Autonomy in Future Space Missions

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Abstract

NASA missions are becoming more complicated due to the decreasing cost of spacecraft; the increased sensitivity and data gather capability of onboard instruments, and the need to use multiple spacecraft to accomplish new science. To accommodate these new missions current ground and space operations will need to use new paradigms to implement these new missions while keeping costs and logistics manageable. This paper gives some background on some of the new multi-satellite missions in the near future, challenges of these types of missions, how autonomy could be added to these missions and why adding autonomy will be necessary to make them successful from a science gathering, operational and financial standpoint.

Introduction

As NASA and other space missions become increasingly complex and the quantity of data being collected increases, PIs and program managers are looking for technology that can help them implement these missions as well as to decrease the cost of the spacecraft and operations. To gather more sophisticated data, missions are starting to utilize multiple spacecraft in the form of constellations or swarms to accomplish their science. These multi-spacecraft systems make performing the needed science easier, but create new challenges in the areas of communications, coordination and ground operations. In addition, there are now large quantities of data that need to be downloaded from these missions.

Until recently, space missions have been operated manually from ground control centers. The high costs of satellite operations have prompted NASA and others to seriously look into automating as many functions as possible. A number of more-or-less automated ground systems exist today, but work continues with the goal of reducing operation costs to even lower levels, especially with multi-satellite missions. Cost reductions can be achieved in a number of areas. Greater autonomy of satellites and ground control is one way (Hallock et al. 1999) (Truszkowski and Hallock 1999).

With current operations, spacecraft send their data (engineering and sensor) back to earth for processing and then receive their commands from analysts at the control center. As the number of satellites increase, it is taking an increasingly large number of control personnel to operate them. Table 1 shows the current ratio of number of spacecraft controllers need per spacecraft in the group (either constellation or swarm) as well as future goals for reducing this ration. As can be seen from this table, large reductions in controllers will be needed to keep operations costs in line. The most effective way of accomplishing this reduction is through adding autonomy to these future missions.

To accomplish cost reductions, NASA has set far-reaching autonomy goals for ground-based and space-based systems. More reliance on "intelligent" systems and less on human intervention characterizes its autonomy goals. These goals of cost reduction have been further complicated by multi-satellite systems, which NASA has little experience operating even manually, much less with autonomous systems. The following discusses some of these upcoming missions.

NASA Missions and Autonomy

Examples of some of the upcoming multi-satellite missions are like ANTS, STEREO, Magnetosphere, NMP-ST5, the many constellation missions that are being planned, as well as current coordinating missions like TDRSS. Flying clusters of multiple satellites reduces the risk of the entire mission failing if one system or instrument fails. To implement these systems, developers are proposing intelligent and autonomous systems.

The following discusses some of these upcoming missions and how autonomy is being planned for the mission and/or how autonomy could make the mission more successful.

FY	Number of s/c	Number of FTEs w/current technology	Current People:s/c	Goal People:s/c
‘00	1 (e.g. MAP)	4	4:1	
‘00	66 (e.g. Iridium)	200	3:1	
‘00	48 (e.g. GlobalStar)	100	2:1	
‘03	3	12		1:1
‘09	50-100	200-400		1:10

*GlobalStar and Iridium represent a simpler constellation concept than what is being proposed by future NASA Science Mission.

Table 1: Ratio Goals for People Controlling Spacecraft

ANTS Mission

One of the new proposed missions that would use large amounts of autonomous software is the ANTS (Autonomous Nano-Technology Swarm) mission, shown in Figure 1. The ANTS mission will have swarms of autonomous satellites that will search for asteroids that have specific characteristics.

There will be a number of satellites involved in the mission, initially carried to the asteroid belt by a mother ship. Some will have specialized instruments (called workers) that can 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. The third types of satellites are called messengers and they 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 send other appropriate satellites with specialized instruments to the asteroid to gather further information. Testing such systems for errors, especially since the satellites are heterogeneous and autonomous, will be a difficult task.

NMP ST5

The New Millennium Program's (NMP) Space Technology 5 (ST5), is shown in Figure 2. Magnetometers onboard each of the satellites will measure

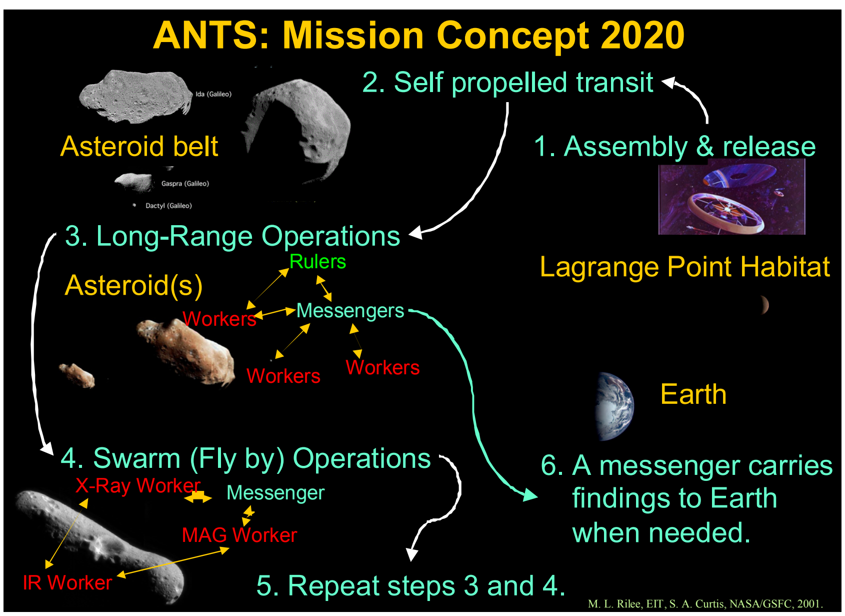

Figure 1: ANTS Mission Concept

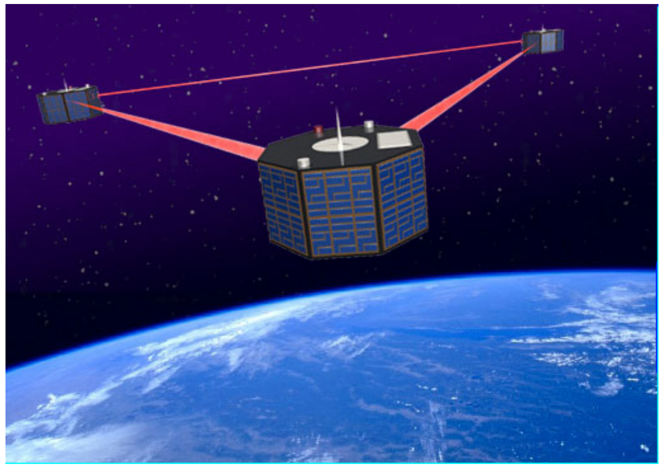

Figure 2: New Millennium Program

the magnetosphere. Currently ST5 is slated for each of the satellites to be commanded individually and communicate directly to the ground. There will be one week of "lights out" during which the nanosats will fly "autonomously" with preprogrammed commands in a test to determine if ground commanding is necessary. One idea that has been explored is the idea of having proxy agents on the ground that operate as if they are onboard [Truszkowski and Rouff 2001]. Future nanosat missions will fly with tens to a hundred spacecraft.

STEREO

The Solar-Terrestrial Relations Observatory (STEREO) mission, Figure 3, will study the Sun's coronal mass ejections (CMEs) which are powerful eruptions in which as much as ten billion tons of the Sun's atmosphere can be blown into interplanetary space, which can cause severe magnetic storms on Earth. It will track CME-driven disturbances from the Sun to Earth's orbit and determine 3D structure and dynamics of coronal and interplanetary plasmas and magnetic fields, among other things. It will use two spacecraft with identical instruments (along with ground-based instruments) that will provide a stereo reconstruction of solar eruptions.

MMS Magnetosphere Multiscale

For the magnetosphere mission, each spacecraft will be positioned so that it is located at one of the four points of a pyramid. This arrangement will allow three-dimensional structures to be described, for the first time, in both the

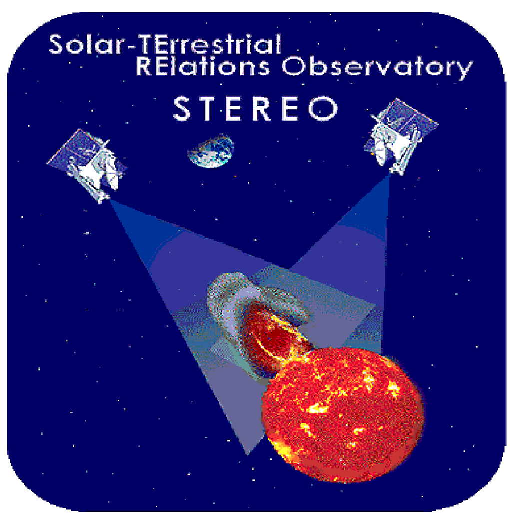

Figure 3: STEREO Mission studying the sun.

magnetosphere and solar wind. The four Cluster II spacecraft will observe the response of Earth's magnetosphere to the ebb and flow of the solar wind.

Distances between the Cluster spacecraft will be adjusted during the mission to study different regions and plasma structures. Comparison of simultaneous measurements from the different spacecraft will be combined to produce a three-dimensional picture of plasma structures.

TDRS

The Tracking and Data Relay Satellite (TDRS) is involved in relaying communications between satellites and the ground. There is no autonomous operations or cooperative behavior with TDRS, but this is an application were cooperative behavior could be added. In addition to data relay, TDRS is in a position that could perhaps also provide such things as computing services to missions so that a central computing resource is available and each spacecraft would not have to be launched with as much computing power. This would provide a savings by reducing the on onboard computing resources and the corresponding weight to launch duplicate resources among satellites.

Other Missions

Other multi-satellite missions that are being proposed or planned include:

- TWINS A and TWINS B that will stereoscopically image the magnetosphere (2004),
- GEC/Geospace Electrodynamic Connections is a cluster of four satellites that will study the ionosphere-thermosphere (2009),
- LISA/Laser Interferometry Space Antenna will consist of three spacecraft to study gravitational waves (2010),
- CON-X/Constellation X will provide teams of x-ray telescopes working in tandem to observe distant objects (2010), and
- MC/Magnetotail Constellation will constist of 50-100 nano-statellites that will study the Earth's magnetic and plasma flow fields (2011).

As can be seen from the above, NASA is planning on relying heavily on cooperating multi-satellite systems to perform new science that would be difficult or impossible to do with single satellites.

Motivations for Autonomy

There are several ways autonomy can assist multi-satellite systems in the above missions. The following are some of the areas that autonomy could be used.

Communications Delays

One area that has been realized where autonomous software is needed is when communications can take more than a few minutes between the spacecraft and the ground. When communications is lengthened, the risk of losing data or the spacecraft increases because monitoring the spacecraft in real-time (or near real-time) is now longer possible. The mission is flown more from a historic basis,

Figure 4: Tracking and Data Relay Satellite (TDRS)

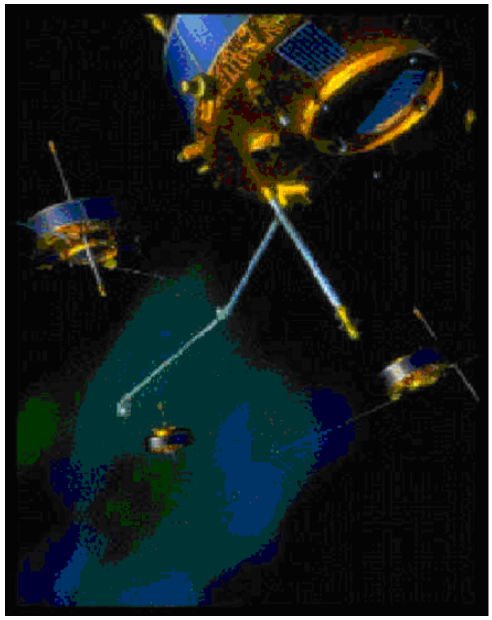

Figure 5: Magnetosphere

and the operator needs to stay ahead of the mission by visualizing what is happening and confirming it with returned data. Science of opportunity is usually not possible on missions with large communications lead times. This type of science is usually impossible or not practical because the science can be gone once the data is transmitted back to Earth, analyzed and then satellite instructions transmitted back. PIs are now looking at autonomy or semi-autonomy to take advantage of science of opportunity. Also, for spacecraft health and safety, the large lead time in communications can also mean that a spacecraft can be in jeopardy (such as when flying close to an asteroid in ANTS), and without quick response, a spacecraft could be lost.

Number of Spacecraft

For missions that are planning to use constellations of satellites or swarms of satellites (or other vehicles), autonomous software is being planned for controlling them. The more spacecraft, the more people will be needed to control them, and therefore higher operations costs. It is being noticed that autonomous software is the only way to control a large number of vehicles without having to have huge computing resources on the ground, and corresponding large communications systems onboard the vehicle to transmit the large amount of data these vehicles will collect, which will be needed to compute the coordination between them.

Interaction of Spacecraft

Spacecraft that interact with each, either in the form of formation flying or performing science, also have the problem of having to download large amounts of data for coordination purposes. They will also have large state spaces for trying to keep track and coordinate the spacecraft.

Combination of Items

The combination of communication delays, large number of satellites and interacting spacecraft increases the need for autonomy even more, as has been seen with the ANTS mission. State space can explode and requiring people to deal with the large state space may be overwhelming. As these types of missions began to be implemented, autonomous spacecraft and operations will become better understood accepted through necessity of implementing the mission.

Cost Savings

One area that has been recognized where autonomy can play a vital role is in reducing the size of the communications components. New instruments on spacecraft are able to collect large amounts of data. Historically, mission PIs have wanted all data to be transmitted back to earth for archival purposes and for rechecking calculations. This data often needs further processing to get it into a usable format. Until now, it was important to have all of the data. Historically instruments did not collect as much data and it was not an issue in sending it down because the onboard resources were available. As instruments become more sophisticated and are able to collect large amounts of data, tradeoffs now need to be made. These tradeoffs require comparing the need to download all of the data and include costly (heavy) high throughput antennas and power sources, versus doing preprocessing of the data onboard and reducing the cost of the mission (or do more science by affording to have multiple instruments on a platform) by reducing the amount of communications between the spacecraft and the ground.

Challenges and Opportunities

There are several challenges and opportunities for autonomy and related technology for multi-satellite systems. The following gives a few of these.

Reluctance To Use New Technology

Introducing new and revolutionary technology into a space mission is often met with resistance. From the viewpoints of the PI and the Mission Operations manager, new technology adds risk to an already risky endeavor. A proven success rate for a technology is usually mandated before using it in a mission. Years of work are often on the line, so tried and proven technology is usually favored unless the potential positives heavily outweighs the negatives, such as the science would be impossible without the new technology, or additional science could be added to a mission with little overhead and risk.

With the new mission concepts that are taking shape, an excellent opportunity now exists to insert autonomy and agent technology into these missions (Rouff and Truszkowski 2001). Since autonomy is now needed to make these missions possible, the science community is now looking to the AI and agent software community to implement these ideas in flight software.

Software Reliability

As with most NASA missions, software reliability is extremely important. The cost of a software failure can mean the lost of an entire mission. Ground based systems can often just be reset when a failure occurs. In unmanned space systems, of course, this is not possible.

One of the challenges to adding autonomy to multi-satellite systems is for the AI and agent communities to implement these ideas so they work reliably. The software must be robust enough to run on a spacecraft and as part of a community of spacecraft predictably, as well as be able to be implemented in a reasonable timeframe and for a reasonable cost (reasonable, of course, is relative to the type and cost of the mission).

Autonomous systems often require flexible communication systems, mobile code, and complex functionality all of which is not always fully understood at the outset. A particular problem is that such systems can never really be tested to any degree of sufficiency, as an intelligent system may adapt its behavior on every execution. New ways of testing and monitoring this type of software is needed to give PIs the assurance that the software is correct (Rouff 2002).

In addition to being space-based, many of the proposed missions will be operating remotely and out of contact with a ground-based operations system or with a long communications lag time. This makes detecting and correcting software errors even more important because patching of the software after launch will be much more difficult, impractical, or impossible.

Verification and Validation

Autonomous missions are new to NASA, and the software development community is just learning to develop such systems. These highly parallel systems can have very complex interactions. Even simple interacting systems can be difficult to develop, as well as debug, test, and validate. In addition to being autonomous and highly parallel, these systems may also have intelligence built into them, can be distributed and asynchronous and can have large time delays between the systems due to the large distances between them. Consequently, these systems are difficult to verify and validate.

With new multi-satellite autonomous systems, new verification and validation techniques must also be used (Rouff, Rash and Hinchey 2001) (d'Inverno and Luck 2001). Current techniques have been developed based on large monolithic systems. These techniques have worked well and reliably, but do not translate to the new autonomous systems that are highly parallel and nondeterministic.

Heterogeneous Satellites

Like heterogeneous agents, in the future connecting heterogeneous satellites together to do cooperative missions may be needed. It is now known that different phenomenon are interrelated and that data from one mission could be shared with other missions to explore opportunistic science and for coordinated science. Solving this problem for heterogeneous agents will give a model of implementation for heterogeneous satellites.

Adjustable and Mixed Autonomy

Complete autonomy may not be desirable or possible for some missions. In these missions adjustable and mixed autonomy may need to be used. In adjustable autonomy the level of autonomy of the spacecraft can be varied depending on the circumstances or the desires of mission control. The autonomy can be adjusted to complete, partial or no autonomy. In these cases the adjustment may be done automatically by the spacecraft depending on the situation (i.e., the spacecraft may ask for help from mission control) or may be requested by mission control to either help the spacecraft accomplish a goal or to perform an action manually. Challenges in adjustable autonomy include knowing when it needs to be adjusted, how much and how to make the transition between levels of autonomy.

In mixed autonomy, autonomous agents and people are working together to accomplish a goal or task. Often the agents are performing the low level details of the task (e.g., formatting of a paper in a word processor) while the human performs the higher-level functions (e.g., writing the words of the paper). Challenges in this area are how to get humans working with the agents, how to divide the work up between the humans and agents, and how to give the humans a sense of cooperation and coordination, especially if the levels of autonomy are changing over time.

Conclusion

Autonomous operations of spacecraft are being proposed in future NASA missions due to mission complexity, potential cost of operations and safety. Doing new science using multi-spacecraft is a definite trend. Adding autonomy to these spacecraft provides an opportunity for NASA to conduct data gathering that would be impossible to do with a single spacecraft, and gives practitioners and researchers an opportunity to insert new technology into space missions. Before being able to provide these new capabilities, there also remain many outstanding issues to autonomous software that need to be resolved that will give confidence to PIs and NASA that the technology is mature enough for space-based applications. As with many previously new technologies, once autonomy is used in space applications, it will be given greater acceptance and will be used more in commercial and other non-space applications.

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