EXTREME MOBILITY: GAITS FOR TETRAHEDRAL ROVERS. P.E. Clark[1], S. Kessel[2], M.L. Rilee[3], G. Brown[4], C. Cooperrider[4], S.A. Curtis[5]. [1]Catholic University of America (Physics Department) at NASA/GSFC, Code 695, Greenbelt, MD 20771 (email: pamela.clark@gsfc.nasa.gov); [2]NASA/GSFC, Eleanor Roosevelt Student Intern Program, Greenbelt, MD 20771 (email: pamela.clark@gsfc.nasa.gov); [3]Computer Sciences Corporation at NASA/GSFC, Code 606, Greenbelt, MD 20771; [4]NASA/GSFC, Code 544, Greenbelt, MD 20771; [5]NASA/GSFC, Code 695, Greenbelt, MD 20771.

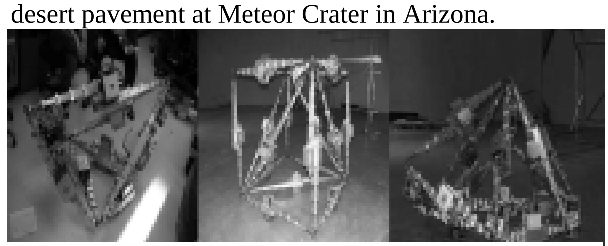
Rationale for Tetrahedral Rovers: Tetrahedral Explorer Technology is addressable reconfigurable robotic architecture applied to achieve high mobility rovers [1,2]. TETs are shape shifting mobile platforms based on the tetrahedron as 'building block' with reversibly deployable struts forming edges and connecting via nodes at apices (Prototype I Figure). Conformable tetrahedra are the simplest space-filling forms the way triangles are simplest plane-filling facets. The 12Tet consists of 26 struts and 9 nodes forming 12 interlinked tetrahedra. These undifferentiated (with no permanent appendages such as wheels) interlinked forms have the degrees of freedom necessary to develop a variety of gaits from simple rolling to crawling or reaching, and, at their most efficient, resembling amoeboid movement. As a result, tetrahedral rovers are optimally reconfigurable to allow operation on rugged, unprepared surfaces in natural terrains.


Prototype I: Tumblin' Tetrahedron

Exploration requires high mobility. Often, the features of greatest potential interest can only be reached by crossing a variety of rugged terrains. Such areas can thus be largely inaccessible to permanently appendaged vehicles [3,4]. For example, interior basins, walls, and ejecta blankets of volcanic or impact structures must all be studied to characterize a site, assess its potential for containing resources such as volatiles, and understand its history. One surface might be relatively flat and navigable, while another could be rough, variably sloping, broken, or dominated by unconsolidated debris. To be totally functional, structures must form pseudo-appendages varying in size, rate, and manner of deployment (gait). Rugged environments require the ability to operate in '3D', over a range of temperatures, lighting (including darkness), and ambient atmospheres (ranging in humidity and corrosive or toxic gas or fluid abundance), on a surfaces with a variety of friction coefficients.

Control is a key challenge in realizing a rover with a highly addressable structure that can operate in highly irregular terrain filled with rock piles or sheer cliffs, where locomotion requires an intimate blending of dynamics and statics, i.e. pushing, bracing, and balancing to make progress. Most means of locomotion "finesse" the situation by minimizing the complexity of the terrain: typically, rovers have featured wheels or legs that are larger than the terrain scale sizes, or locomotion that is slow to allow expert computer systems time to figure out where to go next. The 12 TET rover is designed to become a moving part of the terrain, its vision system providing volumetric information about its surroundings. Gaits suitable to rugged terrains and metrics to measure performance are being developed and tested. With information about the geometry of its environment as well as information about its own geometry, the 12 TET places itself within and moves through its environment.

Progress in Meeting Tetrahedral Mechanical/Mobility Challenges: To date, we have built and tested two operational prototypes and have almost completed the third. The first working prototype (Prototype I Figure) of a tetrahedral rover, built the summer of 2004, is a single tetrahedron, or 1TET, with six struts and four nodes. 2:1 extension ratio struts are nested aluminum tubes with nylon top and bottom pieces. The deployment mechanism is string-pulley actuated with hobby shop motors using Kevlar fishing line and COTS development kit electronics on protoboards. Nodes consist of universal joints on a plate surrounded by pipe foam. The Tetrahedral Walker can reversibly deploy struts from tetrahedral nodes for locomotion over regular surfaces at Goddard and has been demonstrated to climb over 20 degree slopes on desert pavement at Meteor Crater in Arizona.


Prototype II: Arnold crawling, standing, and tumbling

The second prototype (Prototype II Figure), built the summer of 2005, was designed to be a 12Tetrahedral rover. It also had cable-pulley actuation, but with steel cable, custom built addressable electronics boards, and powerful motors with planetary gearheads and worm gears. Heavier gauge square aluminum tubes formed the struts, and virtual nodes were formed from tying wire loops in a tight cluster. Although 4:1 extension ratio and complex gaits was achieved, the overly heavy structure and uncertainty in knowledge of strut deployment length made maneuvering difficult.

Tests with these prototypes led to requirements and constraints for Prototype 3 (Figure), a 12Tetrahedral Walker with 5:1 extension ratio and double sided struts expandable in two directions as in Prototype 2. Its construction is nearing completion at the time of this writing. It has extrudable plastic, strong but lightweight struts and nodes, with keyed shape to prevent slipping, and with a final weight an order of magnitude less than Prototype 2. Prototype 3 (Figure)) has a more ruggedized (screw drive) deployment mechanism, patented string pots allow accurate determination of strut length, 3-axis accelerometer chip measure strut inclination, and lightweight piezoelectric gauges to assess strain on deployment mechanisms. The more robust ZigBee broadcast mode replaces BluTooth multiple, synched channels. The metrics we will use to test the performance of the 12TET as an 'off road' vehicle are currently being developed. Terrain parameters involve variation in roughness across scales ranging from topographic (meters-scale slope), terrain (meter-scale slope, obstacle), to surface (centimeter or less scale grains influencing surface compaction and hardness). Power consumption and speed are also considerations, as are the ability to extend into a 'third' dimension (reach, flatten). Metrics involve comparison to the known performance parameters for wheeled rovers as the most familiar and widely used rovers.

Prototype III: Preliminary Test

Progress in Meeting Tetrahedral Command and Control Challenges: We have initiated the development of TET operational scenarios by considering mobility requirements as a function of terrain and by developing test gaits, such as the 'amoeboid gait' [1] (Figure showing 12 step sequence from top left through bottom right) inspired by the most efficient naturally-occurring 3D locomotion mechanism [5]. The present prototypes are teleoperated, which has required the design of macros for coordinated movements, definition of actuator commands and incorporation of sensor telemetry parameters as feedback for the actuation process via a wireless communication scheme through a user interface. The next step will be to develop autonomic intelligence to modify the basic gaits as the terrain requires. The ultimate goal is to achieve bilevel intelligence, combining autonomic with heuristic intelligence and the capability for target selection and evaluation. Effective maneuvering and navigation will require the incorporation of inputs from systems which will allow gait selection. These systems undergoing independent development here at Goddard and elsewhere include: a multichannel laser altimetry system for near (maneuvering relative to obstacles) and far (navigating relative to target) scene characterization, combined with touch and motion sensors (accelerometers), transmitter/receiver, and a camera.

The next step: We are arranging for Prototype III to climb in and out of Sedan Crater, a TET Challenge, to take place later this year. Over the next three years we will design the next generation TETs, which will be 12TET field model prototypes for Planetary Rovers capable of fully autonomous complex behaviors and movements with many degrees of freedom.

References: [1] Clark et al (2007) Proc STAIF-06; [2] http://ants.gsfc.nasa.gov; [3] Robovolc (2000) http://www.robovolc.dees.unict.it/home/home.htm; [4] MERS (2005) http:// aaa.gsfc.nasa.gov/mers/environs.html [5] Clark et al (2004) AIAA ISTC Proc, Chicago, Session 29-IS-13: ANTS, #29-IS-13-02.

Kessel Amoeboid Gait