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ANTS (Autonomous Nano Technology Swarm): An Artificial Intelligence Approach To Asteroid Belt Resource Exploration

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ANTS (AUTONOMOUS NANO TECHNOLOGY SWARM): AN ARTIFICIAL INTELLIGENCE APPROACH TO ASTEROID BELT RESOURCE EXPLORATION

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The final frontier of solar system exploration after the flyby of Pluto will be asteroid belt between the orbits of Mars and Jupiter. Although there has been much speculation concerning the resource potential of the asteroid belt for the exploration and industrialization of space, we are still very far from the required detailed and quantitative data to make informed decisions. The ANTS NASA advanced concept envisions the use of a large SWARM of pico-class (1kg) totally autonomous spacecraft to prospect the asteroid belt. The SWARM using a social insect type of artificial intelligence would individually fly using solar sails directly from the outer edge of Earth's gravity well to the targets in the asteroid belt of 1 kilometer or greater diameter. Many asteroids (>1000) would be visited by the SWARM. Data would be transmitted to Earth via returning SWARM members. Replacement workers would join the ongoing SWARM from Earth as needed. Each SWARM worker would have a specialized instrument capability (magnetometer, x-ray sensor, gamma-ray sensor, Visible/IR sensor, neutral mass spectrometer) needed to evaluate the resource potential of each target asteroid. We discuss the technical requirements for such a mission and the role that near term precursor missions could play.

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INTRODUCTION

After the exploration of Pluto and full mapping of Mercury, there is another major planetary frontier: the Asteroid Belt with thousands of asteroids with diameters of greater than 1 kilometer (km). Exploration of this region may offer great insights about the origin and evolution of the solar system and its potential resource value both for space exploration and Earth. This region offers major challenges for would-be explorers. Visiting many bodies at reasonable cost demands extremely high autonomy, minimal communication requirements to Earth, and very small explorers with few consumables. These requirements far exceed current capabilities, but may be feasible within twenty years.[1] The Autonomous Nano Technology SWARM (ANTS) would provide such a means. ANTS would allow the totally autonomous exploration of the asteroid belt with the goals:

(1) Scientifically categorize all asteroids greater than 1 km in diameter;
(2) Perform initial prospecting expedition for resources becoming depleted on Earth and that are of use in space exploration and development.

A SWARM of 1000 picospacecraft (mass <1 kg each) would fly from Earth orbit to the Asteroid Belt using solar sails, Figure 1. As an insect colony analog, ANTS is composed of specialized workers using remote sensors including imagers, spectrometers, radiation and particle detectors involving active and passive techniques. Exciting progress in Robotics and Artificial Intelligence (AI) has been made using insect-analogs, and we believe their application to space based systems will be profitable.[2]

The individual elements of ANTS, one of which we call an ANT, are to be autonomous, but highly heuristic with a hierarchical intelligence shared by all members of ANTS. ANTS will have the capability of dividing into a number of groups, each with a full complement of workers to study many asteroids simultaneously. Data will be returned to Earth by sending multiple workers back after using the on-board computational and heuristic capabilities of ANTS workers to minimize data volume and to incorporate knowledge gained into their efforts to prospect more efficiently. Individual worker lifetimes are less of an architectural driver since new workers could be sent from Earth as needed.

The heuristic systems enabling technology for ANTS would profoundly affect all later space missions in allowing complicated many platform missions to be executed with far less continuous terrestrial monitoring and guidance than even simple single platform missions today.

Presently, Goddard Space Flight Center (GSFC), is vigorously pursuing technologies for nanospacecraft (10kg or less)[3]. GSFC is pioneering studies into the design, manufacturing, and operations of large Constellations of nanospacecraft (100 or more). ANTS represents a direct extension of GSFC's present efforts to evolve multiplatform missions toward greater numbers of increasingly smaller platforms. This evolutionary sequence includes NASA's Sun Earth Connections' (SEC) 5-miniplatform Magnetospheric Multi Scale (MMS) Mission, the ST-5 nanospacecraft technology demonstration mission using 3 microplatforms, and the 60–100 nanoplatform SEC Magnetospheric Constellation Mission.[4] This research provides a pathway toward meeting the computing performance requirements implicit in the autonomy goals of ANTS.

The purpose of this paper is to outline the ANTS concept. We present a variety of technical aspects about the ANTS system including architectural possibilities, instrumentation, and the demands on spacecraft subsystems. To illustrate the level of autonomy required and the possible ways that ANTS may achieve mission goals, an operational scenario is presented. This paper opens a discussion on the requirements for a mission to survey thousands of Main Belt asteroids and the technologies that must be developed to enable ANTS.

TECHNICAL ASPECTS

System Architectures

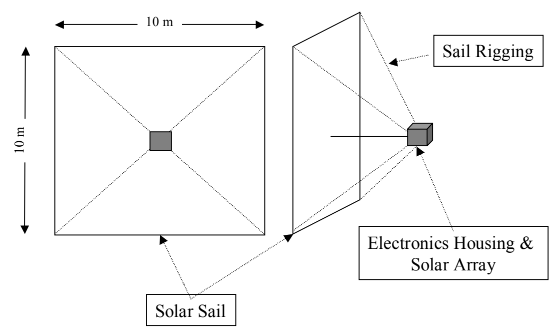
The system architectures include: 1) the overall mission design for ANTS; 2) the design of the individual workers for ANTS; 3) the mission operations scenario for ANTS as a near totally autonomous undertaking; 4) the evolutionary scenario to ANTS from plans for near-term nanospacecraft Constellations; 5) use of artificial intelligence, distributed artificial intelligence, and the holistic integration of knowledge shared among ANTS in some predefined social hierarchy; 6) use the highly homogeneous integration of benefits of artificial intelligence, software, and hardware as one in the ANTS spacecraft system architectures. Together, these represent a dramatic departure from traditional, reductionist system concepts. The highly homogeneous spacecraft integration, artificial intelligence on-board, and the holistic integration of shared knowledge make artificial intelligence a part of all systems, instruments, ANTS spacecraft, on-board operations, and mission.

As an integrated development of the artificial intelligence ANTS on-board system, the study of system architectures for ANTS includes looking at the possibility of assuming the knowledge and expertise of the following agents.

Scientist For ANTS to make local determinations of what is interesting to keep or observe and also what to seek requires the functions that are now the domain of the scientist. The on-board scientist is needed for resolving conflicts for what science or search has the most value, based on current prevailing conditions, and what resource risks are worthwhile. The scientist's knowledge will be used to set to priority, assignments, and actions of that ANTS mission.

Navigator Like a sailor of old, an ANT will need to account for changes during the flight caused by events like solar winds due to solar storms. The navigator will need to account for variations in the

Schematic ANT Configuration



Total Mass: 1 kg
Solar flux: ~172 W m^{-2} at 2.8 AU
Transfer time from Earth: 3.5 Years

$$\left.\frac{\Delta a}{\Delta t}\right|_{a=2\,AU} \approx \frac{10^5\,km}{1/2\,day}$$

Figure 1. A schematic ANT under full sail at 2.8 AU. A large 100 m^2 sail is required to reflect enough light to achieve acceptable accelerations. Solar radiation flux is 7.8 times less at 2.8 AU than at Earth.

performance character of the sails. The navigator will need to deal with the dangers and opportunities that foreign objects present.

Operator Like the operations person that normally would be on the Earth making decisions for the spacecraft, ANTS will need to make its own decisions locally. These decisions are based on knowledge the ANT was given initially, but it may be possible for an ANT's knowledge and ability to grow in time via machine learning techniques. To be studied are aspects of operations within the ANT to handle locally the assignments of ANTS, route planning, optimize search methods, communications, organization science data, resource management, and house keeping.

System Elements

The major system elements are the major spacecraft subsystems, including instruments, and owing to the highly integrated nature of the mission, the mission designs itself. As an example, a predefined social hierarchy for study could include a "ruler" class ANT and a "worker" class ANT. The ruler class ANT may consist of one ANT or some fraction of the total colony. The worker class ANT may consist of one or several types of specialized spacecraft with each focusing on a particular science goal. The SWARM's social structure may be determined by a particular set of science and mission requirements. Cooperation amongst peers, coordination by an oligarchy, and even competition in a market are among the possible ways that desirable emergent behaviors might be elicited from the SWARM. Representative system elements may include:

ANTS (General Functions):
- Distributed Intelligence Operations
- Communications (SWARM, Messenger)
- Resource management
- Navigation
- Collision-Avoidance, Rendezvous
- Local status, housekeeping
- Local conflict resolutions

ANTS (Ruler):
- Includes general ANT functions
- Ruler of SWARM Heuristics Operations Planner
- Overall mission objectives
- Assignments for worker ANTS
- Maintain shared SWARM statistics
- Sharing science discovery data
- Mission conflict resolutions
- Resource management for SWARM
- Messenger delivery of science, status

ANTS (Worker):
- Includes general ANT functions
- Worker Heuristics Operations Planer
- Possible ascension for ruler replacement
- Science data acquisition processing

Spacecraft Subsystems:
- Artificial intelligence heuristic systems involve every spacecraft function.
- Attitude Determination and Control
- Communications
- Command and Data Handling
- Power
- Thermal
- Structures and Mechanisms
- Guidance and Navigation
- Solar Sail Propulsion System

Pico spacecraft mission architecture

Present planning for nanospacecraft will be extended to the picospacecraft regime. Attention will be given to solar sail accommodation and the specialized instruments for each type of ANTS worker. The highly integrated individual spacecraft system architecture is envisioned, and may drive a "Spacecraft on a Chip" paradigm. Implementing ANTS will require technology expansion in radiation hard technology, memory density, package size, power, and computer processing. Planning for the prospective picospacecraft architecture will promote a more homogeneous approach at the chip structure level to support the mission function level of integration. Holistic relationships will be sought between specialized worker ANTS and the common mission. A guiding theme of this work is the use of heuristic systems to integrate the varied elements of the mission architecture to achieve mission goals. These varied architectural elements range from the individual spacecraft to the distribution of the SWARM in mission operations, planning, autonomy, parallel processes, and fault tolerance.

Miniaturized instruments

It is assumed in the following section that the initial goal of a mission employing the ANTS design scenario will be a general survey of some type. In such a mission it will be important to catalog the mass, density, morphology and chemical composition, including any anomalous concentrations of specific minerals, of a large number of relatively small bodies. Basic instrumentation for such a SWARM would most likely include the following:
- IR/Visible/UV imagers and spectrometers,
- X-ray and Gamma Ray detectors,
- magnetometers,
- accelerometer and laser rangers,
- neutral mass spectrometers, and
- Radio sounders and rangers.

Each of these instruments has unique viewing requirements for optimal data collection: in general, a survey mission incorporating many different instrument types on a single spacecraft makes a large number of compromises in order to accommodate the needs of each specific instrument for at least a portion of the mission. In the ANTS concept, each instrument collects data in an optimal mode for the entire time it remains in the vicinity of its target. Brief descriptions of instruments and their data collection modes follow.[5]

Magnetometers The multipoint characterization of the magnetic signature of planetary bodies has proven key to our better understanding of not only surface characteristics of planetary bodies, but also their bulk properties and internal structure. The use of magnetometers on Mariner 10 at Mercury, on the NEAR Shoemaker asteroid flybys, the MGS orbiter, Voyager encounters at Jupiter, Saturn, Uranus, and Neptune, as well as the Galileo Jupiter orbiter. Provide extensive examples of this.[6] Simultaneous observations by several ANTS would provide a detailed characterization of the magnetic properties of the asteroid.

Radiosounders A new emerging technology for the sensing of the interiors of planetary bodies to a depth of several kilometers is radiosounding. Using radio waves to actively probe below the planetary surface is being actively explored for Mars missions as well as the Europa Orbiter. A radiosounder specialized Ant could map conductivity variations over the entire surface to several kilometers depth.

X-ray Fluorescence Spectrometers In our solar system, x-rays from the sun excite fluorescent x-rays from elements on the surfaces of airless bodies such as asteroids, the moon and quiescent comets.[7] The x-ray emission comes from material within a few tens of Angstroms of the surface of the body and is therefore highly sensitive to both the excitation and viewing geometry: low angles of incidence lead to high attenuation of the signal. The best analytical attitude for an ANT carrying an x-ray spectrometer is to look straight down on the target with the sun at its back. In this attitude the sun directly illuminates the target and the fluorescent x-rays emerge at normal incidence to the surface.

Gamma-ray Spectrometers Galactic Cosmic Rays permeate our solar system and excite characteristic gamma rays from as deep as several meters beneath an airless body. In addition, natural radioactive elements such as Potassium, Thorium and Uranium also emit characteristic gamma rays. Since the gamma rays from both cosmic ray induced emission as well as from natural radioactivity emerge independent of the sun angle, the ANTS carrying gamma-ray spectrometers can be positioned anywhere around the body under examination.

Accelerometer/Camera The mass, density and morphology of the target body are intimately related. An ANT optimized to determine these important parameters would carry an accelerometer and a relatively high-speed, moderate-resolution, monochromatic camera. Initial passes over the body would photograph the sunward-facing side of the target as it rotated: simultaneously recording variations in the gravitational acceleration measured at the ANT. Once an initial digital model of the surface was constructed from these images, close passes over selected areas would be made to measure the variation in gravitational acceleration from specific portions of the target and thus derive a measure of local density. Passes over the terminator could be used to derive a measure of the surface roughness by recording the contrast variations per unit area due to variable illumination of craters, crevices and other surface irregularities.

Radio Ranger Another instrument that can obtain good measurements of asteroid density and mass distribution involve radio ranging and accelerometry.[8] The method consists of measuring small shifts in the frequency of radio transmissions from spacecraft being accelerated by bodies of mass. This technique has been used to develop mass distribution models of the Earth and other planets. Because around ten ANTS may encounter an asteroid at a time, the potential amount of acceleration data is great, and it may be possible to rapidly develop a asteroid mass distribution model.

Visible/Near-Infrared Spectrometers The mineralogy of the surface can be determined to some extent by subtle absorption features in the visible through infrared spectral regions. For the visible and Near-IR regions, the best viewing geometry is looking directly down on the target with the sun at zenith. This yields maximum signal in the reflected sunlight. Mineralogy can be very important indicator of the processing history of the body under study and of the resources it might contain.

Thermal-IR Spectrometers The best viewing geometry for Thermal-IR instruments is just beyond the terminator as the body under study rotates out of the sun. The thermal infrared spectrum of the body can be another very useful indicator of the mineralogy of the body, while the time-dependent rate of change in the thermal IR emission of a particular region can indicate the thermal inertia or internal heat-flux. The former can be a measure of the density or porosity of an area while the latter might indicate a localized radioactive heat source or a local “cold-sink”. Such a cold sink could be due to a large mass of ice kept at constant temperature via sublimation.

UV/Visible Spectrometers Volatile emissions from the surface of a small body could be an extremely important indicator of the presence of water or hydrocarbons – both very valuable resources necessary for the future exploration and utilization of space. The best position for an ANT carrying an UV-Visible spectrometer is either just beyond the terminator. It would view the sun on the "horizon" through the maximum extent of any residual atmosphere and search for atmospheric absorption features. Or view along the terminator searching for fluorescent atomic. Or search for molecular emissions from atmospheric constituents escaping from the interior of the body.

Mass Spectrometers Confirmation of the presence of large deposits of volatile materials such as hydrocarbons or ice might require the use of a mass-spectrometer optimized for the detection of low mass, volatile molecules. The measurements would be optimized with close fly-bys over suspected surficial vents following maximal heating by the sun. Depending on the geometry of the body, such passes would be made from ~ local noon to ~ local sunset. In extreme cases, there might be some advantage in flying the ANT into a suspected vent system to confirm the presence and obtain a detailed analysis of the volatiles present. Unless an onboard propulsion system was available, the ANT thus deployed would be lost from the SWARM.

For each of the instrument types enumerated above, very lightweight detector systems are already available for laboratory use. NASA's PIDDP Program, the SBIR Program, and various interagency agreements are now financing several studies of new, lower-mass, more-capable sensors with fewer restrictive operational parameters. These smaller, more capable instruments are needed for the next generation of Lander and Rover missions to both Mars and to minor planets. Terrestrial applications of such smaller sensors (such as in Forensic Investigations – currently being funded jointly by the National Institute for Justice and NASA) could spur increased economic incentives for the improvement of existing sensors or the development of new technologies. In particular, for each of the instrument types that are most useful in a resources survey mission, sensors already exist with the required sensitivity and operational capabilities at masses that are less than half a kilogram. Future developments should push the masses of most such systems down near the 100-gram range within a decade or so. The onboard computational capabilities of the ANT must be sufficient to operate the instrument, analyze the data, and optimize the data-gathering phase of an encounter. Then only portion of a traditional space instrument need be incorporated into the individual ANT version of the low-mass sensors now under development.

Propulsion

Both inflatable and other types of solar sail designs will be considered and optimized for the picospacecraft of the ANTS. We will be studying the control of the solar sails with heuristic systems including the navigator, attitude control, and power management. The solar sail may be useful to concentrate the light but needs the heuristic systems to balance the need for power with navigation and attitude control.

Heuristic systems

The architecture for the ANTS heuristic system must be developed with an aim toward near total autonomy. The hierarchical structure among the ANTS workers will be defined in the developed mission design context. The mission design context will refine the details of the hierarchical architecture, specialized responsibilities, the goals of the collective, and the social structure of the ANTS. As the mission is developed, rules will be defined that use the locally available, intermediate, partial knowledge and allow ANTS to efficiently search its set of actions for mission planning and scheduling. The developed heuristics are to enhance many important mission parameters, including the science return, mission operations efficiency, and the efficiency in the spacecraft systems.

The layers of social structure of the SWARM, relationships between spacecraft, sets of rules, the layers and methods of artificial intelligence will together determine how autonomous planning and execution will be achieved. The top layer of the heuristic topology may be a planning system that makes the top-level decisions. These layers may include genetic algorithms to help in the creation of new strategies or the elimination nonproductive strategies, a virtual blackboard system for multiple agent management and support management of the mission. Approaches to be studied include: 1) Neural Nets, a model free, or implicit model, discipline that would have the training supervised autonomously by higher level system components, used to learn about empirical system function, patterns, and control requirements; 2) Fuzzy Logic, also a model free discipline useful in control and conflict resolution applications arising in ANTS: navigation, attitude control, collision avoidance, systems and subsystems; 3) distributed artificial intelligence to support, e.g.: mission objectives, SWARM collective intelligence, SWARM system architecture, management of system, navigation, attitude, command and data handling; 4) genetic algorithms to support, e.g.: effective search and navigation; 5) on-board operations planner supporting, e.g.: mission objectives, navigator, encounters for science, data management, ANTS systems architecture management.

Mission development will define the planning system mission objectives with respect to current status of the SWARM, control of individual SWARM spacecraft operations, navigation planning, orbit determination, maintenance communications with the virtual network of ANTS spacecraft, maintenance the leadership responsibilities of the swarm of ANTS.

The mission development will define goals, roles and responsibilities among the social structure of ANTS. This development will define how autonomous commands will be generated, passed, assignments made, coordination of SWARM and the sharing of science or status data.

Advanced on-board computation

Advanced on-board computation will be examined from the perspective of limiting the volume of data to be returned to Earth, coupled with the heuristic systems to increase autonomy and worker productivity by optimizing the prospecting strategy at each asteroid and across numbers of asteroids. We need to investigate the concept of a “spacecraft on a chip”, where a generic highly configurable processing chip could be set up to perform the unique support required for Worker ANT, Ruler ANT, spacecraft artificial intelligence system, individual instruments, and subsystem support. This investigation will include benefits for reduction of mission complexity, reduction of interfaces, reduction of cost, improved performance, and improved survivability.

Attitude control

As all the individual ANTS will have solar sails they all will require an attitude control system capable of at least rough three-axis pointing. A sun sensor can provide one direction reference, but at least two are needed. In deep space, each individual will need to able to perform stellar navigation unless some other reference is provided externally. A star camera can provide the reference information but may be expensive to put on every spacecraft. Another approach to study would be to place the star camera on only a few ants and they would broadcast an ANTS network GPS like signal that the others could receive. A relay network communications should be studied to avoid a limitation of this GPS approach to avoid the ANTS needing to stay close together, i.e.; the slowest member would limit the progress of the group. This may be merged navigator and communications as part of the various heuristic systems and disciplines such as distributed artificial intelligence, fuzzy logic, on-board operations planner, to be studied could come into play to support this relay network communication and attitude.

Power

Power for the ANTS project will have unique problems to study. The sun's intensity falls of with the square of the distance reducing the effectiveness of solar cells. Areas for study include the use of a solar sail as a concentrator for solar cells. The study of the heuristic systems necessary to support power control and management is also required.

Thermal

Thermal design for the ANTS project has unique problems. The spacecraft will be cold and power for the spacecraft is likely to be low.

Navigation

Decisions that are made in-route will need to anticipate navigation changes with enough time for the solar sail to respond to the changes. The Navigator is an artificial intelligence mission spacecraft system, functioning like the sailor of old.

Once in the vicinity of an asteroid target, the target will have to be imaged to obtain fine scale navigation data to enable close approach. The limited detail data we have on small astronomical objects suggests that a significant percentage will be complex objects. They may be non-uniform and rotating or binary objects creating tidal forces. They may have moonlets that create collision hazards. Or they may be emitting gasses or particles that could be hazardous. All of these will need to be assessed locally by the ANTS to determine if it is safe before a close approach to the target can commence.

Communications

The communication design will need to part of the highly autonomous nature of ANTS and the need to share knowledge, data between the Ruler and Worker ANT, and assignments issued to the Worker ANTS. Communications is an artificial intelligence mission and spacecraft system. A communications method such as a network relay is a candidate for all communications within ANTS. Also communication relays may be used for messengers that are assigned to report back the science and SWARM house keeping status to an earth orbiter such as Space Station.

Command and Data Handling

The highly autonomous nature of ANTS and the ANTS predefined social hierarchy will cause much of the command and data handling control to be contained within the heuristic systems of the ANTS and addressed also in the Communications. Data processing will also need to be addressed to support the instruments. Command and Data Handling is an artificial intelligence mission and spacecraft system.

Mission design

A mission design is required for a highly autonomous expedition, which will optimize the prospecting strategy in terms of time and propulsion requirements. In order to make efficient use of the individual ants; target assignments will need to be made while in-route. This will permit attrition and sailing performance to be accounted for.

Operational Strategies

A detailed scenario for the ANTS Asteroid Belt prospecting mission is required. This will include the social structure of ANTS: the division of workers in groups and the size of the groups and the number of asteroids to be investigated simultaneously. Once deployed ANTS on-board execution of operational strategies will need to be autonomous and an artificial intelligence mission and spacecraft system.

Evolutionary Scenarios

Evolutionary scenarios will be examined starting with a nanospacecraft-class ANTS mission to near-Earth asteroids with a smaller number of ANTS workers, more limited autonomy and on-board computation and alternative propulsion systems such as hydrazine.

AN OPERATIONAL SCENARIO

To explore the way individual ANTs might work together we develop an operational scenario involving an ANTS encounter with an asteroid. In this scenario, ANTS detects an asteroid, tracks it, passes information about the asteroid's trajectory to the SWARM. Rulers, workers, and messengers each act on this information accordingly. The preceding discussion has revolved around the possibilities associated with ANTS-like architecture. The scenario presented here briefly sketches one such possibility.

The Asteroids

An order of magnitude estimate for a mean distance between asteroids may be found by dividing the mass of Mars into 1 km diameter chunks and distributing them evenly in a ring of thickness 0.1 AU with and inner and outer radii of 2 and 4 AU respectively. This yields a mean distance of about 3×10^4 km. The ANTs as configured above can change their semimajor axis by about 2×10^5 km in a day. Therefore ANTs can spend most of their time in the vicinity of asteroids and very little time in transit between them. Spacecraft communication range then drives the physical size of ANTS.

The Spacecraft

Before discussing the asteroid encounter we briefly describe the spacecraft that make up the SWARM. First, we presume that individual ANTs are complete spacecraft capable of orienting themselves, operating their sensors, monitoring themselves and their surroundings, maintaining health and safety, and pursuing goals such as trajectories or orbits. This already implies a highly advanced level of autonomy, but a level of autonomy that can be developed in the single spacecraft context. In addition, individuals will have at least a low and a high bandwidth (LBW, HBW) communication capability. The LBW communication link is to be used for collective operations and behaviors, while the HBW link is mainly for close range ANT to ANT transfers. We suppose that these communication links use omni directional antennae. For example, the bandwidth and range of the LBW link might be on the order of ten bits per second at 2×10^5 km, respectively. The HBW link may deliver megabits per second at a few hundred kilometers. Avoidance of collisions with asteroids or spacecraft is within the domain of system health and safety and must be a fairly low level autonomous behavior. Thus each ANT has a package of software and hardware for traversing space and encountering asteroids while maintaining their place in the SWARM.

The SWARM

The number of asteroids within ANTS depends on its physical length scale, $\sim l_{swarm}\, l_{lbw}$ where the LBW range is l_{lbw}. A rough estimate for the number of asteroids is:

$$\left(\frac{l_{swarm}}{1}\right)^3\left(\frac{l_{lbw}}{1.5\times10^5\,km}\right)^3\left(\frac{l_{asteroid}}{3\times10^4\,km}\right)^{-3}\approx 125.$$

For $l_{swarm} \sim 1$, all members of the SWARM are within LBW contact of each other. ANTS's optimal operating mode for studying individual asteroids has yet to be determined. For example, one could have roving teams of ANTs or teams could form within the SWARM as needed. In either case, we can crudely estimate the mean number of ANTS required to study an asteroid as a number of Workers supported by an overhead of Ruler/Messengers. From the discussion of diagnostic instrumentation above, we see that there are perhaps 8-12 types of instruments, and hence Workers, that would be useful. The optimal ratio of Workers to Ruler/Messengers depends on the reliability of the Ruling/Messaging support, as well as how well information travels through the SWARM. Recall that Messengers are responsible for high volume data transfers through the SWARM and to Earth. We may try:

10 Workers + 2 Ruler/Messengers = 12 ANTs/asteroid

as a first guess. A more detailed analysis modeling the information transfer, command, and control strategies is required for further progress. We note that, unlike terrestrial ants, robotic or natural[1], ANT spacecraft do not readily interfere with each other's operations; there is plenty of room for ANTs to avoid collisions while seeking to achieve their goals. Therefore limits on system scalability and cooperation for ANTs differ from those readily realizable in terrestrial labs.

With these estimates, we see that ANTS can be reasonably sized at about one thousand spacecraft, which could study about 80 asteroids at a time. Within this scheme, ANTS would study all of the asteroids within one "coordinate cube" and then move *en masse* to the next. If it takes about two weeks to study an asteroid, then perhaps 2000 asteroids per year could be studied, before taking into account inefficiencies due to conflict resolution, hazard avoidance, etc.

For the sake of discussion, we consider a SWARM of 1000 spacecraft composed of about 12 types with about 80 spacecraft of each type. The three broad types of spacecraft have already been mentioned: Ruler, Messenger, and Worker. Most ANTs fall within the Worker class. Each type of Worker is specialized with a given sensor, in addition to those systems required for space faring. The Ruler and Messenger have similar requirements: both must communicate with possibly large numbers of ANTs and both must store or process data from the SWARM. This points to the Ruler and Messenger having good information handling capabilities, i.e. memory, processor, and communication (including physical speed). However, Ruler and Messenger do have slight differences, mainly in their handling of data and responsibility for directing ANTS. An intriguing possibility is to use a single Ruler/Messenger type, in which the qualities required for one role are latent in the other. For example, processing capability available to a Ruler may be latent, i.e. turned off, in a Messenger. The behavior of a Worker depends a great deal on the particular sensor it carries, making such polymorphism more difficult.

Therefore, we consider a SWARM with about 160 Ruler/Messengers that are central to the goal achieving behavior of the SWARM. The remaining 840 are divided among the various sensor platforms required for the survey. These spacecraft may be grouped according to the kind of spacecraft trajectory required by their role. Possible categories include: (1) Cruisers, (2) Orbiters, and (3) Hoverers.

Cruising Cruisers include those spacecraft that do not need to drop very close to asteroids. Such spacecraft include Rulers and Messengers as well as those that have certain remote sensing capabilities. For example, Multispectral imagers, particularly those using IR telescopes are useful for detecting and tracking asteroids. Furthermore, having dozens of these in a SWARM opens up interesting possibilities for obtaining asteroid parallax and proper motion information, i.e. asteroid range, speed, and bearing information. ANTs not requiring proximity to asteroids for resolution or signal strength can be cruisers.

Orbiting Orbiters require proximity to the asteroid of interest. This is the case when an instrument such as a spectrometer needs to be brought close to the asteroid because a map is to be constructed or because the phenomena to be measured is weak. Imaging spectrometers are an example of an instrument that could produce resource maps of asteroid surfaces. Gamma ray spectrometers are an example where a weak signal is to be maximized. Some spacecraft may only require one pass to make their observations, but for our purposes we may consider these orbiters as well.

Hovering There is the possibility of matching the gravity of an asteroid with the force generated by an ANT's solar sail, in which case trajectories in which the spacecraft hovers over the asteroid may be possible. Such a trajectory may be useful for asteroid mapping or SWARM logistical roles, e.g. Rulers and Messengers may hover at an asteroid to wait for and communicate with the Workers there. As described previously for Radio Rangers, another possibility is that a Hoverer, by monitoring its radio contact with Orbiters, could obtain acceleration data from which information about an asteroid's mass distribution could be extracted.

Asteroid Encounter The operational scenario is as follows. The spacecraft of ANTS are traveling through the asteroid belt as a number of irregular clumps all within LBW communication of each other. The size and distribution of the individual clumps will depend on the history of the SWARM and the range of HBW communications.

Detection and Tracking Workers that have IR/Visible/UV (IVU) imaging capability are constantly keeping track of the asteroids. As new asteroids are detected the information is propagated through the array. The IVU data is used to catalog the asteroids and to determine asteroid orbits. Ruler ANTS maintain HBW communication with the IVU Workers and decide when nearby asteroids are interesting.

Rulers React The Rulers put information about important asteroids onto the LBW link; individual ANTs receive this information and respond according to their role and the nature of the Rulers' communication. Rulers may designate important asteroids or may assign degrees of importance to asteroids. These degree assignments could act as inhibitory or excitory signals in analogy with neurophysiology or subsumption techniques[9]. Cruising imagers maintain their watch on the asteroid as Hoverers and Orbiters head for important asteroids. The decision of an individual ANT to drop towards an asteroid should depend on the excitement level of the Rulers towards that asteroid and its own ability to perform its task. Because all spacecraft will have resource limits, e.g. memory for data storage, ANTs may not always be able to perform detailed observations of asteroids.

Arrival at the Asteroid A Messenger, being faster than most Workers arrives in the vicinity of the asteroid, perhaps at the hover point. The Messenger also has somewhat better than average communication range and can act as a communication node for other spacecraft. Furthermore, the Messenger attempts to take data from the Workers for eventual transmission to Earth. Rulers and Messengers might also act as timing beacons for positioning and asteroid gravity studies. Simple models of the asteroid may be created and transmitted to the ANTs starting to SWARM about the asteroid; these models may help individual ANTs plan trajectories about the asteroid.

Workers Acquire Data Workers arrive and begin seeking trajectories that will allow efficient operation of their instruments. As the spacecraft drop towards the asteroid the aforementioned collision avoidance functions gain importance. To reduce the possibility of single point failures, we believe that trajectory determination should be distributed to the individual spacecraft rather than handled through a central controller.

Workers with Gamma Ray detectors seek orbits with low periasters on the dark side of the asteroids; those with X-ray spectrometers seek high integration times on the sunlit side. Workers with magnetometers seek orbits with a wide and deep coverage of the space around the asteroid. As mentioned previously, a hovering spacecraft that can measure the Doppler shifts of radio beacons of the Workers could fairly rapidly build a model of the mass distribution of the asteroid. ANTs should be able to adapt their observing plans to take advantage of interesting features as they are detected.

Workers Complete Observations As the spacecraft complete their measurements or fill their data buffers, they start to move away from the asteroid. Moving away from the asteroid creates the opportunity for other spacecraft to approach the asteroid. Workers may also require time to digest or reduce their raw data into models and statistics that are more suitable for transport. Workers may call Messengers via the LBW link and then transfer the reduced data via HBW links to Messengers who move from Worker to Worker as needed. Once done transferring data to the Messengers, the Worker proceeds to the next important asteroid for more data.

Messengers Consolidate Results The Messengers respond to the calls of Workers and Rulers for data transfers, and also share data amongst themselves. When a Messenger reaches the limit of its memory store, it uses its superior mobility to move rapidly to Earth where it downloads its information to an appropriate communications point.

Scenario Summary In this operational scenario we have described the role that Rulers play in assessing information provided by Imaging Workers that detect and track asteroids. The Rulers propagate signals throughout the SWARM that cause Workers to drop towards important asteroids where the Workers collect their data. Workers collect their data and, when full, process the data into more transportable forms. Messengers work to alleviate Workers of their data load so they may return to work. Messengers transfer reduced data and other information throughout the SWARM and eventually to Earth.

CONCLUSION

There are several areas that require further study for a realistic assessment of the feasibility of the ANTS concept. First there should be a careful analysis of the utility of each individual instrument in terms of potential mission goals, the current state-of-the-art in terms of the sensor technology employed in the measurement and the likelihood that the technology would be significantly improved by the time frame of the mission. Second, the parameters for the automated survey of the target by an individually instrumented ANT would need to be specified in terms of realistic objectives achievable with the sensors expected to be available at the time of the mission. Finally, an optimal mission strategy that specifies the primary mission objectives is required. Several key requirements must be elucidated: 1) the optimal number of each of the specific instruments deployed within each SWARM; 2) the time requirements to survey each target object to a specific degree of accuracy; 3) the utility of each instrument in achieving the primary mission goals; 4) a straw man exploration strategy to be followed by the SWARM after arrival at each target.

Mission requirements and cost will be affected by the technology available during mission implementation.

A goal of this work is to point out areas in which technology development should be fostered. A multispacecraft mission was advocated to increase SWARM robustness to hazards and faults, to decrease mission implementation and operational costs, and to enable the survey of thousands of asteroids. A simple operational scenario was presented to help illustrate how ANTS might function. Necessary and desirable system traits and functions within the analogy of social insect behavior point towards the importance of single-spacecraft autonomy operating within a system that achieves goals via emergent, collective behavior. Single spacecraft autonomy is an existing important technological thrust for NASA, while understanding and utilizing emergent, collective behaviors is a fundamental problem driving current research in Computer Science. In addition to the technologies that deal with self-directed and collective operations, a broad range of sensors and other spacecraft subsystems were mentioned with their needs for technological advance in mind.

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[1] For a discussion of the state-of-the-art in small spacecraft and sensor technology, including technology roadmaps, see the *Proceedings of the Second International Conference on Integrated Micro/Nanotechnology for Space Applications*, E. Robinson ed., 1999, *et seq*.

[2] M. Krieger, J.-B. Billeter, & L. Keller, "Ant-like task allocation and recruitment in cooperative robots", *Nature*, 406, 992, 31 August 2000 provides experimental evidence for the utility of the insect analogs. Another use of an insect-analogy in the development of a distributed autonomous control system is C. Ferrel, "Global Behavior via Cooperative Local Control", *Autonomous Robots*, 2:2, 105-125, 1995. A somewhat more conventional approach, but within the context of spacecraft autonomy is N. Muscettola et al., "Remote Agent: To Boldly Go Where No AI System Has Gone Before", *Artificial Intelligence* 103(1-2):5-48, August 1998.

[3] P. Panetta et al., "NASA-GSFC Nano-Satellite Technology Development", in *Proceedings of the 12th AIAA/USU Conference on Small Satellites*, 1998.

[4] NASA Sun-Earth Connections: "sec.gsfc.nasa.gov".

[5] The Near Earth Asteroid Rendezvous (NEAR) mission is the current state-of-the-art in asteroid exploration. A. Santo, S. Lee, and R. Gold, "NEAR Spacecraft and Instrumentation", *J. Astronomical Sciences*, Vol. 43, No. 4, 373-397, 1995. A sample of NEAR science results appears in the 22 September 2000 issue of *Science*.

[6] M. Acuña, C. Russell, L. Zanetti, and B. Anderson "The NEAR magnetic field investigation: Science objectives at asteroid Eros 433 and experimental approach", *J. Geophys. Res.,* 102, E10, 23751, 1997.

[7] J. Trombka, et al., "The Elemental Composition of Asteroid 433 Eros: Results of the NEAR-Shoemaker X-ray Spectrometer", *Science*, 289, 2101, 22 September 2000.

[8] D. Yeomans, et al., "Radio Science Results During the NEAR-Shoemaker Spacecraft Rendezvous with Eros", *Science*, 289, 2085, 22 September 2000.

[9] R. Brooks, "A Robust Layered Control System for a Mobile Robot", *IEEE Journal on Robotics and Automation*, RA-2, 1, March 1986.