SPHERES: a Laboratory for Formation Flight and Docking Research

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Abstract

The MIT Space Systems Laboratory is developing the SPHERES formation flight testbed to provide multiple investigators with a long term, replenishable, and upgradable testbed for the validation of high risk metrology, control, and autonomy technologies. These core technologies enable distributed satellite and docking missions such as TechSat21, Starlight, Terrestrial Planet Finder, and Orbital Express. The laboratory provides a risk-tolerant and cost-effective environment that facilitates the design process and reduces the development costs of unproven technologies. The testbed operates in 2-D on a laboratory platform and in 3-D on NASA’s KC-135 microgravity aeroplane and inside the International Space Station.

Introduction

The SPHERES (Synchronised Position Hold Engage Re-orient Experimental Satellites) testbed, under development at the MIT Space Systems Laboratory (SSL), creates a laboratory environment for the research of control and autonomy algorithms both in 1-g and μ-g set-ups. The SPHERES testbed provides a cost-effective, long duration, replenishable, and easily reconfigurable platform that allows the testing of (1) relative attitude control and station-keeping between satellites, (2) re-targeting and image plane filling manoeuvres, (3) collision avoidance and propellant balancing algorithms, (4) array geometry estimators, and (5) docking control architectures. The experimental validation of control algorithms and their development processes is an essential step in reducing the considerable risk associated with future formation flight missions.

Motivation

The SPHERES testbed provides a vehicle to demonstrate and validate formation flight and docking technologies that can be used in missions such as Starlight, Terrestrial Planet Finder, TechSat21, and Orbital Express. Starlight and Terrestrial Planet Finder are separated spacecraft interferometer missions. These missions combine the light collected by telescopes on multiple spacecraft to obtain a high resolution synthesised image comparable to that of a monolithic mirror the diameter of the separation of the spacecraft. The TechSat21 space-based radar units are expected to be spread out during normal operations to observe large areas; when more precise information is needed, the TechSat21 satellites will come together to focus on a smaller area. In the case of failure of one or more units, the cluster can reconfigure itself to provide the new optimal level of service. The cluster concept consists of micro-satellites that operate co-operatively to perform the function of a
larger, single satellite. The concept eases performance upgrades by allowing upgraded satellites to join a cluster, increasing the overall performance. The Orbital Express project hopes to develop and demonstrate techniques for autonomous rendezvous and docking to enable on-orbit servicing and upgrades of large satellites.

**Laboratory Design**

The SPHERES testbed consists of three autonomous free-flyers, a laptop computer, and five small transmitters. It is designed specifically for operation in the shirtsleeve environments of the SSL laboratory, KC-135 reduced gravity aeroplane, and International Space Station (ISS).

The individual self-contained satellites have the ability to manoeuvre in six degrees of freedom, to communicate with each other (satellite to satellite: STS) and with the laptop control station (satellite to ground: STG), and to identify their position with respect the experiment reference frame. The laptop control station is used to collect and store data as well as to upload control algorithms to the satellites. Figure 1 shows an operational concept for the SPHERES testbed.

**Subsystems Descriptions**

Figure 2 shows a picture of an assembled prototype SPHERES satellite floating in NASA’s KC-135. The units are 25cm in diameter and have a mass of approximately 2.5kg. The individual sub-systems are described next.

- **Propulsion** – The satellites are propelled by pressurised carbon dioxide propellant. A manually adjusted regulator sets the pressure to between 20-55 psig. Twelve thruster assemblies allow 6DOF manoeuvres enabling both attitude and station keeping control. The propulsion system may be easily replenished.
• **Position and Attitude Determination** – The Position and Attitude Determination System (PADS) consists of local and global elements. The local PADS element consists of three rate gyros and three accelerometers that provide inertial measurements at 50 Hz. The global element uses ultrasonic time-of-flight measurements from transmitters placed at known locations in the testbed’s reference frame to receivers on the surface of each satellite. These time-of-flight measurements are converted to ranges and used to derive position and attitude.

• **Avionics** – A Texas Instruments C6701 Digital Signal Processor (DSP) provides the computational power. DSP processors provide multiple features that ensure real-time operation. Further, the DSP processors include all support functions of a standard processor, allowing it to control the whole unit.

• **Software** – The main sections of the software system are the controller interrupt (1kHz), propulsion interrupt (up to 50Hz), and background processes (free running). All other functions (for example position and attitude determination, communications, and housekeeping) are parts of the software architecture that may be exchanged between the different sections.

• **Communications** – Each SPHERES unit uses two separate frequency communications channels with a data rate of 115.2kbps. One channel is used for satellite-to-satellite (STS) communications; the other channel enables satellite-to-ground (STG) communications.

**Operational Environments**

The SPHERES testbed is operable in 2-D on a ground laboratory platform and in 3-D on the International Space Station. Table 1 summarises the attributes offered by each operational environment.

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<th></th>
<th>Repeatability and Reliability</th>
<th>Physical End-to-End Simulation</th>
<th>Hardware Reconfiguration</th>
<th>Supporting Extended Investigations</th>
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Table 1. Desired Attributes Present in Various SPHERES Operating Environments
• **2-D Ground Laboratory** – The 2-D ground test environment at the MIT Space Systems Laboratory utilises an air-bearing system to provide simulated 3DOF microgravity effects in a 1-g environment. The ground environment is inherently risk tolerant, as any algorithm or hardware failures may be controlled and the testbed can be repaired if necessary. The ground environment makes it very easy to make testing a human-in-the-loop process, where the researcher can observe behaviour and manipulate the test conditions.

• **International Space Station** – In addition to 6 DOF, the ISS environment allows extended investigations. During experiments, the SPHERES free flyers will be released and manoeuvred in the ISS cabin, with an astronaut monitoring their status. Results from the ISS experiments will be downloaded to the ground, so that researches can modify their programs. Within a few days the SPHERES testbed allows several cycles of design to take place. SPHERES is currently manifested for launch to the ISS in early 2003.

### Research Areas

SPHERES is a laboratory to develop the fundamental concepts associated with distributed satellite systems (DSS). It helps mature those key technologies that enable multiple satellite systems to provide features beyond those of single unit systems. At the core of the features lies adaptable interfaces: the ability to change and upgrade both the operational and hardware features of the system. By being adaptable, the system fulfils a multitude of features that not only enable the basic needs of different flight programs, but also allows them to benefit of future technologies.

### Key Technologies for DSS

The key technologies that can be investigated using SPHERES include: metrology, control, autonomy, artificial intelligence, communications, and human/machine interfaces. The tested technologies can be customised for use in specific flight programs, knowing that their success in SPHERES ensures a higher probability of success in the final mission.

• **Metrology** – Each satellite in a DSS requires knowledge of both its attitude and position as well as that of the other satellites. One must investigate the need for absolute measurements (e.g. a radar pointing towards Earth) versus differential measurements (e.g. docking) and between coarse (e.g. radar) and precise measurements (e.g. interferometry).

• **Control** – The control fields vary over a large range. High-level architecture determines the type of hierarchy in the system (e.g. leader/follower); an example of an intermediate level is fuel-balancing algorithms; low level control includes rigid body control of each unit.
- **Autonomy** – One goal of DSS is to minimise human intervention. At a minimum, the main manoeuvres of the system should complete autonomously; human intervention should only occur at high levels, such as specifying the current task.

- **Artificial Intelligence** – AI goes a step beyond autonomy by providing the extra advantages of automatic system reconfiguration and error detection and correction, among others. AI technologies in DSS help further minimise human intervention in the case of a problem or a new mission goal.

- **Communications** – DSS satellites require communications both to ground (high power) and between the units (low power). Each program must study its optimal communications configuration.

- **Human/Machine Interfaces** – Given the limited interaction between humans and free-fliers in space, the possible uses and interfaces between satellites and humans must be studied.

**Features of DSS**

Using the technologies mentioned above, multiple satellite systems can out-perform the tasks of a single larger satellite if the design provides adaptable interfaces and a robust architecture. The adaptability of the system allows the same units to perform a multitude of tasks which could not be performed by a single unit. A robust system design must enable the ability to overcome problems and to accept new technologies. An adaptable and robust system benefits from the following features: modularity, upgradeability, reparability, serviceability, and the ability to reconfigure.

- **Modularity** – A multiple satellite system can take advantage of redundancy in having multiple units deployed.

- **Upgradeability** – Upgrading a distributed satellite system can be accomplished in multiple ways: expansion by adding additional units to enhance operations; updating with new technologies that further enhance the system. By docking new components, the features of each unit can be upgraded individually.

- **Reparability** – Multiple satellite systems benefit from the ability to reconfigure and therefore maintain a maximum level of service with any operational units.

- **Serviceability** – DSS research seeks to benefit from the ability to develop a standard and low cost method to service units of deployed program satellites.
• **System Reconfiguration** – Separated satellite systems can perform orbital manoeuvres to reconfigure and allow the use of existing assets to satisfy a new mission goal, even if it was not in the original program plan.

**Applications**

Multiple missions which utilise distributed satellite systems (DSS) technologies will launch within the decade. These include, but are not limited to, formation flight, docking, and sample capture.

• **Formation Flight** – Formation Flight satellites are controlled to maintain relative attitude and position at large separation distances (100m-1km). Interferometry missions require high precision relative position and attitude control. Radar missions require less precise control, but by changing their baselines the mission can provide either large coverage or precision detection. Cluster communications missions can use artificial intelligence and the reconfigurability of the system to provide coverage in variable areas and ensure robustness.

• **Docking and Rendezvous** – To reduce the costs of docking, these manoeuvres must occur with minimal human intervention. Smaller satellites that perform all the tasks autonomously will lower the costs. Docking can then become standard for servicing, refuelling, upgrading, and assembling.

• **Sample Capture** – Several future missions call for spacecraft to land on Mars or other bodies and obtain samples. An orbiting craft will capture the sample and proceed with the return to Earth. The task must be performed autonomously by the orbiting craft, with co-operation from the sample unit.

• **Human Support** – Support from robotic spacecraft can enhance the work performed by humans. Satellites can be sent into locations where the human cannot go or where it would be dangerous. Adaptability in the satellite would allow addition of tools to perform different tasks.

• **Human Training** – The SPHERES testbed can also be used for training purposes. The SPHERES testbed allows a human operator to be trained to manoeuvre a unit, perform docking tasks, and train on limited feedback.

Table 2 presents a summary of the technologies that enable DSS. The SPHERES testbed enables testing of these core technologies and has been designed with the necessary features. The results of tests in SPHERES can then be customised for use in the specific missions.
Table 2. The technologies and features of DSS systems.

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<th>Technologies</th>
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<td>• Metrology</td>
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<td>• Control</td>
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<td>• Autonomy</td>
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<td>• Radar</td>
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<td>• Artificial Intelligence</td>
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Guest Investigator Program

A main feature of a laboratory is the ability to conduct multiple research investigations. By allowing multiple programs to use the facilities, the cost of the laboratory is greatly reduced, since it shared among the programs. The SPHERES project has a Guest Investigator Program (GIP) to allow multiple investigators. Figure 3 presents the program overview. The GIP program consists of:

- **GIP Simulation** – The GIP simulation is intended as a tool for the development and coding of SPHERES control algorithms. The GIP simulation provides enough fidelity to verify compilation of guest investigator code.

- **GFLOPS Simulation** – This simulation runs on the Generalised Flight Operations Processing Simulator (GFLOPS) at MIT. The GFLOPS simulation is intended as a high fidelity, easily reconfigurable verification tool.

- **SSL Laboratory** – The SPHERES ground laboratory testbed, at the MIT SSL, can be operated at a very low operational cost. The hardware used in the laboratory will be identical to the ISS flight hardware, and realistic imperfections, uncertainties, and unmodelled effects will be present.

![Figure 3. GIP Flow Diagram](image-url)
ISS Laboratory – The ISS test process is expected to have a turn-around time of approximately one to two weeks, once SPHERES is operational in the ISS. Tests are run by the astronauts in the ISS, who save the data and then download it to ground. Data analysis occurs a few days after the test, with the ability to restart the iteration also within a few days.

Conclusion

The SPHERES testbed provides a laboratory environment where multiple investigators can develop and mature the key technologies that will enable distributed satellite systems. Formation flight, autonomous docking, sample capture, and human support projects can all benefit from the risk-tolerant, μ-g environment provided by the testbed. Metrology, control, autonomy, communications and human interface technologies can all be studied. The successful development of the technologies in the SPHERES laboratory increases the probability of success of the mission, and allows the technologies to be pushed as far as possible to obtain the best results. The GIP provides the necessary interfaces between the multiple researchers and the SPHERES group to ensure successful completion of the programs.

References
