SMART Power Systems for ANTS Missions

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Abstract. ANTS Architecture is based on Addressable Reconfigurable Technology (ART) adaptable for the full spectrum of activities in space. ART systems based on currently available electromechanical (EMS) technology could support human crews on the lunar surface within the next 10 to 15 years. Two or more decades from now, NEMS (Super Miniaturized ART or SMART) technology could perform fully autonomous surveys and operations beyond the reach of human crews. Power system requirements would range from 1 kg to generate tens of Watts for near term ART applications, such as a lunar or Mars Lander Amorphous Rover Antenna (LARA), to <0.1 kg to generate hundreds of mWatts for more advanced SMART applications.

POWER SYSTEMS FOR FUTURE MISSIONS

Availability of small radioisotope power system (RPS) technology will enable opportunities for scientifically valuable missions which were previously unachievable (Mondt, 2000; Johnson, 2002). Batteries based on this technology will allow modest vehicles to operate in areas of minimal to non-existent insolation over long periods of time, in unilluminated hemispheres of terrestrial planets, or in or on targets beyond the asteroid belt. Such vehicles would include subsatellites and small rovers with reasonable payloads with power requirements in the tens of watts to tens of milliwatts range, equipped with supplemental systems for peak load operations. This power generation technology is particularly applicable to ANTS architecture applications, which are extremely efficient in operation, and thus have modest power and minimal weight requirements (Curtis et al, 2000; Clark et al, 2004a, 2004b, 2004c).

THE ANTS CONCEPT

The Autonomous NanoTechnology Swarm (ANTS) Architecture is based on Addressable Reconfigurable Technology (ART) adaptable for the full spectrum of activities in remote/hazardous environments such as space. The architecture is based on the tetrahedron as a building block, with edges consisting of struts deployed from nodes at apices. Tetrahedra are combined to form space-filling networks of nodes and struts. ANTS systems based on available electromechanical technology (@ 1kg/m2) could support human crews on the lunar surface within the next 10 to 15 years. A prototype of such a system is currently under construction. ANTS systems based on NEMs (Super Miniaturized ART or SMART) technology (@ >5g/m2) could perform fully autonomous surveys and operations beyond the reach of human crews two or more decades from now. Basic structural components are highly modular, addressable arrays of robust nodes, from which highly reconfigurable struts, acting as supports or tethers, or surfaces, are efficiently reversibly deployed/stowed, transforming the structures as required for all functions in space and on the ground. Reusability of ANTS components thus limits the need for resources, along with cost, mass, size, bandwidth, power, and, of course, expendables. ANTS systems have already been conceptualized for three applications spanning three decades (LARA: Lander Amorphous Rover Antenna; PAM: Prospecting Asteroid Mission; SARA: Saturn Autonomous Ring Array) (Clark et al, 2004b, 2004c, 2004d) where solar illumination could be minimal, including high latitude or polar regions, below ground, or beyond 3 AU. Thus, the use of small radioisotope power systems is particularly appealing.

ANTS APPLICATIONS

Near Term: The LARA Applications

Lander Amorphous Rover Antenna (LARA) (Figure 1, Table 1) is a near term EMS level mission concept applicable to autonomous or human/robotic exploration of planetary surfaces. (Clark et al, 2004b) (See LARA: The Movie at the official ANTS website). The LARA vehicle transforms itself to follow the required function (Table 2). These functions could include transmitting or receiving information, carrying a payload such as a sample collector/analyzer, or providing of a shelter or storage facility. These functions could be performed autonomously, or through interface with crew either in situ or remote.

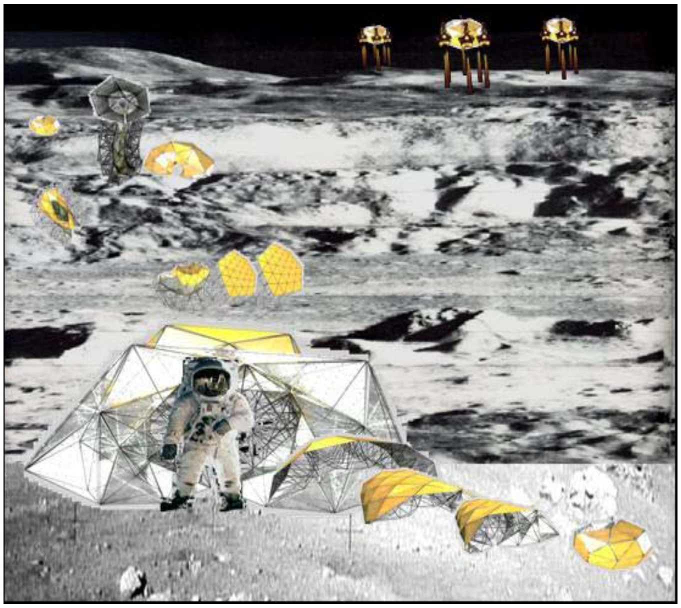

FIGURE 1. LARA Mission Components, including landers on top, antennae in crater and astronaut shelter in foreground. Amorphous rover in various contortions stretching from back to front of scene

TABLE 1. LARA Characteristics and Requirements

Characteristic	Requirement
Launch Date:	2010-1015
Duration and Location:	Months or even years, 1.0 – 2.0 AU
Environment:	low G, adequate illumination, planetary surface
Spacecraft Mass, Materials:	10-50 kg, 10-100 g/cm^2
Engineering:	3 axis stabilized spacecraft, Tet walker surface, EMS components
Power system:	Solar Cells or Nuclear Batteries
Power system mass:	5 kg
Power requirement:	100 Watts
Torque at node:	50 kg
Propulsion system:	Space Chemical Mini-thruster/Ground Node and Strut
Operation Notes:	
Autonomous or through link with crew, Individual or collective operation, Cover tens of kilometers per day	
No single point failure, Robust to minor faults and major failure	

LARA tetrahedral frame components are electromechanical structures forming a network of struts which are reversibly deployable/stowable from EMS or MEMS nodes equipped for wireless operation. Payload and subsystem components are attached ‘inside’ the tetrahedral network, between layers of nodes, and thus protected. After manufacture, the frame could be reduced to a minimum strut extension size for shipping to a launch or deployment size. Nodes and Struts make up the frame and would be used for all functions The greatest number would be structural nodes which deploy/stow flexible struts based on one of several design schemes, ranging from a) telescoping struts extended or contracted by various mechanisms, including cables or springs, and b) double 'tape measure' device which links or unlinks the oppositely wound flexible rolled sheets. Rolls with opposite orientations develop great tensile strength when combined. Similar nodes could be used as attachment points for payloads, such as instruments (Clark et al, 2004a, 2004c; Curtis et al, 2004). An outer covering for the LARA craft (Clark et al, 2004a, 2004c) could be provided by specially designed nodes which would deploy carbon fiber composite 'memory' sheets with relatively low aerial density using Polymer/Carbon Nanotube Composite (PNC) springs and structural elements (ESLI website, PF 2004 website).

TABLE 2. LARA Forms Follow Function

Function	Form
Lander/Space Mobility:	Flattened with mini-thruster nodes
Amorphous Rover/Surface Mobility	Size for terrain scale, Gait for roughness, Shape for required movement: amoeboid for very rough, slither for steep traction, spheroid for smooth
Payload Carrier/Transportation	Same as rover
Antenna/Communication	Beacon/Bowl shape, single or arrayed
Shelter Provider	Extended cover over natural enclosures or hut-like in open
Specialized Task/Reconnaissance	Form stable platform for measuring or collecting operation

The LARA vehicle transforms itself as necessary to perform required functions (Figure 1, Table 2). The LARA Lander is formed by flattening the tetrahedral network so that mini chemical propulsion thrusters are effectively attached around the periphery. The LARA Amorphous Rover is created by continuous contraction and extension of struts in a way that optimizes the efficiency of movement across a terrain, and thus depends on the variability and scale of the relief and roughness in a given terrain. A payload could be placed within active or passive nodes on the 'inside' of the continuous tetrahedral structure. LARA vehicle is transformed into an Antenna whenever significant bandwidth communication is required. The tetrahedral network itself, bowl-shaped above with a broader base below, would be equipped to receive and transmit data. The same vehicle could be transformed into a shelter for crew or equipment by creating a tent-like structure. A key to performance of such a system is efficiently designed mechanisms based on opposing force principles, a crucial design feature in biological locomotion (Clark et al, 2004a).

Ultimately, with interconnecting, space filling tetrahedral material, very high degree of freedom movement emerges, more 'natural' than wheels, effectively allowing 'flow' across a surface and into a particular morphological form (Figure 2). The ability to control the timing and extent of strut deployment allows control of the scale and gait of the rover. A single tetrahedron, like the prototype we are currently building, rocks from side to side as it moves forward. Put an additional strut at each node and divide that tetrahedron into 4 tetrahedron (like the 4Tet we are proposing to field test), and an inner space is created for attachment of a payload. In a 12Tet model, motion is far more continuous. Clear amoeboid-like movement can be observed for very rough surface, more 'natural' than wheels, effectively allowing 'flow' across a surface or into a particular morphological form. For a very smooth surface, or for 'storage' the minimum surface area spheroid, rolling across the ground, could be effective. Uphill climb or slipping through narrow openings could require a slithering snakelike morphology. When surmounting obstacles, the rover could either change its scale, growing in size, or use a climbing motion, pulling itself over using facets on the obstacle itself as 'toe holds'.

A wide variety of mission scenarios could be employed in using LARA systems. Deployment and use could be either entirely robotic and autonomous, or through a human interface. The human interface could be remote in near real time, through telepresence, or in situ, acting as extensions for a human crew active on the surface. LARA craft could first land payloads autonomously, then form roving 'advance reconnaissance teams', mapping, gathering and analyzing samples and images of the terrain for use in site selection. Such analysis of samples, to determine elemental, mineral, water, biogenic material, or rock abundances, or terrains, to determine stratigraphy, morphology, age, would inevitable lead to the identification of sites with important clues on the origin of planets, the solar system, or life itself. Whenever necessary, rovers could form antenna to transmit findings and receive instructions. Such systems could also be used to provide shelter, by creating, seeking, and enclosing natural semi-enclosed formations. LARA craft could also find, collect, or mine materials of use in exploration or construction. A network of LARA craft could be used to form a temporary or permanent communication, navigation, or observatory facilities.

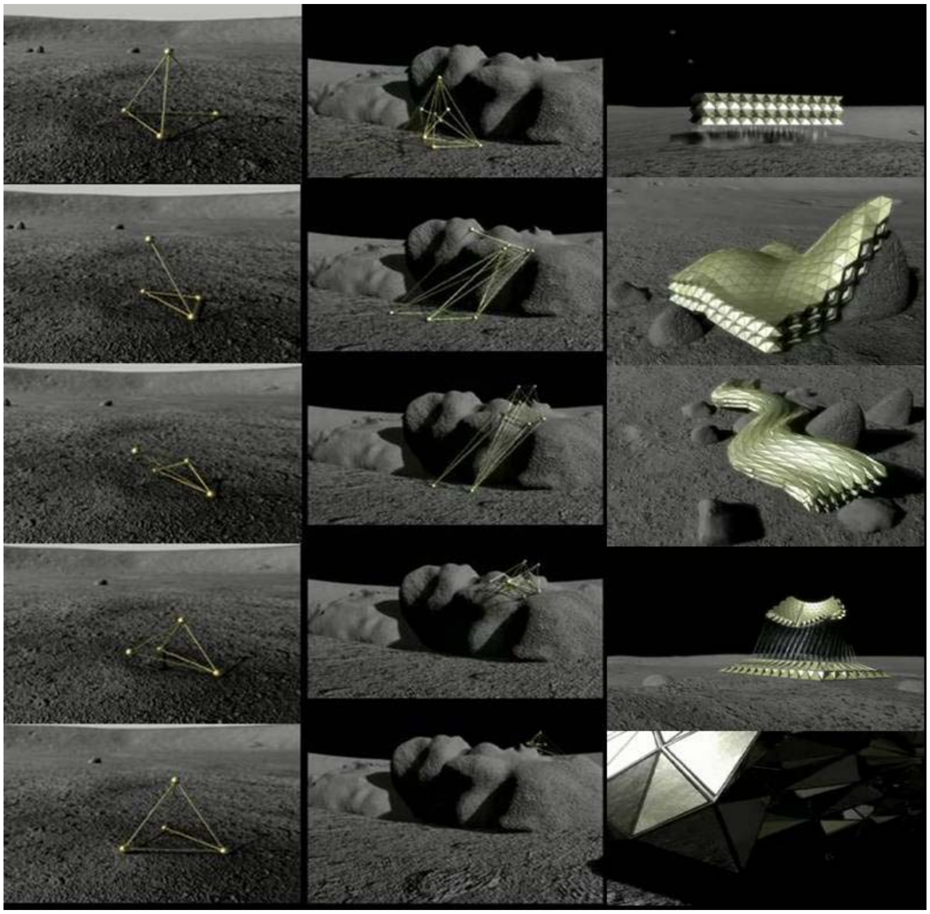

FIGURE 2. Tetrahedral Walker movement by continuous strut extension and contraction, evolving from simple, punctuated movement of single tetrahedron on left, to more complex, smoother climbing of 12Tetrahedron in middle, to high degree of freedom 'flow' of a continuous tetrahedral network on right. 12Tet W alker or above is proposed for LARA.

Near Future: The PAM Application

The Prospecting Asteroid Mission (PAM) application, the first application considered for ANTS architecture (Figure 3, Table 3) requires MEMS (Miniaturized ART or MART) to NEMS (SMART) level application of the ANTS architecture. This technology should be available in about two decades, in keeping with long-term Exploration Initiative plan for robotic exploration of the next target, mainbelt asteroids, beyond Mars.

Whereas the traditional missions excel at exploring larger asteroids sequentially, the PAM concept is designed for the systematic studying of an entire population of objects (Curtis et al, 2000, 2004; Clark et al, 2004c). The ANTS approach involves the use not of a smart spacecraft with 'drones' but of a totally autonomous truly distributed intelligent network of sensors, or sciencecraft, with solar sails for propulsion, and thus minimal requirement for expendables (See also ANTS: The Movie at the official ANTS website). Sciencecraft each have specialized instrument capability (e.g., advanced computing, imaging, spectrometry, etc.) and heuristic systems that are both adaptable and evolvable. Subswarms of sciencecraft can operate autonomously, allowing the optimal gathering of complimentary measurements for selected targets. Many subswarms would operate simultaneously within a broadly defined framework of goals to select targets from among available candidate asteroids.

PAM is a 1000-member swarm of picoclass (1 kg) autonomous sciencecraft based on carbon-based NEMS technology and utilizing Super Miniaturized Addressable Reconfigurable Technology (SMART) (Rilee et al, 2004a, 2004b). The basic design elements are self-similar low-power, low-weight, addressable, reconfigurable components and systems capable of operating as fully autonomous, yet adaptable units as called for by swarm demands and environmental needs. Craft use highly configurable solar sails capable of autonomous attitude control, a highly maneuverable, no expendables propulsion system well suited to this application. The swarm would be composed of 10 science specialist classes (approximately 100 members of each class), identical except for one specialty 'instrument'. Classes include Leader/Messengers (CPU/Communication enhanced), and sciencecraft including imagers, various spectrometers, altimeters, radio science, and magnetometers. The swarm would be divided into 10 to 20 subswarms with approximately equal numbers of each class in each subswarm. Within each subswarm, each class would operate autonomously at an asteroid target, because orbital configuration and viewing strategy for the classes are highly variable and depend on the requirements of the class 'instrument'. 10 to 20 subswarms would operate concurrently. Target observation times would be on the order of one month. Typical distances of hundreds of thousands of kilometers between kilometer-size asteroids would allow detection (by imagers) and selection of the next target even before departure from a given target, and travel to that target on the order of weeks. Thus, tens or even hundreds of asteroids could be explored during a the anticipated 5 year traverse of the asteroid belt.

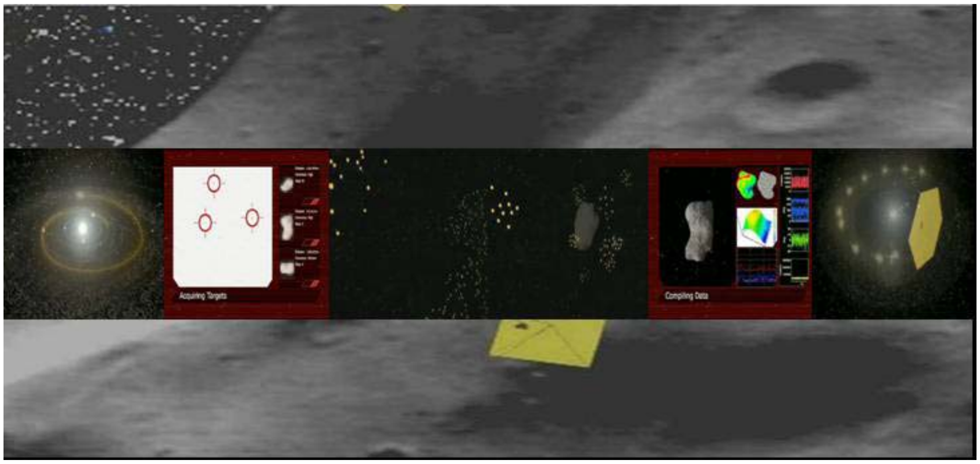

FIGURE 3. PAM Mission Scenario, including from left to right across, Solar Sail trip to asteroid belt, target of opportunity selection with imagers, separation of subswarms, virtual team operation of subswarm at target, target characterization, return of Messenger with data from multiple target encounter.

TABLE 3. PAM Requirements

Characteristic	Requirement
Launch Date	2025
Duration and Location	10 years from 1.0 to 3.5 AU
Environment	low G, high target density, solar illumination
Vehicle Mass and Aerial Density	1 kg, 1 to 5 g/cm^2
Power system, mass requirement	Nuclear batteries, 0.25 kg, 100-300 mWatts
Propulsion system and mass	Solar Sails, 0.5 kg, 10^3 change in effective sail area
Engineering	3-axis stable spacecraft, MEMS components
Organization	1000 spacecraft, 10 specialist classes, 10-20 subswarms, simultaneous operation
Operational notes	Deep space with no direct link to Earth, individual Messengers return data
	Full instrument suite deployed 1 month/asteroid optimal science
	Concurrent operations ~10 asteroids, >50 targets per year
	No single point failure, robust to failure, Optimized in spite of 10% attrition/year

Each class (Table 4) would employ different strategies in the use of components and subsystems during the active part of PAM (Curtis et al, 2000, 2004). Leader/Communicators would be enhanced for high level communication and processing functions which would occur at some distance from a target to keep the subswarm in view, and wouldn't require the fine adjustment in attitude control needed by sciencecraft requiring measurements closer to the target. Science operations could vary substantially from instrument to instrument. Visible imaging spectrometers would be used extensively during cruise to detect potential targets, and then refine knowledge of the location and nature of the target on the way to the selected target. Spectrometers (X-ray, Near IR, Gamma-ray, Neutron) would acquire compositional data. Altimeters and radio science packages would provide dynamic models. The required viewing conditions for each instrument vary considerably, and might well affect the choice of targets. Optimal operation is easily accommodated in either near terminator orbits or darkside stationkeeping for the majority of instruments. However, the Near Infrared and X-ray spectrometers, crucial for determining composition, are the most difficult instruments to accommodate, requiring as much close proximity, illumination and direct (subsolar point, nadir pointing) geometry as possible. Real 'stationkeeping' would be virtually impossible to achieve on the sunlit side of an asteroid due to combined photonic and gravitational forces. On the other hand, an equatorial orbit of a string of instruments in a given spectrometer class would be possible, provided the effective sail area can be decreased by a factor of a thousand, something which should be very achievable to a 10,000 partially deployable facets. PAM spacecraft would study a selected target by forming 'Virtual Teams' (Clark and Iyengar, 2002; Clark et al, 2004c). 'Virtual Instrument Teams' would be formed from those within each class, to optimize data acquisition. Another strategy would involve providing a comprehensive set of measurements to solve a particular scientific problem, by forming 'Virtual Experiment Teams' of multiple sensors (Table 4).

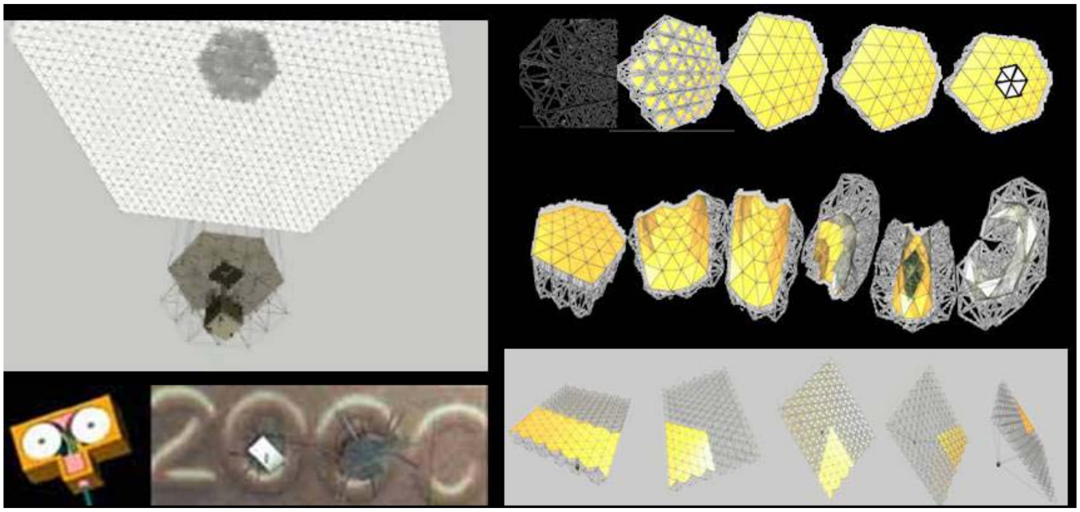

FIGURE 4. PAM Components and Behaviors. Left top, model Pam Spacecraft showing sail on sail frame in background with instrument bearing space platform in foreground. Left bottom, model node releasing/spooling mechanism for struts and relative size of nodes on 2000 penny. On right, Sail configuration, from top to bottom, for self repairing by regrowing struts, changing shape, and changing sail deployment patterns for attitude control.

TABLE 4. PAM Virtual Teams within Subswarm

Class/Instrument	**Role/Requirement**
Leader/Messenger	Processing, Strategy, Communication/Out of way yet within range
Workers	Data Gathering
Imager	Target Detection, 3D Model, Photogeology/Some illumination
Visible/IR Spectrometer	Mineral Abundances/Close, Nadir, Full sun
X-ray Spectrometer	Major Elements/Close, Nadir, Full sun
Gamma-ray/Neutron Spectrometer	Heavy Element, Volatiles/Close, Nadir, Fill FOV
Altimeter (Ranging)	Shape, 3D Model,Topography, Morphology/Nadir Pointing
Radio Science/Magnetometer	Gravity and Magnetic Fields, Interior, 3D Model/Over poles
Radio Sounder/IR Radiometer	Regolith Characteristics/Close, Nadir
Neutral Mass Spectrometer	Volatile characterization/Close, Full sun

Using this approach to survey the main asteroid belt, a population consisting of millions of small, remote bodies, is most cost/effective in terms of science and resource exploration. Although a large fraction of solar system objects are asteroids, relatively little data is available for them because the vast majority of them are too small to be observed except as single point measurements except in close proximity (Clark et al, 2004c). Within the asteroid population are remnant planetesimals dating back to formation of solar system, the most primitive, unmodified material known. These small bodies originated in the transitional region between inner (rocky) and outer (solidified gases) solar system, the asteroid belt. Determination of the systematic distribution of physical, compositional, and dynamic properties within the asteroid population is crucial in the understanding of the solar system formation. In addition, there has been interest in asteroids as sources of exploitable resources. Far more reconnaissance is required before a true assessment is achieved. Such an assessment could focus on a systematic survey.

PAM spacecraft (Figure 4) components are nanotechnology-based SMART structures forming tetrahedral networks of nano-struts, tethers, or sheets which are reversibly deployable/stowable from MEMS or NEMS nodes equipped for wireless operation (Curtis et al, 2004; Clark et al, 2004c). Such mechanisms require low mass, low wattage power systems. Most nodes are used to deploy/stow struts using a mechanism which links or unlinks oppositely wound tubules (Figure 4). Tubules with opposite orientations develop great tensile strength when combined, or vice versa, as in fact, to a somewhat lesser extent, two such EMS tape measures would. Similar nodes are also used to deploy/stow tethers or as attachment points for nanocomponent subsystems, such as instruments. Nodes could also be used to deploy sheets consisting of carbon-based materials, including nanotubules, or even highly compressible carbon fiber composite sheets with 'memory' and relatively low aerial density (5 g/cm^2) (ESLI website). Such nodes would be used in the 100 square meter solar sail which would consist of 10,000 100 sq cm triangular facets supported by a space frame consisting of two layers of interconnected nodes, forming a lightweight 3D truss structure. Very effective solar sail navigation and attitude control could potentially be achieved by a 10,000 reversibly deployable component sail on a highly reshapable frame seen in Figure 4 (See Sail Animations at official ANTS website). Attached to the space frame by a network of long tethers would be a small space platform consisting of three layers of interconnected nodes, making a more robust framework to which all subsystems are tethered. The extent and direction of all tether deployment can be controlled. This design allows the propulsion system to operate completely independently of all other subsystems.

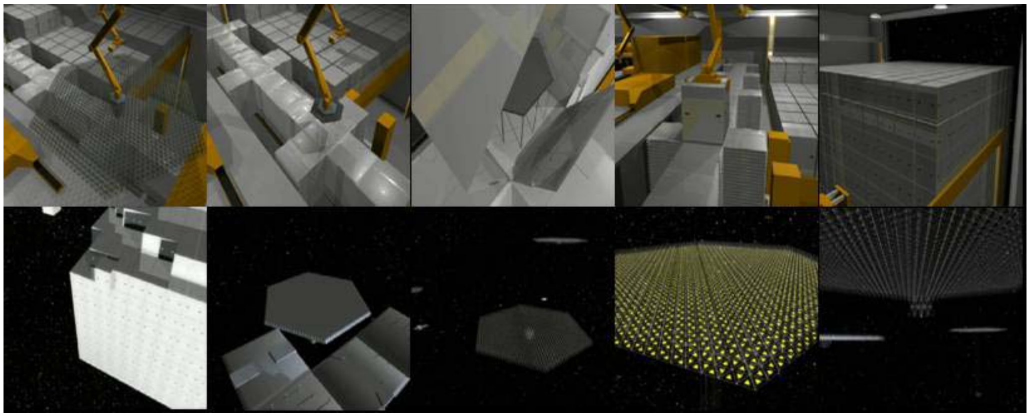

FIGURE 5. ANTS architecture for Pam Manufacturing (top) and deployment (bottom) sequences.

In fact, the spacecraft assembly process employs ANTS architecture and is part of the PAM mission concept. at the MEMS level or higher (Curtis et al, 2004; Clark et al, 2004c) (Figure 5) (See also Manufacturing Movie at the official ANTS website). The assembly facility would probably take advantage of readily available solar power near the Earth rather than nuclear power. The entire spacecraft is initially assembled elsewhere and stowed (predeployment) in a 100 cm^3 SMART box, allowing for a much smaller pre-deployment size and minimizing 'cargo' requirements during travel from the assembly to deployment sites. The box is equipped with nano communication and propulsion devices, so it can travel and communicate with the swarm for short distances in space. Once the box delivers and releases the spacecraft, it can form a flat sheet and return itself for reuse. 1000 such boxed craft are initially packaged in a 1 cubic meter SMART cube at the assembly site, for delivery to the deployment site in deep space. The facility, which could be located on the Earth or in a low G environment, is equipped to generate tetrahedral networks of any size or shape, using ANTS strut-deploying, layer-deploying, and instrument subsystem deploying nodes.

Future: The SARA Application

The Saturn Autonomous Ring Array (SARA) mission concept (Curtis et al, 2003; Clark et al, 2004d) is a suggested application for the Autonomous Nano-Technology Swarm (ANTS) architecture (Figure 6, Table 5). The SARA concept includes assembly of self-packaging, self-deploying, self-similar components at facilities built on ANTS architecture as described for the ANTS Prospecting Asteroid Mission (PAM). Transportation requirements and capabilities are being considered as part of a propulsion system trade-off study for SARA, which combines navigating in low gravity with maneuvering in the high gravity regime of Saturn's rings, demanding hybrid propulsion. The ANTS paradigm applies well to exploration of high surface area and/or multi-body targets by minimizing costs and maximizing effectiveness of survey operations. Systems designed with ANTS architecture are built from potentially very large numbers of highly autonomous, yet socially interactive, specialists, in approximately ten specialist classes. The current mission plans calls for a SMART solar sail 'hive' to ferry tethered individual nanocraft out to the far edge of the asteroid belt. At that distance, maneuvering individual craft with solar sails is not feasible. A SMART propulsion system considered has been mini-thermal nuclear, capable of self-configuring for control of thrust by varying the temperature and criticality of the fuel element through changing shape (Figure 6). Such a system should also be capable of providing adequate power for other operations.

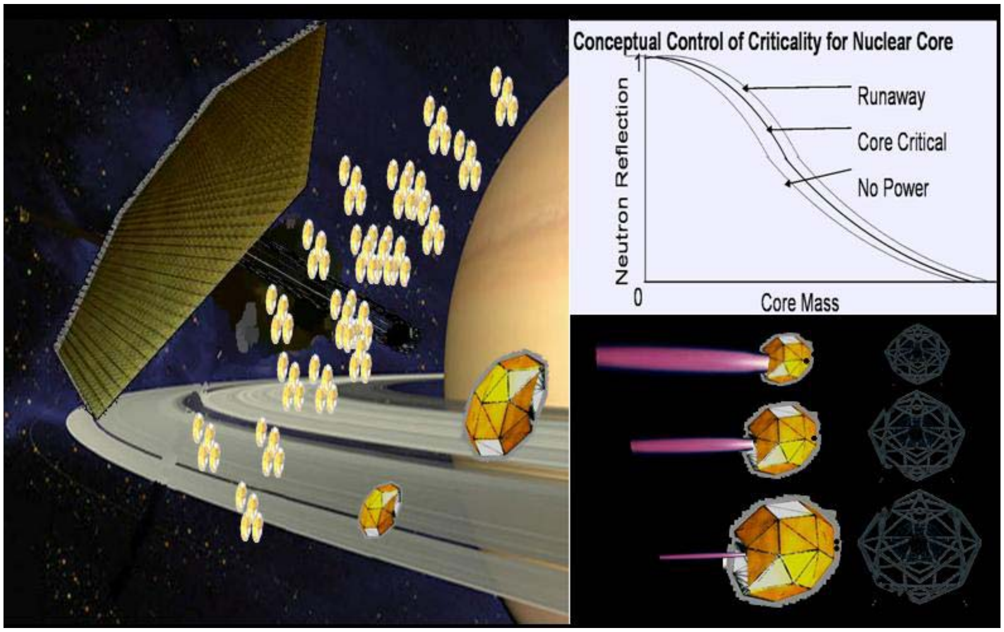

FIGURE 6: SARA Mission Scenario: On left, Mission concept of individual craft deploying from Hive ship. On right, concept of configurable nuclear propulsion system, with thrust directly related to criticality and inversely related to propulsion system volume.

TABLE 5. SARA Requirements

Characteristic	**Requirement**
Launch Date	2035
Duration and Location	15 years from 1.0 to 5 AU
Environment	High G, high target density, adequate to minimal solar illumination
Vehicle Mass and Aerial Density	Carrier 2000 kg, Individuals 1kg, 1 g/cm^2
Power system, mass requirement	Nuclear batteries, Individuals 0.25 kg, 100-300 mWatts
Propulsion system and mass	Carrier: Solar Sails, 500 kg, Individuals: Nuclear propulsion, 0.5 kg
Engineering	3-axis stable spacecraft, NEMS components
Attitude control	Carrier change in effective sail area, Individual change nuclear source criticality
Organization	1000 spacecraft, 10 specialist classes, 10-20 subswarms, simultaneous operation
Operational notes	Deep space with no direct link to Earth, individual Messengers return data 100's in situ observations ring particles, 1000's ring measurements per day No single point failure, robust to failure, Optimized in spite of 10% attrition/year Special challenge: rapid reconfiguration of nuclear propulsion system

SARA would perform in situ observations of Saturn's rings, both from the individual particle and collective plasma standpoints. This population is of great interest from the standpoint of solar system origin However, such in situ observations of spacecraft-scale targets with high density distribution in a large gravity well represents a challenge unachievable by conventional (direct control of single spacecraft from Earth) or even evolutionary (direct control of multiple spacecraft from Earth surrogate) mission designs. Each nanocraft would be on the order of kilograms in mass, and thus require gossamer structures for all subsystems. Onboard power requirements, met by small nuclear batteries, would be constrained to milliwatts. The hundreds or even thousands of individual specialists include Workers, the vast majority, that acquire scientific measurements, as well as Messenger/Rulers that provide communication and coordination.

TABLE 6. SARA Science Activities

Specialist	Measurement	Mode of Study
Particle/Plasma	Electrodynamics: Plasma, particles	Particle populations
Search Coil	Electrodynamics: Waves	View from outside of ring plane
Magnetometer/E-Field	Electrodynamics: Fields	
UV/Visible Imaging	Ring thickness, density	
Mid to Thermal IR	Reflectivity, size, volatility distribution	
Radio Sounder	Reflectivity and Emissivity distribution	
APX, Laser ablation MS	Refractory element abundances	Individual particles
UV/Visible/IR Spectrometer	Mineral Assemblages	Collect thru ring
Mass Spectrometer	Volatiles, organics	

Potential science goals for SARA (Table 6).provide the context for this discussion. The high density distribution of particles on the scale of particles size, combines with the high intensity gravity and magnetic field environment to produce dynamic plasmas. Although composition is essentially cometary with high volatile abundances, great variations remain in the dust/gas ratio and the composition of dust component for individual particles. Thus, a broad spectrum of in situ instruments, with very different requirements, are required, with specialists developing strategies to obtain in situ measurements as individuals, teams, in a highly dynamic environment, as appropriate. Plasma, particle, wave, and field detectors will probably fly just above or below the ring plane to observe the result of particle interactions. Imagers and spectrometers will need to develop a strategy for serial rendezvous with individual particles through the ring. The high density of particles, some nanocraft-scale, makes collision avoidance a problem that must also be solved autonomously in situ. The numbers and distances of these particles, as well as anticipated high attrition rate, require large numbers of each specialist class. Allowing for a high attrition over the couple of years required for a survey and initial size of 100/subswarm, ten to twenty of such subswarms should be able to characterization of thousands of particles and ring features over the course of the traverse of the rings.

POWER REQUIREMENTS FOR ANTS APPLICATIONS

Power system requirements (Table 7) would range from tens of Watts for near term ART applications, such as a lunar or Mars Lander Amorphous Rover Antenna (LARA), to hundreds of mWatts for more advanced SMART applications. Are 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 tens of watts per kilogram, even at the current level of development (NASA nuclear power website, 2004).

TABLE 7. ANTS Architecture Progression in Power Requirements

Application	Time	System	Power	Mass Power Subsystem/System
Lander Amorphous Rover Antenna	2015	EMS	<100 Watts	<10 kg/50 kg
Prospecting Asteroid Mission	2025	MEMS (10^{-2} EMS)	<1 Watts	<0.5 kg/1 kg
Saturn Autonomous Ring Array	2035	NEMS (10^{-4} EMS)	<100mWatts	0.1 kg/1 kg

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).Tiny MEMS batteries, long-lasting and with efficient thermoelectric 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. For PAM and SARA, the smaller power generation requirement met by EMS RHU-based systems is not well correlated with required mass.

CONCLUSIONS

The current capability of generating hundreds of milliwatts per kilogram puts it ‘within the ballpark’ of ANTS requirements at the current ART/EMS level of development. Anticipated improvement in the thermal output and relatively inefficient thermoelectric conversion rate by at least half an order of magnitude are highly desirable and necessary for more advanced ANTS applications. The efficiency of conversion in the MEMS nuclear batteries under development (Johnson, 2002) could potentially meet this requirement. Improvements in the current power output to weight ratio by a factor of ten would be ideal for future ANTS applications.

NOMENCLATURE

ANTS = Autonomous NanoTechnology Swarm Space Architecture
ART = Autonomous Reconfigurable Technology (EMS)
MART = Miniaturized ART (MEMS)
SMART = Super Miniaturized ART (NEMS)
EMS = Electro Mechanical Systems
MEMS = Micro Electro Mechanical Systems
NEMS = Nano Electro Mechanical Systems
PAM = ANTS Prospecting Asteroid Mission Concept
LARA = ANTS Lander Amorphous Rover Antenna Mission Concept
SARA = ANTS Saturn Autonomous Ring Array Mission Concept
TetWalker = 1, 4, 12, or many tetrahedra system used as ANTS rover
Node&Strut= deployment mechanism for ANTS structures: nodes apices, struts sides of tetrahedra

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