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SPHERES DEMONSTRATIONS OF SATELLITE FORMATIONS ABOARD THE ISS

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Starting in 2007 the SPHERES team expanded its research operations aboard the ISS to include algorithms for formation flight systems. Based on the experiences learned by developing complex docking algorithms, the team began research to mature algorithms to perform imaging maneuvers and add autonomy to allow a formation system initialization and safing in case of failures. The imaging maneuvers research started with basic circular motion of independent satellites; these tests were highly successful. Next spiral maneuvers were performed. These proved more challenging as two things were changed in the tests: the dynamics of the system and the controller. Initial fixes to the controller improved performance, but not sufficiently. A distributed control algorithm, cyclic pursuit, was implemented, yielding high quality results. The autonomy algorithms included formation initialization from random locations and in random orders. The tests were partially successful, allowing the team to propose a potential algorithm and providing insight into potential failures modes of such algorithms (which were not exhibited during simulation). The scatter of a formation was demonstrated and subsequently used in the recovery part of a simulated thruster failure. A communications failure algorithm was implemented, but the tests aboard the ISS were not successful. A collision avoidance algorithm with low overhead was demonstrated. The data obtained from this test enables the team to validate the methods used to determine the size of safety areas between the satellites in a formation flight system, especially during reconfiguration of the constellation.

INTRODUCTION

The Synchronized Position Hold Engage Re-orient Experimental Satellites¹ (SPHERES) have operated aboard the International Space Station since May 2006. The long-duration program continues to provide valuable information for scientists at the MIT Space Systems Laboratory and an array of guest scientists from other institutions. The major milestones of 2006 were achieved in the advancement and demonstration of docking algorithms². Throughout 2007³ and 2008 the research SPHERES expanded to include substantial research in formation flight algorithms. Table 1 presents a summary of the test sessions (TS) which have helped mature new algorithms for formation flight systems.

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Table 1. SPHERES ISS Test Session with Formation Flight Research.

| TS | Date | Science |
|----|---------------|--|
| 7 | Mar 24, 2007 | 2-Sat Lost-in-Space ⁴ , 3-Sat Formation Flight ⁵ |
| 8 | Apr 27, 2007 | 3-Sat Formation Flight* |
| 10 | Dec 12, 2007 | 2-Sat Formation Initialization & Scatter |
| 11 | Jan 27, 2007 | 2-Sat Formation Initialization & Scatter |
| 12 | Aug 30, 2008 | 2-Sat Spiral Formations |
| 13 | Sep 27, 2008 | 3-Sat Collision Avoidance |
| 14 | Oct/Nov, 2008 | 3-Sat Simulated comm & thruster failures, 2-Sat Spiral Formations |

Three-satellite formation flight experiments began in TS7 with basic circular formations. The research then grew into two main areas: control of rotating formations and algorithms to provide autonomy for distributed satellite systems. An extensive set of algorithms was developed based on the need for satellite formations to reconfigure in response to operational goals and the status of individual satellites. The SPHERES developments include tasks on four main areas:

- Imaging maneuvers: creation of circles and spirals to simulate the motions of potential separated spacecraft radar/telescopes.
- Formation acquisition: algorithms to initialize a formation from random initial conditions, including “Lost-in-space” algorithms, optimally joining an existing formation, and random selection of a formation leader.
- Formation maintenance: geometry reconfiguration, low-level collision avoidance, use of different sensor information, and changing between relative and absolute frames of reference.
- Fault detection and recovery: reconfiguration after a (simulated) satellite failure (sensors, actuators, and/or communications), scattering of operational satellites to avoid a failed satellite.

This paper presents the latest results of the SPHERES tests geared toward formation flight missions. A short overview of the SPHERES program introduces the reader to the SPHERES hardware and operations aboard the ISS. Next, the sequence of tests to develop increasingly complex and better imaging maneuvers is presented. Lastly, the results of the autonomy algorithms for distributed satellite systems are analyzed. This paper specifically discusses the results of formation initialization, scatter, collision avoidance, and reactions to simulated communications and thruster failures.[†]

SPHERES OVERVIEW

The SPHERES laboratory for Distributed Satellite Systems⁶ consists of a set of tools and hardware developed for use aboard the ISS and in ground based tests. Three micro-satellites, a custom metrology system (based on ultrasound time-of-flight measurements), communications hardware, consumables (tanks and batteries), and an astronaut interface are aboard the ISS. Figure 1 shows the three SPHERES satellites being operated aboard the ISS during TS 13. The satellites operate autonomously, after the crew starts the test, within the US Destiny Laboratory. The ground-based setup consists of an analog set of hardware: three micro-satellites, a metrology system with the same geometry as that on the ISS, a research oriented GUI, and replenishable consumables. A “guest scientist program”⁷ provides documentation and programming interfaces which allow multiple researchers to use the facility.

* To be published separately. See <http://ssl.mit.edu/spheres/library.html> for latest publications.

[†] The results for “Lost-in-Space” are presented in Ref. 4; results on changing planes during circular formation flight are presented in Ref. 5.



Figure 1. SPHERES Operations aboard the International Space Station. (NASA)

The SPHERES satellites were designed to provide the best traceability to future formation flight missions by implementing all the features of a standard thruster-based *satellite bus*. The satellites have fully functional propulsion, guidance, communications, and power sub-systems. These enable the satellites to: maneuver in 6-DOF, communicate with each other and with the laptop control station, and identify their position with respect to each other and to the experiment reference frame. The computer architecture allows scientists to re-program the satellite with new algorithms. The laptop control station (an ISS supplied standard laptop) is used to collect and store data and to upload new algorithms. It uses the ISS network for all ground data communications (downlink and uplink). Figure 2 shows a picture of an assembled SPHERES satellite and identifies its main features. Physical properties of the satellites are listed in Table 2.

Table 2. SPHERES Satellite Properties.

| | |
|---------------------------|------------------------|
| Diameter | 0.22 m |
| Mass (w/tank & batteries) | 4.3 kg |
| Max linear acceleration | 0.17 m/s ² |
| Max angular acceleration | 3.5 rad/s ² |
| Power consumption | 13 W |
| Battery lifetime | 2 h |

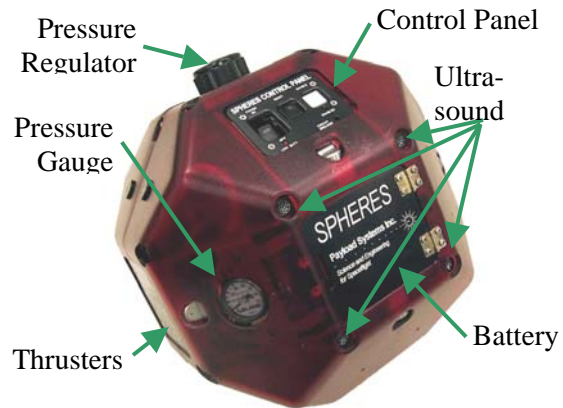


Figure 2. SPHERES Satellite.

IMAGING FORMATIONS

A primary objective of formation flight mission is to enable the creation of very large imaging systems in space, including both radar and telescope systems. This concept has been widely discussed in the scientific community in missions such as the Terrestrial Planet Finder⁸, DARWIN,

and the Stellar Imager⁹. The use of separated space-based radar is also popular¹⁰. These missions require that the satellites maintain and rotate the formation. The SPHERES team has researched two main types of imaging formations: circular and spiral motion. This section presents the results of several of these tests during Test Sessions 7-14. More importantly, the lessons learned from the increasing complexity of the tests are presented.

Circular Formation Flight

Circular formations of three satellites took place during TS 7. In this test each satellite initialized to a pre-determined position and then moved on a pre-programmed circular plan. Each satellite operated independently. The satellites used PID control with gains obtained during the docking experiments. Data analysis shows that the satellites:

- 1) Correctly calculated the circular path to follow.
- 2) Were able to follow the path with acceptable performance.
- 3) Required communications synchronization the tests to work.

Figure 3 shows the telemetry data from the three satellites performing formation flight. The satellites began well aligned and performed the circle smoothly; the blue satellite, which was low on fuel, had the largest errors; approximately 5cm errors throughout. The red and orange satellites maintained formation within 2cm. At the end of the test the blue satellite ran out of fuel, which can be observed by it deviating substantially from the circle, moving away due to centrifugal forces. The success of this test allowed the team to increase the complexity of the maneuvers towards spiral tests, which have similar dynamics but add one level of complexity by having a non-zero radial velocity.

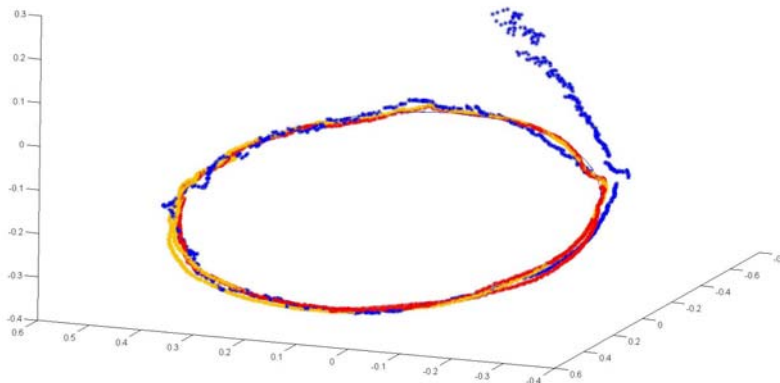


Figure 3. 3-satellite circular formation flight during Test Session 7.

Spiral Formations during TS12

The goal of this test was to demonstrate the control of two satellites through a spiral maneuver. 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. Another objective of the test was for the controller to optimize fuel consumption during the maneuver. The team used a phase-plane LQR (“switchLQR”) controller to perform the spiral. In the test the two satellites

start 0.2m apart and have 120s to perform the spiral expansion to a separation of 0.3m. The satellites travel in the same plane, in opposite directions, without rotating. Figure 4 shows the target and actual X and Y position of the satellites as they spiraled outwards in a 2D plot.

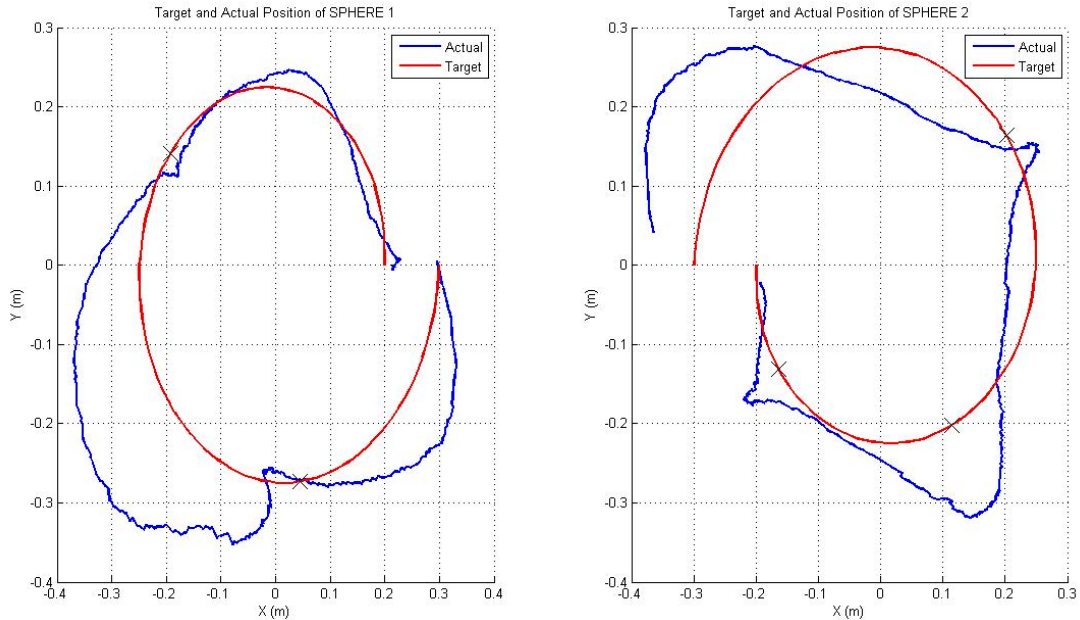


Figure 4. Spiral Maneuver, X-Y Position results in TS12.

While both SPHERES completed the test, the results were not successful. The satellites attempted to follow the spiral path, but the position error was very high throughout the test. After analyzing the data, it was determined that there was an error with the switchLQR controller that caused the observed issues.

This test demonstrated the importance of not changing too many variables at one time. While the circular formation provided exceptional results, the spiral formations tests failed during this first attempt because of the introduction of a new controller. The controller was fixed for the next iteration.

Spiral Formations during TS14

After correcting the error in the switchLQR controller, the test was attempted again during TS14. Figure 5 shows the target and actual paths of the satellites in the X-Y-Z plane. The position error remained within approximately five centimeters throughout the test, achieving the goal of centimeter level precision control. However, the precision is not as good as what was observed during the circular formation flight. This is an important result, as it indicates that by simply changing the maneuver from a standard circle to a spiral, there exist new dynamics that require the control algorithms to change substantially.

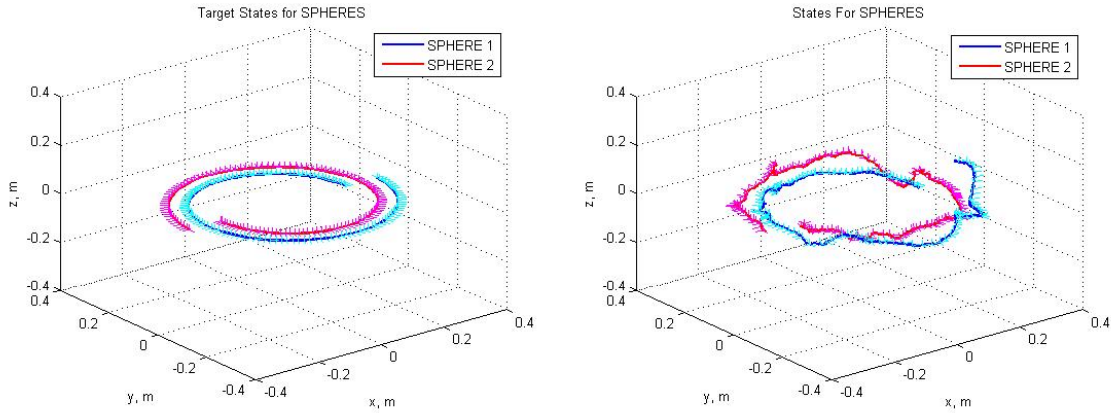


Figure 5. Spiral Maneuver, X-Y Position results in TS14.

Cyclic Pursuit during TS14

The SPHERES team prepared a separate set of algorithms to demonstrate formations in TS 14. Rather than following paths independently of each other, this test demonstrates the capabilities of the *cyclic pursuit*¹¹ algorithm, which uses the relative information to one (and only one) other vehicle in the formation to control each satellite's position. It can be used to perform circular trajectories, ellipses, spirals, reconfiguration maneuvers, and addition of vehicles, among others. The test was divided into three parts:

1. Perform a circular rotation maneuver in the x-z plane.
2. Change the radius and transition through a spiral.
3. Follow an elliptical pattern to demonstrate the ability of the algorithm to achieve non-circular formations.

The test ran successfully demonstrating the capabilities of a cyclic pursuit-based algorithm; the results are shown in Figure 6. The satellites achieved a circular rotating formation, although the intended radius of 0.5m was not exactly achieved*. Next, the satellites spiraled out to achieve a larger formation size (Figure 6a). Lastly, a transformation to achieve a slightly elliptical formation with eccentricity 0.8 occurred (Figure 6b). Overall, the performance of the algorithms was satisfactory. The errors are substantially less than those observed during the standard spiral maneuvers.

Through this series of tests SPHERES demonstrates its unique capability to enable incremental algorithm development in a low risk environment. The SPHERES team was able to take the risk to develop unique new controllers, always learning important steps without risking losing a mission. One controller was not successful (switchLQR), while a second one achieved the performance desired (cyclic pursuit). These tests also provided important insights into the fact that small dynamic changes to formations (from a circle to a spiral) require more controller changes than simply modifying the target. In this series the use of relative information between the satellites provided substantial improvements.

* The effects of time discretization cause divergence in the radius of the formation which has to be compensated by adjusting the pursuit angle

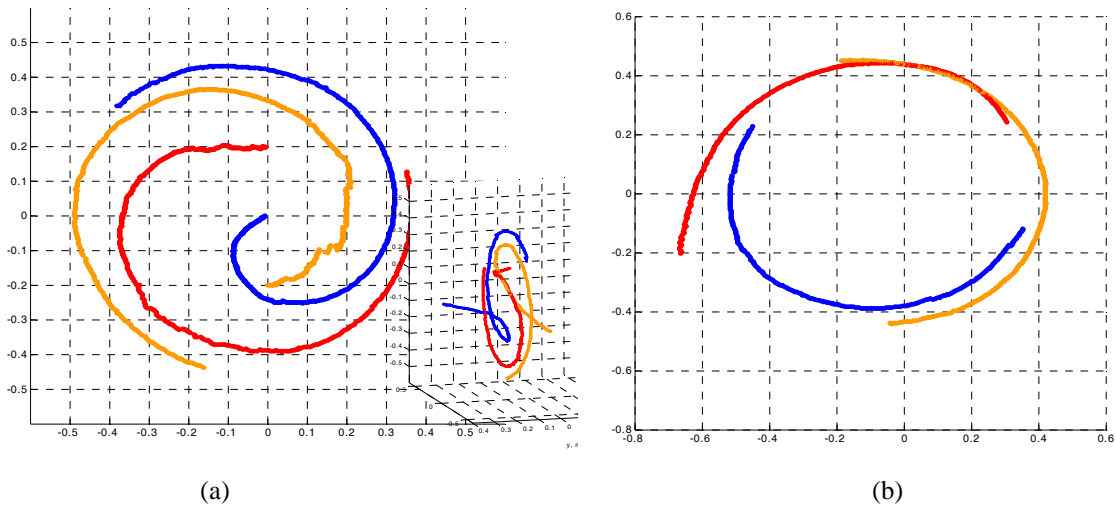


Figure 6. Cyclic Pursuit results during TS14.

ALGORITHMS FOR FORMATIONS

This section presents the results for four types of algorithms that will enhance the autonomy of formation flight systems. These tests are: formation initialization, scatter, collision avoidance, and fault-detection and isolation with simulated failures. Formation initialization and scatter tests have gone through a full iteration, while the other algorithms have only been tested once. The process and lessons learned during the iterations are highlighted.

Formation Initialization

In the likely event that formation flying satellites are deployed from their launch vehicles in random order, it is important that each satellite be independently capable of creating a formation or joining an existing one. In TS10, a formation initialization test using a leader-follower method was designed to demonstrate the ability of three satellites to join a circular formation pattern in a random order. The initialization order was selected by the crew, who randomly pushed the satellites one-by-one into the test volume after they had settled at their specified starting positions. In addition to initializing the formation, the first satellite to be pushed was programmed to request leadership of the formation from other satellites.

The first run of the formation initialization test was disrupted by a communications error that caused the primary satellite to prematurely terminate execution just as the satellites reached their starting positions. Without a functioning primary satellite, the remaining satellites ceased to receive metrology updates, putting their estimation into propagation-only mode. The resulting behavior, pictured in Figure 7, shows an example of an uncoordinated formation initialization in the presence of a major navigational sensor failure. Both the secondary and tertiary satellites attempted to join the formation but failed to follow the circular path due a poor estimation solution. It should be noted that due to the failure of the first satellite, leadership was not transferred to the secondary satellite. Thus, the intended equal spacing between satellites in the final circular formation could not be achieved.

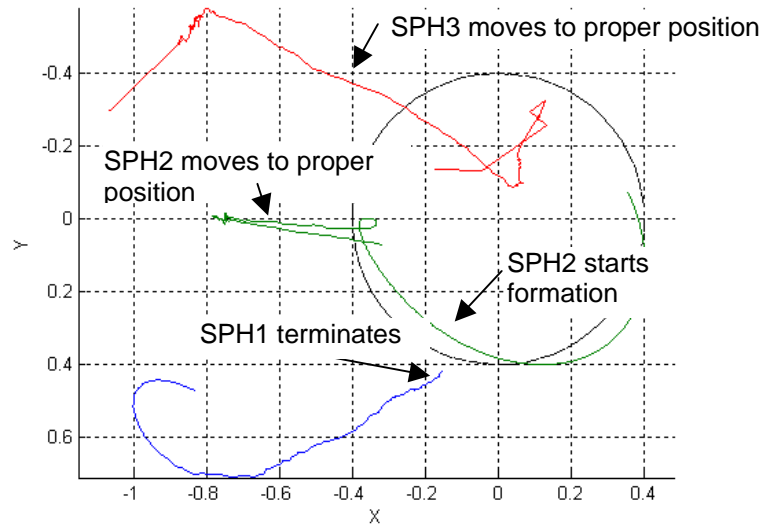


Figure 7. Top down view of initialization.

A two-satellite version of the formation initialization test was repeated in TS11 to reduce the probability of disruptions from errors outside of the algorithm. In this test, the satellites appeared to “self-initialize,” first reaching their initial positions, then turning to start the circular formation without a push from the crew. While unexpected, this resulted in formation initialization. As shown in Figure 8, after the erroneous initializations, both satellites managed to join the formation. However, another communications failure prevented a leadership assignment in this test as well, which indicates the satellites independently attempted to start the formation.

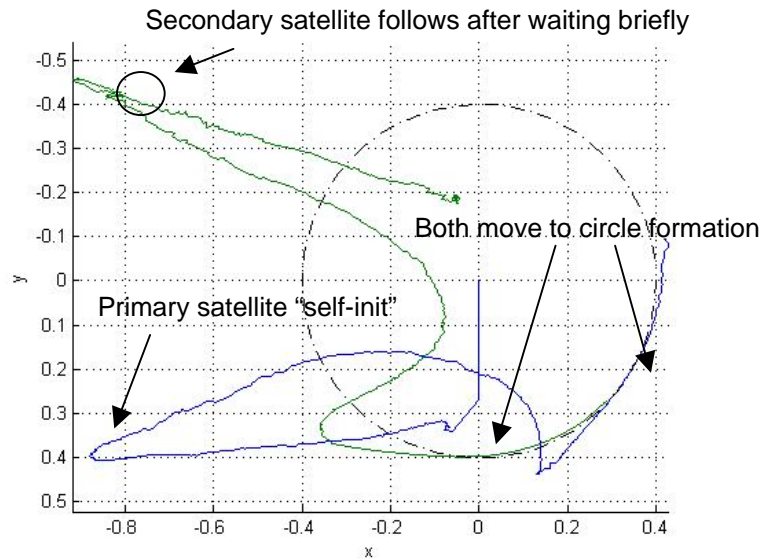


Figure 8. Top down view for second initialization.

In light of repeated communications failures in both test sessions, we conclude an important aspect of any automatic formation initialization is a contingency for lapses in communication

between satellites. The partial success in creating a formation without a designated leader satellite suggests that holding locations or fail-safe trajectories could be used to create a loose formation until communication can be reestablished.

Scatter

After initializing a formation, autonomous satellites may be required to quickly change their formation configuration in response to an external command or the detection of a fault among the formation members. In this test each satellite activated a control law that commanded a thrust directly away from the other satellites to quickly disperse the formation and avoid collisions (i.e., the satellites move in a direction determined dynamically during the test, rather than to a pre-determined position which could result in unintentional collisions). After building up velocity the satellites picked a final destination on a virtual bounding volume and attempted to come to rest at this location.

During Test Session 10 the satellites initialized a circular formation. Only the primary and tertiary satellites to completed the maneuver, which was sufficient to evaluate the test. A scatter command was issued by the crew, and the satellites moved to scatter directly away from each other (including away from the estimated position of the disabled satellite). As shown in Figure 9, the satellites took paths that were approximately 120 degrees apart, as expected if they were evenly spaced on a circle of three satellites. Analysis of the data and an examination of the test code shows that the limits of the virtual bounding volume had been accidentally placed well outside of the test volume, approximately 1.33m from the center in all directions. For the +/- XZ plane, this target was past the station wall, and when the primary satellite (blue line) attempted to move to a target position of (0.193, -1.33, -0.264) m, it collided with the wall. The tertiary satellite (red line) scattered along the -X-axis to (-1.33, 0.665, -0.553), allowing it to exit the test volume without impacting the wall.

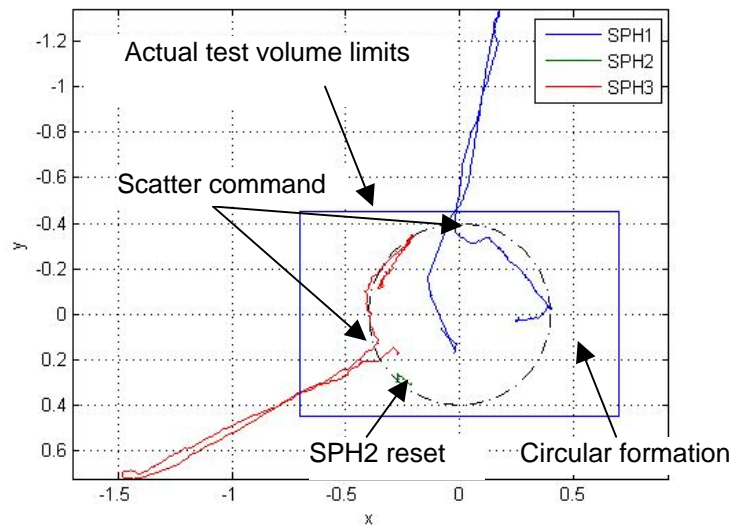


Figure 9. Top-down estimated trajectory for first scatter test.

After 30 seconds, an automatic timeout brought the satellites back to the center of the volume. With its erroneous state estimate, the primary satellite failed to return to the circle and moved erratically until the test was terminated. Thus, the return section of the primary satellite on Figure 9

shows an incorrect trajectory. On the other hand the tertiary satellite was able to return to the formation where it then circled briefly before the test terminated. This test can be considered a partial success, having shown that at least two satellites scatter in the proper direction and that at least one returns successfully.

As with the formation initialization test, a two-satellite version of the scatter test was created for the next test session with corrections to prevent a wall collision. The virtual boundaries of the maneuver were moved to the position limits shown in Table 3 (which has since become the “operational volume” of SPHERES in the US Destiny Laboratory).

Table 3. Updated test volume boundaries.

| | |
|----|--------------------|
| X: | $\pm 0.7\text{m}$ |
| Y: | $\pm 0.45\text{m}$ |
| Z: | $\pm 0.6\text{m}$ |

During Test Session 11 the scatter maneuver was successful. The trajectories are in opposite directions (allowing slight errors due to communications delay between the satellites) as desired for a fast scattering maneuver. In addition to scattering in the proper directions, the satellites were able to stay within the test volume, thus correcting the problem from the previous session. Figure 10 shows that during all the scatter maneuvers, the satellites stopped at the test boundaries. This success allowed the scatter maneuver to be ready for use in future tests.

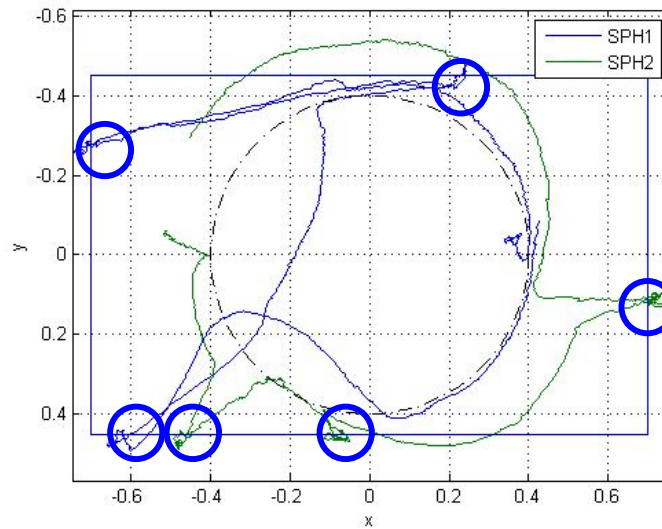


Figure 10. All scatters stopped at the boundaries of the test volume.

Collision Avoidance

For nominal operations of formations in close proximity, it is desirable to have a simple, always-active control law to prevent potential collisions. Test Session 13 demonstrated the use of a behavior-based collision avoidance method for multiple-satellite formations. The maneuver is based on a steering law that attempts to maximize the distance between the satellites at their Closest Point of Approach (CPA). The avoidance algorithm checks to see if a collision is imminent by projecting the current velocity forward in a straight line and finding the CPA distance for each of the other satellites. If the CPA distance is below a specified threshold and the collision

event is in the future, the satellite activates the avoidance routine. This avoidance steering law commands a velocity change that corresponds to climbing the gradient of the CPA distance with respect to relative velocity. This maneuver has the effect of increasing the CPA distance and decreasing the CPA time. In the limit, if the satellite had infinite control authority, the CPA time could be moved to the present time, and the current separation would be the CPA distance.

A successful test was performed with all three satellites demonstrating avoidance behaviors. Figure 11 shows a collision avoidance event between the secondary satellite and the primary satellite from 148s to 162s into the test. In this part of the test, the primary satellite maintained position at the center of the test volume and acted as an obstacle while the secondary satellite moved to avoid it. Figure 11a displays the estimated distance at closest approach as calculated by propagating the background telemetry of the primary and secondary satellite. Figure 11b displays the estimated time until the closest point of approach at each time step.

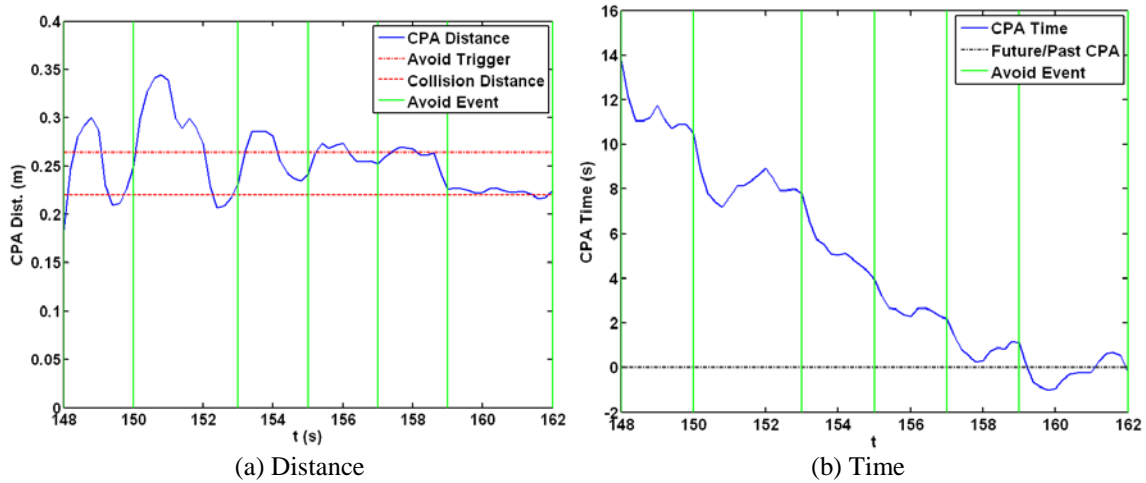


Figure 11. A sample collision avoidance event.

At $t=150$ s, the secondary satellite activated the collision avoidance maneuver as shown by a vertical line in the distance plot. As indicated in Figure 11a, this was the first time the CPA distance was below the avoidance trigger distance of 26.5cm at the beginning of a control cycle. The algorithm continued to function as expected with decreasing CPA times and increasing CPA distances after each avoidance event. It is also interesting to note that near the end of this event, the avoidance maneuver was activated every other control cycle. Here it is possible that the nominal PD controller kept driving the satellite back toward a collision on every other cycle.

During the test, the crew noted grazing contact between the satellites. It is expected that this can be corrected by increasing the minimum CPA distance in the collision detection algorithm. Due to the behavior-based nature of the maneuver, it is difficult to develop a definitive guarantee that collisions will be avoided, but it is possible to use Monte Carlo simulations to develop an estimate of the probability of collision for a given maneuver.

The preceding sections show the development and testing of a variety of maneuvers that will form a toolbox for creating and maintaining future formation flight experiments. The ability to create low level maneuvers and verify their performance over several test sessions is an inherent advantage of the iterative nature of SPHERES facility. As we will show in the next section, these components can also be used as building blocks for more complicated maneuvers.

Fault Detection, Isolation, and Recovery (FDIR)

The objective of these tests was to demonstrate the *recovery* portion of a “communications failure” and a “thruster failure” FDIR algorithm. The FDIR process is explained to clearly understand the *recovery* phase tested:

- Failure detection is the ability to determine if a failure has occurred.
- Isolation is identifying what subsystem has failed.
- Recovery is the change that occurs in the system to compensate for the given failure.

Recovery from a communication failure involves physically isolating the failed satellite. Recovery from a thruster failure means minimizing the probability of collision between any satellites.

Communications Failure Simulation

This test begins with three satellites evenly spaced 120° flying in circular formation. A communication failure on the primary satellite is simulated 140 seconds into this maneuver. It is important to note that no communications *detection* technique has been implemented yet; instead, the satellites are programmed to know that a failure has occurred at the given time during the test. At the failure point, the primary satellite is commanded to drift since it simulates no longer being able to communicate with the other two satellites — any thrusting would increase the chance of collision. The other two satellites can still complete their mission without the primary satellite. They move out of the plane of the original circle and continue the circular formation flight, this time spaced 180° apart.

Figure 12 shows a plot of the positions of the three satellites over time. For the first 10 seconds, no maneuvering is performed, allowing the Extended Kalman Filter (EKF) to converge to the actual state of the satellite. During the second part, as shown between the magenta lines, the satellites position themselves in the appropriate place in the circle. The secondary satellite, orange, reset during this maneuver and drifted for the rest of the test. The primary satellite, red, begins its third maneuver at 26s because it has reached its target state. However, the tertiary satellite, blue, has not reached its target state yet and begins the third maneuver at 40s due to the maneuver timing out. This means that the satellites do not begin the circular formation flight at the same time, and are therefore not spaced 120° apart. More importantly, the simulated communication failure event will not happen at the same time on all satellites. Since blue was not able to reach its initial state, its tracking performance was degraded throughout the rest of the test.

The test was not successful, but it provided the team with important information about how to conduct FDIR testing. While multiple attempts were made to test only “one-thing-at-a-time”, i.e., not test a full FDIR system, but only the “R”, real failures prevented the test from being successful. The reset of the orange satellite was unfortunate, but irrelevant. However, the motion of the blue satellite resulted in stopping the test before it was productive. Therefore, it is not only important to isolate the specific part of the algorithm to test, but also to reduce the operational requirements before it can be tested. In this example the desire to complete a full “normal” circle required 120s before the “simulated failure.” However, having followed a $\frac{1}{4}$ circle instead of a full circle would not have changed the validity of the test. The test also demonstrated the constant need to improve “termination conditions”. These are the conditions that must be met before the next maneuver is started (e.g., between going from “initial conditions positioning” to “follow circle”). The use of an open-loop timeout prevented the blue satellite from achieving a steady circle. These “termination conditions” are applicable to any autonomous system, and the ability to use SPHERES to demonstrate when they work correctly and when they do not is valuable to the whole community.

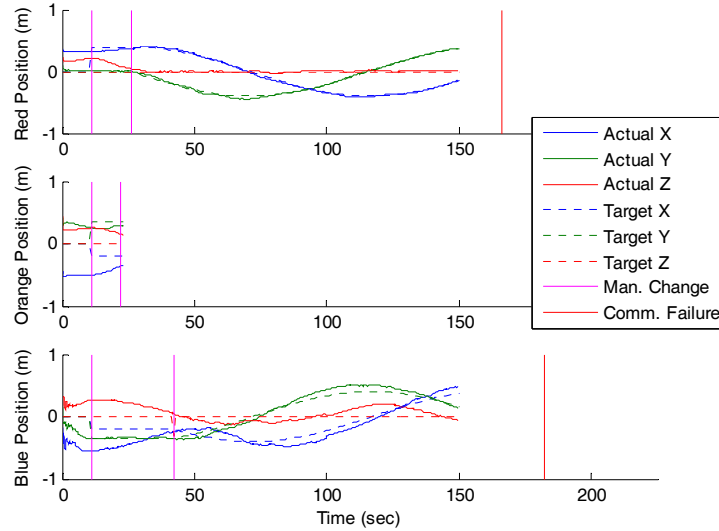


Figure 12. Communications Failure Simulation test results (satellite states).

Thruster Failure Simulation

The purpose of this test was to demonstrate the *recovery* from a thruster failure by physically isolating the failed satellite. This test begins with the three satellites performing a circular formation. At 140 seconds into this maneuver, the primary satellite thrusts for 200 ms, simulating a failed-on thruster failure. The other two satellites are programmed to know that this failure occurred (there is no actual FDI capability, as with the test above) and scatter to the edge of the test volume — a maneuver developed in test sessions 10 and 11. This failure mode has a higher danger level than the communication failure, which is why the two recovery techniques are different. In this case, the failed satellite has a higher risk of colliding with another satellite. Therefore the other two satellites are commanded to travel directly away from all other satellites to reduce the probability of collision.

Figure 13 shows 3D plots of the (a) commanded and (b) measured positions of the three satellites. In these figures, the satellites start on the circle travelling clockwise and end with the scatter maneuver away from the circle. Certain points along the circular trajectory are offset in the z-direction. This is due to code included for the communication failure isolation test presented above. The flag signaling that a communication failure occurred was set during the previous test, and not re-initialized during this test. Since the effect of this communication failure flag was not limited to that test, it caused a Z-axis offset to appear in this test. These offsets are tracked by the satellites. The benefit of this glitch is the availability of data for the recovery of a communications failure. The plots show how the two “good” satellites move to a new plane together. Of course, further tests are required to fully test the communications recovery algorithm, since no phase changes were conducted during this test. Aside from providing initial insight into the behavior of the communications recovery, this glitch, does not impact the science results of the thruster recovery mode.

During the test, at the specified time, a thruster on the primary satellite (red) had a simulated failure. At this moment, the secondary (orange) and tertiary (blue) satellites scatter to the edge of the test volume, directly away from the other satellites as red continues to drift. Note how the satellites move as far as possible from each other; even the primary satellite was commanded

(Figure 13a) to move away from the other two, even if it could not fire. This demonstrates that the blue and orange satellites are able to avoid collision from a satellite with a failed-on thruster.

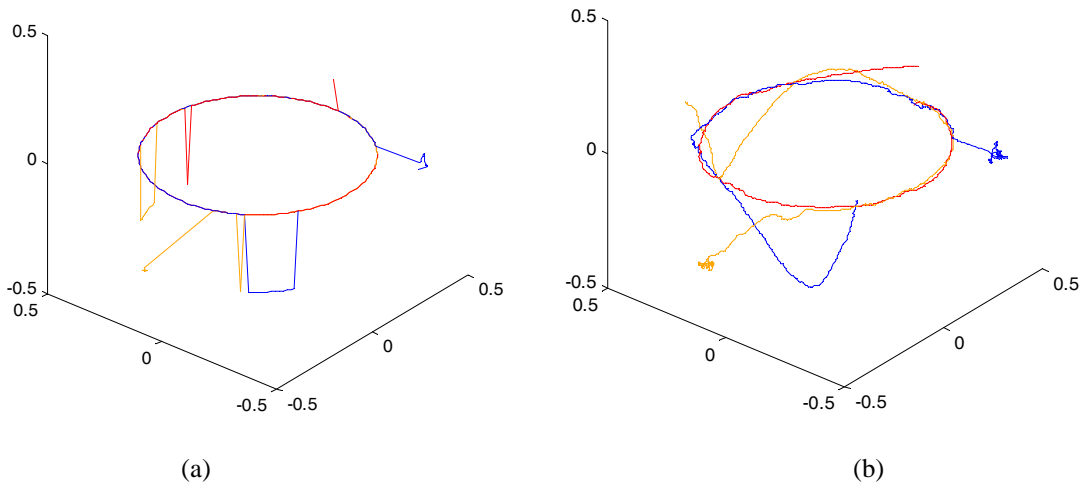


Figure 13. Thruster Failure Simulations test results during TS14.

The test simulated a thruster failure in the most likely scenario: in the direction of motion of the satellite, i.e., the thrusters in use. Of course, there could be a combination of thruster firings which would bring the red satellite in a path which would collide with one of the other two satellites. However, at that point the other two satellites could conduct another “scatter” maneuver, since it is assumed that communications and metrology system are still operational.

These two tests represent the initial demonstrations of FDIR algorithms for distributed satellite systems. Future tests will improve the individual algorithms and combine them to allow for multiple types of failures.

CONCLUSIONS

The 2007 and 2008 SPHERES formation flight tests concentrated on imaging maneuvers and autonomy algorithms. The imaging maneuvers used a wide range of controllers: PID, LQR, and cyclic pursuit. The use of basic PID controllers in circles was sufficient. But LQR controllers did not provide acceptable performance in spirals, exposing the need to use more complex controllers as the dynamics of spirals did not prove to be a simple extension of circular motion. The use of the decentralized controller resulted in the best performance to follow a spiral path.

The autonomy algorithms covered a wide range of possible actions which must be taken by a distributed satellite system. Formation initialization from random deployment conditions tests allowed the team to identify multiple potential problems which would cause an algorithm to fail; these issues are sometimes directly related to the algorithm (e.g. potentially having no formation “leader”) and also from other parts of the satellite (e.g. losing communications).

The lessons learned from the development of scatter maneuver algorithms include the somewhat obvious need to fully identify your surroundings, but also the importance of a scatter maneuver to dynamically determine the scatter direction. All satellites should move in opposite directions from each other, rather than move to a pre-determined “safe” location.

Collision avoidance tests demonstrated the ability to use a low-overhead process to enable this autonomous behavior on spacecraft systems. The tests have provided initial data to fully under-

stand the empirical relationship between operational noise (i.e., deviations from an ideal path) and the “safety” box around a physical system.

Lastly, the SPHERES team proposed two different methods for a formation flight system to recover from potential failures of one of the satellites. For communications failure, where the failed satellite is expected to be able to stop its motion, the suggested *recovery* is to change the plane of the formation. For thruster failures, the team suggests that a scatter maneuver is necessary to safeguard the operational satellites. The thruster failure simulation test demonstrated the validity of the scatter maneuver for this type of failure.

The team will continue to present results and lessons learned of improvements to these algorithms, and design new tests that integrate them, so developers of future missions have robust algorithms and know potential failure modes.

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