Tumbleweed: A New Paradigm for Surveying the Surface of Mars

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1 Introduction

Mars missions to date have interrogated the planet at very large scales using orbital platforms or at very small scales intensively studying relatively small patches of terrain. In order to facilitate discovery and eventual utilization of Martian resources for future missions, a strategy that will bridge these scales and allow assessment of large areas of Mars in pursuit of a resource base will be essential. Long-range surveys of in situ resources on the surface of Mars could be readily accomplished with a fleet of Tumbleweeds - vehicles capable of using the readily available Martian wind to traverse the surface of Mars with minimal power, while optimizing their capabilities to perform a variety of measurements over relatively large swaths of terrain (Kuhlman et al., 2009). These low-cost vehicles fill the niche between orbital reconnaissance and landed rovers, which are capable of much more localized study. Fleets of Tumbleweed vehicles could be used to conduct long-range, randomized surveys with simple, low-cost instrumentation functionally equivalent to conventional coordinate grid sampling. Gradients of many potential volatiles relevant to astrobiology and in situ resources (e.g. H2O, CH4, etc.) will also tend to follow wind-borne trajectories thus making the mobility mode of the vehicles well matched to the possible target resources. These vehicles can be suitably instrumented for surface and near-surface interrogation and released to roam for the duration of a season or longer, possibly on the residual ice cap or anywhere orbital surveillance indicates that usable resources may exist. Specific instrument selections can service the exact exploration goals of particular survey missions. Many of the desired instruments for resource discovery are currently under development for in situ applications, but have not yet been miniaturized to the point where they can be integrated into Tumbleweeds. It is anticipated that within a few years, instruments such as gas chromatograph mass spectrometers (GC-MS) and ground-penetrating radar (GPR) will be deployable on Tumbleweed vehicles. The wind-driven strategy conforms to potential natural gradients of moisture and potentially relevant resource gases that also respond to wind vectors. This approach is also useful for characterizing other resources and performing a variety of basic science missions. Inflatable and deployable structure Tumbleweeds are wind-propelled long-range vehicles based on well-developed and field tested technology (Antol et al., 2005; Behar et al., 2004; Carsey et al., 2004; Jones and Yavrouian, 1997; Wilson et al., 2008). Different Tumbleweed configurations can provide the capability to operate in varying terrains and accommodate a wide range of instrument packages making them suitable for autonomous surveys for in situ natural resources. Tumbleweeds are lightweight and relatively inexpensive, making them very attractive for multiple deployments or piggybacking on larger missions.

2 History and Development of Tumbleweed Vehicles

Tumbleweeds are large, lightweight, spherically shaped wind-propelled vehicles that can enable exploration of vast areas of Mars. A variety of vehicles referred to as Tumbleweeds and inspired by the Russian thistle (Salsola tragus) have been investigated by numerous groups of investigators. Jacques Blamont of NASA’s Jet Propulsion Laboratory (JPL) and the University of Paris originally conceived
the first known Mars wind-blown ball in 1977, shortly after the Mars Viking Landers discovered that Mars has a thin CO₂ atmosphere with relatively strong winds (Blamont, 1977). Blamont’s “Mars Balls” were conceived as relatively large, 3- to 10-meter diameter inflatable balls that could carry payloads, of 20-30 kg for distances of at least 100 km (Janes, 1989). These proposed balls could be powered either by the wind or powered and steered by an inner drive mechanism.

2.1 Inflatable Tumbleweeds

In 2000, Jack Jones of NASA JPL was testing a three-wheeled inflatable rover (Figure 1) in a windy sand dune area in California’s Mojave Desert when one of the wheels broke off and took off over the sand dunes, while Jones’ crew chased the ball with a dune buggy (Jones, 2001). The renegade 1.5 m diameter ball was able to climb steep slopes, over large boulders, and through the jagged brush without hesitation. This seemingly unlucky incident produced the inspiration for the current Tumbleweed vehicle (Behar et al., 2004). JPL then went on to measure performance of a 1.5 m sphere in the Mojave Desert (Jones, 2001), which was confirmed by theoretical analyses performed by the University of Southern California (Wang et al., 2002). The inflatable Tumbleweed has since successfully been tested in Greenland in 2003 and in Antarctica in 2004 (Figure 2). The latest version of the rover was deployed in Greenland in May 2004, where it autonomously traveled more than 200 km across an ice sheet during a 4-day period. Communicating via the Iridium satellite network, the vehicle successfully and reliably relayed live GPS, temperature, and pressure data to a ground station at JPL.

![Figure 1. Original 3-wheeled inflatable rover shown with inventor, Jack Jones, NASA Jet Propulsion Laboratory (Jones et al., 1999).](image)

Modeling and testing have shown that an inflatable 6 meter diameter Tumbleweed is capable of climbing 25° hills, traveling over 1 meter diameter boulders, and ranging over a thousand kilometers of terrain (Wang et al., 2002). Tumbleweeds have a potential payload capability of about 10 kg and could potentially generate 10-20 W of power by means of using an internal kinetic energy production device (Jones, 2009). Stopping for measurements can be accomplished using partial deflation or other braking mechanisms (Figure 3). Carnegie Mellon University (CMU) has also conducted empirical testing of the JPL inflatable concepts (Apostolopoulous et al., 2003). The primary purpose of CMU’s test was to characterize the rolling resistance, drive torque, drive power and tire wear of a single inflatable sphere, for use on the three-wheeled rover, which utilized the inflatable balls for wheels. A testbed apparatus was developed for these tests that allowed variation of tire design, wheel speed/acceleration, tire pressure, soil/obstacle properties and traverse length.
Inflatable Tumbleweeds have been tested by NASA JPL in Greenland and Antarctica carrying a complete central payload consisting of batteries, inflation/deflation pumps, communications, and a winch. The winch can be used to pull on one or more of the central payload tension lines while the ball deflates. This will create a “turtle” shape and allow the ball to stop, forming a volume underneath that can be used to collect gases emanating from the soil that might indicate hidden subsurface resources (Figure 3). This chamber is very conducive to the collection of gases because its volume to basal area ratio can be very small, providing more rapid feedback to the concentration gradient driving molecular diffusion across the surface (Livingston and Hutchinson, 1995).

2.2 Deployable Structure Tumbleweeds

Tumbleweeds utilizing lightweight deployable structures to harness the wind for mobility have been developed by NASA Langley Research Center (LaRC). LaRC engineers were inspired by the Mars Pathfinder airbag landing system, which traveled a significant distance across the surface of Mars (much farther than the wheeled Sojourner rover ultimately would travel) before coming to a rest and deflating. Various methods were considered for maintaining the rolling motion, with the Martian wind appearing to be the most promising (Antol et al., 2003). Leveraging LaRC’s expertise in lightweight structures, several notional concepts of Tumbleweeds (Figure 4) were defined with the goal of providing vehicles with superior aerodynamic properties for capturing the wind (Antol, 2005).

The “Box Kite” concept uses fabric sails, similar to a kite, but with the sails attached to spring hoops to provide increased rolling capability. The “Dandelion” concept was biomimetically inspired with the objective of creating a branch structure similar to that of a Tumbleweed plant (Figure 5). However, the configuration evolved into a symmetric array of legs extending from a spherical core and having pads at the ends to prevent sinking into soft surfaces, thus resembling a dandelion more than a Tumbleweed. A variation of the Dandelion that more closely resembles the Tumbleweed plant is the “Eggbeater Dandelion,” which replaces the legs with multiple curved struts resembling egg-beaters or whisks. The “Tumble-cup” consists of open-ended cones around a spherical core to maximize aerodynamic surface area while reducing rolling resistance. The open configurations of the deployable structure Tumbleweed concepts have the additional advantage of allowing unobstructed access to the environment for scientific instrumentation.
Figure 3. An inflatable Tumbleweed can be stopped by partially deflating the ball and pulling on one of the central payload tension cords to create the “Turtle mode.” This mode of stopping also creates a collection chamber for gas measurements (Jones, 2001).

Figure 4. NASA LaRC Tumbleweed Concepts (left to right): Box kite, Dandelion, Eggbeater, and Tumble-cup. Image courtesy NASA/AMA Inc.
3 Tumbleweed Deployment

Launch and deployment of Tumbleweed vehicles promises to be simple and relatively low-cost. A small number of Tumbleweeds could piggyback along with other missions, or fleets of Tumbleweeds could be launched together and released at one or multiple locations depending upon the coverage desired. Mobility of a wind-driven system is inversely proportional to mass and directly proportional to atmospheric density and drag coefficients. To increase the system mobility, mass should be minimized. Increasing the size of a Tumbleweed will increase the driving force from the wind, but increases the structural mass, which will limit the additional mobility. Communication systems tend to need high levels of electric power. Power systems tend to be heavy to begin with and increase in mass with increased capacity. The preferred approach is to reduce the size and mass of system components such as the structure, power and communication systems.

Figure 5. Artist depiction of NASA Langley Research Center Dandelion Tumbleweeds on Mars. Image courtesy NASA/AMA Inc.

Figure 6. NASA LaRC Box Kite Tumbleweed Prototype.
4 Targets for Astrobiology and In situ Resources

Since the potential resources of Mars will be discussed in detail in the book, “Mars: Prospective Energy and Material Resources,” (Badescu, 2009), we will briefly touch upon the resources that can potentially be surveyed using a fleet of Tumbleweed vehicles. It should also be noted that Tumbleweeds and their highly configurable payloads could perform a variety of basic science missions, particularly astrobiological surveys. The most important resource for both astrobiology and human habitation is arguably water. A well-defined supply of water is deemed a necessity for a base that is expected to flourish and grow (Taylor, 2001). Tumbleweeds can survey for water in two ways: surface mounted sensors and ground penetrating radar (GPR). Both will be discussed in the following section on instrumentation. GPR in particular will be capable of characterizing the location and abundance of near-surface water, critical both for locating potential biology or for locating a future Martian base (Jakosky and Zent, 1993). In addition to ice and underground aquifers, water may be present in the pore spaces of clays and other hydrated minerals, making these materials potential important water resources on Mars (Baker et al., 1993). Tumbleweeds would be capable of identifying areas of hydrothermal activity and thus deposits of hydrated minerals, such as those found in Nili Fossae by Mars Express (Bibring et al., 2006; Poulet et al., 2005) and Mars Reconnaissance Orbiter (MRO) (Mustard et al., 2008).

Hydrogen and oxygen (both likely derived from water) are key components in the synthesis of fuels and propellants (Stoker et al., 1993), Tumbleweeds would also be useful components in the search for quantities of water that will be needed to fuel a base on Mars and provide transportation off the surface. Tumbleweeds equipped with gas sensors could also be used to locate sources of methane plumes observed on Mars in recent years (Krasnopolsky et al., 2004; Mumma et al., 2009). These sources could be important for production of fuels and propellants as well as being of relevance to astrobiology.

Human colonists of Mars will need to have soil for agricultural activities (McKay et al., 1993; Taylor, 2001). Ever since Viking, there have been indications that the regolith contains montmorillonite (a swelling clay) and other components that may make it difficult to use for agriculture (Bibring et al., 2006; Poulet et al., 2005). Information about pH (seeking the neutral soil), clay types, heavy metal contents, etc. would be target information that would pertain to this goal. Both a multispectral imager and X-ray fluorescence spectrometer would allow Tumbleweeds to survey these properties of the martian regolith (Marshall et al., 1997). These instruments would also be critical to locating sources of nitrates and phosphates, which will be critical to the agricultural enhancement of regolith local to a martian base (Stoker et al., 1993; Taylor, 2001). Tumbleweeds would also be well suited to survey for sulfur compounds, which would be important for a variety of industrial processes that one would assume to be important to a base on Mars.

Conversely, recognition of perchlorate (and possibly chlorate) as discovered recently by the Phoenix mission (Hecht et al., 2008) would be important for two reasons. Natural perchlorate on Earth is thought to be formed by photolytic processes in the atmosphere (Ericksen, 1981). Similar processes produce nitrate. Thus, perchlorate could be a pathfinder for much larger nitrate deposits. Both of these materials are very soluble salts and can accumulate on the Earth’s surface in very arid regions, like the Atacama Desert, where the average perchlorate forms less than 0.05% of nitrate deposits (Ericksen, 1983). While nitrate is a valuable fertilizer, perchlorate and, to a much greater extent, chloride, are herbicides. Concentrations of perchlorate of up to 0.8% have been reported in nitrate fertilizer from Chile (Bohlike et al., 1997). Perchlorate is a powerful oxidant and could be a useful energy source in the same way as it is used in solid fuel rockets.

Tumbleweeds outfitted with similar instruments will also be useful for locating resources of building materials. Aggregates, calcium-sulfates and carbonates are all important materials for building infrastructure (Schmitt, 2004; Taylor, 2001). Calcium-rich sulfates, most likely gypsum, have been observed in several locations on Mars by OMEGA/Mars Express (Gendrin et al., 2005; Langevin et al., 2005). Carbonates have recently been observed at the Phoenix lander site (Boynton et al., 2009; Kounaves et al., 2009; Sutter et al., 2009). Even after a base is established, Tumbleweeds may be used to survey for long-term resources such as ore-bodies, sources of metals, organic compounds and extensive clay deposits. Tumbleweeds will be particularly useful for long-range surveys.
for resources that require intensive, global geological exploration suggested by Taylor, 2001: sedimentary deposits, hydrothermal deposits, and differentiated igneous provinces. Taylor (2001) suggests that these global searches for resources be started early in the process in order to attract capital for martian investment. Fleets of low-cost Tumbleweeds could play an integral role in such reconnaissance.

5 Example Instrumentation for Astrobiology and ISRU Surveys

A suite of instrumentation can be envisioned for a fleet of Tumbleweeds for deployment on Mars for astrobiology and/or in situ resource surveys. An example instrument suite could include surface mounted soil moisture sensors (SMSMS), ground penetrating radar (GPR) to characterize subsurface layering, aquifers and voids, sensors for a variety of useful gases, a miniature X-ray fluorescence and/or X-ray diffraction spectrometer for elemental analysis of martian regolith and a multispectral imaging system for characterizing grain size and shape distributions as well as surface mineral composition. Other suites of instruments could be envisioned based upon the requirements of specific survey scenarios. A full description of the proposed instrumentation is described in (Kuhlman et al., 2009)

6 Conclusions

A variety of wind-driven Tumbleweed concepts have been proposed, studied and tested in extreme terrestrial environments as potential scouts for various mission scenarios on Mars. Multiple Tumbleweed rovers could be outfitted to autonomously survey large areas of Mars for astrobiology and/or in situ resources at relatively low cost. Similar missions could also be configured for performing basic science.

Tumbleweed rovers could also be networked together to provide additional communication and navigational support. Since the Tumbleweed rovers are significantly lower mass and compactable than traditional wheeled robotic rovers, many more of the Tumbleweeds can be deployed on the Mars surface during a single mission. A group of Tumbleweed rovers could survey a particular region of Mars with each Tumbleweed having a unique sensor or long-range communications capabilities. When something interesting is detected by a 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. Such networking and swarming behavior is currently being studied for robotic systems by several groups (Bae and Lee, 2005a, b; Baxter et al., 2006; Clark et al., 2003; Hashimoto et al., 2008). An added benefit of a swarm of multiple Tumbleweeds is that a stuck rover would be to act as a fixed facility to gather temporal data while other Tumbleweeds proceed.

Low-mass, highly mobile autonomous vehicles capable of making survey measurements will fill the current void between orbital reconnaissance and landed rovers with limited range. Thus, Tumbleweeds are an attractive option for performing surveys of potential in situ resources available on Mars.

7 References


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