Small Power Technology Systems for Tetrahedral Rovers

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Abstract. The Small Power Technology (SPOT) being studied at GSFC has the potential to be an efficient and compact radioisotope based power system. Such a system would provide power for innovative tetrahedral robotic arms and walkers to support the lunar exploration initiative within the next decade. Presently, NASA has designated two flight qualified Radioisotope Power Supplies (RPS): the Multi-Mission RTG (MMRTG) which uses thermocouple technology and the more efficient but more massive Stirling RTG (SRTG) which uses a mechanical heat (Stirling) engine technology. With SPOT, thermal output from a radioisotope source is converted to electrical power using a combination of shape memory material and piezoelectric crystals. The SPOT combined energy conversion technologies are potentially more efficient than thermocouples and do not require moving parts, thus keeping efficiency high with an excellent mass to power ratio. Applications of particular interest are highly modular, addressable, reconfigurable arrays of tetrahedral structural components designed to be arms or rovers with high mobility in rough terrain. Such prototypes are currently being built at GSFC. Missions requiring long-lived operation in unilluminated environments preclude the use of solar cells as the main power source and must rely on the use of RPS technology. The design concept calls for a small motor and battery assembly for each strut, and thus a distributed power system. We estimate, based on performance of our current tetrahedral prototypes and power scaling for small motors, that such devices require tens of watts of power output per kilogram of power supply. For these reasons, SPOT is a good candidate for the ART baseline power system.

Keywords: Small Radioisotope Power, Rover, Robot, TetWalker, Piezoelectric, Shape Memory, Heat Pipe, RTG
PACS: None found

INTRODUCTION: SIGNIFICANCE OF SPOT

To meet the goals of the exploration initiative (President's Commission, 2004), to establish bases on the Moon and Mars, will require efficient radioisotope power supplies capable of operating in the range of conditions found on these planetary surfaces (NASA RPS Report, 2005). Architecture for such a facility should be multifunctional, efficient, durable, and reusable. Of particular utility and perhaps even essential in creating a working infrastructure would be structures that are also inherently addressable, reconfigurable, and thus mobile. At GSFC, we are attempting to develop this architecture (Curtis et al, 2000; Clark et al, 2004b, 2004c, 2005), referred to as Addressable Reconfigurable Technology (ART) for all-terrain arms and rovers in its present form and Autonomous NanoTechnology Swarm (ANTS) for efficient larger structures of the future. One major constraint is adequate power under all conditions, which is why RPS systems look so attractive. On the other hand, the efficiency per mass of the presently flight-qualified RTGs is marginal for even present ART applications. Presently, Radioisotope Power Supplies (RPS) are dominated by two thermal-to-electrical energy conversion technologies (NASA RPS Report, 2005; Mondt, 2000), thermocouple (as in the MMRTG), which has the virtue of a simple design with no moving parts but the limitation of only a few percent conversion efficiency, and the Stirling mechanical heat engine (as in SRTG) which is far more efficient but is more massive and has moving parts. Thus, efforts are underway, to make RTGs with higher efficiency per mass. SPOT converts heat to electricity without mechanical parts, thus keeping efficiency high with an excellent mass to power ratio. A proposed SPOT system capable of utilizing the

radioisotope thermal source appropriate for the mission conditions, would be designed to provide up to 10 watts of electrical power where needed (Clark et al, 2004a).

This paper will describe the conceptual design and application of the Small Power Supply Technology (SPOT) (Clark et al, 2004a), an efficient small radioisotope power supply currently under development at NASA/GSFC. Potential use of SPOT in the context of the exploration initiative over the next decades will be considered, in particular innovative highly modular, reconfigurable tetrahedral manipulators and walkers currently being prototyped at GSFC (Clark et al, 2004b, 2004c, 2005). We will discuss how SPOT addresses the power system needs of these innovative robots and very low power instruments.

APPROACH TO SPOT DEVELOPMENT

Small Power Technology (SPOT) converts heat from a radioisotope thermal source to electricity by using a collection of proven technologies, including heat pipe, shape memory metal (SMM), and piezoelectric crystal (PC). This approach is designed to maximize efficiency while minimizing mass. In this way, SPOT development would address the power system needs of innovative robots and payloads by providing Watts of electrical power continuously and efficiently.

Several radioisotope thermal sources could be used, but the mission and detail design considerations would determine the selected material. For example, very long duration missions might use Plutonium-238 which has an 87 year half-life, but is in short supply and has a high cost. On the other hand, Curium-242 with less then a year half-life is less then a sixth the cost of Plutonium. Other mission design considerations, such as the radiation and particle background produced by the isotope and its effect on the payload, can be just as important in the selection.

The radioisotope heat source is a proven technology and the SPOT idea begins with this thermal source coupled to a heat pipe which pumps heat to the thermal to mechanical conversion subsystem. This heat initiates, via Shape Memory Metal (SMM), the mechanical loading of a piezoelectric crystal. The heat is then decoupled from the SMM via a one-way valve, the metal cools, the mechanical loading of the crystal relaxes, and the cycle can begin again, producing an alternating EMF. (In detail, as seen in Figure 1, the cold end of the tube (Heat Out) contains the thermal to mechanical conversion mechanism which incorporates the technologies of the Heat Pipe and SMM. When the SMM reaches temperature it elongates to shut off hot gas flow as well as strain the piezoelectric crystal to generate the EMF. After cooling the SMM shrinks, allowing the heat to flow, beginning the next cycle.) Of course rectification, power conditioning and storage are necessary to complete a power system.

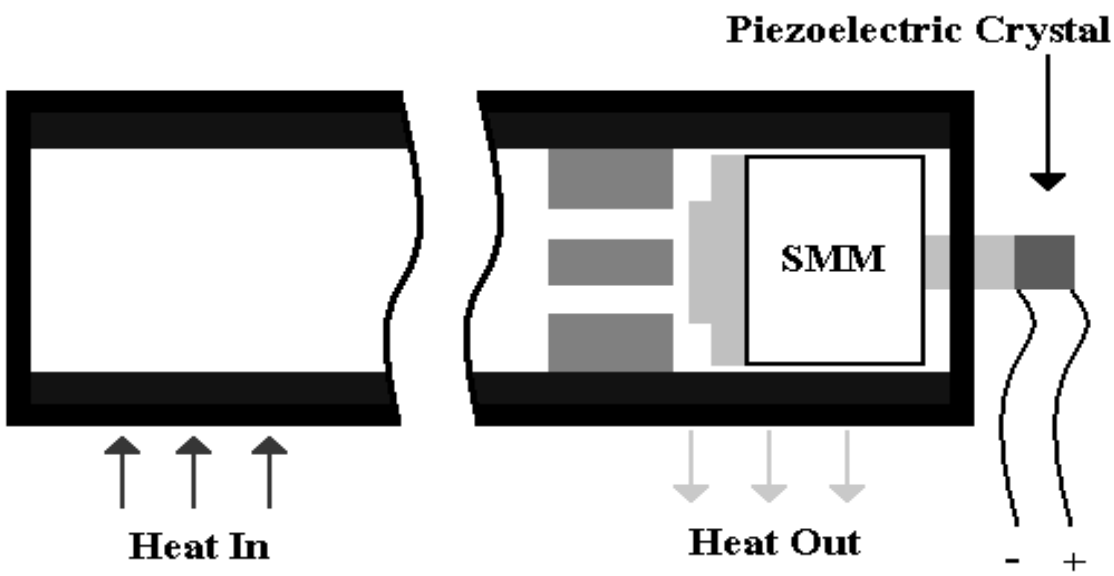

FIGURE 1. The SPOT Design is a Closed Tube that Looks Very Much Like a Typical Heat Pipe.

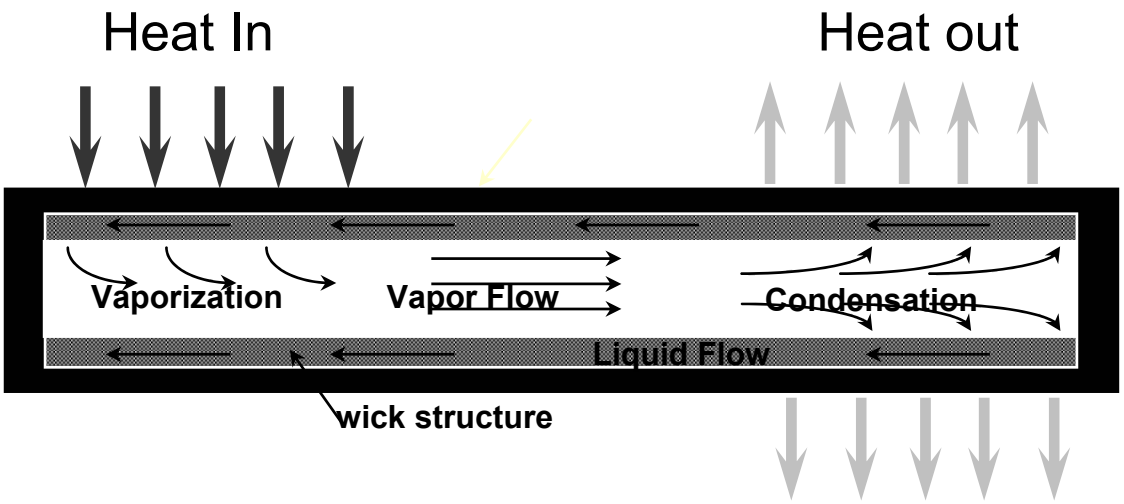

FIGURE 2. The Heat Pipe is a Closed Tube with a Working Fluid. The Fluid Evaporates on the Hot End and Condenses on the Cold End. An Inner Wall Wick Returns the Fluid to the Hot End Via Capillary Action.

To describe the evolution of the SPOT concept, we start with a standard heat pipe. A standard heat pipe (Spacecraft Thermal Control Handbook, 2002) is coupled to the radioisotope heat source (Figure 2). Heat pipes utilize the latent heat of vaporization of the working fluid to transfer large amounts of heat efficiently at a relatively constant temperature. This is accomplished with the use of wick materials in a closed tube device, and is done entirely passively with no mechanical pumping. Over the years, thousands of heat pipes have been used for spacecraft thermal control, as well as in terrestrial applications such as maintaining the perma-frost for the Alaska pipe line. In the proposed SPOT application, the heat pipe will be modified to work in conjunction with the shape memory alloy to act as a switch, allowing heat to flow when needed, and then shutting off for the cooling portion of the cycle. This is a very efficient device for moving heat short distances. It is the parasitic losses for a particular design that dominate the efficiency for this part of the system. We have done only preliminary calculations for the efficiency of this design, and modeling small thermal systems if more difficult and less accurate than modeling large systems. However, we anticipate better than fifty percent efficiency, contingent upon more detailed modeling.

The thermal to mechanical conversion efficiency for the Shape Memory Metal (SMM) component of SPOT has been evaluated for a mission environment at the polar regions of the Moon. Without considering the parasitic losses that must exist in real hardware, the thermal to mechanical efficiency has been calculated to be 34%.

Once the heat has initiated the SMM strain on the piezoelectric crystal it is necessary to shut down the heat flow so that the SMM can cool and the cycle can begin again. That part of the SPOT design uses Loop Heat Technology (Figure 3). The Loop Heat Pipe was developed in Russia during the 80's and can efficiently move heat a meter or more. The Hot evaporator chamber contains a uniquely designed wick of fine pore size for developing capillary pressure to drive the working fluid to the condenser. At the valve section, the wick is designed to create a liquid block, preventing backflow of fluid or hot gas bypass. It is the sealing off of the SMM chamber by the elongation of the SMM and the liquid lock in the wick that shuts off the heat flow and allows that end to cool. Now the cycle can repeat and an alternating potential is developed by the piezoelectric crystal. Mechanical to electrical efficiencies using small piezoelectric crystals can be better than sixty percent. The particular design for straining the crystal is under study and ranges from a direct stress design to a cantilevered construction.

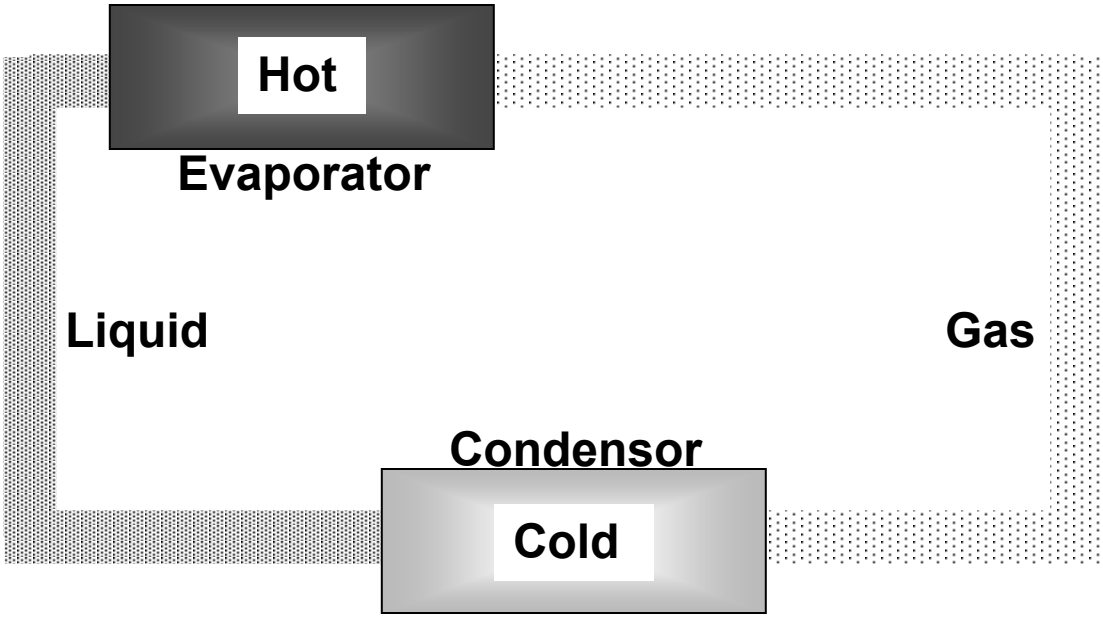

FIGURE 3. The Hot Evaporator Chamber Contains a Uniquely Designed Wick. The Wick is Fine Pore Size for Developing Capillary Pressure to Drive the Gas Through the Tube to the Condenser. Essentially a Liquid Lock Prevents the Liquid from Being Driven into the Gas Section.

METHODOLOGY FOR SPOT DEVELOPMENT

The conceptual application of a SPOT module is to produce a small amount of electrical power continuously for either a low power instrument or simply one mechanical node of a robot. Of course each power producing element is small and takes seconds to cycle. A completed power module of ten watts or less would have many elements drawing heat from a radioisotope heat pellet and connected to a control/storage module. Here again the mission determines the design, but the very technology that SPOT uses restricts its size. SPOT uses technology that can not be efficiently scaled up in size, but is an effective power conversion method on a small scale.

SPOT RESULTS TO DATE

We have developed a conceptual design for SPOT (Figure 1) after performing research on the capabilities and limitations of state-of-the-art components in heat pipe, shape memory metal, and piezoelectric technology. Based on this model (Tables 4 and 5), we have performed preliminary calculations of constraints and efficiency.

APPLICATION TO INNOVATIVE TETRAHEDRAL ROBOTIC CONCEPTS

Addressable Reconfigurable Technology robots (Curtis et al, 2000; Clark et al, 2004a, 2004b, 2004c, 2005), including manipulators, walkers, and structures, are being designed to operate in extreme environments: certainly the rough, permanently shadowed areas inaccessible to modules now in use (ANTS, 2005) Such areas, on the Moon and Mars, are of particular interest because they may contain resources and landforms which could help to support a human presence. ART systems and structures are being developed as stepping stones to the very advanced Autonomous NanoTechnology Swarm (ANTS) architecture. The tetrahedron is the 'building block', acting singly, or connected to other tetrahedra 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. Tetrahedral locomotion occurs by continuous contraction and extension of struts in a way that optimizes the efficiency of movement across a terrain, by changing size, gait, and speed. Terrain can be crossed as required and probed as interest dictates regardless of variability and scale of its relief and roughness. Single tetrahedra give high

flexibility, move by controlled tumbling. Continuous networks give high degree of freedom resembling amoeboid movement. reusable, reconfigurable, relocatable, multi-functional, and self-repairing to operate as and when needed to meet mission requirements. Robust, 'form follows function' tetrahedral 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. ART systems could operate autonomously as a robotic mission or through an interface to support human exploration. The requirement for long-lived operation in unilluminated environments precludes the use of solar cells as the main power source and relies on the use of the most efficient RPS technology.

Near-Term Subsystem: Autonomous Lunar Manual Assistant

ALMA (Autonomous Lunar Manual Assistant) (Table 1, Figure 4), the first usable tetrahedral structure, will be a detachable arm acting as sample gathering subsystem on an existing rover for either the Moon or Mars (ANTS website, 2005). Continuous contraction and extension of struts and specially designed tetrahedral digits (hand) at either end will allow it to 'worm' its way across terrain carrying a payload, fetch and take measurements of samples in inaccessible places, including crevices and ledges, close to or at some distance from a rover. Such a tetrahedral subsystem would act as a demonstration of the technology in preparation for construction of a tetrahedral rover, the Autonomous Lunar Investigator (ALI).

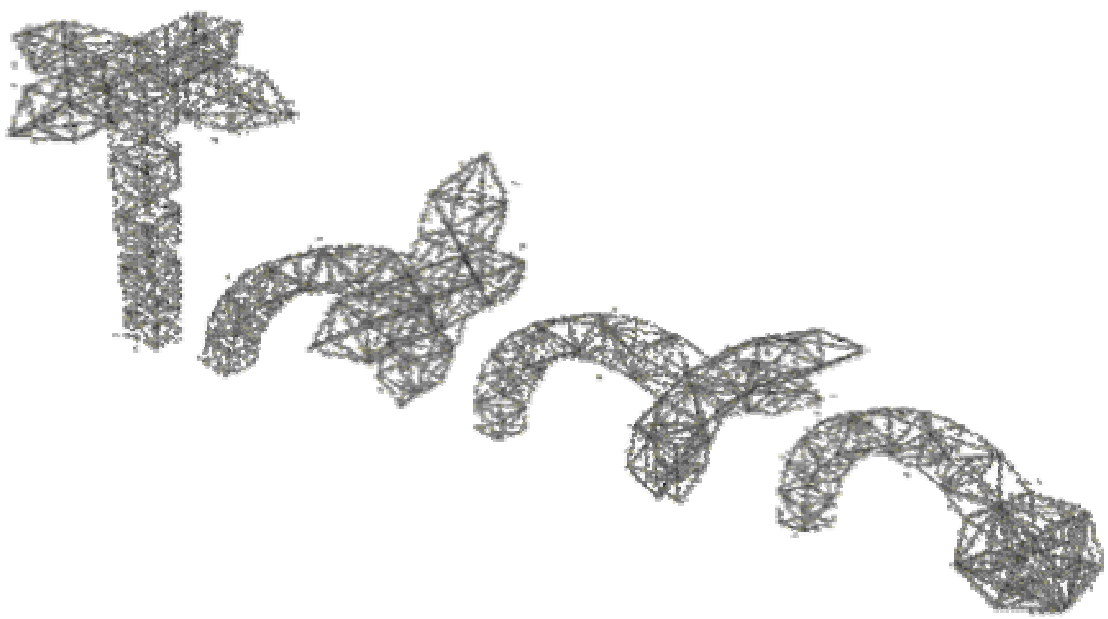

FIGURE 4. ALMA Concept, Illustrating Tetrahedral Arm Progressively Bending and Grasping from Left to Right.

TABLE 1. ALMA Characteristics.

Characteristics	Requirements
Mission	Sample Subsystem
Availability	Near-Term (5 years)
Environment	range of temperatures and illumination, rugged, inaccessible
Material	ElectroMechanical System, tens of kg, $0.1 m^2/kg$
Power	tens of watts, nuclear battery
Challenges	power: long duration operation at reasonable mass

Near-Future Rover: Autonomous Lunar Investigator

ALI (Table 2, Figure 5) is a more advanced EMS level mission concept, an autonomous rover for exploring the lunar poles within the next decade (Clark et al, 2005; ANTS, 2005). ALI would consist of one or more 12tetrahedral walkers capable of rapid locomotion in all terrains and equipped for navigation in the unilluminated, inaccessible and thus largely unexplored terrains where lunar resources are likely to be found: the polar regions. 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. Low mass, volume, and power active spectrometers now being designed for the next generation of Mars landers would be appropriate payload candidates. Destinations could be selected and autonomous operational modes could be commanded and controlled through a higher level interface. A multi-channel laser altimeter combined with motion and touch sensors at each node would allow knowledge of position and navigation. Dust control would occur via ion discharge, low dielectric surfaces, and sealing of deployment mechanisms. ALI would require a small motor and battery assembly for each strut, and thus a distributed power system. Optimally, to reduce space and cabling requirements and minimize losses, power would be generated, utilized, and stored locally where needed for strut reconfiguration. Analogously, glucose metabolism is associated with muscle activity in the human body. Efficient SPOT Nuclear batteries would meet these requirements.

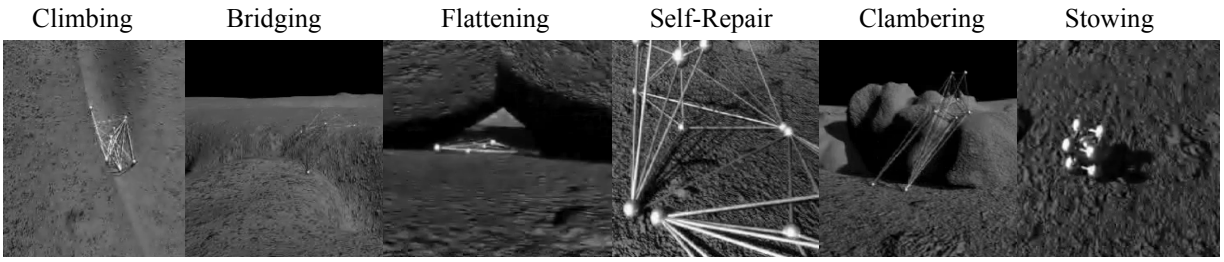

FIGURE 5. ALI Concept, Showing Reconfigurability and Multi-functionality of 12Tetrahedral Walker in Range of Movements Including Climbing, Bridging, Flattening, Self-repair, Clambering over Obstacle, Stowing to Smallest Volume.

TABLE 2. ALI Characteristics.

Characteristics	Requirements
Mission	Autonomous Rover(s) for unexplored terrains with potential resources
Availability	Near-Future (10 years)
Environment	Unilluminated, cold (50K), rugged, inaccessible
Material	ElectroMechanical Systems, tens of kg, $0.1m^2/kg$
Power	tens of watts, nuclear battery
Locomotion	tens of km/day
Challenges	efficient power, long duration, avoiding holes too big to bridge

Future Infrastructure: Lander Amorphous Rover Antenna

LARA (Lunar Amorphous Rover Antenna) (Table 3, Figure 6) is a future MEMS/NEMS level concept for infrastructure to support lunar bases (Clark et al, 2004c; ANTS, 2005). Both struts, acting as skeletal muscular structure, and surfaces, acting as skin, would be deployable/stowable with many degrees of freedom. Modules, inherently changeable in shape and position, would act as a reconfigurable infrastructure and could arrive as landers, launched from remote manned or unmanned locations. Modules could become rovers, using amoeboid motion including rolling, slithering, creeping for exploring, monitoring, building, transporting materials and act as multi-platform instrument carriers, antenna arrays or beacons for communication, navigation, or observation, or as specialized equipment nodes for construction, maintenance, industrial, or raw material recovery operations.

FIGURE 6. LARA concept, Illustrating Variety of Infrastructure Functions for Transportation in Space, on the Ground and for Communication.

TABLE 3. LARA Characteristics

Characteristics	Requirements
Mission	Autonomous Infrastructure for Lunar Bases to support human activity
Availability	Future (20 years)
Environment	Near and at rugged surfaces
Material	MEMS to NEMS, 10 kg, $1m^2$/kg
Power	watts, nuclear battery
Locomotion	Chemical Propulsion Mini-thruster (flight), RPS (ground)
Challenges	Adaptability, durability, reconfigurability for structures and surfaces

Tetrahedral Robotics Power Requirements

Power Requirements (Table 4) (ANTS, 2005; Clark et al, 2004a, 2004b), based on performance of our current prototype and power scaling for small motors, are estimated to be tens of watts of power output per kilogram of power supply for ALMA or ALI locomotion, the most strenuous activity. For these systems, current RTG systems are baseline. The ALMA subsystem could even be connected to onboard power if necessary. Power system requirements are estimated to be in the range of watts for future application LARA. The more efficient SPOT would readily meet requirements for distributed power in ALI and LARA. Ideally, power supply and driver motor would be packaged together within each strut (Figure 7). Our estimates are in line with Moore's Law: anticipated power requirement should decrease by up to two orders of magnitude for increments of EMS to MEMS and then from MEMS to NEMS technology. Several kilograms are budgeted for the power subsystem for near term applications, making the multiple RHU version of RPS technology usable, with capabilities of watts per kilogram, even at the current level of development (NASA nuclear power website, 2004). There is an additional incentive for the use of RPS technology. The availability and utility of nuclear battery technology is being improved by the development of MEMS level designs, currently being tested, and NEMS level concepts (e.g., Johnson, 2002, Blanchard and Lal, 2004). Tiny MEMS batteries, long-lasting and with at least a few percent efficiency thermoelectric or electromechanical conversion mechanisms generating small increments of power (micro-amps), could be embedded into ANTS structures where needed. This technology should be available for future ANTS applications which allow considerably smaller mass budgets, perhaps tenths of a kilogram, for the power subsystem, but still need to generate hundreds of milliwatts.

TABLE 4. ANTS Architecture Progression in Power Requirements.

Application	Time	System	Power	Mass Power Subsystem/System
Manipulator Subsystem (ALMA)	2010	EMS	<100 Watts	<10 kg/50 kg
Autonomous Rover (ALI)	2015	EMS	<100 Watts	<10 kg/50 kg
Multi-functional Infrastructure (LARA)	2025	MEMS (10^{-2} EMS)	<10 Watts	<1 kg/10 kg
Fully Autonomous Robotic Systems	2035	NEMS (10^{-4} EMS)	<100mWatts	0.1 kg/1 kg

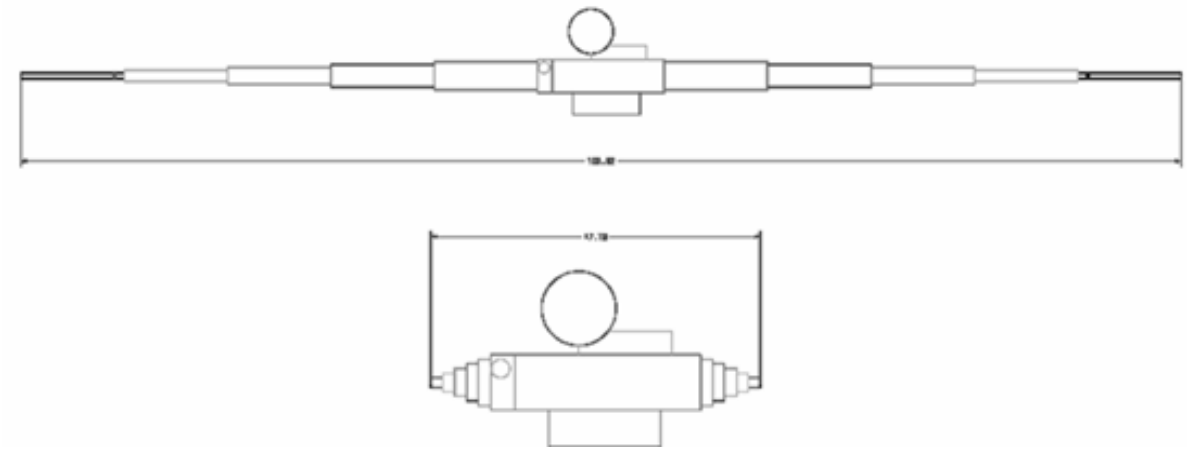

FIGURE 7. Schematic of 12Tetrahedral Strut with Circle Showing Position of Motor and Power Supply.

CONCLUSIONS

Demands on engineering power systems for NASA's new initiative to explore the surface of the Moon and Mars are high. Clearly the vanguard for these missions will be robotic rovers with scientific instruments. A good example of this vision is the tetrahedral robots project headed by Steve Curtis at Goddard Space Flight Center (ANTS website, 2005). Spot is uniquely suited to provide the electrical power for robotic architectures like ANTS and shows promise as an RPS system of choice in future robotic applications based on (Clark et al, 2004a) (Table 5).

TABLE 5. Comparison of Performance of Radioisotope Power Supplies

Characteristic	MMRTG	SRTG	SPOT
Fuel Source Output/Mass	8 GPHS* 2000 Watts/4 kg	2 GPHS* 500 Watts/1 kg	2 GPHS* 500 Watts/1 kg
Energy Conversion	thermocouple 3-5% efficient	stirling generator 12-15 % efficient	pulsed piezoelectric mechanism 10-20% efficient
Trades off	no moving parts large waste heat	moving parts less waste heat	no moving parts less waste heat
Battery Output/Mass	100 Watts/45 kg total mass	100 Watts/34 kg total mass	100 Watts/10 kg total mass**

*GPHS = 0.5 kg PU-238@250 Watts
** assuming worst case of 1:10 fuel:total mass ratio based on MMRTG

NOMENCLATURE

ALI Autonomous Lunar Investigator
ALMA Autonomous Lunar Manual Assistant
ANTS = Autonomous NanoTechnology Swarm Space Architecture
ART Addressable Reconfigurable Technology
EMS Electromechanical System
GPHS General Purpose Heat Source
LARA Lander Amorphous Rover Antenna
MEMS MicroElectroMechanical System

MMRTG Multi-Mission Radio Thermal Generator
NEMS NanoElectroMechanical System
PC Piezoelectric Crystal
RHU Radioisotope Heater Unit
SMM Shape Memory Metal
SRPS Small Radioisotope Power Supply
SPOT Small POwer Technology
SRTG Stirling engine Radio Thermal Generator
TetArm Tetrahedral Robotic Arm
TetWalker Tetrahedral Robotic Walker

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