INTELLIGENT SATELLITE TEAMS FOR SPACE SYSTEMS

Final Report for the NASA Institute for Advanced Concepts Program

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Abstract

This program examined the feasibility of developing of Intelligent Satellite Teams (IST's) for complex space missions such as construction of space hardware, or Earth or space science. IST's are composed of many *nanosatellites* (mass < 10kg) or *picosatellites* (mass < 10g). IST development is a synergy of many disciplines, such as: *intelligent control* including formation flying, collision avoidance, knowledge sharing, and adaptive reconfiguration; *microtechnology* including microelectromechanical systems (MEMS), microfabricated sensors and actuators, nanotechnology, and integrated wireless communication; *mission analysis* – high-level planning and control of mission, satellites, and procedures. Recent rapid technological advances in these fields open up exciting new possibilities for future space missions: *space science missions* such as testing gravitational variation, detecting and characterizing near-Earth asteroids and comets, and comprehensive exploration of the solar system; *Earth science missions* such as distributed measurements for assessment of climate processes. This report gives a summary of the results of a six-month study into the feasibility of IST's, focusing on deriving the types of missions amenable to the IST concept, the integration of microtechnology into space systems, and the coordination of the individual satellites in a group. This systems-level study shows that the IST concept is applicable to many missions, and while the technologies are complex, the development can be built on current trends in the fields and overcoming several major issues in integration. These issues will be pursued in Phase II of the program.

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Chapter 1: Introduction

Space presents great potential for a wide range of activities including human space travel, and Earth and space science. An untapped potential still remains, however, because of a number of factors, including launch vehicle size and cost, complexity and fragility of the facility, budget constraints, and remoteness for inspection and repair. Redundancy of space systems has been very high in order to prevent even small failures from undermining the mission. These factors have lead to an increased usage of smaller satellites for concepts such as precision space telescopes, arbitrarily large antennas, and robotic assistance with the International Space Station assembly. By controlling and coordinating these small satellites, a system is developed that is more capable and redundant than a single satellite.

Technology is now envisioned that, coupled with the small satellite concept, will revolutionize the range of space activities. The two most important technologies are microtechnology and intelligent control. Microelectromechanical systems (MEMS) have led to significant advances in actuator and sensor technology, especially in the fields of medicine, communication, and transportation. Intelligent control has long been used in robotics development, and is now envisioned in the coordination of multi-element systems in manufacturing, automated transportation, and precision control systems.

Intelligent Satellite Teams (IST's) [1] is a concept of a focused, coordinated team effort involving tens, hundreds, or thousands of similar entities (nanosatellites – 10g-10kg or picosatellites – 10mg-10g). A wide variety of technologies have matured to levels where feasibility studies of mission concepts can be made. The primary advantages of the IST concept are distributed functionality, autonomy, and adaptability. Through a NASA Institute for Advanced Concepts Grant, the UW has studied the requirements and technologies to enable the usage of IST's. NASA missions, Intelligent Control, and MEMS subsystems were each examined concurrently, with the Mission development placing requirements and driving technology in the other two areas. The program is inherently cross-disciplinary, as shown in Figure 1. IST's would enable a wide variety of NASA missions that require a high degree of autonomy for multiple tasks and distributed science measurements all at low costs.

This program has been designed to specifically address the NIAC and NASA goals: to develop a system or architecture to enable future NASA missions. This program does not enhance current programs at UW or elsewhere. As such, the Phase I portion of the program was treated as a derivation of the requirements and viability of the IST concept, while Phase II will examine the major feasibility issues derived in Phase I. This report summarizes the Phase I results in terms of the IST concept and the Phase I goals.

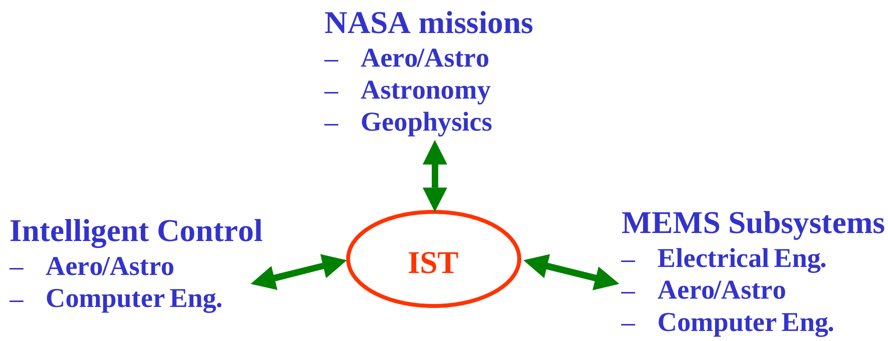

Figure 1: Intelligent Satellite Teams (IST's) are cross-disciplinary, and the missions feed direction and requirements to Intelligent Control and MEMS Subsystems areas.

The outline of this report is as follows. Chapter 2 gives an overview of many applicable missions for IST's. This list was derived with collaboration from scientists in the Geophysics and Astronomy departments at the UW, as well as scientists at NASA JPL and Goddard. Chapter 3 gives an overview of Micro-subsystems for satellites, focusing on components as well as integrated systems. Chapter 4 discusses the coordination approaches and issues for the IST organization to work "greater than the sum of their parts." Chapter 5 gives a summary of the major feasibility issues and challenges to the IST concept. Chapter 6 explores the application of the IST concept for one mission, namely a deep space mission for planetary exploration. Many issues are discussed in more detail to demonstrate the advantages of the IST concept. Chapter 7 summarizes the results of the Phase I portion of the program in terms of the goals and questions laid out in the Phase I proposal. It is very important to note that each one of the Phase I goals has been met, while several complementary goals that developed during the program were also met. Note also that there is a direct link between these results presented in Chapters 5 and 7, and the Phase II proposal.

Chapter 2: Missions

The primary advantages of the IST concept is distributed functionality, autonomy, and adaptability. There are a wide variety of missions that could be enabled using these technologies. Figure 2 shows a summary of several of these missions, as a function of the intelligence and number of spacecraft (which is of course enabled by MEMS). The most enabling of these is a deep space remote sensing mission. This mission would have multiple tasks and require distributed science measurements. Because of this, and the use of large numbers of satellites, the mission also requires high levels of autonomy. Other missions that can utilize these technologies include a space weather and warning system, autonomous servicing, supply, and repair of satellites, any distributed Earth science mission, and finally, autonomous construction of a space facility. This figure is not meant to be an exhaustive list, only a list to show the broad applicability of the IST concept. Many of the results from this chapter were derived with collaboration from UW scientists in the Geophysics and Astronomy departments. Each of these missions is described next.

2.1. Space weather and warning system

As human activity in the solar system expands beyond Earth in the next century, detection of solar events and forecast of solar radiation will be important to the safety of astronaut crews. Communication of information is limited by the speed of light, thus advanced warning of high energy electromagnetic radiation is not possible. However particle radiation emitted by the sun travels at much slower speeds and thus lags electromagnetic radiation by hours. It is therefore possible to gain advanced knowledge of particle radiation characteristics. Deployment of a distributed system of nanosatellites in the inner solar system can serve as a radiation forecast network. Equipped with particle flux detectors, a distributed system of nanosats can provide sample data that, when relayed at near light speed to forecast centers, can be used in computer models to predict radiation levels at Earth and beyond hours ahead of the arrival of particle radiation. This would provide valuable information for astronaut crews and industries on Earth affected by increased solar activity, such as communication and electric utilities, and LEO satellites and astronaut crews.

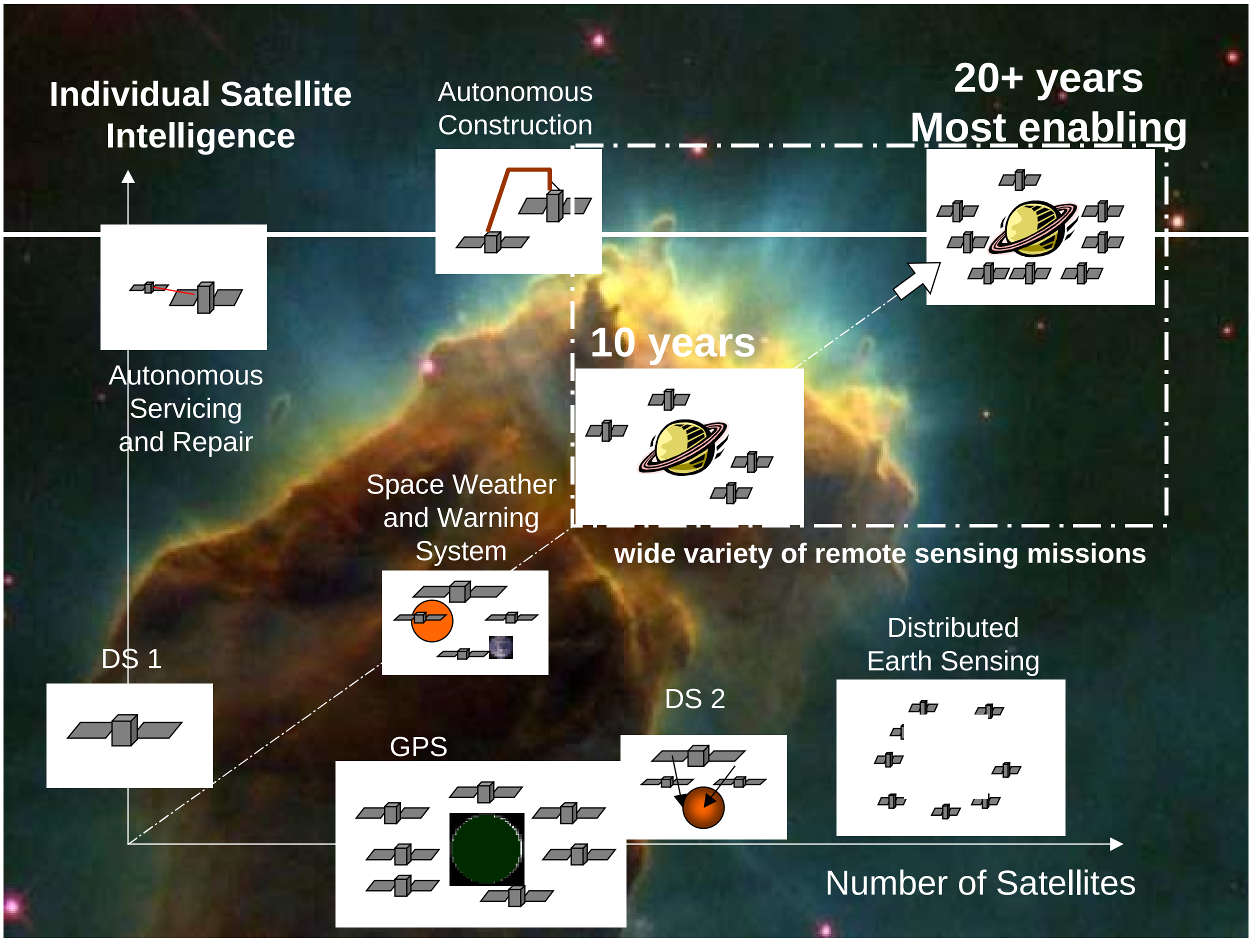

Figure 2: Trade space for IST missions as a function of the intelligence and number of satellites (driven by MEMS).

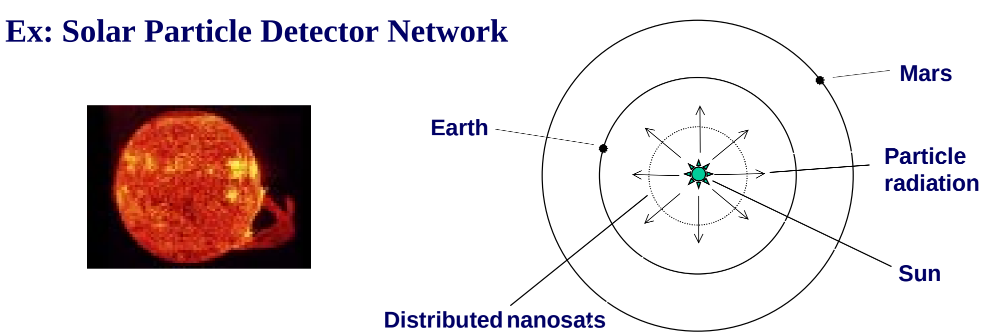

Figure 3: Space weather and solar flare warning system.

2.2. *Autonomous Construction of a Space Facility.*

Consider an IST consisting of tens of nanosatellites, each with on-board intelligence and the ability to "adapt" to unexpected situations. This form of IST could be used to autonomously build or service a space facility. For instance, plans for a new space facility, including parts and supplies, would be drawn up electronically, encrypted in the on-board memory, and inserted into precision robotic nanosatellites. A rocket could be used for launch, possibly with modular supplies built into the vehicle. Once in orbit, nanosats deploy and coordinate in an IST, as shown in Figure 4. Precision robotic satellites, serving as specialized workers, use collective intelligence to autonomously work on a specific portion of the facility. A leader satellite supervises construction and relays information to human operators on Earth, or the robotic satellites could be reconfigured into an antenna for communication. At the end of construction, the IST could be reconfigured in support of the space facility.

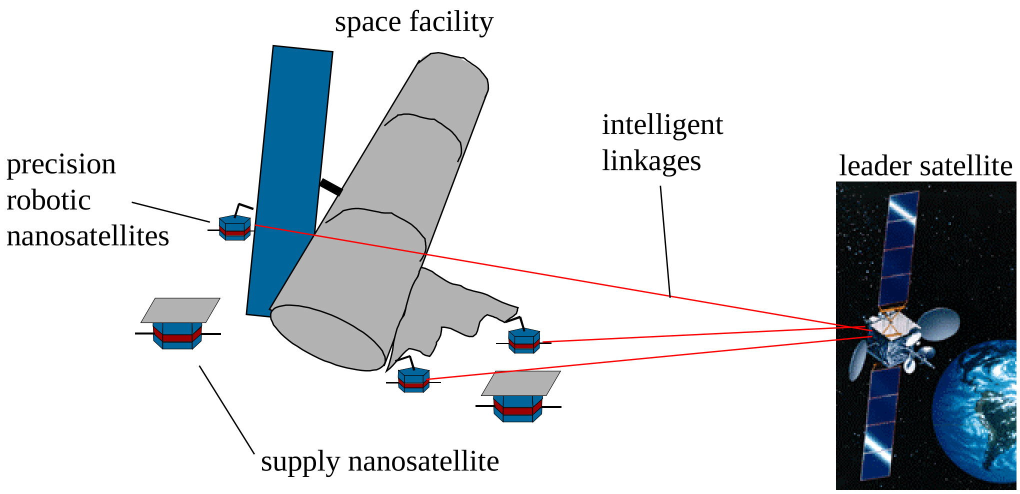

Figure 4: Concept of IST's for space construction.

2.3. *Comet or Asteroid Science*

Motivated by the potential of hundreds of picosats in an IST, many picosats could be fabricated in a batch process, and launched (using a vehicle or non-conventional means) toward an asteroid or other object of scientific interest. Once in orbit, the IST would organize itself in a grid, and gather and share scientific information (Figure 5). For example, detected changes of relative position of the picosats due to the asteroid's gravity would give a measurement that is very difficult to obtain by other means. The IST could perform distributed measurements of asteroid and comet surface and density, collect, analyze or return distributed samples of asteroid surface, comet coma, comet tail matter, and place tracking beacons on Earth-crossing asteroids.

Consider a large number of satellites orbiting the Sun using optical and infrared sensors to look for asteroids. The satellites share tracking data, and at least one spacecraft is sent to rendezvous with each identified asteroid. After orbital insertion or during flyby, the satellite releases a tracking beacon that impacts and sticks to the asteroid. The signals emitted by the beacons are received at Earth, and are used to track individual asteroids. When possible, multiple satellites are sent to rendezvous with large or scientifically interesting asteroids to measure density and perform other distributed measurements.

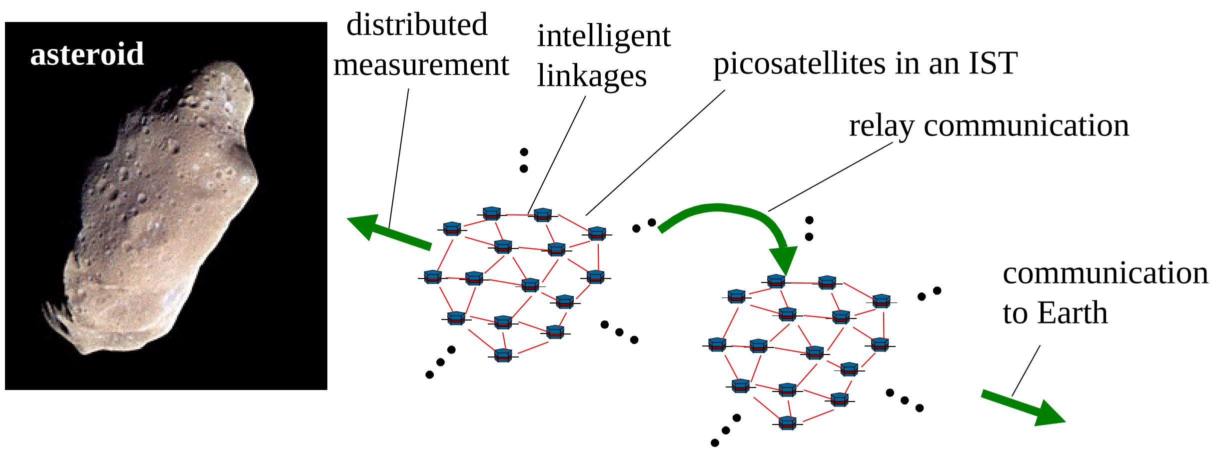

Figure 5: Concept of IST's for space science and communication.

2.4. Deep Space Planetary Science

Consider a mission to perform distributed measurements from orbit of planetary and moon atmospheric composition, weather patterns, fluid and electromagnetic phenomena over a range of altitudes, atmospheric measurements during descent to the planetary surface, soil and/or ocean sampling where appropriate upon landing, and seismic activity and local surface weather monitoring until end of life. In addition to multiple science tasks, the IST could also be used for GPS, and to develop accurate distributed science models. It can handle uncertain events, such as the loss of a part or uncertain atmosphere or terrain.

Small probes with aeroshells could be launched on low-energy trajectories to one of many planets or moons that have atmospheres. After orbital insertion at the target body, the probes begin to collect science data in orbit and periodically transmit it to Earth. Atmospheric drag degrades the orbits of the probes, pulling them into lower orbits and allowing for data acquisition at different altitudes in each probe's orbital plane. Probes use parachutes and airbags to survive landing.

Incorporation of advanced MEMS technology would reduce mission cost, allow for more probes per mission, and allow greater flexibility in science objectives. A large number of probes would allow for better spatial characterization of the quantities being measured. Probe artificial intelligence and inter-satellite communication could be used to reduce human operator workload and broaden mission scope as new science opportunities arise.

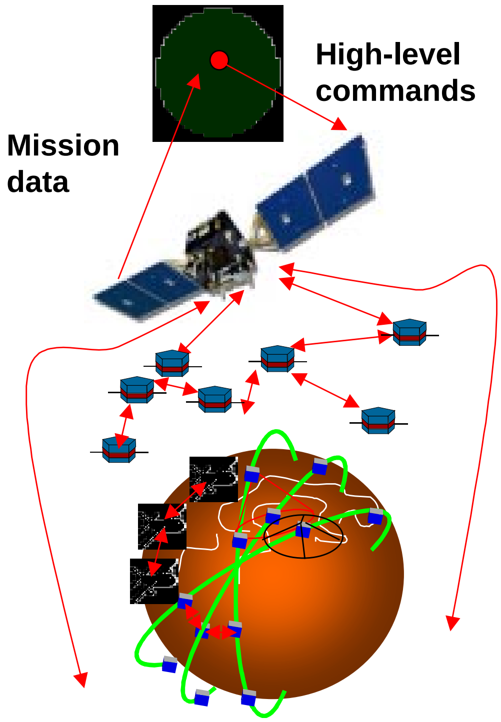

Figure 6: Deep space planetary science mission using IST's.

2.5. Autonomous Servicing and Repair

The use of IST's for servicing yields the benefits of a small satellite that has the ability to autonomously inspect, service, and repair other satellites. IST's have the potential to save both the commercial and military satellite industries billions of dollars. An autonomous servicing satellite would have many beneficial functions, such as closely inspecting malfunctioning satellites. It will be able to approach and inspect an existing satellite that is either out of control or damaged. Often, the visual information, attitude, and relative motion of the satellite can provide necessary data for developing a solution. After the cause of a satellite malfunction has been diagnosed, IST's could repair problems such as mechanical and exterior damage. A very common mechanical problem present among many satellites is an undeployed solar array, which reduces the power available to the satellite and introduces dynamic instabilities. Other common types of exterior damage that could be repaired by IST's are thermal blanket and thermal coating.

For the new satellites that have been designed with consideration of maintenance and upgradability, IST's can provide a wider variety of services. The Earth orbiting satellites may be modular in design such that all sub-components may be upgraded or replaced upon failure. Modular sub-components include solar arrays, propulsion, communications, battery, processor, attitude determination and control, and science payload packages. Any of these sub-components may be launched at a lower cost than an entire satellite.

2.6. IST Missions Conclusions

The Missions summary was intended to show the broad applicability of the IST concept. In order to understand how the IST concept could be applied as well as the limitations, UW Earth and space scientists were heavily drawn upon for this analysis. Although still quite general, this discussion has lead to several of the major feasibility issues discussed in the following sections. In addition, if the scientists believe that the concept is enabling for their missions, and are willing to work with the engineers on its development, the IST concept has a very high success rate. The following specific conclusions can be drawn from this section:

- IST's enable missions that require distributed measurements at low manufacturing cost by primarily using the MEMS technology to develop low cost, light weight, modular satellites. An example of this type of mission is an Earth ionospheric measurement mission.
- IST's enable missions that require high levels of intelligence at low operator cost by primarily using intelligent control to coordinate the entities into a coherent community. An example of this type of mission is the inspection, supply, and/or repair of satellites.
- IST's enable a new set of missions that require both MEMS subsystems and intelligent control. Two examples of this type of mission are the autonomous construction of a space facility and multi-task Earth and space science.

Chapter 3: Micro-Subsystems

The small size, mass, and modularity of MEMS devices opens up new possibilities for IST's with hundreds or even thousands of smaller picosats. Very large quantities (~1M or more) of picosats can be loaded onto a conventional launch system, transported to a target location and then released. Furthermore, MEMS devices are (a) extremely strong and can withstand many thousands of g's of acceleration and (b) very light (mg or less). Consider a "ballistic launch" system (installed in earth orbit or on the moon) for accelerating micro spacecraft. A linear accelerator of 5km length could be used to generate 10,000g's on a picosatellite. This would result in an exit velocity of 30 km/sec, and a launch time of 0.3 sec. Over 1000 picosatellites could be launched in under an hour. [Note: Such a system would require about 1.4 MW power.] In addition, many picosats can be fabricated in a batch process, thus reducing the costs immensely and treating the satellites as an "assembly line" production. A more subtle benefit, beyond cost, to a fabricated satellite is that all the subsystems sit on a single wafer reducing the weight, volume and failures found in the connectors and wiring harnesses of conventional sized satellites. For these reasons, miniaturization of satellite components is currently receiving more attention. Satellite subsystems that are currently being examined in the MEMS community include attitude determination sensors and control and actuators, propulsion, communications, power, flight computers, mission instrumentation, satellite scale thermal management, and the spacecraft chassis.

3.1. State of the Art in Small Satellites

The current state of the art in small satellites is currently in the University Nanosatellite Program, funded by the Air Force, DARPA, and now NASA. This is a program in which 10 universities were selected to design and build 10 kg satellites that are as functional as possible. The University of Washington is one of these 10, and is unique because it will be the smallest satellite ever flown that has propulsive capability. It is doing this by flying small Pulsed Plasma Thrusters (PPT's) in a joint effort with Primex Aerospace Company. Below are the specifications of the PPT, and a smaller version now being designed.

Table 1: Summary for the PPT and μ-PPT.

	PPT	μPPT
Satellite Mass (kg)	100-5,000	5–100
Impulse Bit - I_{BIT} (μNs)	700	70
Specific Impulse - I_{SP} (sec)	1150	800
Energy - E (J)	50	5
Mass - m (kg)	6	1
Thrust - T (mN)	1.4	0.14

The design heritage of the UW nanosatellite is used to list the state of the art of current small satellite capabilities. This is shown in the table below.

Table 2: Table showing the current state of the art in functional small satellites, and the mass and power budgets for two satellites of increasing capability.

Current State of the Art in Small Satellites					Small Low Precision		Medium High Precision	
System	**Comment**	**Mass (kg)**	**Ave Power min W**	**Ave Power max W**	**M (kg)**	**P (W)**	**M (kg)**	**P (W)**
Structure								
Al and composite	20% of total				2.1		4.0	
Propulsion								
8 PPT's for 5 axes	cm accuracy	4.0	6.0	12.0	4.0	12.0		
12 PPT's for 6 axes	mm accuracy	5.0	12.0	25.0			5.0	25.0
ADCS	Propulsion for actuation							
Rate Gyros		0.5	0.5	10.0	0.5	1.0		
Star Trackers		4.0	5.0	20.0			4.0	10.0
Magnetometers		0.5	0.5	0.5	0.5	0.5		
C&DH								
Motorola 68032	Cabling high mass	0.5	0.1	0.5	0.5	0.1		
Strong Arm		0.5	0.5	2.0			0.5	2.0
Cabling	10% of total	1.5			1.0		1.8	
Thermal Control								
Blankets		0.5	0.0	0.0	0.5	0.0	0.0	0.5
Power								
Solar Cells	5.32 g/cm3, 244 W/m2, 24%				0.5		1.0	
Batteries (Ni-Cd)	30W/kg+20% for power dist				0.9		2.2	
Communications								
Ground-LEO	patch/tape ant, Tx, Rx	1.0	4.0	7.0	1.0	4.0	1.0	7.0
Inter-satellite	patch/tape ant, Tx, Rx	0.5	1.0	4.0	0.5	2.0	0.5	2.0
Navigation								
GPS	antenna	0.1	1.0	2.5	0.1	2.0	0.1	2.0
Science Payload								
Spectrometer		4.0	2.0	10.0			4.0	6.0
Plasma Probe		0.5	1.0	2.0	0.5	1.0		
Total					**12.6**	**22.6**	**24.2**	**54.5**

Most aerospace structures are made from aluminum for its light weight and structural integrity. However, composite structures are becoming more common, and the UW nanosat will fly composite panels that are integrated with an aluminum isogrid structure. Small satellite propulsion ranges from colloidal micro-thruster to cold gas to the small PPT thruster described previously. Electric propulsion will be the future for these satellites because of their high I_{SP}. Active attitude control actuators include reaction wheels and propulsion systems. Wheeled systems are much too heavy at this time. Several sensors have been miniaturized, such as micro-rate gyros and magnetometers. But the more accurate star trackers are still quite large. Motorola processors have been used for year aboard satellites, but with the development of embedded systems such as palm pilots, computational capability in terms of clock speed/W is drastically increasing. The StrongArm processor, due out in months, will have a clock speed of 600 MHz at a power of 0.5 W. Solar cells are now currently being developed that are 24 and 26% efficient. While novel Li based batteries are starting to replace NiCd because of their storage capability, it will be a few years before they are space qualified. Communications (and GPS) have drastically improved with antenna developments such as the patch and tape antennas. And although there are too many science instruments to list, the plasma impedance probe or a simple spectrometer are two instruments common to earth scientists.

3.2. MEMS Based Components

Satellite subsystems that are currently being examined in the MEMS community include attitude determination sensors and control and actuators, propulsion, communications, power, flight computers, mission instrumentation, satellite scale thermal management, and the spacecraft chassis. Within this list, the most mature systems are those that offer the greatest benefit from implementation in MEMS or those with terrestrial market pressure. The current pressure within the personal communication industry is driving a number of technologies that can directly cross over into the space community. Two of the more dramatic devices, that will both soon be ready for satellite integration and flight testing are MEMS gyroscopes and RF switching components.

<u>Attitude Determination Sensors</u>

Greater than an order of magnitude improvement in volume and power can be found in moving from large scale gyroscopes to the MEMS equivalent. The typical drift performance for MEMS gyroscopes is between 0.1 degrees per second [26] and 0.16 degrees per second [23]. This is worse than its macro scale equivalent which can routinely obtain drift rates from 0.003 degrees per hour to 1 degree per hour [24]. Researchers are currently working to ensure that the MEMS version quickly catches up to this standard for the reason that drift is a large factor in determining the usefulness of the device in a given application and is proportional to the pointing accuracy of the satellite under gyroscopic control. Even if they lag in this parameter, MEMS devices are inherently better in other regards. In comparing the power required by the two types, the MEMS version needs on the order of milliwatts due to its capacitive sensors while full scale gyroscopes require between 10 and 200 watts [24]. Weight is another parameter where MEMS excel. MEMS gyroscopes are small and light, requiring only a small IC package which may weigh only a few grams. On the other hand, a conventional gyroscope can weigh between 3 and 25 kg and take up 100 cubic centimeters or more [24]. Although MEMS gyroscopes are not quite ready for space flight they are under substantial development pressure due to the clear advantages concerning power, weight and volume consumption.

This advancement in the MEMS community towards finding solutions to spacecraft subsystem problems does not end with strictly mechanical, movable structures. One possible inroad for MEMS is the star tracker. The current state of the art combines a CCD camera, digitizer and computer to produce the final instrument. Even though this system has undergone numerous stages of optimization and minimization, an assembled instrument is unavoidable because the semiconductor processes for these components are mutually exclusive. In addition, CCD technology is notorious for its power consumption. Using MEMS and a CMOS imager, this entire package could be shrunk to a single semiconductor die. Currently CMOS imagers are available that allow for separate, electronic shuttering over the focal plane [18] and whose designed purpose is as star trackers. The independent shuttering feature enables local control over sensor integration times so that a greater range of stellar magnitudes can be used when determining orientation. This device does not currently incorporate focal plane processing; however, data converters and processors have been integrated with these sensing elements in the past. This would allow the star tracker to shrink to a single chip, possibly to a single IC package with a commensurate reduction of power and volume requirements.

Attitude Control Actuation

Beyond sensing systems, MEMS can provide means to control the satellite's orientation. Momentum devices overcome some of the disadvantages of rocket-based approaches by featuring high pointing accuracy, precisely controllable slew rates, and potentially very long life span -if powered by solar energy. The UW is currently investigating MEMS devices that use momentum to produce attitude adjustments, including momentum wheels and momentum actuators. Typically these devices generate low levels of torque; but their pointing accuracy is high. In the case of momentum wheels, torque is exerted on the spacecraft by changing the speed of multiple spinning disks. In MEMS implementations, the lack of absolute speed control and very low friction bearing surfaces make this scheme difficult. The second technique, which lends itself more to MEMS technology, is to mount a spinning disk on gimbals. As the platform is actuated, force is imparted due to the change in direction of the angular momentum vector. Even though MEMS devices can only generate relatively small momentum due to their small size and low weight, arrays of devices and additional miniature flywheels are options to overcome these limitations.

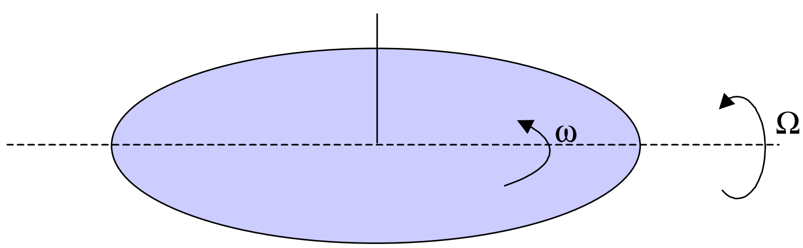

Figure 7: Wheel of a CMG.

Momentum wheels and control moment gyros are the two main techniques used to control the attitude of a spacecraft (3 angular degrees of freedom) that do not rely on thrusters. Momentum wheels are based on the principle of conservation of moment of inertia. Change in the angular velocity of a spinning disk results in an angular (de-)acceleration of the spacecraft, where its rate is proportional to the disk acceleration as well as the ratio between disk and spacecraft moment of inertia. Momentum wheels require a continuously spinning disk. Since low friction bearings are difficult to achieve with microfabrication, momentum wheels are currently impractical for small spacecraft.

In addition, it appears that MEMS is ill-suited for all systems that take advantage of (moment of) inertia, due to the unfavorable scaling effects at the microscale. Mass scales with the third power of size, and moment of inertia scales with the fifth power. Moving from meter-scale devices down to millimeter scale may result in a downscaling of the effective forces or torques by a factor of 10^{15}! However, the following analysis argues that these scaling effects do not always apply, and that it is indeed practical to build a micro control moment gyro.

Control moment gyros (CMG's) take advantage of the Coriolis force that acts on a system when a spinning disk is forced to change its axis of rotation. The resulting torque can be calculated as

$$T = I \quad \Omega$$

where $I = \pi/2 \; \rho \; hr^4$ is the moment of inertia of the spinning disk with radius r and height h, ω is its angular velocity, and Ω describes the change in the axis of rotation. To avoid problems with continuously spinning disks as mentioned above, the MEMS CMG uses *oscillating* deflections rather than continuous rotation. If the maximum deflection is given by Θ_0 and f is the frequency of deflection, then the deflection can be described as

$$\Theta(t) = \Theta_0 \; \sin 2\pi ft$$

and

$$\omega(t) = \dot{\Theta}(t) = 2\pi f \Theta_0 \cos 2\pi ft$$

Furthermore, if the disk is mounted on a gimbal that oscillates at the same frequency f and with a maximum deflection of Ψ_0, then the following deflection is obtained:

$$\Psi(t) = \Psi_0 \sin 2\pi ft$$

and

$$\Omega(t) = \dot{\Psi}(t) = 2\pi f \Psi_0 \cos 2\pi ft$$

The torque T can be calculated resulting from the Coriolis force as

$$T = I\omega\Omega = \tfrac{\pi}{2} \rho hr^4 \cdot 2\pi f \Theta_0 \cos 2\pi ft \cdot 2\pi f \Psi_0 \cos 2\pi ft = 2\pi^3 \rho f^2 hr^4 \Theta_0 \Psi_0 \cos^2 2\pi ft \geq 0$$

Note that T is a time-dependent but always non-negative. This shows that it is possible to generate a non-zero torque without a continuously spinning disk. In addition, it is straightforward to show that a phase difference of 180° between disk and gimbal oscillation results in a negative resulting torque T.

The question remains about the effectiveness of a micro CMG, based on this analysis. Note that the torque generated by the CMG, as well as the required torque for attitude change, are proportional to the moment of inertia, and thus scale at the same rate. Hence, if the relative size of the CMG and the spacecraft are held constant, then the effectiveness of the CMG is scale-independent.

Based on these promising theoretical results, a design study for a CMG has begun that could be fabricated with a standard MEMS foundry process. Several issues pose challenging constraints on such a design:

1. Ensure a high oscillation frequency f to obtain reasonably-sized torques (recall that $T \sim f^2$).

2. Ensure that the natural frequency of the oscillating disk matches the natural frequency of the gimbal mechanism.

In both cases, torsional springs are employed whose stiffness can be varied by the dimensions of the torsional beam (length, width, thickness). However, the fabrication processes set severe limitations on these dimensions. Preliminary calculations show that a torque of $T = 3\ 10^{-13}\ Nm$ are feasible. This torque would accelerate a silicon sphere of radius 1mm by about 4°/sec^2, by far sufficient for attitude control.

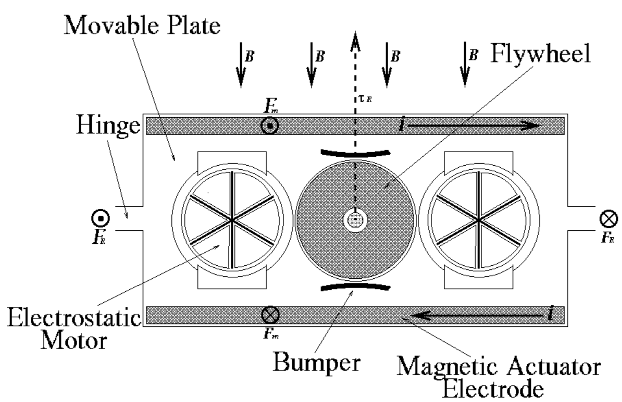

Figure 8: Micro Control Moment Gyro.

In a CMG, two torques are generated: a desired torque in one direction and an undesired torque in an off-axis direction. In scaling down the CMG and placing many of them side by side, the resultant torques from the off axis can be canceled, and the spacecraft is left with simply a summation of the desired torques for attitude control.

Figure 8 shows a schematic view of the elements and orientations of the various components (not drawn exactly to scale). The platform is suspended above an underetched section and holds the rotor and its stators which are driven out of phase with each other. A metal flywheel can be deposited on top of the rotor to increase the angular momentum of the spinning disk. The rotor itself, made from polysilicon, is attached to the plate using a polysilicon bearing. The plate on which the rotor and flywheel spin is attached to the substrate by two torsion suspension arms. These arms allow the platform to gimbal in one dimension and allow for power connections to the movable section. The motion of the rotor can be produced either by magnetic or electrostatic actuation.

Micro-Propulsion

The development of micropropulsion is seen as a key development for IST's because of their possible remote location and distributed measurement requirements (such as various forms of interferometry). In addition, this area is currently receiving a lot of attention in the MEMS community [3]-[7]. Current thrusters fall into three main categories: monopropellant, bipropellant and electrical. As technology has improved, each of these types has carved for itself its own niche, specifically suited to its characteristics.

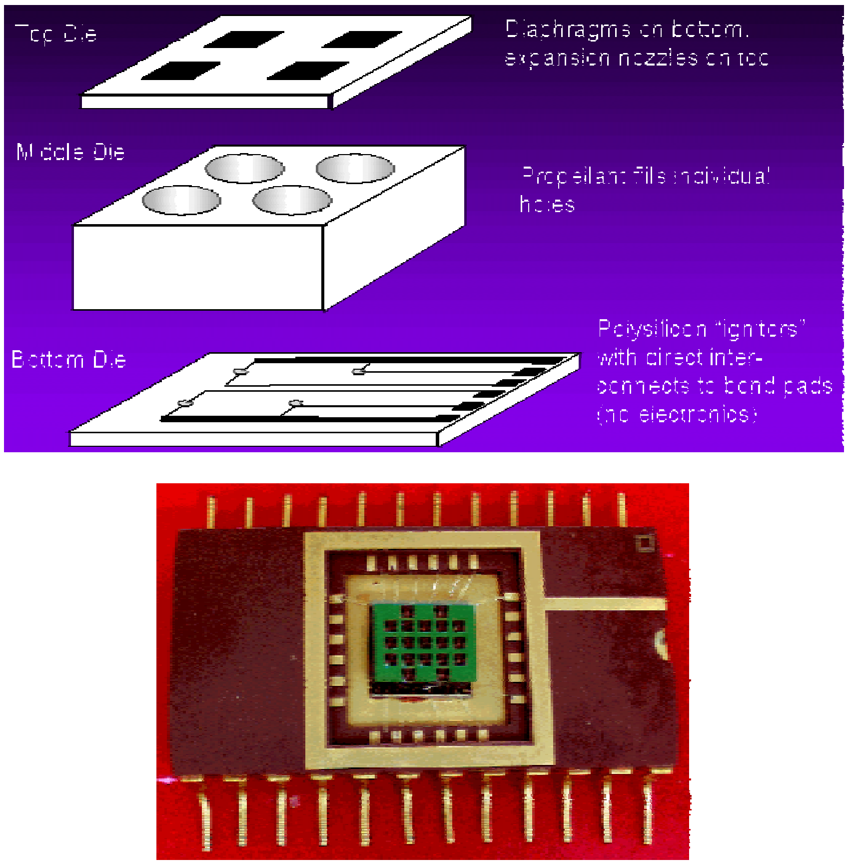

Figure 9: Fabrication of micro-propulsion. The top figure shows the digital thruster concept from Lewis et al [3]. The bottom figure shows the micro-thruster chip package.

All of these systems can be implemented at a MEMS scale with enough effort. Small scale versions of solid rockets are easily integrated with numerous advantages compared to larger scale systems. To their benefit, the MEMS solid propellant engines are compact, involve no microfluidics, and provide throttle control by allowing numerous tiny, single use thrusters to be fired together or individually depending upon the necessary thrust. These systems currently are limited in their thrust duration - typically less than 1ms. Monopropellant systems are better in some regards, but more difficult to realize. A monopropellant system has the advantage of high impulse without cryogenic fuels, dual fuel tanks and complex methods of ignition. A monopropellant system does allow for resizable fuel tanks (based on mission specification), consistent nozzle placement and continuous thrust over solid propellant systems. Finally, bipropellant systems, similar to their macroworld counterparts, offer the best performance at the highest level of cost and complexity.

Communications

RF switches are another technology under terrestrial market pressure; however, these are virtually ready for space flight. A conventional RF switch and filter combination requires 880 cubic cm and weighs 1.5kg for an X-band system and 608 cubic cm and 1.2 kg for a Ku-band system [24]. Just including this component will take up the entire weight budget for a small satellite and severely stress the volume requirement as well. This package could be replaced by an entirely microfabricated system which will exhibit better performance at workable weights and volumes. RF switches have already been exhibited, taking up only a few thousand square microns of chip area and handling powers in excess of 1W. If more power handling is needed, these devices are easily fabricated as arrays. A typical device works from DC to GHz frequencies and has an insertion loss below 0.1 dB [9j]. For filtering, mechanical RF filters are becoming available that rival conventional components in insertion loss and quality factor [3j]. With the possibility of fabricating both of these devices on the same substrate the volume and weight are decreased even further. The possibility exists for shrinking the above, conventional device to a few milligrams and much less than one cubic cm while improving performance.

Communication subsystem development, especially inter-satellite communication, is also receiving a lot of attention as the bandwidth requirements increase. These new systems facilitate the efficient pointing, tracking, and high-bandwidth modulation of optical and microwave beams by the smart design of new materials and devices. Switching and processing of information is ultimately limited by the mutual interactions between signals and the ability of the hardware to filter and amplify these signals as they climb into optical and microwave frequencies. A substantial step towards this goal were polymer modulators, developed at the UW, which hold the world record modulation rate of greater than 340 Gbps. The development of this type of MEMS will be central to pointing and tracking of optical and microwave beams for intersatellite optical links and microwave up/down links; and will also radically improve the viability of putting high-performance communications-grade lasers into space-based intersatellite optical links. New manufacturing processes for polymer fibers enable lower network connection costs for devices on the spacecraft chassis and will facilitate the development of new high performance communications transmitters.

In the here and now; MEMS are ready to make serious inroads on specific RF design problems independent of high frequencies and purely semiconductor nature of typical RF devices. The first major inroad is the RF switch. Typical RF switching is done with PIN diodes and, although it is an adequate scheme, these introduce harmonics that may need to be filtered, insertion losses and another set of coaxial interconnections [25]. MEMS RF switches on the other hand are like relays for RF frequencies. When energized they physically close or open, making or breaking the link between the amplifier and the antenna. This switch technique results in dramatically less loss, no unwanted harmonics and since these devices are IC technology compatible they can be fabricated in situ with RF amplifiers for a further savings in volume [24]. Using this technology and various delay lines it is easy to imagine creating digitally controlled delay lines for integrated phased array systems.

MEMS oscillators are closely behind RF switches in their development curve and will shortly become an important player in the RF field. Most current RF systems rely on crystal oscillators to produce an accurate frequency reference. These have a long development history and show up in a myriad of applications; however, there is no method to place these oscillators directly onto the communications chip to yield a fully integrated solution [19]. Mechanical resonators can solve this problem and allow the local or reference oscillator to be integrated along side the rest of the RF transistors in the communication system [19]. This solution relies on the high and clean resonance frequencies of silicon beams to produce frequencies that are stable enough to use in communications devices.

Power

None of these devices will function without a source of power and here, MEMS has a contribution to make as well. For solar power there are issues in solid state physics that limit the conversion between light and electricity to around 30% [17]. In the terrestrial world, conversion efficiencies hover just under 20% and satellite designers typically consider 15% to be the eventual, on orbit conversion efficiency of their solar panels [24]. MEMS technology can help bring that number closer to the theoretical maximum with a number of techniques. First, lenses can be etched directly into the surface of the silicon wafer. This focuses the light onto the diodes that make up the light gathering component of the cell improving efficiency. Secondly, the necessary metal interconnects can be angled such that the light otherwise lost in their shadow is captured [20]. Both these methods can be currently found in prototypical solar panels poised for entry into the commercial market [24] and could be quickly incorporated into miniature or full scale satellites.

MEMS can go beyond improving solar conversion and take a role in actively regulating or storing electricity. One example of this is the possible development of solar cells with smart shadow compensation. In a conventional solar array, if any single cell is shadowed then the entire string that cell is attached to will become and open circuit. This becomes an especially thorny issue near satellite chassis and results in solar arrays being mounted on booms away from the satellite. By combining solar cell technology with the mechanical switches similar to the RF switches smart solar cells can be constructed that automatically remove themselves from the chain if light ceases to fall on them. If these cells are used in spacecraft solar panels then the individual cells can be wired in the most convenient manner and the panels themselves placed on shorter booms. Another example of smarter solar cells is to place sensing hardware right on the solar panel. This would eliminate another set of connectors and provide for a greater density of device packing on the satellite. Good candidates for this style of integration are sun and earth sensors.

To store electricity, the MEMS community is moving quickly to establish workable thin film batteries [27]. At the moment these batteries are limited to slow discharge rates and absolute power storage but the future is open to massive parallel and series arrays of these batteries. These configurations stand to improve current battery technologies by allowing for a far greater anode and cathode surface area. Outside of the MEMS community, the Li Polymer batteries are both higher in storage and environmentally acceptable. In addition, the polymer battery being developed could be used in a multi-functional nature, such as part of the structure.

3.3. Systems-Level Integration of MEMS Based Components

Integrating many of these subsystems together, a proposed MEMS based docking system for small spacecraft is given as follows. Consider, e.g., the free-flying camera satellite. At the end of a free-flight mission, the satellite navigates towards the docking site. The free flyer must first locate the secondary platform and navigate towards the docking site. As the two spacecraft get closer, the requirements on their positioning become more stringent. Contact is then made with some position uncertainty, based on limitations of the navigation vision system and precision docking requirements. The coarse navigation step can be accomplished using GPS for sensing and a variety of thruster systems. Fine navigation (just before docking) is more difficult because cm level accuracy is required. Sensing can be accomplished using several approaches: GPS using the differential carrier phase, or a laser/vision system and three "targets" on the secondary spacecraft. The actuation must be accomplished by a thruster system with a very small impulse capability, such as pulsed plasma thrusters.

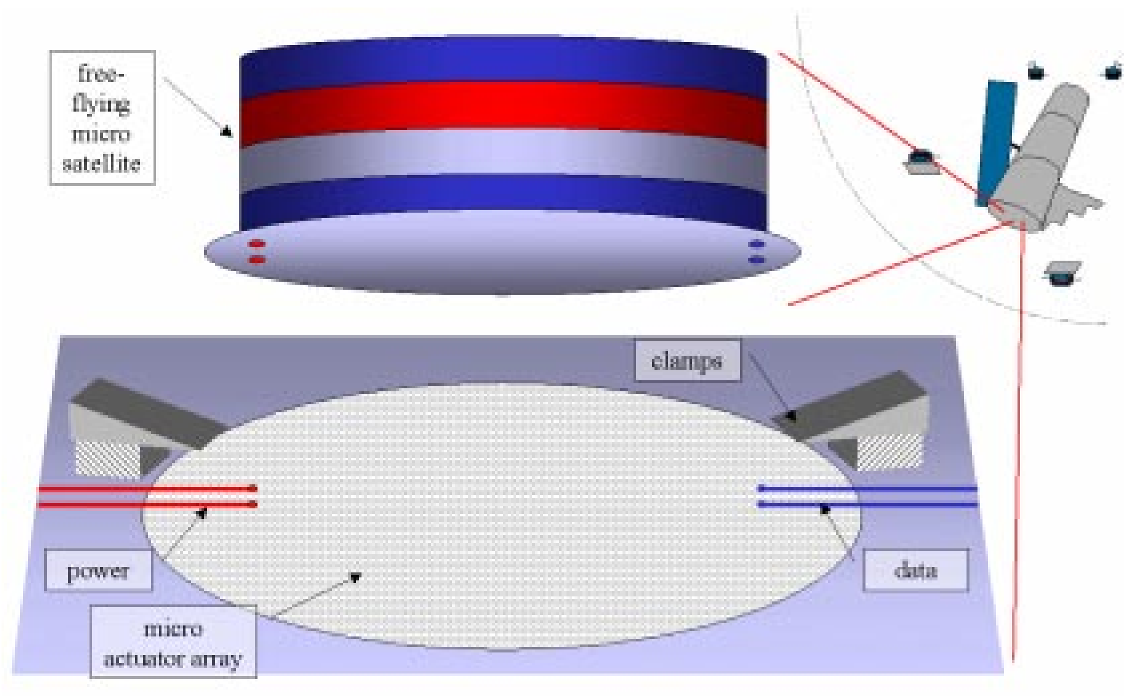

Figure 10: Conceptual MEMS based docking system.

A design by the UW takes advantage of recent advances in microelectromechanical systems (MEMS) which allow batch fabrication of thousands of devices in a single fabrication run on a silicon wafer. The proposed system is based on microactuator arrays [8]-[10] that have been developed in our group over the past six years. These devices have already been used in successful demonstrations of precision positioning under optical and scanning electron microscopes (air or vacuum as ambient medium). The lift capacity of a single actuator has been determined as approximately 76μN [8]. A motion pixel consists of 4 actuators and covers $(1.1\text{mm})^2$. Thus, for a disk with a 4in diameter, a maximum normal force $F_N = 4 \times 76\mu\text{N}$ /

$(1.1mm)^2 \times \pi\ (2in)^2 \times (25.4mm/in)^2 \approx 2N$ is obtained to keep the satellite in contact with the docking site.[1] Hence, if a docking plate with a 4in diameter is chosen, the normal force must be held under 2N. To maintain this force, the most efficient approach is to use a magnet[2] (and possibly a force/displacement sensor in closed loop). The shear forces can be approximated by $F_S = ¼\ \mu_r\ F_N$ (μ_r is the friction coefficient) since force in a specific direction can be generated usually only with ¼ of all available actuators. Note that these calculations are conservative. Far less thrust is required to maintain contact without slipping, thus low power pulsed plasma thrusters are an alternative. In experiments very low normal forces (several µN) were sufficient to induce motion in silicon chips. Ultimately, the speed of operation will depend upon the normal force as well as the inertia of the smaller satellite (or, more precisely, the reduced mass of the pair).

The MEMS actuators have been used in micromanipulation experiments where positioning accuracy in the single micrometer range was demonstrated. Strategies for open-loop positioning with submillimeter accuracy is possible as well [11]. The current actuator design achieves speeds of up to several cm/min. A prototype with 256 actuators requires approximately 50mW of average electrical power when operated in vacuum. For an array with a 4in diameter, an energy-optimized design operating at less than 1W is envisioned. The MEMS positioning system is less than 1mm thick, resulting in a mass of less than 10g (far less than the clamps or magnets). Furthermore, since the force generated by individual actuators is in the micro-Newton range, damage to the surface of the plate is not expected, even if the surface consists of, e.g., a solar panel. Hence the plate can be used for different purposes during free-flight.

Another interesting MEMS concept is the integration of more than one MEMS component into a micro-device. For instance, one could conceive of layering several of the following thin components: thin film layers for power (solar cells or thin film batteries), microelectronics (navigation, signal processing), propulsion and actuation (micro combustion, CMG), communication (laser - short range, µwave phased arrays - long range), and sensors (cameras, spectrograph). Each of these devices is currently under development, although not for integration into one package.

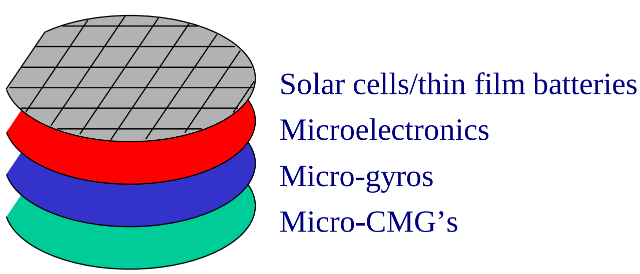

Figure 11: Integrated micro-system of a future micro-satellite.

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[1] If force is exceeded, actuators are completely flat and no actuation is possible. However, they are not damaged by higher normal forces.

[2] Magnet is analogous to magnetic bases on optical tables, which achieve pull to weight ratios of 50:1 (e.g. Edmund Scientific H39926)

3.4. Performance and Cost Benefits for MEMS

The performance and cost benefits of using MEMS based subsystems are derived in three areas: the small size and weight, the power consumption, and the low manufacturing cost due to batch fabrication. These benefits may be of several orders of magnitude, and may involve one or several of these parameters. It is noted, however, that these benefits may come with trade-offs in system performance and life expectancy. MEMS reliability is an area of very active research. To this date, data on long term performance and fatigue in MEMS devices is sparse. Exposure to harsh space environments and radiation without shielding may increase the effects of material deterioration and defects. In general, the largely reduced cost in manufacture and delivery of MEMS space systems will more than offset a somewhat shorter lifespan of these systems. The following is a summary of the near term estimated performance and cost benefits of using particular MEMS components.

For the communications field MEMS currently offers solutions to filtering, switching local oscillation [19], [25]. Radios are currently adapting an increasingly integrated processes as semiconductor materials are able to handle higher frequencies. By using MEMS wherever possible not only is there a weight and volume benefit from the device itself but from the lack of associated connectors, cabling, casework and packaging.

Table 3: Summary of MEMS communication components advantages.

Frequency Range	Macro sized mass [24]	Macro sized volume [24]	MEMS mass	MEMS volume
X-Band	1.5 kg	880 cm^3	100 g	0.5 cm^3
S-Band	2.0 kg	2700 cm^3	100 g	0.5 cm^3
Ku-Band	1.2 kg	608 cm^3	100 g	0.5 cm^3

The MEMS weight and volume remains constant because for MEMS RF switches the size is frequency independent and for mechanical filtering the carrier package dominates the weight and volume figure over the die mass [17]. For the table above the numbers reflect a full duplex communications link.

Antennas sizing is largely driven by carrier frequency bandwidth and as a consequence MEMS, fabricated antennas are seen as unlikely. There is the possibility for MEMS to be used as digitally controlled, phased array delay lines; however, this is still one step back from the antenna proper.

In expanding the definition of MEMS to include highly integrated, mixed signal devices an avenue for MEMS based imaging systems is opened. These have the advantage of being able to vary exposure time across the focal plane while consuming far less power than similar CCD systems [18].

Table 4: Summary of MEMS attitude determination sensor advantages.

Pointing Family	Macro sized mass	Macro sized power	MEMS mass	MEMS power
Star tracker	3 – 7 kg	5 – 20 W	1 – 5 kg	100mW – 1W
Horizon sensor	2 – 3.5 kg	0.3 – 10 W	0.5 – 2 kg	200mw – 1W
Sun sensor	0.2 – 2 kg	0 – 3 W	0.2 – 1.5 kg	0 – 1W
magnetometer	0.6 – 1.2 kg	<1W	150 mg – 0.5 kg	< 500mW

For the first three entries there is no dramatic weight loss because all of these systems require external optics for operation. In this instances, MEMS is more valuable for its reduced power consumption than the reduced mass. One of the most useful modifications is moving the horizon sensor away from its current spinning mirror to a MEMS positioning system.

The ability to generate power from solar radiation has benefited remarkably from the application of MEMS techniques. Using surface micromachining it is possible to integrate small surface lenses directly into the solar cell and to angle the metallic interconnections to reduce shadowing. For the table below the figures are given assuming 1353 W/m^2 of solar radiation and a photocell that is 0.5mm thick [17].

Table 5: Summary of MEMS attitude determination sensor advantages.

	Si (2.328 g/cm^3)	GaAs (5.32 g/cm^3)
Macro area efficiency [24]	190 W/m^2	244 W/m^2
MEMS area efficiency [20]	392 W/m^2	
Macro mass efficiency	163 W/kg	77.2 W/kg
MEMS mass efficiency	336 W/kg	

In the future it is easy to imagine further improvements, such as micromachined heatsinks covering the back of the cell for thermal dissipation or microactuators individually steering each solar cell for maximum power generation capacity.

The macro world provides no realistic solutions to propulsion in a micro-satellite. The smallest commercial thrusters, weighting tens of kilograms and producing Newtons of thrusts, typically dwarf even the largest micro-satellites [24]. For even a ten kilogram satellite the thruster alone uses up the entire weight, power and volume budget. To address these concerns smaller thrusters are now under development. These include conventional devices built to a smaller scale and true MEMS. Primex Aerospace Company and the UW has begun the development of small scale PPT that deliver 0.14 mN of thrust while only taking 100 cm^3 and using 12 watts of power. While this device is conventionally machined and produced, it has direct applicability to the microsatellite community due to its small size and simplicity. A strictly MEMS based solution to this problem is embodied by the TRW digital thruster. This approach involves the fabrication of thousands or millions of single use, chemical thrusters on a silicon wafer. Prototypes, so far, have consisted of a layer of micromachined pits into which the propellant is placed and a combination burst plate and nozzle which is fitted over that. Circuitry to handle ignition is typically placed on the first layer [22]. The systems demonstrated so far typically leave 80 percent of their propellant unburnt; however, effort is underway to improve that figure and to test this device in space as soon as possible [22].

3.5. Prototype MEMS Based Satellite for IST Missions

In order to assess the full impact of MEMS on satellites within the IST, the results of the MEMS research is compiled into a table analogous to that of the current state of the art in small satellites, shown on Page 12. It is noted that this table is derived from current research projections from UW, NASA, industry, and other government organizations. It is meant to show the trend in future satellites, not necessarily the ease in development of course. Note, however, that the tables were designed to have approximately the same performance capability in terms of movement and science.

Table 6: Table showing the projected MEMS components and microspacecraft that are fully functional. Included are the mass and power budgets for two satellites of increasing capability.

Projected Microtechnology Based Small Satellites					**Small**		**Medium**	
		Mass	**Ave Power**		**Low Precision**		**High Precision**	
System	**Comment**	**(kg)**	**min W**	**max W**	**M (kg)**	**P (W)**	**M (kg)**	**P (W)**
Structure								
Composite, Self-consu	10% of total	2.5	0.0	0.0	0.5		0.8	
Propulsion								
MEMS Digital Prop	cm accuracy	0.5	20.0	20.0	0.5	20.0		
MEMS Digital Prop	mm accuracy	1.0	40.0	40.0			1.0	40.0
ADCS	Propulsion for actuation							
Rate Gyros		0.1	0.1	0.1	0.1	0.1		
Star Trackers		1.0	1.0	1.0			1.0	1.0
Magnetometers		0.2	0.2	0.2	0.2	0.2		
C&DH								
From Embedded Systems		0.2	0.1	0.1	0.5	0.1		
Cabling	2% of total				0.0		0.1	
Thermal Control								
Blankets		0.5	0.0	0.0	0.5	0.0	0.0	0.5
Power								
Solar Cells	3 g/cm3, 494 W/m2, 35%				0.2		0.4	
Batteries (Li-Poly)	300W/kg+20% for power dist				0.1		0.1	
Communications								
Ground-LEO	patch/tape ant, Tx, Rx	0.1	4.0	7.0	0.1	4.0	0.1	7.0
Inter-satellite	patch/tape ant, Tx, Rx	0.1	1.0	4.0	0.1	1.0	0.1	4.0
Navigation								
GPS	antenna	0.1	1.0	1.0	0.1	1.0	0.1	1.0
Science Payload								
Spectrometer		1.0	1.0	1.0			1.0	1.0
Plasma Probe		0.1	0.5	0.5	0.1	0.5		
Total					**2.9**	**26.9**	**4.6**	**54.5**

The mass reduction is the result of the use of composite structures and multifunctional structures, such as using Li Polymer batteries. MEMS based propulsion, along the lines of the work at TRW should provide excellent propulsive capability for the small satellites. Intelligence facilitates reconfigurability of a satellite system which allows the system to achieve a higher level of upgradability and fault tolerance. The attitude determination sensor is a MEMS based star tracker for the higher precision satellite, and MEMS based gyros and magnetometers for the low precision satellite. The processor has benefited from heavy developments in embedded systems to yield a very low power system. The percentage of cabling mass has drastically diminished because of the advanced packaging of MEMS components into integrated micro-systems. Solar cell efficiency (and individual cell pointing) have improved the power generation, although only by a factor of two. Batteries are now taking advantage of the multi-functionality and energy storage of Li polymer batteries. Communications components now in weight and volume from the device itself, as well as the lack of associated connectors, cabling, casework and packaging. The spectrometer has also decreased in size and power using MEMS technology.

This aggressive use of MEMS spacecraft subsystems results in mass reduction of at least a factor of four in the low and high precision satellites. Power consumption by both satellites is about the same because the power budget of both systems is dominated by identical propulsion systems. If the MEMS based satellite in this example had used a system similar to TRWs digital thruster then an order of magnitude reduction in power could have been realized. By reducing the mass of the satellite there is an obvious reduction in the cost to place the satellite into orbit and once their maneuver it.

3.6. Micro-Subsystem Conclusions

With all these technologies there is no quick and easy solution. Thus, the challenges facing the MEMS community are great when it comes to the development of an integrated MEMS spacecraft. There are a number of efforts underway for specific MEMS components, such as micro-propulsion and micro-sensing and instruments. However, once these problems are solved, the real challenge begins in integrating these subsystems into one, inexpensive, manufacturable package. Once this is commonplace, the final challenge is laid out: the development of a complete MEMS spacecraft. To get to this point engineers and scientists must look beyond technical hurdles to a field of psychological and conceptual issues. The foremost of these is letting the mission be driven by the technology as opposed to the converse. With emerging technology such as this there is a tendency to force MEMS to fit into a technological niche or to overlook a better performing, large scale analog in the pursuit of the perceived state of the art. In the upcoming years and after a few successes, MEMS will be touted as the must have technology for any space mission. It is important that even with all the fanfare, of which quite a bit is deserved, MEMS is treated as any other technological tool as opposed to a panacea. In the long run the use of MEMS in spacecraft subsystems will benefit more from a calm, analytical perspective than irrepressible enthusiasm.

Other specific conclusions for MEMS components in space include:

- Several subsystems are well on their way to maturity because of government and industry funding. These include MEMS based propulsion, micro attitude determination sensors such as gyros and star trackers, and low power processor boards based on embedded systems.

- The key to developing a MEMS based satellite is integrating the smaller components into modular, low power, lightweight, and possibly multi-functional packages that can be manufactured inexpensively, and can be used in several types of satellites.
- The biggest roadblock to a MEMS based satellite in deep space is power. The solutions for this include low-power devices and circuitry in combination with improved solar cells and thin/thick film batteries, In addition, novel energy are sought, such as beamed energy source from a local mother satellite, or one-shot energy supplies that allow a short burst of energy for long range communications once the mission of the picosat has been finished.
- Within 10 years, a satellite of equal capability can be developed using MEMS components at a mass savings of a factor of 4.

Chapter 4: Autonomy

While miniaturized devices are now being researched and developed, the potential for large number of satellites within the fleet creates a dire need for distributed control and higher levels of autonomy. With tens, hundreds or thousands of satellites envisioned, they must autonomously work together for mission success in order for the IST vision to become a reality. Many questions require answers, such as: How much intelligence is required on each satellite?, Are all satellites identical?, and How can a mission objective be encoded and accomplished by a fleet of autonomous, intelligent satellites?

4.1. Overview of Autonomy Concept for IST's

A complex autonomous system of interacting satellites would have a control structure composed of three levels. Since the system will interact with human ground control, the first level will be interactive mission control. The second will be the outer loop navigation of the IST. The third level will be the inner loop control for individual satellites of the IST. These three levels are shown in Figure 12. This hierarchy fits naturally into the framework of intelligent control systems which are based on fuzzy logic, artificial neural networks, evolutionary programming (or combinations thereof) [12]. While the current state of technology holds great promise for multi-level control of complex systems, there are still many issues that need to be addressed in the context of the specific systems to which the technology will be applied. The capabilities of an ideal multiple satellite system include:

- Coordinate in close formation, at a variety of precision levels (distributed control).
- Receive a mission goal and distribute tasks to individual satellites (planning).
- Decide which platforms, how many, and when individual satellites should act (scheduling).
- Evaluate an individual satellite failure and recover from it (fault detection and recovery).
- Adapt the information flow (communications) depending on changing system parameters.
- Upgrade a new satellite that is possibly different (upgrade).
- Train for a mission, or learn from any mistakes that occur during the mission (learning).

These are succinctly shown in Figure 13.

Figure 12 also shows that traditional AI technologies have now been expanded in terms of the fleet. Planning and scheduling includes scheduling for different platforms (fleet), as well as their subsystems (individual). Communication can occur between the ground station and fleet,

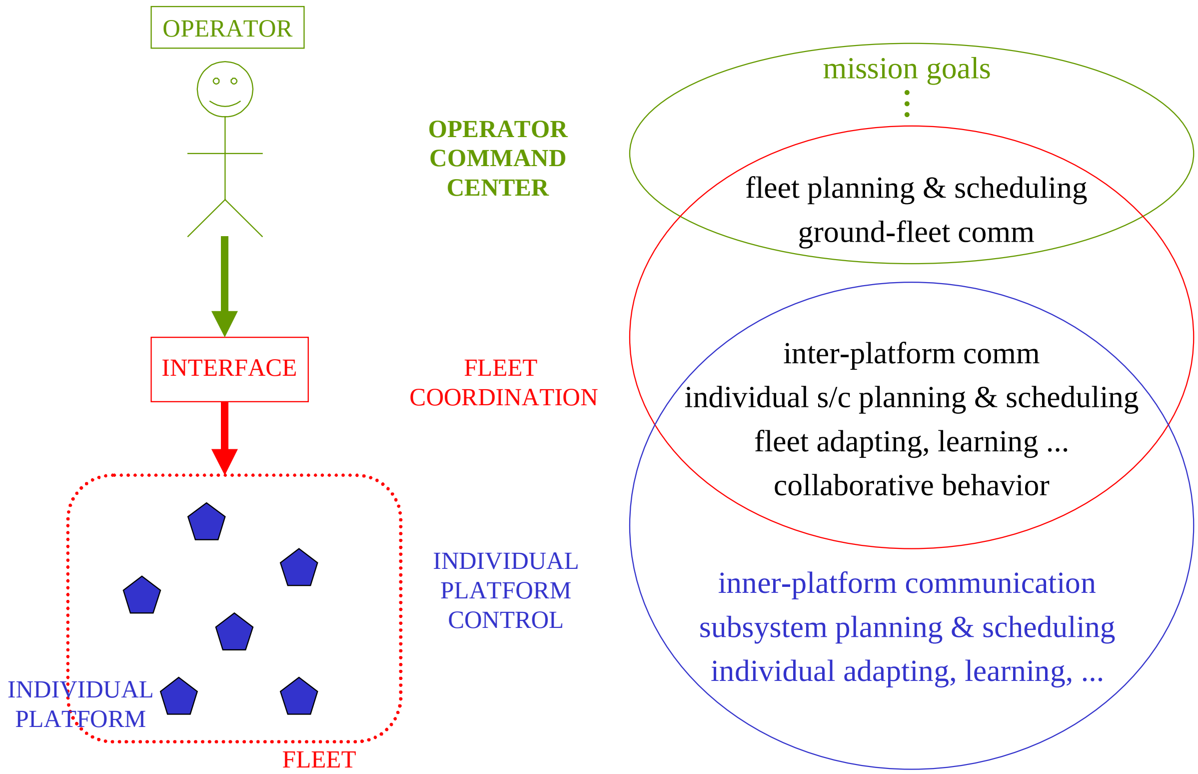

Figure 12: Flow chart showing the general hardware on the left, and the layered architecture on the right. Overlapping aspects can exist on either layer.

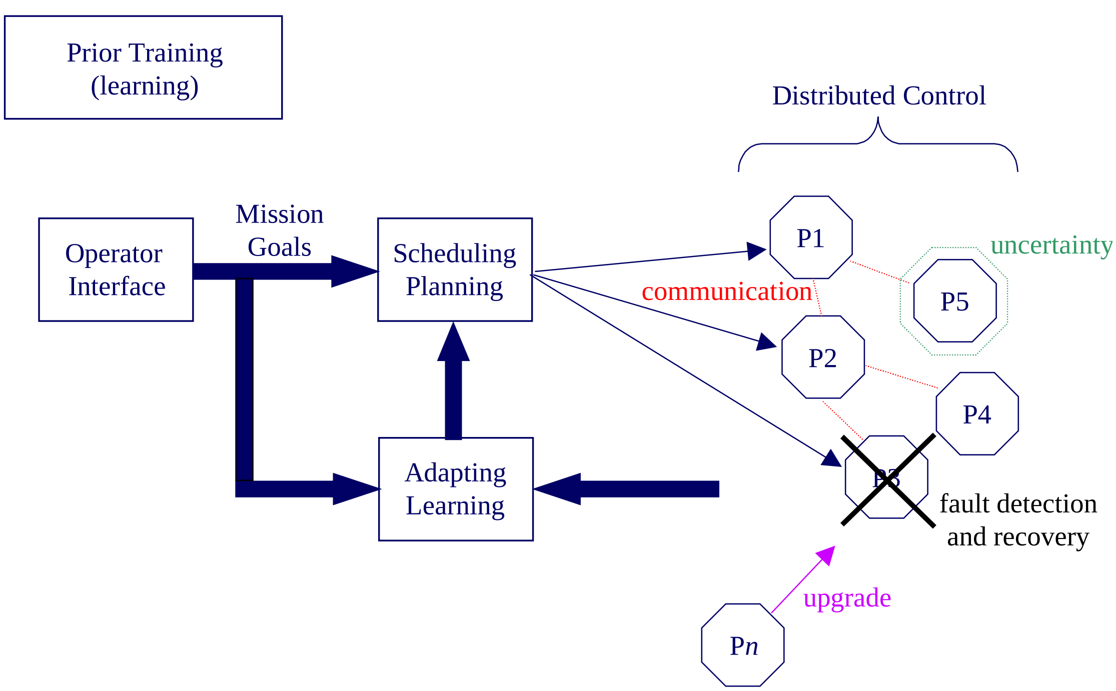

Figure 13: Summary of the capabilities for a fully autonomous, multi-agent system for IST's composed of multiple satellites.

and between the individual spacecraft. Robustness now applies to failures of a platform within the fleet, as well as within each platform. Mission objectives are now embedded into the fleet, not an individual platform. A process of sharing information occurs, thus improving the fleet's chances of mission success. The fleet can reorganize itself, and allow different entities to enter and exit as needed.

Consider one of the most important tasks of an intelligent system, especially for multiple satellites: scheduling. This is a key issue because it can be used at a variety of levels. First, it can be used to break down mission goals into specific platform tasks. Second, it can be used in a hierarchical approach, such that mission goals from the operator are taken to fleet tasks, which are taken to platform tasks, which are taken to subsystem tasks, and finally implemented using a separate scheduler/planner agent at each level. This process is shown in Figure 14.

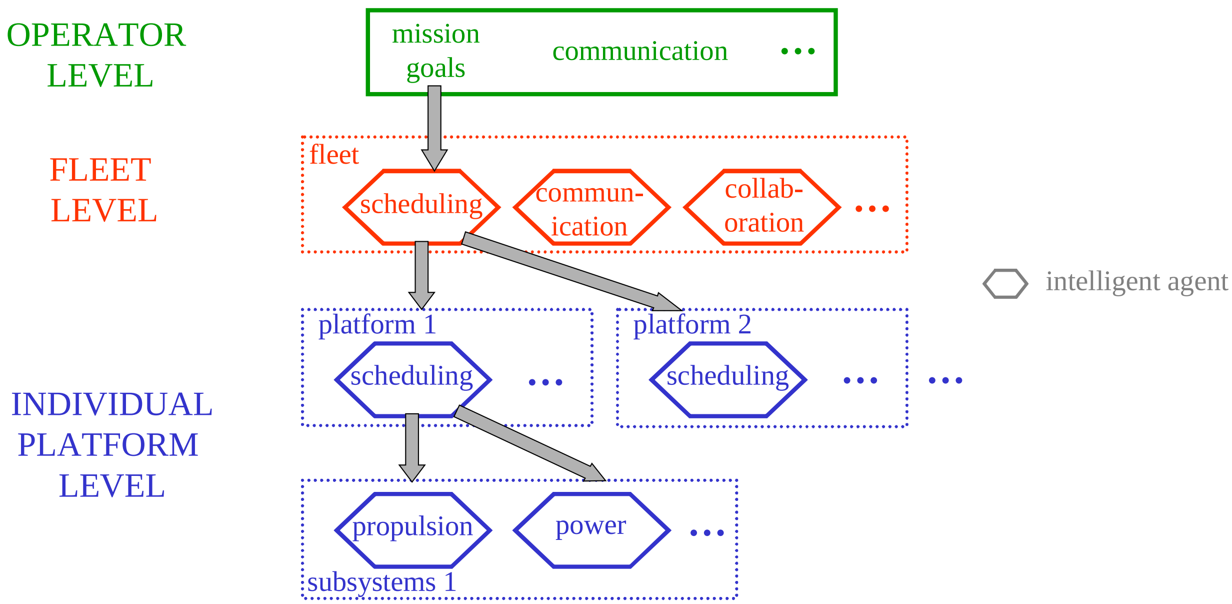

Figure 14: The hierarchical approach to scheduling in a fleet of coordinated platforms, using layers of intelligent agents at the operator, fleet, and individual platform levels.

Because of the wide variety of uses for scheduling and planning, several approaches can be used. Most scheduling and planning tasks allow for many options. Exact solutions are not common, but rather heuristics are used to get as good as solution as possible. For example, suppose a task is sent to a satellite with a scheduling intelligent agent. This agent's duty is to locally schedule a set of tasks to complete its goal. If the set of tasks is large and unpredictable, a common approach for the agent is to randomly pick many sets of tasks and see which sets satisfy the goal. Then, the set which is most efficient (in terms of number of tasks, time, cost, etc.) is chosen. Or better still, once there are several sets of tasks that satisfy the goal, each of these sets can be altered slightly by changing a few or deleting tasks. After each change, the agent evaluates if the set of tasks still achieves the goal, and if the new set is more efficient than the old set. Thus, our solutions are locally optimized. Much work is done on improving local optimizations so the schedule approaches the global optimum. Obviously, there is a trade-off between cost and optimality of our solution. Greater insights into a specific problem domain allow more efficient heuristics.

The above example shows that organizing and coordinating the IST is a very important and complex task. There are many options, and it is not clear which may be the best. Once the organization is set, then there are a variety of tools that can be used to facilitate the other areas such as communication and fault tolerance.

4.2. State of the Art in Intelligent Agents and Autonomy

Although artificial intelligence (AI) research extends over many fields, relatively little AI has been applied to the domain of space satellites. For instance, planning and scheduling [28], [32], [47] as well as reasoning [35], [43], [44] are well developed areas of AI, but only recently have they been incorporated *onboard* (e.g. Deep Space 1 and other New Millenium projects). Another area of AI research, multi-agent systems (MAS), has not been developed as well as planning or reasoning, but its application to space systems offers tremendous possibilities in terms of improved performance and reduced cost of missions. It will be now considered the current state-of-the-art of multi-agent systems in AI and of intelligent agents in space, since the application of the former to the latter is not only helpful in achieving high-performance, low-cost future missions, it is in fact necessary.

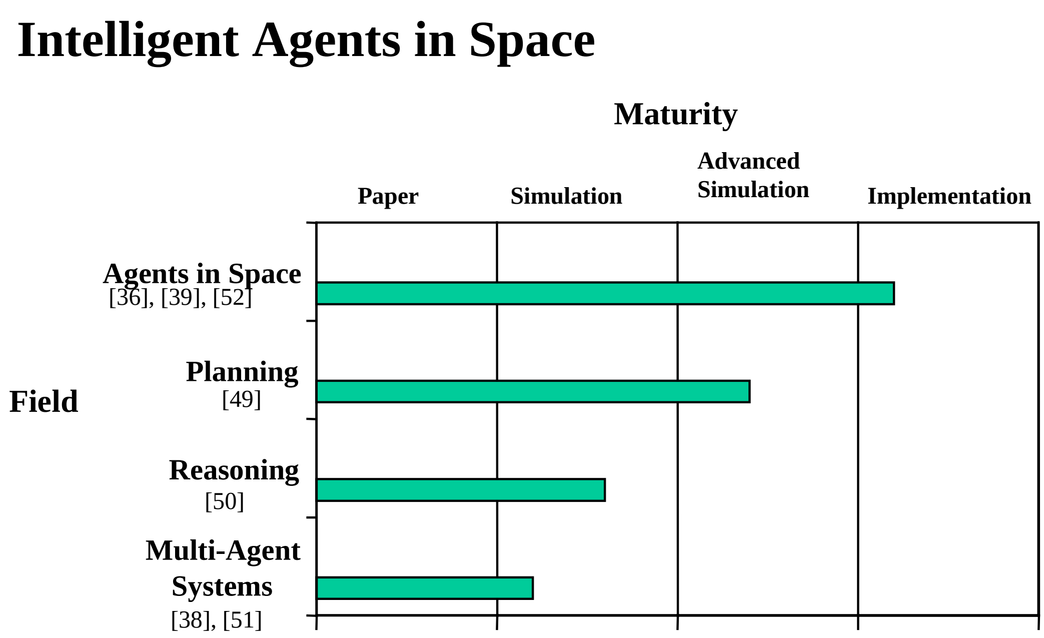

Figure 15: Maturity of using intelligent agents in space applications.

As one gains experience in space satellite systems, more of the decisions which need to be made during the course of a mission can be automated. Some decisions, for which a totally reliable, expert choice is imperative, must always be made via ground support. However, for most choices, a locally intelligent decision can be made onboard a satellite. Such on-board artificial intelligence eliminates satellite-to-earth communication (and the corresponding ground support) which is an expensive aspect of space exploration. Specifically, for a mission such as Pluto Express, it is unreasonable to suppose many real-time mission decisions can be made on Earth when communication costs are so expensive in terms of power and time. Intelligent space agents not only offer an enabling technology, but they allow reduced costs, faster realization of mission goals which leads to increased exploration results, and overall improved performance.

Planning and scheduling in an intelligent agent (such as a satellite) allow users to send high-level goals to the agent rather than a set of exhaustive, detailed actions. The agent, then, can take the high-level goals and determine sub-plans which it can follow to achieve the goals. The agent will carry out the sub-plans by computing a schedule of its resources and subsystems which realize the sub-plans. This intelligence will be applied to space agents for the first time with the New Millenium projects.

Reasoning in an agent allows the agent to reach an intelligent conclusion or decision about a given set of data. A set of data might consist of results obtained from science measurements or information regarding the status of a sub-system. A set of data generally cannot be defined explicitly because the data set is too large or because data is unpredictable (certain science measurements may be unanticipated or a strange system failure may yield unexpected feedback). Thus, an agent must reach an intelligent conclusion about its unanticipated data. Deep-Space 1 [13] began to take advantage of the autonomy allowed by reasoning with an agent. By comparing data from star trackers with pre-stored images, Deep Space 1 has been able to effectively calculate its location on several occasions. Further use of reasoning aboard agents will offer better adaptability to unknown situations and more autonomy of the agent. But it should be noted that the transition of the idealized technologies to actual space implementation, as was found in DS-1 [14].

To date, multi-agent systems have not been incorporated into satellite missions, although future New Millenium projects will begin to utilize these ideas, such as formation flying for interferometry missions (LISA [51]). Ideally, multi-agent systems will be employed in a hierarchical fashion. For instance, one can think of a particular sub-system, like propulsion, as an individual agent. The current satellite location and the desired satellite location may be sent to the propulsion agent (as a high level goal), with which the propulsion agent will plan and schedule its resources (thrusters) to achieve the goal. Thus, the propulsion subsystem will have intelligence and can be thought of as an individual agent, so the organization of all the sub-systems, each an individual agent, will form a multi-agent system which comprises an entire single satellite. Of course, the single satellite will be an agent part of a satellite constellation (IST) which makes up a multi-agent system.

In a multi-agent system, each agent contains intelligence on its own, as well as all the agents exhibiting intelligence as a group. A few multi-agent systems have been implemented for real-world applications [29], [30], [42], but it is difficult to implement effectively a multi-agent system [48].

Multi-Agent Systems

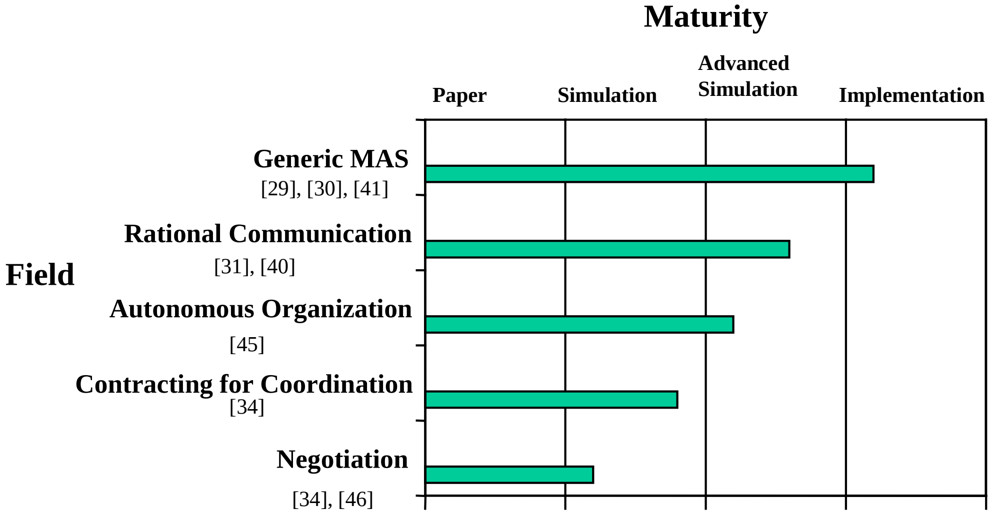

Figure 16: Maturity of multi-agent systems with applicability to IST's

Since communication is a premium in the space domain, it is important with a constellation of satellites to ensure intelligent communication among the satellite agents so that communication is not too costly. For the purposes of reducing communication, not only is it advantageous to filter data sent from a MAS to Earth, but it is also critical to determine which satellites in the group need information from which other satellites and what information needs to be sent. Noh and Gmytrasiewicz [40] consider these issues in the domain of air defense by prioritizing communications within the MAS and intelligently classifying and selecting agent interactions.

Autonomous organization of a MAS refers to the groups ability to autonomously determine where in the group (since each agent has some intelligence) intelligent actions will take place. For instance, only one satellite might communicate with Earth, and this satellite can do all planning and scheduling for the other satellite agents, or depending on the mission, the planning and scheduling might be distributed among the MAS. Turner et al. [45] demonstrate the autonomous formation of intelligent underwater vehicles. The underwater domain (deep sea) closely parallels the space domain in that agents are essentially inaccessible by humans and communication is expensive/limited. In the underwater example, autonomous organizations allows for additional agents and lost agents so that the MAS will reconfigure, and thus, it provides a highly adaptive system.

Once a MAS is organized, further intelligent agent interaction can benefit the system. When an agent determines a plan to achieve a goal, the agent might recognize the benefits of utilizing other agents in carrying out its plan. Thus, the agent might contract other agents to aid in its plan. This "contracting for coordination" is useful in realizing goals when not all agents are being utilized, but in the space domain, where agent resources are precious, it may make more sense to define goals explicitly for each agent. Another approach, for improving MAS performance once a plan for all the agents has been determined, is to allow each agent to attempt to optimize the plan so less resources will be used. Here agents try to "negotiate" a better plan. This idea has been considered for air-traffic control [46] where each aircraft proposes improvements to the current flight take-off/landing plan at an airport. The negotiation can yield substantial plan optimizations, but tends to work best when each agent is competing with other agents (e.g. for take-off/landing time) and trying to optimize the overall plan for its own benefit. In the space domain, satellite agents generally do not compete with each other; however, if a satellite schedules tasks for its sub-systems based on power constraints, each sub-system agent may negotiate for a better plan where the sub-system is afforded more satellite power. Although multi-agent systems are still in their infancy in terms of AI research, there is great potential in their application to space satellite systems.

Figure 21 shows a summary of the coordination options for IST's, as a function of individual agent intelligence and time. Currently, the best approach is a "Top-Down" approach, where there is one high level agent that has does most of the scheduling and planning, etc., with little interaction with lower level agents except for information exchange. This is similar to the Deep Space 1 model [13]. With new developments in on-board planning and reasoning, a new organization can be developed termed "Multi-Agent Planning," where a centralized hierarchy is still used, but now the underlying agents can interact with the high level agent for the betterment of the IST. After this technology advancement, the next step is to allow the agents to coordinate together, in a distributed Multi-Agent Planning architecture. This is the ideal case for IST's, as they take full advantage of their capabilities in terms of adaptability, distribution, and intelligence. Finally, if each of the individual agents is very intelligent, and has models of the capabilities of each of the other agents, an architecture that allows individual planning can be developed. This architecture is the most complex, and requires the most intelligence and communication between agents. And, it is not clear that there is a large benefit in jumping from the previous level. This architecture could work very well with more intelligent missions such as the autonomous construction of a space facility.

4.3. Performance and Cost Benefits for Autonomy

When presenting autonomy ideas to both scientists and traditional space engineers, the question always arises, "Why should we change?" Put another way, "What can autonomy do for me?" This is a question so very important to the IST concept that it was addressed during Phase I. Table 7 shows a summary of tasks for which autonomy based technologies can be used, versus the "faster, better, cheaper" mantra of NASA. As with any advancement, there are trade-offs. For instance, one can reason about what science or telemetry data to send back. This has the benefits of sending back better data if there is a limit of communications, but it also has the potential of making more mistakes than a human would. This is especially true of critical, complex science decision. In addition, the power required to send the information has decreased. As another example, the IST must reconfigure if there is a loss of a satellite – a probable scenario with the IST concept because of the large numbers of satellites. By using autonomous operations, this could be done quickly such that the effects of the loss are minimized. If telemetry data must be sent back to earth to evaluate the problem and wait for commands, valuable science time and performance has been lost. In addition, the cost of operators has just increased.

Table 7: Autonomy based tasks and their potential performance/cost benefit.

	FASTER	BETTER		CHEAPER	
	TIME	SCIENCE	RELIAB	DOLLARS	POWER
Reasoning					
about what science/telemetry data to sent back		+	-		+
about science/telemetry data to decide next task(s)	+		-	+	+
about science/telemetry data to decide next task(s) - *enabling*		+			
Scheduling and Planning					
plan tasks for science	+		-	+	+
schedule tasks for computations	+		+		-
Adaptation					
reconfigure upon a loss of instrument or agent	+		-	+	+
reconfigure upon a loss of instrument or agent - *enabling*					
reconfigure upon a gain of instrument or agent		+			
adapting to small, unforseen events that limit performance	+		-	+	+
Learning					
learning from events to prevent their recurrence		+	-	+	+

Table 7 shows the most prevalent examples for IST's. One should note that the most prevalent disadvantage is reliability. And reliability in this case refers to the reliability in getting the best science data – per the NASA mission. It should be noted, however, that reliability in simple decision making for satellites has been shown to be better if the decisions are automated [57]. Basic telemetry data fits this category. Therefore, this study primarily examines science data in important, complex decisions. The benefits include more time to collect science data, decreased operations costs, and lower power. These general trade-offs are now explored.

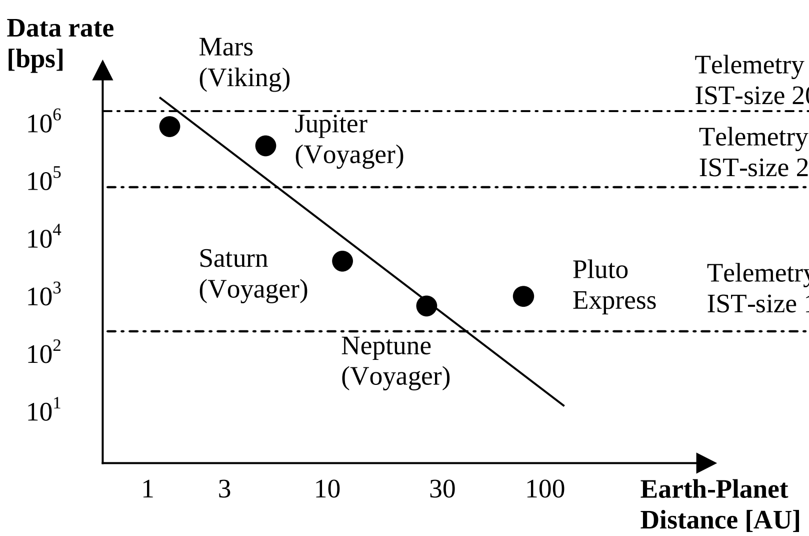

Figure 17: Downlink data rate as a function of Earth-planet distance.

It takes both time and power to send data back to earth from space. Figure 17 shows a plot of the downlink data rates for several missions [56]. Note the correlation, which is primarily driven by the large communications distance and the falling off of solar energy for communication power. This shows that the communication rates are fairly predictable for space missions, at least until optical communications become more common. Note also that several cases of IST's and their telemetry data are plotted, based on a minimum case of 500 bps for each satellite. As the numbers of satellites increase in the IST, deep space missions become much more difficult without some level of autonomy described in Table 7.

Figure 18 shows a plot of the time it takes for a general iteration with a satellite on a task that requires the communication of 1 MB of data back to earth (and this data can be for any of the time critical tasks shown in Table 7). An example of this is the data required to reconfigure an IST after a failure. If this procedure were automated, notice the time savings that would occur, which obviously increases dramatically in deep space. This is more succinctly described in Figure 19 as the percentage of time communicating over total mission time, as a function of the number of events that require input from earth. This is based on a 100 satellite IST and a 6 month mission. Assuming one event per day (180 total), one can see that the three outer planets would waste all six months of time, while the inner planets waste several percent. By automating at least the simple procedures within a mission, much more time could be devoted to communicating back science data and/or moving on to the next science task.

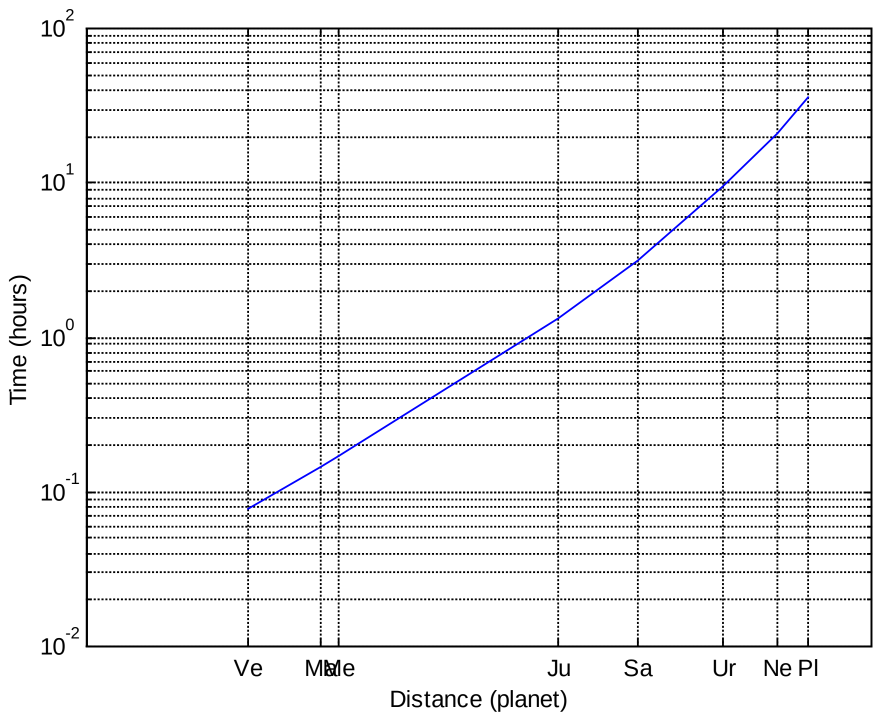

Figure 18: Plot of the communication time for 1 MB of data back to earth.

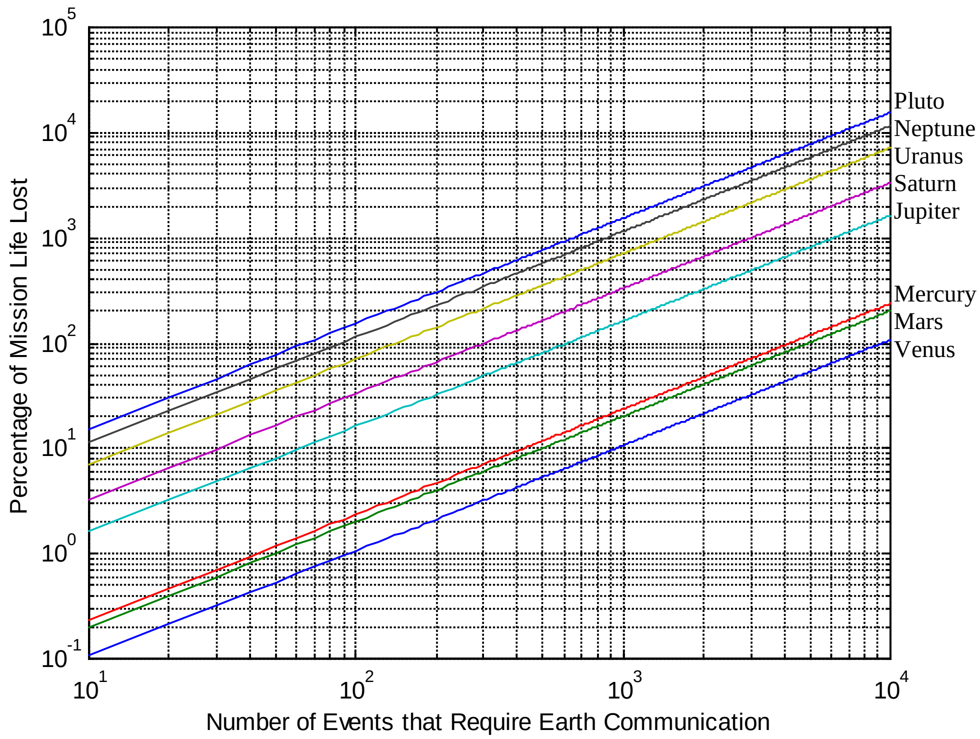

Figure 19: Plot of the percentage of time that could be used elsewhere if the system were automated, as a function the number of events that require earth communication. The plot is based on a 6 month lifetime.

Operations costs can be tremendously high for complex satellites. Figure 20 shows a plot of the mission operating cost versus the amount of personal needed to run the operation team [59]. The units are Dollars versus man year per satellite. UoSAT-5 is a small satellite built and operated by the University of Surrey in cooperation with Surrey Satellite Technology. The satellite was launched in low earth orbit to perform communication task and Earth-imaging. Alexis is a micro satellite which was launch in earth orbit in 1993. The mission objective is produce sky maps in the EUV range and to do VHF ionospheric measurements. SAMPEX is the first of the NASA explorer missions. Sampex is designed to detect solar and interplanetary charged particles, galactic cosmic rays on energies. NEAR is a mission in the NASA Discovery series intended to rendezvous with and explore a near-Earth asteroid. Pluto express is a 2-spacecraft flyby of Pluto. Final mission definition is still evolving. The objective of the Clementine mission was fight-qualification of advanced technology for lightweight sensors with planetary exploration objectives such as lunar mapping.

As shown in the diagram, the operating cost increases nearly linearly with the complexity of the task and the level of science experiments. Therefore the projected cost for an IST with tens to hundreds of satellites, even compared with current low cost satellite missions, would be much too high because of the large numbers of satellites. Thus, autonomy based technologies are enabling for IST's in order to reduce the mission operating cost.

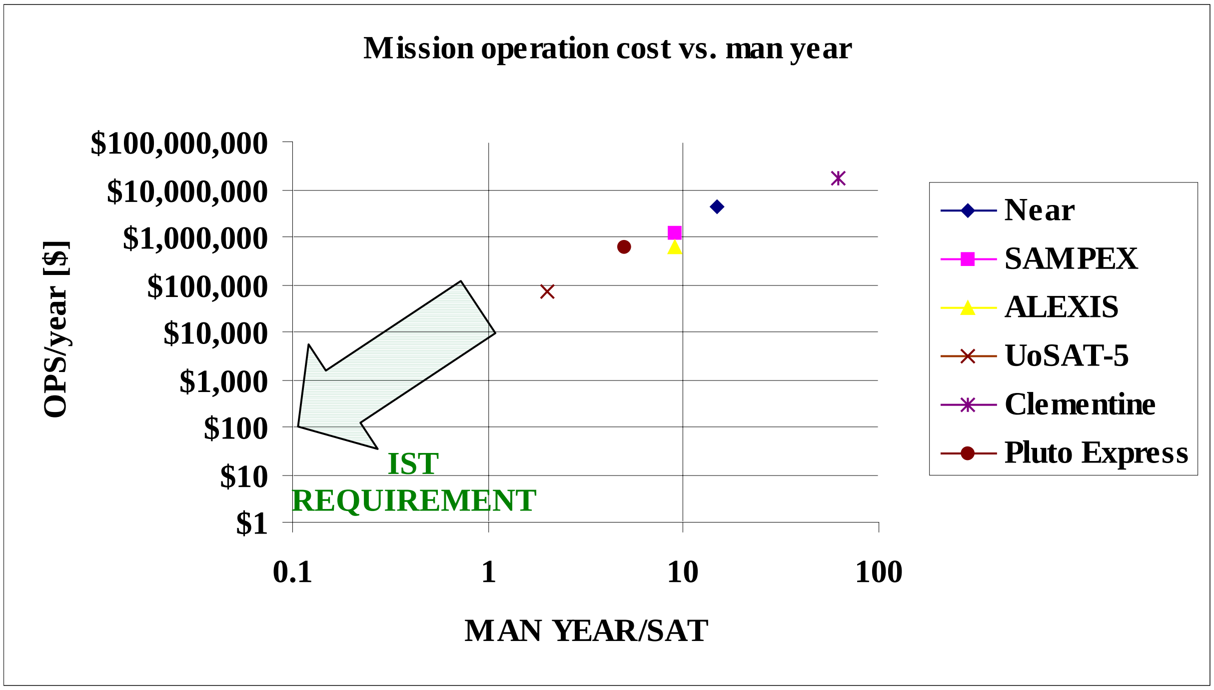

Figure 20: Several mission operations costs as a function of man year / satellite. For IST's, autonomy is required in order to get these numbers reasonably lower. This chart shows that autonomy is an enabling technology for multiple satellite systems.

4.4. IST Design and Organization

In order to develop a coherent working community within the IST such that all of the capabilities shown in Figure 13 can be achieved, the organization must be designed very carefully. It must be adaptable to prevent of faults, avoid bottlenecks, and allow reconfiguration. It must be efficient in terms of time, resources, information exchange and processing. And it must be distributed in terms of intelligence, capabilities, and resources. This type of organization is enabling for IST's, and is many years away from maturity. The following discussion describes the evolution process of the IST organization, along with tools to aid in its development. These include:

Organizational Coordination
- Top-down coordination
- Hierarchical multi-agent planning
- Fully distributed multi-agent planning

Tools for Coordination
- Contracting for coordination
- Negotiation

Organizational Coordination

There are several possible organizations for the agents of a multi-agent system such as an IST. Four of these are shown in Figure 21. In a simple top-down organization, agents are coordinated in a hierarchical fashion, where the agents at the top of the hierarchy make the majority of intelligent group decisions. Then, the decisions are passed down to the rest of the agents in the organization. This organization is fairly rigid since it has centralized intelligence, but it is the most straightforward to implement as it requires almost no communication between low-level agent (agents at the bottom of the hierarchy) since these agents exercise little group intelligence.

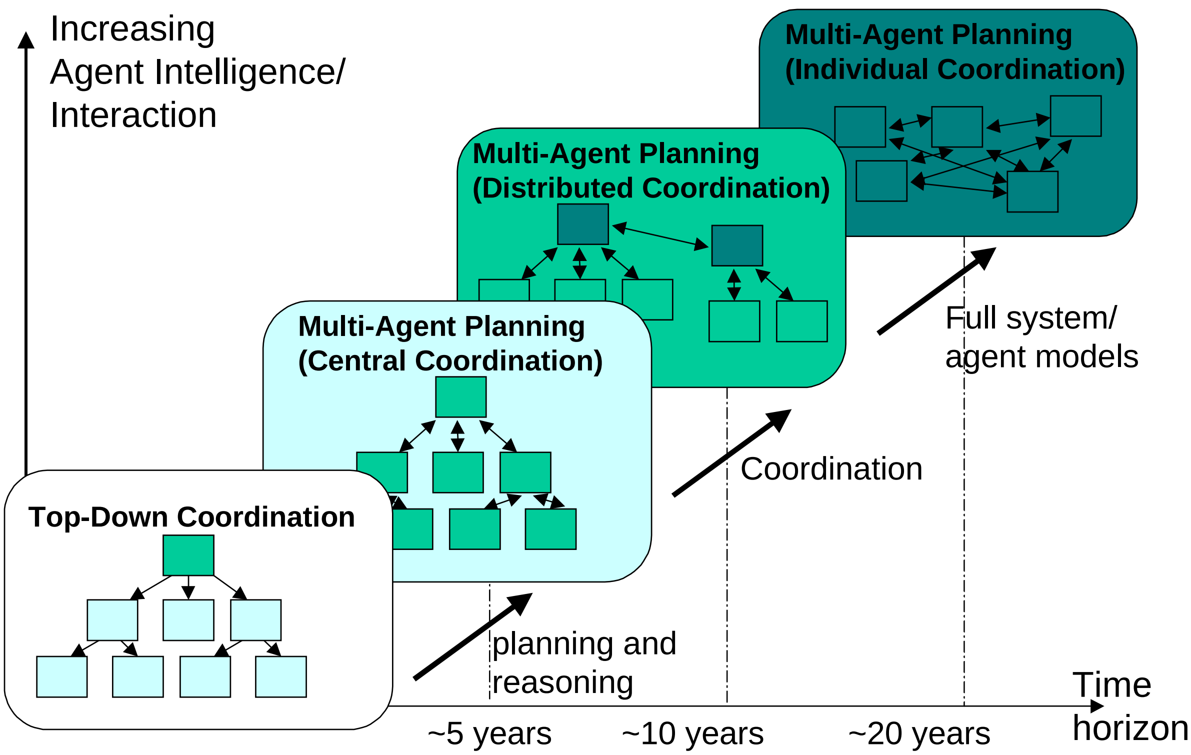

Figure 21: Coordination architectures for coordination of multiple agents for IST's.

In other hierarchical multi-agent organizations, lower-level agents exercise more intelligence in making group decisions. For instance, lower-level agents may formulate plans for the entire system to follow, and then a centralized agent (or small group of agents) decide on the best plans produced by the individual lower-level agents. This organization is more complex and requires more communication between agents, but the intelligence is better distributed throughout the system, which makes for a more flexible, adaptive, and efficient organization.

These organizational ideas can be extended to the point where each agent in the system has "full group intelligence", by which we mean any agent has intelligence equal to any other agent equal to the combined intelligence of the group. In this case, there is no hierarchy. In order to achieve this, however, there must be extensive communication between all agents in the system. This has the advantage of being highly adaptable and reliable, as any agent can exercise intelligence for the entire system as well as any other agent (so a decision never has to be passed to other agents), but the organization is complex and requires elaborate inter-agent communications.

Tools for Coordination

Once a multi-agent organization has been formed, there are a several intelligence tools available to aid the system in achieving its goals. If an individual agent has a goal which it is trying to realize, it may try to enlist other agents with unused resources to help it accomplish its plan. Agents can contract other agents that are available so that a small group works to fulfill the goal of a single agent. This approach requires large communication costs between agents, but it allows high-level planning of goals, flexibility in achieving the goals, and natural load balancing within the multi-agent system.

Another approach, once a group has determined a plan for all the agents of the group, is to allow each agent to try to improve the overall group plan. Each individual agent attempts to modify the group plan so that the agent can more efficiently achieve its goals. This plan negotiation is useful in that it distributes the intelligent process of optimizing a group plan among all the agents of an organization, but it is complicated in that it requires high-levels of intelligence in each agent and there must be substantial communication between all the agents. As these intelligence tools are successfully incorporated into multi-agent organizations, the performance of these systems can be substantially improved.

Optimization for the Best Organization

It appears from the evolution standpoint of Figure 21 and the reliability of distribution that the multi-agent planning organization would be best for all applications. This, however, is not necessarily the case. The actual organization is a function of many parameters, such as the traditional spacecraft parameters of total mass and power, reliability, performance; as well as the IST parameters of autonomy, adaptability, efficiency, and distribution. As an example, consider Figure 22 consisting of three organizations. Organization I is a very flat "Top-Down" organization to help with redundancy, communication, and intelligence, but also performance because of the large numbers of science instruments. There is one mother satellite with all intelligence and communications capabilities, and each small satellite has one instrument on board. Organization II is distributed "Multi-Agent Coordination", with three mother satellites with all intelligence and communications capabilities for redundancy, and each small satellite has two instruments on board. Organization III is a fully intelligent, distributed, individual "Multi-Agent Coordination," with 13 fully intelligent, fully capable satellites. Organizations II and III have the capabilities of reconfiguring upon failure, and utilizing multiple instruments. Shown in the figure is the organization for a constant mass system, one typical driver in space applications.

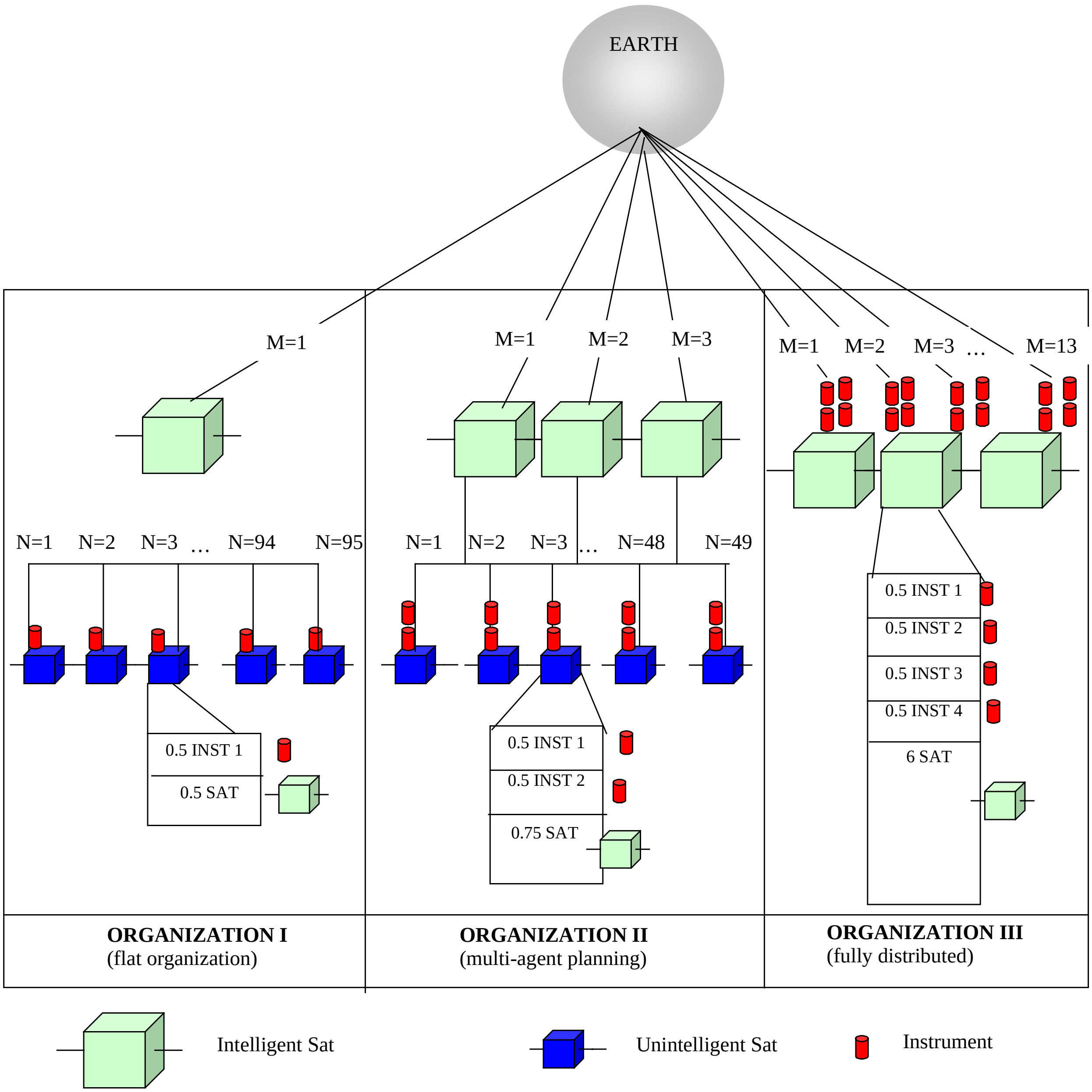

Figure 22: Three organizations for the IST concept, each with the same mass.

The following constraints are placed on the organization, based primarily on mass estimates from [16], [24], [59], [60] and past experience:

- There are four different instruments; each has a mass of 0.5% of the total mass of the system.
- The non-instrument portion of the satellite (computation, inter-sat comm, propulsion, etc.) account for 0.5% with one instrument on board, 0.75% with two instruments on board, and 1% with four instrument on-board.
- The reliability is 0.9 for all major components shown.
- The performance is measured by the number of instruments being flown, multiplied by average probability of not failing during the lifetime.

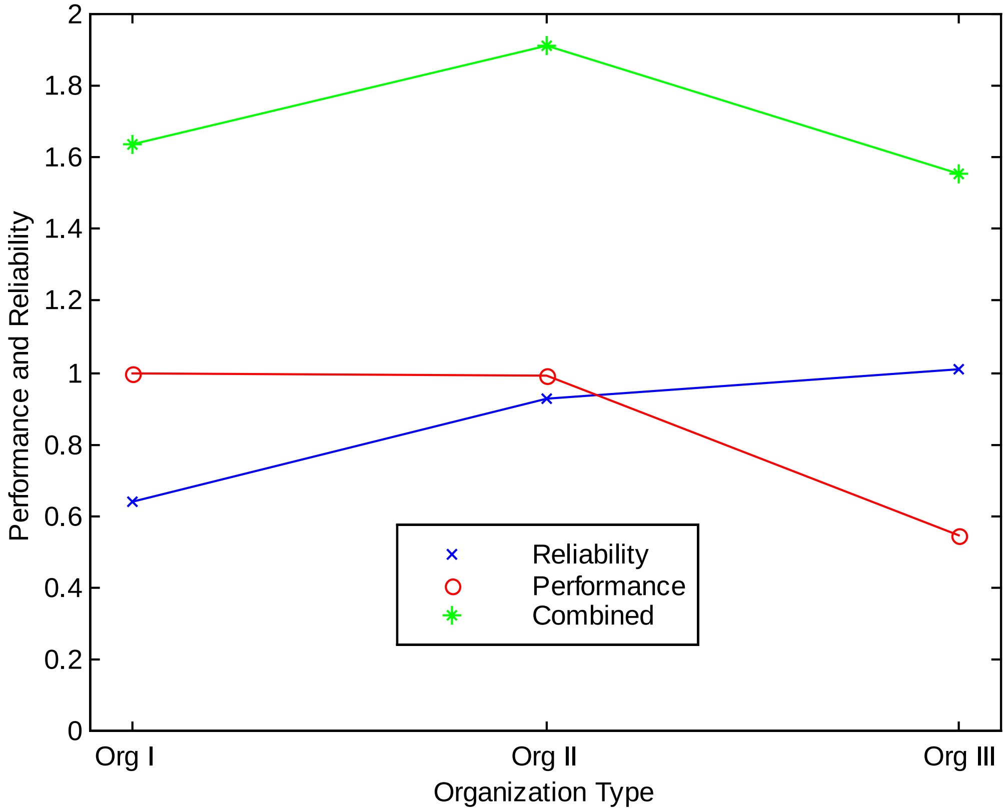

Figure 23: Plot of the reliability, performance, and combination of the two as a function of the three organizations in Figure 19.

Figure 23 shows a plot of both the system reliability and the system performance, along with the sum of the two. Notice that Organization II works out to be the best. Organization I has the best performance only because it has used most of its mass budget on instruments. Organization III has the best reliability because it is fully distributed and intelligent, thus allowing the organization to be reconfigured. Organization II is a compromise between the two.

This example shows that although autonomy is a very important aspect of IST's, it must be added smartly. Thus, an organization optimization is envisioned that is application depended, and is a function of important system parameters, such as mass, power, reliability, performance, adaptability, and efficiency.

4.5. Autonomy Conclusions

The addition of autonomy to a mission is clearly a good approach in terms of cost savings, time for science data, and power for communications. There are times, however, when the cost of the software is does not make up to the decrease in reliability (although the reliability could increase if the automated tasks are straightforward). The following specific conclusions can be drawn from the autonomy area.

- Added intelligence usually increases the amount of science while also decreasing the operator costs. However, this usually comes with a cost of reliability in terms of making correct decisions about science data, unless the decisions are straightforward. In this case, human reliability is lower.
- One key to developing intelligent IST's is a communication system that is high bandwidth and adaptable such that not all satellites have to talk to each other, and their linkages can change. If the communication system can also be used as a range sensor, or pointing sensor, the costs would also be decreased.
- The primary roadblock to using intelligence in systems has been transitioning the artificial intelligence technologies from simulation to the applications. For instance, it is easy to make an adaptable communications system in a simulation, but the reality of transmitting and receiving at specific frequencies, with specific data structures that now must change is a very difficult task.
- The best IST organization is distributed and hierarchical, but is also application dependent. Intelligence must be added smartly. The organization must be optimized to important system parameters such as mass, power, communications, reliability, performance, adaptability, and efficiency.
- Intelligence facilitates reconfigurability of a satellite system which allows the system to achieve a higher level of upgradability and fault tolerance.
- For IST's that require actively controlled coordination, the integration of on-line, distributed control technologies into the organized architecture with traditional autonomy technologies, is a challenge that requires much development.

Chapter 5: Feasibility Issues and Challenges

The IST concept is an enabling idea for missions that require distribution of measurements, high levels of autonomy, and low cost. Although ambitious, the IST idea can open up a new set of missions that have only been dreamt about. The most appropriate mission to develop is a deep space science mission because it can be scaled down to a version that is implementable within 10 years, and it can drive technology that is enabling for many other missions to come. This feasibility study was geared towards NASA missions "far in the future." Thus, the challenges are many and great.

The primary challenge will be communications. Each entity with the IST must be able to communicate with another, exchanging relevant information at different times. The communications must be high bandwidth, thus indicating laser or optical communications, which opens a new set of very stringent control and coordination requirements. In addition, in order to take full advantage of the IST concept, the communications should be adaptable to allow the optimal data flow to occur, and to be able to handle faults within the system. There are numerous options for communication relay to earth. The simplest option is for the IST to communicate through a fully capable mothership (or even simply communications capable). Unfortunately, this may not realize the cost advantage of IST's. Another option would be to set up a stream of picosatellites from earth to the mission site. Individually, these satellites would be capable of short distance communication, but collectively they would relay data from distant missions. Redundancy in the link would be required so that a single failure would not jeopardize the mission.

The big challenge within the MEMS area is the development of an integrated MEMS spacecraft. There are a number of efforts underway for specific MEMS components, such as micro-propulsion, micro-sensing and instruments. However, the real challenge will lie in integrating components such as solar cells, electronics, batteries, actuation, and sensing into one package. The ultimate goal (and challenge) is a complete MEMS spacecraft.

The challenge within the Autonomy area is the ability to take the AI developments and integrate them into a real world spacecraft. DS-1 is testament to the fact that this is not an easy task [14]. There are many new and exciting ideas within the AI community, but these must be mature enough to take them first to the experimental ground testing level, and then ultimately to the space demonstration and application level. In addition, complex control and coordination strategies, such as formation flying, must be integrated into the multi-agent system.

Other challenges include propulsion and power on the satellites. Generation of on-board power is one of the main technological difficulties with IST's for interplanetary missions. Solar radiation is weak at great distances, making the use of solar arrays difficult. Traditional power sources need to be miniaturized before they can be used on a picosatellite. Options include small batteries, small highly efficient solar cells, or miniature RTG's. Electromagnetic waves produced either by a mothership or found in-situ may be collected and turned into useful power for the IST. These energetic waves could also be transmitted from earth or a near-earth space-based power source. The IST could require a great deal of power for a relatively short period of time, such as RF communication back to earth. A short burst of power could be generated by a stored chemical reaction of constituents. An analogy for this is the popular chemlight that is chemically activated to generate light for a short duration. One scenario may place the IST on a low power requirement for the majority of the mission while it gathers scientific data and then near the end of life, use this burst of power to communicate the data to earth.

Propulsion is another aspect of IST's that is a challenge. The use of a solar sail for IST's has some inherent advantages, such as the use of in-situ solar wind which reduces weight. One of the simplest concepts for delivering the IST on-station is to employ a mothership as a ferry. This eliminates the need for a coordinated formation flight to deep space, which may be more difficult. In this role, the mothership would serve as a relatively low technology, inexpensive shell providing the IST with power and environmental protection along the route. Individual picosatellites would be contained within the mothership and dispersion would take place on-station. To the extreme, the IST could collectively make up most of the mothership's intelligence and processing while the mothership is primarily an engine and propellant.

Once on-station, the IST may need propulsion for formation flight, accurate distributed measurements, or docking maneuvers. Propulsion may not be necessary, however, if the mission could be accomplished using the IST as free-flying sensors. If the IST were tethered to a mothership, it would eliminate the need for on-board propulsion. Current on-board propulsion systems are generally too big for the picosatellite. A promising candidate is electric propulsion. Electric propulsion has proved useful for a wide variety of satellite applications. Pulsed Plasma Thrusters (PPT's) [15] are one of the simplest of these systems. A micro PPT [16] is envisioned that would give very small and accurate impulse bits. Current research is being performed to reduce these to the size that they are useful on a fully capable nanosatellite (total mass less than 10 kg). It is not difficult to imagine this system reduced by an order of magnitude. Again, any leverage from in-situ propellants should be explored such as using the Interplanetary Magnetic Field (IMF) for electric propulsion.

Chapter 6: Application of IST's – Deep Space Mission Profile

Thus far, the utility of intelligence for satellite teams has been examined in general. This chapter discusses an an investigation of these advantages within the context of a specific mission. The mission considered here is opportune in that it combines the need for distributed satellite teams with the interesting and challenging goal of advanced planetary exploration. The mission is aimed at gathering information about a previously unexplored planet, and consists of 3 submissions: surface probing with GPS guidance, topography mapping in combination with interferometry, and atmospheric science.

A specific organization is presented as an IST which can carry out this mission, based on the intelligence and modularity available for the individual satellites. This IST is designed to motivate how the combination of onboard intelligence, modularity and micro-technology can result in missions that are "faster, better and cheaper" compared to current state-of-the-art missions.

6.1. Mission overview

<u>Mission objective</u>

The objective for this mission is two fold:

1) Install a ring of GPS satellites at Neptune, which will serve for the current and future missions.
2) Perform science experiments consisting of planetary surface mapping (topography) in combination with examination of the composition and structure of the planetary surface and performing measurement of the composition of the planetary atmosphere.

There are three orbits designed to around Neptune, with eight nanosats on each orbit. One of the orbits is a polar, and the other two orbits are set such that a combination of all three orbits provide maximum coverage of the Neptune surface from the North to South poles at all time.

The design mission lifetime for the science part of the mission is set to be three months. Small Micro-Rovers are used for planetary surface exploration and area mapping of a limited section of the planet. The area covered by the rovers is in the range of a circle with radius of 100m. GPS is used to accurately determine the position of the rovers. The rovers move independently in different directions and gather scientific data in form of images and/or soil sampling data. Satellite formation flying teams are used in combination with interferometry for planetary mapping of a small strip of the planet. Small satellites acting as atmospheric probes perform distributed measurements of the composition of the atmosphere of the planet. The satellites have on-board propulsion, which allow them to gather data at specific interesting points. In addition, they use the GPS nanosats for autonomous orbit determination and control.

Mission Timeline

The mission is separated into three parts, consisting of launch and cruise phase, payload deployment phase, and science phase, as shown Figure 24.

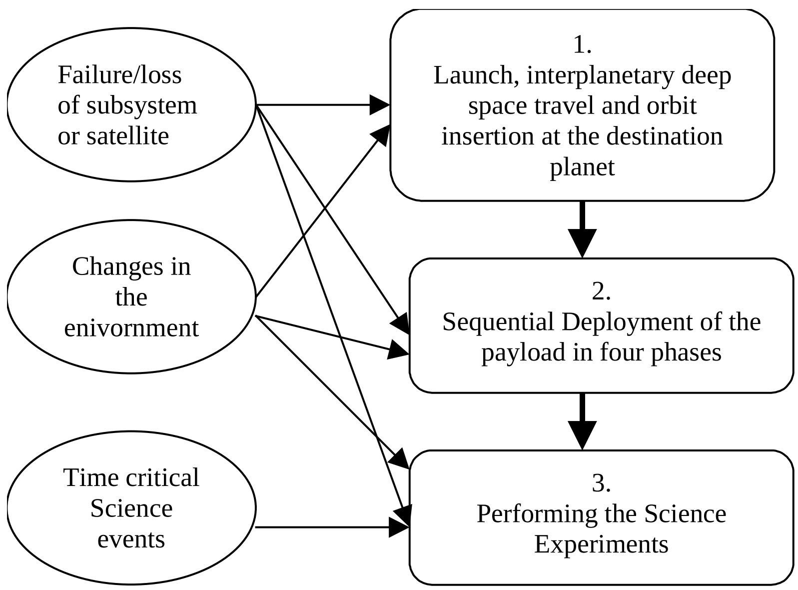

Figure 24: Mission timeline and unanticipated events

In addition, Figure 24 also shows a list of unanticipated events that occur during each mission phase. These events include

- a failure or loss of a subsystem, or, in the worst case, the whole satellite;
- changes in the environment, i.e. abrupt changes of atmospheric composition for example and,
- in the case of the science part, highly time critical changes on the subject of scientific interest, i.e. eruption of a volcano.

In order to achieve the goal of "faster, better and cheaper", future deep space missions must be capable of handling these events. In the following sections 6.3 and 6.4, these issues are addressed by showing how the use of micro technology, modularity and artificial intelligence techniques can accomplish these goals.

6.2. *Proposed IST configuration*

The proposed IST configuration is shown in Table 8 below.

Table 8: Hardware configuration of the mission

Quantity	Hardware element	Estimated mass
1	Central Mother Satellite	400 kg
3	Micro Satellites	450 kg
12	GPS nanosats	180 kg
6	Interferometry nanosats	150 kg
12	Multifunctional nanosats (both science and GPS capable)	600 kg
10	Micro rovers	150 kg
Σ		1930 kg

As shown, the configuration consists primarily of

- A central satellite, called “**mother satellite**”, capable of acting as "space ferry" for the IST;
- 3 **micro satellites**, which act as “space ferry” for the nano satellites and have the capability to serve as members in an interferometry science team;
- 12 nano[3] satellites, acting as local GPS satellites on the planet;
- 6 nanosatellites, capable of acting as a member of the interferometry team;
- 9 nanosatellites capable of acting as GPS satellites and as a member of the inteferometry and topography science team;
- 10 Micro-Rover for the exploration of the planetary surface.

6.3. *Discussion of the mission steps*

Launch and Interplanetary deep space travel

For launch, an Atlas II Launch Vehicle is used in GTO orbit with a launch mass of 2700 kg and Launch size of 4.2m (diameter) x 9.7m (height). The net mass available after orbit insertion at Neptune is 2000 kg. Since launch space and mass are highly constrained, this is an important driver. Therefore a package configuration is used, consisting of the mother satellite which contains the IST. As shown in Figure 25, the mother satellite contains the micro rovers and three micro satellites, which in turn contain each of the ten nano satellites. In order to save space, an unconventional design of the

> ☺ Saving launch space and mass through intelligent packaging and stowage

[3] Remark: the terminology "nanosatellite" is used, although actually the mass is higher than 10 kg

micro and nano satellites is used, where the satellites are "folded", resulting in a highly efficient usage of the launch space. The US Air Force TechSat 21 Program steps also forward into this direction, proposing to use inflatable solar arrays [53] for their satellites. All hardware is packaged and launched together.

☺ Using the mother satellite as "space ferry" and aerocapture for the insertion

One of the simplest concepts for delivering the IST on-station is to employ a mothership as a ferry. This eliminates the need for a coordinated formation flight to deep space, which may be more difficult and would definitely require more propellant and control effort. In this role, the mother satellite serves as a relatively low technology, inexpensive shell providing the IST with power and environmental protection along the route. The individual satellites are contained within the mother satellite and dispersion takes place on-station. For the interplanetary cruise, a direct trajectory to the Neptune is used. A good description of this trajectory can be found in [54]. A very promising propulsion system for this type of space travel is solar electric propulsion. Since a short cruising phase requires a very high speed, a large change in velocity is required for the orbit insertion at the Neptune. In order to save weight and propellant, an Aerocapture could be efficiently used for the orbit insertion. A discussion of Aerocapture design can be found in [55].

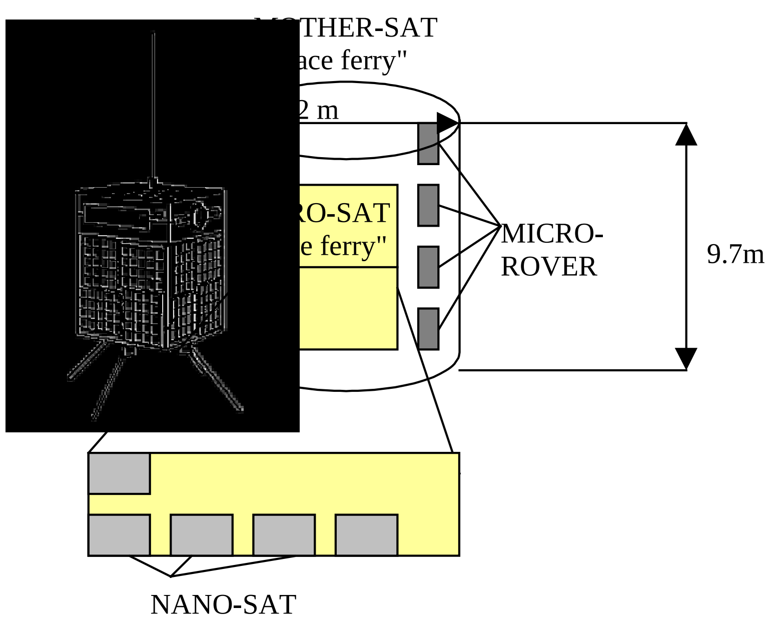

Figure 25: Principal Package and Stowage configuration for the launch

Deployment of the scientific equipment:

After orbit insertion, **Phase 1** begins as the the mother satellite deploys the three micro satellites in three different orbits, as shown in Figure 26. The micro satellites function as "space ferryies", carrying the nano satellites to the destination orbit and deploying them (**Phase 2**).

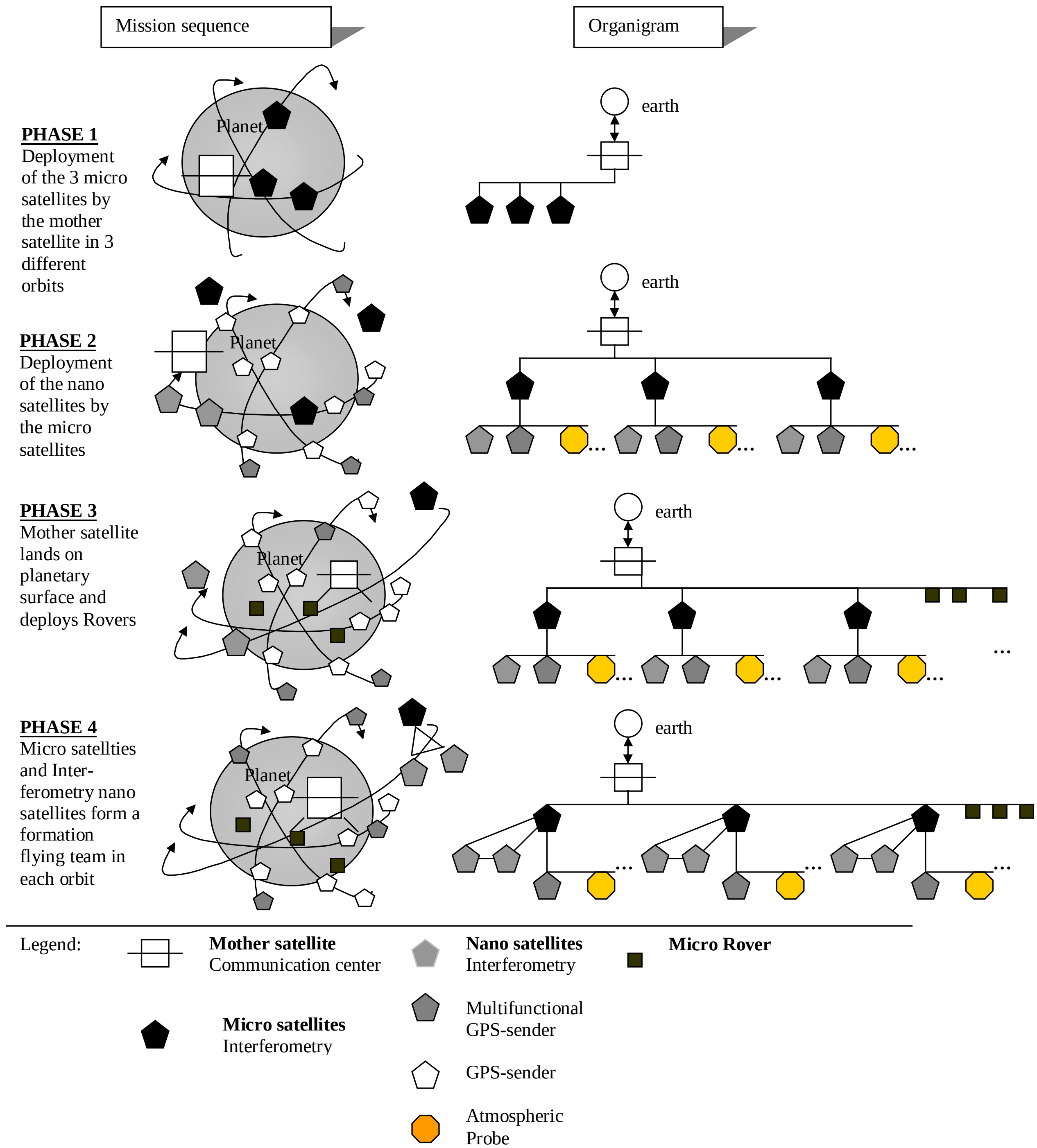

Figure 26: Deployment phases of the IST constellation

There are several techniques that could be utilized to safely deploy the IST from a space ferry once on station. This is primarily a mechanical issue. Stanford's small satellite, OPAL, uses a spring-loaded mechanical arm to launch picosatellites the size of hockey pucks on a curved

☺ Proposed deployment of the IST results will result in less control and communication effort

track inside the structure [57]. Any number of these internal rail designs could be envisioned to eject the satellites one at a time. They could also be released from a body-mounted configuration. The satellites could make up most of the external real estate on the space ferry. The munitions industry has experience in dispersion techniques that may be applied to this slightly different area. The primary difference would be dispersion in the zero-g vacuum environment.

After the 3 groups of 8 GPS-nano satellites are distributed equally in the three different orbits, they serve as GPS-transmitters. The mother satellite then start its landing operation at a central hub on the planetary surface (**Phase 3**). After landing on the surface and deploying power generation modules and communication antennas, the mother satellite deplosy the 10 micro rovers. Each micro satellite coordinates with the two interferometry nano satellites in a formation for the interferometry mission (**Phase 4**).

<u>Science Mission Task</u>

One of the most important measures of a successful mission is the returned data volume, which is related to the data down link rate. As shown in Figure 17, the downlink data rate decreases nearly linearly with increasing distance from the earth for the last deep space missions. Another very important aspect of a mission is the reduction of mission operating costs. The goal is therefore to maximize the amount of science data sent back to earth and at the same time, minimize the cost due to ground support and planning. Both issues address using autonomy-based software tools for the IST. Figure 27 shows the principal communication flow in the IST, including uplinked commands and downlinked science data. Note that no telemetry data is returned to Earth unless requested by the command center.

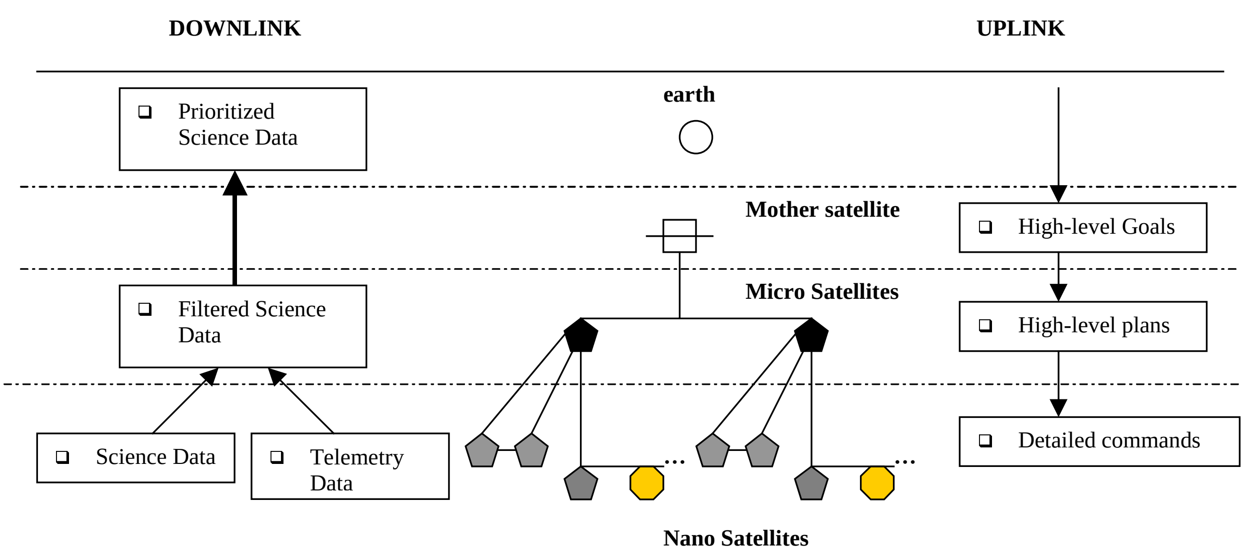

Figure 27: Communication flow in the IST.

As shown, the mother satellite acts in the proposed constellation as the central communication and command center for down and up link to the earth. The central gathering of the data enables a central communication center to search over all science data and decide what are the most important to send back, or what data to use for the decision making process for the next task. The AI functionality required for this includes pattern and object recognition of the science instrument data, as well as data sampling. Both the mother satellite and the micro satellite have increased intelligence onboard, consisting of basic AI functionality such as reasoning, planing, and as already mentioned, feature and object recognition.

The central planner of the mother satellite creates global high-level plans for the next mission task to do, based on the received science data or commands from the ground. Based on these high level plans the micro satellites generate detailed command sequences for the nanosats. Each micro satellite acts as a local communication center and planner for its nano satellites in their specific orbit, and can additionally act as a central communication center in the case of a failure of the mother satellite, see also Chapter 6.4.

☺ "Putting the Operator and Scientist on board" => better science, less cost!

One critical aspect for deep space missions with an IST is the handling of telemetry data. With increasing number of satellites in the IST, it much more difficult to send telemetry data back to earth, due to the highly constrained up- and downlinks. Therefore, in the proposed IST constellation, the micro satellites gather all telemetry data from their subordinates via inter-satellite crosslinks and monitor the health status. Only in case of an anomaly or failure, the micro satellite sends the information to the central mother satellite, which in turn decides if the problem can be resolved using reconfiguration (see Chapter 6.4) or if the failure must be communicated back to earth. The AI techniques required for this include reasoning about telemetry data in combination with using an onboard expert system

☺ Autonomous health monitoring in the IST results in increased science data return to earth due to saving of highly constraint downlink capacities.

6.4. Handling unanticipated events

<u>Time critical events</u>

Time critical events have a very short duration, such as a flyby mission near an asteroid, discrete science events on the planet surface, or mission related aspects such as rendezvous maneuvers. For the Neptune mission, time critical events that occur include: deployment of the satellites, landing operation of the central mother satellite, and time critical science events. Due to the highly constrained up and downlink to earth, sending science data to earth, evaluating it using a team of scientists on the ground, and uplinking new command and planning sequences for retargeting the IST is not feasible. Therefore, a sequence of AI techniques must be used including:

☺ AI techniques are ENABLING for discrete, time critical events for deep space missions.

a) Onboard analysis of the science data and feature detection,

b) Autonomously reasoning about the next science tasks,

c) Generating a new command sequence for retargeting the spacecraft.

An example of a time critical science event, consider the eruption of a volcano on the surface of the planet during the mission lifetime. The time required for generating a new command sequence using conventional techniques can be roughly computed (see Figure 28 for explanation) by

$$T_{conv} = \frac{Size_{data}}{d_{crosslink}} + \frac{Size_{data}}{d_{deepspace}} + T_{eval} + \frac{Size_{commands}}{d_{deepspace}} + \frac{Size_{commands}}{d_{crosslink}}$$

The following are assumed:

- the deep space communication rate to Neptune is $d_{deepspace} = 10^3 \frac{bit}{s}$,
- the intersatellite communication rate is $d_{crosslink} = 10^9 \frac{bit}{s}$,
- the size of the picture taken is $S_{data} = 2MB$ and
- the size of the new command sequence is $S_{command} = 250k$.

Using an estimation for the time it takes to evaluate the data on the ground and to generate a new command sequence as $T_{eval} = 5\min$, the equation above results in $\underline{\underline{T_{conv} = 1.08hrs}}$.

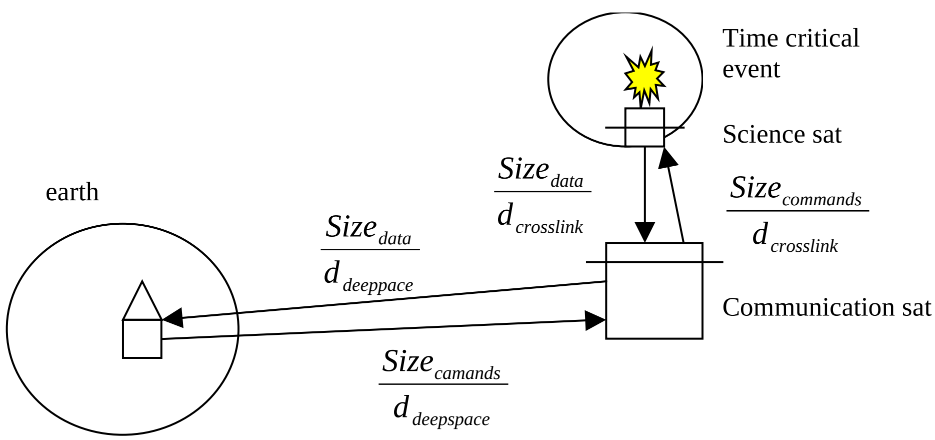

Figure 28: Communication case for Earth based decision making.

The equation for the time required to generate a new command sequence using onboard AI simplifies to

$$T_{AI} = \frac{Size_{data}}{d_{crosslink}} + T_{eval} + \frac{Size_{commands}}{d_{crosslink}},$$

Since the time costly deep space communication can now be ignored, the same total data requires $\underline{\underline{T_{AI} = 0.016s + 300s + 0.02s = 300.036s \approx 5\min = 0.083hrs}}$.

Failure or loss

A designer of space systems must always consider the probability of failures during the mission lifetime. This is especially true for IST's, where the individual satellite reliability has decreased, but the overall system reliability has increased. For example, if the communication system of the mother satellite fails, and there is only one satellite with this capability, the entire mission is deemed a failure. Another example is the failure of a topography mapping satellite in an interferometry team. The failure of one single satellite result in the failure of the team, since the minimum number necessary to run the interferometry mapping team is three satellites.

The proposed mission, therefore, utilizes **multifunctional** satellites, which have the ability to reconfigure. Reconfiguration, in this context, allows the switching of the assigned task of a satellite. As outlined earlier, the three micro satellites have interferometry science instruments, and additional communication capabilities onboard. This allows them tp act redundantly as a central communication center in case of a failure of the mother satellite. In addition to the science nano satellites, nine of the GPS nano satellites have science instruments on board, which allow them to replace a science nano satellite in the case of a failure.

☺ Multifunctional satellites in combination with reconfiguration increases the overall reliability of the mission

Multifunctional satellites, in addition to its reliability improvement, also increases the adaptability of the IST, depending on a particular situation or task. Consider a scenario, in which a very important science event occurs, as described above, and there is a failure. The central mother satellite generates a new plan, which results in a reconfiguration of the nine GPS satellites to three interferometry science teams as shown in Figure 29.

☺ Multifunctional satellites in combination with reconfiguration can increase the science return.

The GPS interferometry science teams now gather data of the eruption of the volcano in addition to the existing three interferometry teams. The minimum GPS coverage is still guaranteed, since four GPS satellites remain in each orbit.

Clearly, adding multifunctional capabilities to the satellites increases the weight of the single satellite and decreases the performance. But, as outlined earlier (see Chapter 4.3), the additional weight is occasionally worth the price of a limited number of satellites. This also shows the complex trade-offs that occur in the IST design, thus motivating an optimized organization.

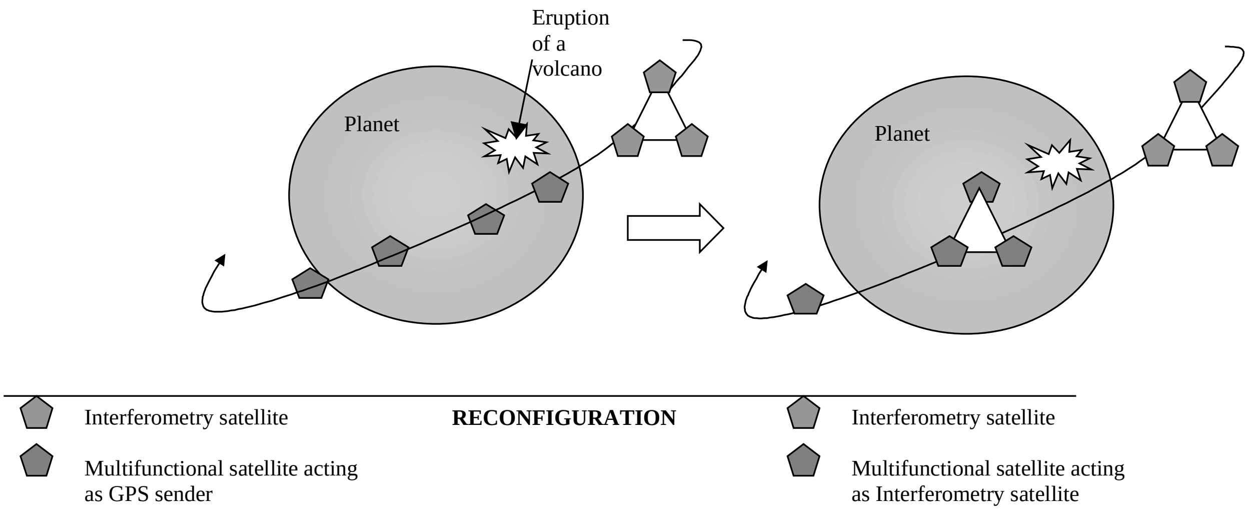

Figure 29: Reconfiguration of multifunctional GPS satellites

<u>Changes in the environment</u>

In addition to a fault or failure of a system, one must also consider unanticipated changes in the environment. Assume an abrupt change in the gravitational field of the Neptune, which result in a required change of the control characteristic for the attitude control system of each of the satellites. The conventional approach to this problem is:

- Detecting the anomaly by the ground team,
- Generating a new control characteristic and
- Upload of the new software to the space craft.

Due to the highly constrained deep space communication, this approach is not practical for the proposed mission. In addition a delayed response could even cause a failure of the spacecraft. Therefore one must utilize AI techniques for this kind of problem. First, the IST autonomously detects the anomalies in the environment. The AI technology required includes reasoning about environmental information, i.e. comparing the actual sensor data with knowledge from an implemented expert system. Second, the implementation of the software is adaptive. Having detected an anomaly in the environment, the control software for the attitude control system should be easily changeable. In addition, the other satellites could be warned before the anomaly affects them.

Chapter 7: Phase I Results Summary and Conclusions

The objective of Phase I, as written in the proposal, was to "explore the concept of Intelligent Satellite Teams (IST's), comprising tens to thousands of nano/picosatellites that innovatively use intelligence control and MEMS technologies." To achieve this objective, the UW attempted to answer, in varying levels of detail, a list of technical questions in the three inter-disciplinary areas of IST's: Mission Assessment, Intelligent Control, and Nanosat Subsystems. These questions, and their answers based on the results presented in this final report, are given subsequently. Note that the answers are based on the write-up in previous chapters, so only a short summary answer is given here.

Technical questions answered during the course of this program in order to properly assess the potential of IST's are grouped into three general areas: Mission Assessment, Intelligent Control, and Nanosat Subsystems.

<u>Mission Assessment</u>

Mission Assessment assesses the type of missions, satellites, and procedures that will be used. Specifically:

Q-MA-1. What types of future missions are envisioned for IST's? (science, construction, servicing)

The types of future missions that the IST concept is applicable vary widely. Figure 2 shows a summary of several of these missions, as a function of the intelligence and number of spacecraft (which is of course enabled by MEMS). The most enabling of these is a deep space remote sensing mission. This mission would have multiple tasks and require distributed science measurements. Because of this, and the use of large numbers of satellites, the mission also requires high levels of autonomy. Other missions that can utilize these technologies include a space weather and warning system, autonomous servicing, supply, and repair of satellites, any distributed Earth science mission, and finally, autonomous construction of a space facility. This figure is not meant to be an exhaustive list, only a list to show the broad applicability of the IST concept.

Q-MA-2. What type, size, and lifetime of satellites is required for these missions? (robotic, nano/pico)

The type, size, and lifetime vary for each mission, and is a complicated question. Obviously, robotic satellites are required for autonomous construction missions; passive sensing satellites are required for simple remote sensing missions; and MEMS docking systems are required for autonomous repair and supply of satellites. But for missions for more that one objective, such as deep space planetary science, the type of satellite is a complex blend of instruments and intelligence. The selection of the type, size, and lifetime can be found by deriving an organization optimization that is application depended, and is a function of important system parameters, such as mass, power, reliability, performance, adaptability, and efficiency.

Q-MA-3. What type of intelligence (i.e. control) is required for each type of satellite? (little on-board intelligence, or collective behavior approaches using intelligent control)

Intelligence is enabling for the IST concept. But as shown in the example in Figure 23, too much intelligence may not be the answer – not to mention that it is years away from maturity. Therefore, an organization optimization is required that is application depended, and is a function of important system parameters, such as mass, power, reliability, performance, adaptability, and efficiency. Figure 2 summarized several missions and their level of intelligence. As the intelligence increases, more capabilities shown in Figure 13 enter the architecture.

Q-MA-4. How can modularization, multi-functionality, self-assembly, and reconfigurability concepts be innovatively used in the missions?

Modularity is a central concept in MEMS based subsystems and integrated packages such as those in Figure 11. As the numbers of satellites increase with applications and MEMS technologies, modularity based on MEMS will take hold. There are already several multi-functional satellite concepts in spacecraft. One example is embedding the antenna into the structure, while another is the self-consuming satellite where the structure is made of fuel bars. As Li Polymer batteries become more commonplace, they can be integrated into the structure as well. For small MEMS based satellites, the most appropriate multi-functional aspect is packaging them to develop a solid spacecraft for launch. MEMS components are so strong, that efficient packaging would enable the use of more science instruments as well as making the system stronger for launch. Self-assembly methods and especially reconfigurability are central concepts to higher levels of autonomy. With intelligence, the IST can be reconfigured for multiple tasks, or reconfigured with a loss or gain of a satellite.

<u>Intelligent Control</u>

Intelligent Control refers to control and coordination, sharing information, and on-board intelli-gence of multiple satellites in the IST's. Specifically:

Q-IC-1. What are the limitations and benefits of orbital mechanics (3-dimensional coordination)?

The limitations of orbital mechanics involve major changes in orbits for smaller satellites. Unfortunately, reconfiguration of the IST by moving the individual satellites far distances is difficult. The benefits of orbital mechanics are, however, that there are a number of stable orbit patterns for clusters of satellites. Groups at both the Air Force Research Lab and NASA Goddard have been studying these and have made excellent headway. This work, primarily done for earth based satellites, could be extrapolated to other planets and to novel deployment methods of the individual satellites of the IST.

Q-IC-2. What is the relationship between satellites, and between the IST and human operator?

A complex autonomous system of interacting satellites must utilize autonomy to reduce cost. Autonomy is an enabling technology. Thus, the control architecture is composed of three levels. Since the system will interact with human ground control, the first level will be interactive mission control. The second will be the outer loop navigation of the IST. The third level will be the inner loop control for individual satellites of the IST. These three levels are shown in Figure 12. This hierarchy fits naturally into the framework of intelligent control systems which are based on fuzzy logic, artificial neural networks, evolutionary programming (or combinations thereof). The most appropriate organization is a hierarchy of intelligent agents.

Q-IC-3. What leverage can be made of intelligent robotic systems, normally in two-dimensions?

Leverage can be made in two particular areas of artificial intelligence. The first area is the individual technology developments in AI, namely scheduling, planning, and reasoning – a lot of which was developed in the robotics community. These technologies must be expanded into multiple levels of intelligent agents, but the work in these areas is very valuable to the IST concept. In terms of multi-agent systems, the area is not as mature. There are several analogous applications such as underwater sensors and vehicles. This work, however, is not particularly mature, and does not have the important mass, power, and remoteness constraints of space missions such as IST's.

Q-IC-4. If high intelligence is required for many satellites, can it be put into an "intelligence chip?"

There have been some developments on the side of building processors that act "intelligent." These are a long way in the future, however. Intelligent software within a chip is a more likely scenario, and several software based approaches, such as planning and scheduling, could be placed on a modular chip. This area deserves much more attention, and it is currently getting it from the Computer science community. But this technology is years from maturity in robotics, let alone space qualification.

<u>Nanosat Subsystems</u>

Nanosat Subsystems leverages microtechnology and MEMS for the construction of the functionally very capable nanosatellites. Specifically:

Q-NS-1. What leverage can be made of current MEMS technology for micro spacecraft? (navigation, propulsion, sensing, power)

MEMS research on all these topics is currently underway with varying degrees of success and maturity. Not surprisingly, the most highly developed devices in the MEMS community are those with popular, terrestrial uses. These include pressure and acceleration sensors within the automotive community and RF devices in the personal communications field. Another terrestrial field, quickly growing in size, is MEMS gyroscopes for use in personal navigation devices. All of these devices are ready now or will be in the near future and all will find useful duty aboard space based platforms. A characteristic of MEMS space subsystems is that of "trickle up" from the private, terrestrial sector to traditional aerospace contractors.

Beyond these terrestrial applications, MEMS are also being actively developed for exclusively space based tasks. There are at least two thrusters, from TRW and Standford, that should soon be ready for space qualification. Strides are also being made to improve solar cells and in the production of imaging systems that combine sensor, D/.AC and processing on a single chip. In the next five years most, if not all, of this technology should find its way onto orbiting satellites.

Q-NS-2. What does a prototype nanosatellite or picosatellite entail?

A prototype nanosatellite or picosatellite would have, due to substantial mass and volume constraints, a host of microfabricated subsystems. In the initial stages of development the satellites would be on the whole, larger and pushing the 10kg weight classification and not every system would be MEMS based. In the first few iterations the satellite will have MEMS making up substantial portions of the avionics and sensor suite together with some use in communications and payload. As development continues and MEMS satellite subsystems garner greater flight time and performance, satellite sizes will shrink as their percentage of MEMS components expands. This trend terminates at the development of a nanosatellite that is fully MEMS based and suitable for mass fabrication.

Q-NS-3. Extrapolating micro spacecraft components for 5, 10, 20 years based on recent developments, what could such a system do?

Most of this data has been covered in more detail in other sections of the report; however, it is summarized here in tabular form.

Summary of five year technologies

Communications

MEMS RF switches in place of PIN switches
Mechanical, vibratory elements making up filters and local oscillators

Power

MEMS intensive solar panels with micro-lense and micro-heatsinks

Propulsion

MEMS digital thrusters
micro pulsed plasma thrusters
colloidal thrusters

Attitude Determination and Control

MEMS vibratory gyroscopes

better accelerometers

Summary of ten year technologies

Communications

A/DC and D/AC moving closer to antennas

Higher frequencies in use

Communications companies assume even more of the development risk

Power

Solar panels top out at 30%

Power system integration

Thin film batteries provide chip level backup

Propulsion

MEMS bipropellant and monopropellant systems

sublimation thrusters

Attitude Determination and Control

MEMS momentum devices

improved sensors

Summary of twenty year technologies

Communications

Very high frequencies

Power

Thin film batteries in massive arrays

Self pointing solar panels

Attitude Determination and Control/Propulsion

Lighter and cheaper than 10 years - proven track record

In these predictions, five years correspond to MEMS systems that are just now wrapping up development, ten years correspond to those systems just entering development and twenty years constitutes ideas that seem good, but are not now under active investigation

Q-NS-4. What are the limitations of MEMS for space applications?

As satellite subsystems built from MEMS begin to be commonplace, new classes of limitations, revolving around scaling and physical laws, will be found nearly as quickly. Size, one of the greatest assets of MEMS, can also be one of its greatest detractions. A good example of this can be found in the development of thin film batteries. Devices have already been fabricated using conventional battery materials with improvements in specific energy and energy density because of the large electrode surface area to volume. Yet due to their small size, these batteries suffer from a low discharge rate and typically only store power in volume proportion to their larger counterparts. Physical laws can also be a problem when dealing with devices such as antennas. The physical dimensions of these devices are sized according to the communications frequency over which they operate. These are typically nonnegotiable measurements that dwarf the size of the largest MEMS devices.

Beyond these physical problems are a host of psychological and conceptual limitations. With this technology promising so many benefits and advantages there is a tendency to force MEMS to fit into a technological niche. Or in another situation, to use MEMS in an area where a better performing, large-scale analog is a better choice in an effort to pursue the perceived state of the art. It is important that even with all the fanfare, of which quite a bit is deserved, that MEMS is treated as any other technological tool as opposed to a panacea. By knowing about these limitations and planning for these difficulties, physical and otherwise, subsystem design choices can be made to mitigate these problems or remove them altogether.

Q-NS-5. What actuators and sensors are required for precision robotic satellites? Can smart materials be leveraged?

In general, most sensors and many actuators can be miniaturized using MEMS type approaches. An example of a smart material is the micro docking system, where small “cilia” arrays are used to position one satellite relative to another. And while other smart material concepts such as the piezoelectric and shape memory alloy families are applicable, they were not explored in full detail because they are really only applicable to one mission: autonomous construction. This does not affect the generality of the IST concept, however.

<u>Expected Results</u>

The expected results written in the Phase I proposal consisted four items:

1. At least two specific science missions that take full advantage of the functional, coordinated, and reconfigurable IST’s will be profiled.
2. An intelligent control approach for IST’s is developed, considering control of the nanosats relative to one another, control of the IST as a whole, and interaction with the human operator.
3. A micro spacecraft is prototyped based on current technology and mission profiles. Using extrapolated progress of MEMS spacecraft components for 5, 10, 20 years, the potential of MEMS and nanosats for these types of missions are evaluated.
4. A proposed plan for Phase II will be developed, including a study of the feasibility issues associated with cost, performance, development time, and key technologies for making IST’s a reality for the chosen mission set.

The first result, in the end, was slightly different. Instead of two missions in detail, the UW group evaluated many more missions that are applicable to IST’s, and fully detailed one mission. A multi-agent distributed control approach appears to be the best approach for IST’s, although the development is complex and the organization should be optimized. MEMS based components for space were evaluated. The UW group also developed 5, 10, and 20 year predictions of satellites, but this approach was very difficult and fuzzy for the 20 year plan.

Therefore, the current state of the art in small satellites (including current MEMS components) were compared to a prototype satellite in 10 years. Finally, initial cost and performance issues with both MEMS and Autonomy were examined in the IST framework, and a Phase II proposal was developed.

The following is a summary of the primary conclusions of the Phase I portion of the program:

- IST's enable missions that require distributed measurements at low manufacturing cost by primarily using the MEMS technology to develop low cost, light weight, modular satellites. An example of this type of mission is an Earth ionospheric measurement mission.
- IST's enable missions that require high levels of intelligence at low operator cost by primarily using intelligent control to coordinate the entities into a coherent community. An example of this type of mission is the inspection, supply, and/or repair of satellites.
- IST's enable a new set of missions that require both MEMS subsystems and intelligent control. Two examples of this type of mission are the autonomous construction of a space facility and multi-task Earth and space science.
- Several subsystems are well on their way to maturity because of government and industry funding. These include MEMS based propulsion, micro attitude determination sensors such as gyros and star trackers, and low power processor boards based on embedded systems.
- The key to developing a MEMS based satellite is integrating the smaller components into modular, low power, lightweight, and possibly multi-functional packages that can be manufactured inexpensively, and can be used in several types of satellites.
- The biggest roadblock to a MEMS based satellite in deep space is power. The solutions for this include low-power devices and circuitry in combination with improved solar cells and thin/thick film batteries, In addition, novel energy are sought, such as beamed energy source from a local mother satellite, or one-shot energy supplies that allow a short burst of energy for long range communications once the mission of the picosat has been finished.
- Within 10 years, a satellite of equal capability can be developed using MEMS components at a mass savings of a factor of 4.
- Added intelligence usually increases the amount of science while also decreasing the operator costs. However, this usually comes with a cost of reliability in terms of making correct decisions about science data, unless the decisions are straightforward. In this case, human reliability is lower.
- One key to developing intelligent IST's is a communication system that is high bandwidth and adaptable such that not all satellites have to talk to each other, and their linkages can change. If the communication system can also be used as a range sensor, or pointing sensor, the costs would also be decreased.
- The primary roadblock to using intelligence in systems has been transitioning the artificial intelligence technologies from simulation to the applications. For instance, it is easy to make an adaptable communications system in a simulation, but the reality of transmitting and receiving at specific frequencies, with specific data structures that now must change is a very difficult task.

- The best IST organization is distributed and hierarchical, but is also application dependent. Intelligence must be added smartly. The organization must be optimized to important system parameters such as mass, power, communications, reliability, performance, adaptability, and efficiency.
- Intelligence facilitates reconfigurability of a satellite system which allows the system to achieve a higher level of upgradability and fault tolerance.
- For IST's that require actively controlled coordination, the integration of on-line, distributed control technologies into the organized architecture with traditional autonomy technologies, is a challenge that requires much development.

Because:

- each of the questions were answered successfully, and
- the expected results matched the Phase I proposed items, and
- the IST approach appears to be feasible and applicable to many future NASA missions in the context of "faster, better, and cheaper,"

the Phase I portion of the program is deemed a success.

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