SPHERES: Development of an ISS Laboratory for Formation Flight and Docking Research

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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.

If one cannot simulate the space environment in the laboratory, simulate the laboratory environment in space.
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.
SPHERES 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
Research Functions

- 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
Laboratory Characteristics

- **Data feedback precision**
  - Create an environment similar to final system
  - Ensure precision of feedback data does not limit experiments

- **Repeatability and reliability**
  - Ensure testbed has better repeatability and reliability than the algorithms to be tested
  - Provide controlled environment

- **Physical end-to-end simulation**
  - Provide a simulation of all parts of the intended system

- **Support extended investigations**
  - Maximize the number of iterative research cycles under repeatable conditions
  - Allow long term tests for full mission simulations

- **Generic and specific equipment**
  - Enable basic testing of research areas through generic equipment
  - Ensure successful demonstrations through the addition of specific equipment

- **Hardware reconfiguration**
  - Enable manipulation to test different scenarios and add complexity to the tests
SPHERES Laboratory Characteristics

- Risk tolerant environment
  - Allow tests of new unproven technologies by ensuring benign failure modes
  - Enable investigators to push theory to the limits
- Software reconfiguration
  - Increase versatility and ease of use, especially for technologies manifested via software
- Human observability and manipulation
  - Allow humans to directly observe the experiment, provide feedback, and manipulate the environment
- Facilitate iterative research process
  - Ensure the research process is sped up
- Support multiple investigators
  - Reduce operating costs
  - Enable reconfiguration for multiple investigators
  - Provide ongoing support for off-site researchers

The laboratory characteristics determine the design requirements
SPHERES Testbed

- **SPHERES free-flier units**
  - Up to 3 units can be used simultaneously (with possible upgrade to more units).
  - Each independent unit contains propulsion, power, wireless communications, metrology, and processing sub-systems.
  - Sensors and actuators provide full state vector (6DOF, 12 states) of each unit.

- **Laptop unit**
  - ISS standard PC laptop serves as a base station for software reconfiguration and telemetry downloads.
  - Laptop provides access to the Ku-band for ISS to ground communications.

- **Metrology**
  - Five external metrology transmitters, mounted to the body of the ISS, create frame of reference.

- **Communications**
  - Satellite-to-satellite (STS) for formation/docking control.
  - Satellite-to-ground (STG) for telemetry download and software upload.
SPHERES Testbed

• Structures
  – Aluminum internal frame
  – Lexan covers
  – External expansion port

• Propulsion
  – Replenisahable 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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• Software
  – Bootloader allows full reconfiguration
  – Modular high-level API
  – Allows low-level access by investigators

• Guest Investigator Program
  – Provide a multi-level development environment for control algorithms on the SPHERES testbed
  – Development and verification of code occur on four platforms
    • SW Simulation
    • GFLOPS Simulation
    • SSL Lab 1-g testbed
    • ISS μ-g testbed
## SPHERES Testbed

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<tr>
<th>Feature</th>
<th>Structure</th>
<th>Propulsion</th>
<th>Metrology</th>
<th>Power</th>
<th>Avionics</th>
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SPHERES Testbed Environments

- 2D Laboratory Experiments
  - Long duration 2D tests (3DOF)
  - Preliminary low-cost testing prior to KC or ISS deployment

- KC-135 Reduced Gravity Airplane
  - Full 6DOF dynamics
  - Short duration

- ISS
  - Long duration fully representative 6DOF dynamics

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SPHERES Testbed Validation

- 2D Formation Flight Experiments
  - Master/Slave formation flight
  - Controlled 1-DOF rotations about the Z Axis
  - Autonomous rotation of Master Unit
  - Slave unit follows sensed motions of Master; Master ignores slave motions

![Graph showing STS Test Pos Master/Slave: Full State @ 10Hz](image)
• **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
SPHERES 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 Testbed designed to fulfill all the characteristics set forth in the philosophy
• 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 environment
  – 2D Laboratory testing provided initial insight into communications requirements for Formation Flight systems
  – 2D Demonstrations of both Formation Flight and Docking Algorithms are ongoing

• ISS Deployment in early 2003
  – Manifested in Flight 12A.1 of the ISS for May 2003
  – Minimum mission span of 6 months
  – Guest Investigator Program will allow access to the testbed by multiple researchers