NASA/DoD University Nano-Satellites for Distributed Spacecraft Control

Military Uses of Small Satellites in Distributed Systems
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Abstract

Commonly referred to as 'virtual platforms', 'formation flying', 'virtual spacecraft', the implementation of Distributed Spacecraft Control technologies is being aggressively pursued internal and external of the National Aeronautics and Space Administration (NASA). Distributed spacecraft control architectures are characterized by interactions between spacecraft, cooperation between spacecraft, and common behavior among spacecraft within a constellation or formation. Collectively, these attributes enable a distributed network of individual spacecraft to act collaboratively as a single functional unit that exhibits a common system wide capability. Such capabilities will usher in the next generation of NASA Earth and Space science missions through the exploitation of new vantage points, the development of new sensing strategies and revolutionary measurement concepts, and the implementation of system-wide techniques which promote agility, adaptability, the ability to evolve over time, scalability, and affordability within mission concepts. A broad set of technology products is required to address the challenges presented within distributed spacecraft control architectures. Several technology development programs sponsored by NASA and the Department of Defense (DoD) have been or are now supporting efforts to develop these products. Building off the individual technology development programs and the foundations laid, DoD and NASA are teaming with one another to address common challenges, take advantage of the resources and opportunities available, and expedite the development and subsequent infusion of distributed spacecraft control technologies. The DoD University Nano-Satellite Program is serving as a focal point for such collaborative efforts.

Introduction and Objectives

The NASA Cross-Enterprise Technology Development Program (CETDP) is responsible for the development of critical space technologies that lower cost, improve performance, and enable new missions. The CETDP focuses on long-range strategic technologies that have broad potential to span the needs of the NASA Earth Sciences Enterprise, Space Sciences Enterprise, and Human Exploration and Development of Space Enterprise. Distributed spacecraft control technologies (more commonly referred to as 'virtual platforms', 'formation flying', or 'virtual spacecraft') represent a key enabling technology for the next generation NASA missions (Table 1) and as a result a key investment area for the CETDP program.

Distributed spacecraft control architectures are characterized by interactions between spacecraft, cooperation between spacecraft, and collective behavior among spacecraft within a constellation or formation. Interaction among spacecraft enables information related to the state of the formation to be shared and incorporated within the management of the formation. Introducing concepts such as decision making, hierarchical control, decentralized control, etc., within the management of the formation enables spacecraft to cooperate with one another. Such cooperative schemes will enable greater optimization of formation control parameters such as fuel consumption and time to configure/re-configure as well as increased flexibility and autonomy within the control of the formation to support the ability to adapt to changing conditions, requirements, and anomalies. Combining appropriate levels of interaction and cooperation within the management of the formation, desired behaviors emerge and enable the formation to perform as a single functional unit (versus a collection of independent assets) in response to the objectives of the mission being flown.

Projected Launch	Mission Name	Mission Type
99	New Millennium Program (NMP) EO-1	Tech Demonstrator
01	University Nanosats/Air Force Research Laboratory	Tech Demonstrator
01	Gravity Recovery and Climate Recovery (GRACE)	Earth Science
02	Auroral Multiscale MIDEX (AMM)/APL	Space Science
02	MightySat 2 (AFRL)	Tech Demonstrator
02+	Next Generation Lightweight Synthetic Aperture Radar (LightSAR)	Earth Science
03	New Millennium Program (NMP) ST-3	Tech Demonstrator
03	New Millennium Program (NMP) ST-5	Tech Demonstrator
03	Techsat-21 (AFRL)	Tech Demonstrator
04	Constellation-X	Space Science
05	Magnetospheric Multiscale	Space Science
05	Space Interferometry Mission (SIM)	Space Science
07	Global Precipitation Mission (EOS-9)	Earth Science
07	Global Electrodynamics	Space Science
08	Magnetospheric Constellation	Space Science
08	Laser Interferometric Space Antenna (LISA)	Space Science
09	DARWIN Space Infrared Interferometer/European Space Agency	Space Science
11	Terrestrial Planet Finder	Space Science
tbd	Astronomical Low Frequency Array (ALFA)/Explorers	Space Science
tbd	MAXIM X-ray Interferometry Mission	Space Science
05+	Leonardo	Earth Science
05+	Soil Moisture and Ocean Salinity Observing Mission (EX-4)	Earth Science
05+	Time-Dependent Gravity Field Mapping Mission (EX-5)	Earth Science
05+	Vegetation Recovery Mission (EX-6)	Earth Science
05+	Cold Land Processes Research Mission (EX-7)	Earth Science
05++	Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)	Space Science
15+	NASA Goddard Space Flight Center Earth Sciences Vision	Earth Science
15+	Very Large Optics for the Study of Extrasolar Terrestrial Planets	NIAC
15+	Ultra-high Throughput X-Ray Astronomy Observatory with a New Mission Architecture	NIAC
15+	Structureless Extremely Large Yet Very Lightweight Swarm Array Space Telescope	NIAC

Table 1 - Representative sampling of NASA missions driving the Distributed Spacecraft Control technology development program.

A broad set of technology products is required to implement these capabilities and address the challenges presented within distributed spacecraft control architectures (Figure 1). Current efforts are focusing on products to determine the relative positions and orientations of spacecraft within a formation, to share information among spacecraft within a formation, to manage information in distributed systems, and to manage (i.e., control) the positioning and pointing of spacecraft within the formation. Several technology development programs sponsored by NASA, DoD, and others are underway to develop these products.

Particularly critical to the development and infusion of Distributed Spacecraft Control technologies within flight projects are the on-orbit validation and demonstration of these technologies. The complexities associated with managing multi-spacecraft systems and the levels of autonomy required within these systems far exceeds the current state of the practice, resulting in a heightened demand for on-orbit demonstrations to validate these technologies prior to infusion within operational missions. The very nature of the technologies being developed necessitates the use of multi-spacecraft missions to adequately demonstrate and validate technology products.

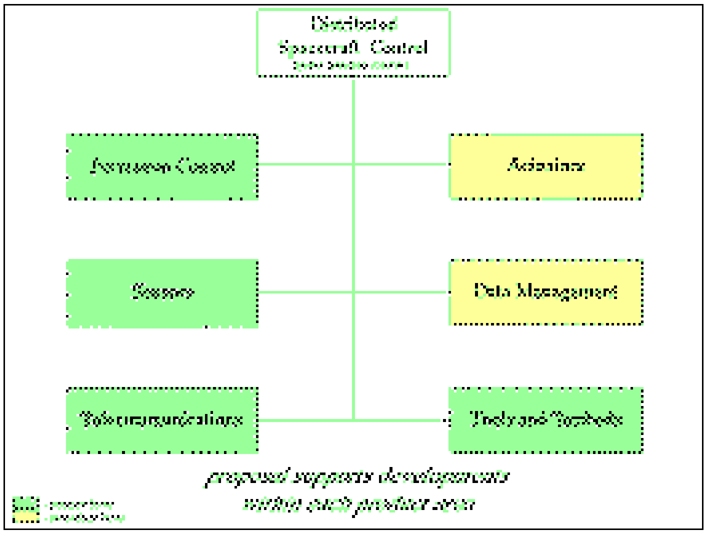

Figure 1 - Cross-Enterprise Technology Development Program Distributed Spacecraft Control Product Breakdown Structure (as of 12/15/98).

Because multi-spacecraft missions are uncommon, however, significantly fewer opportunities for on-orbit demonstrations are available. To address these shortcomings and in addition to sponsoring efforts to develop Distributed Spacecraft Control technology products, the CETDP is supporting the development of tools and testbeds to facilitate the development, validation, demonstration, and application of these products.

The Air Force Research Laboratory (AFRL), Air Force Office of Scientific Research (AFOSR), and Defense Advanced Research Projects Agency (DARPA) are jointly sponsoring a number of activities to promote the development of these technologies. Two such activities, TechSat21 and the University Nano-Satellite Program were initiated in 1998 to focus development activities in this area. Through the University Nano-Satellite program, the DoD is leveraging innovative thinking at U.S. universities to pioneer "out-of-box" solutions for nanosats and to demonstrate advanced mission concepts such as those embodied by Distributed Spacecraft Control technologies. 10 universities were selected in December 1998 to participate in this program which will culminate with the launch of 10 nanosats in the late 2001 timeframe.

The NASA CETDP, in partnership with the AFRL, is leveraging off the DoD University Nano-Satellite program to establish on-orbit testbeds to support a broad examination of distributed spacecraft control technology products and facilitate the on-orbit checkout and demonstration of these products. The NASA augmented DoD University Nano-Satellite program will provide a rapid, low-cost opportunity providing a strong technology push to target key technological challenges and strong technology pull to demonstrate the benefits and feasibility of the techniques being pursued. Through the augmented program, distributed spacecraft control technology development efforts will be supported by (1) the establishment of target designs that will facilitate a more comprehensive understanding and characterization of the technology products required, (2) the provision of an environment to stimulate the development and demonstration of these products, and (3) the provision of an on-orbit testbed to verify and validate technology products.

Approach

Building off existing technology development programs within each organization, the AFRL and NASA are leveraging each other's investments to establish a number of on-orbit testbeds through the University Nano-Satellite Program (Figure 3). These testbeds will be used to accommodate a variety of NASA sponsored distributed spacecraft control technology products now under

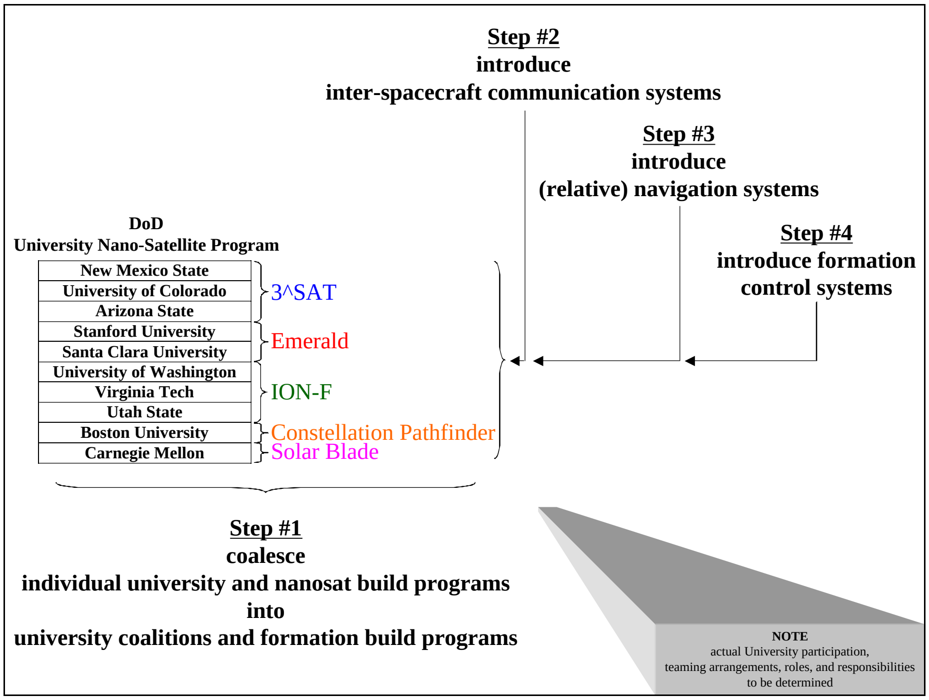

Figure 2 - DoD University Nano-Satellite Program augmentation to support the development and demonstration of distributed spacecraft control technologies.

development and this opportunity will be extended to the broader US government, industry, and academic community to demonstrate relevant technologies.

Establishing on-orbit testbeds...

Included in the DoD University Nano-Satellite solicitation was a special sub-topic to stimulate the formation of university coalitions and subsequent implementation of fleets of spacecraft capable of supporting some level of formation flying demonstrations. Some coalitions were formed as a direct result of the solicitation and various levels of formation flying experiments have been suggested. NASA and AFRL are working with the individual universities and their associated nanosat build programs to strengthen the university coalitions already formed and stimulate the formation of new university coalitions and associated fleet build programs. All of the participating universities have expressed great interest in supporting a more comprehensive program which would strengthen existing coalitions, establish new coalitions, increase commonality, and provide focus to the formation flying elements of the program to insure a meaningful and viable Distributed Spacecraft Control technology demonstration will be conducted. NASA is working closely with and providing additional sponsorship to the participating universities to create this opportunity, support the accommodation of the Distributed Spacecraft Control experiments within the university nanosats, and support execution of the experiments on-orbit.

Accommodating distributed spacecraft control technologies...

The focus of the augmented program is on inter-spacecraft communication subsystems, relative spacecraft navigation and guidance subsystems, and formation control algorithms. The nature of the University Nano-Satellite Program enables significant flexibility to be exercised when considering the readiness level of the technology products to be flown. In general, no requirements for flight qualified systems, subsystems, components, or parts exist. Experiments involving technology products in the low- to mid-Technology Readiness Levels (Figure 3) which will benefit from early on-orbit checkout are being supported. As expected, payload accommodation requirements are constrained and vary widely across the

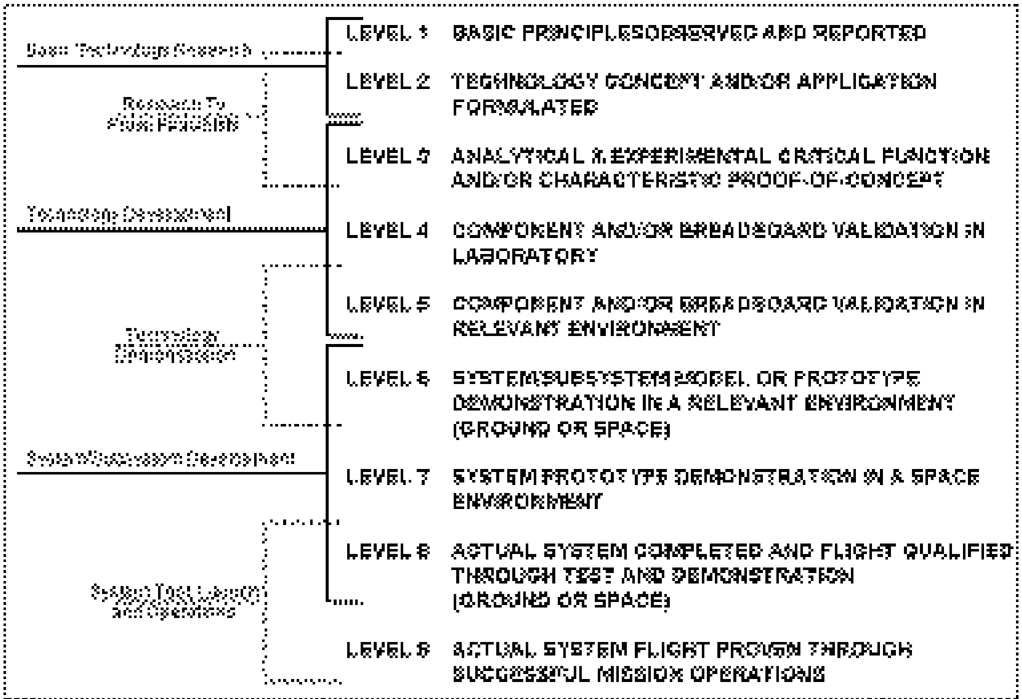

Figure 3 - NASA Civil Space Technology Readiness Levels (TRL)

university nanosats. However every attempt is being made to accommodate experiments of interest to NASA and the AFRL.

Defining the technology suite...

The Distributed Spacecraft Control technology suite to be accommodated within the University Nano-Satellite Program will be composed of technology products currently under development within established NASA technology development programs as well as those currently being developed external to NASA.

NASA has been pursuing the development of technologies in each of the Distributed Spacecraft Control product areas through a number of technology development programs including those sponsored by the CETDP, the Earth Science Technology Office, the Space Operations and Management Office, and the Office of Space Science Advanced Technology Development Program. The identification of reference missions to support development activities has proven to be beneficial and, in some cases, as challenging as the technologies themselves given the novelty of the concepts being developed. In addition, because of the significant levels of autonomy necessitated by distributed spacecraft architectures, on-orbit demonstration and validation of concepts, methods, and technologies is mandatory. The NASA development efforts can benefit significantly from the focus which will be brought to the program in the form of a target application and the provision of a development and testbed environment to progress these technologies beyond concepts. An assessment of NASA technology development programs will be conducted and candidate technologies will be identified for accommodation within the University Nano-Satellite Program.

To further take advantage of the University Nano-Satellite Program flight opportunity and to encourage broad participation by US government, industry, and academic organizations in this opportunity, a Request For Information (RFI) was released on 5/27/99 through the NASA Office of Space Science. The intent of the RFI was to solicit information on potential formation flying experiments to be conducted through the University Nano-Satellite Program. Applicability to NASA/AFRL Distributed Spacecraft Control objectives, ability to deliver the proposed technology, ability to accommodate the technology within the University Nano-Satellites, and the maturity of the technology being proposed are key factors being considered during the evaluation and selection of proposals received in response to this solicitation.

Status

With the selection of the universities participating in the University Nano-Satellite Program in December 1998 and approval for the NASA CETDP augmentation in May 1999, efforts are proceeding rapidly to establish university teaming arrangements, on-orbit testbed accommodation opportunities, and the Distributed Spacecraft Control technology suite to be accommodated within the program.

Establishing on-orbit testbeds...

To date, teaming arrangements across the 10 universities have resulted in the creation of 4 independent nanosat formations: 3^SAT, ION-F, Emerald, and Constellation Pathfinder. A fifth formation involving the Carnegie Mellon University Solar Blade nanosat and a possible companion spacecraft to monitor the deployment and function of the Solar Blade nanosat is being formulated. NASA, AFRL, and representatives from each of the university teams are actively working to define available spacecraft resources and accommodation opportunities for Distributed Spacecraft Control technology demonstrations. Brief descriptions of each of the University Nano-Satellite formations follows.

- The 3^SAT formation is composed of 3 identical nanosats being developed at Arizona State University, University of Colorado Boulder, and New Mexico State University. The primary objectives of the mission are to demonstrate stereo imaging, formation flying and cellular-phone communications technologies, and innovative command and data handling in addition to a number of university specific experiments. Each spacecraft is hexagonal in shape, approximately 45 centimeters wide and 25 centimeters high with a mass of approximately 10 kg. All 3 nanosats will provide attitude determination and control to +/- 5 degree pointing accuracy, GPS based navigation, and some level of orbit control. An AFRL provided micro-propulsion system is expected to be flown on the Arizona State nanosat. The 3^SAT formation plans to utilize a commercial communications LEO network (e.g., cellular communications) as the primary inter-spacecraft communications mechanism for the formation.

- The ION-F formation is composed of 3 similar nanosats being developed at Utah State University, University of Washington, and Virginia Polytechnic Institute and State University. The primary objectives of the mission are to investigate global ionospheric effects which affect the performance of space based radars and other distributed satellite measurements, formation flying and local communications within a formation, and a number of new technologies including micro-thrusters, gimbaling magnetic attitude control, and advanced tether systems. The Utah State nanosat is hexagonal in shape, approximately 45 centimeters wide and 12 centimeters high. The University of Washington and Virginia Tech nanosats will also be hexagonal in shape but slightly larger in dimension, approximately 45 centimeters wide and 25 centimeters high. All 3 nanosats will satisfy the 10 kg mass requirement. All 3 nanosats will provide attitude determination and control to +/- 3 degree pointing accuracy, GPS based navigation, and some level of orbit control. A cold gas or micro-PPT propulsion system is expected to be flown on the University of Washington nanosat.

- The Emerald formation is composed of 2 identical nanosats being developed at Stanford University and Santa Clara University. The primary objectives of the mission are to investigate phenomena within the ionosphere and serve as an on-orbit testbed to characterize the performance of spacecraft components in space and for a variety of formation flying technologies including relative navigation, inter-spacecraft communications, formation control, and mission operations for distributed spacecraft systems. Each spacecraft is hexagonal in shape, approximately 45 centimeters wide and 30 centimeters high with a mass of 15 kg. Both nanosats will provide attitude determination and control to a few degrees pointing accuracy, GPS based navigation, and orbit control via active (advanced colloid micro-thrusters) and passive (drag control) position control systems. The Emerald formation will utilize differential GPS techniques to determine relative spacecraft positions and commercially available radio modems or wireless Ethernet systems for inter-spacecraft communications.

- The Constellation Pathfinder formation is composed of as many as 3 identical nanosats being developed at Boston University. The primary objective of the mission is to demonstrate the feasibility of fabricating and launching one to three 1 kg / 1 watt satellites that are capable of collecting and returning quality scientific and engineering data. The Boston University nanosats are cylindrical in shape, approximately 20 centimeters across and 4 centimeters high with a mass of 1 kg. Each nanosat is expected to provide attitude determination on the order of several degrees pointing accuracy and will not possess any attitude or orbit control capability. In addition, some forms of inter-spacecraft communication (e.g., signaling) are being considered to support interactions between the spacecraft. Consideration is also being given to the development of a "mother ship" which would carry and dispense the nanosats. The "mother ship" may possess some level of functionality which will enable it to interact with the individual nanosats or serve as a focal point for interactions within the formation.

Defining the technology suite...

Definition of the final Distributed Spacecraft Control technology suite is currently underway. Efforts to identify candidate NASA sponsored technologies have been completed and proposals received in response to the RFI are currently being reviewed. Selection of proposals and finalization of the technology suite is expected in the early-August 1999 timeframe.

An assessment of ongoing NASA technology development programs has been conducted and 4 candidate technologies have been identified for accommodation within the University Nano-Satellite Program: NASA/Stanford Orion microsat, Stanford Differential GPS Relative Navigation System, Johns Hopkins University Applied Physics Laboratory Cross-Link Transceiver, and the NASA Hybrid Dynamic Facility for Formation Flying. Table 3 illustrates the accommodation of these technologies within the University Nano-Satellite Program. Brief descriptions of each of these technologies follows.

- The NASA/Stanford University Orion microsat is a rapid (about 1-year or less to build), low-cost (about $250K to build) on-orbit testbed facility designed specifically as an engineering testbed for formation flying technologies. The Orion program is sponsored by the Space Operations and Management Office Technology Development Program. A single Orion class microsat will be launched by the AFRL with the other University Nanosats and fly in formation with the Emerald formation to enable a number of relative navigation and formation control experiments.

- Stanford University, under sponsorship from the Cross-Enterprise Technology Development Program, Earth Science Technology Office, and Space Operations and Management Office Technology Development Program, has developed a relative navigation sensing system based on differenced GPS observations. This system will be hosted on the Orion microsat and Emerald nanosats.

- The Johns Hopkins University Applied Physics Laboratory, under sponsorship from the Office of Space Science Advanced Technology Development Program, Earth Science Technology Office, Office of Space Science Explorers Technology Development Program, and Space Operations and Management Office Technology Development Program, is developing an integrated relative navigation and inter-spacecraft communications system known as the Cross-Link Transceiver (CLT). Laboratory demonstration versions of the CLT will hosted on the ION-F nanosats.

- The NASA Hybrid Dynamic Facility for Formation Flying provides a ground testbed environment for the development and verification of formation flying sensing and control techniques and systems. The facility also supports formation mission analysis and design functions and flight software development and testing through high-fidelity, end-to-end simulations of spacecraft systems, ground systems, and environmental parameters. The ION-F team will utilize this facility to support mission design and development activities associated with the ION-F formation.

Formation Control	**Decentralized Control of University Nanosats** NASA GSFC	**Orbit Design Optimization and Control Methodologies** Mu Enterprises	**Formation Control using GPS LQG/LTR Feedback Controllers** SPA Inc.	**Autonomous Formation Control Using Autocon** AI Solutions

Sensors	**Vision Based Navigation System** Texas A&M	**Low Power Transceiver** Stanford Telecom		
Communications	**Electronically Despun Antenna** NASA GSFC	**Low Power Transceiver** Stanford Telecom		
Actuators	**Colloid Micro-Thrusters** Stanford University			
Data Management	**Formation Control and Ground Systems** AI Solutions, Altair	**Distributed Space System Autonomy** Stanford University, JPL, NASA AMES, LMMS		
Tools & Testbeds	**Formation Control and Ground Systems** AI Solutions, Altair			

Table 2 - Distributed Spacecraft Control technologies identified in response to the Request for Information.

A total of 10 responses were received in response to the RFI and are currently being evaluated. Final selection is expected in the early August 1999 timeframe. Proposals were received within each of the NASA Distributed Spacecraft Control technology focus areas (Table 2).

Following the RFI proposal review and selection process, NASA, AFRL, and representatives from the participating Universities will establish the technology suite for each of the University Nano-Satellites and Nano-Satellite formations. Table 3 illustrates an EXAMPLE of what the technology suite might consist of.

Conclusion

The Distributed Spacecraft Control technology suite is expected to be finalized in the mid-August 1999 timeframe. Following these activities, efforts will transition to the implementation, accommodation, and operations of the various technologies to be flown. To support the late 2001 launch of the University Nano-Satellites, technology payload delivery is required in the early/mid 2001 timeframe. Significant challenges remain to implement the University Nano-Satellite and Nano-satellite formations, to accommodate the proposed distributed spacecraft control technologies, and to conduct the proposed technology experiments on-orbit through this program. However, NASA, AFRL, and the participating Universities have to date exhibited strong working relationships and commitments and expectations are high that these challenges will be overcome and a successful program will be flown. Further, it is envisioned that with the success of this program, a precedent will have been established in the use of university class spacecraft as vehicles to provide an effective, low-cost, and rapid mechanism to progress technology development and demonstration efforts.

Acknowledgements

This work has been made possible only through efforts and dedication of several individuals. Included among these are Maurice Martin and Rich Cobb, of the Air Force Research Laboratory, Kate Hartman of the Cross-Enterprise Technology Development Program, and particularly the faculty and students from the universities participating in the University Nano-Satellite Program.

	Formation Control	Sensors	Communications	Actuators	Data Management	Tools & Testbeds
Emerald	**ORION** Stanford University, NASA GSFC **Decentralized Control of University Nanosats** NASA GSFC	**ORION** Stanford, NASA GSFC **Differential GPS** Stanford University	**ORION** Stanford, NASA GSFC	**Colloid Micro-Thrusters** Stanford University	**Distributed Space System Autonomy** Stanford University, JPL, NASA AMES, LMMS **Formation Control and Ground Systems** AI Solutions, Altair	**Formation Control and Ground Systems** AI Solutions, Altair
ION-F	**Orbit Design Optimization and Control Methodologies** Mu Enterprises **Autonomous Formation Control Using Autocon** AI Solutions	**Cross Link Transceiver** JHU/APL	**Cross Link Transceiver** JHU/APL		**Distributed Space System Autonomy** Stanford University, JPL, NASA AMES, LMMS **Formation Control and Ground Systems** AI Solutions, Altair	**Hybrid Dynamic Simulator for Formation Flying** NASA GSFC **Formation Control and Ground Systems** AI Solutions, Altair
Constellation Pathfinder		**Low Power Transceiver** Stanford Telecom	**Low Power Transceiver** Stanford Telecom		**Distributed Space System Autonomy** Stanford University, JPL, NASA AMES, LMMS **Formation Control and Ground Systems** AI Solutions, Altair	**Formation Control and Ground Systems** AI Solutions, Altair
3^SAT	**Formation Control using GPS LQG/LTR Feedback Controllers** SPA Inc.	**Vision Based Navigation System** Texas A&M			**Distributed Space System Autonomy** Stanford University, JPL, NASA AMES, LMMS **Formation Control and Ground Systems** AI Solutions, Altair	**Formation Control and Ground Systems** AI Solutions, Altair
Solar Blade	TBD	TBD	TBD	TBD	**Distributed Space System Autonomy** Stanford University, JPL, NASA AMES, LMMS **Formation Control and Ground Systems** AI Solutions, Altair	**Formation Control and Ground Systems** AI Solutions, Altair

Table 3 - EXAMPLE technology suite for the University Nano-Satellite Program. Pending RFI selections in mid-August 1999.
[grey box] - Distributed Spacecraft Control technologies proposed in response to the RFI.