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PAM: BIOLOGICALLY INSPIRED ENGINEERING AND EXPLORATION MISSION CONCEPT, COMPONENTS, AND REQUIREMENTS FOR ASTEROID POPULATION SURVEY

P.E. Clark
Location: Code 695, NASA/GSFC, Greenbelt, MD 20771 USA
Affiliation: L3 Communications, GSI., 3750 Centerview Drive, Chantilly, VA 20151 USA
Pamela.Clark@gsfc.nasa.gov

M.L. Rilee
L3 Communications, GSI, 3750 Centerview Drive, Chantilly, VA 20151 USA
Michael.L.Rilee.1@gsfc.nasa.gov

S.A. Curtis[1], C.Y. Cheung[1], W. Truszkowski[2], G. Marr[3]
[1]Code 695, [2]Code 588, [3]Code 595, NASA/GSFC, Greenbelt, MD 20771 USA
u5sac@lepvax.gsfc.nasa.gov

M. Rudisill
MS 328, NASA/LARC, Hampton, VA 23681 USA
m.rudisill@pop.larc.nasa.gov

ABSTRACT

PAM, the Prospecting Asteroid Mission, is an application of the Autonomous NanoTechnology Swarm (ANTS) mission architecture. Here, we analyze the nature and use of spacecraft structures required for PAM, an ANTS mission application for a low gravity, low density multi-body target population survey. PAM consists of 1000 picocraft organized into 10 specialist classes with highly maneuverable/configurable solar sails, a no-expendables propulsion system suitable for this application. The basic design elements are self-similar low-power, low-weight, addressable components and individual systems capable of operating as fully autonomous, yet addressable, adaptable units as called for by swarm demands and environmental needs. With 10 to 20 subswarms operating simultaneously, hundreds of asteroids could be explored during a mission traverse of an asteroid belt. We discuss conceptual and physical models of spacecraft and components, now achieving realization due to the construction of the first ANTS prototype with fully addressable nodes capable of reversible deployment of struts with required rigidity. The PAM concept will be enabled through incremental advances in technology leading to the availability of NEMS systems and allowing construction of space-adapted gossamer structures, including tethers, struts to provide structural frameworks, and multi-layer surfaces for the sail or instruments.

CONTEXT OF THE ANTS APPROACH

The ANTS approach to exploration [1,2,3,4,5] discussed here is directly relevant to the NASA's Exploration Initiative goals of robotic exploration of the solar system emphasizing origins, evolution, and fate (future) of the physical universe on scales ranging from planetary to cosmic [6,7]. The mission application, Prospecting Asteroid Mission, is directly in line with the new Initiative science agenda, where the focus is on exploring small bodies to search for evidence of life [6,7]. Study of the main asteroid belt, a dynamic small body population which includes the oldest remnants of the early solar system, will provide insight on origin and evolution of the solar system, the dynamic processes and components, physical, chemical, and biological, which shaped it.

The PAM concept would result in direct use of enabled technologies and further development of enabling technologies identified in the Initiative [6,7] as well: a) self-repairing autonomous systems and robotics, b) formation flying capability, including capability for responsive attitude control in close range, c) low-cost close-range communication and tracking capability, d) advanced power and propulsion, e) strong, durable, low aerial density structures, and f) low power and mass sensors.

In this paper, we will describe the conceptual framework, design, and models, for PAM hardware and its operation, based on ongoing work. We will identify requirements and essential features, and assess capabilities the ANTS architecture to provide a comprehensive asteroid survey (**Tables 1 and 2**).

What is the nature of the contribution to solar system exploration that multi-spacecraft missions can provide, as compared to the currently utilized single spacecraft missions or near Earth observation programs [8a, 8b]? Ground based or even Earth orbiting observatories, even with projected improvements in sensitivity, will be not be able to provide measurements for more remote, smaller, or darker asteroids, which must be observed by spacecraft. We must have observations from these more-difficult-to-observe objects in order to understand the formation and evolution of the asteroid belt. Single spacecraft missions are useful in providing extensive documentation for one to a handful of previously observed asteroids, but are not designed for surveying a wide range of unexplored asteroids, an application for which multi-spacecraft missions are ideally suited. Multi-sensor spacecraft have flown before (NEAR) or are about to fly (DAWN) to solar system bodies such as asteroids. For optimal operations, essential sensors, such as imagers, spectrometers, and altimeters, have very different requirements for a) illumination conditions, b) pointing geometry, c) distance to target, and d) orbital configuration. This translates into constant compromise to meet sensor requirements and results in less efficient collection of high quality data, a problem that is magnified when a small, irregularly shaped, low gravity object, such as an asteroid, is being explored.

The ANTS/PAM [1,2,3,4,5] calls for clusters of single sensor spacecraft, working individually or as teams, to meet these challenges (**Table 3**). In this way, individual instrument operational and overall science requirements can be met, and optimized, simultaneously, reducing the time required to obtain comprehensive observations as well as increasing the quality of those observations, for each target.

THE ANTS CONCEPT

ANTS SMART (Super Miniaturized Addressable Reconfigurable Technology) architecture was initiated at Goddard Space Flight Center (GSFC) to develop a new kind

Table 1: Asteroid Mission Challenges
Large number targets or extensive area.
Wide range of instruments and operational requirements.
Inaccessible and/or remote terrain.
Large Delta V requirement for 'fully loaded' spacecraft.

Table 2: Asteroid Survey Requirements
Optimal science operations at each object and concurrent operations at many objects.
Ongoing evolution of tactics and strategies as a function of object characteristics.
No single point failure, robust to minor and catastrophic loss.
Highly autonomous constellation of specialized workers.

Table 3: ANTS Solution
An insect colony analog: (Worker, Messenger, Leader).
Large number of very small spacecraft.
Very specialized spacecraft.
Solar sails for Delta V.
Highly autonomous operation

of structural material capable of changing its form to optimize its function, adapt to a new environmental demand, or repair itself (4,5). The basic unit of the structure is a tetrahedron consisting of nodes interconnected with struts that can be reversibly deployed or stowed. 3D networks are formed from interconnecting reconfigurable tetrahedra, making structures which are scalable, massively parallel system that can be fabricated presently using macroscopic electromechanical systems (EMS)-***ART***, and in the future Micro-EMS (MEMS)-***MART*** or nano-EMS (NEMS)-***SMART*** (with aerial densities of 100, 5, and 1 g/cm^2, respectively) as enabled by technology advancement. This highly integrated 3-dimensional mesh of actuators and structural elements is composed of nodes that are addressable as are pixels in an LCD screen. The full functionality of such a system requires fully autonomous operation, and will ultimately be realized through a neural basis function (NBF) which possesses bilevel intelligence at every level, from subsystem to swarm. Such capability allows both autonomic operation at the actuator level in response to an environment demand and heuristic operation for decision making among various options or in response to an external request. The ANTS architecture for PAM will be discussed here. The development and basis of SMART material and the NBF is discussed elsewhere (9a,9b,9c).

PAM: APPLICATION OF ANTS TO AN ASTEROID SURVEY MISSION

The PAM application, summarized in **Table 4**, requires MART to SMART level application of the ANTS architecture, which 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.

Major milestones in the exploration of small bodies, the Near Earth Asteroid Rendezvous (NEAR) mission to asteroid 433 Eros and DS1 mission to comet Borelly, have already occurred in this decade. NEAR (10), the first mission to demonstrate the capability to remain in long-term stable orbit around an asteroid to perform a mapping mission, has provided a rich context for understanding the characteristic complexity of an asteroid and demanding requirements for mission

Table 4: PAM Characteristics

* “target of opportunity” asteroid survey
* search for resources, evidence for life
* 1000 spacecraft swarm
* 10 specialist classes with common bus
* 10 to 20 subswarms concurrently operating
* subswarm@1 month/asteroid, 5 asteroids/year
* 100’s of asteroids in 5 year traverse of belt
* Operation at low target density, low G
* Propulsion: solar sails
* Power: nuclear batteries

maneuvering and data-taking operations. DS1 (11) demonstrated the feasibility of a low thrust propulsion system for small body encounter as well as the capability for automated optical navigation based avoidance of debris dynamically generated around an active comet. DAWN (12) is about to harness the gains made by both of those mission, by using ion propulsion to map two large asteroids representing extremes in asteroid evolution, Vesta and Ceres, from orbit.

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 [1,2,3,4,5]. 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 (**Figure 1**) (See also ANTS: The Movie at the official ANTS website [1]). 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.

Figure 1: Snapshots of PAM simulation, clockwise from top left, trajectory to asteroid belt, selecting target, virtual teams viewing asteroid, leader analysis of asteroid.

We first considered the Autonomous Nano-Technology Swarm (ANTS) architecture for a future application, the PAM concept: a 1000-member swarm of picoclass (1 kg) autonomous sciencecraft based on carbon-based NEMS technology and utilizing Super Miniaturized Addressable Reconfigurable Technology (SMART) (3) [13]. 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), 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

Table 5: Knowledge of mainbelt asteroids

Type of Observation	now	2025	Primary Source
Orbits/Magnitude	~105	106	Ground-based Telescopes
Light curves	~5,000	50,000	Ground-based Telescopes
Visible spectra	~2,500	25,000	Ground-based Telescopes
IR measurements	~2,500	25,000	IRAS
Surface properties	~100	1,000	Ground-based Telescopes
Shape models	~10	100	Spacecraft, HST Ground-based Radar

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.

SCIENCE RATIONALE FOR PAM

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 (**Table 5**) [8a,8b]. 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 systematic survey questions:

1) What is the true distribution of elements, minerals, rock types, parent bodies from early solar system, and potential resources? Where are the olivine-dominated samples of parent body ‘mantle’ and chondrites which, according to models and the meteorite collection, should dominate?

2) What is the nature of regolith formation and modification in space (Space Weathering) and its potential use for construction?

3) What is the nature of the relationship between dynamical and compositional properties in the small body population, and, by implication, in the early solar system?

ANTS/PAM DESIGN FEATURES

PAM **spacecraft (Figure 2)** 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 and equipped for wireless operation [13]. The design is optimized for both pre-and post-launch operation.

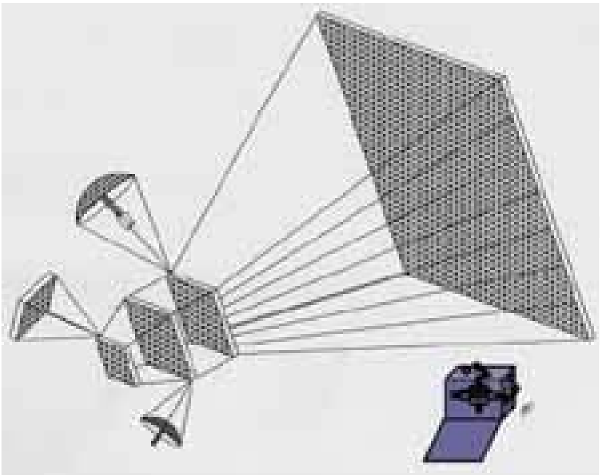

Figure 2. Simple model of PAM spacecraft illustrating the attachment of instruments to space platform tethered to space frame. Insert of SMART box is shown in lower right corner.

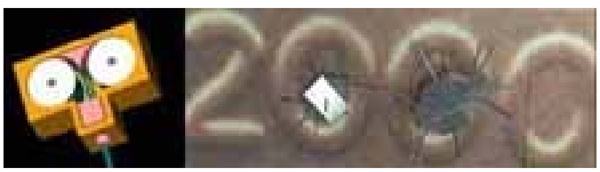

Figure 3 Spooling mechanism design at node, and relative size of MEMS nodes shown on 2000 penny.

Figure 4 Physical Model of small portion of Space Frame with Sail (left) and Space Platform (right).

MEMS nodes are used in several ways. The greatest number are structural nodes which spool/unspool nanotubule struts using a MEMS opposing 'tape measure' kind of device which links or unlinks the oppositely wound tubules **(Figure 3).** 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 can also be used to deploy nanotubules, or even carbon fiber composite with 'memory' and relatively low aerial density (5 g/cm^2) currently available, in layers, to form sheets, using a stack of tape 'roll' devices and nanotubes, or carbon fiber composites, with highly compressible structural properties. Such nodes would be used in the solar sail.

A **100 sq meter solar sail** consisting of 10,000 100 sq cm triangular facets is supported by a **space frame** consisting of two layers of interconnected nodes, forming a lightweight 3D truss structure. A portion of this sail is illustrated in **Figure 4**. The sail would be made of specially designed carbon-based material with 100 times aerial stretch capability. Layers of interlocking nanotubes, specially designed dendritic springs [14,15,16,17], would reversibly deploy in arcs from tape 'roll' nodes. Tailored, multi-feature nanotube design is certainly a major technology driver. So, another option would be to use 'memory' carbon film on carbon microfiber composite [18], currently available at 5 g/cm^2 aerial density, deployed on Polymer/Carbon Nanotube Composite (PNC) springs and structural elements [19].

Very effective solar sail navigation and attitude control **(Figure 5)** 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 [1]). Each sail facet's effective area can be controlled, as the number of layers and the extent to which each layer is deployed, is changed. By controlling the extent and placement of deployed facets, the amount and center of pressure can be controlled, and the speed and direction of the sail, and spacecraft, changed. Theoretically, depending on the geometry of the sail, it would be possible to deploy as few as 3 or 4 facets properly distributed, and lower sail area by more than a factor of 1000 (the nominal requirement)

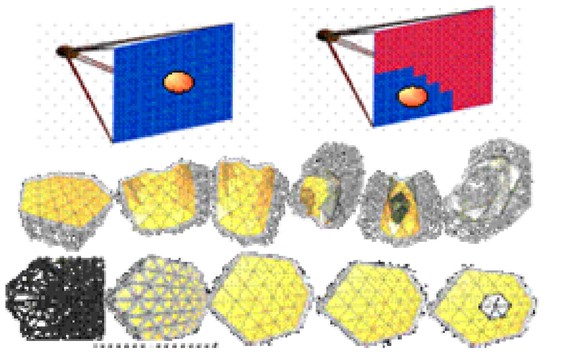

Figure 5 Sail changing center of pressure (orange sphere) (top) or morphology (middle) for attitude control. The same capability allows sail to self repair (bottom).

while controlling the attitude. The shape and size of the space frame itself can also be dramatically modified, reorient the sail, quickly change the direction of momentum vectors, accelerate, decelerate, or make the spacecraft effectively 'disappear'. The implementation of the solar sail is discussed elsewhere in detail [20].

Attached to the space frame by a network of long tethers is a small **space platform** consisting of three layers of interconnected nodes, making a more robust framework to which all subsystems are tethered, including SMART instruments **(Figure 2)**. 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. When instruments need to 'see' through the sail, the extent and direction of tether deployment can be changed and a 'viewing hole' easily accommodated in the sail and its frame.

The entire spacecraft is initially stowed (predeployment) in a 100 cm^3 **SMART box (Figure 2 inset)**, 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.

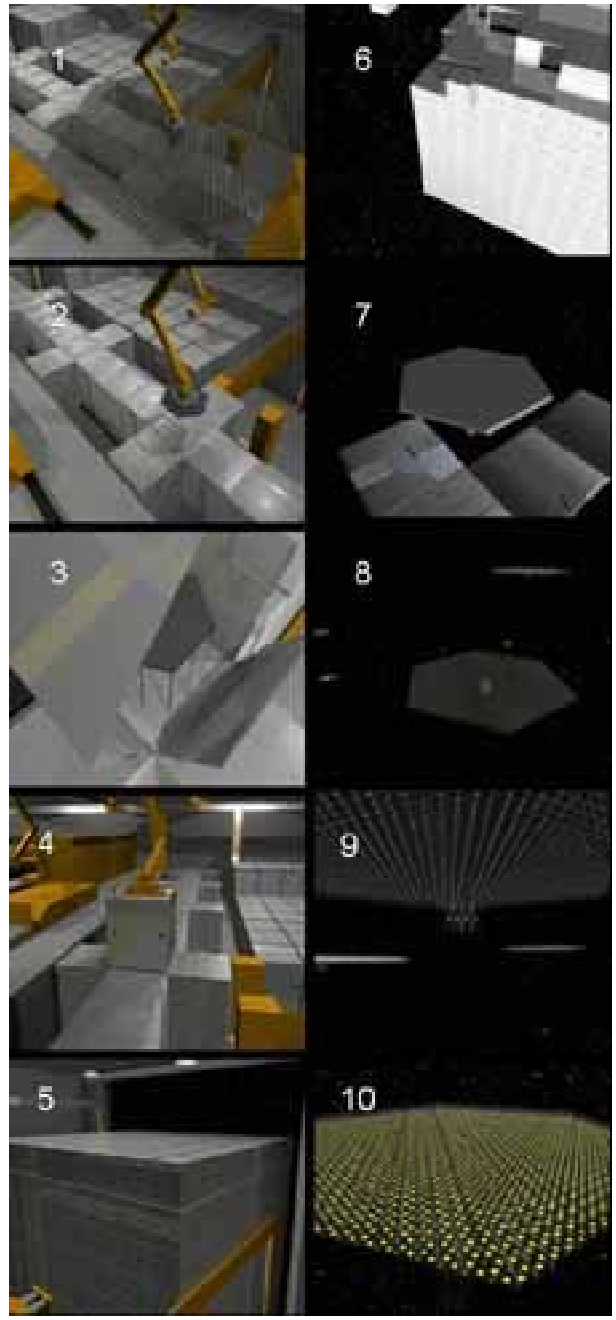

Figure 6: ANTS Assembly in sequence.

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. In fact, the spacecraft assembly process employs ANTS architecture and is part of the PAM mission concept. **(Figure 6)** (See also Manufacturing

Movie at the official ANTS website [1]). 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. In the case of PAM, the large Space Frame would be constructed from two layers of structural nodes. A layer of sail-deploying nodes would be attached to the top layer. Tether deploying nodes would be attached to the bottom layer. Meanwhile the space platform would be constructed from a small space frame with an additional layer of nodes, plus nodes for each subsystem. The space platform would then be attached to the space frame via its tethers. The entire spacecraft would then by stowed to its smallest possible size, a cluster of interconnected nodes, attached to and enclosed in the SMART box, which would then be attached to its neighboring boxes to form the SMART cube. If already in deep space, the SMART cube could travel to the deployment site directly. Alternatively, the SMART cube could be placed in a cargo hold for transportation to a location in deep space.

PAM SCIENCE OPERATIONS

Each class (**Table 6**) would employ different strategies in the use of components and subsystems during the active part of PAM [4,8]. 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. Instruments are listed in rough sequence, in terms of stringency of operational requirements, by distance (furthest to closest) and time (least to most) requirements. Most likely, the visible imaging spectrometer 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. 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

Table 6: Instruments and Roles

Specialization Class	Primary Task, Requirements
Leader	Processing, Strategizing Out of way w/in range
Messenger	Communication Out of the way w/in range
Workers: Imaging (Visible)	Data Gathering 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/Magnetic fields, Interior, 3D Model Over poles
Radio Sounder/ IR Radiometer	Regolith Characterization Close, Nadir
Neutral Mass Spec	Volatile Characterization Close, Full sun

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 certainly study a selected target by providing the highest quality and coverage of measurements from a particular class, forming 'Virtual Teams' [4,8a,8b]. '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 6**). First, a 3D model would be generated for adequate navigation and maneuvering around a target. Thus, the **Asteroid Detector/StereoMapper** team would be necessity go in first. It would consist of two wide field imaging spectrometers with enhanced navigational (location and pointing awareness) capability separated by distances varying from hundreds of kilometers to kilometers would be used to detect and determine the orbit of potential targets at a distance, or move to within kilometers of a target to obtain astronomical classification and figure properties and identify candidates for detailed studies. The **Dynamic Modeler** consisting of an enhanced radio science instrument, altimeter, and wide field imager separated by tens of kilometers to kilometers would be used to acquire detailed figure parameters (including shape model) and dynamic properties (spin, density, mass distribution).

Various combinations of instruments could be used to study composition and history. A **Petrologist** consisting of X-ray, Near Infrared, Gamma-ray, Thermal IR, and wide field imager separated by tens of kilometers to kilometers would be used to determine the abundances and distribution of elements, minerals, and rocks present, from which the nature of geochemical differentiation, origin, and history of the object, and its relationship to a 'parent body' could be inferred. A **Photogeologist** consisting of Narrow Field and Wide Field Imagers and Altimeter separated by tens of kilometers to kilometers would be used to determine the nature and distribution of geological units based on texture, albedo, color, and apparent stratigraphy as expressed on the surface, from which the nature of the dynamic history and origin of the object could be inferred. A **Prospector** consisting of altimeter, magnetometer, Near Infrared, Infrared, and X-ray spectrometers separated by tens of kilometers to kilometers could be used to determine the distribution of 'resources', including Fe/Ni and volatiles on preselected candidates for 'mining'.

REALIZING THE ANTS CONCEPT: REQUIREMENTS AND ENABLING TECHNOLOGIES

As part of the ANTS/PAM study, we have determined the major requirements for such mission **(Table 7**) [13]. We should be able to meet all of these requirements with anticipated, incremental technology developments over the next two decades.

We require incremental improvements in subsystems in a couple of key areas. To meet our power requirements more than 2 AU from the sun, we require batteries weighing well under a kilogram and producing tens or

Figure 7: PAM Requirements

Launch Date: 2025
Duration: 10 years
Location: 1.0-3.5 AU
Spacecraft Mass: 1 kg
Spacecraft Materials: 1 to 5 g/cm^2
Power system and mass: Nuclear batteries 0.25 kg
Power requirement: 100-300 mWatts
Propulsion system and mass: Solar Sail 0.5 kg
Attitude control: 10^3 change in effective sail area
Deployment Temperature: 40 deg C
Spacecraft Attitude: 3-axis stable
Operations:
- Deep space with no direct link to Earth
- Individual craft (Messenger) return data
- One month of optimal science/asteroid
- Full instrument suite deployed/asteroid
- Concurrent operations at ~10 asteroids
- No single point failure
- Robust to minor faults and major failures
- Optimal operations in spite of 10% attrition/year

hundreds of milliwatts. Such nuclear batteries are already under development. Small, low power communication, navigation, and tracking devices are also under development.

Key technology drivers for ANTS/PAM are the use of **carbon-based materials and structures** (MART or MEMS systems) and, ideally, NEMS for all mechanical components, in order to minimize mass and power requirements. Ultimately, to minimize the mass and power requirements, ANTS structures will be built entirely on carbon-based materials. Currently available carbon fiber composites [19] are the most lightweight, durable, and rigid materials that are currently available, and now approach are minimal aerial density requirement (5 g/cm^2). Specially manufactured thin sheets of this carbon film on fiber material with shape memory have already been manufactured as potential solar sail material [18]. A particular area of concern for our application would be the ability to 'retain' memory over potentially millions of deployments, and the power expenditure requirement to hold the material at partial deployment. Carbon nanotubules themselves [14,15,16,17] are even stronger and lighter weight, have lower aerial densities (1 g/cm^2) and, if the ability to create very long (many centimeters to many meters) CNTs while retaining the properties of individual CNTs is realized, these would be an ideal basis for structural elements [21]. We would then use CNTs with the attributes already observed in individual CNTs and required for a particular ANTS functions, long and straight, or shorter, spring-like, and branching.

The development of **autonomous navigation without appendages** is another critical area. We have already developed simulations of the movement of single, 4, 12, and continuous tetrahedral structures (See still and movies at the official ANTS website [1]). The first demonstration model of an EMS-level (ART) single ANTS tetrahedron, designed to be a walker (TET), will be completed in October 2004 (TRL 3). Plans are underway to test the TET in January 2005 in Antarctica with remote operation via the Internet using a 3-D graphical user interface. We have completed a preliminary conceptual design of a 4-tetrahedron system (4-TET) capable of carrying a scientific payload in a central node, and have proposed to build and test that system on a field campaign in Iceland ('Mars on Earth') (TRL 6). The next milestone will be to build the 12TET model. At this level, the ability for 'continuous' movement clearly emerges.

PAM utilizes a totally new type of space architecture based on an autonomous, addressable, reconfigurable components. The potential flexibility and adaptability of such a system demands a level of artificial intelligence we are in the process of developing through our role in ST-8 COTS High Performance Computing and Multi-agent Simulations using Beowulf clusters here at GSFC [1,9c].

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