The SPHERES ISS Microgravity Testbed as a testbed for AR&D and servicing

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Objective: to develop a reconfigurable and risk-tolerant laboratory for maturing close-proximity satellite GN&C algorithms under micro-gravity conditions

- Long duration μ-g is essential
  - Full 6-DOF motion (incl. quaternion slews, tumbling, nutation)
  - Proper contact dynamics
  - Key element of space environment needed for reaching higher TRL’s
- Reconfigurable
  - Permit spiral development through reconfigurable software
  - Enable mission specialization through mounted payloads
- Risk-tolerant
  - Push technology under both nominal and off-nominal conditions

- Three nano-satellites inside US Laboratory on ISS
  - Cold-gas propulsion, inertial and ISS-relative sensing, expansion port, RF-communication
SPHERES Design

- Currently on ISS: 3xSPHERES, 5xmetrology beacons, batteries, tanks, etc.
- Upload algorithms and download data through ISS laptop
- Test every ~2 mos. to allow S/W redesign

SPHERES nano-satellite

Control Panel

Pressure Regulator

Ultrasound Sensors

Pressure Gauge

Battery (2x)

Thrusters

Beacons (5)

ISS Laptop

SPHERES (3)

Crew

Test Volume on ISS

Courtesy Boeing Co
SPHERES for AR&D and Servicing

- Algorithm Development
  - Can develop, test, and mature algorithms related to AR&D and servicing
- Close Proximity Operations
  - Docking
  - Reconfiguration
  - Fuel Slosh
  - Vision-Based navigation
  - Path Planning

- Expansion Port Payloads
  - Can augment SPHERES functionality with additional payloads through Expansion Port
  - Docking Port, Camera, …
Reconfiguration: Joint Thruster Firing

- **Method**
  - Crew starts by joining two satellites by the Velcro face
  - The satellites are both one
  - One satellite calculates the control for all thrusters (in both satellites), and radios the thruster on-times to the second satellite as they maneuver together with both position and attitude control

- **Results: Success**
  - Position error < 2cm in steady state
  - Response within 60 seconds to large displacements (10cm)
  - Attitude error is basically zero; response within 20 seconds

- **Future Tests**
  - Perform path following for assembly scenarios
Expansion Port Payloads

Universal Docking Port
- Fully autonomous
- Genderless
- Provides
  - Docking to ±1° accuracy
  - Relative state estimation capability

Goggles Camera
- 2 cameras
- LED Lights for illumination
- 1 GHz processor for image processing
- 802.11g Wi-Fi
- Lithium-Polymer battery
- 895 g package
## International Space Station Hosted SPHERES Integrated Research Experimentation (InSPIRE)

<table>
<thead>
<tr>
<th>Problem</th>
<th>Distributed Computing (TTO)</th>
<th>μ-EMFF/WiTricity (TTO)</th>
<th>Micro Atomic Clock Testing and Characterization (MTO/TTO)</th>
<th>Fuel Slosh (KSC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High thru put, low power, rad hard processing for distributed computing</td>
<td>• Prop-less maneuvering via micro electromagnetic formation flying</td>
<td>• Ultra-small, low-power, atomic time and frequency reference unit</td>
<td>• Poorly modeled zero-g fluid dynamics</td>
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<tr>
<td>• Prop-less maneuvering via micro electromagnetic formation flying</td>
<td>• Inductive wireless power transfer</td>
<td>• On-orbit data needed to calibrate (natural freq and damping ratio of fluid)</td>
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<td>• Inductive wireless power transfer with visual cue (light, meter)</td>
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<table>
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<tr>
<th>Experiments</th>
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<tr>
<td>• Demo SPHERES performing command/control of neighboring SPHERES</td>
<td>• Demo Reactive Collision Avoidance (RCA)</td>
<td>• Demo anticipated accuracy drift</td>
<td>• Measure fuel slosh at zero-G conditions</td>
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<tr>
<td>• Demo wireless power transfer with visual cue (light, meter)</td>
<td>• Demo wireless power transfer with visual cue (light, meter)</td>
<td>• Calibrate vibration modes and structure stability</td>
<td>• 2 tanks attached to a truss connected between 2 SPHERES</td>
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<table>
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<tr>
<th>Hardware</th>
<th>Distributed Computing (TTO)</th>
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<tr>
<td>• One (1) HyperX computing module</td>
<td>• Three (3) 30 cm diameter electromagnetic coils with expansion port module</td>
<td>• One (1) Integrated Micro Atomic Clock Primary Clock Technology (CSAC) module</td>
<td>• Truss containing two (2) transparent tanks of dyed water and camera module</td>
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<th>Metric Today</th>
<th>Distributed Computing (TTO)</th>
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<tr>
<td>• RAD750: 266 MIPS</td>
<td>• uEMFF – 3 DOF relative maneuvering on flat floors, air carriages at 60cm</td>
<td>• uEMFF – 3 closing SPHERES maintain closest approaches btw 15-20cm</td>
<td>• Temex RMO</td>
<td>• No sustained 0-G data collected to date</td>
</tr>
<tr>
<td>• No on-orbit distributed control</td>
<td>• WiTricity – AFS Demo of 80% eff. over 40 cm, 60W output</td>
<td>• WiTricity - &gt;80% eff. at 1m</td>
<td>• Timing error – 1 μ-sec/day</td>
<td>• Parabolic flight tests not feasible (fluidic settling times, etc)</td>
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<td></td>
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<td>• Power – 10 W</td>
<td></td>
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<td></td>
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<td></td>
<td>• Volume – 230 cm^3</td>
<td>• Volume – 1 cm^3</td>
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<th>InSPIRE Goal</th>
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<tr>
<td>• HyperX - 50,000 MIPS</td>
<td>• uEMFF – 3 closing SPHERES maintain closest approaches btw 15-20cm</td>
<td>• uEMFF – 3 closing SPHERES maintain closest approaches btw 15-20cm</td>
<td>• CSAC</td>
<td>• First ever systematic 0-G natural freq. and damping ratio characterization</td>
</tr>
<tr>
<td>• First ever non-local control of satellites</td>
<td>• WiTricity - &gt;80% eff. at 1m</td>
<td>• WiTricity - &gt;80% eff. at 1m</td>
<td>• Timing error – 1 µ-sec/day</td>
<td>• 30-40% improvement in fuel slosh model accuracy</td>
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### Experiments – cont’d

<table>
<thead>
<tr>
<th>LiIVe* (NRL)</th>
<th>Grand Challenge</th>
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<tr>
<td><strong>Problem</strong></td>
<td>• Stereo visual navigation for inspection and close proximity ops</td>
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<td>• Host a software design challenge to engage high school and college students in space design and development</td>
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<tr>
<td><strong>Experiments</strong></td>
<td>• Demo collision avoidance with dead reckoning navigation</td>
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<tr>
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<td>• Fiducial tracking and re-acquisition</td>
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<td></td>
<td>• Collision avoidance</td>
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<td><em>Example challenges:</em></td>
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<td>• Chaser SPHERE tries to hit target SPHERE while Target SPHERE tries to evade chaser SPHERE</td>
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<td>• Capture the flag</td>
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<tr>
<td><strong>Hardware</strong></td>
<td>• Optical sensor module</td>
</tr>
<tr>
<td></td>
<td>• No hardware, only software mods</td>
</tr>
<tr>
<td><strong>Metric Today</strong></td>
<td>• &lt; 5 cm pos err using fiducial @ 3 m on air bearing table (2D)</td>
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<td></td>
<td>• Robotics competitions are limited to terrestrial and atmospheric flight regimes</td>
</tr>
<tr>
<td><strong>InSPIRE Goal</strong></td>
<td>• &lt; 5 cm 3D pos err w/ fiducial @ 3 m</td>
</tr>
<tr>
<td></td>
<td>• Demo collision avoidance taking 90 deg turns on ISS</td>
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<td></td>
<td>• Enable high school and college students to design, test, and implement S/W code on 0-G environment</td>
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### Hardware Status:
- Current Technology Readiness Levels: TRL-4
- Technology Readiness Levels post flight: TRL-7
- SPHERES, metrology, and RF comm on ISS
- Experiment-Specific Hardware: April 2011
- Consumables (batteries, CO2): before April 2011

### Uniqueness:
- First ever on-orbit
  - Non-local control of satellites
  - Electromagnetic formation flight
  - Wireless power transfer
  - Micro atomic time keeping validation
  - Long-term, iterative characterization of 0-G fluid slosh
  - Competition for high school and college students
Docking: LQR Control

**Method**
- Perform the same on-line path planning docking as in TS10, but use an LQR controller to follow the calculated path.
  - Target satellite points away from chaser; chaser must go around target to dock properly

**Results: Success**
- Successful docking
- Path following error reduced from ~10cm to ~5cm

**Future Tests**
- Use integral LQR during close proximity

*LQR Error (TS12)*

*NOTE: plots re-sized to same scale*