ABSTRACT

Since beginning operations aboard the International Space Station (ISS) in May 2006, the Synchronized Position Hold Engage Re-orient Experimental Satellites (SPHERES) facility has completed a total of twelve test session with over 150 tests. As a testing environment for distributed satellites systems, SPHERES research concentrates on the development of estimation, control, and autonomy algorithms for missions that include docking, formation flight, close proximity operations, and in-space assembly. By operating in the risk-tolerant environment created by the ISS, the SPHERES scientists can push the limits of the algorithms and attempt tests which would never be conducted as part of normal missions. During 2007 and early 2008 four SPHERES test sessions were conducted. The test sessions completed demonstrations of algorithms for docking using on-line path-planning, using high speed IMU data for closed loop ΔV control, performing different types of closed proximity operations for inspection missions, and conducting different scenarios for fractionated spacecraft.

I. 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 spacecraft.[1],[2]

By operating inside the ISS, SPHERES exploits the microgravity environment to represent the dynamics of complex missions while operating in a risk-tolerant environment. Therefore, SPHERES allows scientists to push the algorithms to their limits in various realistic mission scenarios, learning about both their theoretical and physical limitations.[3]

SPHERES began operations aboard the ISS on May 2006. Results [4],[5] on the major areas of research (docking, formation flight) have accomplished multiple “space firsts” including docking to a tumbling satellite[6],[7] and three-satellite formation flight[8],[9],[10]. The mission continued during 2007 through four test session:

- Test Session 9 - 2007/Nov/16
- Test Session 10 - 2007/Dec/12
- Test Session 10a - 2007/Dec/29
- Test Session 11 - 2008/Jan/27

The end objectives of SPHERES through the ISS program are to:

- Docking
  - Demonstrate autonomous docking to a tumbling (nutation) target in the presence of simulated sensor and actuator faults.
  - Demonstrate the use of safe docking trajectories which guarantee that
uncontrolled contact between two satellites will not occur in the case of failures in the actuators.

- Demonstrate the ability to autonomously assemble large space structures by docking together modules of similar masses using only one actuating module (a tug) which reconfigures its control parameters after each docking operation.

- Research close proximity operations for tasks such as satellite inspection (without actual docking), maintenance, and repair.

- **Formation Flight**
  - Investigate different control algorithms to create formation flight systems usable for separated space telescopes or space-based radar, including algorithms for plane coverage, plane precession, and fuel balancing.
  - Demonstrate formations relevant to the Terrestrial Planet Finder mission and other space-based optical telescopes (e.g., the Stellar Imager).
  - Demonstrate and mature path planning algorithms for changing formation configurations autonomously while avoiding collisions and any uncontrollable obstacles, and maintaining mission constraints such as restricted pointing (e.g. sun avoidance).
  - Perform these maneuvers for cases relevant to both precision flying formations (e.g., space telescopes) and fractionated spacecraft which do not require precise formation but require high availability of the multi-satellite system.

The four test sessions discussed in this paper covered parts of both docking and formation flight experiments. Specifically, the advance autonomous docking algorithms, including safe docking maneuvers, online path planning, and space-assembly steps. Formation flight research concentrated on fractionated spacecraft, demonstrating maneuvers which take advantage of the separated spacecraft ability to easily reconfigure. The team also performs tests common to any space missions; these included using accelerometers to improve the use of closed-loop $\Delta V$ commands.

The major accomplishments achieved during this time towards the SPHERES primary objectives include:

- On-line path planning demonstration of docking to a fixed target, including obstacle avoidance (multiple space firsts).
- 1kHz closed loop $\Delta V$ control demonstrations.
- Demonstrated control of two docked spacecraft with joint thruster firing (space first).
- Performed a “mesh” inspection simulation visual-based navigation.
- Fractionated spacecraft and formation flight demonstrations of:
  - Formation initialization.
  - Formation scatter (space first).

In addition, Increment 16 provided initial data for the team to continue onto the next steps of spacecraft assembly and autonomous inspection.

## II. TEST SESSIONS OVERVIEW

The primary objectives during each of the test sessions, as related to the three “threads” presented above, are presented in Table 1. Docking continued to be a strong element of the SPHERES research aboard the ISS throughout all test session. Formation flight research progressed in two areas: precision formation flight for space telescopes and coarse fractionated spacecraft. TS10a was a special session dedicated to work with the crew to counteract airflow effects by the addition of “Harmony” (Node 2) to the ISS. During the session we attempted multiple science tests, but the primary objective was to use a new operational mode, described below.
<table>
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| 9  | • Perform basic motions of two attached satellites to demonstrate reconfigurable control.  
   • Demonstrate docking of an “assembly” of two satellites to a third satellite.  
   • Demonstrate the use of “safe docking” paths which prevent uncontrolled contact between satellites. | • Perform path-following on pre-planned optimal paths for array reconfiguration. | • |
| 10 | • Obtain basic maneuver data for reconfiguration with inactive objects.  
    • Obtain basic maneuver data for reconfiguration using joint thruster control.  
    • Demonstrate new safe docking paths with obstacle avoidance.  
    • Demonstrate the use of online path planning to dock with a cooperative satellite.  
    • Use Linear Quadratic Regulator (LQR) methods to dock with obstacles in the path. | • Demonstrate formation initialization from random initial conditions.  
    • Perform a formation reconfiguration while avoiding satellite collision.  
    • Demonstrate formation scatter upon crew commands. | • Obtain initial accelerometer data to enable closed loop ΔV control.  
    • Determine the presence of Node 2 airflow and potential solutions. |
| 10a| • | • | • Determine how to best overcome the airflow due to the addition of Node 2. |
| 11 | • Demonstrate reconfiguration docking maneuvers with inactive and active satellites.  
    • Demonstrate LQR docking methods with obstacle avoidance.  
    • Perform virtual inspection maneuvers - autonomous and human control. | • Continue formation initialization, reconfiguration, and scatter. | • Perform closed loop ΔV control with more complex maneuvers and path following. |

Table 1. SPHERES Test Session 9-11 Objective Summary

The SPHERES team prepares a test plan for each test session, which consists of groups of tests for one, two, and three satellites as necessary. The plans are usually aggressive, trying to accomplish large amounts of science. Usually the crew accomplishes the majority of
the tests, being able to run several of them multiple times. The team arranges the tests in order of importance, to obtain the maximum science return possible.

III. RESEARCH AREA RESULTS

This section is divided into research areas, rather than individual test sessions. In this manner one can see how SPHERES enables the maturation of a wide range of estimation, control, and autonomy algorithms. Multiple of these research areas saw tests in more than one test session, showing the “iterative” nature of SPHERES.

A. Off-Line Optimal Path Planning

*TS9, Group A, Test 2: Triangle Reconfiguration – Relaxed Version*

This test consists of a three SPHERES reconfiguration maneuver that switches from one equilateral triangle configuration to a smaller one. The SPHERES have to point to each other within a cone of 75 degrees, which is equivalent to defining some hot and cold faces, and forcing the cold faces to face each other during the whole maneuver. Therefore the maneuver involved collision avoidance and inter-spacecraft pointing constraints. It is a highly coupled maneuver because the states of all three SPHERES are coupled in the formulation of the constraints. The trajectory of each SPHERES was computed offline, and it was followed online using the low-level PID Controller of the SPHERES. The test ended successfully. Figure 1(a-c) shows that the state error levels were relatively low for the first half of the test (first 40 sec), but increased significantly thereafter. This behavior is the result of the setup error. Even with the setup problem, the collision avoidance constraint was satisfied during the maneuver.

Figure 1. State errors of the three SPHERES satellites over time.
B. Closed Loop ΔV Control

*TS10, Group A, Tests 5 & 6: Closed Loop Accelerometer Tests;*

*TS11, Group A, Tests 2 & 4: Translations – ΔV Control vs. Forces and Torques;*

*TS11, Group A, Tests 3 & 5: Rotations – ΔV Control vs. Forces and Torques*

*TS11, Group A, Tests 6 & 7: Path Following – ΔV Control vs. Forces and Torques*

Although the SPHERES satellites are each equipped with three gyroscopes and three accelerometers (one for each axis), only the gyroscopes have typically been used for GN&C. This is because the accelerometers exhibit a high frequency ringing phenomenon when the thrusters are actuated; when a thruster is opened or closed, the measured acceleration oscillates rapidly. Initially, the amplitude of these oscillations is on the order of tens of cm/s², but it subsides after a period of about 200 milliseconds. These tests attempt to filter the measurements from the accelerometers in real time, and use them to impart a commanded ΔV on the satellite. Normally, the actuation of the thrusters on a SPHERES satellite is open loop. A control algorithm computes a vector of desired forces and torques, which is converted into thruster on and off times by a software module called the mixer. The thruster on and off times are calculated from an idealized model of the satellite’s physical characteristics and the performance properties of its thrusters. However, the actual performance of the propulsion subsystem on any thrust varies due to several factors. These factors include the number of thrusters open simultaneously, the regulator pressure, the quantity of fuel remaining, and small differences in the construction of each SPHERES satellite. Although it is possible to try and account for some of these variables in the mixer algorithm, an alternative is to use the accelerometers to monitor thruster performance. These tests implement a new low-level thrust controller that measures the imparted ΔV and uses this information to terminate a burn when a target ΔV is reached.

To reduce the accelerometer ringing during thruster actuation, all measurements are passed through a low-pass filter before being used by the controller. The filtered reading takes about 40 milliseconds to converge to the new acceleration after a thruster is actuated. The behavior of the filtered value during this transient region can be somewhat erratic, and so it is not used by the control algorithm. Instead, the ΔV imparted during the transient is estimated from the converged filter reading. The filtering process cleans up the measurements significantly, as illustrated in Figure 2.

Figure 3 shows a portion of the results from the TS10 tests. The graphs plot the measured ΔV versus the burn time. Shaded regions indicate the target velocities. For these tests, a conservative tolerance of +/- 3 mm/s was used. Due to the way the algorithm checks termination conditions, the thrusters are deactivated once the measured velocity enters these regions.

The fact that both burns achieved a final ΔV within the specified tolerances for all 3 directions is visible in these figures. In Figure 3, the algorithm switched thrusters two times during the burn. These times are marked by the vertical dashed lines. The first switch was to turn off the +Y thrusters when ΔVₚ was reached. The second switch was to provide a small boost at the end of the burn to bring both ΔVₓ and ΔVᵧ into the desired region.

Figure 4 and Figure 5 show the measured ΔV for the +X burn for both the closed-loop and open-loop test cases during Test Session 11. In both cases, the leftmost graph shows the axial and angular ΔV as measured by the IMU throughout the burn. The angular rates are needed so that the centripetal acceleration of the satellite can be subtracted from the accelerometer readings. The rightmost graph shows the global metrology system’s estimated axial velocities for the satellite. Note that the global metrology system only runs at around 4 or 5 Hz, so the frequency of measurements is much less than for the IMU data, which runs at 1 kHz. Also, the velocities given by the estimator are absolute, whereas the measurements from the IMU are relative (and initially zeroed at the start of a burn). As expected, the closed-loop results coincide with the IMU measurements very precisely.
The true $\Delta V$ applied for each of the burns likely lies somewhere between the results given by the closed-loop algorithm and the estimator. The open-loop mixer clearly has a tendency to deliver less than the desired $\Delta V$, as this trend is reflected by both the IMU and estimator measurements. On average, the closed-loop thrust controller performed better. According to the estimator, both closed-loop burns overshot, but it’s not entirely clear that the estimator had fully converged to the new velocity when the measurement was taken 6 seconds after the burn.

The rotation tests also consist of two burns. The first applies a $\Delta V$ of 25 deg/s about the $+Z$ axis, and the second applies a $\Delta V$ of 25 deg/s about the $-Z$ axis. For estimating the angular velocities, the estimator does not rely on any sort of thruster integration. This is because the gyroscopes provide a direct measurement of the current angular velocities of the satellite. Consequently, better agreement is expected between the IMU and metrology estimates. The IMU results for the second burn are shown in Figure 6 for both algorithms. The open-loop results are consistent with the translation tests – the algorithm delivers less than the desired $\Delta V$. However, for rotations, the percentage error seems to be smaller (5% - 10%) than for translation (10%-20%). The closed-loop algorithm performed very well on the rotations, achieving $\Delta V$ within 2% of the goal. Once more, it shows the tendency to overshoot slightly, which indicates that there is still some possible room for improvement. A probable source of this error is incorrect estimation of acceleration delivered during the transient region. This region is shaded gray in Figure 6. During this region, the filtered IMU values have not yet converged, and so a precise measure of acceleration is difficult.

The path tests consist of an attitude maneuver (180 degree rotation), followed by flight to three waypoints, with another rotation at the end. A simple PD controller is used to generate a series of $\Delta V$ commands in real-time. Since the other closed-loop tests are simple maneuvers to obtain specific measurements, this test demonstrates a more realistic use of the controller. Test 6 accomplished the objective of showing that the new controller performs reasonably well both for attitude control and translation. Plots of the state trajectory for the closed-loop case are shown in Figure 7. After the initial rotation at a
test time of 20 seconds, the attitude is held steadily throughout the maneuver. Also, the graphs show that the satellite’s motion is visibly smooth.

Figure 4. +X Burn for the closed-loop algorithm.

Figure 5. +X Burn for the open-loop algorithm.

C. Assembly & Reconfiguration [11]

TS10, Group B, Test 3: 3D Translations Joint Firing

TS11, Group C, Test 3: Reconfiguration - No Proof

TS11, Group C, Test 4: Reconfiguration - Satellite Proof

TS11, Group C, Test 8: Reconfiguration – Battery Proof
Figure 6. Z Burn for the closed-loop (top) and open-loop algorithm (bottom).

The objective of these tests was to demonstrate attitude and position control of satellites when the mass properties of the control plant change. The mass changes were achieved by attaching two satellites together or a SPHERES battery pack to one side of the satellite.

The TS10 tests used two satellites attached, using thrusters on both satellites. The algorithm being tested is a new thrust mapping algorithm that accounts for mass, inertia, and center of mass shifts, as well as varying number of thrusters. Three targets were issued for this test: Pos1 = [0.4,0,0], Pos2 = [0.4,0.4,0] , and Pos3 = [-0.4, -0.4, -0.4].

Figure 8 gives the position error history of this test. This test was successful in demonstrating good control in 3DOF when two satellites are working together.

Figure 7. Attitude and state trajectory for closed-loop trajectory test.

Figure 8. 3D translations: Joint firing, Position State Error.

The first set of TS11 tests demonstrated a new thrust mapping algorithm was run in a single
satellite configuration to ensure similar performance to the nominal thrust mapping algorithm used. The new thrust mapping algorithm accounts for mass, inertia, and center of mass shifts. The baseline test consists of three targets: $\text{P1} = [0.4,0,0]$, $\text{P2} = [-0.4,-0.4,-0.4]$, and $\text{P3} = [0.4,0.4,0]$ meters. The magenta vertical lines indicate target changes. The performance shown in Figure 9 matches the performance of the nominal thrust mapping algorithm very well. There is very minimal overshoot and the system is critically damped. This test was very successful and the data will be used to compare later tests.

The next TS11 test was to demonstrate control with a large proof mass. This test uses the new thrust mapping algorithm that accounts for mass, inertia, and center of mass shifts. Two satellites are attached via Velcro, however only one satellite is actuating. The test consists of three targets: $\text{P1} = [0.4,0,0]$, $\text{P2} = [-0.4,-0.4,-0.4]$, and $\text{P3} = [0.4,0.4,0]$ meters. The magenta vertical lines indicate target changes. Figure 10 shows the position error history of the satellite for Test 4. The satellite decreases its error quite well, but overshoots significantly. This is due to plume impingement of the Primary satellite’s thrusters onto the attached satellite. The satellite loses one degree of freedom because it cannot stop, since the plumes hit the attached satellite. Future work includes incorporating specific maneuvers in order to account for this lack of freedom.

Figure 11 shows the position error history of the satellite for TS11, Group C, Test 8. Performance is much closer to the baseline (Test 3). The largest difference is when there are multiple satellites with large errors. Then, the performance shows more overshoot, up to 20 cm while the baseline case had overshoot within a couple centimeters.

D. Docking

TS10, Group B, Test 5: Docking Fixed – Online Path Planning

The objective of this test was to demonstrate for the first time in microgravity (space) the use of online path planning to autonomously dock to a satellite. In addition, the planning included obstacle avoidance and was coupled into a docking scenario where the target satellite was actively holding its position but facing its back
to the chaser. Thus, the path planner needed to plan a path around the target satellite while avoiding collision to get in front of the docking port face. Figure 12 depicts the online calculated paths (dashed line) and the actual path (solid) followed by the chaser spacecraft. The plotted red circle is the target satellite, while the larger purple transparent circle represents the “obstacle” sphere the chaser planned to avoid.

The test was a complete success. This was the first time online path planning was performed in microgravity for a docking task. In addition, obstacle avoidance was included. The test provided significant amount of insight for future path planning, forming docking phases, and trajectory following controllers. Full details are presented in [12]

E. Fractionated Spacecraft [13]

TS10, Group C, Test 3: F6 Scatter

TS11, Group C, Test 4: F6 Scatter

These tests were designed to demonstrate the ability for satellites to quickly change their formation configuration in response to an external threat or command. To perform this maneuver, each satellite activated a control law that commanded a thrust directly away from the other satellites. After building up velocity the satellites picked a final destination on a virtual bounding volume and attempted to come to rest at this location.

As shown in Figure 13, the satellites took paths that were approximately 120 degrees apart, as expected if they were evenly spaced on a circle. Shortly after the formation began to rotate, the secondary satellite reset, leaving only the primary and tertiary satellites to complete the maneuver. At test time T=78s, a scatter command was issued by the crew, and the two active satellites moved to scatter directly away from each other and the estimated position of the disabled satellite.

After 30 seconds, an automatic timeout brought the satellites back to the center of the volume. Due to an error in the state estimate, the primary satellite failed to return to the circle and moved erratically until the test was terminated. The last satellite, using mostly dead reckoning was able to return to the formation where it circled briefly before the test terminated.

Figure 13. Top-down trajectory for F6 Scatter.

A two satellite version of the test was created for TS11. Figure 14 shows the thrust directions calculated by the satellites when they initiated the scatter maneuver. Allowing for some delay in the exchange of state between the satellites, the thrust directions show the proper direction of thrust for the scattering control law.
Figure 14. Scattering maneuver
In addition to scattering in the proper directions, the satellites were able to stay within the test volume.

TS11, Group B, Test 2: Random Formation Initialization

The objective of this test was to show the ability for a satellite formation to initialize in a random order. The starting order was selected by the crew by randomly pushing the satellites into the test volume from their starting positions. In addition to starting the formation, the first satellite pushed was programmed to negotiate a leadership exchange with the other satellites by broadcasting a leadership request.

The crew was instructed to allow the satellites to settle at their starting positions before providing the initialization push. The satellites appeared to “self-initialize,” reaching their initial positions, then turning to start the circular formation. To switch maneuvers the satellite was to remain within 10 cm of its starting target for at least 6 seconds. The satellites approached the 10 cm radius, drifted through it, and exited just as the maneuver switched. This was detected as a push, and the satellite moved to begin the formation. The second satellite had a similar behavior but took longer to drift past its initial position. This resulted in an unexpected though still random formation initialization. As shown by Figure 15, after the erroneous initialization, both satellites that moved managed to join the formation. A bug in the communications routines prevented the satellites from properly exchanging leadership as they entered the formation.

Figure 15. Top down view for initialization

F. Inspection [14]

TS11, Group C, Test 2: NPS Virtual Obstacle Avoidance

TS11, Group C, Test 5: Mesh Inspection

TS11, Group C, Test 9: Human in the Loop Inspection

The inspection tests demonstrate the ability of a satellite to autonomously perform complete “inspections” of satellites by safely operating in close proximity of other satellites and performing maneuvers that would enable full image capture by a video camera.

A multiple spacecraft close-proximity control algorithm developed by the Naval Postgraduate School (NPS) was implemented and tested with SPHERES. During this flight test, a chaser satellite successfully approached a virtual target satellite, while avoiding collision with a virtual obstacle satellite. This research contributes to the control of multiple spacecraft for emerging missions, which may require simultaneous gathering, rendezvous, and docking. The control algorithm implemented combines the efficiency of the Linear Quadratic Regulator (LQR), and the robust collision avoidance capability of the Artificial Potential Function method (APF). The LQR control effort serves as the attractive force toward goal positions, while the APF-based repulsive functions provide collision avoidance for both fixed and moving obstacles.
The location of the target and the obstacle were pre-determined and hard-coded in the software, to simulate a virtual target and a virtual obstacle (conserving batteries and simplifying operations). Figure 16 shows The, chase approaching the virtual target following a trajectory that would have led to docking, given a real target at that location.

Throughout the experiment, the trajectory was very smooth. Docking would have occurred at 230 seconds. At that time, the velocities along all three axes were estimated to be less than 1 mm/s.

For the next test, the NPS algorithm in Test 2 was modified to work with an obstacle that has a complex shape. The NPS algorithm is designed to create a spherical exclusion zone around an obstacle. For a more complex non-spherical shape, multiple exclusion zones can be meshed together as shown.

Figure 17. The black markings in Figure 17 show the path of the satellite around the mesh from the telemetry of the test. These test results show that the satellite successfully maneuvered around the mesh of exclusion zones.

During the ISS test, the satellite started partially inside an exclusion zone. Because the repulsion force grows exponentially towards the exclusion zone center, the satellite pushed out of the zone with large forces. This caused the satellite to move quickly towards the ISS wall. Once it touched the wall, it recalculated its LQR and APF forces, and began moving towards the goal point. Thus, despite starting inside an exclusion zone, the satellite maneuvered around the mesh and the test was a success.

The third test obtained “control” data to showcase the difference between a human making a first-time inspection of an area, which will later on be compared to the ability of a vision-based satellite to perform similar “inspections”. The test also reversed the usual way of controlling satellites: instead of the human being the supervisor and “turning on the breaks” when the satellite was too close to a specific area, the human was allowed free control until the satellite detected it was too close to the “edge” of the operating volume. At that point the satellite took over control of that dimension (X, Y, or Z), and prevented the satellite from moving further along that direction to prevent any contact with a wall.

Both goals were clearly accomplished during this test. The motions created by the crew was clearly indicative of traversing a wall, as well as moving in the three dimensions. The crew made clean transitions between “inspecting” the +Y and -X walls, while clearly testing the limits on the Z direction. Figure 18 shows a plot of these results. Figure 19 shows the times when the computer took over control of the satellites. The
The top three sub-plots show the X, Y, and Z control inputs to the satellite; the green lines show large spikes when the satellite takes over control to stop the satellite from making contact with the walls. The blue lines are the crew control. A good example of the computer’s ability to take over is in the Y axis, at about 170 seconds into the test. After the large crew request to move in the -Y direction (time ~150s), the satellite detected it had to stop earlier than the crew (the green spike is first). If the satellite had waited for a crew command a few seconds later, it would have collided with a wall. It is of interest to see in the last sub-plot that after the satellite took over, the crew continued to send multiple commands.

**Figure 18.** 3D Plot of Human Controlled Inspection.

**Figure 19.** Control Telemetry and Command Data for Human Controlled Inspection

### IV. TEST SESSION 10A

This test session was requested as an attempt to find a method to overcome the new airflow in the SPHERES operational area which appeared after the addition of Node 2 “Harmony”. While during TS9 the anomaly was noticed, it was not clear whether the main problem was due to the crew attempting to deploy the three satellites at one time or because of new airflow. TS10 demonstrated that airflow did exist. This session was planned solely to try and overcome the airflow by changing the test deployment procedures. However, the crew was never trained on these procedures, since they had to be developed in a short period of time. Therefore, the SPHERES team limited the test plan to a few selected tests which did not perform successfully during TS10 (effectively a repetition of TS10 Group C). The tests were:

- **Group A: MIT 10ops: 3 Satellite Deployment Tests**
  - Formation flight: initialization, reconfiguration, and scatter
  - Inspection with obstacle avoidance

13/15
• Safe docking with obstacle avoidance

The updated test program developed by MIT did not reach the ISS correctly for the test session. However, since the SPHERES team was prepared to run these types of tests, including the “fix” for airflow, during TS10, the crew was able to use TS10 Group C for the session.

The “fix” proposed by MIT consists of having the satellites actively hold their position when deployed, one at a time, by the crew member. Usually the satellites remain passive during deployment, but they are capable of knowing their position and holding it while the crew deploys other satellites and starts the test from the control laptop.

The test session proved that the slow deployment required to overcome airflow (especially during deployment of three satellites) is too complex to teach during a session (i.e., in real-time) the crew. Because the crew was still not able to deploy three satellites fully during the test, there was no relevant data for scientific purposes.

Two tests, the “quick checkout” and “activate position hold” were the initial attempts of the SPHERES team to explain to the crew what would happen after the test “Activate Position Hold” was run. A critical element of this test was that after position hold was activated, then each satellite had to be deployed one at a time and allowed to activate its position hold control before deploying the next satellite. However, it was not possible to convey this operational mode to the crew in real time until.

The special session allowed the SPHERES team to push the limits of “remote operations” with the ISS crew. While the session did not fully complete its objectives, it provided essential information to determine the changes needed in the SPHERES procedures as well as the crew training material. It clearly set the limit to the capabilities available and the possibility of changing procedures in real-time.

V. CONCLUSIONS

Through these four test session the SPHERES team has once again created multiple space firsts:

• Docking using on-line path-planning (including obstacle avoidance)
• Demonstrations of maneuvers relevant to fractionated spacecraft
• Performing “mesh inspections”
• Joint control of two attached spacecraft of similar (equal) mass & authority.

The team will continue to grow upon these results to achieve the remaining goals of the program. Of special importance to the team is to achieve docking to complex rotating targets, continue research of precision formation flight maneuvers with three satellites, and to demonstrate the scenarios for fractionated spacecraft in an integrated test which would simulate a complete mission.

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VII. BIBLIOGRAPHY


