SPHERES 18\textsuperscript{TH} ISS Test Session

Abstract

The SPHERES ISS Test Session 18 occurred on August 15\textsuperscript{th}, 2009 operated by Michael Barratt and Timothy Kopra. The session lasted three hours and thirty minutes and had no major operational difficulties. The issues with the beacon locations seen in Test Session 17 were solved and all beacons were placed correctly. There were, however, issues with the programming of the algorithms: one test did not run properly, and two other tests did not use the desired controller. Seventeen unique tests were run in total during the session.

The one-satellite tests explored fluid slosh, wall collision avoidance, and recovery for a satellite with a failed thruster. The fluid slosh tests looked at the differences in effects due to nearly full and nearly empty fuel tanks. The thruster failure recovery test successfully demonstrated a simple technique to control a spacecraft with a single failed-off thruster. Data from this test will serve as a performance baseline for more robust control techniques, namely Model Predictive Control.

The two-satellite tests explored spiral maneuvers for interferometry. The first spiral test showed that the SPHERES are capable of centimeter-level precision control during a spiral trajectory. The stop and stare test improved on the results from Test Session 14. The diamond test will need to be re-run, as there was an error in the code. Both the Park and Anticipatory tests were not successful, as they used a PID controller instead of the desired advanced controller.

The three-satellite tests explored formation acquisition and fuel balancing. The three lost in space tests validated the three-satellite lost in space algorithm, but were not fully successful due to issues with the onboard beacon. The fuel balancing tests did not show good path following during the fuel-balancing maneuver.
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8 SPHERES Team
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1 Test Session Objectives

The session included the following research topics:

(a) Fluid Slosh
   i. Obtain data on the effects of slosh due to the liquid in the gas tanks of a SPHERES satellite.
   ii. Differentiate slosh effects between the short and long axes of the tank.
   iii. Measure differences in effects of slosh with a (almost) full tank and an (almost) empty tank.

(b) Collision Avoidance
   i. Test a collision avoidance strategy for inspection operations.

(c) Thruster Failure Recovery
   i. Observe the effect of a failed-off thruster on a satellite performing a translation maneuver.
   ii. Obtain data on the performance of a satellite with a failed-off thruster following a simple, human-planned trajectory.

(d) Spiral Maneuvers
   i. Test new methods for fuel-efficient trajectory following and precision control.
   ii. Obtain data to compare performance of controllers while following circular and spiral trajectories.

(e) Formation Acquisition
   i. Demonstrate a Lost in Space algorithm for formation acquisition based on detection and recognition of the other vehicles in the set using relative measurements.

(f) Fuel Balancing Maneuvers
   i. Demonstrate algorithms for fuel balancing strategies in formation flight.

(g) Operations
   i. Ensure that the beacons are entered correctly in the GUI to eliminate the estimation errors seen in Test Session 16 and Test Session 17.

2 Timeline Summary

The MIT team was on console at approximately 1:30 PM GMT on August 15th, 2009, and setup began at approximately 2:00 PM. Setup completed at approximately 3:15 PM. This included a 15-minute break for a meal. Twenty-two tests were run during the session in a total time of 4:30 hours. This included a 1:00 hour break for a conference after test 4 of P265. Table 1 below shows a summary of the tests run during this session. Overall, the test session ran smoothly without any significant operational delays.

<table>
<thead>
<tr>
<th>Program</th>
<th>Test</th>
<th>Description</th>
<th>Start time</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>P264</td>
<td>T1</td>
<td>Quick Checkout</td>
<td>3:29 PM</td>
<td>7:11</td>
</tr>
<tr>
<td></td>
<td>T1</td>
<td>Quick Checkout</td>
<td>3:36 PM</td>
<td>1:54</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>Z Motion Fluid Slosh T1 (partially used tank)</td>
<td>3:38 PM</td>
<td>12:08</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>Z Motion Fluid Slosh T1 (partially used tank)</td>
<td>3:50 PM</td>
<td>6:13</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>Z Motion Fluid Slosh T2 (partially used tank)</td>
<td>3:56 PM</td>
<td>5:53</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>Wall Collision Avoidance: 3D Corner</td>
<td>4:02 PM</td>
<td>14:39</td>
</tr>
<tr>
<td></td>
<td>TA</td>
<td>Z Motion Fluid Slosh T1 (new tank)</td>
<td>4:17 PM</td>
<td>5:34</td>
</tr>
<tr>
<td></td>
<td>TB</td>
<td>Z Motion Fluid Slosh T2 (new tank)</td>
<td>4:22 PM</td>
<td>5:35</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>Wall Collision Avoidance: 3D Corner</td>
<td>4:28 PM</td>
<td>7:50</td>
</tr>
<tr>
<td></td>
<td>T6</td>
<td>Thruster Failure: Simple Trajectory</td>
<td>4:36 PM</td>
<td>15:32</td>
</tr>
<tr>
<td>P265</td>
<td>T1</td>
<td>Quick Checkout</td>
<td>4:57 PM</td>
<td>23:58</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>Spiral</td>
<td>5:21 PM</td>
<td>15:05</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>Spiral: Stop and Stare</td>
<td>5:36 PM</td>
<td>12:03</td>
</tr>
</tbody>
</table>
3 Operations

3.1 Operational Anomalies

During this test session, two anomalies were encountered. The first involved incorrect positioning instructions in an html file. The second involved errors in the code of three tests.

3.1.1 Incorrect Satellite Positioning Directions

The positioning instructions for Test 5 in Group C were not consistent. The positioning instructions in the html file include both text and an image to aid the astronauts in positioning the satellite. The text portion indicated that all satellites should have their tanks pointing towards overhead, but the image showed all tanks pointing towards port. This caused unnecessary confusion when the astronauts were attempting to position the satellites.

3.1.2 Incorrect Code

Tests 5 and 6 in Group B were intended to test two new controllers on SPHERES. However, there was an error in the MIT code that led to the SPHERES using a PID type controller instead of the Park and Anticipatory controllers, as planned. There was a note in the code indicating that this error should be fixed before sending to the ISS. In order to avoid this in the future, MIT will put markers in the code of items that need to be addressed before the program goes to the ISS. All tests will be automatically checked before the SPF files are sent.

Test 4 in Group B also had a coding error that resulted in the satellite performing the maneuver sequence incorrectly. More exhaustive testing before sending the test to the ISS would have revealed this error.

3.2 Consumables Consumption

During the test session, the following consumables were used:

- Batteries:
  - Orange Satellite: PSI02265J (new, depleted), PSI02267J (new, depleted), PSI02231J (new, saved as “used”), PSI02233J (new, saved as “used”)
  - Red Satellite: PSI02232J (new, saved as “used”), PSI02239J (new, saved as “used”)
  - Blue Satellite: PSI02262J (new, saved as “used”), PSI02274J (new, saved as “used”)
- Tanks:
  - Orange Satellite: PSI01103J tank inserted (removed and saved for return PIS01104J)
  - Red Satellite: PSI01087J tank used
4 Results Analysis

4.1 Program 264 “Fluid Slosh and Proximity Operations”

Three types of tests were run in this program, investigating topics in fluid slosh, collision avoidance, and thruster failure recovery. The objectives of the fluid slosh tests were to obtain data on the effects of slosh in the SPHERES tanks, differentiate the slosh between the short and long axes of the tank, and measure the differences in the effects of slosh with an almost full and an almost empty tank. The objectives for the wall collision avoidance test were to demonstrate a method for detecting impending collisions with a surface, and to demonstrate a steering law for avoiding surfaces and concave corners. Both objectives were met. One thruster failure test was run, and its objective was to obtain data to provide a valuable means to compare future thruster failure recovery techniques against.

4.1.1 Program 264, Tests 2, 3, A, and B: Z – Motion Slosh Tests

Four tests were conducted in the first group of Florida Institute of Technology’s Slosh Experiments on the ISS platform provided by MIT’s SPHERES Guest Scientists Program. The Slosh experiments goals were to create a slosh wave with hardware currently available on board the ISS. Linear translation motion profiles hopefully would create a slosh wave of the liquid CO\textsubscript{2} sufficient enough to cause feedback that causes the sphere to fly an undesirable trajectory. The initial thought was that a linear translation from rest with even thrusting would provide a motion that would end at rest. If it continued moving the motion would be a result of the propellant sloshing against the inner walls of the tank. After running this test it is clear that the thrusters caused rotation and we must first characterize the thruster profiles for available spheres prior to directly attributing the undesired motion to slosh.

The goals of the tests are to fly a linear translation motion with an equal and opposite acceleration and deceleration. Any residual motion would be closely scrutinized to determine if it is attributed to the sloshing of liquid CO\textsubscript{2} in the propellant tanks. It is important that the accelerations are large enough to cause substantial reorientation of the fluid. This test is the first group of FIT’s slosh experiments aboard the ISS and will set a base line for further test development.

The tests were broken into two different motion profiles, each with two different fill levels. In order to achieve large accelerations for both phases the thrusters were pulsed twice for 0.8 sec with a 0.2 sec delay between pulses. The motion profiles were different only in that the drift time between the acceleration thrust and deceleration thrust was 4 sec in Test 2 and 5 sec in Test 3. The original plan was to have drift times of 3 sec and 5 sec. The difference in the delay time is an attempt at catching the slosh wave in different locations. Recent ground tests show that the influence of slosh feedback is magnified when the wave is oriented opposite to the wall due to be impacted.

In this report the tests will be discussed as follows because the first two and last two tests are the same motion profiles:

• Test 2: Z Motion Fluid Slosh T1 (partially used tank)
• Test 3: Z Motion Fluid Slosh T2 (partially used tank)
• Test A: Z Motion Fluid Slosh T1 (full tank)
• Test B: Z Motion Fluid Slosh T2 (full tank)

In all tests the crew noted a roll about the x-axis of the SPHERE. This is also seen in the background telemetry data, IMU data, MATLAB simulations and ISS videos. One direct cause for this is equal time length pulse from the thrusters. The KSC-135 thrust scaling report states that the thrusters do not exert equal force. This differential thrust
causes sufficient torque to rotate the sphere about the x-axis. The magnitude of the rotation rate changes depending on the fill level of the tank. It is also noted that the braking thrust, which uses thrusters 11 and 12 (Thrust 3, 4 in Figure 1), causes more rotation than the acceleration thrust, which uses thrusters 5 and 6 (Thrust 1, 2 in Figure 1). The effect of thruster asymmetry is also coupled with a dynamic value of inertia due to redistribution of the liquid propellant. Further tests must be conducted to mark the difference.

![Figure 1. Thruster Balance for all tests using Background Telemetry Data (Left) and IMU Gyro Data (Right)](image)

Estimations of thrust differential were conducted using both the IMU gyroscope data, and the Background Telemetry angular velocity. Assumptions were made based on those in the KC-135 Thrust Scaling Report.

- The center of mass of the SPHERE is at the geometric center
- The thrust vectors are parallel to each other and perpendicular to the sphere faces
- The thruster positions are symmetric with respect to the geometric center
- Thruster 5: [0 9.65 -5.16] (cm)
- Thruster 6: [0 -9.65 -5.16] (cm)
- Thruster 11: [0 9.65 5.16] (cm)
- Thruster 12: [0 -9.65 5.16] (cm)
- The thrust vector produces a moment about only one axis (In this case x)
- The opening and closing delays of the thrusters are negligible

In addition to the above, the following assumptions were applied:

- One thruster is perfect
- Treat increase of angular velocity as linear
- Data samples were taken at 1 sec intervals
- \( I_{xx, \text{wet}} = 0.0230 \text{ kgm}^2 \) (Used for Full Case)
- \( I_{xx, \text{dry}} = 0.019 \text{ kgm}^2 \) (Used for Partial Case)
- Necessary torque was calculated using the equation:
  \[ \tau_{\text{necessary}} = I_{xx} \cdot \alpha_{\text{thrust}, \#} \]
- Differential Thrust was calculated using the equation:
Fill level was calculated using a value of 500000 counts as empty; however in the partially full cases the count value was ~3e6. The notes for the following test T4 state that the tank was empty at the end of 2:00 minutes into the test. The tank count value for empty was taken from that number.

- Partial Fill - Empty Tank Count = 3339000

The values for tank fill seem too small when compared to the amount of propellant that each thrust uses in the full tank tests. The calculated fill levels at the beginning of each test and after each thrust are shown below in Table 2.

<table>
<thead>
<tr>
<th>Percentage Fill %</th>
<th>initial</th>
<th>after thrust 1</th>
<th>after thrust 2</th>
<th>after thrust 3</th>
<th>after thrust 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 Full</td>
<td>66.57</td>
<td>66.36</td>
<td>66.15</td>
<td>65.93</td>
<td>65.72</td>
</tr>
<tr>
<td>T1 Partial</td>
<td>0.96</td>
<td>0.90</td>
<td>0.87</td>
<td>0.81</td>
<td>0.78</td>
</tr>
<tr>
<td>T2 Full</td>
<td>65.63</td>
<td>65.41</td>
<td>65.20</td>
<td>64.99</td>
<td>64.77</td>
</tr>
<tr>
<td>T2 Partial</td>
<td>0.75</td>
<td>0.69</td>
<td>0.66</td>
<td>0.60</td>
<td>0.57</td>
</tr>
</tbody>
</table>

The values for partial fill must be recalculated using a better method for determining the fill level if the counter is not reset. Fill level is an important parameter for tracking the ratio of fluid mass to vehicle mass.

4.1.1.1 P264, Test A - Z Motion Fluid Slosh T1 (full tank)

This test begins with a tank fill of 66.57% two pulses of 0.8 sec are triggered from thrusters 5 and 6 causing a translation in the +Z direction as seen in Figure 2. There is a drift time of 4 seconds before the braking thrust occurs.

The acceleration thrust causes a counter clockwise rotation about the x-axis. In between pulses the rotation rate is constant, during the pulse phase the rotation rate decreases linearly seen in Figure 3 (bottom). During the first
acceleration phase there is missing data. The braking thrust (thrusters 11, 12) causes a larger angular acceleration than the first thrusting. Angular accelerations are listed in table 3.

<table>
<thead>
<tr>
<th></th>
<th>Thrust 1</th>
<th>Thrust 2</th>
<th>Thrust 3</th>
<th>Thrust 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU Gyroscope</td>
<td>-0.019179</td>
<td>-0.020600</td>
<td>-0.045462</td>
<td>-0.046173</td>
</tr>
<tr>
<td>Background Telemetry</td>
<td>-0.021238</td>
<td>-0.016990</td>
<td>-0.045324</td>
<td>-0.046036</td>
</tr>
</tbody>
</table>

The data from the IMU has more noise that the Background Telemetry is displayed in Figure 4 but can be filtered to obtain accurate values for angular velocity and linear accelerations.

![Figure 4. Motion Data from External Sensors T1 Full](image)

4.1.1.2 P264, Test 2 - Z Motion Fluid Slosh T1 (partially used tank)

This test begins with a tank fill of 0.9584% calculated using Figure 5; two pulses of 0.8 seconds are triggered from thrusters 5 and 6 causing a translation in the +Z direction.
The acceleration thrust causes a counter clockwise rotation about the x-axis. Unlike the full tank case the acceleration during this thrust tapers off, additionally the magnitude of the second pulse is less than the first in both the acceleration phase and braking phase. The non-constant thrust in results in an angular acceleration that is also non-constant. Like in the full case, the braking thrust (thrusters 11, 12) caused a larger angular acceleration than the acceleration phase; results are listed in Table 4.

**Table 4. Angular Acceleration for T1 Partial Tank about x-axis**

<table>
<thead>
<tr>
<th></th>
<th>Thrust 1</th>
<th>Thrust 2</th>
<th>Thrust 3</th>
<th>Thrust 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU Gyroscope</td>
<td>-0.002887</td>
<td>-0.002707</td>
<td>-0.005775</td>
<td>-0.003609</td>
</tr>
<tr>
<td>Background Telemetry</td>
<td>-0.002872</td>
<td>-0.002872</td>
<td>-0.005396</td>
<td>-0.003605</td>
</tr>
</tbody>
</table>

For the differential thrust calculations the angular acceleration was assumed to be linear for 1 second periods.
Background telemetry data in Figure 7 is similar to T1 Full case; the major differences can be seen in rotation rate, and position.

4.1.1.3 P264, Test B - Z Motion Fluid Slosh T2 (full tank)

This test begins with a tank fill of 65.63% and two pulses of 0.8 sec are triggered from thrusters 5 and 6 causing a translation in the +Z direction as seen in Figure 8.

![Thruster Activity](image1)

![Accel (top) and Gyro (bottom) for T2 Full](image2)

Figure 8. Thruster Pulses for Test 2

Figure 9. Accel (top) and Gyro (bottom) for T2 Full

The acceleration thrust causes a counter clockwise rotation about the x-axis. The delay from thrust phase to thrust phase for this set of tests is 5 seconds as compared to 4 seconds in the first two tests. In between pulses the rotation rate is constant, during the pulse phase the rotation rate decreases linearly as seen in Figure 9 (bottom). The IMU data for this test is fairly clean, and does not having any missing points like T1 Full. Angular accelerations are presented in Table 5.

<table>
<thead>
<tr>
<th></th>
<th>Thrust 1 (rad/s²)</th>
<th>Thrust 2 (rad/s²)</th>
<th>Thrust 3 (rad/s²)</th>
<th>Thrust 4 (rad/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU Gyroscope</td>
<td>-0.005594</td>
<td>-0.004872</td>
<td>-0.011369</td>
<td>-0.011550</td>
</tr>
<tr>
<td>Background Telemetry</td>
<td>-0.005023</td>
<td>-0.005038</td>
<td>-0.011326</td>
<td>-0.011885</td>
</tr>
</tbody>
</table>

Table 5. Angular Acceleration for T2 Full Tank about x-axis
4.1.1.4 P264, Test 3 - Z Motion Fluid Slosh T2 (partially used tank)

This test begins with a tank fill of 0.7487% and two pulses of 0.8 seconds are triggered from thrusters 5 and 6 causing a translation in the +Z direction. Accelerations and resulting angular velocities are displayed in Figure 11.

The acceleration thrust causes a counter clockwise rotation about the x-axis. Unlike the full tank case the acceleration during this thrust tapers off, additionally the magnitude of the second pulse is less than the first in both the acceleration phase and braking phase. The non-constant thrust results in an angular acceleration that is also non-constant listed in Table 6.

<table>
<thead>
<tr>
<th></th>
<th>Thrust 1 $\alpha (\text{rad/s}^2)$</th>
<th>Thrust 2 $\alpha (\text{rad/s}^2)$</th>
<th>Thrust 3 $\alpha (\text{rad/s}^2)$</th>
<th>Thrust 4 $\alpha (\text{rad/s}^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMU Gyroscope</td>
<td>-0.002346</td>
<td>-0.001443</td>
<td>-0.004512</td>
<td>-0.001624</td>
</tr>
<tr>
<td>Background Telemetry</td>
<td>-0.002325</td>
<td>-0.001431</td>
<td>-0.004141</td>
<td>-0.002337</td>
</tr>
</tbody>
</table>
4.1.1.5 P264 Mechanical Dynamics Simulation Study for Motion Profile T2 with Full Tank

According to the experiment data of T2 with full tank, the uncertainty of thrust force difference between thrusters (shown in Figure 14) and moment of inertia of SPHERE satellite body becomes major factor to influence SPHERE motion trajectories. Therefore, a further study of mechanical dynamics simulation with T2 full tank motion profile is conducted in order to fully understand the relation between thrust force difference and moment of inertia variation.

The simulation modeling is based on two liquid CO2 fill level scenarios:
- 1/3 of the propellant tank is filled with liquid CO2.
- 2/3 of the propellant tank is filled with liquid CO2.

![Figure 13. Motion Data from External Sensors T2 Partial](image)

![Figure 14. Thruster Balance for all tests using Background Telemetry Data (Left) and IMU Gyroscope Data (Right)](image)
The 2/3-fill level is used to replicate the actual full tank test case, while the 1/3 test case is to represent half full case. Note that the 1/3 case does not represent the partial fill cases discussed in previous sections. The 1/3 case is simulated using the same thruster profiles as in the 2/3 case to directly see if reducing the propellant mass by half has a substantial effect on rotational dynamics. The 1/3 case was used internally to discover whether it is worth developing a test matrix that varies fill level. It was noted that it is difficult from an operational standpoint to start SPHERES tests at prescribed fill levels. It is much easier to use a full tank. Motion profiles for future test campaigns will use full tanks. The different simulation cases are shown in Figure 15.

![Figure 15. SPHERE body modeling with different liquid CO2 distribution](image)

### 4.1.1.5.1 Moment of Inertia Study

Moment of inertia is calculated for each of these six models. A comparison of moment of inertia values from MIT and FIT is listed in Table 8. Currently the most accurate moment of inertia values are those measured empirically and provided by MIT. They are used as reference data for this study. A percentage difference between MIT measured data and simulation model calculated data is also shown in the table.

### 4.1.1.5.2 Mechanical Dynamics Simulation with Different Thrust Force Configurations

A total thrust force of 0.22 N in each direction is used for all simulations. Four different thruster imbalance settings in each direction are listed below and demonstrated in Figure 16:

- Even Thrust (0.11 N Each Thruster)
- 1% Difference
- 5% Difference
- 10% Difference
Figure 16. Thrust Force Configurations

The force percentage difference is referred to the total difference between each two thrusters and it is assumed that the difference is evenly divided to each thruster. For example, “1% difference” for Thruster #5 and Thruster #6 means Thruster #5 has 0.5% more thrust force than 0.11 N while Thruster #6 has 0.5% less. Also Thruster #5 and Thruster #12 are always setup as more thrust force than Thruster #6 and Thruster #11. "+/−" is used to mark the difference. Table 7 lists the entire simulation cases based on different liquid CO2 distribution and thrust force configuration.

Table 7. Simulating Cases List

<table>
<thead>
<tr>
<th></th>
<th>Bottom</th>
<th>Side</th>
<th>Round</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even Thrust</td>
<td>1/3 CO2, 2/3 CO2</td>
<td>1/3 CO2, 2/3 CO2</td>
<td>1/3 CO2, 2/3 CO2</td>
</tr>
<tr>
<td>1% Difference</td>
<td>1/3 CO2, 2/3 CO2</td>
<td>1/3 CO2, 2/3 CO2</td>
<td>1/3 CO2, 2/3 CO2</td>
</tr>
<tr>
<td>5% Difference</td>
<td>1/3 CO2, 2/3 CO2</td>
<td>1/3 CO2, 2/3 CO2</td>
<td>1/3 CO2, 2/3 CO2</td>
</tr>
<tr>
<td>10% Difference</td>
<td>1/3 CO2, 2/3 CO2</td>
<td>1/3 CO2, 2/3 CO2</td>
<td>1/3 CO2, 2/3 CO2</td>
</tr>
<tr>
<td>Inertia (kg m²)</td>
<td>MIT CAD Model</td>
<td>MIT* Measured</td>
<td>FIT 1/3 CO₂ Bottom</td>
</tr>
<tr>
<td>----------------</td>
<td>---------------</td>
<td>---------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Ixx</td>
<td>0.023</td>
<td><strong>0.0257</strong></td>
<td>0.0217 (15.6)**</td>
</tr>
<tr>
<td>Iyy</td>
<td>0.0242</td>
<td><strong>0.0225</strong></td>
<td>0.0217 (3.6%)</td>
</tr>
<tr>
<td>Izz</td>
<td>0.0214</td>
<td><strong>0.0203</strong></td>
<td>0.0178 (12.3%)</td>
</tr>
<tr>
<td>Ixy</td>
<td>0.0001</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>Ixz</td>
<td>-0.0003</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>Iyz</td>
<td>0</td>
<td>N/A</td>
<td>0</td>
</tr>
</tbody>
</table>

* Currently MIT measured SPHERE body moment of inertia is the most accurate reference data

** Percentage difference between FIT mechanical modeling and MIT measured data
Figure 17 to Figure 24 show the results from the simulated cases:

**Figure 17. Results 1: Even Thrust Test**

As Figure 17 shows, liquid CO2 symmetric distributed cases (Bottom and Round) have no rotating motion with even thrust force. On the other hand, because of the asymmetric distribution, the SPHERE body with the liquid CO2 on the side causes rotation regardless of an even thrust force.

**Figure 18. Results 2: 1% Thrust Difference Test**

With 1% thrust difference all cases are showing rotating motion in Figure 18. Liquid CO2 on the side cases have larger angular acceleration than other cases. The simulating cases with 2/3 of liquid CO2 in the tank have relatively smaller angular velocity output than 1/3 liquid CO2 cases.
The results in Figure 19 show that angular velocity output is close for the first two thrust pulses for all cases when thrust force difference increases to 5%. But liquid CO2 on the side of the tank cases have maximum angular velocity while the liquid CO2 at the bottom cases have minimum angular velocity.

When thrust force difference is setup to 10%, the angular velocity output from each case becomes closer. Figure 20 shows that the SPHERE body rotation rate mainly changes with thrust force difference after it increases to 10%.
Figure 21. Results 5: Mass Distribution Test (Bottom)

Figure 22. Results 6: Mass Distribution Test (Side)
Figure 23. Results 7: Mass Distribution Test (Round)

Figure 21 to Figure 23 show the comparison of same mass distribution with different thrust force setup. Higher angular velocities are observed for a reduction in mass with a given mass distribution (bottom, side and round).

Figure 24. Results 8: Total Displacement

Figure 24 is the results of total displacement from all cases. The plots show that the mass distribution and the thrust difference have small impact on the SPHERE body total displacement.

4.1.1.5.3 Conclusions for Mechanical Dynamics Simulation Study for Motion Profile T2 with Full Tank

According to the simulation results conclusions are made as follows:

- 2/3 of the propellant tank filled with liquid CO2 at bottom model from FIT has closest moment of inertia values as MIT measured data.

- Lower fill levels cause higher angular velocity and longer drift distance can be obtained because of the mass and moment of inertia variation. Therefore, the thrusters’ setup might need to be readjusted for following tests as a function of fill level.

- The simulation results of liquid CO2 distributing along aside show a higher angular velocity than bottom and round cases because of asymmetry about rotation axis. The SPHERE body motion varies with different liquid CO2 distribution inside the tank.
• Uneven thrust forces from thrusters is a major factor that can dramatically influences angular velocity output but it has minimal impact on total displacement output since the total thrust force from each two thrusters keeps the same (0.22 N).

4.1.2 P264 Test 4: Wall Collision Avoidance

This test demonstrated two technologies for use in satellite inspection operations: 1) a technique for detecting impending collisions with a virtual mesh described by triangular faces, and 2) a steering law to avoid collision with the mesh. The collision detection method propagates a ray in the direction of the satellite’s velocity and in four equally spaced “probe” directions at $\alpha=45$ degrees from the velocity vector (see Figure 25). A fast ray-triangle intersection algorithm efficiently determines potential intersections between the rays and the virtual mesh along with the estimated time to collision. If the collision time is within 4 seconds, the steering law is activated to redirect the velocity of the spacecraft away from the mesh. Avoidance steering is achieved by thrusting with maximum effort in the direction defined by

$$\mathbf{d} = (\mathbf{V} \times \hat{n}) \times \mathbf{V}$$

where $\mathbf{n}$ represents the average normal vector of all triangles that the probes intersect, and $\mathbf{V}$ is the velocity of the satellite. This approach helps to guide the spacecraft out of concave corners.

**Figure 25. Five collision detection rays are determined from the satellite's velocity**

T4 was designed to test the performance of the collision avoidance algorithm by placing the satellite within a set of rectangular virtual walls in the test volume and aiming its initial trajectory to cause a collision. Each wall of the volume consists of two coplanar triangles, oriented to form a rectangular wall as shown in Figure 26 and Figure 27. The initial trajectory was selected in the direction of the intersection of three orthogonal walls to test avoidance of concave corners. Aside from the initial targeting maneuver and the avoidance events, the satellite attempted to maintain a constant velocity of 1.5 cm/s.

**Figure 26. Each virtual wall is composed of two coplanar triangles.**

Two runs of T4 were performed during TS18. In the first run, the satellite performed an initial thrust maneuver in the direction of the corner and then exhausted its propellant, leaving it to drift outside of the virtual boundaries as shown in Figure 27. After exiting the boundaries, the satellite experienced a reset, indicating a potential bug in the
collision detection algorithm when no ray-triangle intersections occur. Future versions will have an explicit contingency for the case of no intersections.

![Trajectory](image)

Figure 27. In the first test of Wall Avoidance, the satellite exited the virtual volume due to an empty propellant tank.

The second run with a fresh propellant tank demonstrated successful wall avoidance behavior. Figure 28 displays a plot of the satellite trajectory with the collision avoidance thrusting directions highlighted in green. Four distinct avoidance events occurred, each of which resulted in directing the trajectory away from the wall. The first event, shown in the inset, produced thrust commands that properly directed the satellite out of the corner. The test was designed to let the satellite perform several additional encounters before terminating. Three subsequent avoidance maneuvers were performed, one with the STBD wall (2), one with the DECK wall (3), and a final maneuver at the intersection of the DECK and PORT walls (4). Each of the maneuvers kept the satellite within the virtual volume, successfully testing avoidance of a plane and a 2D corner.

Due to the large thrust command executed in the steering law, the satellite exited each maneuver with a velocity away from a wall. For eventual applications to inspection, future tests will use a smaller maneuver to achieve a final velocity parallel to the wall.
4.1.3 P264, Test 6 Thruster Failure: Simple Trajectory

The objective of this test was to provide a performance baseline for thruster failure recovery techniques. In past flight missions, such as NASA’s Cassini\(^1\) and ESA’s ATV\(^2\), thruster failure recovery techniques involved functional redundancy. If a thruster failed, the force and torque produced by that failed thruster could be reproduced through a single redundant thruster or a combination of other thrusters. This means that the control allocation module that converts body-fixed forces and torques to thruster actuation commands could be reconfigured to avoid allocating any thrusting commands to the failed thruster and allocate additional thrusting commands to the redundant thrusters. While this is a very effective technique for handling thruster failures, it requires costly hardware redundancy. In future missions with multiple spacecrafts, the additional cost of implementing this type of redundancy on each spacecraft can become prohibitive. This line of research is therefore investigating new techniques for handling thruster failures when the spacecraft has no redundancy and any single failure causes the spacecraft to become under-actuated, with second-order nonholonomic constraints (i.e., constraints on the accelerations that the actuators can produce). Also, it is assumed that thrusters can fail on or fail off. For failed-on thrusters, a valve can be closed converting it to a failed-off thruster. The detection and isolation of these failures is not the primary goal of this research, however research in this topic has been performed extensively in Test Session 2. The primary goal of this test was to test the control of a spacecraft once the thruster failures have been correctly detected and isolated.

This test employs a simple path planning technique to solve this control problem. The path planning uses the fact that a spacecraft can be maneuvered from a zero-velocity state to any other zero-velocity state using two body-fixed torques and one body-fixed force. The path is split into three states: (1) torque is used to orient the spacecraft such that the force is aligned with the desired direction of motion, (2) force is used to translate the spacecraft to the final position.

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position, and (3) torque is used to orient the final attitude of the spacecraft. With this path, the spacecraft can use a regular controller (e.g., PD) to calculate the required forces and torques to follow this path and a control allocator to command the thrusters. This control architecture, however, has two weaknesses. First, the controller may command forces and torques that the control allocator cannot produce. Because of this, disturbances may cause the spacecraft to deviate from the nominal path in such a way that the spacecraft cannot recover. Second, only a single thruster failure can be handled by this path planning technique; additional thruster failures may prohibit the use of this technique since the requisite body-fixed torques and force cannot be produced. These two weaknesses will be addressed by the advanced MPC controller; however the test still provides valuable information as a comparative baseline.

In this test, the satellite positions itself with zero velocity at a position of $r = [-0.3,-0.3,-0.3]^T$ and an attitude of $q = [0,0,0,1]^T$. At this point, thruster 9 (shown in Figure 29) is disabled and the satellite must perform two rotations, a translation, and two inverse rotations to end at a position of $r = [0.3,0.3,0.3]^T$ with the same attitude. Plots of the state of the satellite over time are shown in Figure 30 where the black vertical lines denote maneuver changes and dotted lines in the position and attitude plots indicate commanded values. These plots exhibit excellent control performance, even with thruster 9 disabled, and match the simulated performance closely.
A major concern in this test was the termination conditions for transitioning between maneuvers. An “error sphere” was employed where once the satellite would enter this sphere, the next maneuver would start. A small sphere was required such that the next maneuver would be started with very little velocity, however if the sphere was too small, the satellite would not be able to enter the sphere and transition to the next maneuver. Extensive simulations and ground testing was performed to determine the size of this error sphere. In addition, maneuver timeouts were used to automatically advance maneuvers even if the sphere was not entered. As evidenced by the data, maneuver transitions occurred smoothly and with very little velocity. The values used were: 5 cm for position, 1 cm/s for velocity, 0.9985 for the fourth quaternion, and 0.02 rad/s for angular rate.

The commanded thruster firings are shown in Figure 31. This plot shows the expected firings to start and stop all rotations and translations and confirms that thruster 9 was not used. Further analysis is necessary to determine the robustness of this control technique. Requested thruster 9 firing times must be calculated, which will show the degree to which thruster 9 was required but unavailable. In addition, even though this technique worked this one time it was run, it is possible that different runs with different disturbances and perturbations would have failed. To determine the probability of this occurring, Monte Carlo or a covariance propagation analysis must be performed.

The success of this test provides two performance metrics that can be used to compare to future algorithms: time and fuel used. The total execution time (not including estimator convergence and initial positioning) was 89 seconds and total fuel usage was 2.02% of a tank. An advanced Model Predictive Control algorithm is being developed for the next few test sessions will be compared against this test using these two metrics.

### 4.2 Program 265 “Formation Precision Control”

Program 265 explored spiral trajectories for interferometry. Test 2 showed that the SPHERES are capable of following a spiral trajectory to an accuracy of approximately 1 cm. Test 3 improved on the stop and stare maneuver from Test Session 14. Tests 4, 5, and 6 did not run correctly, due to errors in the code. Test 4 will be re-run in a future session.
4.2.1 P265, Test 2: Spiral

In this test, the two SPHERES satellites independently performed expanding spirals while keeping their –X faces pointing towards the center of the test volume. The goal of this test is to demonstrate control with centimeter precision of two satellites through a spiral maneuver. A similar test was run during Test Session 14, using a different controller. In this test, the satellites use a PID controller. This test was designed to be similar to the circular tests performed in Test Sessions 5 and 7, which also used a PID controller with a revolution rate of 180 seconds per revolution at a separation of 80.0 cm.

A spiral is a useful maneuver for a separated spacecraft interferometer, as several UV points can be sampled throughout the maneuver, providing an improved image. The satellites start with a separation of 26.6 cm and expand to 133 cm while exhibiting two revolutions of a spiral at 180 seconds per revolution. Figure 32 below shows the target and actual positions of the two satellites in the X-Z plane.

![Figure 32. Target and actual position of SPHERES 1 and 2 for P265 T2](image)

The test was run once and was successful. Figure 33 below shows the absolute error for each satellite during the test. The RMS error for SPHERE 1 and 2, respectively during the spiral maneuver was 0.92 cm and 0.85 cm. The relative position error can be seen in Figure 34. The relative RMS error between the satellites during the spiral maneuver was 1.23 cm. A feed-forward term consisting of the centrifugal acceleration caused by the trajectory was added to the control commands to further improve tracking performance. This shows that the SPHERES satellites are capable of centimeter level precision control of a spiral trajectory using a PID controller.
4.2.2 P265, Test 3: Spiral: Stop and Stare

In this test, the satellites perform a single spiral expansion maneuver and hold position at three observation points, spaced by $\pi/2$. This maneuver would be useful for an interferometer; the three stopping points are the places that the spacecraft would make their observations. A similar test was run in Test Session 14 (P235 T6) with different parameters. In this test, the satellites expand from a separation of 53 cm to 106 cm with a revolution rate of 180 seconds per revolution. Each satellite stops at each observation point for 30 seconds. This test was run once, and was successful. Figure 35 shows the target and actual position of the satellites during the test. The stopping positions can be seen on the plot, and show that both satellites overshot the observation points. After overshooting, the satellites attempted to hold position at the observation point, and once the 30-second timeout was completed, the satellites were behind the intended trajectory. This resulted in the large error peaks seen in Figure 36. The black vertical bars in Figure 36 and Figure 37 indicate maneuver changes, making it easier to see where the spiral phases begin and end. The first spiral phase begins at approximately 33 seconds.
Figure 37(b) shows that the relative velocity between the SPHERES satellites was below 0.001 m/s at the end of each observation maneuver. However, the positions were incorrect, which led to the position error after the observation. This low relative velocity would produce a higher quality image than the minimum relative velocity achieved in the Test Session 14 test (which was on the order of 0.01 m/s). The incorrect positions are not as important as the low relative velocity, so this is a positive result. If this test is run again, the test should be modified to reduce overshoot at the observation points. To do this, the satellites should reduce their velocity before reaching the observation points.

Figure 35. Target and actual position of SPHERES 1 and 2 in P265 T3

Figure 36. SPHERE 1 (a) and SPHERE 2 (b) position error, P265 T3
4.2.3 P265, Test 4 Spiral: Diamond

In this test, the SPHERES satellites follow an expanding spiral trajectory while “cutting the corner” to each observation point, separated by π/2. Instead of wasting fuel following the spiral trajectory, the satellites move directly to the next observation point. Figure 38 below shows the intended target states, in the X-Z plane, for the two satellites.

Unfortunately there was a programming error in the test that resulted in the two satellites attempting to move to the next observation point too quickly. Each satellites was to communicate to the other when its position, velocity, and attitude error was low at the observation point, indicating that it was ready to continue to the next observation. However, the error flag was not reset properly, so each satellites thought that it should immediately continue to the next observation point after reaching its initial position. This led to the data not providing any useful science with regards to the objectives. The test was run twice, with similar results each time. The test is scheduled to run in Test Session 20 with the error flag correctly reset.

Figure 38. Target States for P265 T4
4.2.4 P265, Test 5 Park Controller and P265, Test 6 Anticipatory Controller

Tests 5 and 6 were designed to test two nonlinear controllers: Park and Anticipatory. In both tests the two satellites started 60 cm apart and performed a spiral expansion to 100 cm in 180 seconds, performing one revolution of the spiral. Unfortunately a flag in the code that indicated which controller to use was not set properly. Therefore both tests used a PID controller, providing no data on either the Park or Anticipatory controllers. These tests would need to be run again to determine the capabilities of the Park and Anticipatory controllers. Figure 39 and Figure 40 below show the performance of the two satellites in test 5 and Figure 41 and Figure 42 show the performance in test 6. Both have large error near the beginning of the test due to incorrect initial positioning in the code. The average RMS error for each satellite in the two tests was 1.93 cm (excluding the initial positioning error). These tests did not feed-forward the forces due to the spiral trajectory. This indicates that the improved trajectory tracking in test 2 was due in part to adding these forces.

![Figure 39. Target and actual position of SPHERES 1 and 2 in P265 T5](image)

![Figure 40. SPHERE 1 (a) and SPHERE 2 (b) position error, P265 T5](image)
4.3 **Program 266 “Formation Acquisition”**

Program 266 explored both the “lost in space” formation acquisition tests and fuel balancing. The goal of the lost in space tests was to demonstrate a formation acquisition maneuver for three satellites using relative measurements. The fuel-balancing test continued work from a previous test session. The SPHERES onboard beacon did not perform
as expected, so the lost in space tests will be explored further in a future test session. The fuel-balancing test was not successful, as the satellites were not able to accurately follow the desired path.

4.3.1 P266, Tests 2, 3 and 4: Lost In Space Tests

This series of tests was designed to demonstrate formation-capturing techniques using the SPHERES facility. For real formation-flying satellites, if no high-accuracy terrestrial navigation aids like GPS are available, the satellites will be required to create a formation using only relative position measurements, though the global attitude knowledge may be obtained by using a star tracker. Such formation capturing procedure will consist of the following four stages:

1. The multiple satellites are deployed without *a priori* knowledge of the other satellites’ positions (“lost in space’”), emulating a release from a launch vehicle or a case of contingency.
2. The satellites capture the other satellites within their relative sensor range, which typically has a limited field-of-view (FOV).
3. The satellites null their range rates.
4. The satellites position themselves within an array.

Several tests were performed in Test Session 7 with two satellites. These tests were designed to begin the development of the lost in space algorithm for three satellites. The tests involve only steps one and two above, as in Test Session 7.

The SPHERES satellites can directly simulate a system with a directional transmitter and an omnidirectional receiver. Each SPHERES satellite has an onboard ultrasound (U/S) transmitter, which emulates a sensor of an actual system with a limited FOV. The satellites are also equipped with 24 U/S receivers (4 on each of 6 faces), enabling the satellite to receive the U/S signal from any direction. The satellites use an omnidirectional communication channel for the satellite-to-satellite communication.

The three tests performed are of increasing complexity. In the first test, all three satellites begin with their U/S transmitters pointing towards the middle of the formation and do not need to perform much movement to achieve the desired formation. In the second test, one satellite begins with its transmitter facing away from the center of the formation, while the other satellites begin with their transmitters pointed towards each other. In the third test, all three satellites begin with their transmitters facing outwards, and must perform a search to locate the other satellites. In all three tests the satellites actively hold their position, to limit drift, but do not use the global position information for any of the formation capture. The satellites also have global attitude information.

There are three main phases to the three satellite lost in space algorithm. Figure 43 below shows the progression of steps from an overhead view, with the satellites starting with their beacon faces starting away from each other.

1. Each satellite performs a three-dimensional search maneuver (a “peal”) until either the SPHERES’ beacon is received by another SPHERE or the satellite receives a beacon transmission from another SPHERE. The two SPHERES that first locate each other become “partners.”
2. The two satellites that are partners point their beacon faces towards each other using the relative measurements. At the same time, the third satellite points its beacon face at one of the other two satellites (which ever it locates or is located by first). So, one satellite will have two satellites pointing at it, and is now “primary”
3. Once the errors are low, the satellite that originally partnered with the primary satellite will point its beacon face at the third satellite.
The satellites could also finish in an alternate orientation, with SPHERE 1 pointing its beacon face at SPHERE 3, SPHERE 3 pointing its beacon face at SPHERE 2, and SPHERE 2 pointing its beacon face at SPHERE 1.

4.3.1.1 P266, Test 2 L.I.S.: Inward Facing

In this test, the three SPHERES begin the test in an equilateral triangle, separated by 60 cm. All SPHERES have their beacon (-X) faces pointed towards the center of the formation. Figure 44 below shows the desired initial and final positions of the three SPHERES for this test.

This test was run twice, and neither run was successful. During the first run, the Blue SPHERE lost communication, so the test was stopped before any useful data could be recorded. During the second run, the global estimator did not converge properly, and the test was stopped before the SPHERES were able to assemble into a formation. The reasons for the errors are unknown, but the subsequent tests were both successful, so Test 2 was not run again. These tests occurred during loss of signal from the space station, so MIT was unable to request the test to be re-run.
4.3.1.2 P266, Test 3 L.I.S.: One Outward Facing

In this test, SPHERE 1 began the test with its beacon face facing away from the center of the formation. SPHERES 2 and 3 began with their beacon faces pointing towards each other, and slightly away from the center of the formation, as seen in Figure 45a. Figure 45b shows a possible final configuration for the formation.

![Figure 45. Initial (a) and Final (b) desired positioning for P266 Test 3, overhead view](image)

The test mostly performed as expected, and was successful. The satellites successfully located each other using the onboard beacons and rotated into the desired formation. However, the FOV of the beacon was shown to be much larger than expected. SPHERE 1 immediately saw the beacons of both SPHERE 2 and SPHERE 3, before either of those satellites began rotating. So, since it already saw both beacons, SPHERE 1 did not need to perform the pealing maneuver to search for the other SPHERES. Instead, SPHERE 1 immediately began to rotate towards SPHERE 2. As it was rotating, SPHERE 2 saw SPHERE 1’s beacon quite early as well - only a few seconds after SPHERE 1 began rotating, at time t=40 seconds. Figure 49 shows the angle between satellites. SPHERE 2 was able to see SPHERE 1’s beacon when the angle between them was greater than 120 degrees.

Figure 46, Figure 47, and Figure 48 below show the relative estimates made by each SPHERE, as well as the global attitude of each SPHERE. The purple vertical bars indicate a maneuver change. The first three maneuvers are the same for all satellites. The first maneuver, from 0-11 seconds, is estimator convergence. During the second maneuver, from 12-32 seconds, the satellites move to their initial positions. During the third maneuver, the satellites determine if either their beacons are seen by another satellite, or if they can see another satellite’s beacon.

In this test, SPHERE 1 and 2 are partners, as described in section 4.3.1. SPHERE 1 and 2 pointed at each other, and SPHERE 3 pointed at SPHERE 1 (starting at 38 seconds). After the error was low, SPHERE 2 switched and pointed at SPHERE 3 (at 61 seconds). The final configuration was therefore SPHERE 1 pointing at SPHERE 2, SPHERE 2 pointing at SPHERE 3, and SPHERE 3 pointing at SPHERE 1.
S1 begins estimation of S2, points towards SS2

S2 begins estimation of S1, points towards S1

S2 begins pointing towards S3

Figure 46. SPHERE 1’s relative estimate of SPHERE 2’s position and SPHERE 1’s global attitude

Figure 47. SPHERE 2’s relative estimate of SPHERE 1’s position and SPHERE 2’s global attitude
Figure 48. SPHERE 3’s relative estimate of SPHERE 1’s position and SPHERE 3’s global attitude

Figure 49 shows the pointing error for each SPHERE for the test. The vertical bar labeled “1” indicates when SPHERE 1 begins pointing towards SPHERE 2, SPHERE 2 begins pointing towards SPHERE 1, and SPHERE 3 begins pointing towards SPHERE 1. Then, at vertical bar 2, SPHERE 2 switches from SPHERE 1 and begins pointing at SPHERE 3. The figure shows that SPHERE 3’s final pointing error is around 15 degrees, indicating that there was poor relative estimation, resulting in SPHERE 3’s inability to point correctly.

Figure 49. Pointing error between SPHERES
4.3.1.3 P266, Test 4 L.I.S.: All Outward Facing

In this test, all three satellites begin with their beacon faces pointing away from the center of the formation, as seen in Figure 43(1). In this orientation, none of the SPHERES should be able to receive from the other SPHERES’ beacons. All three SPHERES should therefore perform the pealing maneuver in order to locate the other satellites. However, only SPHERE 2 actually began the pealing maneuver. SPHERE 1 immediately saw SPHERE 3’s beacon and began estimation. Two seconds after SPHERE 1 began rotating towards SPHERE 3, SPHERE 3 also saw SPHERE 1’s beacon and began estimation. Meanwhile, SPHERE 2 began the pealing maneuver, but soon saw SPHERE 1’s beacon, and stopped the peal. Figure 50, Figure 51, and Figure 52 below show the relative estimation and global attitude of SPHERE 1, SPHERE 2, and SPHERE 3, respectively. The purple vertical bars indicate maneuver changes, and the vertical blue bars indicate an action made by the SPHERE, described by the accompanying text.

The relative estimation done by SPHERE 1 of SPHERE 3’s position, as seen in Figure 50, was poor at the start of estimation. This was due to the SPHERES pointing away from each other at the beginning of estimation. SPHERE 1 was receiving SPHERE 3’s beacon through muli-path. The beacon either bounced off a wall, another SPHERE, or another object to make it possible for SPHERE 1 to receive the data.

The test completed successfully. SPHERE 1 and SPHERE 3 were partners, as they were the first to see each other’s beacons, and pointed at each other. SPHERE 2 pointed its beacon face towards SPHERE 1. After the error was low, SPHERE 3 switched and pointed its beacon towards SPHERE 2. This completed the formation, with SPHERE 1 pointing at SPHERE 3, SPHERE 3 pointing at SPHERE 2, and SPHERE 2 pointing at SPHERE 1.

Due to the issues with the onboard beacon, future tests will not use the onboard beacon. Instead, each satellite will communicate its global state to the other satellites and then calculate the relative states. These relative states will only be used if the angle between the –X face of one satellite and the center of another satellite is within 60 degrees (the angle the onboard beacon should transmit at). By using the global data, we can synthesize a receiver with any cone of view, making it easy to change the size of the cone. Successful tests could also lead to omnidirectional transmitters and directional receivers, expanding beyond what the SPHERES beacon currently allows us to do.

Figure 50. SPHERE 1's relative estimate (body frame) of SPHERE 3's position and SPHERE 1's global attitude
Figure 51. SPHERE 2's relative estimate (body frame) of SPHERE 1's position and SPHERE 2's global attitude

Figure 52. SPHERE 3's relative estimate (body frame) of SPHERE 1's position and SPHERE 3's global attitude
Figure 53 shows each the pointing error for each SPHERE during the test. Point 1 indicates when SPHERE 1 begins pointing towards SPHERE 3. Point 2 indicates when SPHERE 2 begins pealing and SPHERE 3 begins pointing towards SPHERE 1. Point 3 indicates when SPHERE 2 stops pealing and begins pointing towards SPHERE 1. Finally, point 4 indicates when SPHERE 3 is pointing sufficiently at SPHERE 1 and begins pointing at SPHERE 2. The final pointing error is below 10 degrees for all three SPHERES.

![Figure 53. Pointing error between SPHERES](image)

### 4.3.2 P266, Test 5: Online Fuel Balancing

When the total number of maneuvers of a formation flight mission, or their sequence, is not known in advance, it may be desirable to maintain a similar level of propellant in the different satellites, thereby ensuring that they all have the same future potential control authority before their consumables are depleted and the mission is compromised. In the particular case of formation flying interferometers, the exact number of astronomical targets that will be imaged and their location in the sky is not known at the start of the mission. If the targets are placed in a disadvantageous way, and the interferometer is made to track time-fuel optimal paths, circumstances may arise such that one particular sub-aperture in the fleet could be called upon to perform larger control efforts over the course of the mission than the others, leading to the depletion of fuel in that one satellite, rendering it inoperable and bringing the mission to a premature end. A trajectory that attempts to balance fuel use among the apertures could lead to a greater total number of targets observed, despite the fact that more fuel is used overall.

This test is the second in a series aimed at demonstrating fuel-balancing trajectories in space. The first test was performed in Test Session 14 (P237 T9), in which a trajectory was designed offline to balance the amount of propellant in the satellites while they perform a spiral maneuver relative to each other by solving an optimization problem with an objective function penalizing tracking error, fuel consumption, and differences in propellant levels in the satellite tanks.

The test started with a 10-second maneuver during which the satellites drift, to allow the estimator to converge. The satellites then point to the center of the formation and go to initial positions, an equilateral triangle in the Y=0 frame in ISS coordinates. During the next maneuver, the satellites track the trajectory. Their motion relative to each other is an Archimedean spiral, starting with a 50cm radius and finishing with a 30cm radius after one rotation. The test concluded with a brief stopping maneuver.
Figure 54 and Figure 55 show the actual and target positions of the three SPHERES during the spiral maneuver. There is an initial error due to incorrect initial conditions in the code. The initial positioning error caused the largest problem for satellite 1, as it had a large velocity in the –Z direction at the start of the spiral maneuver, resulting in overshoot. The satellites did not track the trajectory well compared with similar tests using the same PID controller. The reason for the poor tracking is still being analyzed, and this section will be updated when the analysis is complete.

Figure 54. Positions and targets of 3 SPHERES for P266 Test 5

Figure 55. Target states (left) and actual states (right) for the fuel balancing maneuver. Triangles indicate the initial configuration of the formation (smaller triangle) and the final configuration of the formation (larger triangle).
5 Conclusions

The one-satellite slosh tests were overall successful in collecting a foundation of data for CFD input, and future motion profile development. In the fluid slosh tests, both the IMU and Background telemetry data are suitable for the input in the CFD models that use dynamic mesh. Presently the Test Session 18 data is being analyzed to determine if the accelerations achieved by the thrusters is large enough to cause steady state settling. A repeatable initial condition for propellant distribution is needed for CFD simulations. Future tests will attempt to cause steady state settling prior to the simple motion profile. This will be achieved by having a spin-up phase prior to the translation. The next set of profiles will also include an investigation on adverse thrust by repeating motion profile for the same satellite in reverse. By using the same sphere any new data will support existing simulation models as well as determine the effect of the braking maneuver. If the braking maneuver in both directions causes a larger angular acceleration, then the motion cause could be attributed to a slosh event. It could be beneficial to conduct the T2 profile with a full propellant tank using another sphere. The thruster differences are likely to differ from the orange sphere.

The thruster failure recovery test provided valuable data on a simple method of recovering from a single thruster failure. An advanced technique using MPC is being developed for future tests, which will address some of the robustness issues with using this simple technique. These tests will use data gathered in this test session as a performance baseline.

The Wall Collision Avoidance test successfully demonstrated wall avoidance behavior. Future tests will examine less aggressive maneuvers to avoid walls.

The two satellite tests were partially successful. The spiral test showed that the SPHERES are capable of precisely following a spiral trajectory. The stop and stare test improved on the results from Test Session 14 by reducing the revolution rate of the spiral. Due to programming errors in the tests, neither the diamond test nor the advanced nonlinear controller tests performed correctly.

The three satellite tests were also partially successful. The lost in space algorithm was partially validated, as the SPHERES successfully formed the desired formation. However, the field of view of the onboard beacon was much larger than expected, resulting in the SPHERES not needing to perform the pealing maneuver. In future tests, the SPHERES will use global data to calculate the relative states. The fuel balancing maneuver was not successful, as the SPHERES were not able to accurately follow the desired path.

6 Lessons Learned

- The successful thruster failure recovery test provided very useful data on values that should be used for “error sphere” termination conditions. The following values have been tested and verified on the ISS for SPHERES: 5 cm for position, 1 cm/s for velocity, 0.9985 for the fourth quaternion, and 0.02 rad/s for angular rate.
- Add contingency actions for off-nominal behavior to prevent satellite resets.
- The onboard beacon should not be used for future lost in space tests, as the field of view of the beacon is larger than expected, and can be affected by multi-path issues. This should also be taken into account for other tests using the onboard beacon. It is important that the test that is running is testing the limits of the algorithm, not the limits of the SPHERS hardware.
- All tests should be checked for any action items before being sent to the ISS. In the case of the Park and Anticipatory tests, the author of the tests was not present when the tests were put together. There were still action items that needed to be addressed before sending the test to the ISS, and the author marked those items as such. However, the code was not checked for action items, which resulted in the tests using the incorrect controller.

7 Future Actions

- In order to ensure that the html files that are uploaded are representative of the desired initial conditions, the test plan and htmls should be created through a more automated system, ensuring that all htmls look the same, as well.
• A corrected version of the Spiral: Diamond test will be re-run in Test Session 20.
• Create a script to check all tests for action items that need to be addressed before sending the test to the ISS.

8 SPHERES Team

The SPHERES team members who played a direct role in the preparation, operation, and data analysis part of Test Session 18 are identified in Table 9. This group is in addition to the support of the SPHERES sponsor at JSC, the DoD Space Test Program.

Table 9. SPHERES Team Members for TS18

<table>
<thead>
<tr>
<th>Principal Investigator</th>
<th>Prof. David W Miller</th>
<th>ScD ’88</th>
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<tbody>
<tr>
<td>Lead Scientist</td>
<td>Dr. Alvar Saenz Otero</td>
<td>PhD ’05</td>
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<td>MIT Graduate Students</td>
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<tr>
<td>Jacob Katz</td>
<td>PhD Candidate</td>
<td>Collision Avoidance</td>
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<tr>
<td>Christophe Mandy</td>
<td>PhD Candidate</td>
<td>Advanced Controllers and Fuel Balancing</td>
</tr>
<tr>
<td>Caley Burke</td>
<td>Masters Student</td>
<td>Fluid Slosh</td>
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<tr>
<td>Jack Field</td>
<td>Masters Student</td>
<td>Spirals and Lost in Space, Editor</td>
</tr>
<tr>
<td>Christopher Pong</td>
<td>Masters Student</td>
<td>Thruster Failure</td>
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<tr>
<td>Enrico Stoll</td>
<td>Postdoctoral Associate</td>
<td>Operations</td>
</tr>
<tr>
<td>Jaime Ramirez</td>
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<tr>
<td>Martin Azkarate</td>
<td>Visiting Student</td>
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<tr>
<td>MIT Undergraduate Students</td>
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<tr>
<td>David Sternberg</td>
<td>Class of 2012</td>
<td>Operations</td>
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<td>Aurora Flight Sciences</td>
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<tr>
<td>John Merk</td>
<td>Program Manager</td>
<td></td>
</tr>
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9 Revision History

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<td>Initial draft</td>
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<tr>
<td>09/11/08</td>
<td>0.2</td>
<td>Updated results, conclusions, lessons learned, future actions, abstract</td>
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<td>alvarso</td>
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<tr>
<td>09/12/02</td>
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