INTELLIGENT SATELLITE TEAMS FOR SPACE SYSTEMS

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Abstract

This paper examines the development 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 paper gives an overview of the missions, and requirements for both MEMS and intelligent control.

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.

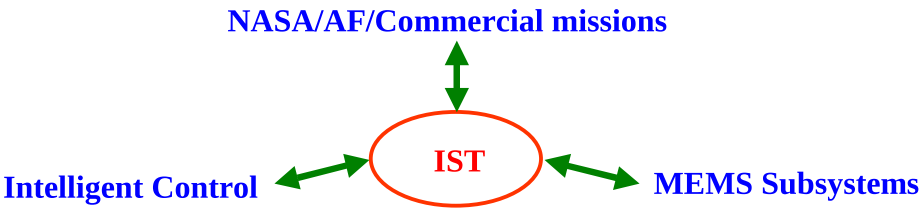

Figure 1: Intelligent Satellite Teams (IST's) are cross-disciplinary, and the missions feed direction and requirements to Intelligent Control and MEMS Subsystems areas.

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. Each of these missions, and their requirements on MEMS and intelligent control are described next.

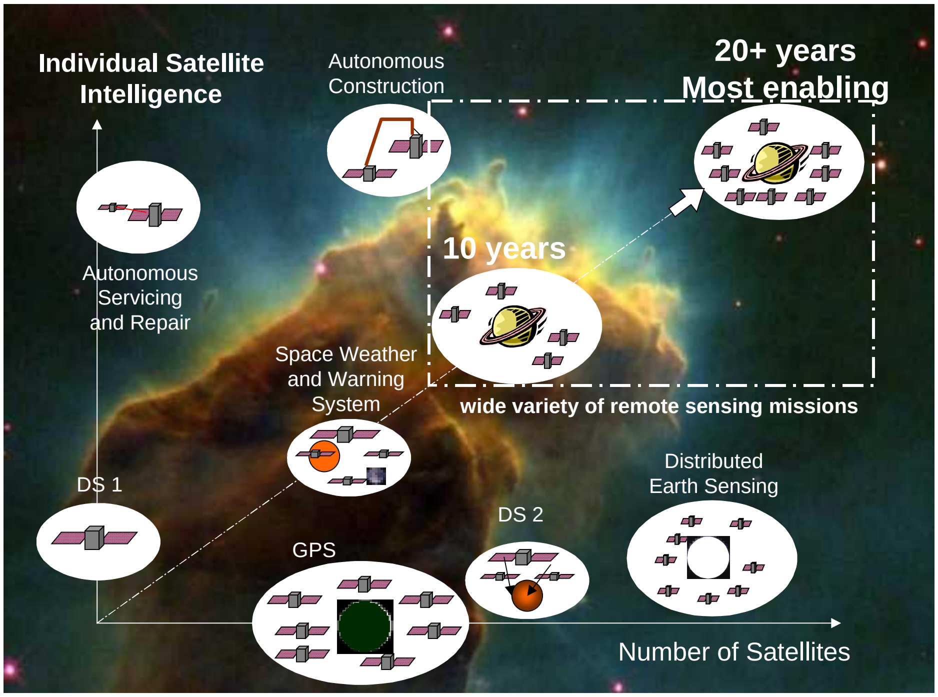

Figure 2: Trade space for IST missions as a function of the intelligence and number of satellites (driven by MEMS).

<u>Space weather and warning system</u>

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.

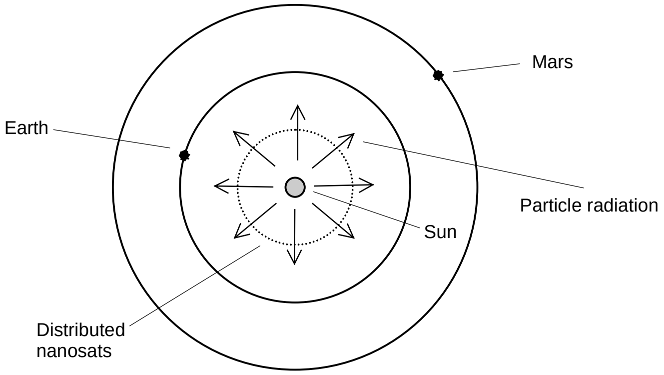

Figure 3: Space weather and solar flare warning system.

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.

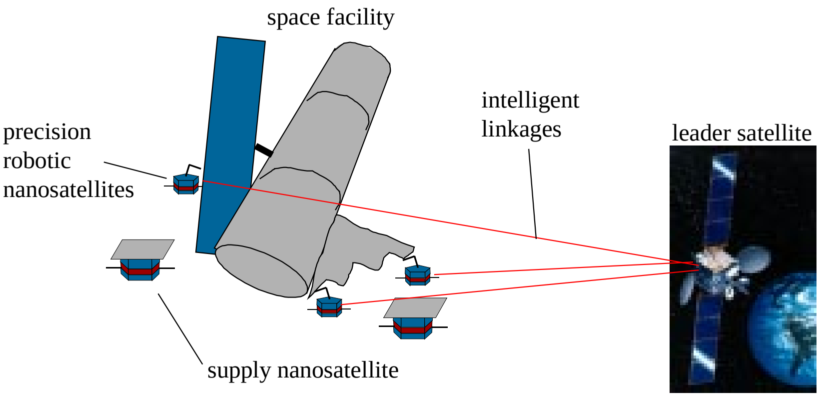

Figure 4: Concept of IST’s for space construction.

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.

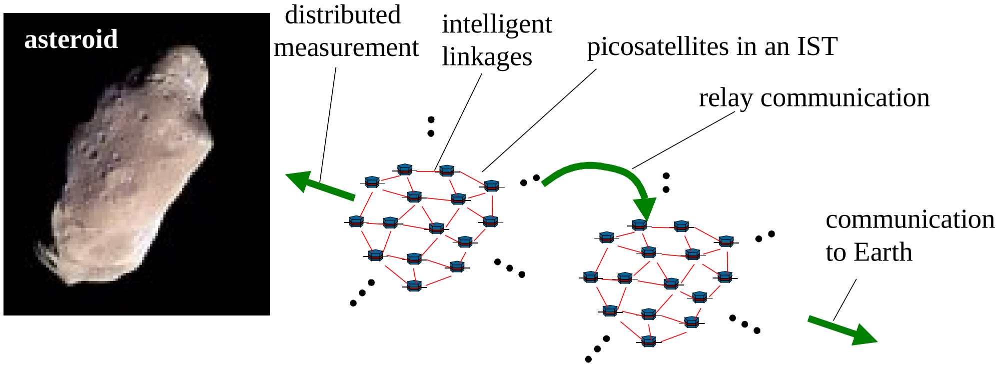

Figure 5: Concept of IST’s for space science and communication.

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.

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.

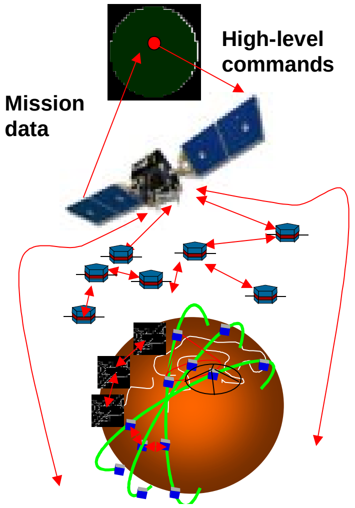

Figure 6: Deep space planetary science mission using

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.

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 the 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.

MEMS 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, (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 106 km/hr, and a launch time of 0.3 sec. Over 1000 picosatellites could be launched in under an hour. In addition, many picosats can be fabricated in a batch process, thus reducing the costs immensely and treating the satellites in an "assembly line" production. The miniaturization of satellite components is currently receiving more attention, although many subsystems need work in order to develop a MEMS satellite. 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.

Attitude control sensors and actuators are currently under heavy development. Micro-rate gyros [2] have been researched for years, and their high g range allow them to be extremely valuable for missions, much like the micro-accelerometers. In addition, soon their bias problems will be very small. Horizon and sun sensors, as well as magnetometers, are also being miniaturized. Star trackers, as the microelectronics of CCD cameras becomes commonplace, will be smaller as well.

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 (when 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 have a low slew rate; 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 unworkable. 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.

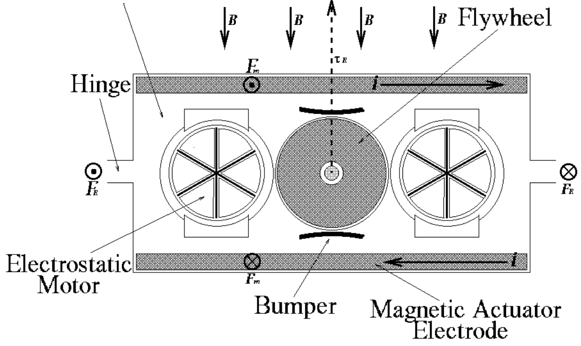

Figure 7: Micro Control Moment Gyro.

Figure 7 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.

In a CMG, usually 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 are canceled, and the spacecraft is left with simply a summation of the desired torques for attitude control. Limitations such as power and friction are now being evaluated, but it appears that scaling is not an issue.

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.

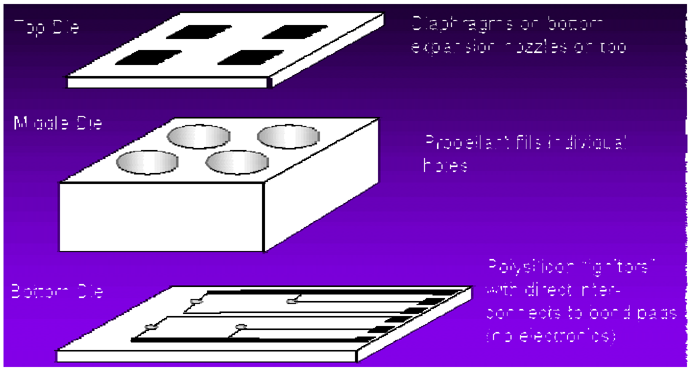

Figure 8: Fabrication of micro-propulsion.

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 its benefit, the MEMS solid propellant engines are compact, involve no microfluidics, and provide throttle control by allowing numerous tiny thrusters to be fired together or individually depending upon the necessary thrust. These systems currently are limited in their thrust duration - typically 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.

Future MEMS communication components include MEMS RF switches which produce less insertion loss and no odd order harmonics, MEMS RF filters with low weight and power, and MEMS RF mixers. Soon the A/D and DA components will be moving closer to both ends of the radio, followed by the ultimate point when radios achieve "direct conversion."

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 (increasingly on optical and microwave carriers) in materials and devices. The UW has developed polymer modulators with world record modulation rates >340 Gbps. Optical- and microwave-MEMS, for example, will be developed to facilitate the 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 will substantially reduce network connection costs and will facilitate the development of new high performance communications transmitters.

MEMS based power components include MEMS based solar cells with smart shadow compensation, micro-lenses on front and micro-heatsinks on back, and thin film batteries. Soon, power systems (and electronics) will begin to be built into other components such as the sun or horizon sensor. Far in the future, thin film batteries could be placed in a massive parallel series connections to create high power density due to packing.

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.

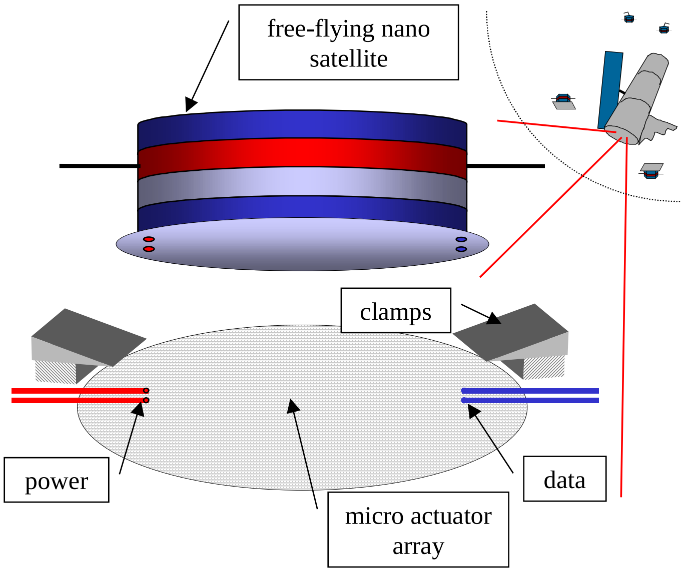

Figure 9: Conceptual MEMS based docking system.

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 $F_N = 4 \times 76\mu\text{N} / (1.1\text{mm})^2 \times \pi\ (2\text{in})^2 \times (25.4\text{mm/in})^2 \approx 2\text{N}$ 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 $F_S = \frac{1}{4}\ \mu_r\ F_N$ (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.

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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)

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.

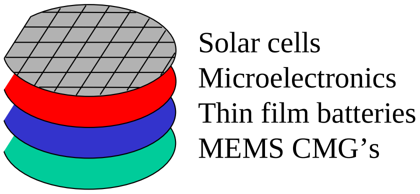

Figure 10: Integrated micro-system of a future micro-satellite.

Intelligent Control

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 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?

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 11. 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).

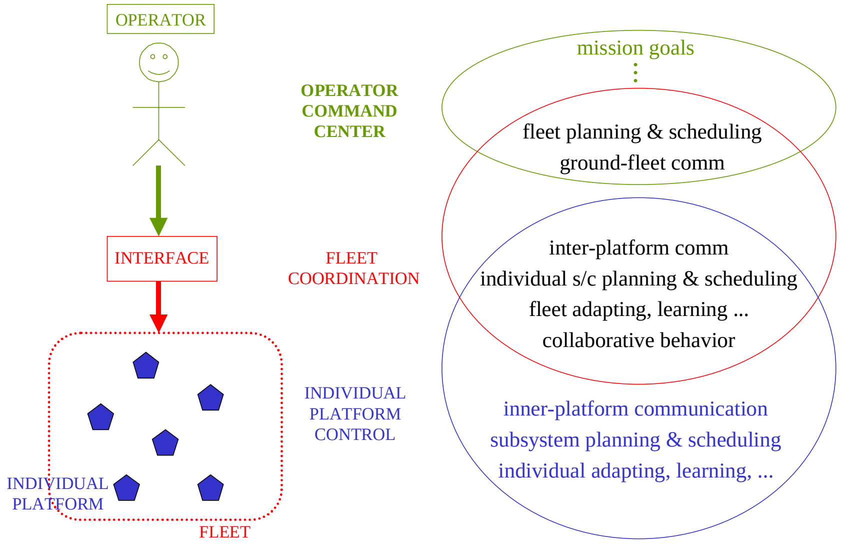

Figure 11: Flow chart showing the general hardware on the left, and the layered architecture on the right. Overlapping aspects can exist on either layer.

Figure 11 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, 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 and planning. 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 12.

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

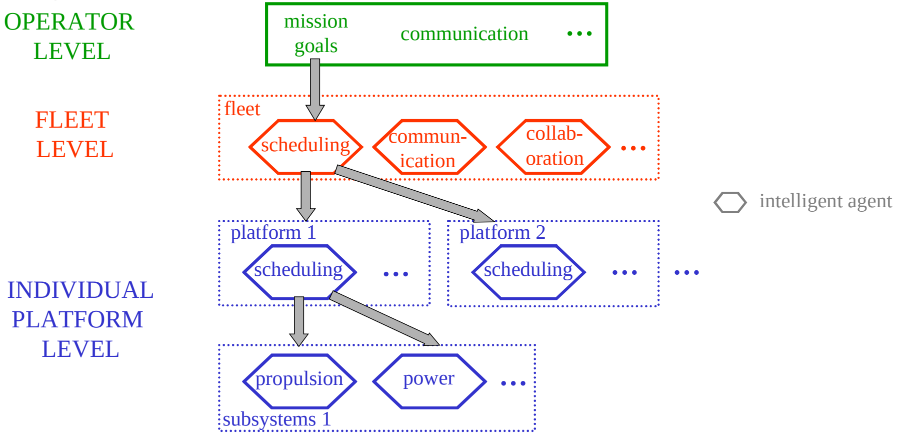

Figure 12: The hierarchical approach to scheduling in a fleet of coordinated platforms, using layers of intelligent agents at the operator, fleet, and individual platform levels.

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.

Figure 13 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.

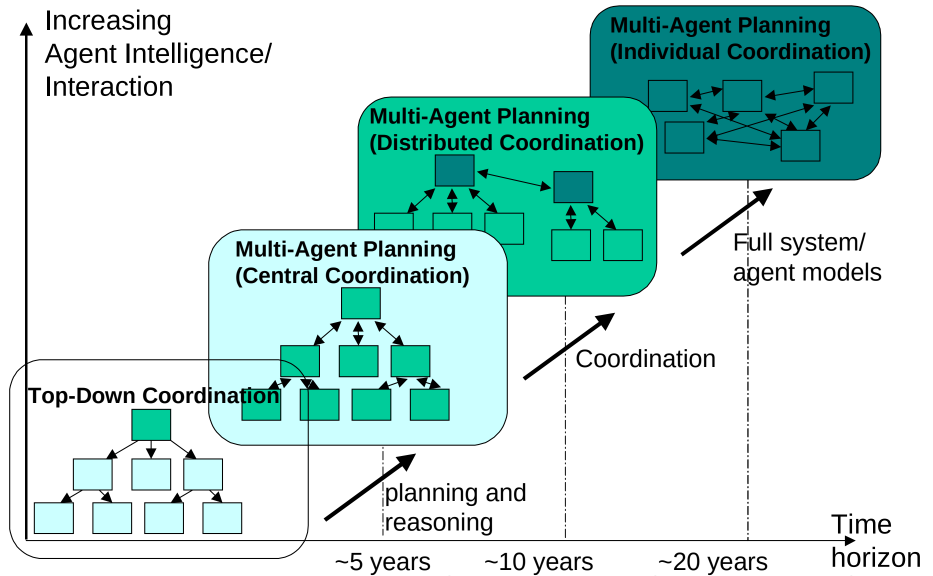

Figure 13: Coordination architectures for coordination of multiple agents for IST

Challenges and Conclusions

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 communicates through a fully capable mothership. 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 and 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 Intelligent Control 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.

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.

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

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.

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

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

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

Figure 7: Micro Control Moment Gyro.

Figure 8: Fabrication of micro-propulsion.

Figure 9: Conceptual MEMS based docking system.

Figure 10: Integrated micro-system of a future micro-satellite.

Figure 11: Flow chart showing the general hardware on the left, and the layered architecture on the right. Overlapping aspects can exist on either layer.

Figure 12: The hierarchical approach to scheduling in a fleet of coordinated platforms, using layers of intelligent agents at the operator, fleet, and individual platform levels.

Figure 13: Coordination architectures for coordination of multiple agents for IST's.