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A New Vehicle for Planetary Surface Exploration: The Mars Tumbleweed

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The surface of Mars is currently being explored with a combination of orbiting spacecraft, stationary landers and wheeled rovers. The scientific data gathered by these missions to date has provided extensive insight into the Martian landscape; however, only a small portion of the Martian surface has undergone in-situ examination. Landing sites must be chosen to insure the safety of the vehicles (and human explorers) and provide the greatest opportunity for mission success. While wheeled rovers provide the ability to move beyond the landing sites, they are also limited in their ability to traverse rough terrain; therefore, many scientifically interesting sites are inaccessible by current vehicles. In order to access these sites and increase our global understanding of the Martian surface, a capability is needed that can transport scientific instruments across hundreds or perhaps thousands of kilometers of varied Martian terrain. A new "rover" concept for exploring the Martian surface, known as the Mars Tumbleweed, will derive mobility through use of the surface winds on Mars, much like the Tumbleweed plant does here on Earth. Using the winds on Mars, a Tumbleweed rover could conceivably travel great distances and cover broad areas of the planetary surface. Tumbleweed vehicles would be designed to withstand repeated bouncing and rolling on the rock covered Martian surface and may be durable enough to explore areas on Mars such as gullies and canyons that are currently inaccessible by conventional rovers. Achieving Mars wind-driven mobility; however, is not a minor task. The density of the atmosphere on Mars is approximately 60-80 times less than that on Earth and wind speeds are typically around 2-5 m/s during the day, with periodic winds of 10 m/s to 20 m/s (in excess of 25 m/s during seasonal dust storms). However, because of the Martian atmosphere's low density, even the strongest winds on Mars equate to only a gentle breeze on Earth. Tumbleweed rovers therefore need to be relatively large (4-6 m in diameter), very lightweight (10-20 kg), and equipped with lightweight, low-power instruments. Being driven by the winds, Tumbleweeds would employ a random survey strategy, scouting many sites over a broad area with the goal of identifying specific locations for follow-on investigation by landers, rovers, or human explorers. Multiple vehicles could be deployed for regional or perhaps global coverage of the Martian surface, performing wide-ranging survey missions to investigate the potential for human habitability and in-situ resource utilization as well as scientific precursor missions. This paper provides an overview of the Tumbleweed concept, presents several notional design concepts, mission scenarios, and highlights recent tests and analyses of Tumbleweed prototypes.

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I. Introduction

The surface of Mars has been explored for the past three decades using a combination of orbiting spacecraft, stationary landers, and wheeled rovers. The scientific data gathered to date by these missions has provided extensive insight into the Martian landscape. However, only a small portion of the Martian surface has undergone in-situ examination. Landing sites are chosen to insure the safety of the vehicles and provide the greatest opportunity for mission success. While wheeled rovers provide the ability to move beyond the landing sites, they are also limited in their ability to traverse rough terrain; therefore, many scientifically interesting sites are inaccessible by current vehicles. In order to provide access to these sites and increase our global understanding of the Martian surface, a new capability is needed that can transport scientific instruments across hundreds or perhaps thousands of kilometers of varied Martian terrain. A new "rover" concept for exploring the Martian surface, known as the Mars Tumbleweed, will derive mobility through use of the surface winds on Mars, much like the Tumbleweed plant does here on Earth. Tumbleweed rovers would be lightweight and relatively inexpensive, allowing multiple rovers to be deployed in a single mission to particular areas of interest. The Tumbleweeds would complement currently planned missions by serving as scouts - pinpointing locations of interest for detailed follow-on investigations by rovers, landers, or perhaps human explorers. With Martian wind speeds typically 2-5 meters/sec (m/s) during the day, with periodic gusts of 10-20 m/s and seasonal dust storms exceeding 25 m/s, all sensors and measurement acquisition equipment would need to be extremely lightweight to enable the Tumbleweed concept to successfully operate in the thin atmosphere of Mars. Because of the Martian atmosphere's low density, even the strongest winds on Mars provide very little dynamic pressure; therefore, Tumbleweed rovers would need to be several meters (m) in diameter and of relatively low mass, on the order of tens of kilograms (kg).

II. Background

Jacques Blamont of the National Center for Space Studies (CNES – Centre National d'Etudes Spatiales) in France developed a wind-driven rover concept for use on Mars in the late 1970s.[1] Blamont's concept was a 3-10 m diameter inflatable ball that could carry payloads of 20-30 kg for distances of approximately 100 kilometers (km), driven by the wind or powered by an inner drive mechanism.[2] His idea evolved into the University of Arizona "Mars Ball" concept, an inflatable 4m by 5m, 500kg rover whose mobility was produced through sequenced inflation and deflation of air bags.[1]

Jack Jones of the Jet Propulsion Laboratory (JPL) developed another concept for a wind-blown Mars rover in 1995, a 1.5 m inflatable ball with a suspended motorized mass beneath the rolling axis to provide a limited steering capability.[3] This concept evolved into a three-wheeled rover, which utilized the inflatable balls for wheels and is capable of traversing 99% of the Martian surface.[4] Testing of a prototype three-wheeled rover in California's Mojave Desert in 2000 led to development of the current version of the JPL inflatable Tumbleweed when one of the wheels separated from the rover and was propelled by the winds over the sand dunes. The wheel was eventually retrieved using all-terrain vehicles.[5]

Langley Research Center's (LaRC) Tumbleweed research was inspired by the Pathfinder mission landing on Mars, which utilized a system of airbags for cushioning the Pathfinder lander and the accompanying Sojourner rover during impact with the ground. The Pathfinder/airbag system traveled a significant distance across the surface of Mars before coming to rest and being deflated, much farther than the wheeled Sojourner rover ultimately would accomplish on its own. The idea to maintain the vehicle rolling through use of the Martian wind was contemplated and several deployable structure concepts were generated, utilizing sails and branching structures.[6]

III. Tumbleweed Concepts

Tumbleweed rover research and development efforts in the United States are currently underway at LaRC, JPL, North Carolina State University (NCSU), and Texas Tech University (TTU). The LaRC, NCSU, and TTU concepts utilize deployable structures, while JPL's Tumbleweed employs inflatable structures.

The LaRC Tumbleweed deployable structure concepts (fig. 1)[6] provide enhanced aerodynamic properties and allow open access to the environment for scientific instrumentation. The **"Box Kite"** concept uses fabric sails to capture the wind, attached to spring hoops to aid rolling and bouncing. Additional hoops (without sails) may be added to provide better rolling characteristics. The **"Dandelion"** concept was biomimetically inspired, or derived from nature. In an attempt to recreate a branch structure similar to that of an actual Tumbleweed plant, and gain the same aerodynamic advantages that the plant has evolved, a spherical core was devised with a symmetric array of struts, legs, etc., which may have pads/feet at the ends to prevent sinking into sand or soft soil. However, in the interest of simplifying the structure for packaging and deployment, it assumed the appearance of a dandelion rather than a Tumbleweed. A variation of the Dandelion that more closely resembles the Tumbleweed plant is the **"Eggbeater Dandelion,"** which uses multiple curved struts, resembling eggbeaters or whisks,[7] the reason for this shape is discussed in Section V. The **"Tumble-cup"** consists of open-ended cylinders around a spherical core maximizing aerodynamic surface area to maximize the drag force while also reducing rolling resistance. The LaRC Tumbleweeds would have a mass of approximately 20 kg, including subsystems and instruments, and would require a diameter of 4-6 meters (m), to capture the very "thin" Martian atmosphere and achieve mobility.

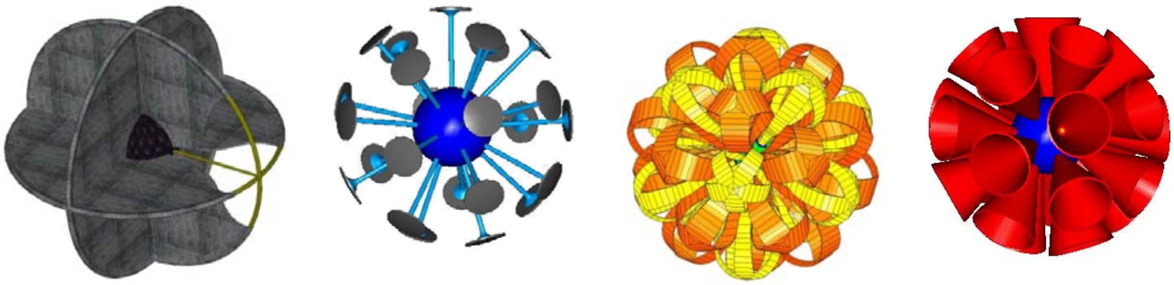

Figure 1. NASA LaRC Deployable Structure Tumbleweed Concepts, from left to right: Box Kite, Dandelion, Eggbeater Dandelion, and Tumble-cup

The JPL Tumbleweed concept is a beach ball-like inflatable vehicle, which could carry internal sensors and systems for conducting scientific investigations (fig. 2). It could be deployed mid-air and bounce onto the surface of Mars, much like the airbag systems used to deploy the Mars Exploration Rovers and Pathfinder. Driven by the Martian winds, the Tumbleweed ball could cover great distances on the surface of Mars and reach speeds of 25 miles per hour. The inflatable Tumbleweed could be partially deflated to stop at particular locations of interest to take scientific measurements. An internal pump system would be used to re-inflate the ball for continued traversing of the Martian surface. The device would be approximately 6 m in diameter and have a mass of 20-40 kg.[5]

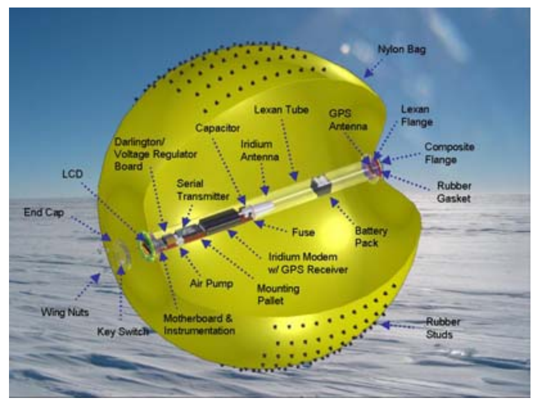

Figure 2. JPL Inflatable Tumbleweed for Earth Polar Exploration

The NCSU Department of Mechanical and Aerospace Engineering, in cooperation with NASA LaRC, conducted wind tunnel tests and analyzed various design aspects of the LaRC Tumbleweed concepts. Based on the resulting data, NCSU developed a scale Tumbleweed Earth Demonstrator (TED) based on the Box Kite design (fig. 3). The TED includes a central instrument core with temperature/pressure sensors, accelerometers, a Global Positioning System (GPS) navigation package and a data acquisition/communication system for collecting data during Earth-based field tests of the concept. A second generation TED is currently being developed and is planned for completion and test in the spring of 2005. [8]

Figure 3. NCSU TED Box Kite

TTU is developing extremely lightweight Tumbleweed concepts that would facilitate miniaturized vehicles, permitting numerous Tumbleweeds to be carried as secondary payloads on conventional Martian surface missions. The Texas Tech Tumbleweeds, with the configuration of a sector removed sphere (fig. 4), would have a diameter of approximately 12 inches and a mass of less than a kilogram.[9]

Figure 4. Texas Tech Tumbleweed Concept

IV. Mission Concepts

The wind-blown mobility of a passive Tumbleweed makes it an ideal platform for conducting random in-situ surveys of the Martian surface. A Tumbleweed has the capacity for taking measurements of broad areas over long distances, filling a niche between the wide ranging remote sensing capabilities of orbiting platforms and the focused, in-situ measurements of conventional landers and rovers. The Tumbleweed is therefore not intended to replace Mars Exploration Rover (MER) type vehicles, but rather complement their missions by providing a scout function to aid in the site selection process of future landers, rovers and human explorers (fig. 5).

The selection of safe landing sites for human explorers is imperative and Tumbleweed can play a vital role in this effort. Tumbleweed rovers could be deployed in locations identified as candidate landing sites for human exploration missions, carrying an instrument complement capable of examining habitability aspects of the region such as: radiation environment, soil toxicity, electrostatic properties of the soil, and residual magnetic field. The data would be used to identify potential hazards to crews across broad areas of interest, allowing greater flexibility in mission planning.

A number of Astrobiology scientific mission concepts have also been identified for Tumbleweed. A team consisting of scientists from JPL, Ames Research Center (ARC), several academic institutions, and NASA LaRC recently defined several Astrobiology concept missions, including an investigation of Martian surface habitability[10] and the exploration of Mars gully formations.[11, 12] The current Mars program strategy in the search for life is to "follow the water;" however, many locations on Mars that are candidates for finding water, such as canyons and gullies, are not accessible by current conventional robotic systems. The Tumbleweed concept may offer a means for accessing these areas. Astrobiology missions will present several challenges for the Tumbleweed vehicle, as the detection instrumentation will require a stationary period to allow proper integration time. One solution would be to employ a deployable instrument package that could be dropped from the Tumbleweed as it rolls. Another method would involve a stop/start capability (e..g., changing the Tumbleweed shape to alter its aerodynamic characteristics), which would allow a Tumbleweed to halt at particular locations and take data.

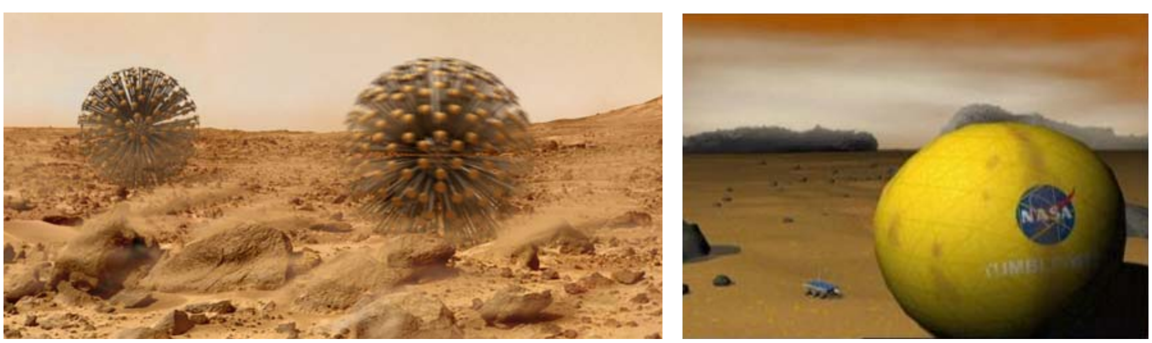

Figure 5. LaRC Dandelion (left) and JPL inflatable Tumbleweed (right) depicted on the Martian surface

The Tumbleweeds could be initially delivered to Mars as a secondary payload or on a dedicated mission where multiple Tumbleweeds are landed on the surface. Deployment of a Tumbleweed could be accomplished in mid-air, or after landing on the surface. (fig. 6)

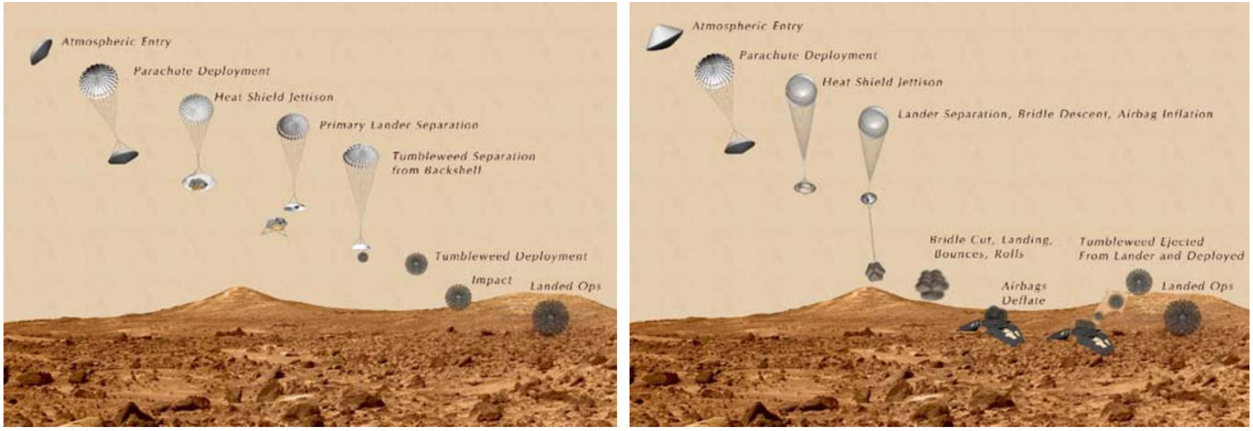

Figure 6. LaRC Tumbleweed Deployment Concepts, secondary payload (left) and primary payload (right)

V. Tumbleweed Subsystems

To support the mission concepts discussed in the previous section, a Tumbleweed vehicle will need to provide not only the structure to house scientific instrumentation, but also the power system to operate it, communications to relay the resulting data back to Earth, and a Navigation system to define the location where the measurements were recorded. The results of recent studies to define structural, power, navigation and communication system options will be summarized in the following paragraphs.

JPL's expertise in landing dynamics and airbag materials was solicited for help in the definition of LaRC Tumbleweed **structural** requirements and preliminary design. A collaborative study with JPL, initiated in 2003, was completed in January 2004.[13] JPL conducted several non-linear impact dynamics analyses of the LaRC Box Kite (fig. 7) and Dandelion Tumbleweed concepts using Livermore Software (LS) DYNA-3D and provided recommendations on the structural design and associated materials for a 6 m diameter vehicle. A viable structural design was derived from the results of the LaRC Box Kite analysis - although not optimized, the design represents a feasible solution well within the design space and mass requirements.

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

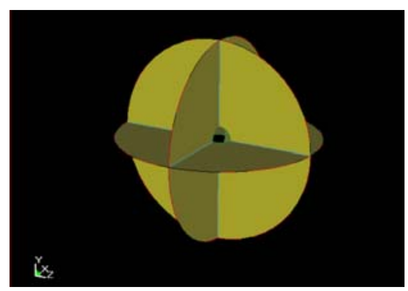

Figure 7. JPL DYNA 3D Box Kite Model

Analysis of the LaRC Dandelion concept demonstrated that a straight beam spoke design would deflect plastically and thus is not a good design option for a Dandelion Tumbleweed. The LaRC team responded by developing a modified design with curved beams – evolving into what became known as the "Egg Beater" Dandelion (fig. 8). However, an impact analysis of the Egg Beater concept was not conducted and is needed to determine a viable structural design, the associated material requirements, and an accurate mass estimate.

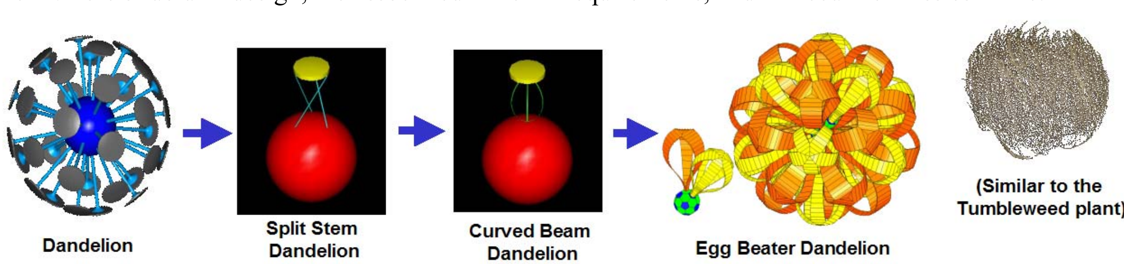

Figure 8. Evolution of LaRC Dandelion Tumbleweed Concept

An investigation of Tumbleweed **power** system options was conducted by LaRC in consultation with the NASA Glenn Research Center (GRC), who recommended the use of mini-sterling, advanced radioactive power sources (ARPS) capable of generating 10 W/kg; however, photovoltaic (PV) cells were also considered a viable, but less robust option. NCSU Aerospace Engineering students conducted an assessment of PV arrays on the NCSU TED.[14] Flexible Silicon (Si) cells were selected for the assessment and were first tested in a simulated Martian spectrum to determine the potential power output on the surface of Mars. A similar silicon array was then mounted to the TED and tested in a dynamic (rolling) Earth environment to examine the effects of the Tumbleweed motion on power generation (fig. 9). While only 1/3 of the available solar cell locations on the TED were utilized, the flexible Si arrays appear feasible, able of providing several watts of power with little mass impact. An even smaller mass impact could be realized if the cells could be incorporated into the TED sail material. NCSU is currently developing a second generation TED (TED II) with expanded solar power capability, navigation sensors, and a "morphing" structure capable of providing a basic stop/start capability. Extensive testing of the TED II will be conducted in the spring and summer semesters of 2005.

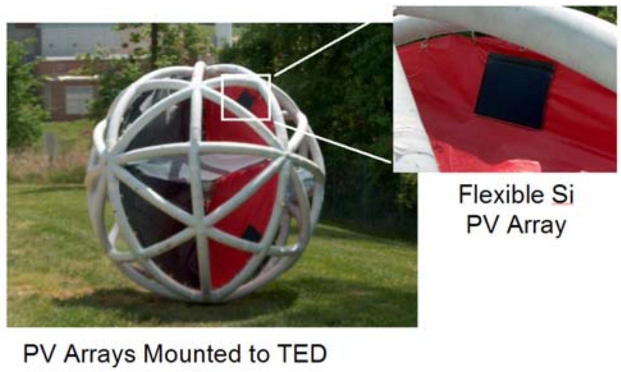

Figure 9. PV arrays installed on the NCSU TED

A preliminary assessment of **navigation** system options identified several possibilities for accurately determining the location of a Tumbleweed rover on Mars, including: Doppler radiometric techniques using existing Mars orbiting assets, odometry using Inertial Measurement Units (IMU), optical terrain mapping, and optical celestial navigation. Dead-reckoning using an IMU or optical position updates from terrain mapping could be used for instantaneous navigation, combined with radiometric techniques for regular position updates. The recommended configuration is a Tumbleweed equipped with a Proximity-1 radio with Doppler capability, a roll sensor, Micro-Electro-Mechanical Systems (MEMS) accelerometers, a MEMS IMU (if the technology matures), and 6 MEMS Sun sensors. It is important to note that this recommendation imposes no new Mars infrastructure; however, technology advancements may be needed in the above components to meet Tumbleweed mass and power requirements.

The primary focus of the **communication** system analysis was a coverage assessment for prospective Tumbleweed landing sites. The entrance to Ma'adim Vallis channel from Gusev Crater was chosen as an initial site for a Tumbleweed mission because of a mission concept for using Tumbleweeds to explore canyons and the large volume of high-resolution data available on the Gusev crater region. The Mars orbiting assets that currently exist (as well as several planned for the near future - a total of six) were assumed to serve as communication relays back to Earth. A Tumbleweed moving at a rate of 1 m/s through the 1 km deep, 17 km wide Ma'adim Vallis channel (assuming multiple viewing angles over the canyon walls) was found to have a maximum continuous duration of approximately 30 minutes, at least once per day. Additional analyses are planned that account for a particular instrument complement and associated data collection and transmission rates, which will define the communication system mass and power requirements. As with the navigation system, the communication system assumptions impose no new Mars infrastructure.

VI. Analysis and Test

To assess the likely motion of a Tumbleweed rover on Mars, several analytical models are being developed to simulate Tumbleweed concepts in the Martian environment. In order to properly model the Tumbleweed, testing of Tumbleweed prototypes is also being conducted to verify assumptions regarding aerodynamic characteristics and rolling properties of the various concepts. Field tests are also being conducted to assess sensor measurement techniques and subsystem capabilities.

A. Dynamic Analysis and Test

LaRC has developed a Tumbleweed Monte Carlo simulator using the commercial off-the-shelf software Vortex and has run several preliminary test cases.[15] Additionally, LaRC is developing a 3 dimensional (3-D) simulation testbed in Matlab/Simulink using a lumped mass dynamics model in order to study of the rolling characteristics of the deployable structure Tumbleweed concepts.

To validate modeling assumptions and to refine the lumped mass dynamics model approach of the LaRC Tumbleweed 3-D Simulation testbed, a series of sophisticated empirical tests were conducted at LaRC using Photogrammetry techniques.[7] Models of three Tumbleweed concepts (a simple sphere, a Box Kite, and an Egg Beater Dandelion) were used in rolling and bouncing-to-rolling tests on an inclined plane (fig. 10). The models were rolled down a 24-foot plywood ramp and their movement recorded using a 6-camera Photogrammetry system. Cameras were located to capture 6 degree-of-freedom (DOF) dynamics at start of motion, middle of the ramp, and at the end of the ramp. The rolling tests were conducted with small initial velocities and the bouncing-to-rolling tests were conducted with large initial velocities. Three-dimensional motion data is being extracted from the test data for use in validating the assumptions and validating the 3-D model.

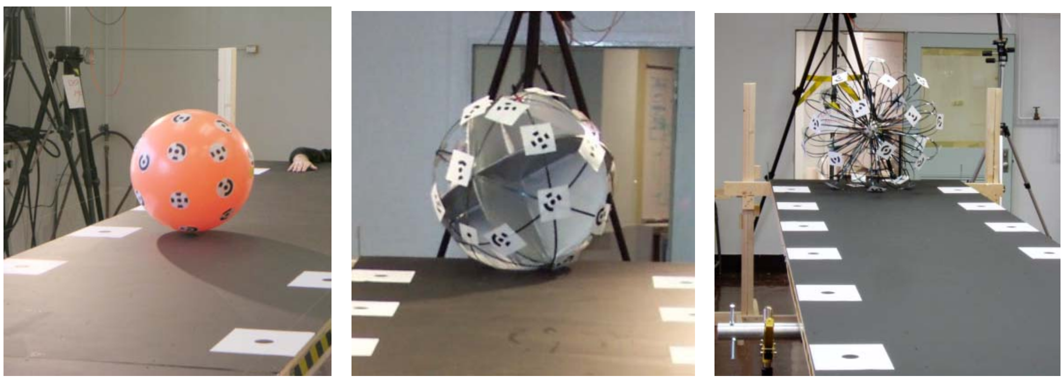

Figure 10. LaRC Sophisticated empirical test models on test ramp (from left to right, sphere, Box Kite, Egg Beater Dandelion)

JPL has also analyzed the inflatable Tumbleweed concept, in collaboration with the University of Southern California. Their analysis demonstrated that a 6-m diameter, 20-kg inflatable Tumbleweed was capable of climbing up hills with up to a 20^{o} incline and over 1m high rocks in strong seasonal Martian winds of 20 m/s.[16] JPL has also conducted sophisticated empirical testing of the inflatable concepts (fig. 11), led by Carnegie Mellon University (CMU). 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."[17]

JPL conducted initial tests of the inflatable Tumbleweed concept in the Mojave Desert using a 1.5m inflated sphere. Follow-up tests have been conducted in Alaska, the Greenland Ice Cap (fig. 11), and in Antarctica.[5] The inflatable Tumbleweed prototype is capable of relaying position information, as well as air temperature, pressure, humidity and light intensity data to a JPL ground station using the Iridium satellite communication network.

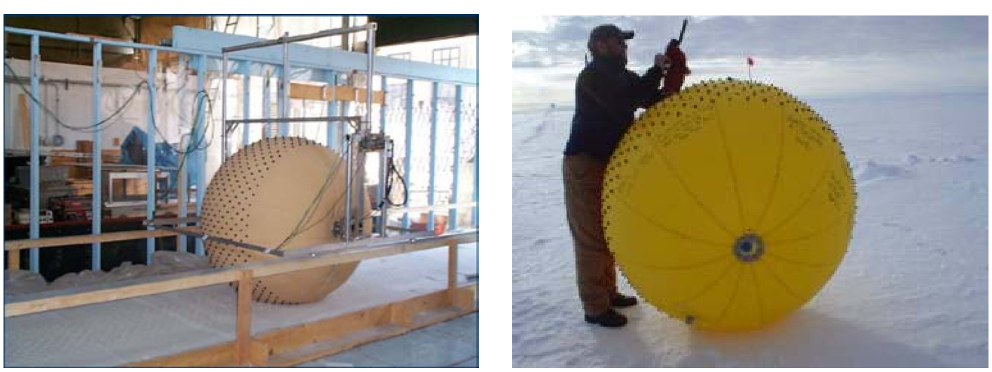

Figure 11. CMU Inflatable Rover testbed (left) and JPL Tumbleweed deployment in Greenland (right)

B. Aerodynamic Test and Analysis

The main objective of the aerodynamic testing is to provide preliminary data on the drag characteristics of the various LaRC Tumbleweed rover concepts for input to the dynamic simulations. The overall strategy for aerodynamic testing of Tumbleweed concepts is three-fold:

- Measure the aerodynamic characteristics (i.e., drag) of Tumbleweed concepts
- Investigate boundary layer surface effects on the aerodynamic characteristics
- Examine Tumbleweeds in a relevant Martian environment

The primary objective of the aerodynamics research is to achieve a drag coefficient (C_d) greater than that of a smooth sphere (~0.5). Using the results of the 2003 testing conducted in the LaRC Basic Aerodynamics Research Tunnel (BART),[18] a set of follow-on tests was planned and conducted in the BART in 2004 to measure the drag properties of evolved Tumbleweed designs (fig. 12).

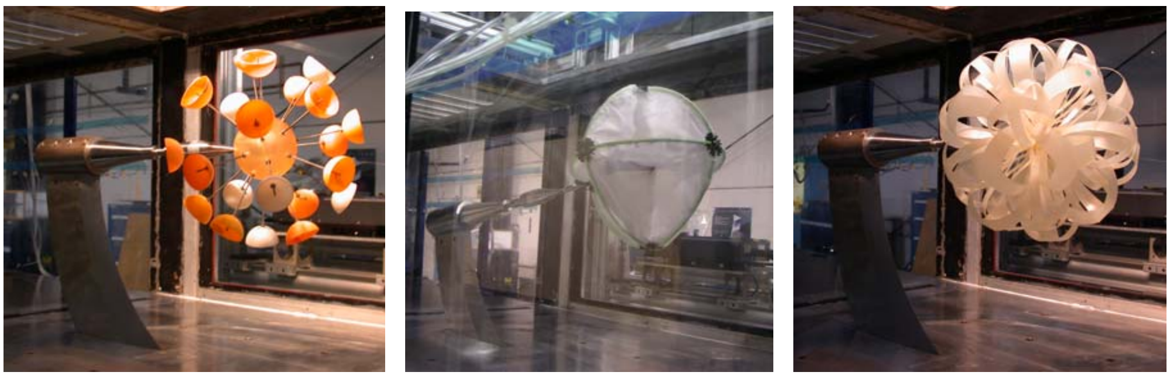

Figure 12. Evolved LaRC Tumbleweed concepts in BART test section (from left to right, cup pad Dandelion, cloth sail Box Kite, and Egg Beater Dandelion)

Preliminary analysis of the Box Kite data verified the angle of attack dependency observed in the 2003 tests, with the C_d varying from 0.8 up to 1.2 depending on the model orientation. Significant differences were observed in the C_d between the metal, wooden, and cloth Box Kite models, requiring follow-on investigation to understand these discrepancies. The symmetric Eggbeater Dandelion models were very consistent across all angles of attack, with an average C_d of 0.8. The results for the Dandelion with cupped pads were significantly lower than expected, with the C_d ranging from 0.4 to 0.5.

The second objective in the aerodynamic testing strategy for Tumbleweed, investigate the near surface boundary layer effects, was addressed by TTU in their TTU Atmospheric Boundary Layer (ABL) wind tunnel.[19] Several LaRC Tumbleweed models were fully submerged in a simulated Martian surface atmospheric boundary layer (fig. 13). The boundary layer was based on Viking and Pathfinder data. The results are show that the Tumble-cup experienced a reduction in drag of 2% - 8% in the boundary layer (versus that measured in the free stream, while the Dandelion experienced a 5% - 15% reduction in drag. The scaling of turbulence energy spectrum was not achieved in the ABL tests; however, the turbulence profiles for the Martian surface are currently unknown.

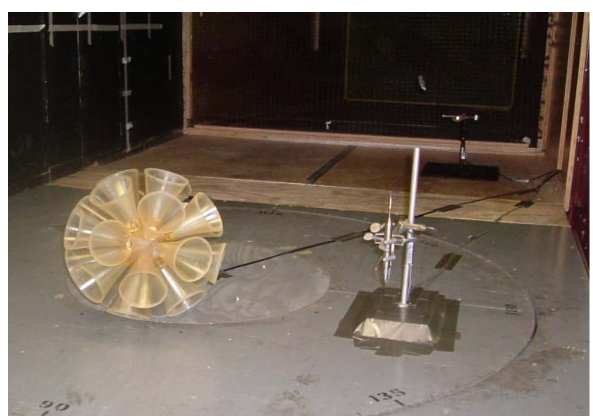

Figure 13. LaRC Tumble-cup model in TTU ABL wind tunnel

The testing of Tumbleweed concepts in a relevant Martian environment was beyond the budget scope of the current LaRC Tumbleweed study; however, a Computational Fluid Dynamics (CFD) analysis capability was initiated to predict aerodynamic conditions on various Tumbleweed configurations at Martian atmosphere conditions. The initial assessment involved a twenty-four (24) stem Dandelion configuration, along with an individual Dandelion stem. The models were developed in Tetrahedral Unstructured Software System (TetrUSS) (unstructured Navier-Stokes) and were initially run under the same conditions as the wind tunnel tests, in order to compare with the experimental data and calibrate the computational method.

After analyzing a baseline sphere, and then a single-dandelion petal through the flow-solver, the twenty-four petal dandelion grid was generated and run (fig. 14). Due to the size of the volume grid required for the twenty-four petal dandelion design, only one run was completed on this detailed grid; however, an idea of how drag is developed by the twenty-four petals can be seen in the flow field (fig. 14). Upstream of each petal, a compression region is generated, increasing the drag of the model. Another compression region occurs in front of the "spherical" core, similar to the results seen for the baseline sphere run. In addition, the downstream region of each dandelion petal creates an expansion region followed by another compression. This shows, and was also indicated in the single-dandelion petal runs, that a potential design improvement would be a petal with back-to-back concave surfaces, creating even higher drag values and thus generating more force that could be used for motion. Additional comparisons to the LaRC wind tunnel data are planned in order to validate the model, to be followed by analyses at Mars atmospheric conditions.

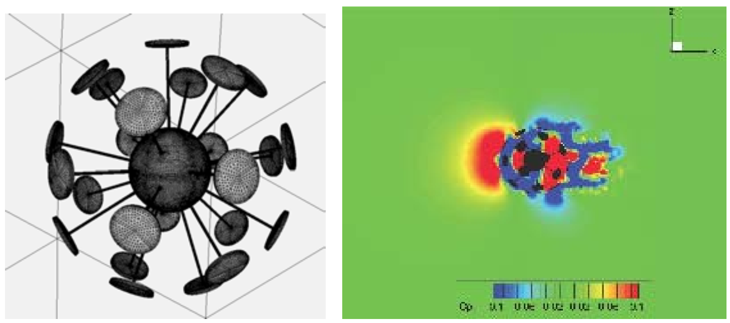

Figure 14. CFD of Dandelion Tumbleweed
(24 Petal Dandelion (left), Example of 24 Petal Dandelion Flowfield (right))

VII. Summary

A new "rover" concept for exploring the Martian surface, known as the Mars Tumbleweed, will derive mobility through use of the surface winds on Mars and could conceivably travel great distances and cover broad areas of the planetary surface. Tumbleweed vehicles would be designed to withstand repeated bouncing and rolling on the rock covered Martian surface and may be durable enough to explore areas on Mars such as gullies and canyons that are currently inaccessible by conventional rovers. Tumbleweeds could play an important role in surveying the habitability of potential human landing sites as well as in Astrobiology missions to search for water and signs of Martian life, past or present.

Acknowledgments

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