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LOOKING BACK AND LOOKING FORWARD: REPRISING THE PROMISE AND PREDICTING THE FUTURE OF FORMATION FLYING AND SPACEBORNE GPS NAVIGATION SYSTEMS

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A retrospective consideration of two 15-year old Guidance, Navigation and Control (GN&C) technology 'vision' predictions will be the focus of this paper. A look back analysis and critique of these late 1990s technology roadmaps outlining the future vision, for two then nascent, but rapidly emerging, GN&C technologies will be performed. Specifically, these two GN&C technologies were: 1) multi-spacecraft formation flying and 2) the spaceborne use and exploitation of global positioning system (GPS) signals to enable formation flying.

This paper reprises the promise of formation flying and spaceborne GPS as depicted in the cited 1999[1] and 1998[2] papers. It will discuss what happened to cause that promise to be mostly unfulfilled and the reasons why the envisioned formation flying dream has yet to become a reality. The recent technology trends over the past few years will then be identified and a renewed government interest in spacecraft formation flying/cluster flight will be highlighted. The authors will conclude with a reality-tempered perspective, 15 years after the initial technology roadmaps were published, predicting a promising future of spacecraft formation flying technology development over the next decade.

INTRODUCTION

The statement "It's tough to make predictions, especially about the future" is widely attributed to the professional baseball player and amateur philosopher Yogi Berra. This statement certainly applies in general but it is especially à propos for space technologists. NASA, industry, and academic technologists face great challenges in their work to develop effective technology planning. Since technology development is at the core of everything NASA does, 'roadmapping' (a particular form of technology planning) is commonly employed to systematically lay out time-phased plans to mature the specific technologies needed to implement new functional capabilities to enable NASA's future science and exploration missions. As mentioned in Reference 3[3], technology roadmapping is critical when technology investment decisions are not straight forward, especially when it is not clear which alternative to pursue, how quickly the technology is needed, or when there is a need to coordinate the development of multiple interacting technologies. The primary benefit of roadmaps is to establish a coordinated path forward framework for multiple targeted

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incremental technology innovations, often developed in parallel but linked together towards a common goal, to be accomplished within a single organization or more broadly, within a discipline-specific community of practice.

Overall, it is fair to say that the methodology of technology roadmapping has had a history of mixed results. Some have been fulfilled while others have not been successfully implemented. The reasons for this vary; perhaps the roadmap itself was flawed (was it simply a list of technologies and not a go-forward path?) or perhaps even the most perfectly constructed roadmap can suffer from a lack of sustained investment commitment by the sponsoring organization.

While, by definition, the roadmapping process is inherently a ‘look forward” or guidance exercise, new perspectives and insights can be obtained by a focused retrospective analysis of certain roadmap products.

This paper reprises the promise of formation flying and spaceborne GPS as depicted in the two cited papers.[1,2] The roadmaps in both References 1 and 2 predicted a bright and strong future for spacecraft formation flying technology development in the coming decade. When these papers were written, more than 15 years ago, these technologies were expected to be transformative. A prevailing viewpoint then was that these technologies had the potential to revolutionize space mission architectures, ground operations and the space vehicles themselves. Swarms of space vehicles flying in formations or clusters would soon be realized, providing new, innovative ways for data gathering and radically changing space observation perspectives through different viewing techniques (e.g., 3D through co-observations, multi-point, temporally, and interferometrically). Formation flying applications and techniques were expected to impact the entire spectrum of space vehicle applications, including Earth and space science, commercial, defense, and human spaceflight. However, 15 years later, the full potential of formation flying and the full utility of spaceborne GPS has yet to be realized. The author’s critique of these late 1990s technology roadmaps, summarized in this paper, shows that, while some progress was attained, their optimistically inclined predictions were not fulfilled. The motivation for performing this retrospective analysis was primarily to objectively assess the maturation since 1999 of spacecraft formation flying technology, and the associated spaceborne GPS technologies that enable formation flying. The secondary motivation was to provide some reality-tempered perspective 15 years after the initial technology roadmaps were published, along with an updated, more conservative, prediction for the future of spacecraft formation flying technology.

FORMATION FLYING PROMISE, CIRCA 1999

In the 1990s the confluence of several technology initiatives and other space-related developments provided a unique opportunity for revolutionary changes in satellite observations from space through formation flying technology. The promise of space-based formation flying was tremendous. It offered unique observation vantage points by providing new, innovative ways to gather data, share this information between space vehicles and the ground, and, as a result, enhance Earth and space science, human exploration, and commercial space endeavors. Some of the key 1990s initiatives and developments that helped foster maturation of formation flying technologies included:

- NASA’s Faster Better Cheaper initiative, introduced by administrator Dan Goldin, to guide NASA back to smaller, less expensive, more risky space missions moving NASA away from its overly risk-adverse posture to a more agile organization that could quickly develop, prototype, and deploy low cost space missions.
- Department of Defense (DoD) initiatives carried out by the Defense Advanced Research Projects Agency (DARPA) and the Air Force Research Laboratory (AFRL), such as the

Strategic Defense Initiative, that introduced smaller satellites, new technologies, and the ability to host on-orbit experiments on these cheaper satellite systems.

- Development of very small, inexpensive satellites, pioneered by AMSAT, internationally commercialized by Surrey Satellite Technology Ltd. (SSTL) (which was founded by Sir Martin Sweeting from AMSAT) and ultimately emulated by many universities and small companies.
- Maturation of GPS as an international navigation utility and the development of space-borne GPS systems that could provide real-time attitude, navigation, and timing measurements.
- Substantial SWaP (Size, Weight and Power) reductions and throughput improvements of space-rated microprocessors.
- A booming commercial space market driven by dot-com companies that planned to “Blacken the Skies” with internet capable satellite constellations.
- Development of key hardware technologies, including cross-links and proximity-sensing systems to enable formation flying and rendezvous, proximity operations, and docking (RPOD).
- Development of innovative formation flying and vehicle autonomy algorithms and software.

Many in the space community anticipated that these initiatives and technologies, when melded together, would forge a system of formation flying capabilities that would fundamentally change how the space community would perform science measurements.[4,5] Moreover, the substantial autonomy embedded in these systems would also significantly reduce the costs of space vehicle operations.

Transforming the vision and opportunity of formation flying from dream to reality was, and continues to be, a formidable task. The breadth and depth of the technologies required is largely due to the vast spectrum of missions planned (e.g., loose formations to precise, nanoradian unified attitude/orbit control); and when combined with the need to validate and certify this technology suite for spaceflight and for these numerous diverse mission types, becomes a daunting challenge. As such, a combined Government-University-Industry team was created in the 1990s to collaborate on the development of a Formation Flying Technology roadmap and to expedite formation flying technology development. As formation flying is a **Systems** capability, it was critically important that the development of the combined system meet the robust standards needed for future space missions.

The team, at the time, included leadership from NASA and the AFRL with specific team researchers from the NASA Goddard Space Flight Center (GSFC), the NASA Johnson Space Center (JSC), the NASA Jet Propulsion Laboratory (JPL), AFRL, the Naval Research Laboratory, the Johns Hopkins University Applied Physics Laboratory (APL), Stanford University, Massachusetts Institute of Technology (MIT), University of California Los Angeles (UCLA), and Space Products and Applications (SPA), Incorporated. The team’s roadmap consisted of six formation flying technology focus areas (Table 1) and a formation flying technology validation “Stairstep” roadmap, which included planned objectives and expected dates of performance completion (Figure 1). This roadmap is described in more detail in the referenced 1999 paper.[2]

Figure 1 illustrates that similar to GPS technology[2], there are several technological “stairsteps” that must be overcome to realize the technology. Formation flying needs to climb the technology stairsteps from autonomous navigation, to constellation control, to one and two-way formation flying, and finally to virtual platforms. As such, the roadmap depicts the planned evolution of formation flying technology from its autonomous navigation state when the paper was written in 1998/1999 to the achievement of virtual platforms planned for 2006.

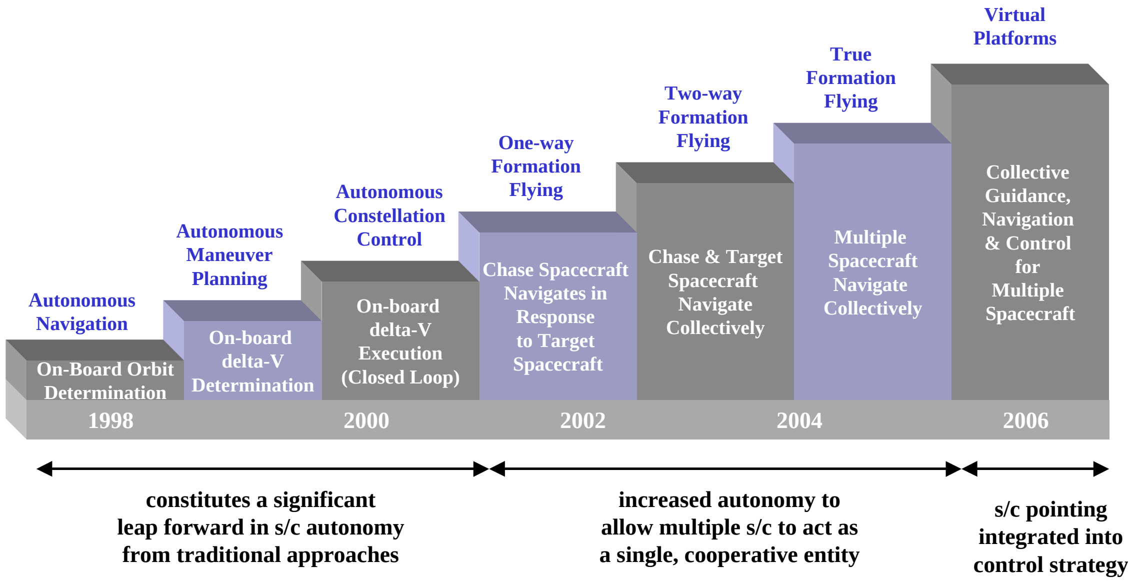

Figure 1. 1999 Roadmap "Stairsteps" to mature Formation Flying and Virtual Platform Technology (from Reference 1).

Table 1. 1999 Formation Flying Technology Focus Areas (from Reference 1).

Focus Area	Product Line Descriptions	Sample Products
Sensors	Emphasis: developing new sensing techniques • Relative position/velocity • Relative orientation	• Autonomous formation flying sensor • GPS/global navigation satellite system (GNSS) relative and absolute navigation and timing • Vision sensors—relative proximity operations and pose • Inertial sensors (e.g., gyros, inertial measurement units (IMU)) • Optical communication, supporting relative navigation and attitude
Actuators	Emphasis: Accommodating formation flying through combined position and attitude actuation • Precision, efficient, high mobility orbit and attitude control systems	• Actuator performance specifications • Formation flying trajectory propulsive options (electric, liquid, solid, etc.) • Attitude options (reaction wheels, control moment gyroscopes (CMG), thrusters)
Telecommunications	Emphasis: adapting communications technologies to new uses • Interspacecraft communications systems	• Crosslink communiation specifications • Radio frequency (RF)-based crosslink transceivers • Optical communication system transceivers
Formation Control	Emphasis: developing new control methods and architectures • Fleet control paradigms • Vehicle control algorithms	• Unified orbit and attitude control techniques • De-centralized control techniques • Synchronized formation rotation and control techniques
Computing	Emphasis: ensuring formation flying	• Processor throughput specifications

and Data Management	techniques can be accommodated • High-performance processors • High-capacity data storage • Real-time distributed computing	• Data storage specifications • Processors and memory
Tools and Testbeds	Emphasis: establishing infrastructure for technology development, verification, and application • Mission analysis and design tools • Flight software emulation environments • Component-, subsystem-, and system-level verification/validation capabilities	• Earth Observing 1 (EO-1) spacecraft platform • FreeFlyer mission design tool • 6-degree of freedom (DOF) coordinated platform testbed (ground-based) • High-fidelity formation flying testbed • Multi-spacecraft, space-based formation flying testbed

The differing mission sets require an entire spectrum of sensing, controlling, and actuation capabilities to satisfy their varied requirements challenges. As project managers will not accept an unproven technology on their mission, validating the formation flying system over the extremely diverse, wide spectrum of mission types and formation technology requirements was a formidable challenge. Achievement required a healthy set of validation missions. These were planned to be piggybacked on NASA and DoD technology missions, (e.g., New Millennium Missions: EO-1, 2, and 3; Deep Space 3 (DS); and Space Technology 5 and 7), on very low cost micro and nanosats missions built by universities, and as hitchhikers on commercial spacecraft. This was similar to the technique used to validate spaceborne GPS technology.

In 1999, NASA's primary focus for formation flying technology was through the "Distributed Spacecraft" thrust area of the Cross Enterprise Technology Development Program (CETDP). The research within this thrust area was focused on the collaborative behavior of multiple space vehicles that form a distributed network of individual vehicles acting as a single functional unit while exhibiting a common system-wide capability to accomplish various mission goals. This technology thrust, coupled with the New Millennium Program (NMP) formation flying missions and the formation flying activities planned by the government-university-industry team represented a robust technology program that is planned to yield great fruit for the space community.

SPACEBORNE GPS VISION AND ROADMAP

As depicted in the formation flying technology focus area table (Table 1), the sensor development and telecommunications focus areas rely very heavily on GPS-based systems. The development and deployment of robust spaceborne GPS systems (focus area 1), used to sense absolute and relative navigation, is critical to enable autonomous formation flying for missions at geostationary altitude and below. These receiver systems were being modified by some[6,7,8] to also transmit formation control information to the vehicles in the virtual platform—providing a telecommunications capability (focus area 3) to the formation and enabling formation control beyond geostationary altitudes.

In the 1998 ION paper on Spaceborne GPS technology[2], a set of capabilities, vision statement, and roadmap were outlined to focus the spaceborne GPS team on the most critical issues and technologies that would support space vehicle autonomy and formation flying. The vision, sensing capabilities, and future engineering applications derived from that paper are shown in Table 2 and the GPS technology roadmap is shown in Figure 2.

Table 2. 1998 Spaceborne GPS Vision (from Reference 2).

Spaceborne GPS Vision

Improve space vehicle autonomy; Reduce design and operations costs through the infusion of new GPS hardware and sensing techniques

GPS Sensing Capabilities:

- Autonomous Orbit Determination
- Accurate Time Synchronization
- Coarse Attitude Determination
- Accurate Relative Ranging Between Vehicles

21st Century Engineering Applications:

- Autonomous Onboard Navigation, Operations, and Orbit Control
- Attitude Determination and Control
- Rendezvous and Proximity Operations
- Formation Flying/Coordinated Platforms
- Microsatellites w/3-axis control
- GPS at Geostationary Earth Orbit (GEO) and Beyond
- Government, University, and Commercial Partnerships

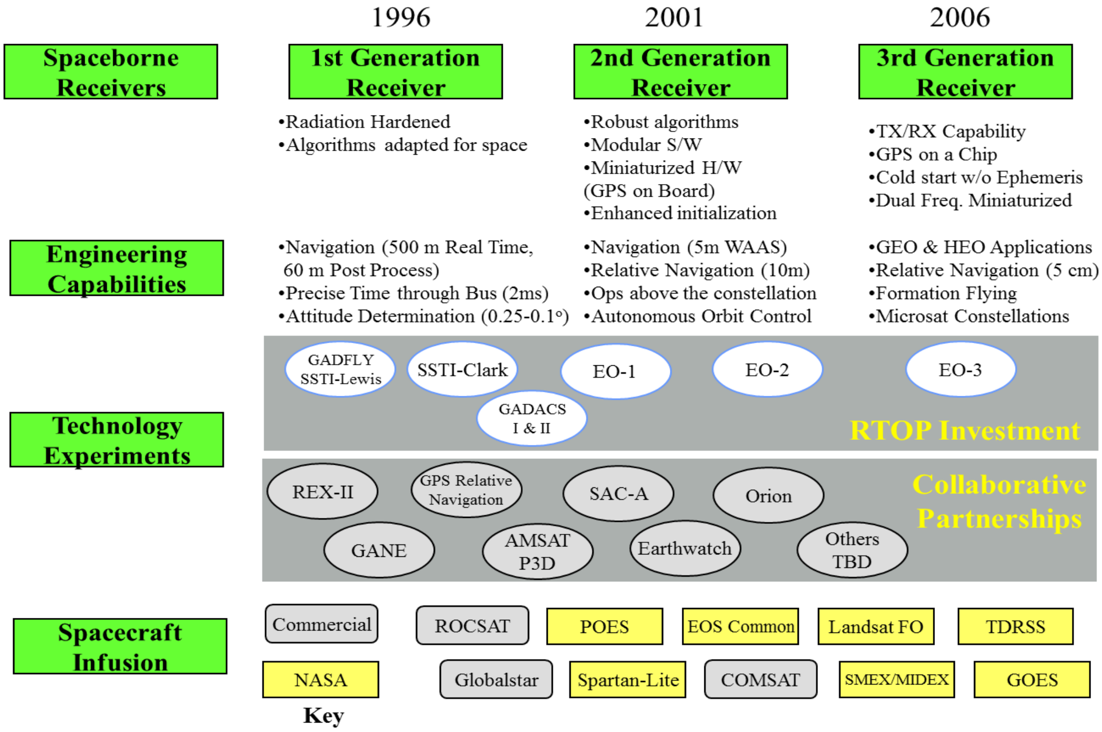

Figure 2. 1998 Spaceborne GPS Technology Roadmap (from Reference 2).

GPS ROADMAP AND VISION: WHAT WAS ACCOMPLISHED?

The development and maturation of spaceborne GPS technology represents a foundational step in the development and maturation of formation flying technology. As such, spaceborne GPS technology development was emphasized first and is much more mature with the 1998 vision mostly realized through the development and space certification of two generations of receiver designs. All the sensing capabilities depicted in Table 2 have been demonstrated and all except relative ranging can be considered operational. Many of the 21st century engineering applications are operational or are soon to be operational. Those lagging behind are formation flying and the microsatellite applications. All launch vehicles and most space missions in low Earth orbit (LEO) operationally employ spaceborne GPS. Also, several science missions in high Earth orbit (HEO), including Magnetospheric Multiscale (MMS), the Orion capsule that will support human exploration beyond LEO, and the GOES-R (Geostationary Operational Environmental Satellite) weather satellite series at geostationary altitude, will use spaceborne GPS. Commercial missions, such as Globalstar, use GPS orbit determination and timing operationally and the International Space Station (ISS) employs GPS for real-time navigation and attitude determination.[9,10] Rendezvous and proximity operations have been routinely conducted on several ISS cargo transfer vehicles, including the European Automated Transfer Vehicle (ATV), the Japanese H-II Transfer Vehicle (HTV) and the U.S. commercial cargo vehicles Dragon and Cygnus.

Referring to the 1998 Spaceborne GPS Technology roadmap (Figure 2), some of the technology experiments shown were not conducted due to funding losses (e.g., GPS Attitude Determination and Control Experiment (GADACS) II, EO-2&3, Orion-Nanosats for formation flying) or due to mission failures or cancellations (e.g., Small Spacecraft Technology Initiative (SSTI) Lewis and Clark, and Earthwatch). Despite this, sufficient technology funding and commercial need existed to evolve spaceborne GPS through two development generations, resulting in the maturation of GPS as a spaceborne position, navigation, and timing utility. Capabilities not fully addressed yet include further miniaturization of the systems to significantly reduce SWaP (GPS on a chip), the development of a combined GPS/satellite crosslink capability to enable real-time relative navigation determination and communication across space vehicles, and a further improvement of absolute and relative navigation determination through the use of additional navigation signals in space, including the use of augmentation systems such as Wide Area Augmentation System (WAAS).

GPS ROADMAP AND VISION: SYSTEM CHANGES SINCE 1998 AND THE WAY AHEAD

Since the 1998 paper was published, additional navigation satellite systems have been developed and deployed from Russia (GLONASS), Europe (Galileo), and China (Beidou). International collaboration, primarily through United Nations-sponsored programs like the International Committee on GNSS (ICG), have resulted in discussion and standardization of GNSS constellation signals to ensure interoperability and availability both on Earth and in space. Also, several new civil signals are being deployed on GPS and other GNSS constellations that are interoperable across all constellations. These international efforts have improved the robustness of navigation signal use in space, especially for missions in HEO or at geostationary altitudes. Collaboration on the standardization of GNSS constellation specifications that assure sufficient “spillover” of signals off the Earth will ensure that more GNSS signals are available for missions in orbits above 3000 km, including missions at geostationary altitudes. The development and specification of GNSS signal availability and signal strength, in the so-called “Space Service Volume”[11] is crucial for assured use of GNSS for navigation and timing applications in space. The NASA/DoD GPS team pioneered the development and approval of the Space Service Volume specification for GPS-III. A template of this specification is now being populated by the other GNSS constellation providers as part of the ICG efforts and will ultimately become part of their constellation’s specification. Once complete, these GNSS constellation signals will enable the development of a 3rd-generation spaceborne receiver. This receiver will exploit the use of all the international GNSS signals in space as well as support relative navigation sensing through a multiple-vehicle crosslink communications/navigation capability. Once this 3rd-generation communications and navigation system is complete, this would round out the remaining elements still missing from the 1998 GPS (now GNSS) roadmap.

WHAT HAPPENED TO PREVENT FULL MATURATION OF THE GPS AND FORMATION FLYING ROADMAPS?

Maturation of formation flying and spaceborne GPS did not fully materialize for three main reasons:

1. The promise of frequent, inexpensive access to space never materialized, primarily due to the 1999–2001 collapse of the dot-com bubble[*]
2. Technology funding priorities shifted away from formation flying and GPS primarily due to the dissolution of NASA's technology programs. A major factor was NASA funding transfers from technology resulting from the initiative, starting in 2004, to return humans to the moon (Constellation Program); and
3. The science community, sensing the seismic shift in space access and lack of technology funding, revamped their strategic plan to focus on single, monolithic missions

The following details on how each of these three resulted in the collapse of technology funding in the 2003–2010 timeframe, severely impacting GPS and formation flying maturation:

Impacts Resulting from Collapse of dot-com Bubble

Prior to the collapse of the dot-com bubble, there were many fledgling small companies and several accomplished companies that promised to "blacken the skies" with constellations of wireless communications satellites. When the bubble burst, the economies of scale negatively shifted very dramatically for low cost space access (launch vehicle payload capability), low cost spacecraft bus purchases, and hosted payloads space on spacecraft. This caused a rapid evaporation of low-cost validation mission capabilities and university payload opportunities. As a result, the many diverse validations missions required to climb the formation flying "stairsteps" never materialized.

Impacts Resulting from Collapse of Technology Funding

It should be obvious that with the loss of the CETDP funding, a significant segment of the technology development performed with NASA (GSFC, JSC, and JPL), with APL and with the universities (Stanford, MIT, UCLA) was stopped or significantly curtailed. This included the formation flying efforts and spaceborne GPS research. NASA's NMP was also significantly scaled back. Critical formation flying demonstration missions were cancelled outright, scaled back, or significantly delayed. These included the cancellation of the DS-3 Starlight mission[12], which planned to demonstrate spaceborne optical interferometry and precise relative navigation and bearing control using the Autonomous Formation Flyer crosslink technology and the cancellation of the Space Technology-9 (ST) Precision Formation Flyer (PFF) demonstration mission[13], a collaboration between NASA GSFC and JPL, Orbital Science Corporation and General Dynamics C4 Systems. ST-9 was planned to enable "mission capabilities for imaging Earth-like planets, black hole event horizons, and stellar surfaces and enable stereo-graphic co-observing imagers of the Earth and the atmosphere." With the cancellation of the NMP DS-3 mission and the low cost university missions on hold or cancelled due to the loss of CETDP funding, ST-9 represented

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[*] Dot-com bubble http://en.wikipedia.org/wiki/Dot-com_bubble.

NASA's last opportunity, within the roadmap timeframe, to demonstrate key formation flying technologies. Some of the key Space Transportation System-9 (STS) technologies included "PFF algorithms and flight software for formation initialization, reconfiguration, relative navigation, and formation control; and inter-satellite communication devices." Unfortunately, words in the ST-9 PFF proposal ultimately rang prophetic: "Without ST-9 PFF, critical science campaigns that require sparse apertures will continue to slip into the indefinite future"

Impacts Resulting from Revamped Science Strategic Plan

The collapse of the internet bubble coupled with the significant decimation of technology funding resulted in a fundamental change in the science community's viewpoint regarding future missions. Making matters worse, failures of some "Faster Better Cheaper" missions, including the failure of the 1999 Mars missions--Mars Climate Orbiter, Mars Polar Lander, and the two DS-2 probes, resulted in a redefinition of the NASA science mission strategic plan. As a result of all these events, most of the distributed space missions, including formation flying missions, were eliminated from the science strategy. With significant technology hurdles still ahead and failures still smarting, the science community could not risk their next generation missions on an unproven technology. The science strategy was modified so that science objectives could be performed with a single monolithic mission or with a two to four loosely coupled spacecraft with no autonomous formation control capabilities. These included GRACE, which is a two-spacecraft loose formation with highly accurate relative navigation sensing through an RF crosslink, MMS[7], which intended to be a four-spacecraft autonomous formation flyer but was descoped to eliminate the RF crosslink and will maintain a periodic, loose formation from ground commands, and NMP ST-5, which evolved into a smallsat technology demonstrator that loosely maintained a three-spacecraft constellation via ground command.

Formation Flying Maturation Impact Summary

Each one of the three above impacts tore out a significant portion of the foundational principles embedded in the development of the Formation Flying Technology roadmap. Coupled together, all three stalled out the U.S. formation flying technology development in the 2003–2010 timeframe for all activities except for those activities being sponsored by DARPA that were already well underway.

RECENT TRENDS: RENEWED U.S. GOVERNMENT INTEREST IN FORMATION FLYING/CLUSTER FLIGHT

Formation flying technology has received renewed interest by U.S. government entities (NASA and the DoD) after the collapse of the effort in the 2003–2010 timeframe. Changes in space industry priorities, including an enhanced focus on space commercialization and small, low cost CubeSat missions, have stimulated this interest. NASA's newly established Space Technology Mission Directorate (STMD) is infusing some funding in the formation flying technology area. Commercial and government missions to the ISS, NASA's Exploration initiative, and NASA and DARPA interest in satellite repair have matured formation-relevant RPOD technologies. The European Space Agency (ESA) interest in formation flying has spawned successful technology demonstrations, showing the world the utility of this technology. Solar occultation formation missions are starting to appear in national and international science strategic roadmaps. Space commercialization and space access initiatives have bolstered opportunities for on-orbit technology validation. And, since 2010, DARPA has invested in technology and systems to enable clusters flying in formation. Specific rationale for this renewed interest is described in the following paragraphs.

Back to the Future: Reinvigoration of Low Cost Smallsat Development and Deployment

The 1998/1999 roadmaps relied heavily on very low-cost on-orbit technology demonstrations. Many of the technology demonstrations were to be performed on low cost university, commercial and government small satellite flights. While slow to grow at first, the past decade has experienced a virtual explosion in the smallsat commercial market. This was significantly stimulated by the 1999 invention of the CubeSat form factor by Bob Twiggs of Stanford and Jordi Puig-Suari from Cal-Poly and by NASA's CubeSat initiative, enabling low- or no-cost rides into space to educational institutions and non-profits. These initiatives, coupled with the sustained sponsorship of the university nanosat program by AFRL, have reinvigorated the opportunity for low-cost formation flying technology demonstration missions. CubeSat 3U and 6U form factors will allow sufficient SWaP capabilities for the formation control systems technologies to be accomplished.

NASA Technology Investments

The NASA STMD's Small Spacecraft Technology Program[14], with a nationwide network of participants and partners, is investing in the development of multiple 'push' technologies for small spacecraft. The objectives here are: 1) to develop and demonstrate new small spacecraft technologies and capabilities for NASA's missions in science, exploration and space operations, and 2) to promote the small spacecraft approach as a paradigm shift for NASA and the larger space community. STMD is pursuing these objectives through a combination of focused technology developments and flight-demonstration projects. Focused small spacecraft technology developments are being conducted in the following areas: communications, avionics, propulsion, power, instruments, manufacturing, and small Earth return vehicle. NASA's STMD has several technology initiatives underway that are furthering smallsat development and autonomous RPOD and formation flight developments. Of particular interest here, given the context of this paper, is STMD's sponsorship of Flight Demonstration projects for both Formation Flight & Docking and Radio & Laser Communications. The first is called the CubeSat Proximity Operations Demonstration (CPDO), led by Tyvak Nano-Satellite Systems LLC. This CubeSat RPOD demonstration is scheduled to be launched in 2015. The latter is called the Optical Communications and Sensor Demonstration (OCSD).

In 2013, several partnerships between NASA centers and universities were awarded to advance smallsat technology[*]. Some of the formation-relevant technology developments underway include:

1. High rate CubeSat S/X band communications systems. Partners: University of Colorado and NASA Marshall.
2. Space Optical Communications. Partners: University of Rochester and NASA Ames.
3. Precision Navigation with MEMS IMU Swarms. Partners: University of West Virginia and NASA Johnson.
4. CubeSat RPOD Software. Partners: UT Austin and NASA Johnson.
5. Integrated Precision Attitude Determination and Control System. Partners: University of Florida and NASA Langley.
6. Propulsion system and orbit maneuver integration into CubeSats. Partners: Western Michigan University and JPL.
7. Compressive sensing for Advanced Imaging and Navigation. Partners: Texas A&M and NASA Langley.

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[*] http://www.nasa.gov/sites/default/files/files/SSTP_Partnerships_Program_Fact_Sheet.pdf

Formation-relevant RPOD Technology Maturation

Autonomous RPOD technology developments, which have many engineering and technology links to scientific formation flying, continued to grow and thrive, despite the 2003–2010 formation flying collapse, as these technologies are necessary for ISS crew and cargo resupply, exploration beyond LEO and satellite servicing. These efforts have helped mature several technologies necessary for future flying missions, including spaceborne GPS navigation, optical sensor developments, algorithm and software development, and crosslink capabilities.

The 2005 AFRL XSS-11 (eXperimental Small Satellite) (see Figure 3)[*] and the 2007 DARPA/NASA Orbital Express (see Figure 4)[†] technology demonstration missions, successfully performed autonomous rendezvous, proximity operations and docking maneuvers. Since then, RPOD has become an operational capability on ISS cargo carriers including the European ATV, the Japanese HTV and the U.S. commercial cargo vehicles Dragon and Cygnus. RPOD technologies are also crucial capabilities for satellite servicing and repair. Satellite servicing/life extension initiatives, such as the DARPA Phoenix Program[‡], started in 2012, and the multiple NASA Goddard Satellite Servicing initiatives[15], and commercial initiatives, such as ViviSat[§], benefit from and provide support to autonomous ARPOD technology development.

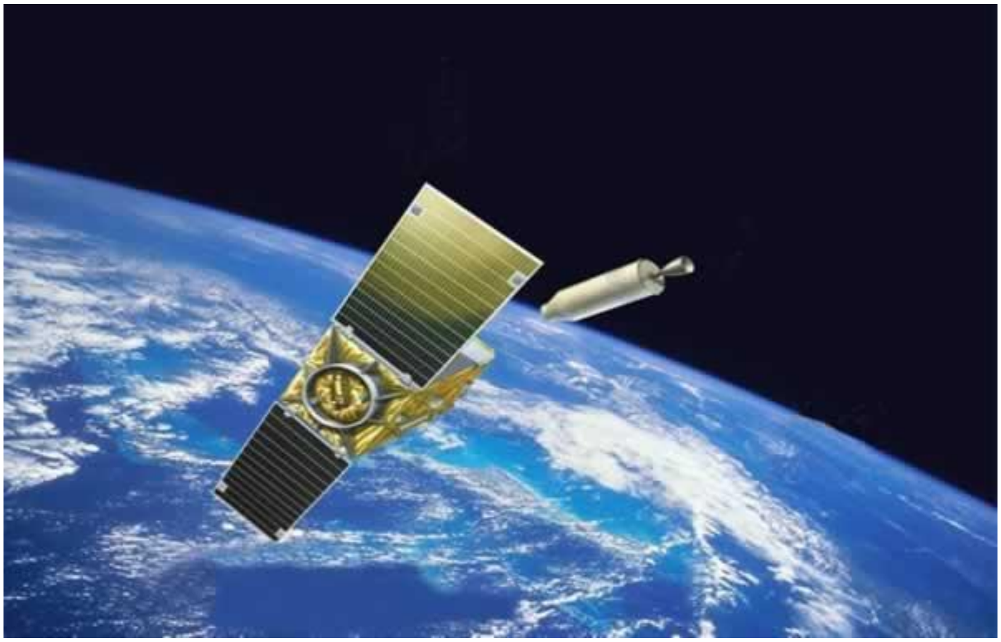

Figure 3. XSS-11 Spacecraft Approaching the Upper Stage of its Minotaur Launch Vehicle (Courtesy United States Air Force (USAF)/AFRL).

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[*] USAF/AFRL XSS-11 Micro-Satellite Fact Sheet, http://www.kirtland.af.mil/shared/media/document/AFD-070404-108.pdf

[†] DARPA/TTO Orbital Express archived web site, http://archive.darpa.mil/orbitalexpress/index.html

[‡] DARPA Phoenix Program, http://www.darpa.mil/our_work/tto/programs/phoenix.aspx

[§] http://www.vivisat.com/

Figure 4. Orbital Express RPOD Activity (Courtesy USAF/AFRL).

MIT/SSL SPHERES FORMATION FLIGHT TESTBED

Recognizing the need for a flexible and low cost laboratory environment for testing of formation flight and docking algorithms the MIT Space Systems Laboratory (SSL) developed the SPHERES (Synchronized Position Hold Engage Re-orient Experimental Satellites) testbed for both NASA and DARPA for the development and maturation of spacecraft formation flight and docking algorithms[16]. SPHERES has been successfully flying onboard the ISS in a shirt-sleeve environment for several years conducting verifications testing of formation flight algorithms in a flight-like environment (see Figure 5). The SPHERES program was specifically designed to develop a wide range of algorithms in support of formation flight systems. Specifically, SPHERES allows the incremental development of metrology, control, autonomy, artificial intelligence, and communications algorithms. The SPHERES testbed consists of two segments. The first is a three self-contained spacecraft testbed onboard the ISS that provides long duration, replenishable, and easily reconfigurable platform with representative zero gravity dynamics. The second is a laptop control station.

Figure 5. The MIT SSL SPHERES Spacecraft.

To produce results traceable to proposed formation flying mission architectures, the individual self-contained SPHERES vehicles have the ability to maneuver in 6-DOF, to communicate with each other and with the laptop control station, and to identify their individual position with respect to each other (as well as the experiment reference frame) using a a customized metrology system.

SPHERES exhibits a wide array of attributes in order to achieve this: 1) facilitate the iterative research process, 2) support experiments, 3) support multiple scientists, and 4) enable reconfiguration and modularity. The effectiveness of these aspects of the facility have been demonstrated by several programs including development of system-identification routines, coarse-formation flight control algorithms, and demonstration of tethered systems. Through the SPHERES testbed, the MIT SSL has successfully demonstrated key maneuvers for, among other applications, the separated spacecraft interferometer version of the Terrestrial Planet Finder mission. These demonstrations were performed using relatively simple estimation and proportional-direct controller schemes.

ESA Technology Demonstrations

ESA, and its national space agency partners, has invested in one formation mission that has flown and a second under construction. These missions, when completed, will remove significant risk in science investigations using two spacecraft flying in formation.

The Prototype Research Instruments and Space Mission technology Advancement (PRISMA) mission[17,18] was the first comprehensive European technology demonstration of formation flying and RPOD techniques. PRISMA was launched in June 2010. From September 2010 to March 2011, the PRISMA spacecraft Mango and Tango successfully executed a series of 22 on-orbit test scenarios to validate autonomous one-way formation flying, i.e. between the 150-kg fully maneuverable Mango spacecraft and the 40-kg minimally capable 3-axis stabilized Tango target spacecraft (see Figure 6). Real-time relative navigation sensing was accomplished with accuracies better than 10 cm and 1 mm/sec (3D root mean squared) in position and velocity respectively. Navigation sensing was performed with a Phoenix-S GPS receiver from the German Aerospace Center (DLR/GSOC). A crosslink communication system between Mango and Tango was devised using an ultra high frequency link to communicate relative and absolute navigation data back to the Mango spacecraft. These data were utilized in an autonomous navigation feedback algorithm, to enable closed-loop trajectory control between the prime vehicle and the target. This “one-way” autonomous formation demonstration successfully validated many scenarios planned for future science missions. In one series of tests, Mango was commanded to point (stare) at Tango during a series of trajectory maneuvers, illustrating the abilities to support combined attitude/navigation maneuvers autonomously. PRISMA was an outstanding, comprehensive opportunity to validate many aspects of formation flying that are a necessary risk mitigator for future science missions.

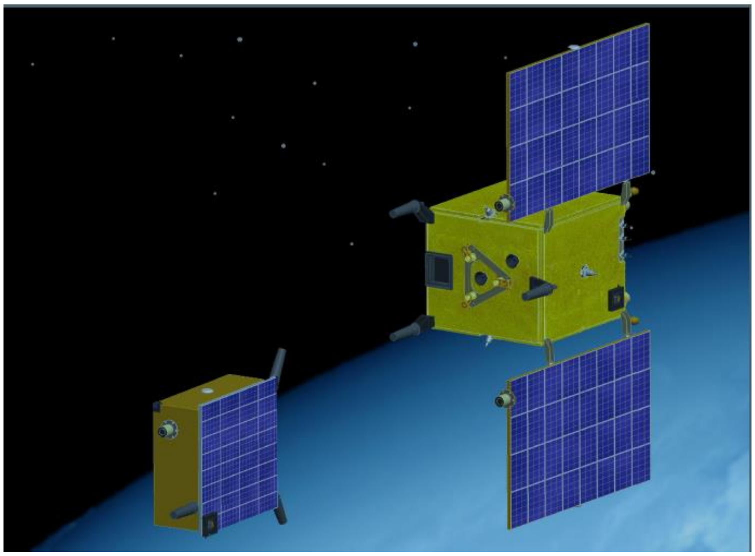

Figure 6. PRISMA Mango (R) and Tango (L) Formation Flying Spacecraft.

The Project for On-Board Autonomy-3 (PROBA) is the third small satellite technology development and demonstration precursor mission within ESA's GSTP (General Support Technology Program) series. It is a combined science and technology demonstration mission, and is expected to be the world's first precision formation flying mission[*]. The two satellites will enable detailed observation of the Sun's corona, a million times fainter than the Sun itself. This will be accomplished by performing precise, combined relative navigation and bearing control of the two PROBA spacecraft. One of the spacecraft will serve as coronagraph, taking detailed scientific measurements of the Sun's corona, and the other will include a spherical shield attached to serve as a Sun occulter. When the two spacecraft are at the precise relative position and orientation with respect to the Sun, the occulter will eclipse the Sun's surface, providing an unprecedented view of the Sun's corona. Launch is currently planned for 2018 into a 600- by 60,000-km orbit. GN&C on each of the vehicles include reaction wheels, star trackers, gyros, Sun sensors, and GPS receivers. The two vehicles will fly 150 meters apart with the 340-kg chronograph lined up with the 200-kg occulter as shown in Figure 7. Formation control will be conducted through an s-band crosslink.

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[*] http://esamultimedia.esa.int/docs/Proba/Proba-3_fact-sheet_final.pdf

Figure 7. PROBA-3 Spacecraft Aligned to Block Sun Surface Light.

Space commercialization and space access initiatives

NASA’s commercialization effort to resupply ISS cargo and crew initiatives have made access to space much easier and cheaper for small satellites. New commercial launch vehicles, such as the SpaceX Falcon 9 and Orbital Cygnus, have augmented the launch vehicle stable, providing more space access supply at a lower price point. Also, in the past 5 years, NASA has opened up launch vehicle access to small satellites, particularly CubeSats, to fly on a large spectrum of launch vehicle missions, including NASA and DoD missions. As a result, frequent, low-cost opportunities to validate formation flying systems is now achievable.

DARPA System F6

In 2011, DARPA initiated a comprehensive cluster flight technology development and validation efforts called System F6 (Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft United by Information Exchange). The primary goal of System F6 was to demonstrate the feasibility and benefits of disaggregated, or fractionated, space architectures. The F6 vision was nearly identical to the formation flying capabilities and roadmaps, in that F6 planned to break apart a large, monolithic satellite architecture into a cluster of crosslink connected vehicles capable of sharing their resources and utilizing resources found elsewhere in the cluster. DARPA’s goals were to develop a systems architecture that allows one to add or remove vehicles from the cluster, to share resources (e.g., data, computational throughput, and sensor information) across the cluster, autonomously configure and reconfigure the cluster to maintain mission safety and to perform mission functions, and to support defensive scatter, re-gather maneuvers to protect the cluster from debris-like events. The technologies and validation required to perform F6 very closely envelopes the formation flying roadmap (see Figure 1 and Table 1). The prime difference is that precise relative attitude/bearing control was not a requirement for System F6.

Unfortunately, System F6 was seriously descoped in May 2013, eliminating the flight demonstration and many of the cluster flight technologies. However, the Cluster Flight Application (CFA), which represents the autonomous cluster flight algorithms and software, which were under development by Emergent Space Technologies, continued development through to completion in July 2014.[19] CFA provides clusters the autonomous GN&C and formation flying services needed to perform relative and absolute navigation sensing and control within clusters of size 2–20, enabling them to safely fly missions in close proximity (or in formation) of one another. Figure 8 outlines the F6 CFA capabilities.

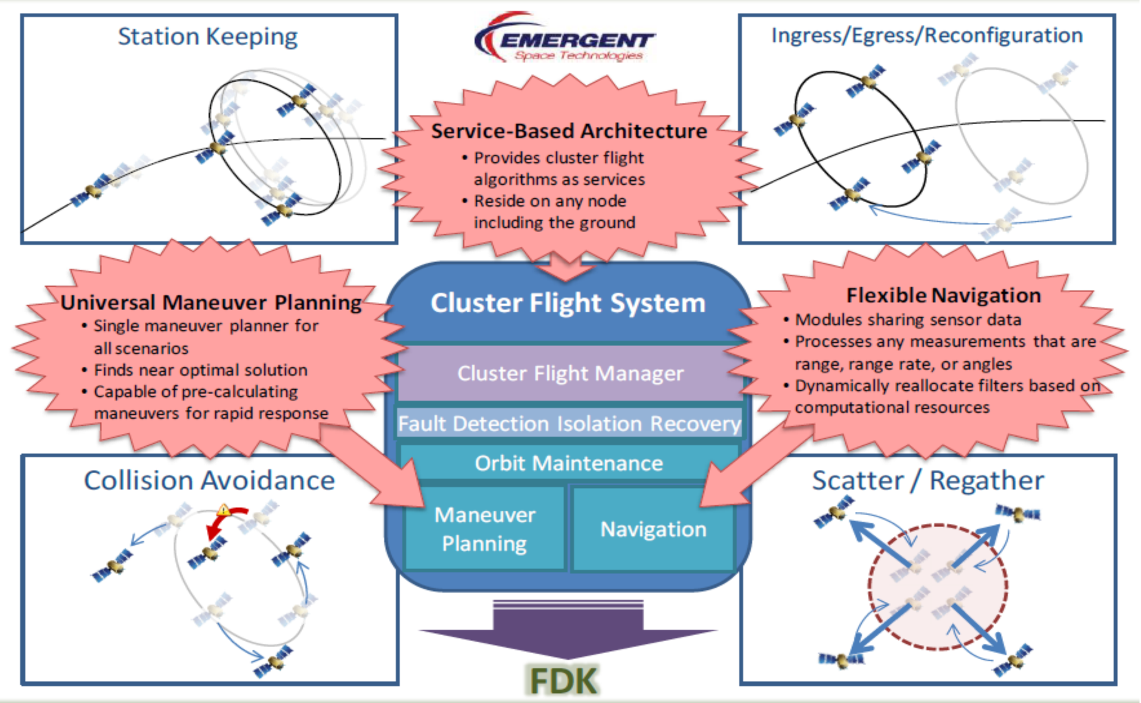


Figure 8. DARPA System F6 CFA Overview (Courtesy of Emergent Space Technologies).

The algorithms and software developed for System F6 represents a substantial leap in the roadmap's Formation Control focus area (Table 1). The algorithms and software modules from F6 can be utilized and exploited by a wide variety of future formation flying missions. Moreover, this software is being made available to outside parties by DARPA as part of the F6 Developers Kit.

2030: A PROMISING FUTURE FOR THE FORMATION FLYING VISION?

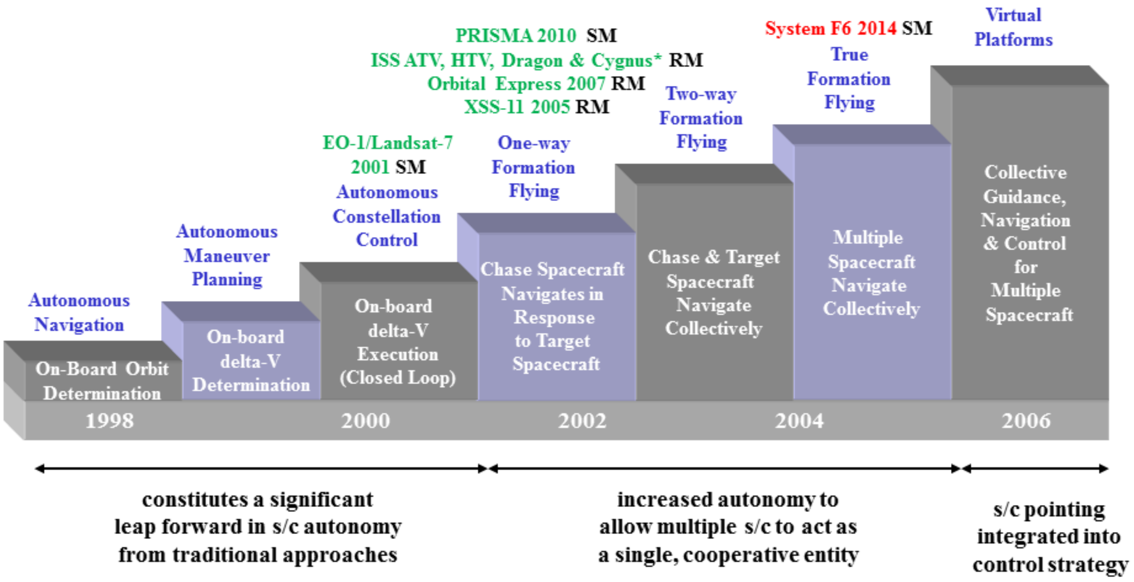
Despite the 2003–2010 collapse of formation flying technology support, some efforts continued in the U.S. and internationally. As a result, several technology products, described in Table 1, have been developed and validated. And several of the validation "stairsteps" illustrated in Figure 1 have been partially or fully conquered.

Referring back to Table 1—the Formation Flying Technology Focus areas—many of the focus area products have been developed or validated. Some of the key technology priorities that still need development include:

- Development of several RF and laser-based crosslink systems and a comprehensive crosslink data standard to support the widely varying requirements of different engineering and scientific missions. These systems should be able to support the transfer of engineering (low-rate) and scientific (high-rate) data across the formation.
- Development of unified navigation and attitude formation control algorithms and software, using the System F6 CFA as the navigation starting base.

- Development of the 3rd-generation spaceborne GNSS receiver which includes multiple, interoperable GNSS signals and circuit miniaturization.
- Development of a new formation flying on-orbit validation plan. This plan will methodically "climb the stairsteps" up to virtual platforms. Final demonstrations will include precise, unified attitude/navigation control of multiple spacecraft in a virtual platform. Precision to 5 nano-radians relative attitude and cm relative navigation control is expected in the most precise demonstrations. These will ultimately support planet finder missions.

Figure 9 depicts the current status of the formation flying roadmap "stairstep" chart, with successful on-orbit formation validation missions shown in green and developments without on-orbit validations in red. As shown, several missions, including PRISMA and numerous RPOD missions, have demonstrated one-way formation flying techniques. However, no missions thus far have demonstrated two-way formation flying, where both the chase and target vehicles maneuver collectively. Algorithms and software are available from System F6 to perform two-way and true formation flying, where multiple spacecraft navigate collectively. However, this capability has not been demonstrated on-orbit—thus, the red color on Figure 9.



Key: SM—Science Mission Capabilities
RM—Rendezvous, Proximity Operations and Docking (RPOD) Mission Capabilities
Completed on-orbit validation or operations; systems developed but not validated on-orbit
*2008-present

Figure 9: Current Status of the Formation Flying Roadmap "Stairsteps."

FORMATION FLYING IN THE OFFICE OF CHIEF TECHNOLOGIST SPACE TECHNOLOGY ROADMAPS

There are a number of NASA SMD science concept missions, "push" missions primarily, that require formation flying technology. According to one of NASA's Office of the Chief Technologist (OCT) Space Technology roadmaps[*], aside from near-term, mission-specific technology al-

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[*] "Science Instruments, Observatories, and Sensor Systems Road map, Technology Area 08 (TA-08)", http://www.nasa.gov/sites/default/files/501624main_TA08-ID_rev5_NRC_wTASR.pdf

ready under development, the NASA Science Mission Directorate (SMD) astrophysics science area requires additional advancements in several areas including “Multi-spacecraft formation flying, navigation, and control” and technologies for “Precision pointing and formation-flying navigation control (i.e., micro-Newton thrusters, etc.)”. Multi-spacecraft formation flying is a long-term technology challenge goal cited in the referenced TA-08 (Technical Area-08) Science Instruments, Observatories, and Sensor Systems (SIOSS) roadmap to be accomplished by 2023 which is only 8 years from now. The specific technology objectives are the alignment and positioning of 20 to 50 spacecraft distributed over 10s (to 1000s) of kilometers to nanometer precision with milli-arc second pointing knowledge and stability. The SIOSS roadmap identifies the New Worlds Terrestrial Probe Astrophysics ‘push’ mission concept as being reliant on formation flying for positioning/pointing as does the Heliophysics Origin of Near Earth Plasma push mission concept. Distributed aperture formation flying is specifically cited in the SIOSS roadmap as an enabling observatory technology needed to satisfy planned and potential several future NASA missions.

Furthermore, a second OCT Space Technology Roadmap which addressed NASA’s future Positioning, Navigation and Timing (PNT) technology needs[*] has identified the need for increased precision in relative navigation solutions, a major PNT challenge area. This was based upon the viewpoint that future missions will require on-board autonomous navigation and maneuvering system capabilities for precision landing, rendezvous, formation flying, cooperative robotics, proximity operations (e.g., servicing), and coordinated platform operations. The referenced TA-05 Communications and Navigation roadmap also identifies the need for relative and proximity navigation sensors and associated algorithms. The capability to perform multi-platform relative navigation (i.e., determine relative position, relative velocity and relative attitude/pose) directly supports cooperative and collaborative space platform operations. There is a cross-cutting mission ‘pull’, from both the envisioned human exploration missions and the robotic science missions, for relative navigation technologies to enable multi-spacecraft formation flight as well as autonomous RPOD (or landing).

A third OCT Space Technology roadmap[†], which focuses on the area of robotics, tele-robotics and autonomous systems, emphasizes the NASA’s technological need for space assets to autonomously rendezvous and operate in close proximity. The roadmap states this is a ”fundamental enabler” for numerous classes of NASA’s missions, and is an “essential capability” for NASA’s future. During the course of RPOD, varying accuracies of bearing, range, and relative attitude are needed for autonomous rendezvous and docking (AR&D). Therefore it is not surprising that, similar to the TA-05 roadmap, the referenced TA-04 roadmap identifies the need to develop relative navigation sensors (long-, mid-, and near-range) as well the associated guidance algorithms. The TA-04 roadmap also calls for development of integrated communications technologies. Current commercial implementations for optical, laser, and RF systems (and combinations of these) are mid-TRL (Technology Readiness Level) and require additional flight experience to gain reliability and operational confidence. Moreover, integrated communication capability (at mid-field to near-field range) greatly enhances the responsiveness and robustness of the AR&D GN&C system, along with its portability.

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[*] “Communications and Navigation Roadmap, Technology Area 05 (TA-05)”, http://www.nasa.gov/sites/default/files/501623main_TA05-ID_rev6_NRC_wTASR.pdf

[†] “Robotics, Tele-Robotics and Autonomous Systems Roadmap, Technology Area 04 (TA-04)”, http://www.nasa.gov/sites/default/files/501622main_TA04-ID_rev6b_NRC_wTASR.pdf

The fact that the OCT Space Technology roadmaps mentioned above recognize, and in some places emphasize, the need for the renewed push to develop formation flying and related GN&C technologies is a positive step forward.

ADVANCED MISSION CONCEPTS REQUIRING FORMATION FLYING TECHNOLOGY

Formation flying science mission concepts are actively being studied and the required mission-unique technology development plans are being formulated. One such space-based direct imaging mission to ultimately find and characterize other Earths is intended to address a long-term priority for space astrophysics as per their most recent decadal survey[20]. The Exo-Starshade (Exo-S) Science and Technology Definition Team (STDT) is tasked by NASA SMD to study the starshade-telescope mission concept under the “Probe” class of space missions, with a total cost of less than $1B (FY15 dollars). Figure 10 from the STDT’s Interim Report[21] illustrates the Exo-S Starshade Probe-Class exoplanet direct imaging mission concept employing an external starshade occulter and telecope operating in formation flight. The starshade is designed to produce a dark shadow that extends radially 1 m beyond the telescope aperture. Contrast degrades rapidly beyond the 1-m specification so formation control is required to keep the starshade center positioned laterally within ±1 m of the telescope boresight. This requires sensing the sunshade lateral position with 3-sigma accuracy better than ±20 cm, relative to the telescope boresight which is pointed at the target star. In the view of the Exo-S STDT, the overall formation flying design is a challenging engineering problem that warrants further study in pre-Phase A. As described in Reference 21, formation flying precision is required to keep the telescope positioned within the dark shadow created by the starshade (lateral tolerance ≤1 m) and the separation distance within the range consistent with the optical bandpass (line of sight tolerance ≤250 km). Separation distances between the telescope and starshade can be as large as 10s of 1000s of kilometers.

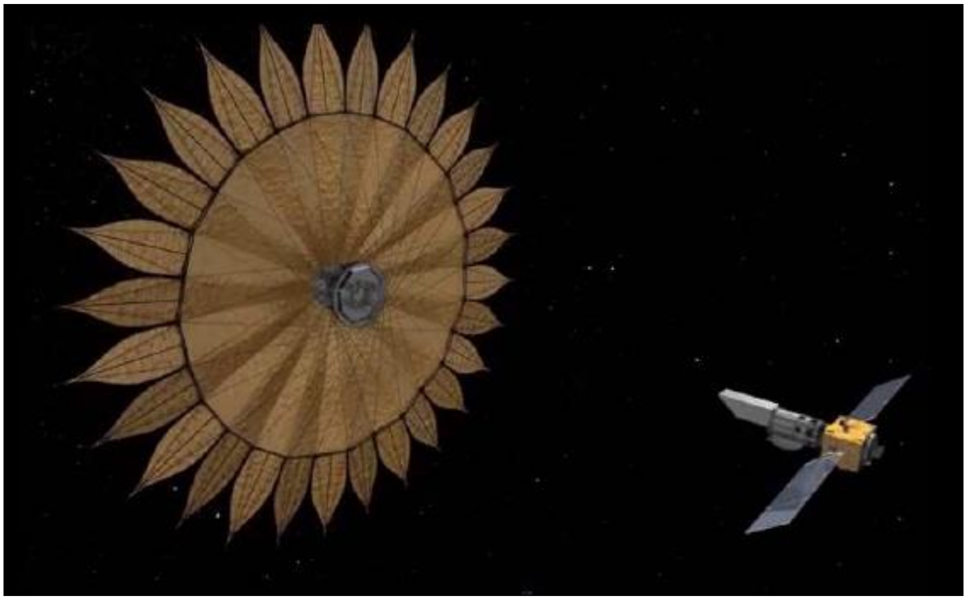

Figure 10. External Occulter and Telecope in Formation Flight for Exo-SProbe-Class Eoplanet Direct Imaging Mission.

The separation distance specification is very loosely controlled to within ±250 km and the distance is not actively controlled during science observations in formation flight. In this Exo-S proposed formation flying system architecture, position corrections would be applied as part of the observatory's periodic retargeting maneuvers. Mitigating the lateral control challenge are the very low environmental disturbance forces afforded by the choice of an Earth-leading heliocentric orbit for this mission. The low-disturbance environment in this Earth-leading orbit is such that the axial position between the starshade and the telescope can drift for weeks at a time without correction. In this proposed architecture, an S-band RF link is maintained between the two spacecraft for both communications and the measurement of separation distance, via two-way ranging.

The primary formation flying challenge therefore is one accurately sensing the lateral starshade-to-telescope relative position and this has been identified as an "unresolved technology issue" for the Exo-S mission concept. Accordingly, the STDT has laid out a comprehensive formation flying technology development plan for demonstrating this relative sensing capability. This sensing challenge appears to be tractable with manageable development risk. This is primarily because the formation sensor can utilize the relatively large science telescope with its Fine Guidance Camera (FGC). The telescope's FGS would simultaneously image both the starshade laser beacon and the target star. It is expected that onboard image processing algorithms, using a model of starshade diffraction properties, would then be employed to estimate centroid positions with 3-sigma accuracy better than 0.3% of optical resolution.

The STDT has formulated a Technology Development for Exoplanet Missions activity focused on developing the system design for formation flying and prototype algorithms for formation sensing, as discussed, in addition to trajectory estimator and formation control algorithms. Early simulations will demonstrate performance and assist in exploring optimal (in propellant usage terms) formation control and acquisition strategies.

CONCLUSIONS

This paper has provided a retrospective analysis and critique of two late 1990s technology roadmaps which predicted a bright future for the GN&C technologies of multi-spacecraft formation flying and the spaceborne use and exploitation of GPS signals to enable formation flying. While some significant progress was attained in these two related technology areas, especially in spaceborne GPS and AR&D, the optimistically inclined visions portrayed in the two late 1990s roadmaps were not fulfilled. The envisioned formation flying dream has yet to become a reality but is perhaps now at the verge of a breakthrough. Several reasons causing that promise to be mostly unfulfilled were discussed and relevant technology trends over the past several years were identified.

Cautious optimism, from a now reality-tempered perspective, for the future of formation flying is justified. After years of diminished attention and investment there appears to be a renewed government interest, both by NASA and the DoD, in spacecraft formation flying/cluster flight. It is encouraging to note (see Figure 9) that a number of the roadmap stairsteps have been accomplished. Formations of spacecraft flying in loosely controlled formations have been accomplished. Autonomous constellation control has been demonstrated on-orbit, as has the capability of a chaser spacecraft to navigate and maneuver relative to a target spacecraft.

There is considerable work to go to move further up the roadmap staircase. True two-way formation flying of two spacecraft, where the chaser and the target spacecraft navigate and maneuver in a collaborative manner, is yet to be demonstrated on-orbit. That objective represents a significant GN&C challenge. Most likely the ESA PROBA-3 mission, in which a coronagraph spacecraft and an occulter spacecraft fly in a science-collecting tandem, will be the first precision formation flying technology demonstration mission in late 2018. NASA's future investments in formation flying technologies will be governed both by the push of the OCT space technology roadmaps and the pull of the science community.

Within NASA, and the GN&C community of practice at large, there is a need to understand and examine the formation flying 'big picture' in a level of detail far beyond what was covered in this short paper. Performing an updated assessment of the formation flying technology state of the art along with an associated gap analysis would be a good first step to take. Coordinating and integrating the various on-going formation flying and AR&D government and commercial technology development activities via a new roadmap would be a logical subsequent step. Performing a NASA technology formation flying demonstration mission, along the lines of the proposed 2006 NMP ST-9 mission, is perhaps what is most needed to reduce the engineering risks, as perceived by the science community, of basing a mission on this technology.

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NOTATION

AFRL	Air Force Research Laboratory
APL	Applied Physics Laboratory
AR&D	Automated Rendezvous and Docking
ATV	Automated Transfer Vehicle
CETDP	Cross Enterprise Technology Development Program
CFA	Cluster Flight Application
CMG	Control Moment Gyroscope
COMSAT	Communications Satellite
CPDO	CubeSat Proximity Operations Demonstration
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DOF	Degrees of Freedom
DS	Deep Space
EO-1	Earth Observing 1
EOS	Earth Observing System
ESA	European Space Agency
Exo-S	Exo-Starshade
FGC	Fine Guidance Camera
FO	Fiber Optic
GADACS	GPS Attitude Determination and Control Experiment
GADFLY	GPS Attitude Determination Flyer

GANE	GPS Attitude and Navigation Experiment
GEO	Geostationary Earth Orbit
GLONASS	Globalnaya navigatsionnaya sputnikovaya sistema (Global Navigation Satellite System)
GN&C	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GSTP	General Support Technology Program
H/W	Hardware
HEO	High Earth Orbit
HTV	H-II Transfer Vehicle
ICG	International Committee on GNSS
IMU	Inertial Measurement Unit
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LEO	Low Earth Orbit
MIT	Massachusetts Institute of Technology
MMS	Magnetospheric Multiscale
NMP	New Millennium Program
NRL	Naval Research Laboratory
OCSD	CubeSat Proximity Operations Demonstration
OCT	Office of the Chief Technologist
PFF	Precision Formation Flyer
PNT	Positioning, Navigation and Timing
POES	Polar Operational Environmental Satellite
PRISMA	Prototype Research Instruments and Space Mission technology Advancement
PROBA	Project for On-Board Autonomy
REX	Regolith Explorer
RF	Radio Frequency
RPOD	Rendezvous, Proximity Operations and Docking
RTOP	Research and Technology Operating Plan
S/W	Software
SAC	Satélite de Aplicaciones Científicas (Scientific Applications Satellite)
SIOSS	Science Instruments, Observatories, and Sensor Systems
SMD	Science Mission Directorate
SMEX/MIDEX	Small Explorers/Medium-Class Explorers
SPA	Space Products and Applications

SPHERES	Synchronized Position Hold Engage Re-orient Experimental Satellites
SSL	Space Systems Laboratory
SSTI	Small Spacecraft Technology Initiative
SSTL	Surrey Satellite Technology Ltd
ST	Space Technology
STDT	Science and Technology Definition Team
STMD	Space Technology Mission Directorate
STS	Space Transportation System
SWaP	Size, Weight and Power
TA	Technical Area
TDRSS	Tracking and Data Relay Satellite System
TX/RX	Transmit/Receive
UCLA	University of California Los Angeles
USAF	United States Air Force
WAAS	Wide Area Augmentation System
XSS	eXperimental Small Satellite

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