SPHERES Operations Aboard the ISS:
Maturation of GN&C Algorithms in Microgravity

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Motivation & Objectives

- Develop and mature algorithms for distributed satellite systems
  - Separated formation flight
  - Docking & rendezvous and space assembly and reconfiguration
  - Tethered formation flight
- Support the *incremental maturation* of a wide range of GN&C algorithms that encompass a *field of study* in a *risk-tolerant* and *representative environment*
- Facilitate iterative research
  - Enable repetition of tests and modification of hypotheses
  - Flexible operations plan for in-house & remote development
  - Multiple operational environments: simulation, MIT SSL, ISS
- Provide focused modularity
  - Simulate a complete satellite bus (6-DOF, long duration μg)
  - Provide a generic and modular software operating environment
- Support multiple scientists
  - Guest Scientists Program
  - Expansion port allows science-specific payloads
    - E.g. active docking port, tethered system, optical precision pointing
SPHERES Overview

- Laboratory environment aboard the ISS
  - 3 6-DOF free-flyer, self-contained micro-satellites
  - Satellite-to-ground (laptop) and inter-satellite communications
  - Custom pseudo-GPS metrology system
- Guest Scientist Program supports multiple investigators

SPHERES Satellite Properties

- Diameter: 0.22 m
- Mass (w/tank & batteries): 4.3 kg
- Max linear acceleration: 0.17 m/s²
- Max angular acceleration: 3.5 rad/s²
- Power consumption: 13 W
- Battery lifetime: 2 h

SPHERES Operations aboard the ISS
ISS Test Sessions Overview

- Activities aboard the ISS during 2006 (Test Session 1 to 5)

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<th>Active</th>
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- Results summary
  - Hardware checkout: **Success**
  - Sensor/actuator FDI: **Success**
  - Estimation algorithms: **Success**
  - On-line mass-ID: **Partial**
  - Formation flight: initial **Success**, ongoing
  - Estimation FDI: **Success**, ongoing
  - Docking “safe”: **Success**, ongoing
  - Docking “tumbling”: **Success!**, ongoing
Case-Study: Docking

Control Architecture:

remote monitoring

autonomous onboard RV-control system

autonomous FDIR

solver (on-line planning)

autonomous MVM mission & vehicle management

Target satellite

CAM

PID controllers

Glideslope controller

Global estimator

Relative estimator

sensors

GN&C modes

actuators

GN&C (spacecraft state control)

plant (chaser states)

spacecraft states

control forces/torques

TC

TM
Docking to a Beacon

- **Objective**
  - Demonstrate preliminary docking experiment with reduced hardware

- **Setup**
  - One satellite, one beacon

- **Estimator**
  - Single-beacon estimator provided 6-DOF navigation information

- **Approach Control**
  - Glideslope, PD

- **Capture Control**
  - Open Loop

- **Result: Partial**
  - Navigation error caused by estimator and IR noise drove the chaser off-track
  - Made contact with the beacon

![Docking Approach Trajectory](image)

![Tangential Alignment](image)
Docking to a Beacon, Video
Docking to a Cooperative Target

- **Objective**
  - Demonstrate docking between two satellites to an actively controlled target

- **Setup**
  - Two satellites
  - Full global metrology

- **Estimator**
  - Global estimator provided full 6-DOF navigation capability

- **Approach Control**
  - Glideslope, PD

- **Capture Control**
  - Open-loop

- **Results: Partial**
  - Satellites made contact
  - Multi-path problems led to state estimates errors and to collision
  - Illustrates the need for fault detection to improve the robustness
Docking to a Cooperative Target, Video
Docking to a Drifting Target

- **Objective**
  - Study effects of plume impingement

- **Setup**
  - Two satellites
  - Full global metrology
  - Target stopped controlling when separation dropped below 50 cm

- **Estimator**
  - Global estimator provided full 6-DOF navigation capability

- **Approach Control**
  - Glideslope, PD

- **Capture Control**
  - Open-loop

- **Results: Success**
  - Satellites made contact
  - Plume impingement effects were clear
  - State estimates smooth throughout
  - Illustrates potential problems with a straight line approach

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**Docking Approach Trajectory**

![Docking Approach Trajectory](image1)

**Tangential Alignment**

![Tangential Alignment](image2)
Docking to a Drifting Target, Video
Docking to a Cooperative Target II

- **Objective**
  - Demonstrate docking between two satellites to an actively controlled target

- **Setup**
  - Two satellites
  - Full global metrology

- **Estimator**
  - Global estimator provided full 6-DOF
  - Measurement error detection embedded in the global estimator

- **Approach Control**
  - Glideslope, PID

- **Capture Control**
  - Closed-loop PID

- **Result:** Success
  - Satellites made contact
  - Crew confirmed alignment
    - Velcro did not latch

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**Docking Approach Trajectory**

**Tangential Alignment**
Docking to a Cooperative Target II, Video
Safe Docking to a Cooperative Target

- **Objective**
  - Dock following a pre-computed safe trajectory that guarantees no collisions in case of GN&C shutdown at the end of the trajectory

- **Setup**
  - Two satellites, full global metrology
  - Simulated detection of a failure followed by GN&C shutdown

- **Estimator**
  - Global estimator provided full 6-DOF

- **Approach Control**
  - PID position control module to track the pre-computed trajectory

- **Capture Control**
  - Not applicable

- **Result:** *Success*
  - Successful capture occurred 5 seconds after simulated detection of failure, compatible with guaranty of no collision

![Docking Approach Trajectory Close-Up](image1)

![Docking Approach Trajectory](image2)
Safe Docking to a Cooperative Target, Video
Docking to a Tumbling Target

- **Objective**
  - Demonstrate the use of traditional GN&C architectures to dock to a tumbling target

- **Setup**
  - Two satellites, full global metrology
  - Target satellite began rotating at controlled -2.25deg/sec after initialization

- **Estimator**
  - Global estimator provided full 6-DOF

- **Approach Control**
  - Glideslope, PID

- **Capture Control**
  - Closed-loop PID

- **Results:** Success
  - Two attempts
    - 1 - Aligned contact
    - 2 - Docking!
  - Estimator FDI successfully rejected external disturbances

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**Docking Approach Trajectory**

- Initialization
- Docking

**Tangential Alignment**

- Initialization
- Docking

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Docking to a Tumbling Target (2)

- Followed expected trajectory
- FDI rejected external disturbances
  - Crew was taking pictures with flash during the test!

Second run demonstrated first autonomous docking to a tumbling target in micro-gravity!
Docking to a Tumbling Target, Video
Conclusions

• SPHERES as a technology maturation laboratory environment
  – Flexible reconfiguration of the SPHERES facilities enabled the team to begin operation with a limited set of hardware aboard the ISS
  – Modularity in the system proved essential to enable incremental technology maturation
  – Multiple unforeseen problems stressed the need to implement FDIR algorithms at all levels of the GN&C architecture

• Docking research
  – Demonstrated effects of plume impingement
  – Observed effects of loss of inter-satellite communications
  – Showed that initial contact between two satellites of similar mass can create substantial disturbances - need both satellites to be active
  – Safe docking provided two lessons on the use of models:
    • Showed robustness to errors in path following
    • Must be conservative in the use of margins
  – Can use traditional GN&C algorithms to dock to a tumbling target

• MORE TO COME!
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