ALI

Autonomous Lunar Investigator

Meeting the Challenges of Lunar Surface Exploration with revolutionary Addressable Reconfigurable Technology (ART)

P.E. Clark[1], S.A. Curtis[2], M.L. Rilee[1], C.Y. Cheung[2], R. Wesenberg[2],

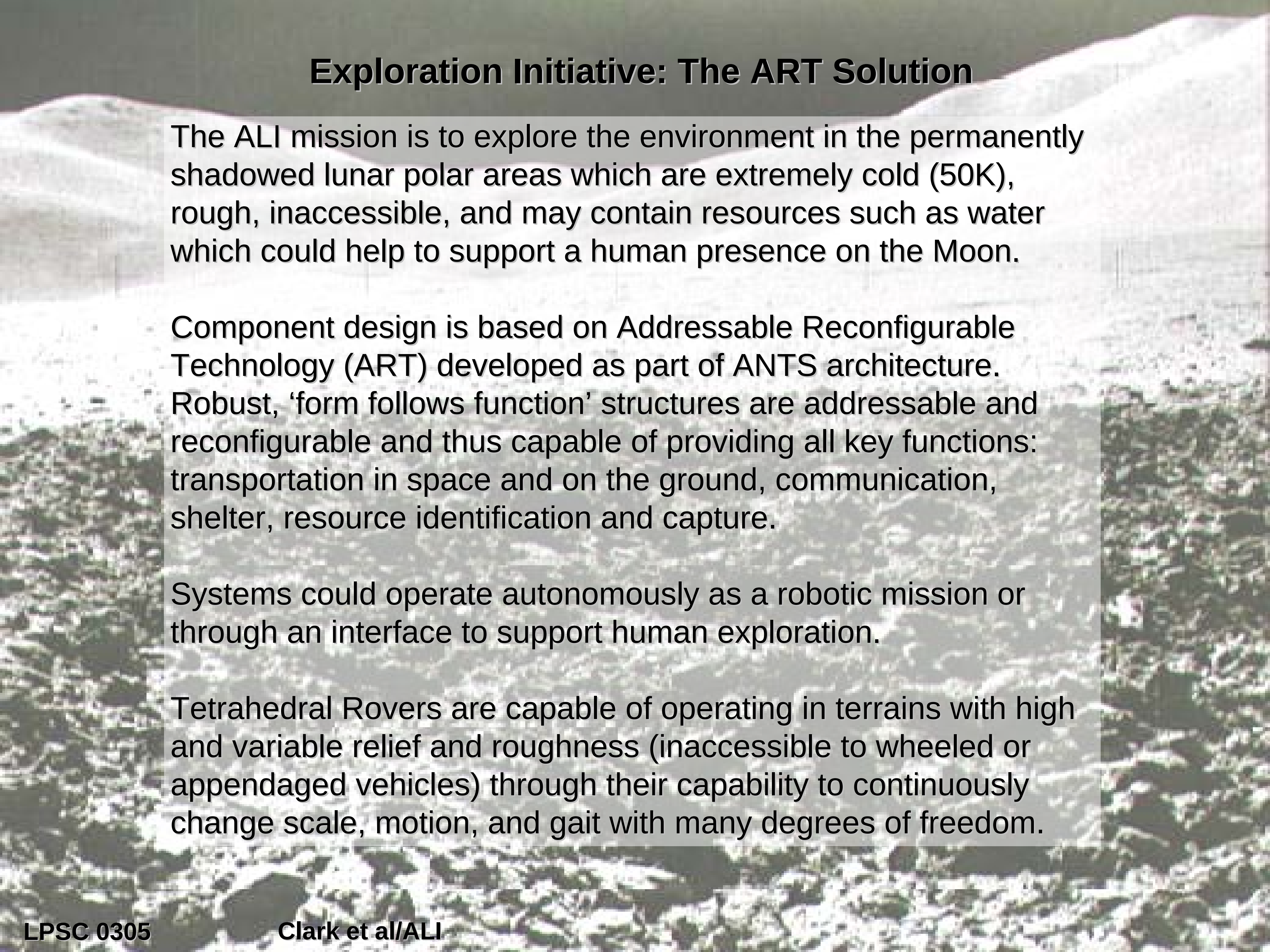
N. Shur[3] , S.R. Floyd[2], B. Blair[2], J. Lemoigne[2], J. Sams[4]

1 L3 Communications, GSI

2 NASA/GSFC, Solar System Exploration

3 NASA/GSFC, ElectroMechanical Systems

4 NASA/LARC



Exploration Initiative: The ART Solution

The ALI mission is to explore the environment in the permanently shadowed lunar polar areas which are extremely cold (50K), rough, inaccessible, and may contain resources such as water which could help to support a human presence on the Moon.

Component design is based on Addressable Reconfigurable Technology (ART) developed as part of ANTS architecture. Robust, ‘form follows function’ structures are addressable and reconfigurable and thus capable of providing all key functions: transportation in space and on the ground, communication, shelter, resource identification and capture.

Systems could operate autonomously as a robotic mission or through an interface to support human exploration.

Tetrahedral Rovers are capable of operating in terrains with high and variable relief and roughness (inaccessible to wheeled or appendaged vehicles) through their capability to continuously change scale, motion, and gait with many degrees of freedom.

ALI Mission Concept

The Autonomous Lunar Investigator (ALI) is an EMS level mission concept which would allow autonomous in situ exploration of the lunar poles within the next decade.

ALI would consist of one or more 12tetrahedral walkers capable of rapid locomotion with the many degrees of freedom and equipped for navigation in the unilluminated, inaccessible and thus largely unexplored rugged terrains where lunar resources are likely to be found: the polar regions.

Because walker locomotion occurs by continuous contraction and extension of struts in a way that optimizes the efficiency of movement across a terrain, a terrain can be crossed as required and probed as interest dictates regardless of variability and scale of its relief and roughness.

A wide variety of ALI mission scenarios and payloads could be envisioned. ALI walkers would act as roving reconnaissance teams for unexplored regions, analyzing samples, soil or rock, along the way. The payload would be designed to provide not only details of composition, origin and age of traversed terrain, but the identification of sites with resources useful for permanent bases, including water and high Ti glass.

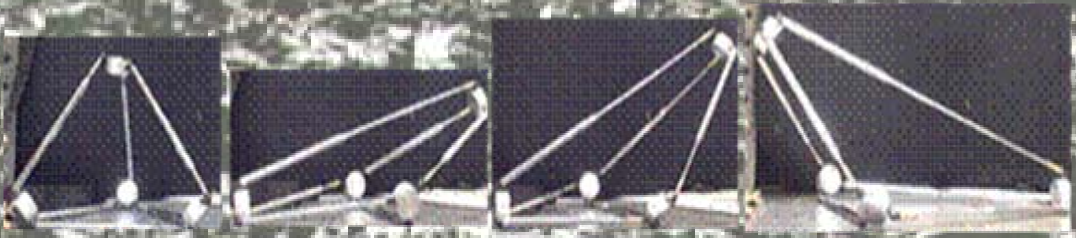
ART Design: Reconfigurable Structures

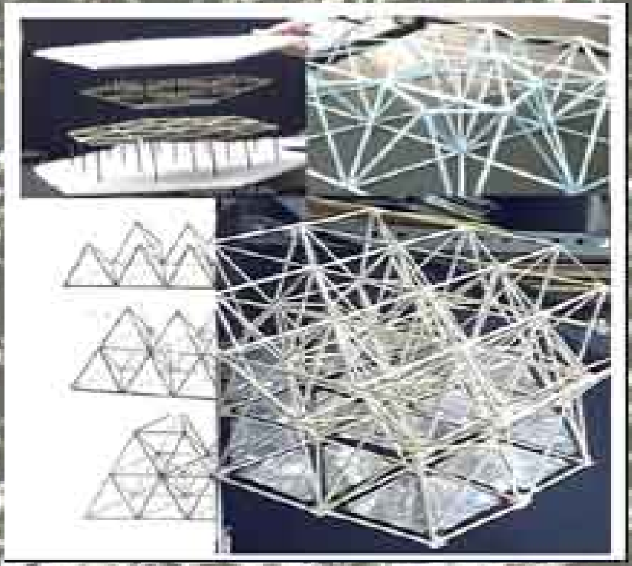
Based on tetrahedron as ‘building block’, acting singly, or connected in continuous network, where apices act as nodes from which struts reversibly deploy.

Conformable tetrahedra are simplest space-filling form the way triangles are simplest plane-filling facets.

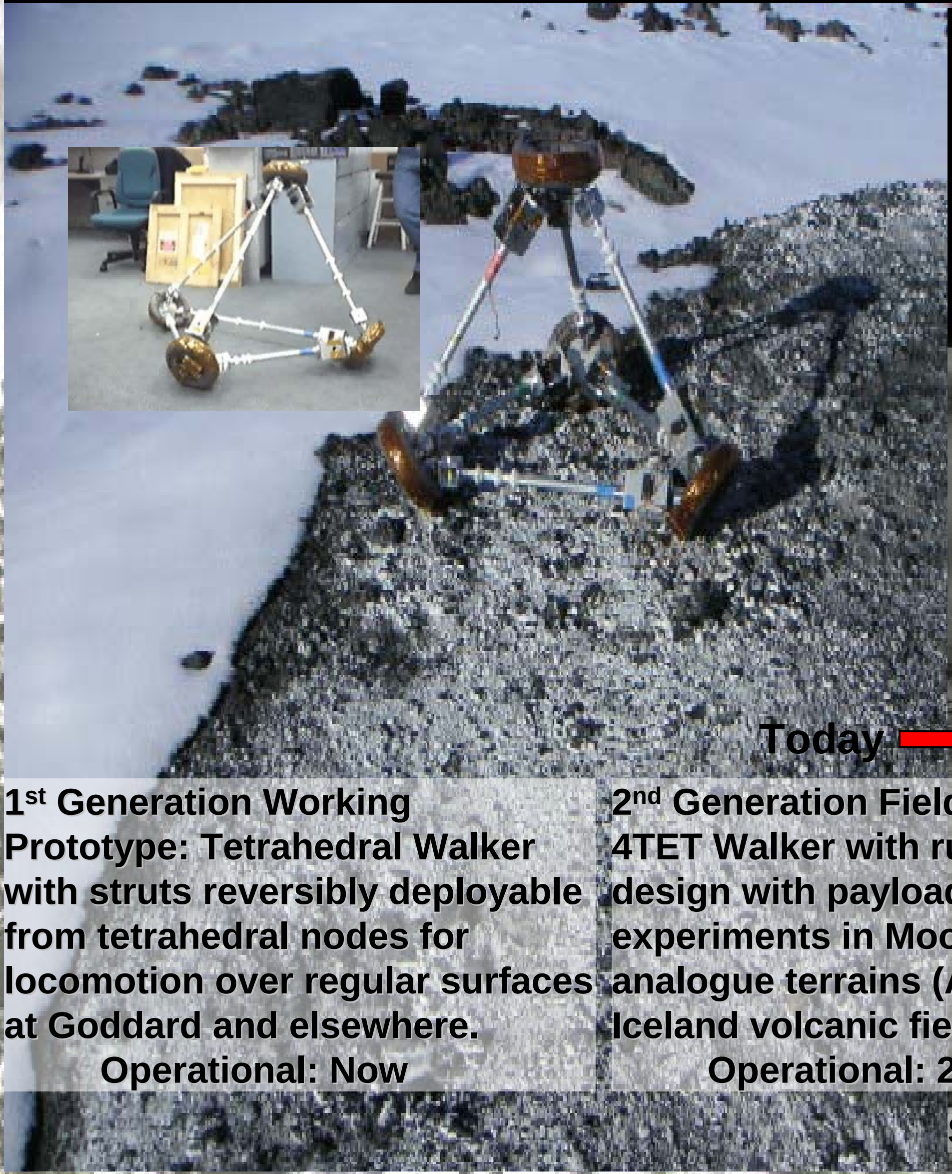
Single tetrahedra give high flexibility, move by controlled tumbling. Continuous networks give high degree of freedom resembling amoeboid movement.

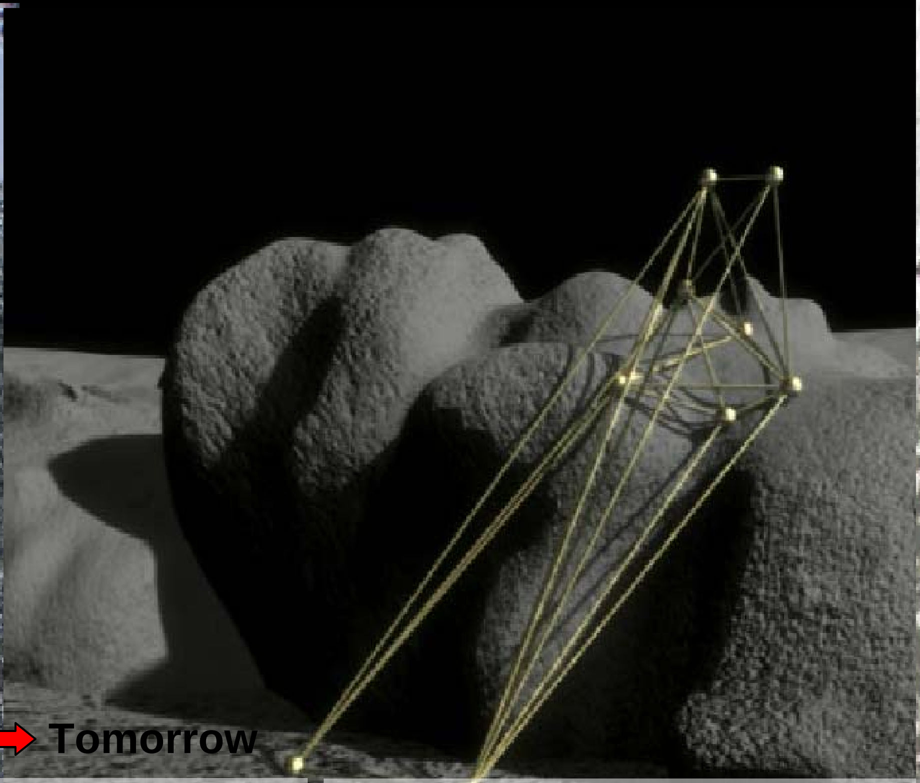
Ultimately, reusable, reconfigurable, relocatable, multi-functional, and self-repairing to operate as and when needed to meet mission requirements.





ANTS: The TETWalker Project
GSFC Codes 690 and 540 Collaboration
Developing Capabilities for Exploring the Surfaces of the Moon and Mars
http://ants.gsfc.nasa.gov





Today → Tomorrow

1st Generation Working Prototype: Tetrahedral Walker with struts reversibly deployable from tetrahedral nodes for locomotion over regular surfaces at Goddard and elsewhere.

Operational: Now

2nd Generation Field Test Models: 4TET Walker with ruggedized design with payload to perform experiments in Moon and Mars analogue terrains (Antarctica and Iceland volcanic fields).

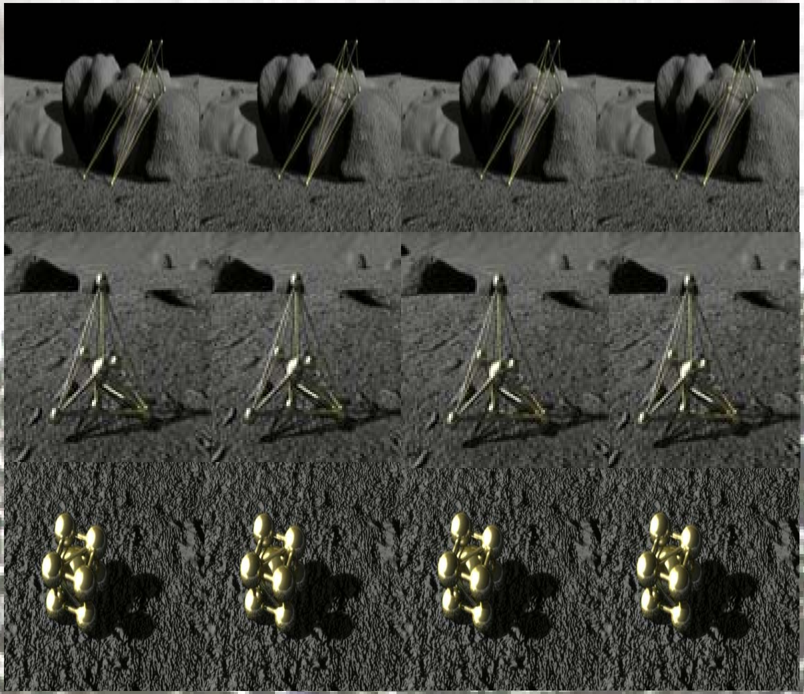
Operational: 2005-2007

3rd Generation Planetary Rovers: 12TET Walker capable of fully autonomous complex behaviors and movements with many degrees of freedom.

Operational: 2010

See Animations of each walker type on our website

ALI First Steps
Returning to the Moon for robotic or robotic-assisted human exploration.



EMS: One or more autonomous 12tetrahedral walkers. Rapid (km/day) **locomotion** with many degrees of freedom for navigating inaccessible, rugged terrain: farside, poles, central peaks, debris fields. Reducible in volume for shipping.

Payload: low mass, volume, and power active spectrometers to measure abundances of elements, minerals, and water.

Command and Control Subsystems: autonomous operational modes in response to terrain for destinations selected through a higher level interface

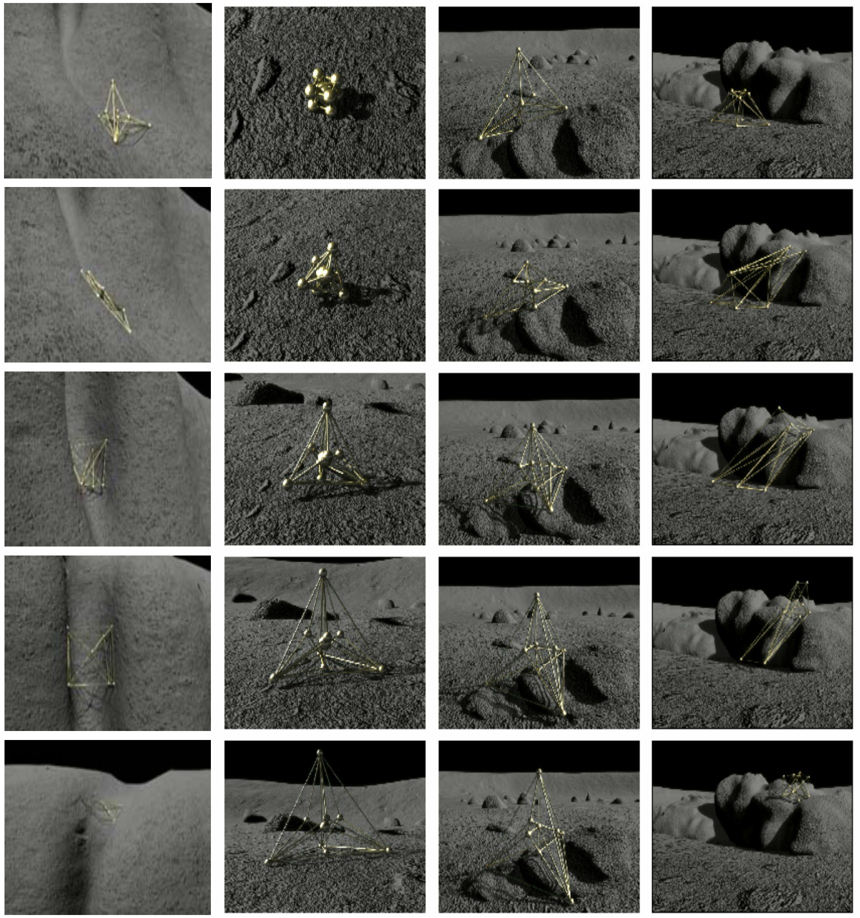
Navigation: Multi-channel laser altimeter combined with motion and touch sensors at each node

Power generation systems: More efficient SPOT Nuclear batteries to allow extensive operation in unilluminated terrain.

Dust control via ion discharge, low dielectric surfaces, sealing of deployment mechanisms.

TetWalker Development Path

From simple tetrahedron walker, making punctuated tumbling movements, sized to navigate the level of roughness, to 4Tetrahedral walker, with an interior node for payload, with movement analogous to 1Tet, to a 12Tetrahedral Walker beginning to exhibit continuous motion.



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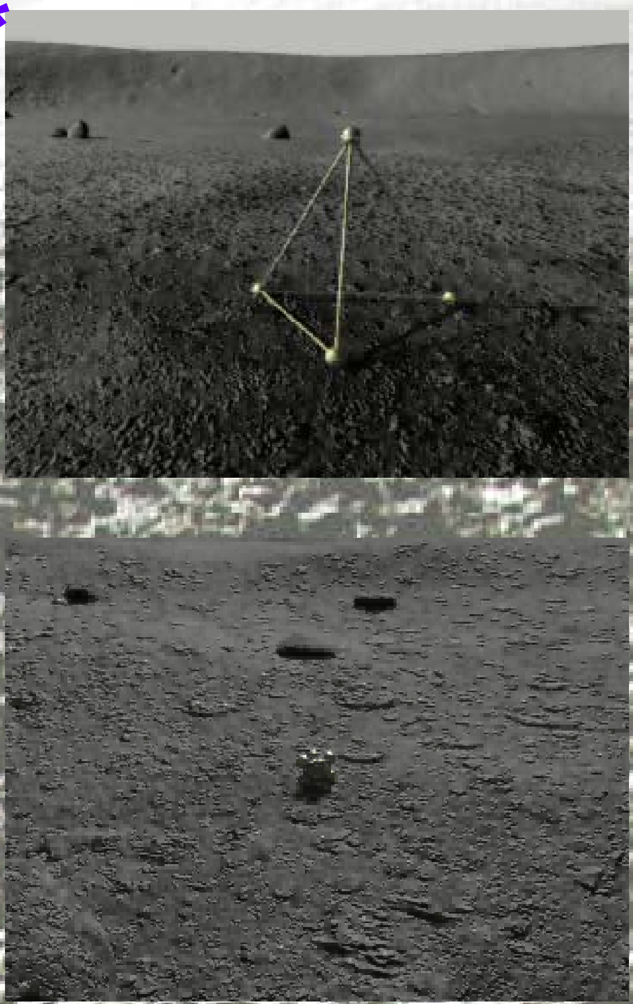

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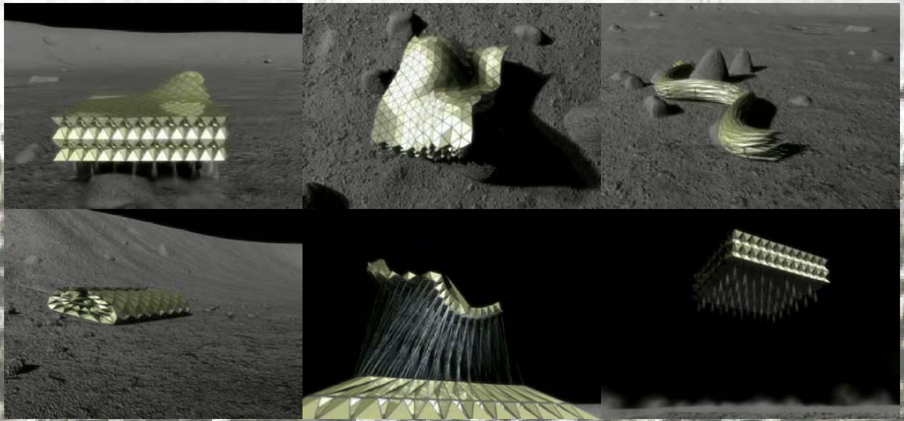
TetWalker Development Path

In a continuous or multi-tetrahedral structure, movements have a high degree of freedom, reminiscent of amoeboid movement. Thus continuous ‘shape shifting’ is possible, from flattened rectangle for stable landing function then conforming to surface, to tetrahedral amorphous rover shifting from slithering to rolling depending on surface, to concave surface formation for antenna function.



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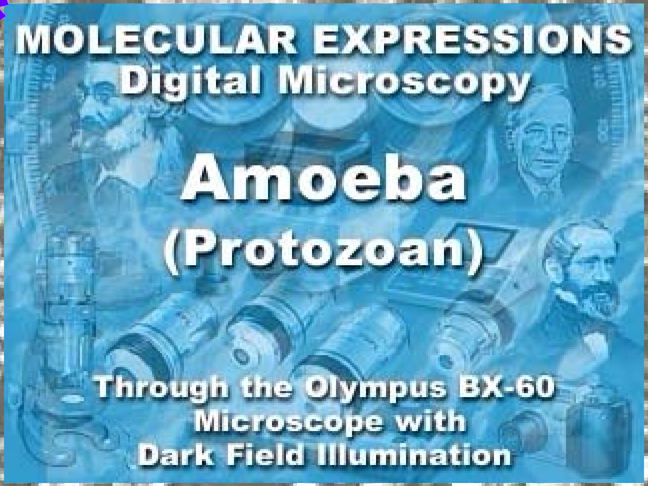

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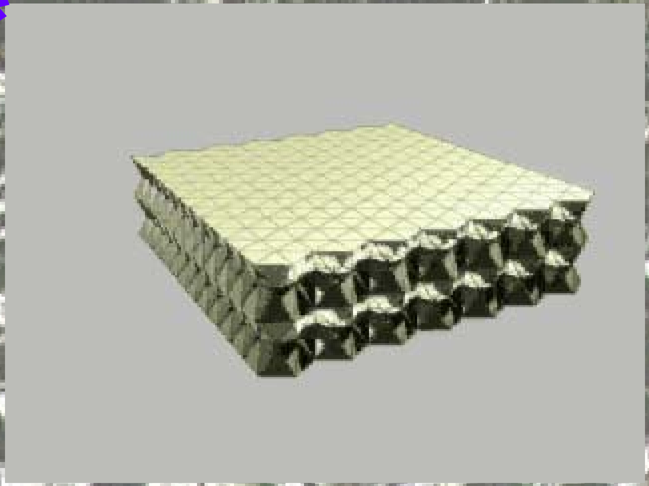
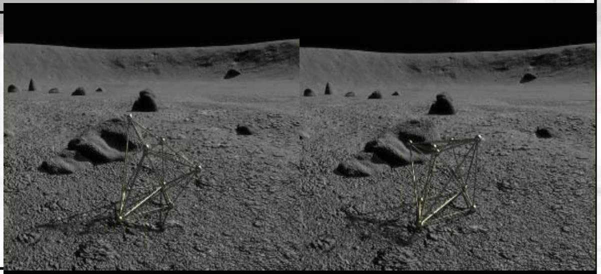
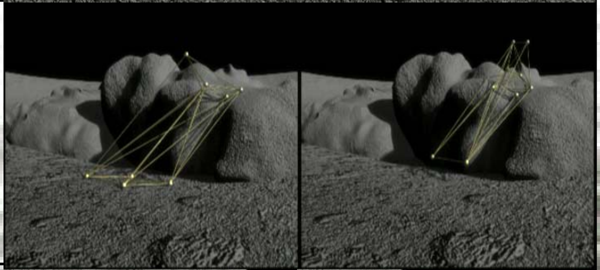
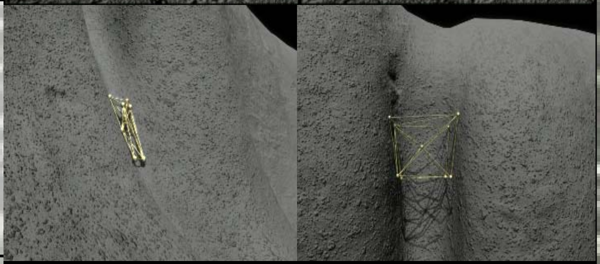
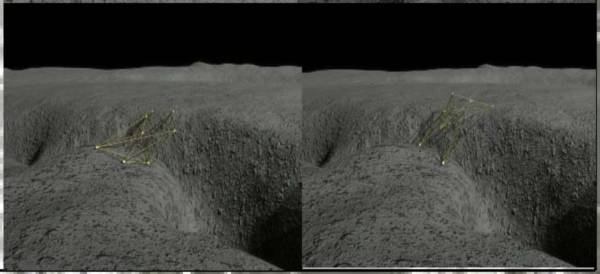
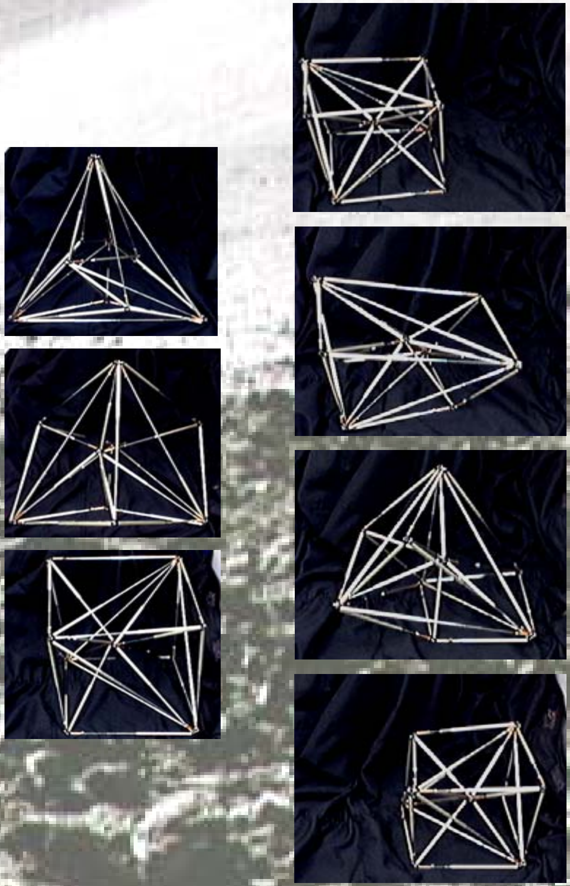
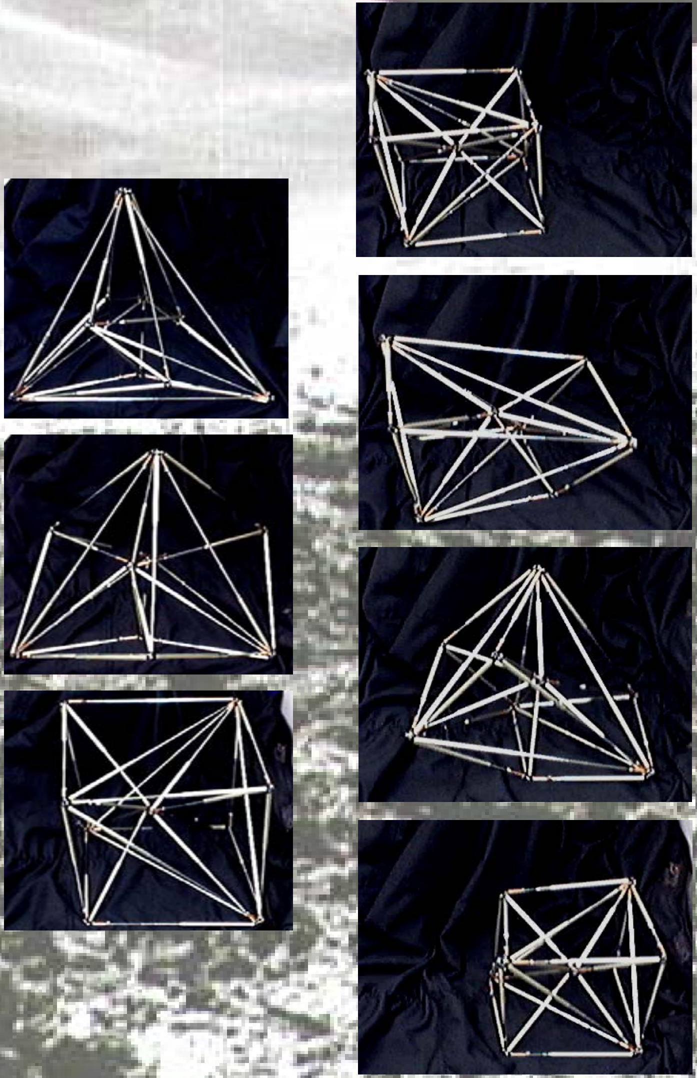


ALI: Form follows Function

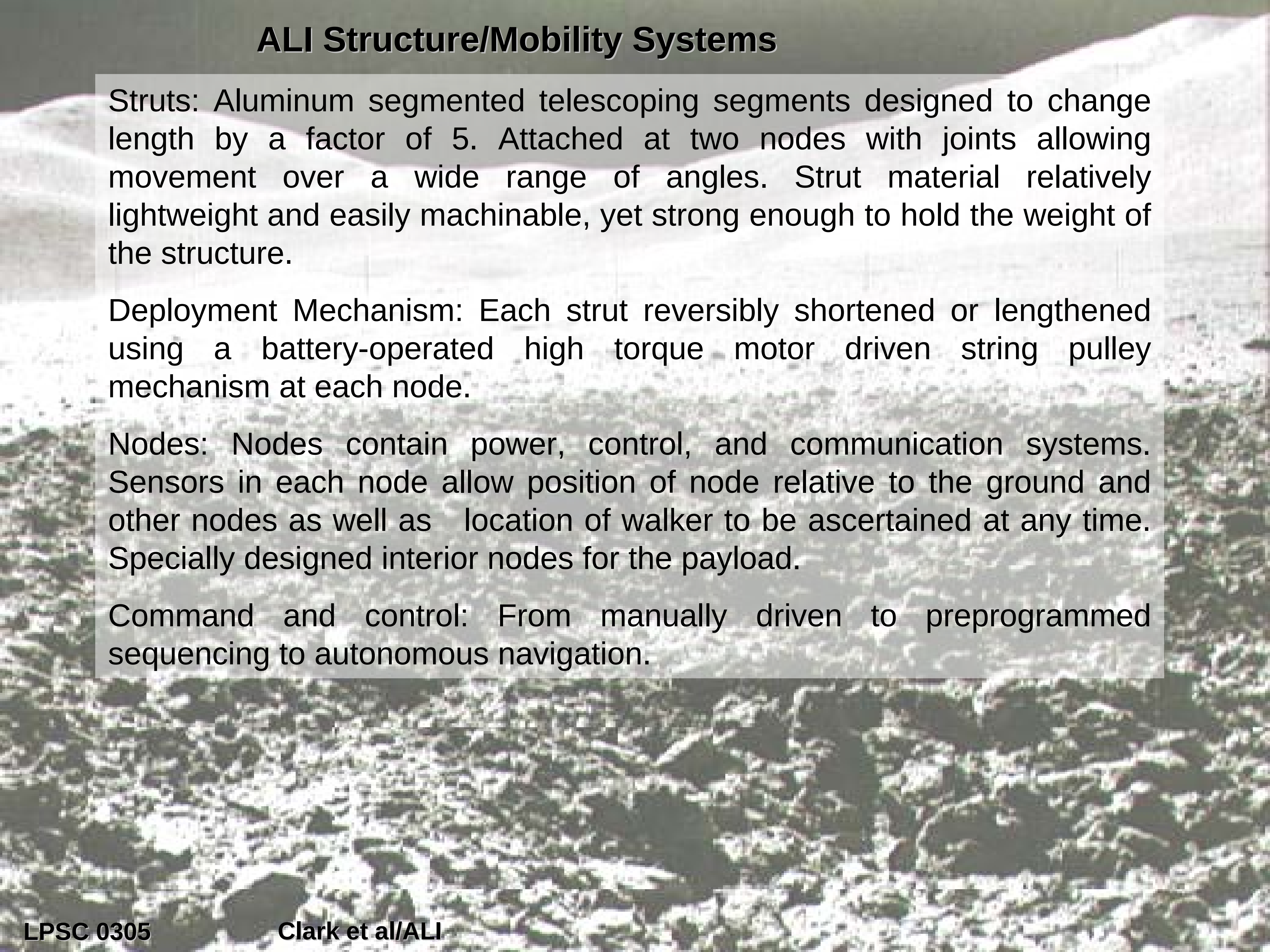
Environment	Operation	
Smooth, Low Relief	Roll	
Rugged, Low Relief	Climb over or roll around	
Cliff	Chimney up crevices	
Crevasse	Bridge	



ALI: Shape Shifting, Moving, Flattened Out



ALI Structure/Mobility Systems

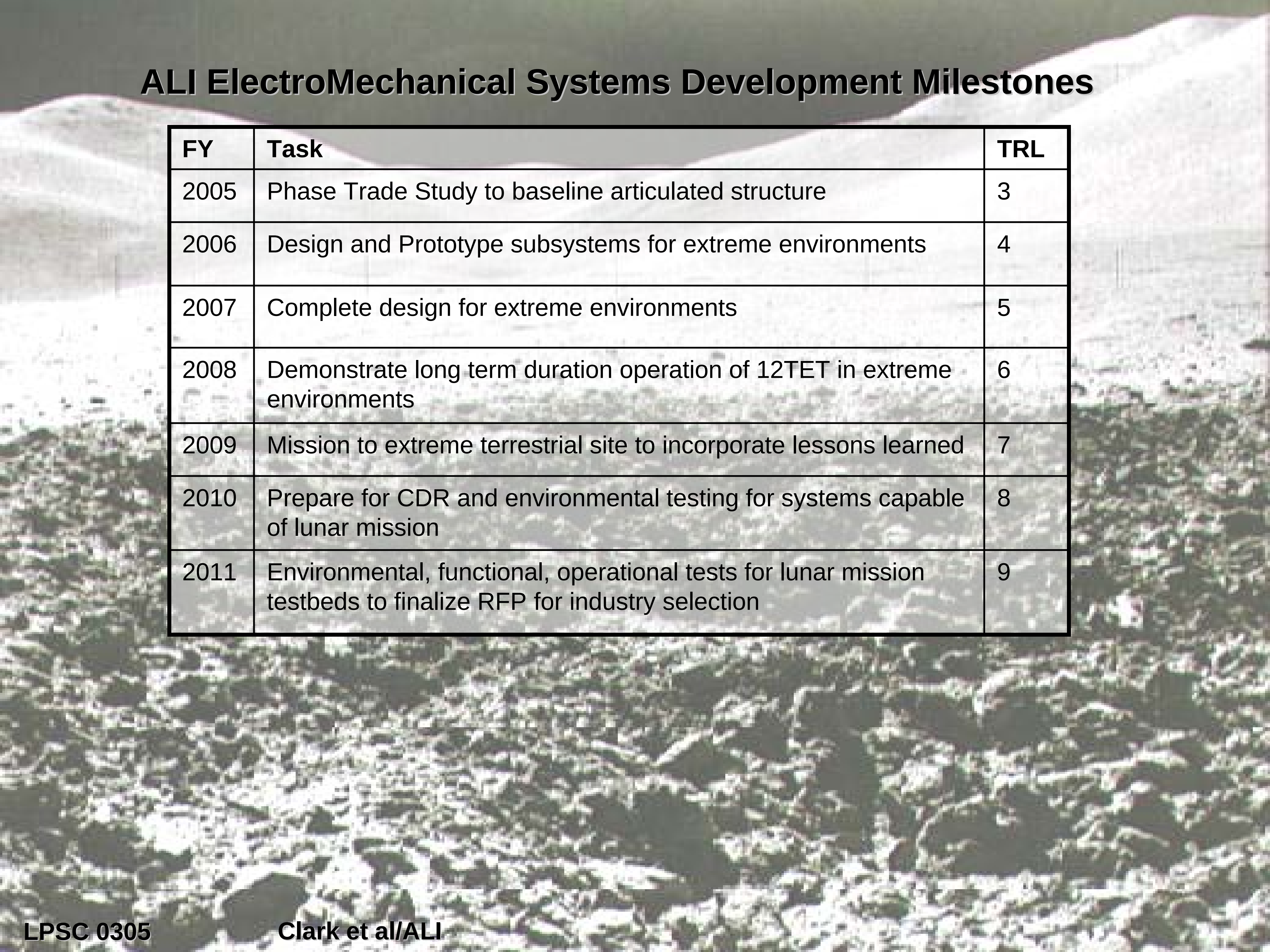


Struts: Aluminum segmented telescoping segments designed to change length by a factor of 5. Attached at two nodes with joints allowing movement over a wide range of angles. Strut material relatively lightweight and easily machinable, yet strong enough to hold the weight of the structure.

Deployment Mechanism: Each strut reversibly shortened or lengthened using a battery-operated high torque motor driven string pulley mechanism at each node.

Nodes: Nodes contain power, control, and communication systems. Sensors in each node allow position of node relative to the ground and other nodes as well as location of walker to be ascertained at any time. Specially designed interior nodes for the payload.

Command and control: From manually driven to preprogrammed sequencing to autonomous navigation.



ALI ElectroMechanical Systems Development Milestones

FY	Task	TRL
2005	Phase Trade Study to baseline articulated structure	3
2006	Design and Prototype subsystems for extreme environments	4
2007	Complete design for extreme environments	5
2008	Demonstrate long term duration operation of 12TET in extreme environments	6
2009	Mission to extreme terrestrial site to incorporate lessons learned	7
2010	Prepare for CDR and environmental testing for systems capable of lunar mission	8
2011	Environmental, functional, operational tests for lunar mission testbeds to finalize RFP for industry selection	9

ALI Payload Components

The ALI payload would be designed to measure abundances of major, minor, and trace elements, minerals, and low molecular weight volatiles, particularly water, in the lunar regolith. Payload components would be attached ‘inside’ the tetrahedral nodal network which would be lowered to the surface to perform measurements.

The low mass, volume, and power strawman payload would include the following active spectrometers designed to operate in an unilluminated environment:

(1) a laser ablation mass spectrometer for measuring major, minor, and trace isotopes as well as volatile abundances,

(2) a combined X-ray fluorescence/diffraction spectrometer for confirming major element abundances and determining mineralogy

(3), and a pulsed neutron spectrometer for detection of H, and, when combined with other measurements, confirmation of the presence of water.

The multi-nodal laser vision system would be enabled to download images on command as well.

Instruments in this payload would be similar to ones already under development for the Mars Science Laboratory to be launched in 2009.

ALI Strawman Payload Description

Active Instrument	Power	Mass	Flight Heritage (TRL 9)
Laser Ablation Mass Mass Spectrometer	3 Watts	0.5 kg	LAMS/ESA ExoMars 2009
XRF/XRD Spectrometer	15 Watt-Hours	5 kg	Chemin/NASA MSL 2009
Pulsed Neutron Spectrometer	1 Watt	0.5 kg	DAN/NASA MSL 2009

Payload: Chemin XRF/XRD Spectrometer

http://www.nasa.gov/vision/earth/technologies/Portable_CheMin.html

http://chemin.lanl.gov/

http://research.hq.nasa.gov/code_s/nra/current/NRA-02-OSS-01-MIDP/winners.html

http://www.cosis.net/abstracts/EGU05/02160/EGU05-J-02160.pdf

http://www.lpi.usra.edu/meetings/lpsc2005/pdf/1608.pdf

http://www.cosis.net/abstracts/EGU05/02966/EGU05-J-02966.pdf

http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/papers/Mars-CHEMIN-USDC-2003-3022.pdf

http://ndeaa.jpl.nasa.gov/nasa-nde/usdc/papers/2004-LPSC-Chipera-comparison.pdf

http://www.dxcicdd.com/03/PDF/P_Sarrazin.pdf

http://www.ees.lanl.gov/pdfs/1_chemin_30.pdf

http://www.cedrat.com/applications/hardware/doc/NASA-ARC_NOVEL-SAMPLE-HANDLING-FOR-XRD-ANALYSIS.pdf

http://vadose.pnl.gov/workshop-00/Bish.PDF

http://marsprogram.jpl.nasa.gov/missions/future/msl.html

http://www.answers.com/topic/mars-science-laboratory

Payload: DAN Pulsed Neutron Spectrometer

http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3109.pdf

http://www.lpi.usra.edu/meetings/sixthmars2003/pdf/3057.pdf

http://research.hq.nasa.gov/code_s/nra/current/NRA-02-OSS-01-MIDP/winners.html

http://research.hq.nasa.gov/code_s/nra/current/NRA-03-OSS-01-MIDP/winners.html

http://www.nuclearspace.com/a_2009_Rover.htm

http://marstech.jpl.nasa.gov/content/detail.cfm?Sect=MTP&Cat=base&subCat=MIDP&subSubCat=MIDPIII&TaskID=2149

http://research.hq.nasa.gov/code_s/nra/current/NNH04ZSS001O/winners.html

http://centauri.larc.nasa.gov/msl/DAN_PIP_May_12_2004.pdf

Payload: LAMS Laser Ablation Mass Spectrometer

http://www.lpi.usra.edu/meetings/robomars/pdf/6027.pdf

http://astrobiology.gsfc.nasa.gov/brinckerhoff_2003.pdf

http://www.esa.int/SPECIALS/Aurora/SEM1NVZKQAD_0.html

http://www.lpi.usra.edu/meetings/LPSC99/pdf/1752.pdf

http://www.phim.unibe.ch/~wurz/RSI_75_2004.pdf

http://techdigest.jhuapl.edu/td2004/gold.pdf

ALI Operational Command and Control

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 try to "finesse" the situation by somehow glossing over 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 will become a moving part of the terrain, its vision system providing volumetric information about its surroundings. 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. Key Challenges include:

1) Determining standard operational modes as a function of terrain, including parameters such as gait, speed, shape, size.

2) Incorporating input from vision system and EMS sensors to assess irregularities and use proper operational mode: plowing through, climbing, bridging, or going around.

3) Developing virtual reality model and high level command language for user interface.

ALI Operational Command and Control Development Milestones

Task	FY05	FY06	FY07	FY08	FY09	FY10	FY11
TET Operational Scenarios: Define TET standard operation modes Analyze and define optimal reconfiguration scheme Define EMS and payload constraints, restrictions	2	3	4	5	6	7	8
Command&Control Systems Define actuator commands Define feedback sensor telemetry parameters Define macros for coordinated movements Define communication scheme Define user interface	2	3	4	5	6	7	8
Planning and Scheduling System 3D laser scanner system: scene analysis and location Navigation System: path planning and location Maneuver planning	1	2	3	4	5	6	7-8
User Interface Develop Virtual Reality kinematic model Develop high-level command language Develop graphical user interface Integration of virtual reality model and commanding	2	3	4	5	6	7	8

ALI Power System Description

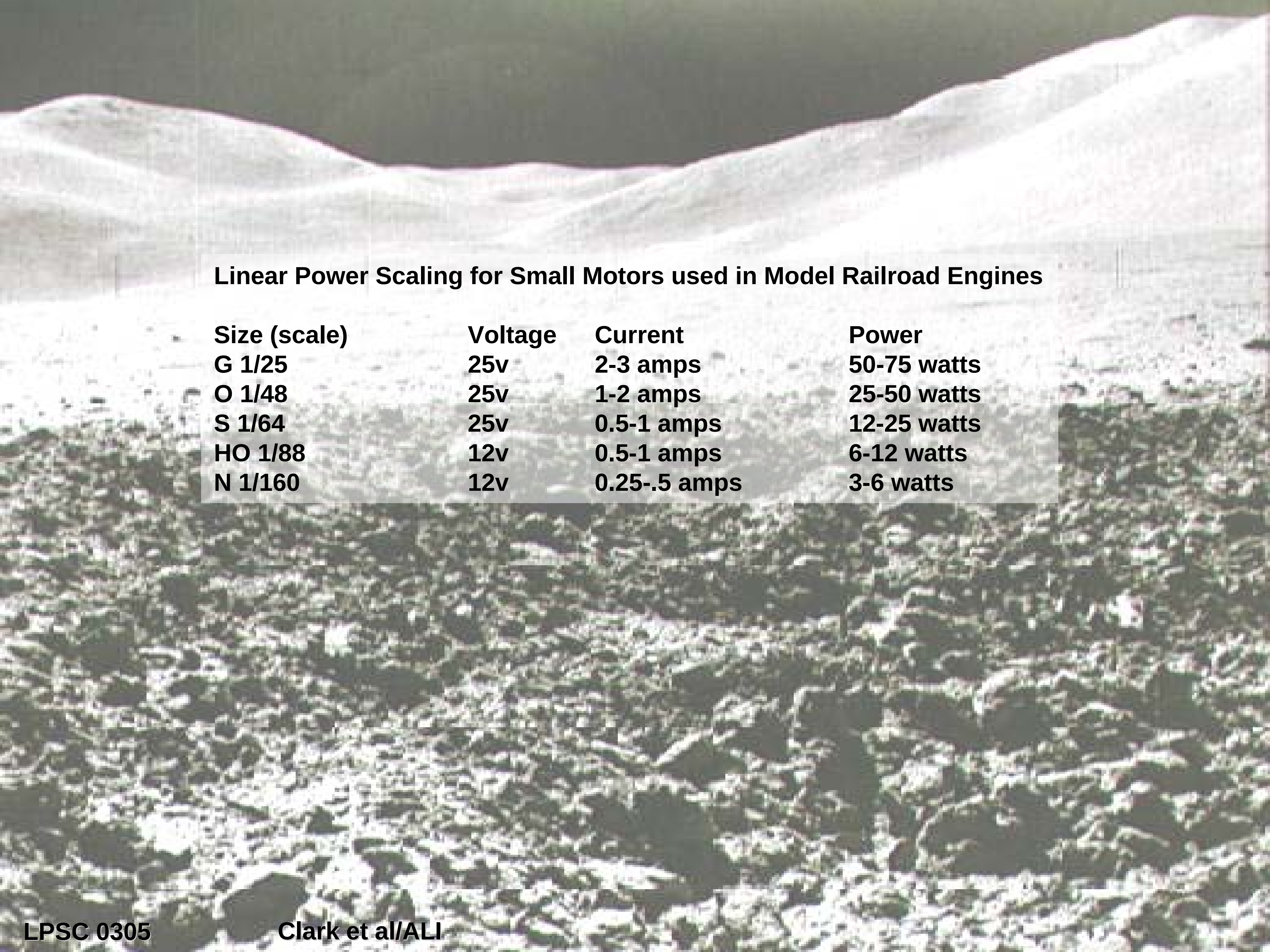
ALI will require small motors capable of generating pounds of torque to deploy struts. We estimate, based on performance of our current prototype and power scaling for small motors, that ALI will require tens of watts of power output for locomotion, its most strenuous activity. The requirement for operation in unilluminated environments precludes the use of solar cells as the main power source. The mass and dimensions of the power source will be constrained, and we would prefer to have a separate power source for each strut, to reduce cabling and improve reliability. For these reasons, batteries based upon heat generated from a radioisotope are baseline. Presently, Radioisotope Power Supplies (RPS) are capable of converting about 3% of the heat generated by radioactive decay into electricity and generating hundreds of milliwatts per kilogram. 5 to 10 times more efficient RPS (Small Power Technology or SPOT) presently under development here at Goddard will greatly reduce required mass and volume. Particular challenges in the development of SPOT power include:

1) Controlling (pulsing) thermal output

2) Interfacing shape memory metal for thermal to mechanical conversion

3) Interfacing piezoelectric crystal layer for mechanical to electric conversion

4) Storing and recovering power as needed



Linear Power Scaling for Small Motors used in Model Railroad Engines

Size (scale)	Voltage	Current	Power
G 1/25	25v	2-3 amps	50-75 watts
O 1/48	25v	1-2 amps	25-50 watts
S 1/64	25v	0.5-1 amps	12-25 watts
HO 1/88	12v	0.5-1 amps	6-12 watts
N 1/160	12v	0.25-.5 amps	3-6 watts

ALI Power System Development Milestones

Task	FY05	FY06	FY07	FY08	FY09	FY10	FY11
Thermal Output Control Includes selection of variable heat control technology, Conceptual Design, Prototyping, and Testing of Component and interface	3	4	5	6	7	8	9
Thermal to Mechanical Conversion Includes selection of shape memory material, conceptual design, prototyping, and testing of packaged component and interface	3	4	5	6	7	8	9
Mechanical to Electrical Conversion Includes selection of piezoelectric crystal material, conceptual design, prototyping, and testing of packaged component and interface	4	5	6	7	8	9	
Energy Storage and Retrieval Includes selection of storage device, conceptual design, prototyping, and testing of component and interface	4	5	6	7	8	9	
Packaging Includes conceptual design of nuclear battery, integration of components, prototyping and testing of device.	2	3	4	5	6	7	8-9

Neural Basis Function Description

For the shortest timescales, the 12 TET is essentially a behavior-based nonlinear dynamical system. A Neural Basis Function (NBF) software architecture is used to define, control, and organize the network of actuators responsible for 12 TET motion.

NBFs are composed of multiple high- and low-level control systems within an Evolvable Neural Interface (ENI) which acts as an active communication medium between the control elements. The high-level components generally rely on a more symbolic approach to control and may involve planning and schedule and other heuristic control. Low-level components are typically directly linked to system actuators and sensors and generally provide a more reactive approach.

Separate behaviors of the 12 TET are typically instantiated as separate NBFs: to add new behaviors the aim is to simply link the ENI of the new behavior into the system and then allow the ENIs to adapt the old and new components to each other. In this way, behaviors may be added together in a way analogous to the basis functions of mathematical physics.

The NBFs for the 12 TET are built on what we have learned applying the NBF architecture to a control system for autonomous rendezvous and capture of a chaotically tumbling target, a problem inspired by the Hubble Space Telescope Rescue mission.

NBF Development Milestones

Task & TRLs for FY	**FY05**	**FY06**	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**
Synthetic Neural System ~ Neural Basis Function							
Simulation	2						
Node-level integration	2	3	4				
Structure-level integration~variable geometry TET truss	2	3	4 - 5	6	7	8	**FLIGHT**
Autonomous locomotion – 12 TET Rover			5	6	7	8	**FLIGHT**

ALI Dust and Thermal Control

ALI will operate in an unilluminated environment, minimizing thermal cycling and heating problems.

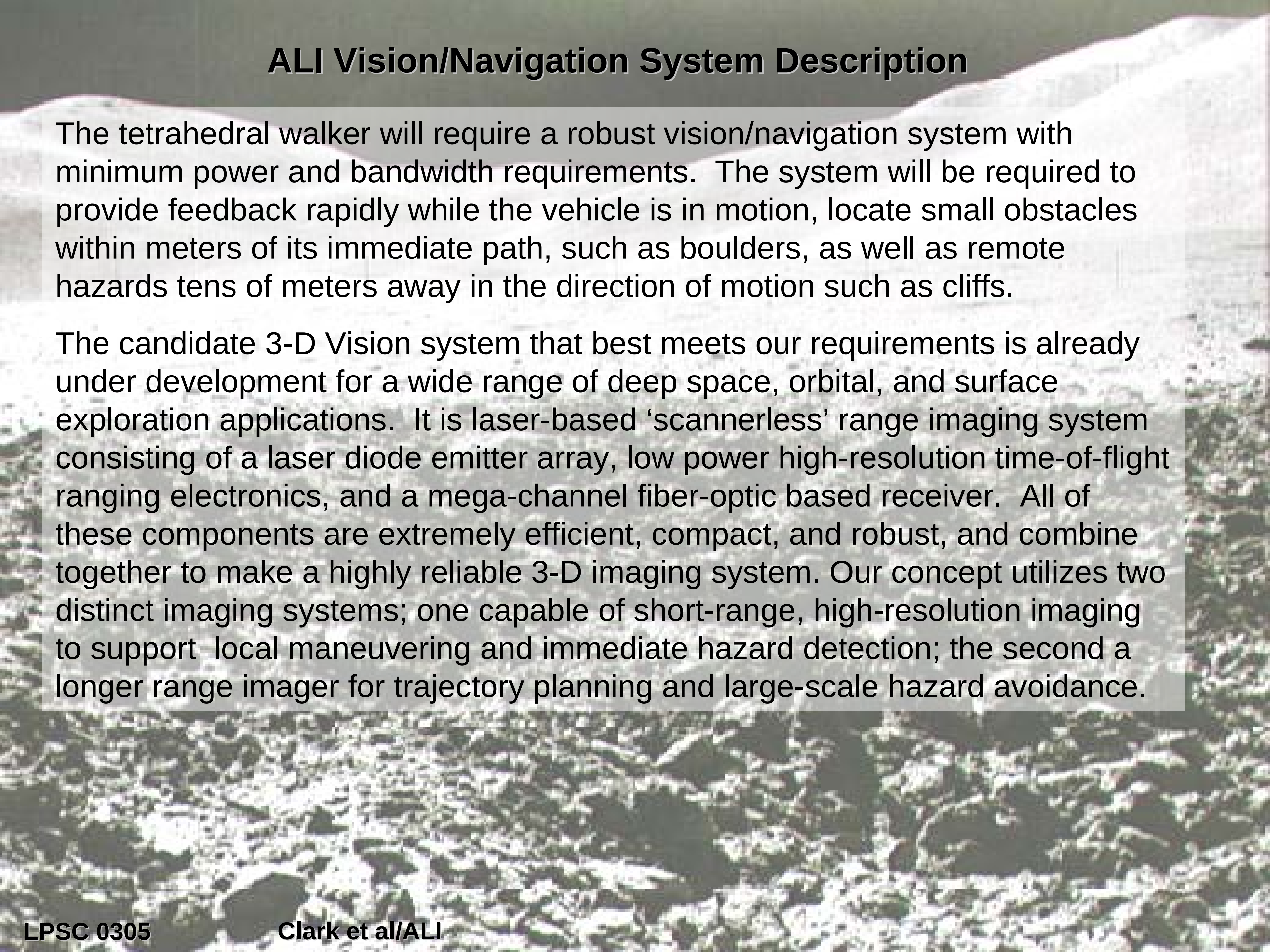
Dust is a critical environmental factor with which all rover technologies must deal. It is particularly important where articulated mechanisms must contend with possible acute and chronic effects of dust accumulation. Dust in the Lunar environment is particularly challenging: as experience with the wear and tear on Apollo equipment has shown. The Moon is airless, bathed in UV radiation (during the day), and very dry, which all lead electrostatic effects to play important roles in dust dynamics. The dust does not have the benefit of Terrestrial weathering and therefore is particularly sharp and jagged on a variety of scale sizes. Furthermore, segregation works differently on the Moon and there exists in abundance on the Moon particles of a wide range of sizes, including sizes that are extremely rare on the Earth. These features of Lunar dust pose problems for mechanical joints and seals in addition to any surface exposed to the dust.

For the Dust Mitigation Subsystem for ALI, we are primarily examining electrostatic means of dust rejection that would keep ALI mechanisms free of Lunar dust. The 12Tet walker will maintain equipotential by using all metal (no dielectric) surfaces and an ion beam source to short the equipotential to the ground, resulting in no dust attraction. O-ring seals around all deployment mechanisms will prevent dust intrusion.

Dust Mitigation and Thermal Control System Development Milestones

Task & TRLs for FY	FY05	FY06	FY07	FY08	FY09	FY10	FY11
Dust Mitigation Subsystem (DMS)							
Electrostatic & Plasma simulation	2						
DMS component test	2 - 3	3	4				
DMS integration with Strut/Node		3	4 - 5	6	7	8	FLIGHT
DMS integration with Strut/Node TET Structure			5	6	7	8	FLIGHT

ALI Vision/Navigation System Description



The tetrahedral walker will require a robust vision/navigation system with minimum power and bandwidth requirements. The system will be required to provide feedback rapidly while the vehicle is in motion, locate small obstacles within meters of its immediate path, such as boulders, as well as remote hazards tens of meters away in the direction of motion such as cliffs.

The candidate 3-D Vision system that best meets our requirements is already under development for a wide range of deep space, orbital, and surface exploration applications. It is laser-based ‘scannerless’ range imaging system consisting of a laser diode emitter array, low power high-resolution time-of-flight ranging electronics, and a mega-channel fiber-optic based receiver. All of these components are extremely efficient, compact, and robust, and combine together to make a highly reliable 3-D imaging system. Our concept utilizes two distinct imaging systems; one capable of short-range, high-resolution imaging to support local maneuvering and immediate hazard detection; the second a longer range imager for trajectory planning and large-scale hazard avoidance.

ALI Vision/Navigation Development Milestones

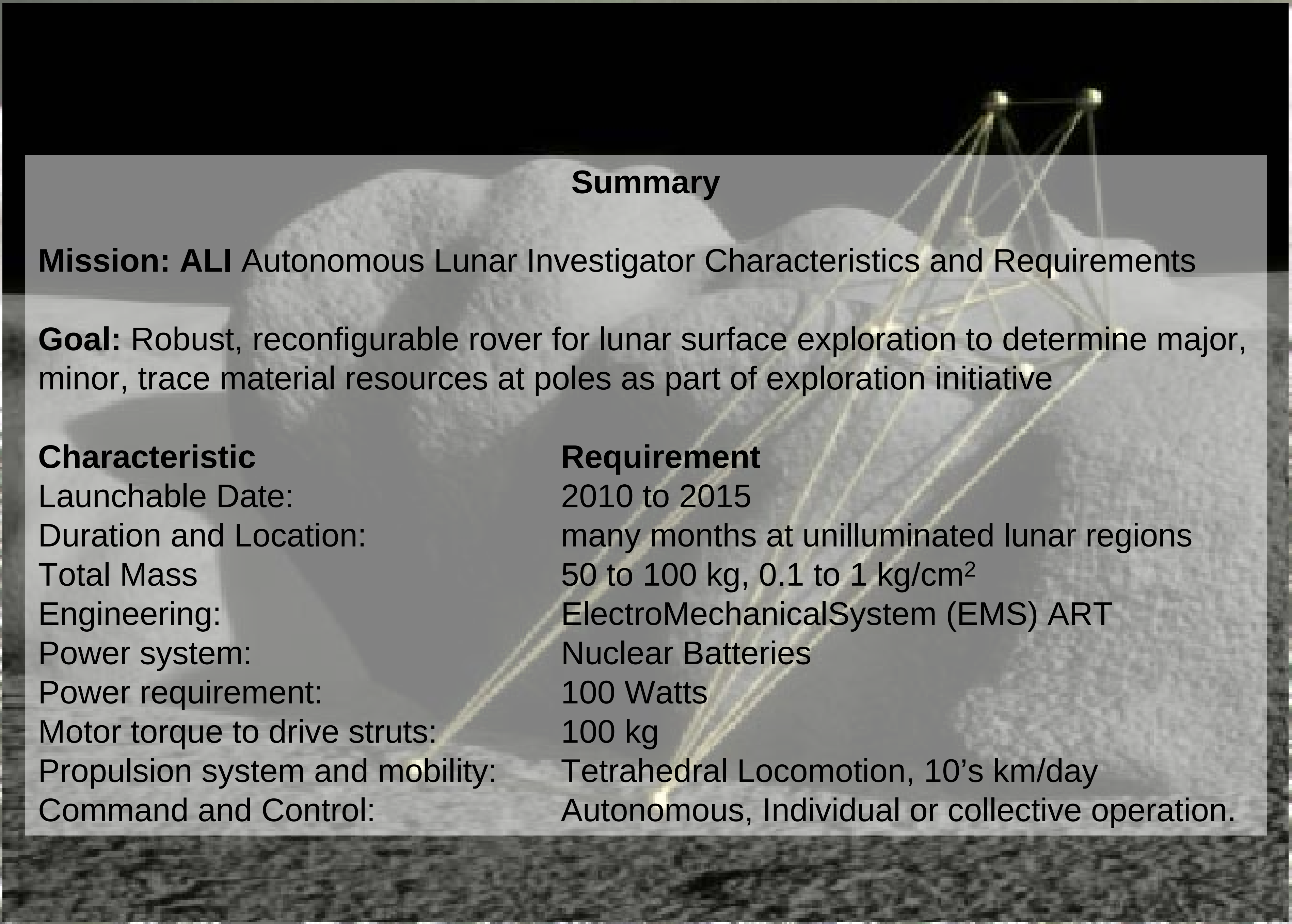
Navigation System Task & TRLs for FY	**05**	**07**	**09**	**11**
Increased resolution for given laser output	Single channel 10^3 pixels	Multi-channel 10^4 pixels	Multi-channel 10^5 pixels	Multi-channel 10^6 pixels
Develop fiber optic based fixed diode emitter arrays with electronic scan capability	4-5	5-6	6-7	7-8
Incrementally improve fiber optic based receiver system optimized for 1 and 100 meter distances	4-5	5-6	6-7	7-8
Increase the number of channels and decrease the mass and size of the timing circuitry for ranging electronics	5	6	7	8

Vision System Task	**FY**	**TRL**
Investigative Studies Lidar 3D, Structured Light, and Hybrid 3D Vision	05	3
Concept Design Prototype Acquisition Sensing System	06	4
Data Analysis Data acquisition, feature extraction, 3D scene representation, and path planning with updating	06-08	4
Laboratory/MERS prototype from acquisition to planning	08-09	5
Integration subsystem integration, testing, and demonstration	09-10	6-7

Advanced Computing

Environmentally Adaptive Fault Tolerant Computing (EAFTC) (D. Brenner/Honeywell DSES): The application of COTS processing components in operational space missions with optimal performance efficiency requires a system-level approach. Of primary concern is the need to handle the inherent susceptibility of COTS components to Single Event Upsets (SEUs). Honeywell in conjunction with Physical Sciences Incorporated, and WW Technologies Group has developed the new EAFTC paradigm for fault tolerant COTS based onboard computing. EAFTC combines a set of innovative technologies to enable efficient use of high performance COTS processors, in the harsh space environment, while maintaining the required system availability. This technology is currently under contract for ST8 at TRL 4, with plans to be at TRL5 next year for the flight build on ST8 in FY08.

Reconfigurable Data Path Processor (RDDP) (P. S. Yeh): The Reconfigurable Data Path Processor (RDPP) is conceived as an ultra-low-power, radiation-tolerant processor for data-intensive, streaming applications such as image and signal processing. Sophisticated space-borne instruments require high-performance data processors. However, the special requirements of space, especially radiation tolerance and low power consumption, impede the use of commercial high-performance processors.



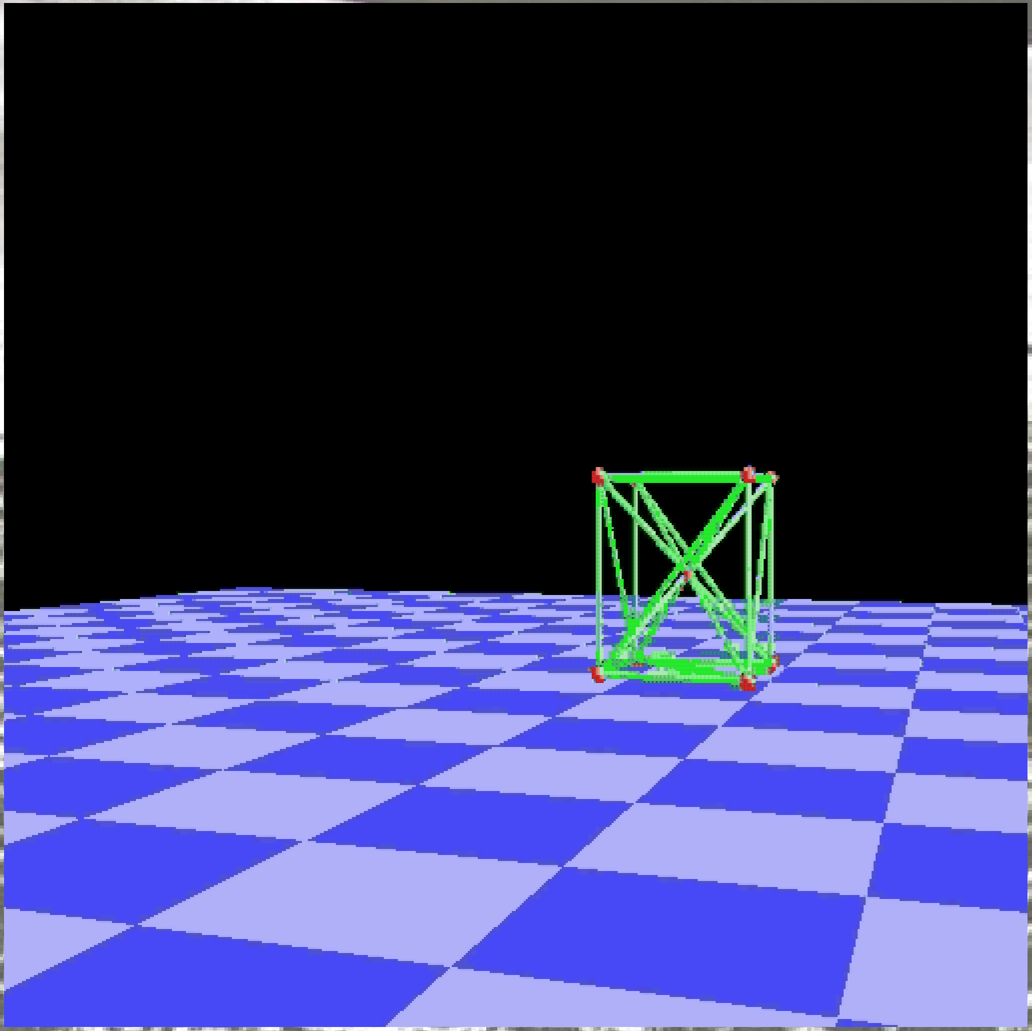
Summary

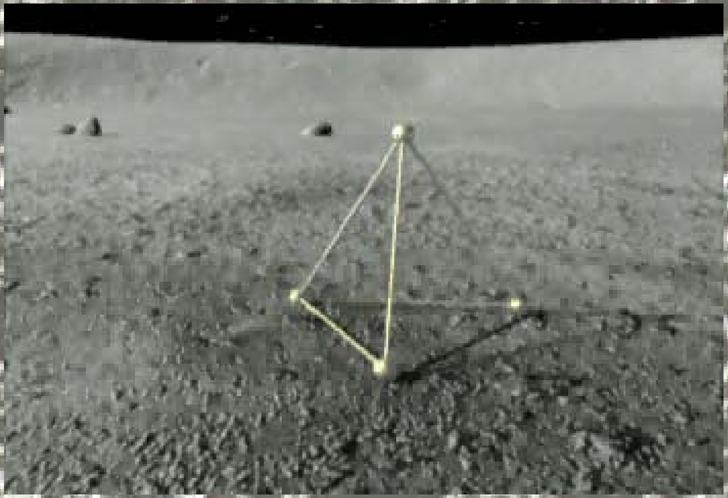
Mission: ALI Autonomous Lunar Investigator Characteristics and Requirements

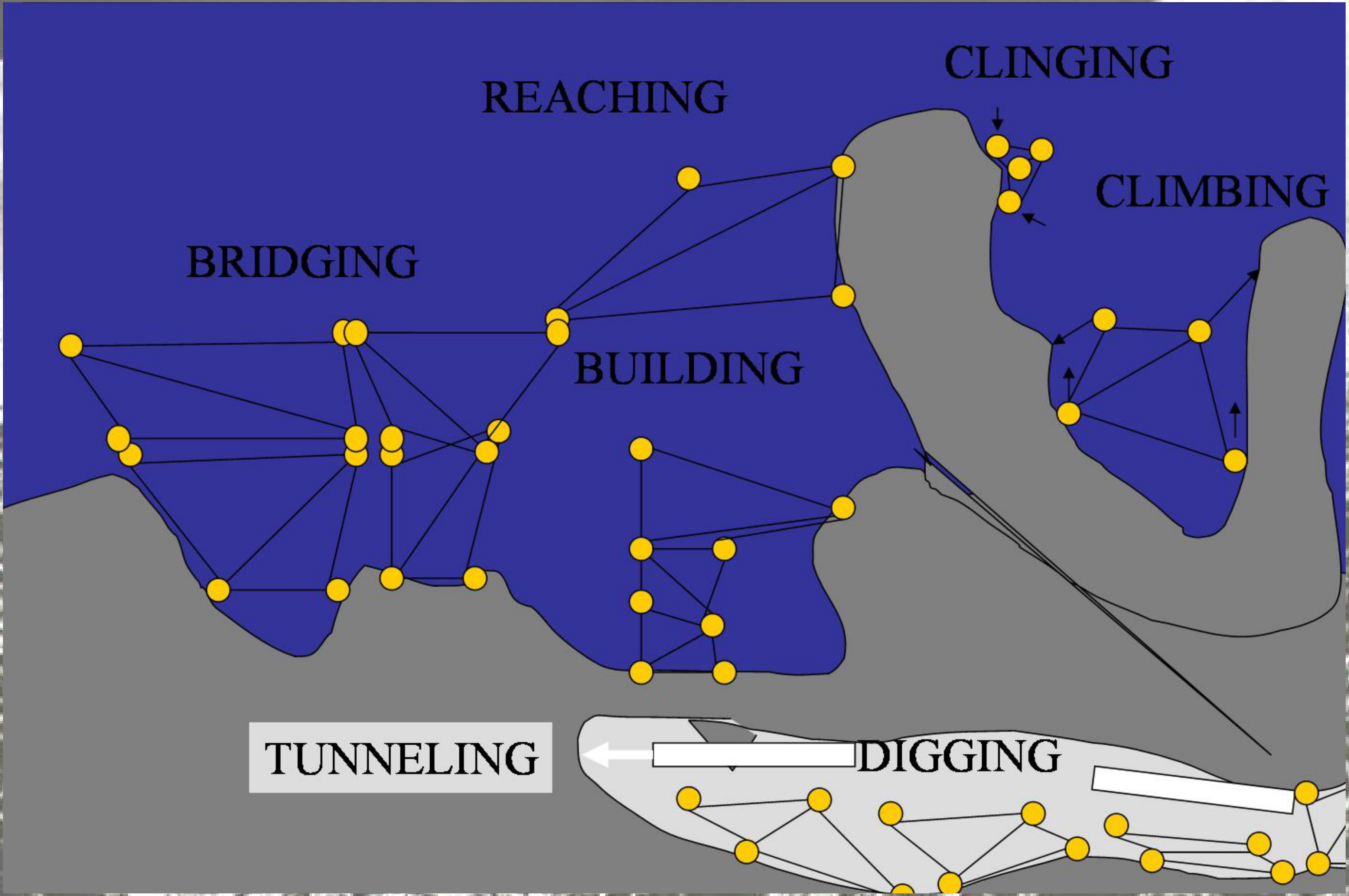
Goal: Robust, reconfigurable rover for lunar surface exploration to determine major, minor, trace material resources at poles as part of exploration initiative

Characteristic	**Requirement**
Launchable Date:	2010 to 2015
Duration and Location:	many months at unilluminated lunar regions
Total Mass	50 to 100 kg, 0.1 to 1 kg/cm^2
Engineering:	ElectroMechanicalSystem (EMS) ART
Power system:	Nuclear Batteries
Power requirement:	100 Watts
Motor torque to drive struts:	100 kg
Propulsion system and mobility:	Tetrahedral Locomotion, 10’s km/day
Command and Control:	Autonomous, Individual or collective operation.

Other Movies: animation, Sampe, and Press Release






CLINGING
REACHING
CLIMBING
BRIDGING
BUILDING
TUNNELING
DIGGING