INITIAL SPHERES OPERATIONS ABOARD THE INTERNATIONAL SPACE STATION

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ABSTRACT

The Satellite Position Hold Engage Reorient Experimental Satellites (SPHERES) program, developed by the MIT Space Systems Laboratory, began operations aboard the International Space Station (ISS) on May 2006. SPHERES was designed as a research facility to demonstrate metrology, control, and autonomy algorithms for distributed satellites systems. By operating in the risk-tolerant environment of the ISS, SPHERES allows researchers to push the limits of their algorithms. Five test sessions, conducted during 2006, achieved multiple objectives for the different areas under study. The first test session was dedicated to hardware checkout. The second test session demonstrated basic 6DOF closed-loop control of the satellites. Fault detection and isolation algorithms were also tested, successfully using the inertial measurement system to detect simulated faults in space. Formation flight tests during the fourth and fifth session demonstrated two types of control architectures. Following the principle of incremental algorithm development, demonstrations of multiple scenarios of spacecraft docking occurred during test sessions one through four; the last session demonstrated docking to a tumbling spacecraft. The results of these test sessions are the basis upon which substantial more research will be conducted in the following years.

1. INTRODUCTION

The MIT Space Systems Laboratory developed the Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) program to incrementally mature algorithms for Distributed Satellite Systems (DSS) in a microgravity environment. SPHERES was specifically designed to help develop algorithms relevant to guidance, navigation, and control of the spacecraft of distributed satellite systems. By operating inside the ISS, SPHERES exploits the microgravity environment to represent the dynamics of complex missions while operating in a risk-tolerant environment. As such, SPHERES allows scientists to push the algorithms to their limits in various realistic mission scenarios, learning about both their theoretical and physical limitations.

1.1 Motivation

The motivation for SPHERES arises from the need to mature estimation, control, and autonomy algorithms for upcoming distributed satellite systems programs. Distributed satellite systems utilize multiple small satellites to achieve the same goals as a single larger satellite would. DSS trades control complexity with the expense and limitations of launch vehicles to send large single satellites to space. DSS includes proposals to use multiple spacecraft to implement reconfigurable space-based radar [1], autonomous docking of spacecraft for re-supply (e.g. Orbital Express [2]) and/or assembly (e.g. the Vision for Space Exploration inter-planetary stacks[3]), and the use of separated spacecraft telescopes (e.g. ESA's Darwin [4] and NASA's TPF [5]) to capture the light of distant planets.

The transition from theory to application has been shown to be a challenging process, but one that is necessary[6]. Traditional algorithm development methods which use simulations or ground-based facilities (see [7] for a complete review) do not provide either the fidelity or time necessary to mature an algorithm. While some of the upcoming missions are termed as "demonstration mission", their cost prohibits scientists from actually *testing* algorithms on them. Therefore, a need exists to provide scientists with a development facility which closely simulates the operational environment without having the risks associated with the planned high-cost missions.

1.2 Design Principles

Based on substantial previous experience in the development of space technology maturation laboratories [8], the MIT Space Systems Laboratory created a design philosophy [4] which was followed in the design of the SPHERES program. The design of the project was based on the need to *support the <u>incremental maturation</u> of a wide range of algorithms that <u>encompass a field of study</u> in a <u>risk-tolerant</u> and <u>representative</u> environment*.

The principle of incremental algorithm maturation prescribes that algorithm development should consist of multiple steps that grow upon each other. This requires planning a set of tests which will demonstrate separate parts of an algorithm and then bring them together to demonstrate the whole. In the case of autonomous control for DSS, it calls for the demonstration of individual maneuvers during initial tests, followed by larger tests that combine the maneuvers for a high-level goal. The long-term life and reprogramming capabilities of the SPHERES facilities enable scientists to run individual tests as necessary and combine the resulting algorithms in subsequent test sessions.

The principle to encompass a field of study calls for a facility to support enough research so that all the areas necessary to demonstrate a complex task can be demonstrated. For example, fields of study such as formation flight or autonomous rendezvous require the study of areas such as estimation, controls, and autonomy. The availability of standard modules for these areas and reprogramming capabilities of SPHERES enables scientists to concentrate on their specific area within DSS.

The requirement to allow testing in a risk-tolerant environment exists in order to enable scientists to push the limits of their algorithms. A practical algorithm development facility does not restrict the user due to the potential of permanent damage/failure of the facility due to an algorithm. Rather, the facility allows scientists to push their algorithms to the limits in such a way that a failure of the algorithm can be clearly observed and evaluated. By operating under human supervision in the controlled environment of the ISS, SPHERES enables scientists an unprecedented level of risk-tolerance.

Lastly, the goal for operating in a representative environment arises from the desire to mature algorithms to ever-higher technology readiness levels (TRLs, [9]). In order to demonstrate that an algorithm has reached readiness, TRLs emphasize the need to operate in a "relevant environment" – for space applications this means operations in 6DOF. SPHERES enables operations in true micro-gravity, allowing the maturation of algorithms to TRL 6 or even 7.

2. OVERVIEW

The SPHERES laboratory for Distributed Satellite Systems [10] consists of a set of tools and hardware developed for use aboard the ISS and in ground based tests. Three micro-satellites, a custom "global metrology" system (based on ultrasound time-of-flight measurements which simulates GPS inside the testing volume), communications hardware (two RF channels), consumables (tanks and batteries), and an astronaut interface are aboard the ISS. Figure 1 shows the SPHERES satellites being operated aboard the ISS and identifies the different elements of the facility. The ground-based setup consist of another set of micro-satellites, a research oriented GUI, and the guest scientist program to allow multiple researchers to use the facility.

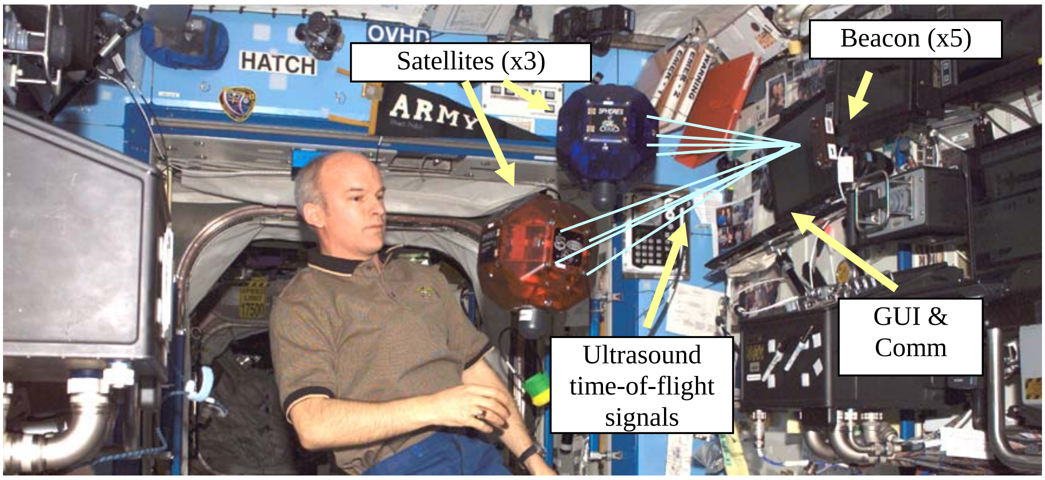


Figure 1 SPHERES hardware components operating aboard the ISS (Picture courtesy of NASA)

The SPHERES satellites were designed to provide the best traceability to proposed formation flight missions by implementing all the features of a standard thruster-based satellite bus. The satellites have fully functional propulsion, guidance, communications, and power subsystems. These enable the satellites to maneuver in 6-DOF, to communicate with each other and with the laptop control station, and to identify their position with respect to each other and to 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.

3. ISS TEST SESSIONS

Five test sessions were conducted aboard the ISS during 2006: May 18, May 20, August 12, August 19, and November 11. Table 1 presents the primary objectives for the first five test sessions The following sections describe each test session in further detail to illustrate the ability of SPHERES to both meet its design principles and help advance our understanding of algorithms required for successful future DSS programs.

Table 1. Test Sessions 1 to 5 Objectives

Session	Objectives
1	• Hardware checkout • Open-loop control, 3DOF closed-loop rotations, and basic maneuvers towards docking
2	• Firmware fix (from session 1) • 3DOF closed loop rotations; fault detection and isolation (FDI) of simulated thruster failures; position hold, and autonomous docking translation maneuvers

3	• Autonomous docking to a fixed beacon • On-line calculation of the mass and inertia of the satellite (Mass-ID) • Two satellite initial tests: formation flight (3DOF slave/master) and docking
4	• Global metrology system checkout • Show “avoidance” trajectories • Two satellite formation flight: 6DOF slave/master • Initial tests of two satellites docking
5	• Continue tests for Mass-ID • Cooperative and uncooperative docking and “safe docking” • Peer-to-peer formation flight maneuver

3.1 First Test Session

The SPHERES First ISS Test Session took place on 18-May-2006. The hardware checkout objectives were successful as all the SPHERES hardware (satellite, beacon, beacon tester, laptop transmitter and consumables) was located, installed and operated. Data was collected during open-loop tests to evaluate the performance differences between two different mixer algorithms that convert force and torque outputs by control algorithms into thruster on/off time commands. Enough data was collected to validate the operation of the global metrology system. The primary obstacle during the first test session was a corrupted FLASH memory space on the satellite which stored the IMU bias and scale factors. The corrupted FLASH prevented closed-loop tests from performing correctly. Despite this issue, the successful operation of the hardware and interfaces, as well as the collection of a substantial amount of data resulted in an overall successful test session. Table 2 presents a chronological list of all the tests performed during the first Test Session. The table shows the inability to complete closed loop tests during this test session. It also shows how the SPHERES team planned the incremental collection of data to validate the system in such a way that future test sessions will benefit from the tests on this session. Further, the ability to recover from these issues demonstrates the risk-tolerant nature of SPHERES.

Table 2. First Test Session Tests

Test	Description	Result
T 1 (2x)	Quick checkout with IMU data download	Success
T 2	Open-loop rotations, old mixer	Success (low gas pressure)
T 3	Open-loop rotations, new mixer	Success (low gas pressure)
T 4	Beacon track attitude PD	Metrology data collection only
T 6 (4x)	Closed-loop XYZ rotation	FLASH corruption error
T 8 (2x)	Dock Free Short S#1 PD	Metrology data collection only
T 2	Open-loop rotations, old mixer	Success (full gas pressure)
T 3	Open-loop rotations, new mixer	Stopped inadvertently by crew
T 3	Open-loop rotations, new mixer	Success (full gas pressure)
T 8.3	Dock Range only S#1	FLASH corruption error

3.2 Second Test Session

The SPHERES Second ISS Test Session took place on Saturday 20-May-2006. The session successfully accomplished a majority of its objectives. The FLASH memory corruption exhibited during the first test session was fixed. Furthermore, several tests involving closed-loop control using the gyroscopes and the ultrasonic navigation system were successful. The data show the ability of the SPHERES satellite to perform closed-loop 3D rotations, to estimate its

6DOF position with respect to a SPHERES beacon, and to detect faults online using fault detection and isolation (FDI) algorithms. The tests which had estimator divergence during this session provided enough data to overcome the issue in future sessions. This test session demonstrated the risk-tolerance of SPHERES by simulating thruster failures without any doubt on the ability of the satellites to continue operations after such failures. Further, it showed the ability to run tests in multiple research areas by showing both control (closed loop 6DOF), estimation (using a single beacon) and autonomous FDI.

Table 3. Second Test Session Tests

Program	Test	Description	Results
P101	T 1.1 (6x)	Flash Memory Test	Communications initialization problem
	T 6 (4x)	Closed-loop XYZ rotation	Communications initialization problem
	T 1.1	Flash Memory Test	FLASH fixed
	T 6	Closed-loop XYZ rotation	Success
	T 14 (2x)	De-Tumble, Track, and Dock	Estimator diverged
	T 16b	Dock Fixed Long S#2 PD	Partial success (wrong initial conditions)
P112	T 1	Failed-on thruster FDI	Lost communications
(NASA	T 1	Failed-on thruster FDI	Success
Ames)	T 2	Failed-off thruster FDI	Success
	T 3 (2x)	Multiple thruster FDI	Lost communications
	T 3	Multiple thruster FDI	Success
	T 4	Closed-loop attitude control	Success
	T 5	FDI with attitude control	Success
P113	T 1	Quick checkout	Lost communications
	T 2	Basic Position Hold	Lost communications
	T 2	Basic Position Hold	Success
	T 15	Attitude path following	Success
	T 3	Stationkeeping 3D – 1	Success
	T 8/8.1 (3x)	De-tumble, Track, & Dock	Reset due to low battery (good start)

3.3 Third Test Session

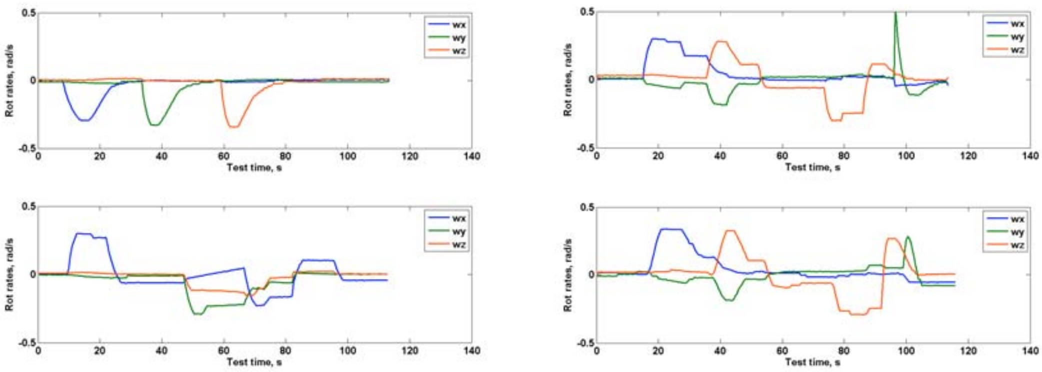
The SPHERES Third ISS Test Session, on Saturday 12-Aug-2006, demonstrated multiple steps towards autonomous docking, collected initial formation flight data, and taught the SPHERES team about important environmental noise factor. As shown in Table 4, tests were not repeated as often as before. On the other hand, many tests were affected by infrared noise; this issue was corrected for future sessions. The first set of tests demonstrated individual maneuvers towards autonomous docking and path-based trajectory following. The second set began the use of two satellites for formation flight and docking. Throughout these tests, state information was successfully transmitted between satellites.

Table 4. Third Test Session Tests

Program	Test	Description	Results
P124	T1	Quick Checkout	IR Noise
MIT	T2	3D Position Hold with Disturbance	IR Noise
Docking	T2	3D Position Hold with Disturbance	Good estimation, but IR Noise
	T3	Docking PD (1.5m)	Success
	T4	De-tumble, Track, & Dock Set 1	Success
	T5	Trajectory 3 (Safety w/rotation)	Good control
	T6	3D Position Hold (Robust)	Started well, estimator diverged

P126	T1	ID all axes	Stuck thrusters
Mass ID	T2	ID all axes, proof mass	No ‘proof mass’ attached
	T2	ID all axes, proof mass	Stuck thrusters
	T3	Single-thruster, proof mass	IR Noise
	T4	Single-thruster firings	IR Noise & stuck thrusters
	T4	Single-thruster firings	Partial success
	T5	Fuel slosh	Partial success
	T5	Fuel slosh	Partial success
	T6	Roll-Pitch-axis spin	Success
	T7	Pitch-Yaw-axis spin	Stuck thruster
	T8	Yaw-Roll-axis spin	Partial success
P125	T1	Quick Checkout	IR Noise
MIT	T2	Twin Rotations: Independent	SN2: success / SN3: low battery
2 Sat	T2	Twin Rotations: Independent	Success
Initial	T3	Twin Rotations: Formation	Success
Tests	T4	Twin Position Hold: Formation	Estimator diverged (IR Noise)
	T5	Two Satellite Docking – Set 1	Drifting “target” prevented docking

Of special interest in this session were the results of multi-satellite operations. Figure 2 shows the attitude of independent rotations (left side) and formation flight rotations (right side, “leader” on top). During independent rotations the satellites did not react to disturbances (in this case IR noise) on the other satellite. During formation flight reaction to external disturbances by the crew (green spike) can be seen at the end of the formation flight tests.



Independent Rotations Formation Flight Rotations

Figure 2. Formation Flight Test Results during Test Session 3

3.4 Fourth Test Session

The fourth Test Session, on 19-Aug-2006, was dedicated primarily to testing the global metrology system. Table 5 shows the two main groups of tests conducted during this session. The tests in the first group collected all the data necessary to develop the robust estimators later used in the fifth and subsequent test sessions; although a configuration problem prevented online estimation from succeeding. The second set of tests (once the configuration problem was corrected) was highly successful, and provided important demonstrations. Algorithms for both formation flight and docking tests were validated during this session, so as to be used with high confidence in future sessions.

Table 5. Fourth Test Session Tests

Program	Test	Description	Results

P131	T1	Quick Checkout	IR Noise
MIT 4a:	T2-7 (8 tot)	Global Sys ID	Valid data collected, invalid beacons loc.
Global	T8 (2x)	3D Position Hold with Disturbance	Valid data collected, invalid beacons loc.
Sys-ID	T9 (4x)	Trajectory: 3D Avoidance	Valid data collected, invalid beacons loc.
	T10	Trajectory: Avoidance w/ Rotation	Incomplete (stopped by crew)
P132	T1	Quick Checkout	Success
MIT 4b:	T2	Ultrasound Shadow: 1.5m	Success
Global	T3	Ultrasound Shadow: 0.5m	Success
Metro-	T4	Ultrasound Shadow: 0.2m	Success
logy	T5	Gyroscope Calibration	Success
Multi-	T6	2 Sat. Position Hold - Independent	Success
Sat	T7	2 Sat. Leader, Follower	Success
	T8	2 Sat. Docking: Target Hold	Estimator diverged after contact
	T8	2 Sat. Docking: Target Hold	Success
	T9	3D Formation	Success
	T10	2 Sat. De-tumble, track, & dock	Success
	T11	2 Sat. Docking: Plume Impingement Check	Success

3.5 Fifth Test Session

The fifth Test Session was accentuated by the successful demonstration of autonomous docking to a tumbling target. Figure 3 presents the trajectory followed by the chaser (blue) satellite while the target (red) satellite maintained a constant rotation and actively held its position with respect to the global frame (ISS frame). One can see a spiral forming in the path of the blue satellite. This success is the result of the incremental development and maturation of algorithms throughout the previous sessions. While only a few tests were run during this session (shown in Table 6), each of the tests is of high complexity. The tests demonstrated complete docking algorithms and full formation flight operations. These tests clearly demonstrate the ability to incrementally maturate algorithms and to cover a field of study by developing multiple areas (specifically controls, estimation, autonomy, and new to this session communications). Further, the risk tolerant nature of SPHERES enabled the team to test these complex algorithms after just four prior test sessions in microgravity (less than 12 hours / seven months of microgravity experience).

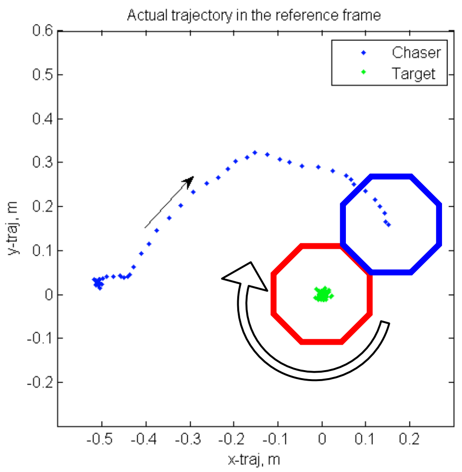


Figure 3 Results of Docking to a Tumbling Target

Table 6. Fifth Test Session Tests in Chronological Order

Program	Test	Description	Results
P142 **Mass ID 2**	T1-12 (15 runs tot)	Multiple tests for Mass ID	Partial – stuck thrusters were not fully identified from previous session
P141	T1 (3x)	Quick Checkout	Incorrect battery installation
MIT 5:	T1	Quick Checkout	Success
Docking	T2	Docking to Fixed Target	Success
Multi-Sat	T6	Docking to Tumbling Target	Success

	T6	Docking to Tumbling Target	Success
	T5	Safe Docking w/fault	Success
	T4	Safe Docking	Success
	T12	Circular Formation Flight	Success

4. CONCLUSIONS

SPHERES has demonstrated its ability to create a laboratory environment aboard the space station for the incremental maturation of DSS algorithms. The first four sessions helped the SPHERES team achieve steady-sate operations, having fully understood the microgravity capabilities and behavior of the facilities and the ISS. Using the data collected from each test session, the SPHERES team incrementally matured formation flight and docking algorithms resulting in multiple “space firsts”. SPHERES was the first free-flyer to operate aboard the ISS. On the second test session it was the first space program to intentionally simulate failures of thrusters in space in order to test fault detection algorithms. During the fifth session SPHERES was the first to demonstrate docking to a tumbling target in a microgravity environment. The circular formation flight was another first (demonstrate covering an optical field in a microgravity environment with separated spacecraft), although there were synchronization problems that prevented the test from being fully successful, so it requires further research. SPHERES is expected to operate aboard the station for multiple years to complete these tasks and more.

5. REFERENCES

[1] A. Das, R. Cobb, M. Stallard, “Techsat 21 - A revolutionary concept in distributed space based sensing”, *AIAA Defense and Civil Space Programs Conference and Exhibit*, Huntsville, AL (1998)

[2] J. Shoemaker. and M. Wright, "Orbital express space operations architecture program," *Spacecraft Platforms and Infrastructure*, *Vol. **5419*** SPIE, 57–65 (2004)

[3] W. Hofstetter, O. de Weck, E. Crawley, “Modular Building Blocks for Manned Spacecraft: A Case Study for Moon and Mars Landing Systems”, *INCOSE 2005 - Systems Engineering Symposium*, Rochester , NY (2005)

[4] C. V. M. Fridlund, “Darwin – The Infrared Space Interferometry Mission”, *ESA Bulletin **103,*** Noordwijk, The Netherlands (2000)

[5] C. A. Beichman, N. J. Woolf, C.A. Lindensmith, C. A., “The Terrestrial Planet Finder (TPF) : a NASA Origins Program to search for habitable planets”, *TPF Science Working Group*; National Aeronautics and Space Administration ; Pasadena, Calif.: Jet Propulsion Laboratory, California Institute of Technology, JPL publication ; 99-3 (1999)

[6] D. W. Miller, G. J. W. Mallory, “Control Testbeds and Flight Demonstrations: Transitioning Theory to Application”, *American Control Conference **(Vol. 2)***, Philadelphia, PA (1998)

[7] Saenz-Otero, A, “Design Principles for the Development of Space Technology Maturation Laboratories Aboard the International Space Station”, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Ph.D. Thesis, Cambridge, MA (2005)

[8] D. W. Miller, J. de Luis, “Using the Shuttle, MIR and ISS for Operating Micro-Gravity Engineering Research Laboratories”, *AIAA-2001-**4648***, Albuquerque, NM (2001)

[9] J Mankins, "Technology Readiness Levels", Advanced Concepts Office, Office of Space Access and Technology, NASA, April 1995

[10] A. Saenz-Otero, A. Chen, et al, “SPHERES: Development of an ISS Laboratory for Formation Flight and Docking Research”, *2002 IEEE Aerospace Conference, **#081***, (2002)