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USE OF SWARM INTELLIGENCE IN SPACECRAFT CONSTELLATIONS FOR THE RESOURCE EXPLORATION OF THE ASTEROID BELT

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ABSTRACT

We describe the Prospecting ANTS Mission (PAM) whose object is to explore the resource potential the Solar System's Asteroid Belt. The mission is consistent with the present NASA strategic plan for the HEDS (Human Exploration and Development of Space) enterprise. In this plan, the automated discovery of space resources is envisioned as a building block for expanding the human presence in space. The Asteroid Belt consists of thousands of widely separated bodies. Targeting thousands of individual asteroids, which will require hovering in a highly irregular gravity field, demands a very large autonomous constellation of specialized workers. The ANTS (Autonomous Nano-Technology Swarm) concept has a number of possible applications of which the PAM mission is one. ANTS, based on a hierarchical insect social order, use an evolvable, self-similar, hierarchical neural system in which individual spacecraft represent the highest-level nodes. ANTS uses swarm intelligence attained through collective, cooperative interactions of the nodes at all levels of the system. At the highest levels this can take the form of cooperative, collective behavior among the individual spacecraft in a very large constellation. The ANTS neural architecture is designed for totally autonomous operation of complex systems including spacecraft constellations.

The PAM mission is envisioned to fly in 20 - 30 years. It assumes a Lagrange point launch, consistent with the HEDS roadmap that projects human occupation during this time. The spacecraft are solar sail powered and reach, flying as a swarm, the Asteroid Belt in a little over 3 years. The swarm would consist of 1000 pico- (1 kg) spacecraft with 9 types of radio-linked, specialized worker spacecraft defined by the remote sensing instrument that they each carry. These instruments would include magnetometers, mass spectrometers, x-ray, UV, visible, and infrared sensors. There would be 100 of each worker spacecraft type, allowing multiple asteroids to be simultaneously explored and allowing any given worker to be expendable, consistent with the social insect analog. In addition to the workers, there are 100 ruler and messenger spacecraft. The messengers return amassed data to the terrestrial Lagrange point and the rulers coordinate the activities of the instrument worker spacecraft at each asteroid encounter. The last data would be returned to the terrestrial Lagrange point about 10 years after departure.

We discuss the operational characteristics of the PAM mission and possible applications of the technology employed in nearer term missions.

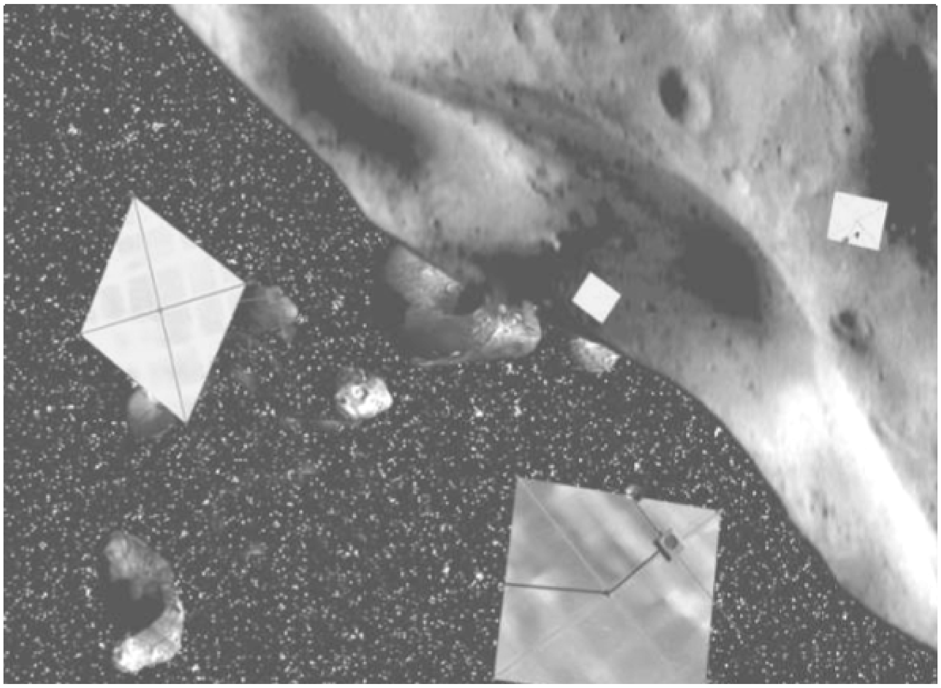

Fig. 1. An artist's concept of Prospecting ANTS Mission during Science Operations.

INTRODUCTION

Prospecting the Main Belt

The Main Belt of Asteroids between the orbits of Mars and Jupiter represents the last great accessible surface to be explored within the orbit of Pluto. The mass of the thousands of objects in the Main Belt is perhaps a fraction of that of Mars, but their combined surface area may dwarf that of the Earth. The outer reaches of the Belt are rich in frozen volatiles including water and other ices. The inner reaches are more refractory. Some asteroids are largely the metallic shards from the cores of larger differentiated bodies that have since been destroyed by collisions with other asteroids. There has been much interest in the exploration and development of asteroids as a resource enabling the continuous human presence in space. Interest driven partly because, compared to other planetary objects, asteroids have weak, but irregular, gravity and a wide variety of resources.

The Prospecting ANTS Mission (PAM) is an advanced mission concept for the 2020s that seeks to perform a first general exploration of the belt to survey and map the surface characteristics and other properties of the Main Belt (Ref. [1], ANTS will be discussed below). Within the time frame of a single mission (5-10 years), thousands of asteroids are to be visited to provide an extensive sample of what exists in the Main Belt. With a goal of characterizing in detail at least one thousand asteroids a year, PAM forces us to reconsider our fundamental approaches to mission implementation. However, the rewards for taking up this challenge are great. The atlas of surface and internal properties that PAM produces will be critical for the future exploration and development of Main Belt resources.

For such advanced missions, a key theme in the long-term roadmap of NASA's Office for the Human Exploration and Development of Space (HEDS) is the close interaction of humans and robots to achieve mission goals. The HEDS roadmap foresees the synthesis of integrated human and robotic technologies enabling advanced missions that involve a continuous human presence beyond low Earth orbit. Robotic autonomy is an important component of the HEDS approach, both for health and safety of systems and subsystems, but also for the reliable interaction of human and robotic components (see Ref. [2] for the ANTS perspective). Multi-element missions must be no more difficult to operate than single-spacecraft missions are today. Furthermore, no cost-savings are to be gained by implementing human-based mission operations locally on deep space missions. Hence, sub-system and component automation and autonomy enable missions. Furthermore, partial autonomy, in the sense of having an external (human) controller in the loop, gains little, for even small deviations from total autonomy will drive human interaction concerns and hence mission costs.

The PAM mission is a case in point. If about a month of observation is required to characterize an asteroid, the requirement to visit a thousand a year implies that about one hundred asteroids are to be visited at any given time. Using current implementation techniques and reasonable budgetary expectations, it is infeasible to field one hundred unmanned deep space missions. Therefore, the requirements of the PAM mission drive us to consider approaches that are highly distributed and fully autonomous and yet are still reliable and cohesive enough to meet mission goals efficiently.

ANTS: The Autonomous Nano-Technology Swarm

ANTS is a mission architecture drawn in analogy to biological social insects (see Refs. [1,2] and references therein). In nature, biological ants are one of the most successful species to appear. Elements of their success lie in their division of labor, their collaboration, and their numbers. Their numbers provide reliability through redundancy for many functions of the swarm. However, individual ants are themselves highly autonomous and capable creatures, however they do depend on other members of their society to perform tasks necessary for their survival and procreation. Because individual ants are specialized to a given task, they are much more likely to succeed in that task than a non-social generalist. The ants and their swarm benefit from these successes, and the colony continues on with its competitive advantage. In some sense, we aspire to produce systems with the robustness and adaptability of ants. Biological ants are capable of relatively sophisticated behaviors with relatively simple neural structures and communication mechanisms, we seek to emulate both the individual and swarm capabilities in the ANTS mission architecture.

The ANTS mission architecture posits highly autonomous spacecraft each specialized to a particular mission function, e.g. data collecting, communications, or control. ANTS spacecraft all are able to perform autonomously tasks that all spacecraft must perform to survive, these include standard functions such as Guidance Navigation & Control, Attitude Control, etc. However, they are experts within their specialty. The physical makeup of the spacecraft themselves, and their operations, including trajectories, can be optimized for their tasks. This greatly enhances mission science return, simplifies science analysis, and leads to a better overall results. Reliability and tolerance to fault and failure is enhanced redundancy at the spacecraft level. Furthermore, the risk vs. payoff trade is significantly transformed: ANTS spacecraft, although already optimized for their task, could occasionally engage in risky maneuvers that are nonetheless scientifically merited that single-spacecraft missions could not even consider. The architecture can be applied to a broad range of spacecraft platforms and constellation concepts.

Applying ANTS to the PAM mission goals leads to the division of mission functions across a thousand or more spacecraft (see Figure 1 for an artist's concept). As the mission concept is set in the 2020s, the spacecraft are to be developed at human habitat at a Lagrange point as aimed for in the NASA/HEDS roadmap. PAM spacecraft are to use solar sails and other technologies that obviate consumable resources. Once released from the habitat, they travel for about two years on their own to the Main Belt. ANTS spacecraft involved in data collection and processing for asteroid characterization are called Workers. There are about 8-10 types of Workers each specialized on a particular kind of scientific instrument and measurement program. ANTS spacecraft involved in swarm cohesion and communications are called Messengers. ANTS spacecraft involved in command are called Rulers. Briefly, Workers working in about 100 teams produce data and some higher-level data products that are then communicated and archived within a network of Messengers. Rulers oversee the data flow and steer the progress of the swarm. At times when enough data has been accumulated a Messenger is dispatched to a terrestrial Lagrange point or other communication node. We believe the preceding scenario is a feasible alternative to the one hundred spacecraft mission alluded previously. The level of communications and interaction between ANTS spacecraft has yet to be determined, but most detailed control must be performed locally, i.e. within Worker teams in the vicinity of asteroid targets. The communications layer formed by Messengers provides long haul (~0.1 AU) communications across the swarm.

Autonomous Formation Flying in Deep Space

The above description of PAM goals and overall mission architecture presents requirements for several kinds of formation flying. Optimally configured and operated science instruments drive one set of requirements: these can be very demanding, e.g. interferometers or other observations that require coordinated sensor operations. Another set of requirements is driven by teaming and resource allocation requirements: for example, spacecraft loss may require reshuffling team membership that places constraints on spacecraft trajectories. Indeed, a key attribute of a team is their relative positioning or formation and how this formation adapts to mission phase: inter-encounter cruise, orbit-insertion, science operations, and de-orbit. Furthermore, within the PAM framework there are several levels of such cooperation. Messengers and Rulers, in the present scenario, do not suffer encounter operations, yet their communications network forms a widely spread team that is critical to mission success: the parameters and requirements for their formation are quite different from the Workers.

Transfer from Earth's Lagrange Point to the Main Belt

The preceding formation flying tasks are difficult enough in free space or while orbiting a major planet. But the requirements for PAM are more severe and fluid to boot. The first phase of a PAM spacecraft's mission is to travel from Earth's Lagrange point along with the rest of the swarm. The PAM spacecraft might be released over some period of time, possibly months, so the PAM swarm might extend over a large region of space. The current PAM mission design calls for this first leg to take between two and three years under solar sail. This allows the spacecraft to operate in the Main Belt for a greater fraction of its mission life. Spacecraft capable of such acceleration should be able to travel quickly between asteroids during science operations, but this remains to be verified. In fact, most aspects of solar sail propulsion for deep space operations require significant technological development.

Operations in the Main Belt: Infrastructure, Teams, and the Unknown

Next, after having raised their orbits by an AU or more, the Messengers and Rulers position themselves to provide communications and control to the swarm. Workers set about their jobs of detecting and obtaining information about Main Belt asteroids. Some Workers work alone, others are continually forming teams to perform science encounters including orbital operations. Workers equipped with large, wide field imagers should detect vastly more asteroids than the tens of thousands we currently have on catalog. From these asteroids, target selection according to mission goals is a critical activity. However, these mission goals change as more is learned about the Main Belt.

The teams of spacecraft will have to construct and use gravity models for irregularly shaped, rotating, and a priori unknown asteroids that may have moons. Orbit planning for coverage and instrument placement will have to occur at the spacecraft or team level. Logistics is also a key activity, for mission goals require the right mix of instruments being on-site for the right length of time during the appropriate phase of an asteroid's year. An asteroid may receive multiple visits during the mission to get different viewing conditions or for a variety of other reasons. And even though the swarm may have many copies of any given kind of spacecraft, none are to be wasted. On occasion the PAM swarm will send a representative back to Earth or another communication node to report on swarm findings.

All of this is to occur without requiring any human intervention in the affairs of a swarm of kilogram-class spacecraft operating under solar sail between 2 and 3.5 AU from the Sun over the course of a decade.

Plan of paper

In the following sections, we present some of the context of the ANTS Prospecting Asteroid Mission. These considerations of asteroid science, instrumentation, and optimal operations drive requirements for formation flying technology and, more broadly, cooperation. Three important kinds of formation flying are delineated from the structure of PAM. The importance of fully autonomous operations in very uncertain environments is discussed.

ASTEROID EXPLORATION CONTEXT

Though much progress has been made, there exists little detailed data to constrain our ideas concerning asteroids. Much has been learned through the analysis of terrestrial meteorite (e.g. Ref. [3]). Most data come from ground-based telescopes and the very successful Near Earth Asteroid Rendezvous (NEAR) mission that landed a spacecraft on an asteroid (for more on asteroid research see Refs. [3,4,5,6,7,8]). A major breakthrough in our understanding of Solar System origin will require survey of a representative cross-section of the Main Belt asteroid population, whereby the following questions can be addressed:

1) What is the nature of smaller, darker, more remote asteroids more difficult to observe from Earth? Do they contain the undifferentiated material that is found prevalently in meteorites but is missing in asteroid spectral evidence?
2) How are elements, minerals, rocks distributed in asteroids and asteroid parent bodies in space and time? Where are the parent bodies?
3) How is regolith formed from the original parent body material on asteroids? What is the role of 'space weathering' in determining the nature of an asteroids surface?
4) What is the relationship between dynamical and compositional properties? What are the distributions and effective limits in size, shape, spin, mass, density, and composition?

These are some of the main issues concerning Solar System and planetary origins. To address them requires detailed observation by an entire suite of scientific instruments including imagers, spectrometers, radio frequency metrology, radars, and magnetometers among others (Ref. [7] provides an example of such a suite). Furthermore, the particular mix of instruments and their optimal operation varies according to the particular scientific issue being addressed. To make progress, then, current space missions must negotiate a compromise that allows mission goals to be met in spite of the necessity of sub-optimal operations.

Multi Spacecraft Mission Applications

What is the nature of the contribution that multi-spacecraft missions, as compared to single spacecraft missions or near Earth observation programs, can provide? Multi-spacecraft missions are uniquely capable of providing measurements for a comprehensive asteroid survey.

1) 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.

2) 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.

3) Multi-sensor spacecraft have flown before (NEAR) or are flying now to solar system bodies such as asteroids. Essential sensors, such as imagers, spectrometers, and altimeters, have very different optimal operational requirements for a) illumination conditions, b) pointing geometry, c) distance to target, and d) orbital configuration. This translates into constant compromising to meet sensor requirements and results in less efficient collection of high quality data, a problem that is magnified when a small, irregularly shaped object, such as an asteroid, is being explored. As mentioned above, the PAM concept calls for single sensor spacecraft, working individually or as teams. Individual spacecraft can be flown to meet optimal instrument operational as well as science requirements simultaneously, reducing the time required to obtain a comprehensive of observations as well as increasing the quality of those observations, for each target.

Flying PAM: The team and 'virtual science instrument' concepts

The first two drivers for PAM formation flying involve teams and the more tightly coupled `virtual science instrument' concepts. Although individual ANTS spacecraft can be flown to optimize their observing capabilities, they can also, using built in reactivity and response capability, acquire simultaneous coverage of the same target, thus providing a comprehensive measurement set required to solve a particular scientific problem. Identical sensor or multiple sensor 'virtual science' teams could be formed. These teams would be chosen to achieve mission goals and their structure is thus determined by the mission science requirements. Particularly useful teams, and the approximate order of their deployment during science operations, are:

1) Asteroid Detector/StereoMapper consisting of two wide field imaging spectrometers with enhanced navigational (location and pointing awareness) capability separated by distances varying from hundreds of kilometers to kilometers which 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, rough shape, and dynamic properties of more likely candidates for detailed studies. These are the 'point men'.

2) Dynamic Modeler consisting of an enhanced radio science instrument, altimeter, and wide field imager separated by tens of kilometers to kilometers which would be used to acquire detailed figure parameters (including shape model) and dynamic properties (spin, density, mass distribution).

3) Petrologist consisting of X-ray, Near Infrared, Gamma-ray, Thermal IR, and wide field imager separated by tens of kilometers to kilometers which 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.

4) Photogeologist consisting of Narrow Field and Wide Field Imagers and Altimeter separated by tens of kilometers to kilometers which 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.

5) Prospector consisting of altimeter, magnetometer, Near Infrared, Infrared, and X-ray spectrometers separated by tens of kilometers to kilometers which could be used to determine the distribution of 'resources', including Fe/Ni and volatiles on pre-selected candidates for 'mining'.

Note these roles or functions are performed by groups of individual specialized spacecraft. An advantage of working with individual spacecraft is that they may be reassigned as the needs of the mission change. Mission priorities will change as more data is gathered about the Main Belt asteroids, and ANTS provides the necessary adaptability. Finally, using individual specialists provides flexibility as the swarm decays and loses spacecraft over time.

Flying PAM: The Swarm

The preceding has emphasized science-driven requirements and configurations revolving around the needs of the asteroid science encounter operations. Viewed hierarchically, the PAM swarm is a team of teams, some of which exist longer than others, each of which is dedicated to a mission task or function. At the level of the swarm, the global structure of the constellation itself drives its own set of requirements. Whereas science teams of Workers are building up a database of a particular asteroid, the Messengers and Rulers are building up a database in which that asteroid is a single entry.

The communications layer that is implemented on the network of Messengers and Rulers must maintain position and trajectory information on every spacecraft in the swarm as a prerequisite for any communications. This is due to the large distance between asteroids and the great size of the PAM swarm itself. As Workers band and disband into their various science teams and virtual instruments, the Swarm must maintain its own global cohesiveness, but must also be able to adapt to changing mission priorities. The requirements for this rather loosely coupled formation are in some ways less stringent than for the virtual instruments and coordinated observations. The time scales are determined the dynamics of solar sail spacecraft in the Main Belt, and these are fairly benign. However, the requirements on communications links are mission critical and their maintenance challenging.

As an aside, the ANTS architectural requirement for no single-point failures implies that there is no single monolithic Ruler whose commands the swarm depend upon. Clearly the details of managing the orbital insertions of a thousand spacecraft around a hundred asteroids are too great for a single Ruler to handle across deep space. Indeed, the nature of the ruling element itself is an open issue. Indeed, Rulers simply might be Messengers with particular responsibilities for decision making and command, or Rulers may be more akin to software agents that travel within the communications network provided by the Messengers (for more on agent technology, see Ref. [9]). However these highest-level decision makers are implemented, how their directives should affect the actual operations of Workers is an open topic.

CONCLUSION

There is much work to be done to realize the ANTS mission architecture, but not all of the problems must be solved before elements of the ANTS concept might be applied to missions. The most immediate work to be done involves the development of subsystem, and beyond that, full system autonomy for spacecraft. However, we make a distinction between subsystem autonomy and partial autonomy: here, partial autonomy implies that external control is required for reliable operations, while subsystem autonomy implies that the subsystem performs its duties without detailed external command and control. As mentioned previously, while partial autonomy drives cost, full autonomy backed up by redundancy, particularly at the spacecraft level, is the keystone of the ANTS architecture.

In the near-term, the construction of spacecraft that have some fraction of the reliability, capability, and autonomy of biological ants would bring us a long way to realizing advanced missions such as PAM. The ANTS architecture posits that autonomous subsystems of a spacecraft would interact to provide a reliable platform for mission functions, in essence a swarm within the box. The specific methods used to achieve the required behaviors depend on the subsystem and are not limited by the architecture. We note that low-level, neural methods of control suit most needs of biological ants. On the other hand, for social interaction, namely teaming, forming virtual science instruments, swarm/constellation cohesiveness, and mission success, higher-level discourse definitely seems warranted.

Another relevant area that requires groundbreaking is in the field of autonomous deep space rendezvous/orbital insertion with spacecraft using continuous low-thrust propulsion, e.g. ion propulsion or solar sails. Solar sail propulsion is attractive for pico-spacecraft operations in the Main Belt, because it adds no consumable resources to the system and is nearly always available. Hovering trajectories may be possible. However, their dynamical and control properties are not well understood. Autonomous attitude control and navigation for individual solar propelled pico-spacecraft, let alone formation flying, are open problems. The dynamic, irregular gravitational fields that surround asteroids compound these problems.

Once autonomous spacecraft platforms are available, there yet exists the question of how they seek to achieve mission goals. Are the encounters with asteroids in PAM to be scripted? If so, to what level of detail? May the scripts be rewritten? Certainly as the secrets of the Main Belt asteroids are uncovered the mission priorities should change, the operational methods should adapt, however this will have to occur without human micro-management.

These techniques might find their first implementation in near-term missions that have special requirements involving multiple sensors. Some measurements in planetary science missions involve identical sensors moving in formation to separate resolve 3-dimensional-space and time effects in phenomena (Ref. [10]). Measurements involving electric and magnetic field measurements, radio science (range and velocity), spectrometry, and imaging all benefit from the improved signal-to-noise, spatial and temporal resolution, or extended coverage that multiple sensors provide. Data from different kinds of instruments may be combined to form higher-level products such as surface geology, changes over seasonal cycles, volatile budgets and circulation, and indicators of resources such as water/ice, Fe/Ni, volcanic material, and Aluminum. If such studies are done, say, on the Moon (as described in Ref. [10]), they would provide an opportunity for the real-time training and development of human/machine exploration ranging from human-led to human-interactive to full machine autonomy.

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