Asteroid Exploration with Autonomic Systems

Walt Truszkowski, James Rash
NASA GSFC
Code 588
walter.f.truszkowski@nasa.gov
james.l.rash@nasa.gov

Christopher Rouff
SAIC
703-676-6184
rouffc@saic.com

Mike Hinchey
NASA GSFC
Code 581
michael.g.hinchey@nasa.gov

Abstract

NASA is studying advanced technologies for a future robotic exploration mission to the asteroid belt. The prospective ANTS (Autonomous Nano Technology Swarm) mission comprises autonomous agents including "worker" agents (small spacecraft) designed to cooperate in asteroid exploration under the overall authority of at least one "ruler" agent (a larger spacecraft) whose goal is to cause science data to be returned to Earth. The ANTS team (ruler plus workers and messenger agents), but not necessarily any individual on the team, will exhibit behaviors that qualify it as an autonomic system, where an autonomic system is defined as a system that self-reconfigures, self-optimizes, self-heals, and self-protects. Autonomic system concepts lead naturally to realistic, scalable architectures rich in capabilities and behaviors. In-depth consideration of a major mission like ANTS in terms of autonomic systems brings new insights into alternative definitions of autonomic behavior. This paper gives an overview of the ANTS mission and discusses the autonomic properties of the mission.

Key Words: Agent, autonomy, autonomic, asteroid, spacecraft

1. Introduction

Autonomous intelligent swarms [3, 4, 5] of satellites are being proposed for missions that have complex behaviors and interactions. These types of missions provide greater flexibility and the chance to gather more science than traditional single satellite missions. The Autonomous Nano Technology Swarm (ANTS) mission is an example of one of the swarm types of missions NASA is considering. The ANTS mission will use a swarm of pico-spacecraft that will fly from Earth orbit to the Asteroid Belt. Using an insect colony analog, ANTS will be composed of specialized workers for asteroid exploration. Exploration would consist of cataloguing the mass, density, morphology, and chemical composition of the asteroids, including any anomalous concentrations of specific minerals. To perform this task, ANTS would carry miniaturized instruments, such as imagers, spectrometers, and detectors.

2. ANTS Mission Overview

The Autonomous Nano-Technology Swarm (ANTS) mission [6, 7, 8, 9] will have swarms of autonomous pico-class (approximately 1kg) spacecraft that will search the asteroid belt for asteroids that have specific characteristics. There will be approximately 1,000 spacecraft involved in the mission. Figure 1 gives an overview of the properties of the mission. There will be several specialized spacecraft involved in the swarms. Many of these spacecraft (called specialist) will have a specialized instrument for collecting data on asteroids. To examine an asteroid, the spacecraft will have to cooperate since they each only have a single instrument on board. To do this they will use an insect analogy of hierarchical social behavior were some spacecraft are directing others. Sub-swarms will exist that will act as teams that explore a particular asteroid based on the asteroids properties. Teams will have to share resources (instruments) between each other.

The spacecraft will initially be carried to the asteroid belt by a transport ship, manufactured along the way and then released into the asteroid belt. Replacement spacecraft will be sent from Earth on an as-needed basis. There will be several types of spacecraft involved in the mission (Figure 2). Some of the spacecraft, called workers, will have the specialized instruments onboard (e.g., a magnetometer, x-ray, gamma-ray, visible/IR, neutral mass spectrometer) and each will obtain specific types of data. Some will be coordinators (called rulers) that have rules that decided the types of asteroids and data the mission is interested in and will coordinate the efforts of the workers. Messengers, the third type of spacecraft, coordinate communications between the workers, rulers and Earth. Each worker spacecraft will examine asteroids they encounter and send messages back to a coordinator that will then evaluate the data, form a team to investigate it that contains the appropriate spacecraft with specialized

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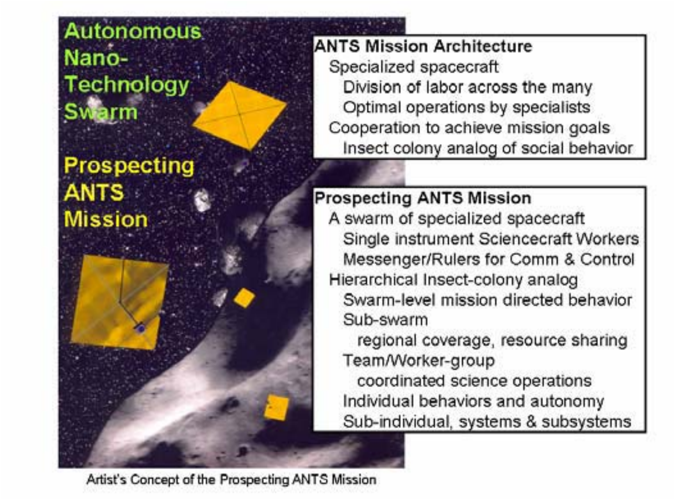

Figure 1: ANTS Mission Overview.

instruments to the asteroid to gather further information if needed. Approximately 80 percent of the spacecraft will be workers. As data is collected, the data is sent back periodically via the messengers.

To implement this mission a high degree of autonomy is being planned, approaching total autonomy and will require autonomic properties. A heuristic approach is being considered that provides for a social structure to the spacecraft based on the above hierarchy. Artificial intelligence technologies such as genetic algorithms, neural nets, fuzzy logic and on-board planners are being investigated to assist the mission to maintain a high level of autonomy. Crucial to the mission will be the ability to modify its operations autonomously to reflect the changing nature of the mission and the distance and low bandwidth communications back to Earth.

A virtual experiment is conducted in the ANTS mission by an ANT subset consisting of a Leader spacecraft and individual worker spacecraft. Details of the operations of the ANTS mission can be found in "Protocol for ANTS Encounters" [1] and "Prospecting ANTS Missions: Applying a New Paradigm to Lunar and Planetary Exploration" [2]. Additional information on the ANTS mission can also be found in papers freely available on the ANTS mission web site [2]. These papers include "ANTS (Autonomous Nano Technology Swarm): An Artificial Intelligence Approach to Asteroid Belt Resource Exploration", "Onboard Science Software Enabling Future Space Science and Space Weather Missions", "ANTS for the Human Exploration and Development of Space, and "Describing Intelligent Agent Behavior". Additional information on ANTS is also available in the presentations "Autonomous Nano Technology Swarm" and "RASC/ANTS Operations

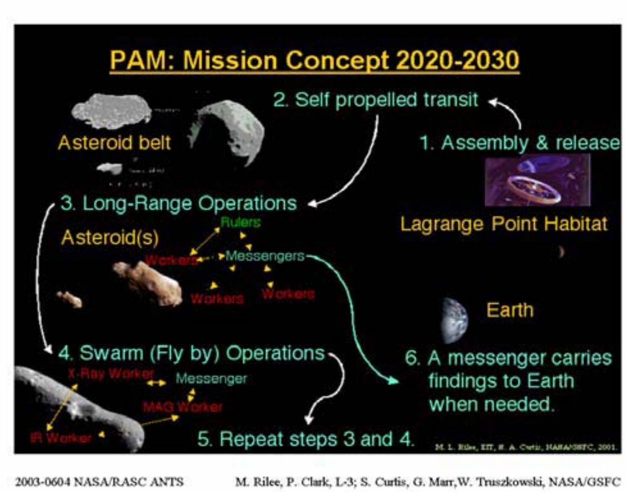

Figure 2: ANTS Mission Concept.

Concept Overview" that are available from the ANTS web site.

A scenario for the ANTS mission is based on the ANTS targeting an asteroid on which to do an experiment and then forming a team to carry out that experiment. The following is a brief description of the scenario (from [2]):

> Team leaders contain models of the types of science they want to perform. Parts of this model are communicated to the messenger spacecraft that then relay it on to the worker spacecraft. The worker spacecraft then take measurements of asteroids using whatever kind of instrument they have until something matches the goal that was sent down by the leader.

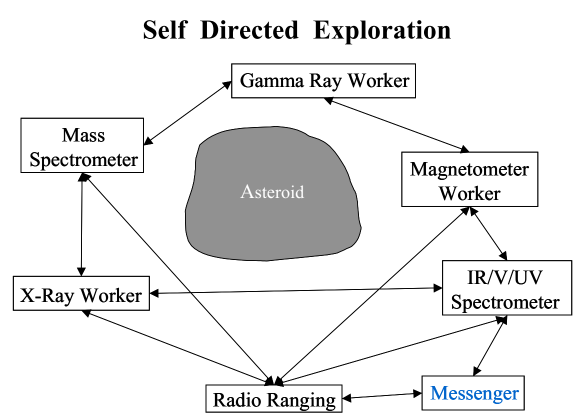

Figure 3: ANTS Cooperation and Collaboration in a virtual experiment.

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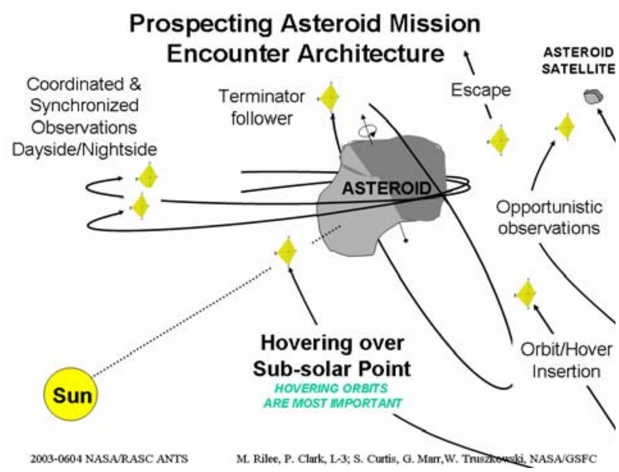

Figure 4: ANTS encounter with an asteroid.

The data will then be sent to a messenger to be sent back to the leader. If the data matches the profile of the type of asteroid that is being searched for, an imaging spacecraft will be sent to the asteroid to ascertain the exact location and to create a rough model prior to the arrival of other spacecraft so they have a model to use for maneuvering around the asteroid.

Other spacecraft that would then work together to finish the model and mapping of the asteroid would include:

- an asteroid detector/stereo mapper team that would consist of two spacecraft with field imaging spectrometers, a dynamic modeler with an enhanced radio science instrument for measuring dynamic properties (such as spin, density and mass distribution)
- a petrologist team that would consist of X-ray, Near Infrared, Gamma-ray, Thermal IR and wide fieled imager to determine the distribution of elements, minerals and rocks present
- a photogeologist team that would consist of Narrow Field and Wide Field Imagers and Altimeter to determine the nature and distribution of geological units based on texture, albedo, color, and apparent stratigraphy
- a prospector team consisting of an altimeter, magnetometer, near infrared, infrared, and X-ray spectrometers to determine the distribution of resources

The above teams would work together to form a model of asteroids as well as form virtual instruments.

Many things can happen when an ANTS team encounters an asteroid (Figure 4). A spacecraft can do a flyby and do opportunistic observations. The flyby can be used to first determine if the asteroid is of interest before sending an entire team to the asteroid, or due to the nature of the instrument on the spacecraft, only a flyby is necessary. If the asteroid is of interest, a mapping spacecraft will map the asteroid and determine its size, rate and axis of rotation, whether the asteroids have any satellites/moons, etc. This information is passed on to other spacecraft that will be doing observations and need to do a flyby, enter an orbit around the asteroid, enter a hovering point, etc.. As more data is obtained about the asteroid, other ANTS maybe sent to the asteroid for further data gathering.

3. Autonomic Systems

An Autonomic Computing System must follow four basic principles [10]. They must be:

- Self-configuring; that is, able to adapt to changes in the system
- Self-optimizing; that is, able to improve performance
- Self-healing; that is, able to recover from errors
- Self-protecting; that is, able to anticipate and cure intrusions

The vision of Autonomic Computing as given in [10] views a system as being robust across these complementary dimensions as shown in Figure 5.

4. Autonomic Properties of ANTS

The ANTS system may be viewed as an Autonomic System as it meets these four requirements.

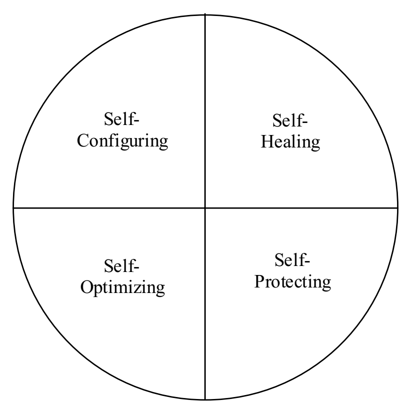

Figure 5: Dimensions of an autonomic system.

4.1. ANTS is Self-Configuring

ANTS has an overall requirement to prospect thousands of asteroids per year with large but limited

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resources. To accomplish this it is anticipated that there will be approximately one month of optimal science operations at each asteroid prospected. A full suite of scientific instruments will be deployed at each asteroid. The ANTS' resources will be configured and re-configured to support concurrent operations at hundreds of asteroids over a period of time.

The overall ANTS mission architecture calls for specialized spacecraft that support division of labor (rulers, messengers) and optimal operations by specialists (workers). A major feature of the architecture is support for cooperation among the spacecraft to achieve mission goals. The architecture supports swarm-level mission-directed behaviors, sub-swarm levels for regional coverage and resource-sharing, team/worker groups for coordinated science operations and individual autonomous behaviors. These organizational levels are not static but evolve and self-configure as the need arises. As asteroids of interest are identified appropriate teams of spacecraft are configured to realize optimal science operations at the asteroids. When the science operations are completed, the team disperses for possible reconfiguration at another asteroid site. This process of configuring and reconfiguring continues throughout the life of the ANTS mission.

Reconfiguring may also be required as the result of a failure or anomaly of some sort. Some examples are:

- A worker may be lost due to collision with an asteroid, failure of its communication devices, or hardware failure. The loss of a given worker may result in the role of that worker being performed by another, which will be allocated the tasks and resources of the original.
- Loss of communication with a worker may mean that the system has to assume loss of the worker, and the role may be allocated to another spacecraft.

4.2. ANTS is Self-Optimizing

Optimization of the ANTS is done at the individual level as well as at the system level. These optimizations are:

- Rulers learning about asteroids
- Messengers adjusting their position
- Workers learning about asteroids

Optimization at the ruler level is primarily done through learning. Rulers over time will be collecting data on different types of asteroids and will over time be able to better determine the characteristics of the types of the asteroids that are of interest and perhaps the types of asteroids that are difficult to orbit or get data from (e.g., an asteroid with a fast rotation that is difficult to focus on). From this information the system as a whole is being optimized since time is not being wasted on asteroids that are not of interest.

Optimization for messengers is done through positioning. Messengers need to provide communications between the rulers and workers as well as back to Earth. This means that a messenger will have to be constantly adjusting its position to balance the communications between the rulers and workers and perhaps adjusting its position so it can send data back to Earth while also maintaining the communications between rulers and workers.

Optimization at the worker level is primarily done through its experience gained with asteroids. As a worker observes asteroids and builds up a knowledge base of the different characteristics of asteroids, a worker may be able to skip over asteroids that are not of interest automatically, thus saving time and optimizing the exploration of the mission as a whole.

4.3 ANTS is Self-Healing

The view of self-healing here is slightly different from that given in [10]. ANTS is self-healing not only in that it can recover from mistakes, but self-healing in that it can recover from failure, including damage from outside force. In the case of ANTS, these are non-malicious sources:

- Events such as collision with an asteroid, or another satellite, loss of connection, etc., will require ANTS to heal itself by replacing one spacecraft with another.
- Loss of use of an instrument may require the worker to take the role of a communication device.

ANTS mission self-healing scenarios span the range from negligible to severe. An example entailing negligible self-healing would be an instance where one member of a redundant set of gamma ray sensors fails before a general gamma ray survey is planned. In such a scenario, the self-healing behavior would be the simple action of deleting the sensor from the list of functioning sensors. At the severe end of the range, an example scenario would arise when the team loses so many workers it can no longer conduct science operations. In this case, the self-healing behavior might be to advise the mission control center and, when a replacement worker arrives, to incorporate the replacement into the team, performing, additionally, any necessary self-configuration and self-optimization. In some possible ANTS mission concepts, instead of "calling home" for help, an ANTS team may only need to request a replacement from

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another team or from a fielded repository of spares orbiting in the vicinity.

Not only the ANTS team, but also ANTS individuals may have self-healing behaviors. For example, an individual may have the capability of detecting corrupted code (software). In such a case, self-healing behavior would result in the individual's requesting a copy of the affected software from another individual in the team, which would enable the individual to restore itself to a known operational state.

4.4. ANTS is Self-Protecting

The self protecting behavior of the team will be interrelated with the self-protecting behavior of the individual members. The anticipated sources of threats to ANTS individuals (and consequently to the team itself) will be collisions and solar storms.

Collision avoidance through maneuvering will be limited because ANTS individuals will have limited ability to adjust their orbits and trajectories, since thrust for maneuvering is obtained from solar sails. Individuals will have the capability of coordinating their orbits and trajectories with other individuals to avoid collisions with them. Given the chaotic environment of the asteroid belt and the highly dynamic trajectories of the objects in it, occasional near approaches of interloping asteroidal bodies (even small ones) to the ANTS team may present threats of collisions with its individuals. Collision-avoidance maneuvering for this type of spacecraft presents a large challenge and is currently under consideration. The main self-protection mechanism for collision avoidance is achieved through the process of planning. The ruler's plans involve constraints that will result in acceptable risks of collisions between individuals when they carry out the observational goals given to them by the ruler. In this way, ANTS exhibits a kind of self-protection behavior against collisions.

Another possible ANTS self-protection mechanism could protect against effects of solar storms. Charged particles from solar storms could subject individuals to degradation of sensors and electronic components. The increased solar wind from solar storms could also affect the orbits and trajectories of the ANTS individuals and thereby could jeopardize the mission. ANTS mechanisms that are protective against effects of solar storms have not been determined or included in the mission design. One possible mechanism would involve a capability of the ruler to receive a warning message from the mission control center on Earth. An alternative mechanism would be to provide the ruler with a solar storm sensing capability through on-board, direct observation of the solar disk. When the ruler recognizes that a solar storm threat exists (either upon receipt of a solar storm warning from the control center or upon reaching its own conclusion from its own direct observations), the ruler would invoke its goal to protect the mission from harm from the effects of the solar storm. In addition to its own action to protect itself, part of the ruler's response would be to give workers the goal to protect themselves. Part of an individual's protective response might be to orient solar panels and sails to minimize impact of the solar wind. An additional response might be to power down subsystems to minimize disruptions and damage from charged particles.

Thus, with such capabilities, an ANTS mission will exhibit self-protecting behavior. As noted in the section on self-configuring behavior, after-effects of protective action will, in general, necessitate ANTS self-reconfiguration. For example, after solar sails had been trimmed for the storm blast of solar wind, individuals will have unplanned trajectories, which will necessitate trajectory adjustments and replanning and perhaps new goals. Further, in case of the loss of individuals due to damage by charged particles, the ANTS self-healing behavior and the self-optimizing behavior may also be triggered. Thus, there is an interrelatedness of the self-protecting behaviors of the ANTS team and the ANTS individuals.

5. Analysis

From the description of how ANTS may be viewed to satisfy the four basic principles required for classification as an Autonomic System, we see significant overlap in the scenarios. In particular, self-healing is often likely to require self-configuration. Clearly this will not always be the case – a system where one component is replaced by a homogeneous component will likely not need to be re-configured. In the case, for example, where a worker loses so many of its sensors that it can no longer make science observations, the ruler may give it the goal to take the role of a communications node (messenger agent), and this would entail a degree of self-reconfiguration (and possibly self-re-optimization) by the ANTS team.

Similarly, self-protection may require the addition of additional components (whether or not they are identical to other components in the system) or replacement of components with others that have better protection mechanisms. This will likely require some degree of re-configuration (in the case of an Autonomic System, to be performed autonomously by the system itself), and possibly some degree of optimization to take advantage of the new components and to ensure that all resources are being used effectively. In the class of systems we are discussing, these would be self-configuration and self-optimization.

In reality, at least for the types of system we are developing, the diagram of Figure 5 is unrealistic and

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overly simplistic. From our experience, we view the complimentary dimensions of [10] as overlapping.

6. Conclusions and Further Work

This paper has begun to establish the fact that the ANTS mission, defined as a swarm of cooperating autonomous spacecraft whose mission is the scientific exploration of the asteroid belt, qualifies as an autonomic system, that is, ANTS is a self-configuring, self-optimizing, self-healing, and self-protecting system. We have tried to establish that:

- the self-configuring and reconfiguring behavior of the limited ANTS' resources is a requirement for the successful science operations of the mission.
- ANTS' self-optimizing behaviors arise, for example, from worker and ruler abilities to perceive and to learn, not only about their environment, but also about each other and themselves in an iterative fashion.
- the ANTS swarm is self-healing due, for example, to its ability to introduce into a formed team a replacement for a dead worker or to accommodate the changes of capabilities of workers over time or as a result of their degradation by the environment. This process also, in general, brings into play the self-configuring and self-optimizing behaviors.
- ANTS' self-protecting behaviors are a complex of individual self-protection behaviors with the self-optimizing, self-configuring, and self-healing behaviors of the team.

Future work will include:

- the development of more comprehensive operational scenarios addressing the full range of desired behaviors for the ANTS' resources
- firmly establishing the autonomic properties of the ANTS system
- establishing formal specifications for the ANTS mission as was started in [11]
- formally capturing the autonomic properties of the ANTS' system, and
- the prototyping and simulation of the autonomic system behaviors in the ANTS context.

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