The SPHERES ISS Laboratory for Rendezvous and Formation Flight

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David W. Miller, Director
SPHERES Team

- DARPA Orbital Express Program
  - Research and flight opportunity sponsor
- Massachusetts Institute of Technology
  - Science lead
  - Prototype design and testing
  - Algorithm development
- Payload Systems Inc.
  - Flight hardware design, fabrication & testing
  - Flight hardware integration & safety
- DoD Space Test Program and ISS Payload Integration Office
  - Flight manifest on ISS
  - Payload integration & safety support
Motivation

- To reduce cost and improve performance, many missions are considering distributed spacecraft architectures
- Routine and autonomous formation flight is essential to the operation of these missions
- Long duration $\mu$-g is impossible to simulate in a ground laboratory
- Therefore, an on-orbit testbed is needed to conduct research in $\mu$-g for maturing these technologies
Motivation

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

*If one cannot simulate the space environment in the laboratory, simulate the laboratory environment in space.*
Design Philosophy

• Design process applies to a laboratory: conceive, design, implement, operate

• Conceive
  – Research topics: Determine the major topics that want to be studied through this laboratory (e.g., control, autonomy, and metrology for SPHERES)

• Design
  – Research functions: Determine the research functions that the testbed enables in order to provide the information to investigate the desired topics

• Implement
  – Laboratory characteristics: Ensure that the laboratory design provides the capabilities for successful research in the selected topics
Design Philosophy

• Demonstration and Validation
  – Demonstration of physical system in operational environment
  – Provides go/no-go high level decisions

• Repeatability and reliability
  – Must obtain similar results under similar conditions
  – Acceptable performance must be observed under the presence of representative disturbances

• Determination of Simulation Accuracy
  – Physical experiments validate simulations, allowing ground researchers higher order of completeness prior to flight tests

• Identification of Performance Limitations
  – Physical tests provide insight to obtain quantitative physical constraints for the development of optimal algorithms

• Operational Drivers
  – Experiments provide information to determine the coupling between constraints

• Identification of new Physical Phenomena
  – Physical tests allow the observation of new physical phenomena
**SPHERES:** Synchronized Position Hold Engage Reorient Experimental Satellites

SPHERES is a **cost-effective, risk-tolerant, interactive testbed** operated inside the ISS for the development and maturation of formation flight, autonomous rendezvous and docking technologies.

Two communications channels:
- Satellite-to-satellite (STS) for formation/docking control.
- Satellite-to-ground (STG) for telemetry download and software upload.
SPHERES Units

- **Propulsion**
  - Replenishable CO2 at 30-50psig
  - Micro-machined custom nozzles
  - 6DOF controllability

- **Metrology**
  - IR/Ultrasound ranging system simulates GPS within ISS environment (1Hz)
  - 6DOF IMU system for high frequency data (50Hz)

- **Avionics**
  - C6701 DSP Main Processor
  - Reprogramable FLASH memory

- **Power**
  - 16 AA batteries

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Diameter</td>
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<td>Mass</td>
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<td>Max Linear Acceleration</td>
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<td></td>
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<td>Tank Life</td>
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GSP Development Plan

M.I.T.
- GSP interface delivery
- Deliver to SPHERES
- GFLOPS simulation
- Laboratory testbed

Guest Scientist at local facility
- Independent source code
- GSP simulation

International Space Station
- Upload code via KU Band
- Astronaut uploads code to SPHERES
- Run tests
- Download Data via KU band

Approximate timeframes:
- ~1 week
- ~2 weeks

Space Systems Laboratory
Massachusetts Institute of Technology
Testbed Validation

- **KC-135 Frame Follower**
  - Master unit attached to KC-135 frame
  - Slave commanded to follow the rotation of the Master: should maintain the same orientation as the frame
  - 10Hz STS communications of full attitude state (3 angles and 3 angular rotations)
  - Slave must recover from initial deployment
Testbed Validation

- 2D Docking Demonstrations
  - Cooperative docking: Master unit awaits the arrival of the slave with full actuation to align docking port
  - Slave unit starts with initial attitude offset, aligns itself with the master, and then translates to perform the docking
  - 10Hz STS communications of full 2D state (4 position, 2 attitude)
Conclusions

- Laboratory Design Philosophy created to successfully develop an environment for development of formation flight and docking algorithms
- SPHERES has demonstrated operation as a Formation Flight and Docking Algorithm testbed in 2D Laboratory and KC-135 environments
  - KC-135 experiments validated the operation of SPHERES in a 6DOF
  - 2D Demonstrations of both Formation Flight and Docking Algorithms are ongoing
- ISS Deployment in July 2003
  - Manifested in Flight 12A.1 of the ISS
  - Minimum mission span of 6 months
  - Guest Scientist Program will allow access to the testbed by multiple researchers
- Science CDR
  - Monday, 18 November 2002
  - MIT, Cambridge, MA, USA
  - spheres@mit.edu