A NEW PARADIGM FOR PLANETARY EXPLORATION – THE MARS TUMBLEWEED ROVER. J. Antol[1] and G. A. Hajos[2], [1]NASA Langley Research Center (M.S. 462, Hampton, VA 23681, Jeffrey.Antol-1@nasa.gov), [2]NASA Langley Research Center (M.S. 462, Hampton, VA 23681 Gregory.A.Hajos@nasa.gov).

Introduction: The NASA Langley Research Center (LaRC) Mars Tumbleweed rover is a concept for a lightweight, spherical, deployable structure, with a configuration that maximizes drag to capture the Martian wind for mobility and extended mission duration. The wind-blown mobility of a Tumbleweed rover makes it an ideal platform for conducting distributed geophysical and meteorological surveys of broad areas on the Martian surface, filling a niche between the wide-ranging remote sensing capabilities of orbiting platforms and the focused, in-situ measurements of conventional landers and rovers (Figure 1).

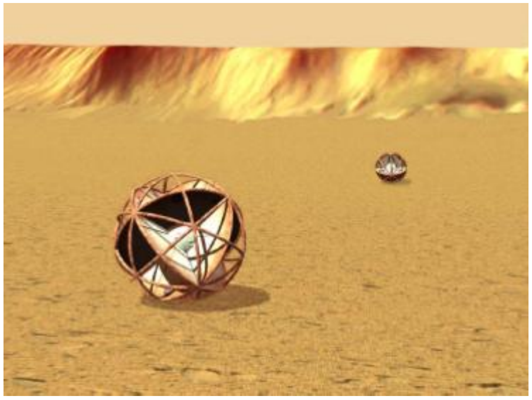

Figure 1. Tumbleweeds depicted on the Martian surface exploring a Valley (e.g., Dao Vallis) [1]

Background: Jacques Blamont of the National Center for Space Studies in France (CNES) was the originator of the Mars wind-driven rover concept in the late 1970s. [2] The idea evolved into the University of Arizona "Mars Ball" concept, an inflatable 4 m by 5 m, 500 kg rover whose mobility was produced through sequenced inflation and deflation of air bags. [3]

The Jet Propulsion Laboratory (JPL) developed a 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. [4] This concept evolved into a three-wheeled inflatable ball rover, testing of which 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. [5]

LaRC's Tumbleweed research was inspired by the Pathfinder mission landing on Mars, which utilized a system of airbags for cushioning the Pathfinder lander and Sojourner rover during impact with the ground. It was observed that the Pathfinder/airbag system traveled a significant distance across the surface of Mars before coming to rest and deflating, 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 discussed and several deployable structure concepts were envisioned utilizing sails and branching structures. [6]

Vehicle Concepts: Tumbleweed rover research has been conducted at NASA LaRC, JPL, Case Western Reserve University (CWRU), North Carolina State University (NCSU), and Texas Tech University (TTU). The LaRC, CWRU, NCSU, and TTU concepts utilize deployable structures, while JPL's Tumbleweed employs inflatable structures.

LaRC has investigated several deployable structure concepts (Figure 2), including the *"Box Kite"* Tumbleweed, which uses fabric sails to capture the wind, attached to spring hoops to aid rolling characteristics. The LaRC *"Dandelion"* concept was biomimetically inspired, in an attempt to gain the aerodynamic advantages that Tumbleweed plants have evolved. However, in simplifying the structure for packaging and deployment, a spherical core was devised with a symmetric array of legs with pads at the ends to prevent sinking into soft ground. A variation of this concept more closely resembling the Tumbleweed plant is the LaRC *"Eggbeater Dandelion,"* which uses multiple curved struts, resembling eggbeaters or whisks. Another LaRC concept, the *"Tumble-cup,"* consists of open-ended cones or cylinders around a spherical core maximizing aerodynamic surface area to maximize the drag force while also reducing rolling resistance. [7]

The LaRC deployable structure design concepts offer several key benefits. First, the drag coefficient is greater than that of a simple sphere, providing a greater capability to capture the wind. Second, the open structure provides access to the environment for scientific instruments. Third, the structure is amenable to solar array installation allowing a longer mission duration than battery-only systems. Finally, a deployable structure does not have a deflation failure mechanism, which lowers risk and also improves mission durations.

Technology Challenges: Achieving Mars wind-driven mobility is challenging but achievable. The Mars atmosphere is 60-80 times less dense at the surface than Earth's atmosphere. Because of this low density, Tumbleweed rovers need to be relatively large in diameter, measuring ~4-6 m, and with a mass less than 20kg, in order to capture the very thin Martian

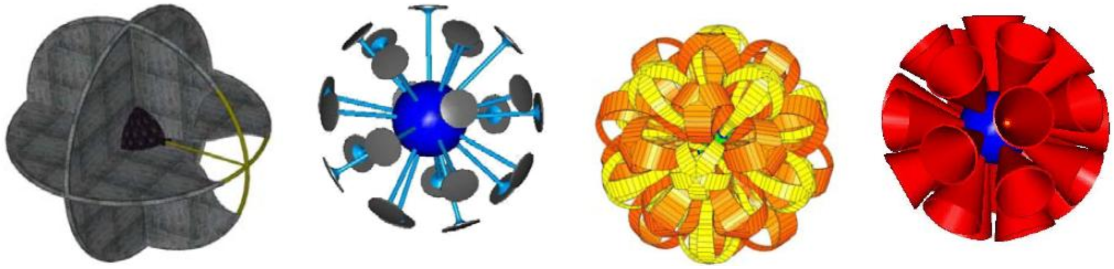

Figure 2. NASA LaRC Tumbleweed Concepts (left to right): Box Kite, Dandelion, Eggbeater Dandelion, and Tumble-cup [7]

atmosphere and move in moderate winds of 10-15 m/s.

Mission Concept: Tumbleweeds could serve as scouts, landing in varied Martian terrain and transporting instrumentation over hundreds or perhaps thousands of kilometers, gaining access to many interesting locations that may be inaccessible to conventional vehicles. [8] Advanced concepts utilizing multiple collaborating vehicles could cover several destinations, deploying sensor packages or micro/nano-rovers to explore specific areas of interest in greater detail.

Candidate instrumentation accommodated by a Tumbleweed rover may include: miniature, low-power environmental sensors for temperature, pressure, and acceleration; a dosimeter to measure radiation environments; a hydrometer or tunable diode laser for detecting water; wheel electrometers to examine electrostatic properties of the regolith; a magnetometer to map the residual magnetic field; or a miniaturized x-ray fluorescence spectrometer to determine regolith constituents. Some measurements could be taken while the Tumbleweed is rolling, while others would be conducted when the Tumbleweed is stopped (during periods when winds are insufficient for mobility). If a Tumbleweed were to fall into a crevice and a wind change could not dislodge it, the vehicle may still have utility as a stationary sensing platform.

Vehicle Models and Prototypes: Wind tunnel models were developed for aerodynamic testing at LaRC [9] and TTU [10] in relevant Reynolds number regimes and surface boundary layers to obtain preliminary drag characteristic data on several deployable structure Tumbleweed rover concepts.

NASA LaRC and NCSU also developed and field tested Tumbleweed prototypes (Figure 3) to demonstrate rolling characteristics and to assesss sensor accommodation. NASA LaRC's lightweight *"Box-Kite"*

Figure 3. LaRC Box Kite (left) and NCSU TED II

prototype, is approximately 6 feet in diameter, about 1:3 scale of the Martian Tumbleweed, made of Titanium hoops covered with sails of rip-stop nylon. A central core suspended from the sails houses avionics and sensors. [11] NCSU developed three generations of Tumbleweed Earth Demonstrators (TEDs), with a design up to 10 feet in diameter made of composite and polyvinyl chloride (PVC) hoops. [12] The NCSU TEDs were tested in relevant wind environments and terrain ranging from sandy beaches to rolling hills. The LaRC prototype was used to assess mobility and sensor placement.

The next stage of development will include deployment tests of Tumblweed prototypes in a Mars relevant environment using high altitude balloon drops and in-depth field tests at Mars analog sites employing prototypes equipped with high fidelity sensors to examine science data measurement techniques and mobility aspects in varied terrain.

References: [1] Southard, L. , et al. (2007) "Exploring Mars Using a Group of Tumbleweed Rovers," IEEE International Conference on Robotics and Automation. [2] Hajos, G., et al. (2005) "An Overview of Wind-Driven Rovers for Planetary Exploration," AIAA-2005-0245. [3] Janes, D. (1989) "The Mars Ball: A Prototype Martian Rover," AAS 87-272, The Case For Mars III, Part II - Volume 75, pp. 569-574. [4] Jones, J. and Yavrouian A. (1997) JPL New Technology Report #9894-20283. [5] Behar, A., et al. (2004) "NASA JPL Tumbleweed Polar Rover," IEEEAC paper #1003. [6] Antol, J., et al. (2003) "Low Cost Mars Surface Exploration: The Mars Tumbleweed," NASA TM-2003-212411. [7] Antol, J. (2005) "A New Vehicle for Planetary Surface Exploration: The Mars Tumbleweed, "AIAA-2005-2520. [8] Hoeg, T., et al. (2006) "Tumbleweed Rover Science Mission to Dao Vallis," AIAA-2006-0070. [9] Antol, J., et al. (2006) "Wind Tunnel Tests of Evolved Mars Tumbleweed Concepts," AIAA-2006-0069. [10] Rose, S., et al. (2005) "Drag Measurement and Dynamic Simulation of Martian Wind Driven Sensor Platform Concepts," AIAA-2005-2490. [11] Antol, J., et al. (2006) "The NASA Langley Mars Tumbleweed Rover Prototype," AIAA-2006-0064. [12] Claycomb J., et al. (2006) "Development and Construction of a Prototype Mars Tumbleweed Rover." AIAA-2006-0066.