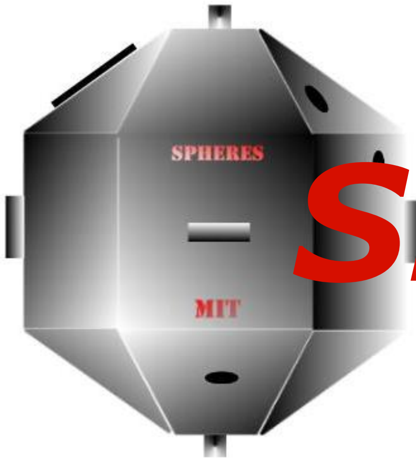


SPHERES

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

Dr. Javier de Luis

Dr. Swati Mohan

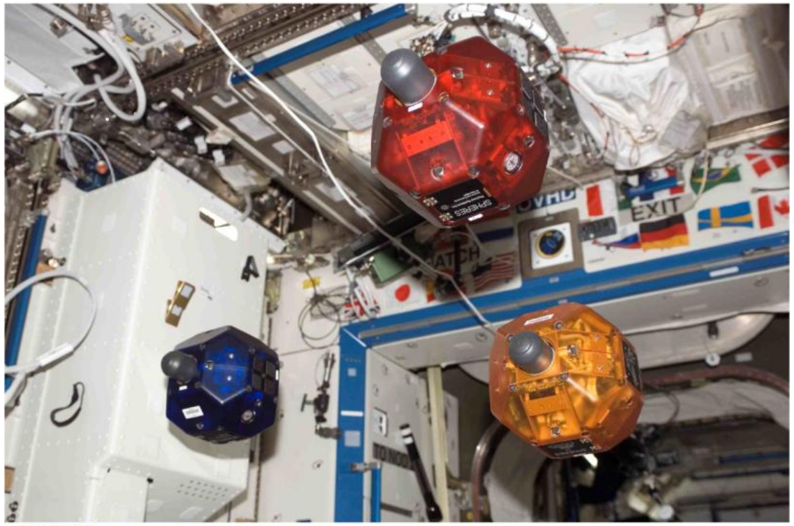
SPHERES

Concept and Motivation

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

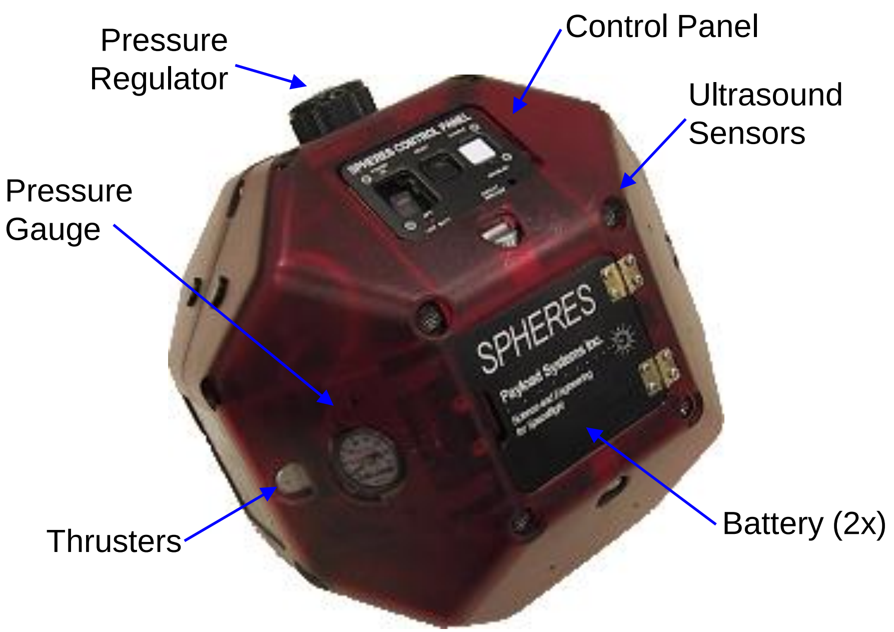
- Three nano-satellites inside US Laboratory on ISS
  - Cold-gas propulsion, inertial and ISS-relative sensing, expansion port, RF-communication



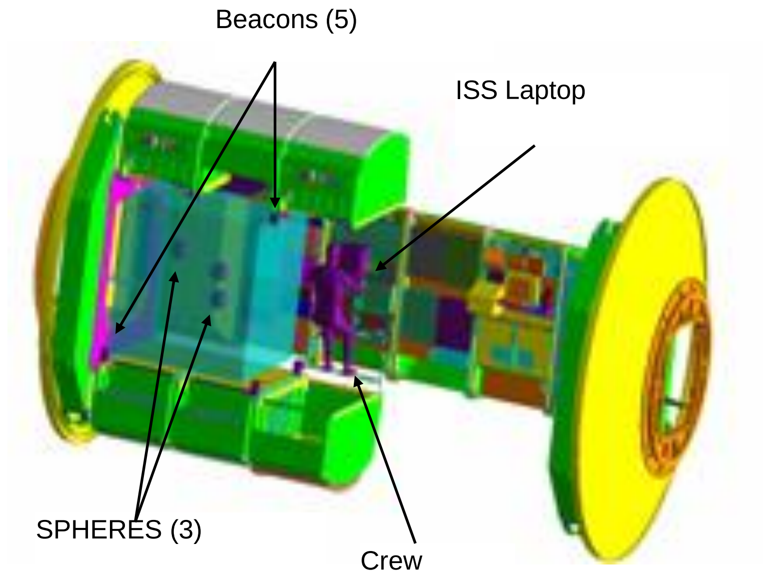
ISS016E014220

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



Courtesy Boeing Co

Test Volume on ISS

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SPHERES for AR&D and Servicing

- Algorithm Development

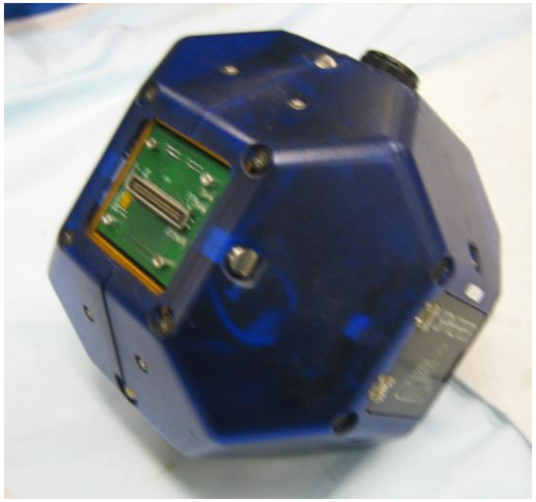
  - Can develop, test, and mature algorithms related to AR&D and servicing

  - Close Proximity Operations
  - Docking
  - Reconfiguration
  - Fuel Slosh
  - Vision-Based navigation
  - Path Planning

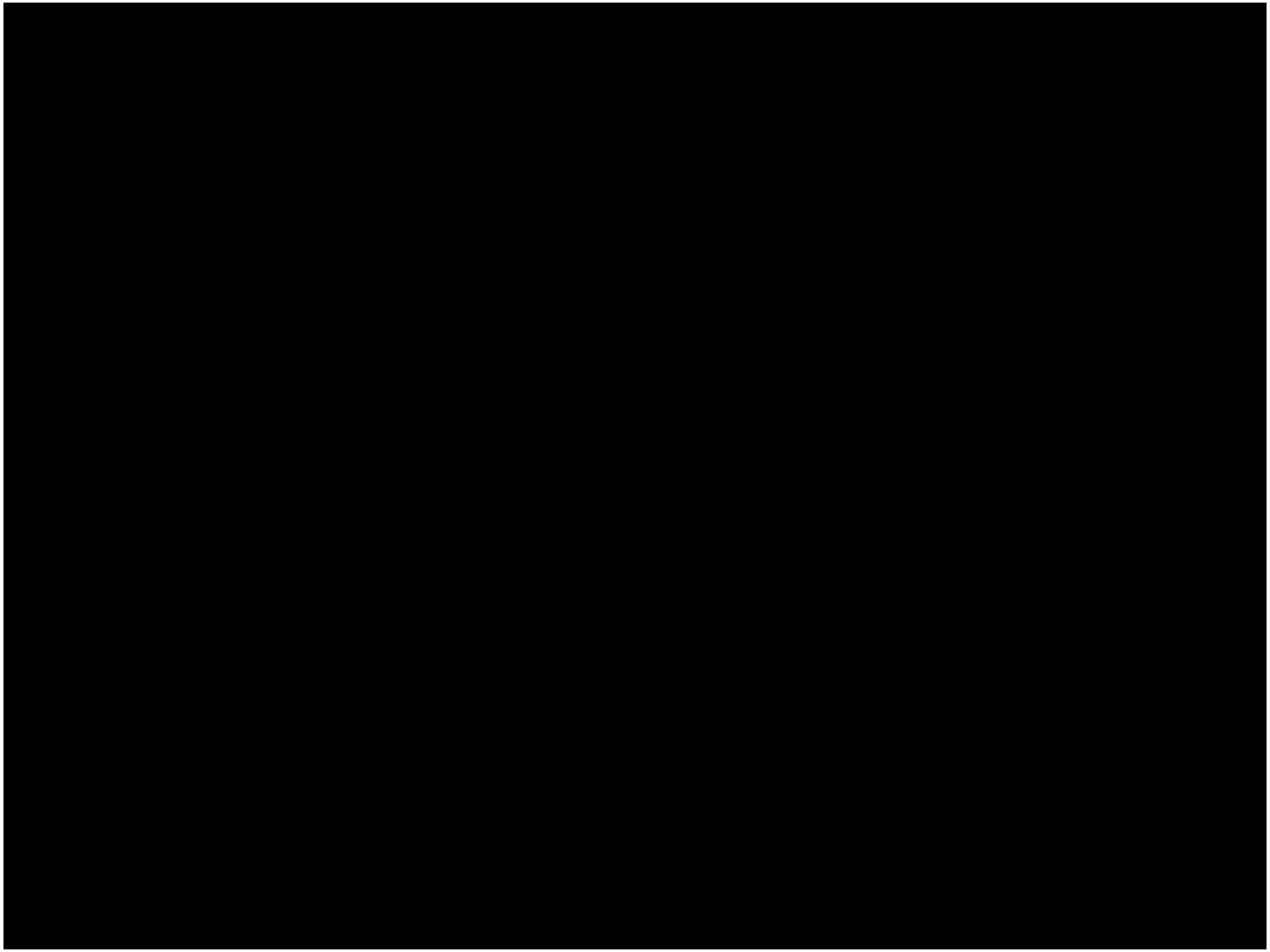
- Expansion Port Payloads

  - Can augment SPHERES functionality with additional payloads through Expansion Port

  - Docking Port, Camera, …

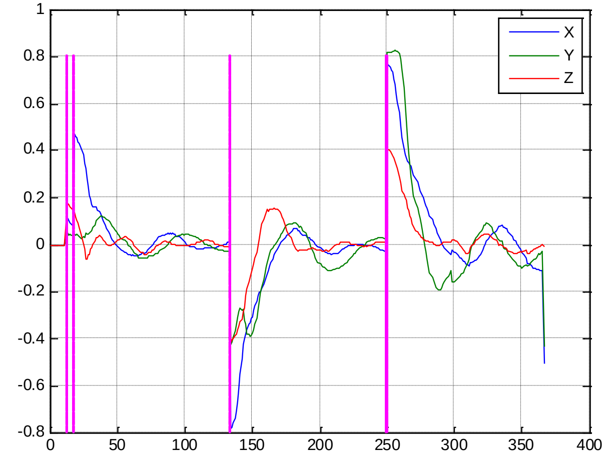


Autonomous Rendezvous & Docking

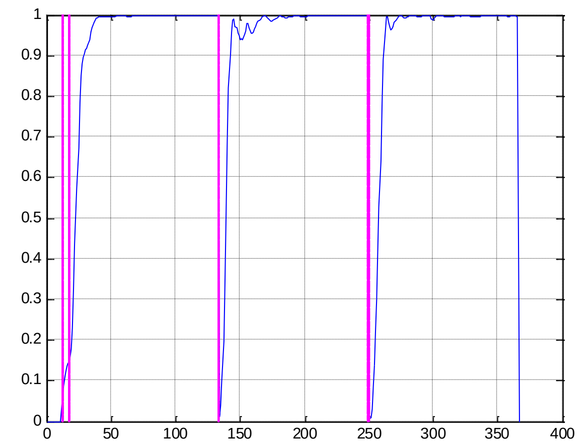


SPHERES Reconfiguration: Joint Thruster Firing

- 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



Position Error



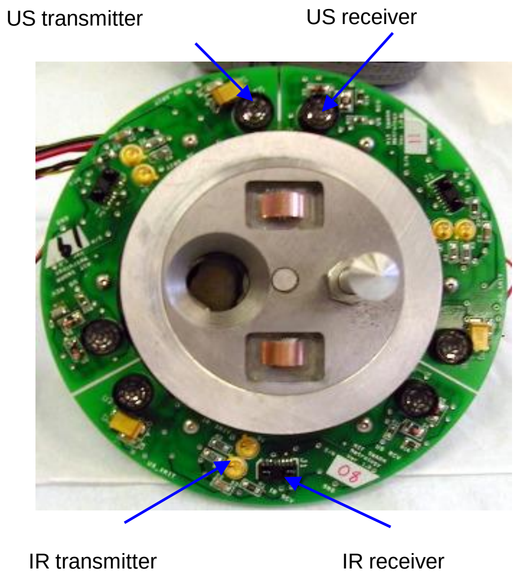
Attitude Error

Expansion Port Payloads

SPHERES

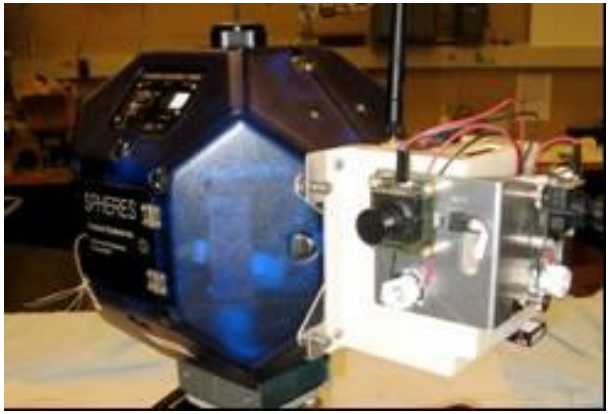
Universal Docking Port

- 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



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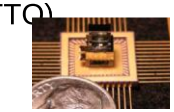
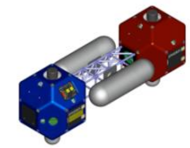
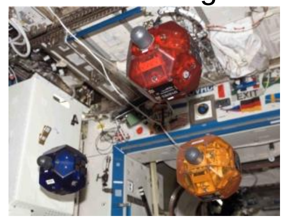
International Space Station Hosted SPHERES Integrated Research Experimentation (InSPIRE)

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

SPHERES

Experiments – cont'd

	LIIVe* (NRL) 	Grand Challenge 
Problem	• Stereo visual navigation for inspection and close proximity ops	• Host a software design challenge to engage high school and college students in space design and development
Experiments	• Demo collision avoidance with dead reckoning navigation • Fiducial tracking and re-acquisition • Collision avoidance	*Example challenges:* • Chaser SPHERE tries to hit target SPHERE while Target SPHERE tries to evade chaser SPHERE • Capture the flag
Hardware	• Optical sensor module	• No hardware, only software mods
Metric Today	• < 5 cm pos error using fiducial @ 3 m on air bearing table (2D)	• Robotics competitions are limited to terrestrial and atmospheric flight regimes
InSPIRE Goal	• < 5 cm 3D pos err w/ fiducial @ 3 m • Demo collision avoidance taking 90 deg turns on ISS	• Enable high school and college students to design, test, and implement S/W code on 0-G environment

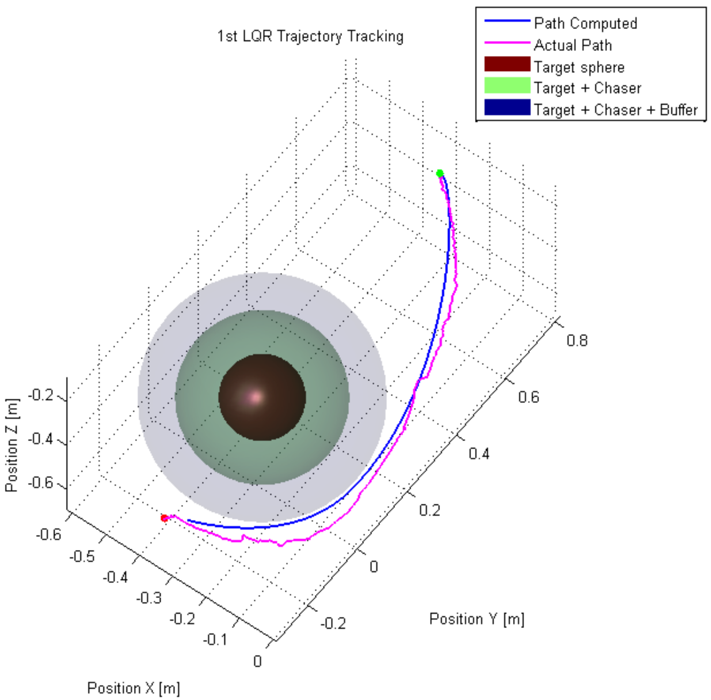
Hardware Status:
- Current Technology Readiness Levels: TRL-4
- Technology Readiness Levels post flight: TRL-7
- SPHERES, metrology, and RF comm on ISS
- Experiment-Specific Hardware: April 2011
- Consumables (batteries, CO_2): before April 2011

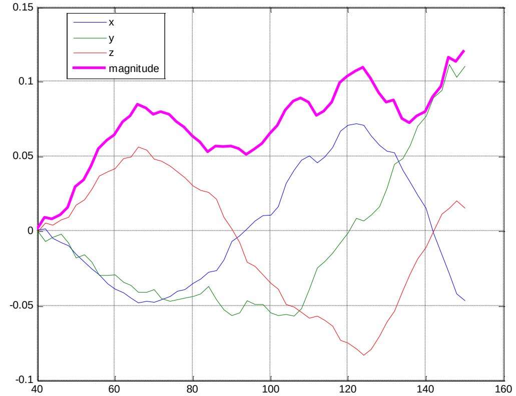
Uniqueness:
- First ever on-orbit
  - Non-local control of satellites
  - Electromagnetic formation flight
  - Wireless power transfer
  - Micro atomic time keeping validation
  - Long-term, iterative characterization of 0-G fluid slosh
  - Competition for high school and college students

Back-Up

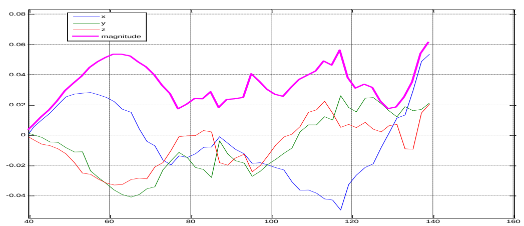
Docking: LQR Control

- 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





PID Error (TS10)



LQR Error (TS12)

NOTE: plots re-sized to same scale