modeling and simulation, attitude coordination, formation geometry, autonomous formation reconfiguration, time constraints, fuel efficiency, optimal maneuvers and collision avoidance.

Figure 1: Earth orbiting formation flying spacecraft interacting with one another for co-observations.

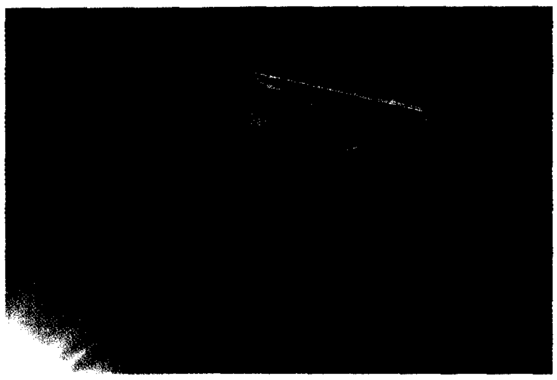

Figure 2: The Terrestrial Planet Finder.

2 - PRECISION GUIDANCE AND CONTROL

Precision formation flying requires having an accurate knowledge of relative spacecraft-to-spacecraft position (range), and orientation (bearing), beyond the traditional need for inertial attitude knowledge of each spacecraft in the formation. The challenge to the spacecraft formation is ultimately to achieve and then maintain a stable geometrical configuration (a virtual structure) desirable for a particular mission application. Precision relative position and orientation control is required to be consistent with the mission goals in order to ensure the necessary virtual structure rigidity and stability for observations. In the case of interferometric imaging of a target light source, the formation must undergo a sequence of maneuvers that correspond to a sequence of light collecting stops. At each stop, the entire formation must pose and collect light from a specified inertial science target. During the collection process, the inter-spacecraft range(s) and bearing(s) must be precisely controlled within tight errors bounds, on the order of nanometers for space interferometers. This level of performance is accomplished through stages of control including micro-thrusters on the spacecraft, optical delay elements and mirror actuations.

The detection of earth like planets is currently beyond our technology capabilities. The TPF mission is designed to detect and study earth like planets in other solar systems. One of the candidate architectures for the TPF mission is based on a separated spacecraft interferometric nulling approach to remove the dominant light source of the central star thus rendering the orbiting planets detectable. This separated spacecraft interferometer approach will utilize multiple free flying spacecraft as collecting apertures relaying the collected light to a central combiner spacecraft – all precisely coordinating and controlling their individual and collective motion to form a stable virtual space observation platform. Unprecedented angular resolution and image quality of science targets are enabled using stable separated spacecraft apertures.

A number of critical FF technologies are required to enable separated spacecraft FF based mission architectures. These include:

1. **Robust, fault tolerant and scaleable formation architectures** for distributed spacecraft communication, control, and sensing.
2. **Formation autonomy.**
3. A new class of **formation guidance, estimation and control algorithms**.
4. **Relative sensor technology** to provide the inter-spacecraft range and bearing measurement.
5. **Precision actuator technology** to enable fine motion (both inertial and relative) control of each spacecraft in the formation.
6. **Ground and flight demonstration testbeds** to integrate and bring these technology elements to a level of maturity for infusion into future missions.

2.1 Robust, Fault Tolerant and Scalable Formation Architecture

Due to the very nature of the distributed system, any suitable FF architecture needs to support a flexible, scalable, and robust sensing, communication and control capability. The ability to dynamically reconfigure the sensing, information flow and control connectivity across each spacecraft in the formation is a key architectural feature. To provide on-board robustness, especially in case of fault conditions, formation and attitude control system algorithms can be designed to circumvent at least a limited number of identified actuator (e.g. thruster/reaction wheel) faults autonomously without any ground intervention. With proximity operations at ranges of few tens of meters, this capability is increasingly important to avoid unnecessary ground-in-the-loop delays and to minimize the chances of collisions due to residual uncontrolled drifts after an on-board (recoverable) failure.

Additionally, it is desirable to provide graceful degradation of performance and functionality within the given on-board hardware redundancy. The formation flying architecture must allow for stand-alone operation in case of inter-spacecraft communication and/or formation sensor faults. Additionally, maximum possible use of analytical redundancy with the control architecture needs to be in place to retain functional capabilities (if not performance) even in the face of limited hardware failures. Such analytical redundancy can be utilized, e.g., to autonomously implement translation maneuvers under a limited set of thruster failures by a combination of a rotation and a translation maneuver using the remaining set of thrusters.

2.2 Formation Autonomy

Considering the in-flight proximity and round trip communication delay of deep space missions, FF missions can only be operated as autonomous coordinated teams with minimal or no involvement from the ground. As a result the on-board software needs to autonomously provide formation as well as individual spacecraft guidance, estimation, and control functions within the framework of high level reasoning and commanding to achieve the desired science goals in a resource efficient manner.

Generalized reasoning capability through advanced distributed software technology and artificial intelligence has the potential to cope with unexpected events and uncertainty and allow closing the loop of perception, decision making and eventually deliberation, on board [Mand 00]. Each spacecraft in a formation may play different interchangeable roles (beyond the on-board science imposed mission system architecture) with a high degree of autonomy and support for coordination among themselves to achieve a common goal. The software supporting these capabilities has to fulfill requirements for distributed systems as well as being reactive or event-driven. The basic system may consist of a collection of distributed software agents that communicate and cooperate with each other to support autonomous decision-making. One of the key elements is the agent's high level of communication capabilities that allows formulating tasks at a generic level. Another important feature will be the capability of effectively distributing computations across platforms and processors, with consideration for both time delays and the non-homogenous nature of the computational platform

2.3 Formation Guidance, Estimation and Control Algorithms

A new set of critical requirements is emerging out of the distributed spacecraft based mission architecture that go far beyond traditional single spacecraft attitude guidance and control. By its very nature distributed spacecraft missions (Especially the deep space science missions.) require:

1. The capability of robust lost-in-space acquisition, i.e. the ability to obtain lock of the relative sensors to initialize the formation after initial deployment or after reset/recovery events.

2. Collision free operation.
3. Consumable resource balancing across all spacecraft.
4. Path planning in both attitude and translation under multiple constraints (e.g. solar, thermal, glint, H/W capability).
5. Precision hierarchical control coordinated across multiple spacecraft.
6. Observation-on-the-fly capability to enable continuous science measurements during formation maneuvers.

For interferometer missions, these functional requirements also take on the added dimension of tight performance limits to satisfy optical tolerances. On the other hand, formation acquisition requires a full 4-pi steradian acquisition range thereby driving the knowledge and control dynamic range requirements to unprecedented levels.

2.4 Relative Sensor Technology

The deep space operating environment, although more quiescient in terms of environmental (orbital) disturbances levels, lacks the benefits of Earth orbiting GPS network and mission serviceability, thus requiring not only a high degree of robustness/fault tolerance, but also on-board relative sensing capability.

A key technology enabling the formation flying mission architecture is to have relative position (range) and orientation (bearing) knowledge among all the spacecraft in the formation. This knowledge of range and bearing ("range vector") between each pair of spacecraft is essential in configuring the overall formation to achieve a desired baseline, and maintaining the baseline within a prescribed tolerance during the course of the science observation. Collision avoidance is another key formation flying requirement enabled by formation sensor based relative range vector knowledge.

To ensure formation acquisition from a lost-in-space condition imposes a full sky coverage requirement, while formation science observation imposes stringent formation knowledge accuracy requirements for the formation sensor. To accommodate such wide dynamic range requirements both in accuracy and field of view, a multi-stage approach is being considered for TPF with a wide field-of-view (FOV) but low accuracy coarse sensing stage, followed by a small FOV high accuracy fine sensing stage. The high accuracy stage is ultimately used to provide the highest requisite accuracy to achieve fringe lock, albeit with a very narrow FOV. Due to the very nature of the wide dynamic range requirements, a combination of RF and optical sensor choices needs to be considered.

2.5 Precision Actuator Technology

Precision actuator technology to enable fine motion (both inertial and relative) control of each of the spacecraft in formation is one of the required key technologies for the distributed spacecraft based interferometry missions. The speed dependent wide band harmonic disturbances emitted by reaction wheels make them less attractive for space science missions, though their presence and selective use in conjunction with propulsive system provides a level of system robustness and flexibility. In order to maximize science returns, especially for cryogenic missions, it is necessary to carry a coarse actuation system for gross retargeting maneuvers and a precision actuation system to enable stable and accurate science pointing and tracking.

There exists a wide selection of traditional propulsion technologies for the coarse stage; however, new developments are needed to provide precision actuation capabilities for formation flying missions. Aside from enabling precision formation control, one potential payoff of precision actuation technology for separated spacecraft interferometer is possible elimination of one or more range/bearing articulation stages which are currently required to compensate for the effect of spacecraft deadbands on science observations.

Some of these precision actuation technologies are already under development [Muel 02] [Hrub 01] [Pran 01].

2.6 Ground and Flight Demonstration Testbeds

Ground demonstration testbeds are critically needed to mitigate technology risk by integrating and demonstrating formation flying technology elements at a mature enough level suitable for flight demonstration and further infusion into future missions.

2.6.1 Ground Testbeds

Testbeds play an important role in the development of formation flying technologies and mitigation of risk associated with space deployment. They provide a framework within which novel guidance, control, and estimation algorithms can be validated. Aircraft, spacecraft, and vehicle formations have provided the motivation for the development of these testbeds. One of the earliest formation flying testbeds, developed at the MIT Space Sciences Lab, used blimps to demonstrate that carrier-phase differential GPS could be used as a formation sensor [Olse 98]. Since this early work, GPS type receivers have become accepted as the standard sensing instrument for most formation flying applications. They have been adapted for use on both model helicopters and rover testbeds of various sorts. Future Mars missions have proposed using a Mars based GPS network for autonomous rover navigation. Stanford's Aerospace Robotics Laboratory has a demonstration testbed for rover navigation using an array of ground-based GPS transmitters called pseudolites (pseudo-satellites).

As the number of vehicles increases, coordination issues become exceedingly complex. To investigate these issues BYU has developed a testbed of mobile robots with embedded micro-controllers. A formation control architecture has been proposed using this testbed that is amenable to analysis using traditional control theory [Bear 00].

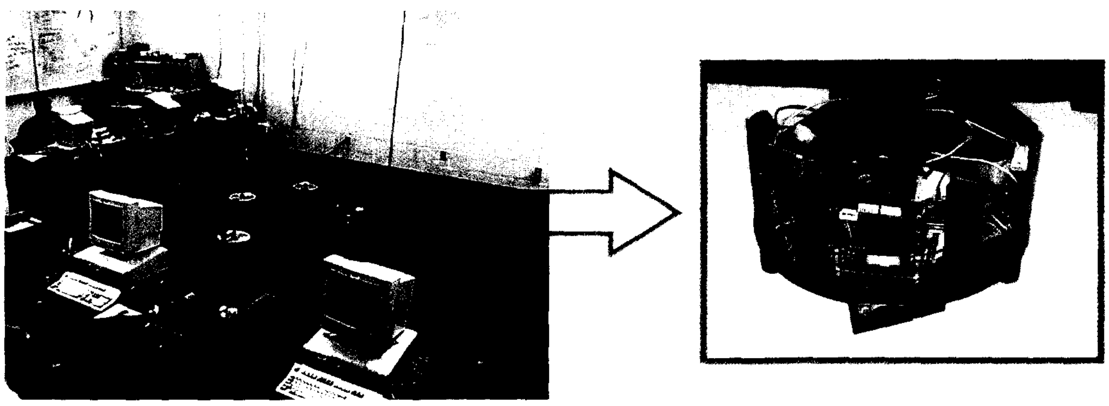

Figure 3: The BYU formation flying testbed.

With future NASA space based observatories as their inspiration, precision formation flying testbeds have been developed using air tables. Fully autonomous robots with navigation and propulsion capabilities have been developed at both UCLA and Stanford [Wang 98] [Cora 98]. These testbeds offer 3 degrees of freedom in a zero g environment and have incorporated metrology-based experiments.

The MIT SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) testbed was developed as a platform with representative dynamics for validation of formation flying algorithms [Oter 02]. SPHERES has been tested aboard the NASA KC-135 reduced gravity aircraft and is intended to transition to the ISS for longer duration tests.

A focused ground testbed is being considering by JPL to demonstrate and validate precision control of a TPF like spacecraft formation in a realistic hardware and dynamics environment. With flight-like functional complexity, this ground testbed will serve as an integrated testing and validation platform for a number of contributing component FF technologies including formation architectures, relative sensors, distributed formation guidance, estimation and control algorithms, and precision actuation.

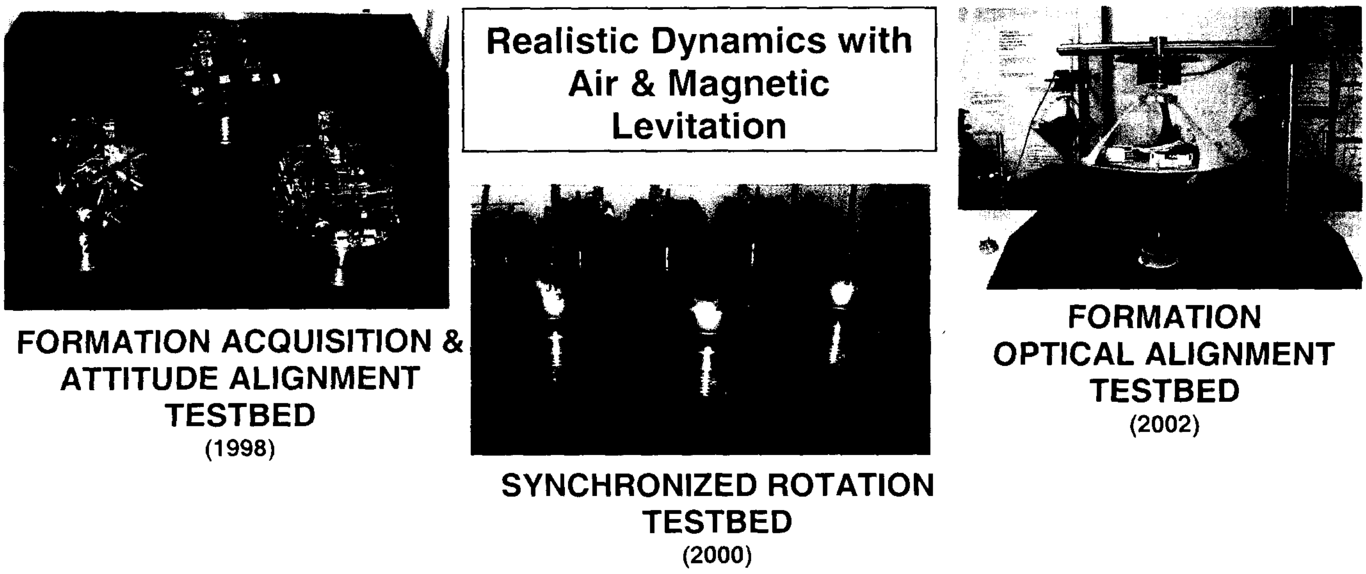

Figure 4: UCLA/JPL formation flying testbeds.

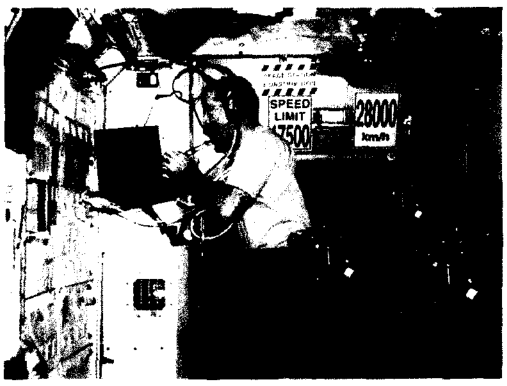

Figure 5: MIT SPHERES in ISS (2003 Flight).

2.6.2 Formation Simulation Testbed

Another alternative to creating a 6 DOF formation flying hardware testbed is to develop a computer simulation of the space environment with high fidelity models for the spacecraft sensors and actuators. The output states of this dynamic simulation can be used for prototyping candidate guidance, navigation, and control algorithms. JPL has developed a formation flying simulation testbed, dubbed FIST (Formation Interferometer Simulation Testbed), with the five spacecraft TPF mission used as the baseline architecture. A novel collision avoidance algorithm based on potential functions has been prototyped using this simulation testbed, for use during formation initialization and reorganization [Sing 01]. Formation estimation and control algorithms have also been developed.

Under a similar formation flying research activity, Goddard Space Flight Center has a similar simulation capability with limited hardware in the loop capability.

2.6.3 Flight Demonstration Testbeds

More recently developed testbeds have progressed outside of the laboratory to space based technology development programs. The nano-satellite program funded by AFOSR and DARPA is a consortium of university partners that will demonstrate miniature bus technologies, formation flying, and distributed satellite capabilities. The EMERALD Project, a cooperation between Stanford and Santa Clara Universities, will demonstrate true two body formation flying using onboard GPS-based relative position sensing, inter-satellite communication, and micro-thrusters for position control. These technologies are applicable to future NASA and ESA interferometry missions such as TPF, LISA, and Darwin where centimeter level position control is required for acquisition of precise astrometric observations.

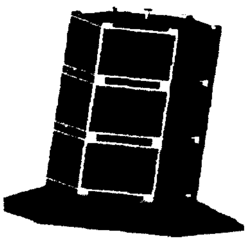

Figure 6: 3-Corner Satellite Constellation

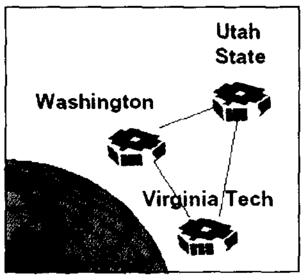

Figure 7: Ionospheric Formation

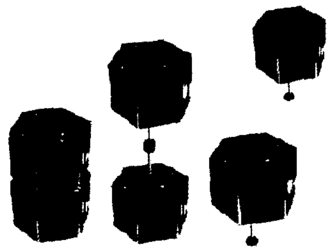

Figure 8: Emerald Spacecraft

The NASA/JPL StarLight and ESA SMART-2 missions are agency funded technology development flight projects. Both of these missions are designed to validate GPS-based formation sensor technology, guidance, thruster control, and ground operations for a formation of two cooperating spacecraft. High precision metrology systems will be used as truth sensors to validate the coarse formation sensor and thruster control system. In addition, interferometry experiments will fly aboard each of these missions. SMART-2 will carry a technology package specifically dedicated to validating an inertial proof mass sensor, which is a key component for the LISA mission. The LISA (Laser Interferometer Space Antenna) mission is a space-based version of the Caltech LIGO (Laser Interferometer Gravity Wave Observatory) interferometer currently under development. These instruments are designed to sense distortions of the space-time continuum between free masses induced by passing gravitational waves.

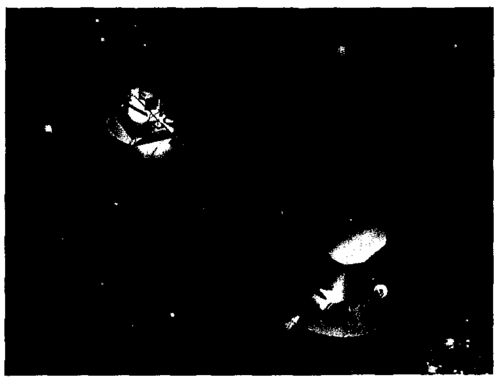

Figure 9: The StarLight formation flying interferometer.

The instrument component of the NASA/JPL StarLight mission will test a fully functional Michelson interferometer with fringe tracking capability. Stellar wavefront tip/tilt and path length between the two spacecraft will be precisely controlled. To enable fringe acquisition of the instrument, the relative attitudes and positions of the two spacecraft formation must be positioned within the dynamic range of the articulated optical components.

3 - ACKNOWLEDGEMENT

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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