

Intelligence in Future NASA Swarm-based Missions

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Abstract

NASA is researching advanced technologies for future exploration missions using intelligent swarms of robotic vehicles. One of these missions is the Autonomous Nano Technology Swarm (ANTS) mission that will explore the asteroid belt using 1,000 cooperative autonomous spacecraft. The emergent properties of intelligent swarms make it a potentially powerful concept, but at the same time more difficult to design and implement. In addition, a reliance on intelligence in each of the spacecraft and collective intelligence in teams of spacecraft will be needed to successfully execute maneuvers in and around asteroids. Designing, verifying and validating this collective intelligence will be one of the major challenges of the mission.

Introduction

NASA is investigating new paradigms for future space exploration, heavily focused on the (still) emerging technologies of autonomous and autonomic systems (Truskowski et al., 2006). Traditional missions, reliant on one large spacecraft, are being replaced with missions that involve smaller collaborating spacecraft, analogous to swarms in nature (Curtis et al., 2000, Curtis et al. 2003). This approach offers several advantages: the ability to send spacecraft to explore regions of space where traditional craft simply would be impractical, greater redundancy (and, consequently, greater protection of assets), and reduced costs and risk, to name but a few.

Concept swarm missions include the use of unmanned autonomous vehicles (UAVs) flying approximately one meter above the surface of Mars, which will cover as much of the surface of Mars in three seconds as the now famous Mars rovers did in their entire time on the planet; the use of armies of tetrahedral walkers to explore the Mars and Lunar surface (Clark et al., 2002); constellations of satellites flying in formation; and, the use of miniaturized spacecraft to explore the asteroid belt, where heretofore it has been impossible to send exploration craft without the high likelihood of loss.

These new approaches to exploration simultaneously pose many challenges. The missions will be unmanned and highly autonomous. They will also exhibit the properties of autonomic systems, being self-protecting, self-healing,

self-configuring, and self-optimizing. Many of these missions will be sent to parts of the solar system where manned missions are simply not possible, and to where the round-trip delay for communications to spacecraft exceeds 40 minutes, meaning that the decisions on responses to exploration opportunities as well as problems and undesirable situations must be made *in situ* rather than from ground control on Earth. To handle these unforeseen situations, intelligence will be added to the missions both to individual spacecraft and collectively in teams.

Intelligent Swarm Technology

Bonabeau and Theraulaz (Bonabeau and Theraulaz, 1997, Bonabeau and Theraulaz, 2000) who have studied self-organization in social insects stated “that complex collective behaviors may emerge from interactions among individuals that exhibit simple behaviors” and described emergent behavior as “a set of dynamical mechanisms whereby structures appear at the global level of a system from interactions among its lower-level components.” These emergent behaviors are the sums of simple individual behaviors, but, when aggregated together, form complex and often unexpected behaviors. The emergent behavior of a swarm is sometimes referred to as the macroscopic behavior and the individual behavior and local interactions as the microscopic behavior.

Intelligent swarms (Beni and Want, 1989) are the use of swarms of simple agents using local interactions (interactions between agents and the environment). There is no central controller directing the swarm, they are self-organizing based on the emergent behaviors of the simple interactions. The emergent behavior is sometimes referred to as the macroscopic behavior and the individual behavior and local interactions as the microscopic behavior. These types of swarms exhibit self-organization since there is no external force directing their behavior and no one agent has a global view of the intended macroscopic behavior. This type of behavior is observed in insects and flocks of birds. In addition to NASA missions, swarm behavior is also being investigated for use in such applications as telephone switching, network routing, data categorizing, and shortest path optimizations.

With intelligent swarms, members of the swarm may be heterogeneous or homogeneous. Even if the members of the swarm start out as homogeneous, due to their differing environments they may learn different things, develop different goals and therefore become a heterogeneous swarm. Intelligent swarms may also be made up of heterogeneous elements from the outset, reflecting different capabilities as well as a possible social structure.

ANTS Mission Overview

Swarm technologies, whereby systems of spacecraft or rovers (of varying degrees of intelligence) mimic swarms, colonies, or flocks in nature (such as bees, ants, or geese) have become a major focus for future NASA missions. These types of missions provide greater flexibility and the chance to gather more science than traditional single vehicle missions. The emergent properties of swarms make these missions powerful, but at the same time more difficult to design and to ensure that the proper behaviors will emerge.

An example of one of these missions is the NASA Autonomous Nanotechnology Satellites (ANTS) concept mission that will exploit swarm technology, launching 1000 picosatellites to investigate the asteroid belt, where a traditional spacecraft could not possibly survive. To examine an asteroid, the spacecraft will have to cooperate since they each have only a single instrument on board. To do this they will use an insect analogy of hierarchical social behavior where 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 to investigate an asteroid.

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 1). 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 determine 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 data back to a coordinator that will then evaluate the data, form a team to investigate it (if of interest to the mission) that contains the appropriate spacecraft with specialized instruments to the asteroid to gather further information if needed.

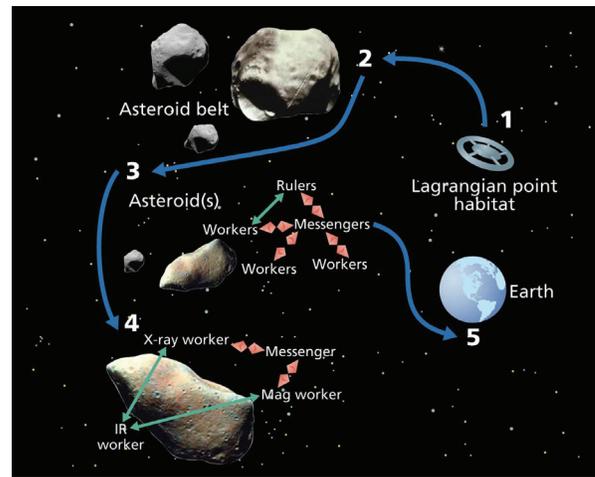


Figure 1: ANTS Mission Concept.

Approximately 80 percent of the spacecraft will be workers. As data is collected, the data is sent back periodically via the messengers. It is estimated that as much as 70% of the picosatellites will be destroyed while passing through the asteroid belt. There must be sufficient in-built intelligence so that functionality can be redistributed to recover from losses as well as accommodate new spacecraft that are added to the mission at a later date.

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. 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:

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.

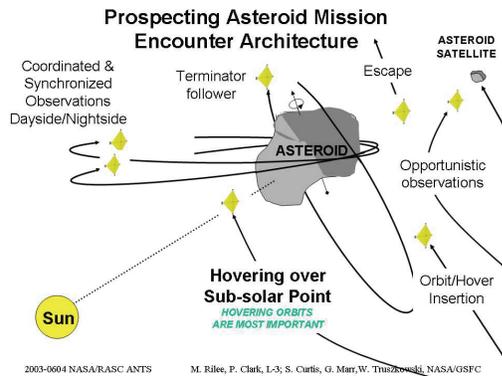


Figure 2: ANTS encounter with an asteroid.

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 mapping 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 field 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 2). A spacecraft can do a flyby and perform 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 may be sent to the asteroid for further data gathering.

Intelligence in Swarm Missions

As can be seen from the above scenario, intelligence is needed at the individual spacecraft level as well as collectively when spacecraft from teams to investigate an asteroid.

For individual spacecraft, intelligence is needed to search out asteroids of interest. The leaders need a level of intelligence to know the attributes of asteroids that are of interest and to not investigate asteroids of the same type that were previously investigated. Workers need the intelligence to navigate in and out of the asteroid belt while searching for new asteroids. Due to the propulsion, solar sails, a large amount of planning has to go into maneuvers. Each individual spacecraft will also have to have autonomic properties (Horn 2001, Murch 2004) for self protection so it does not collide with other spacecraft or asteroids, self optimization since many aspects of the mission will not be known beforehand, and self configuring since they are going to be manufactured in route to the asteroid belt.

The mission will also need to have collective or shared intelligence. Collective intelligence will also be needed so the same asteroids are not searched by spacecraft with the same instruments. This information may not be centralized but be in the form of the swarm's collective knowledge. Collective intelligence will also need to be used when a team performs a virtual experiment. Spacecraft that map asteroids will have to share that knowledge with other spacecraft so they can perform their calculations on how to set up orbits or flybys. In addition, spacecraft will have to sequence themselves so that spacecraft do not run into each other or interfere with each other when they are performing their experiments.

Verification

The *Formal Approaches to Swarm Technology* (FAST) project (Rouff et al., 2006, Rouff et al., 2007) worked on a formal approach to the development and verification of complex swarm-based systems, using ANTS as a baseline for comparing approaches. A formal specification would need to be able to track the goals of the mission as they change and to modify the model of the universe as new data comes in. A formal specification would also need to

allow for specification of the decision-making process to aid in the decision of which instruments will be needed, at what location, with what goals, etc. This approach concentrated on verification of the system as well as detecting race conditions, proving properties correct and predicting emergent behavior.

Measurement of Intelligence

What such missions as ANTS would also need is a method for determining the level of intelligence needed for the mission and if that level of intelligence was obtained. Quantifying the amount of intelligence needed to perform the required tasks and the amount developed would help in verifying this type of mission.

The most famous method of determining intelligence in machines is of course the Turing Test (Turing, 1950). For the above types of missions, a test such as a Turing test would not be applicable. IQ quotients have also been suggested for measuring intelligence of machines (Falqueto et al, 2001). The intelligence of each of the spacecraft may be limited and should only provide enough intelligence that is needed to perform the mission. Too little intelligence and the mission will fail and too much and the system has excess capacity and memory or CPU time is over used and development funds are wasted.

For verification purposes, a general level of intelligence would also not give developers an indication of whether the system had the intelligence to perform specific tasks, like planning or discovery. To this end, quantification of intelligence for specific tasks would allow developers to determine the levels of intelligence needed for a system and verify through testing, formal methods or other means that the indicated level of intelligence was provided.

One method to quantify the various levels of intelligence needed would be giving the system or subsystem a test. The system or subsystem would then have to reach a "passing" grade based on the specified degree of intelligence needed. Determining these tests could be similar to standardized tests given on various subjects in education. This would provide a level of competence by an intelligent system and would also help to develop reusable modules that are verified at a predetermined level of intelligence.

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