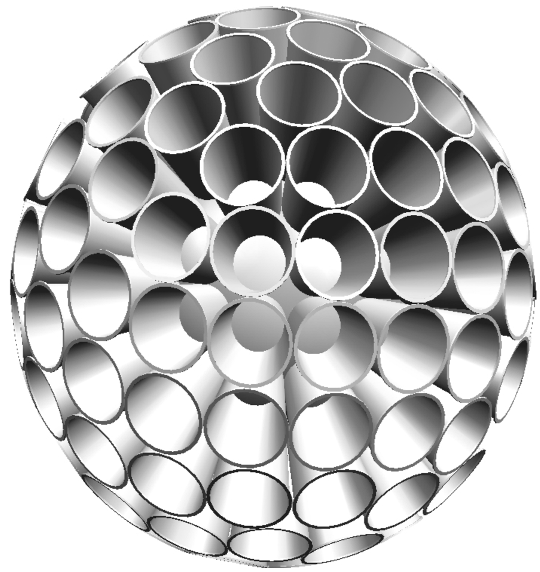


Figure 20. NCSU "Tumble Cup" concept.

The "Hamster Ball" concept (fig. 19) makes use of a conventional roving vehicle within an inflatable sphere; the overall effect is an increase in the apparent tire diameter of the rover. Differential steering of the vehicle can provide some maneuvering of the system. The concept was developed in response to the concern that a Tumbleweed rover would be at the mercy of the wind with no steering capability available to direct it in particular directions. The long-term survivability of an inflatable object is a concern here as it was with the Wedges concept.

The "Tumble Cup" concept (fig. 20) consists of numerous open-ended cylinders around a spherical center, such as a number of coffee cups glued to a ball. The concept seeks to maximize the surface area available in order to maximize drag while also reducing rolling resistance by minimizing the surface that is in contact with the ground. Packaging and deployment methods appear difficult to accomplish.

5.2. NASA LaRC Operations Concept

Tumbleweed rovers such as those in figures 21 and 22 could be delivered to Mars as secondary payloads (serving as ballast) on previously planned lander missions, or perhaps as an upcoming Mars Scout Mission of Opportunity. A dedicated mission may be required to deliver numerous Tumbleweed rovers at one time to provide for global coverage.

The Tumbleweeds could be deployed from a Mars lander aeroshell or backshell after separation from the lander. They would then descend to the surface in a fashion similar to the Pathfinder air bag landing system. However, unlike the Pathfinder, the Tumbleweeds would remain deployed after landing. If the Tumbleweeds were instead attached to the lander, deployment could be accomplished after successfully setting down on the surface. In order to avoid having multiple Tumbleweeds clumping together, deployment could be timed to occur at particular intervals (perhaps tied to the local wind speed), or each deployment could be commanded after visual observations confirm that the previous Tumbleweed is no longer in the vicinity.

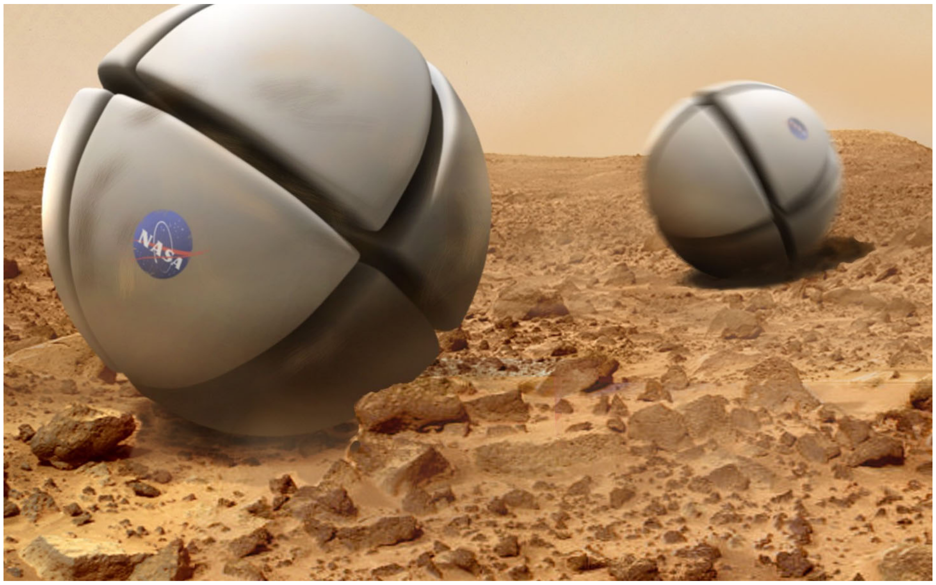


Figure 21. “Wedges” concept on surface of Mars.

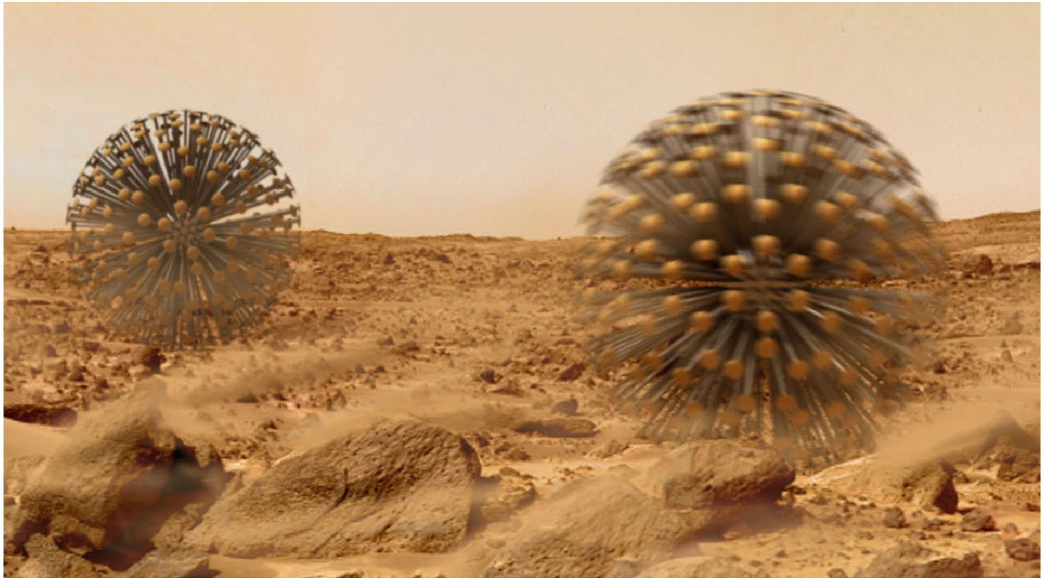


Figure 22. “Dandelion” concept on surface of Mars.

The Tumbleweeds may be designed (mass, diameter, drag coefficient) to roll at particular wind speeds. Therefore, when the wind is below the prescribed speed, the Tumbleweed rover would be stationary, taking data and/or communicating data back to Earth through one of the many communication relay systems planned for upcoming Mars orbiter missions.

Tumbleweed rovers may also be blown into canyons or valleys, which may allow areas to be reached that are not accessible by currently planned landers and rovers. Tumbleweeds may also become wedged between rocks or in a crevice; this situation would not reduce the functionality of the vehicle, it would merely convert the Tumbleweed into a stationary platform, performing the same functions at a fixed location.

5.3. Other Tumbleweed Design Concepts

Tumbleweed rover concepts are also being developed by the JPL, Texas Technical University (TTU), and the Swiss Federal Institute of Technology. Additionally, North Carolina State University (NCSU), in cooperation with LaRC, initiated an effort in the fall of 2002 as a senior aerospace design class project. Collaborative efforts are being fostered with these organizations to leverage their research expertise with that of LaRC.

5.3.1. NASA Jet Propulsion Laboratory

The JPL concept (fig. 23) is derived from the inflatable technology research program that developed the Mars Pathfinder air bag system and is investigating inflatable rover designs (ref. 6). Jack Jones of JPL is leading the effort. A collaborative effort to study Tumbleweed structures, inflatables in particular, is being planned between JPL and LaRC.

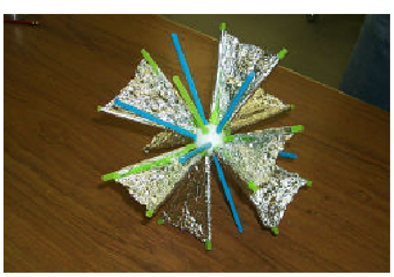
5.3.2. Texas Technical University

The TTU Tumbleweed concepts (fig. 24) were developed as a senior mechanical engineering design class project (ref. 7). The research is being continued through a grant from the Texas Space Grant Consortium and involves the TTU Wind Science and Engineering Research Department as well as the microelectromechanical systems (MEMS) Sensor Technology Center at TTU. Dr. Alan Barhorst is leading the activity. A collaborative effort is being planned between TTU and LaRC to investigate the Mars wind surface boundary layer model and to define applicable microsensor technologies.

(a) Testing of Tumbleweed concept.

(b) Artist rendition of Tumbleweed concept.

Figure 23. JPL Tumbleweed concept.



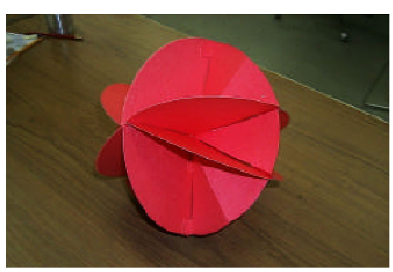


Figure 24. TTU Tumbleweed concepts.

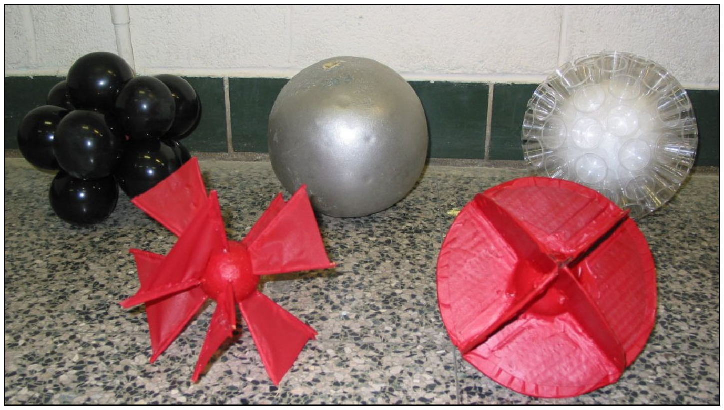


Figure 25. NCSU Tumbleweed concepts.

5.3.3. North Carolina State University

The NCSU senior aerospace design class is a two-semester course that involves concept development, wind-tunnel testing, prototype development, and field testing. Dr. Fred DeJarnette is the faculty advisor. The idea to study a Mars Tumbleweed for the class project was initiated by Langley Aerospace Research Summer Scholar (LARSS) David Minton while working at LaRC during the summer of 2002. The NCSU Tumbleweed concepts are based on the LaRC Wedges, Dandelion, Box Kite, and Tumble Cup concepts (fig. 25). NCSU is also collaborating with students at Carnage Middle School in Raleigh, North Carolina. A prototype Tumbleweed rover, scaled for use on Earth, will be constructed during the second semester. The NCSU results will greatly aid the LaRC Tumbleweed rover research effort by providing preliminary data on Tumbleweed design concepts.

5.3.4. Swiss Federal Institute of Technology

Thomas Estier of the Swiss Federal Institute of Technology has developed concepts for "collapsible wire 'windballs'" while working with the European Space Agency (ref. 8). The windballs would use a shape memory alloy to deploy into a spherical shape at night and when heated by the Sun during the day would collapse into a disk. This activity has only recently been identified and thus no collaborative efforts have been established at this date.

5.4. Advanced Biomimetic Concepts

Understanding how plants and animals operate in nature and then applying that knowledge to engineering problems is called biomimetics, or biologically inspired engineering. Biomimetics involves the study of a natural system to understand the underlying principles governing its behavior or structure, and then applying those principles to an engineering problem where applicable. The fundamental idea underlying this paradigm is that one takes the information from biologists (either already available or obtained via concurrent research) and uses it to construct the highest fidelity analog possible, to the point of even replicating features whose purposes or relevances are not understood. The idea is to introduce an element of serendipity to the design process such that the inclusion of these features will make the design more successful, the logic being that evolutionary processes are known to be excellent nonlinear optimizers (i.e., genetic algorithms). Mother Nature has thus been performing an optimization over potentially millions of years and has most likely come up with clever and robust solutions. If we can duplicate these

Figure 26. Tumbleweed plant, or Russian thistle.

solutions, our chances of success increase dramatically. One can also say that the biological organisms that we are trying to mimic present existing proof that such a design will work if implemented properly.

For example, the tumbleweed plant has developed the capability to harness the wind for movement using an intricate, lightweight branch structure. By developing a similar structure, a high fidelity biomimetic Tumbleweed rover concept could be created that may enhance mobility. Another example involves the rolling properties of the Russian thistle, which typically has a center of mass that is offset from the center of the plant due to its oblong shape (fig. 26). While studying this structure, it may be determined that placement of the center of mass causes the plant to bounce and tumble more than it would if the plant were more symmetrical. *Does this bouncing cause the plant to be able to travel farther by keeping it in the air longer, thereby reducing rolling resistance with the ground? Or does the bouncing motion help dislodge more seeds from the plant? Or is it both?* Developing a high fidelity biomimetic Tumbleweed rover with an offset center of mass may enhance mobility.

Another biomimetic discipline that may be applicable to the Tumbleweed concept is the use of swarm intelligence-based algorithms, such as that used by bees and ants, to coordinate multiple Tumbleweed rovers. For example, a group of Tumbleweed rovers may be searching for water or biomarkers in a particular region of Mars. Each Tumbleweed rover may have unique sensor capabilities. When something interesting is detected by one particular Tumbleweed, it would communicate its findings to the others, activating a swarm intelligence-based algorithm that would direct the others to proceed to the same general area and conduct additional sensing with their unique instruments. This process would require that the Tumbleweeds have a moderate to complex level of control capability (as discussed in section 4.1) in order to maneuver, as the winds allow, in the desired direction.

These aspects of the biomimetic design paradigm will be further researched during the second year of this study in order to develop a high fidelity biomimetic Tumbleweed concept.

Table 2. Preliminary Subsystem Technologies

Subsystem	Technology

Structures/materials	• Inflatable
	  ○ Kevlar®
	  ○ Spectra®
	  ○ Vectran
	  ○ Phenylene benzobisoxide (PBO)
	• Inflatable-rigidizable iso-grid
	• Lightweight fabrics
	  ○ Electrospun fibers
	• Shape memory materials
	• Smart materials
	  ○ Electroactive polymers

Power	• Batteries (nonrechargeable)
	  ○ Lithium thionyl chloride (Mars Pathfinder)
	• Solar array/batteries (rechargeable)
	  ○ GaAs/Ge array (Mars Pathfinder)
	  ○ CuInSe2 thin film array (proposed for a Mars Flyer concept)
	  ○ Plastic solar cells (UC Berkeley)
	  ○ Lithium polymer, thin film battery (proposed for a Mars Flyer concept)
	• Radioisotope microthermal power source
	  ○ Milliwatt radioisotope power supply (proposed for PASCAL Mars mission)
	• Wind
	  ○ Wind turbine (windmill)
	  ○ Piezoelectric actuators (flapping leaf)

Communications	• DS-2 or PASCAL derived system
Data handling	• DS-2 microcontroller

6. Subsystem Technologies

A preliminary investigation of existing, as well as planned, subsystem technologies with potential application to a Tumbleweed rover design was conducted, the results of which are summarized in table 2. An in-depth trade study of various subsystem options will be initiated in the second year of the study.

7. Concluding Remarks

7.1. Summary

A concept for a future rover propelled by Martian winds has been examined. The Mars Tumbleweed rover would be simple, lightweight, and inexpensive, equipped with microelectronic sensors for conducting climate measurements, searching for life, or gathering geologic data. Tumbleweeds could be deployed in large numbers to maximize coverage of the Martian surface and would complement the data being gathered by more complex lander and rover missions.

Three primary goals served as the focus for this first year C&I effort: brainstorming discussions with Langley experts, basic analyses to examine the feasibility of wind-driven mobility on Mars, and definition of science investigations that could be conducted using a Tumbleweed rover (see section 7.2 for a discussion of the corresponding results for each goal).

Several notional concepts of Tumbleweed rovers were developed, consisting of inflatable structures, kite-like structures, and those inspired by the tumbleweed plant. Simple models of these concepts were also developed and the basic rolling characteristics of each concept were observed while being propelled by a fan.

Tumbleweed rover concepts are also being developed by North Carolina State University, the Jet Propulsion Laboratory, Texas Technical University, and the Swiss Federal Institute of Technology. Collaborative efforts are being explored with these organizations.

7.2. Conclusions

7.2.1. Brainstorming Sessions

Feedback was sought on the validity of the concept, applicable technologies, and recommendations for future analysis and/or testing. As a result of those discussions, a need was identified to conduct aerodynamic analysis and/or wind-tunnel testing, at the appropriate Reynolds numbers, to examine the aerodynamic characteristics of proposed Mars Tumbleweed concepts. An interest was also identified in studying the rolling characteristics and drag properties of the tumbleweed plant to determine characteristics that potentially could be incorporated into the Tumbleweed rover design. Biologically inspired "swarming" strategies were considered for coordinating multiple Tumbleweed rovers in order to maximize science return, and lightweight materials and structures were identified that could be applied to Tumbleweed rovers.

7.2.1. Feasibility Study

The feasibility study was divided into three parts:

1. Quasi-static analysis of a Tumbleweed rolling on a smooth, flat surface.

A 5-kg Tumbleweed rover having a drag coefficient of 0.5 would require a radius of 1 to 5 m in order to initiate rolling on a smooth, flat surface in winds from 10 m/s down to 2 m/s. This size appears feasible because the Mars Pathfinder air bag system had approximately a 3-m radius. If the mission can be accomplished by waiting for higher wind speeds, then the smaller radius Tumbleweed could be utilized. Or, a larger radius Tumbleweed could have an increased mass capability if used in the higher winds, accommodating additional payload mass. Likewise, the results show that increasing the drag coefficient (C_D) to 1.0 or greater would have similar benefits.

2. Quasi-static analysis of a Tumbleweed rolling through a typical Martian rock field.

A smooth, spherical Tumbleweed appears not to be the best design for negotiating obstacles and a significant benefit can be achieved by designing the rover to maximize drag in this situation. Similarly, it can be seen that increasing the radius of the Tumbleweed has a significant impact upon the maximum navigable rock size. However, space and weight constraints place strict limitations upon the size of the Tumbleweed. Because of these limitations, preliminary results indicate that an optimum design procedure may be to maximize the drag coefficient of the Tumbleweed rover and then to determine an appropriate radius corresponding to that drag coefficient.

The results of the Monte Carlo simulation also demonstrate that an increased drag coefficient will significantly improve the ability of the Tumbleweed to negotiate a Martian rock field. A Tumbleweed with a drag coefficient of 0.5 would require a radius of approximately 7 m or greater to negotiate the typical rock field. Assuming that a median value drag coefficient can be obtained ($C_D = 1.5$ is approximately the drag of a low porosity parachute), a Tumbleweed would require a radius of about 4 m to negotiate the typical Martian rock field.

3. Dynamic analysis of a Tumbleweed on a slope.

The results show that Tumbleweeds with radii of 3 to 6 m can climb terrain with a 30° slope for reasonable ranges of mass, drag coefficient, wind speed, and rolling resistance. As the drag coefficient is doubled, the radius, required to traverse a 30° slope, is reduced to 4 m in average summer winds and to below 3 m in average winter winds. If the mass and the drag coefficient are doubled, the resulting slope traversed for a given radius and wind speed remains the same.

When the radius is large in combination with high wind the Mars Tumbleweed can climb a near vertical slope. This should remain true if the slope rate of change is gradual enough that the wind boundary layer assumptions are valid for upslope conditions, that is, the wind is always flowing parallel to the slope.

7.2.1. Science Objectives

The most promising science missions for the Tumbleweed appear to be "search for life" and "climate" investigations. The science requirements will be a strong driver of the Tumbleweed design, not only in the areas of system power, data, communications, and structural configuration, but also in aspects of vehicle controllability. A "control capability" may be needed to command a Tumbleweed to stop in locations of interest, take data for a period of time, and begin moving again once the measurements are complete and the winds are favorable. This "start/stop" capability is most likely needed if the instrument is integrated with the rover.

7.3. Plans

The key areas to be addressed in the second year of this C&I study are:

- Science Objectives
    - Refine science objectives/missions.
    - Examine microinstrument technologies.
    - Compare microinstrument requirements with potential capabilities of the tumbleweed concepts.

- Aerodynamic Testing/Analysis
  - Investigate Mars surface boundary layer conditions using existing models such as the Mars Global Reference Atmospheric Model (GRAM).
  - Conduct static tests in the Langley Basic Aerodynamic Research Tunnel (BART) to determine the drag coefficient of each Tumbleweed concept.
  - Conduct dynamic tests to assess the rolling characteristics of each Tumbleweed concept in a representative Mars rock field.
- Dynamic Modeling/Analysis
  - Refine the dynamic models by incorporating the wind-tunnel test results, improving the Mars surface wind boundary layer model, and adding a rock model for the evaluation of motion along a nonsmooth surface.
  - Develop the force and torque models to use as the basis for a dynamics simulation for study of start/stop, speed control, and coordinated motion for examining controlled maneuvering of a single Tumbleweed or group of Tumbleweeds.
- System Definition/Analysis
  - Examine system trades for:
    - Structures and materials.
    - Deployment mechanisms.
    - Power system.
    - Communication system.
    - Data handling system.
    - Navigation system.
  - Define advanced Tumbleweed concepts using a biomimetic design paradigm:
    - Develop a high fidelity biomimetic Tumbleweed concept (mimic the drag properties of the Russian thistle).
    - Define biologically inspired control strategies to enhance mobility (e.g., swarming).
    - Study concepts for morphological adaptation to provide control capability (mechanism for changing shape or drag (e.g., shape memory)).

- Collaboration With Other Organizations
  - A prototype Tumbleweed rover, scaled for use on Earth, will be constructed by the North Carolina State University students during the second semester. The results will greatly aid the Langley Tumbleweed research effort by providing preliminary data on Tumbleweed design concepts.
  - A collaborative effort to study Tumbleweed structures, inflatable structures in particular, is being planned between the Jet Propulsion Laboratory and Langley.
  - A collaborative effort is being planned between Texas Technical University and Langley to investigate the Mars wind surface boundary layer model and to define applicable microsensor technologies.

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Appendix

Potentially Applicable Objectives/Investigations

The subset of the Mars Exploration Program Advisory Group (MEPAG) objectives/investigations (ref. 19) with potential applicability to Tumbleweed rovers includes:

GOAL: Determine if life ever arose on Mars

- Objective: Determine if life exists today.
  - *Investigation: Carry out in situ exploration of areas suspected of harboring liquid water.*
    - For at least 20 stations at 4 targeted sites (based on remote sensing), conduct in situ geophysical and chemical (e.g., "sniffers") searches for subsurface water and other volatiles (e.g., carbon dioxide and reduced gases like methane and ammonia) over km^2 surface areas.
- Objective: Assess the extent of prebiotic organic chemical evolution.
  - *Investigation: Search for complex organic molecules in rocks and soils.*
    - In situ/mobile platforms deployed to at least three well-characterized and diverse sites to assess the mineralogy (e.g., using laser Raman mapping spectroscopy, X-ray diffraction, X-ray fluorescence, etc.), geochemistry (e.g., alpha proton or mass spectrometer methods for elemental and isotopic compositions), and organic materials (e.g., gas chromatography-mass spectrometry; laser desorption spectroscopy, etc.).

GOAL: Determine climate on Mars

- Objective: Characterize Mars' present climate and climate processes.
  - *Investigation: Determine the processes controlling the present distributions of water, carbon dioxide, and dust.*
    - In situ meteorological measurements:
      - Seasonal monitoring: Hourly measurements of temperature, pressure, and atmospheric column dust opacity from 16 or more globally distributed sites for 1 Mars year.
      - Weather monitoring: Diurnally resolved (e.g., hourly) measurements of pressure, wind speed and direction, temperature, and optical depths from sites at high, middle, and low latitudes, in both hemispheres, for a Mars year or longer (at polar sites, winter measurements are not required, but are desirable).
      - Boundary layer processes: High frequency measurements (comparable with, or better than, 1 s sampling) of near-surface wind, temperature, and water vapor concentration for representative portions (≈15 min sampling intervals) of diurnal cycle

(e.g., predawn, midmorning, midafternoon, and postsunset). Needed for representative sites at low, mid, and high latitudes; low and high thermal inertia nonpolar sites; one site dominated by local topography (e.g., canyon or edge of layered terrain). Vertical temperature profiling (1 to 3 levels minimum) highly desired through first few meters.

GOAL: Determine the evolution of the surface and interior of Mars—Geology

- Objective: Determine the nature and sequence of the various geologic processes (volcanism, impact, sedimentation, alteration, etc.) that have created and modified the Martian crust and surface.
    - *Investigation: Calibrate the cratering record and absolute ages for Mars.*
        - Measurement of current impact flux from seismic network and an infrasonic network operating for 1 Mars year, using 12 stations arrayed in triangular groups of 3 spaced 100 to 200 km apart.
    - *Investigation: Evaluate igneous processes and their evolution through time, including the present.*
        - Global seismic monitoring of potential volcanic activity using an array of broadband (0.05 to 50 Hz) seismometers (12 stations in groups of 3 with an internal spacing of 100 to 200 km) distributed globally.
- Objective: Determine the nature and sequence of the various geologic processes (volcanism, impact, sedimentation, alteration, etc.) that have created and modified the Martian crust and surface.
    - *Investigation: Characterize surface-atmosphere interactions on Mars, including polar, eolian, chemical, weathering, and mass-wasting processes.*
        - Network of at least 16 stations to monitor weather (temperature, pressure, wind velocity, and strength) with concurrent visual observations from the surface and from orbit. Mission lifetime of 3 Mars years to determine seasonal and internal variations.
    - *Investigation: Determine the large-scale vertical structure and chemical and mineralogical composition of the crust and its regional variations.*
        - Long-term (at least 1 Mars year) global seismic measurements using an array of broadband (0.01 to 20 Hz) seismometers (at least 12 stations distributed in groups of at least 3, with internal spacing of 100 to 200 km).

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01- 08 - 2003

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Low Cost Mars Surface Exploration: The Mars Tumbleweed

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jeffrey Antol, Philip Calhoun, John Flick, Gregory Hajos, Richard Kolacinski, Ph.D., David Minton, Rachel Owens, and Jennifer Parker

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
274-00-03-36

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18275

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-2003-212411

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 18
Availability: NASA CASI (301) 621-0390 Distribution: Standard

13. SUPPLEMENTARY NOTES
Antol, Calhoun, Flick, and Hajos, Langley Research Center; Kolacinski, Orbital Research Inc.; Minton, North Carolina State University; Owens, Hampton Christian High School; Parker, Rensselaer Polytechnic Institute.
An electronic version can be found at http://techreports.larc.nasa.gov/ltrs/ or http://ntrs.nasa.gov

14. ABSTRACT
The "Mars Tumbleweed," a rover concept that would utilize surface winds for mobility, is being examined as a low cost complement to the current Mars exploration efforts. Tumbleweeds carrying microinstruments would be driven across the Martian landscape by wind, searching for areas of scientific interest. These rovers, relatively simple, inexpensive, and deployed in large numbers to maximize coverage of the Martian surface, would provide a broad scouting capability to identify specific sites for exploration by more complex rover and lander missions.

15. SUBJECT TERMS
Mars; Tumbleweed; Mars rover; Wind driven; Surface exploration

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	43	(301) 621-0390

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18