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DEMONSTRATIONS OF SATELLITE FORMATIONS ABOARD THE ISS

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Science Objectives

• Develop a platform to demonstrate and validate *metrology, control, autonomy, and artificial intelligence algorithms* for distributed satellite systems (DSS)

• Demonstrate different configurations of DSS
  – Rendezvous and docking algorithms
    • Servicing missions
    • Space assembly
  – Autonomous formation flight
    • Optical telescopes (Stellar Imager), space based radar

• Provide a *representative* environment for the demonstrations
  – 6 DOF
  – Long duration μ-g
  – Full satellite simulation
  – Allow science “payloads”
Motivation for use of ISS

- Take advantage of the ISS
  - The ISS provides a low-risk environment for the maturation and validation of 6DOF experiments
    - Laboratory environment enables ability to perform high risk tests
  - Extended test periods of micro-gravity
    - Allows iterations
  - Utilize the availability of humans by making astronauts an integral part of the design loop: the astronauts become scientists in space

If one cannot simulate the space environment in the laboratory, simulate the laboratory environment in space.
Overview

- Laboratory environment aboard the ISS
  - 3 6-DOF free-flyer, self-contained nano-satellites; 3 support satellites in ground operations
  - Satellite-to-ground (laptop) and inter-satellite communications
  - Custom pseudo-GPS metrology system
  - Guest Scientist Program supports multiple investigators and includes in-house simulator
ISS Accomplishments Summary

- 15 science test sessions of ~4 hours each since launch on May 2006
  - Approximately 6 groups of 2 test sessions (~1 week apart) every 4-6 months
- Conducted one, two, and three satellite operations in full 6DOF
- Docking research:

<table>
<thead>
<tr>
<th>Docking</th>
<th>Sessions</th>
<th>Completed</th>
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<tbody>
<tr>
<td>- Traditional + On-line path planning</td>
<td>2-5,8,10, 12,14</td>
<td>Dock to tumbling target</td>
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<tr>
<td>- “Safe”</td>
<td>5-6,9-10</td>
<td>Basic “react to failure” tests</td>
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<tr>
<td>- Assembly &amp; Reconfiguration</td>
<td>5-12</td>
<td>Basic maneuvers, joint thruster firing</td>
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<tr>
<td>- Inspection</td>
<td>10-11</td>
<td>Basic maneuvers, manual control, obstacle avoidance</td>
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- Formation Flight Research:

<table>
<thead>
<tr>
<th>TS</th>
<th>Date</th>
<th>Science</th>
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<tbody>
<tr>
<td>7</td>
<td>Mar 24, 2007</td>
<td>2-Sat Lost-in-Space, 3-Sat Formation Flight</td>
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<tr>
<td>8</td>
<td>Apr 27, 2007</td>
<td>3-Sat Formation Flight</td>
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<td>10</td>
<td>Dec 12, 2007</td>
<td>2-Sat Formation Initialization &amp; Scatter</td>
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<tr>
<td>11</td>
<td>Jan 27, 2007</td>
<td>2-Sat Formation Initialization &amp; Scatter</td>
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<td>12</td>
<td>Aug 30, 2008</td>
<td>2-Sat Spiral Formations</td>
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<tr>
<td>13</td>
<td>Sep 27, 2008</td>
<td>3-Sat Collision Avoidance</td>
</tr>
<tr>
<td>14</td>
<td>Oct/Nov, 2008</td>
<td>3-Sat Comm &amp; thruster failure sims, 2-Sat Spiral Formations</td>
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Incremental and iterative development of rotations which emphasize coverage of the UV plane for separated spacecraft telescopes (e.g. TPF, DARWIN, Stellar Imager).

TS7: Circle
TS12 & TS14: Spirals
TS14: Cyclic Pursuit
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Imaging Formations: Circular Formation Flight

• TS7: 3-Satellite Formation Flight Circle
  – Method: Independent path following, synchronized start, PID control
  – Results: Success
  – Demonstrated ability of 3 satellites to describe a synchronized circular formation within 2cm error

Worked successfully on the first attempt, encouraged team to take a large step into next set of maneuvers...
Imaging Formations: Spirals

- **TS12: 2 Sat Spiral**
  - Method: Independent path following, “switchLQR” control to optimize fuel use
  - Result: Partial
  - The satellites completed the maneuver, but did not maintain <5cm precision
    - Data analysis showed an error in the switchLQR control

- **TS14: 2 Sat Spiral**
  - Method: Fixed switchLQR
  - Result: Partial
  - Improved performance (≈5cm), but not as good as circle
    - Spiral dynamics require a substantial change in controller

*Changing controllers, in addition to dynamics, prevented clear identification of new physical phenomena*
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Imaging Formations: Cyclic Pursuit

- TS14: Cyclic Pursuit Circles & Spirals
  - Method: Decentralized control algorithm capable of using only relative metrology information. Performs maneuver synchronization.
  - Result: Success
  - Demonstrated good initialization, spiral expansion, and elliptical formation
    - Most of the errors are < 5cm
    - Steady state error in diameter of formation due to discretization

Incremental algorithm development allowed identification of new physical phenomena; risk tolerance enabled the team to test two new controllers
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Algorithms for Formations

*Enhance the autonomy of FF systems during initialization, reconfiguration, and in response to satellite failures.*

Formation Initialization (TS10 & TS11)
Formation Scatter (TS10 & TS11)
Collision Avoidance (TS13)
FDIR (TS14)
Algorithms for Formations: Initialization

- **TS10: 3-Sat Random Initialization**
  - Method: Start a circular formation with a random leader satellite selected by crew.
  - Results: Failure.
  - Communications error prevented synchronization.
    - Add contingencies for communications losses.

- **TS11: 2-Sat Random Initialization**
  - Method: Repeat with two satellites.
  - Results: Partial.
  - Formation initialized, but leadership roles were not assigned.
    - Possible to start a formation without leader.
    - Be careful about state-based maneuver termination conditions.
Algorithms for Formations: Scatter

- **TS10: 3-Sat Scatter**
  - **Method:** Rapidly disperse formation by thrusting away from partners
  - **Results:** Partial
  - Demonstrated algorithm successfully determines scatter directions in real-time and 3D
    * Virtual boundaries incorrectly entered

- **TS11: 2-Sat Scatter**
  - **Method:** repeat with two satellites
  - **Results:** Success
  - Simple low-level tool for quickly separating satellites
Algorithms for Formations: Collision Avoidance

- **TS13: 3-Sat Collision Avoidance**
  - Method: behavior-based steering law, maximizes closest approach to nearest satellite
  - Results: Success
  - Demonstrated effective avoidance using a low-overhead algorithm which could reside in permanently in a control system
    - Need to include generous margins to guarantee collision avoidance
    - Be careful about overriding high level controller

![Avoidance Results](image1)

![Target trajectory (First Crossing)](image2)
Algorithms for Formations: FDIR

- **FDIR** = Fault Detection, Isolation, and **Recovery**
  - Recovery: the change that occurs in the system to compensate for the identified failure

- Communications Failure Simulation
  - Method: simulate a failure at known time.
  - Recovery: change in plane (assume failed satellite still has control, can stop)
  - Result: Failed
  - Too much time of “normal” ops was allowed before the failure, and other real failures occurred instead

- Thruster Failure Simulation
  - Method: thruster stuck on failure
  - Recovery: use scatter maneuver
  - Result: Success
  - Operational satellites avoid a drifting and tumbling failed satellite
Conclusions

• Imaging Maneuvers
  – Basic PID controllers with independent satellites was sufficient for circles.
  – LQR controllers with independent satellites did not provide acceptable performance in spirals
    • Spirals add a new level of dynamics that requires more complex control
  – The use of the decentralized “cyclic pursuit” controller resulted in the best spiral performance.

• Autonomy algorithms
  – Formation initialization allowed identification of multiple potential problems which would cause an algorithm to fail:
    • Algorithm: e.g. potentially having no formation "leader"
    • From other sub-system failures: e.g. loosing communications
  – Scatter maneuver demonstrations showed the importance of a scatter maneuver to dynamically determine the scatter direction.
  – Collision avoidance tests demonstrated the ability to use a low-overhead process to enable this autonomous behavior on spacecraft systems.
  – Two different methods for a formation flight system to recover from potential failures
    • Communications failure: change the plane of the formation.
    • Thruster failure: use scatter maneuver to safeguard the operational satellites
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