SPHERES

SPHERES Overview

SPHERES Distributed Satellite Algorithm
Research Aboard the ISS

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http://ssl.mit.edu/spheres

FISO Telecon   6-26-2013

SPHERES

- Develop a platform to demonstrate and validate metrology, control, autonomy, and artificial intelligence algorithms for distributed satellite systems (DSS)

- Demonstrate different configurations of DSS
  - Rendezvous and docking algorithms
    - Servicing missions
    - Space assembly
  - Autonomous formation flight
    - Optical telescopes (Stellar Imager), space based radar
    - Approved by SERB May 2008: Fractionated Spacecraft (DARPA)

- Provide a representative environment for the demonstrations
  - 6 DOF, long duration m-g

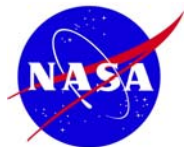*If you can't bring the space environment to the laboratory, take the laboratory into space*

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- The following seven principles capture the *underlying and long enduring fundamentals that are always (or almost always) valid* for space technology maturation laboratories:

    - **Principle of Iterative Research**
        - A laboratory allows investigators to conduct multiple cycles of the iterative research process in a timely fashion

    - **Principle of Enabling a Field of Study**
        - A laboratory provides the facilities to study a substantial number of the research areas which comprise a field of study

    - **Principle of Optimized Utilization**
        - A well-designed laboratory considers all the resources available and optimizes their use with respect to the research needs

    - **Principle of Focused Modularity**
        - A modular facility identifies those aspects of specific experiments that are generic in nature and allows the use of these generic components to facilitate as yet unforeseen experiments. Such a facility is not designed to support an unlimited range of research, but is designed to meet the needs of a specific research area

    - **Principle of Remote Operation & Usability**
        - A remotely operated laboratory, such as one which operates aboard the ISS, must consider the fact that remote operators perform the everyday experiments while research scientists, who do not have direct access to the hardware, are examining data and creating hypotheses and experiments for use with the facility

    - **Principle of Incremental Technology Maturation**
        - A successful ISS laboratory for technology maturation allows technology maturation to transition smoothly between 1-g development and the microgravity operational environment in terms of cost, complexity, and risk

    - **Principle of Requirements Balance**
        - The requirements of a laboratory are balanced such that one requirement does not drive the design in a way that it hinders the ability to succeed on other requirements; further, the hard requirements drive the majority of the design, while soft requirements enhance the design only when possible
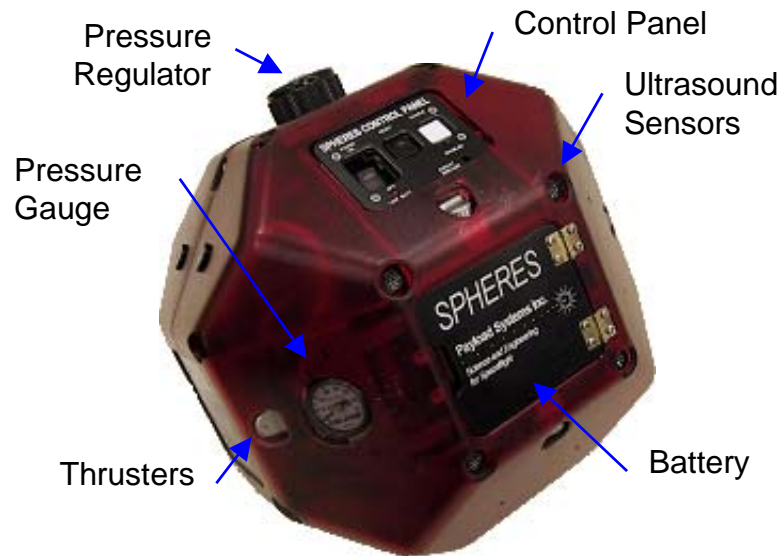
http://ssl.mit.edu/files/website/theses/PhD-2005-Saenz-OteroAlvar.pdf
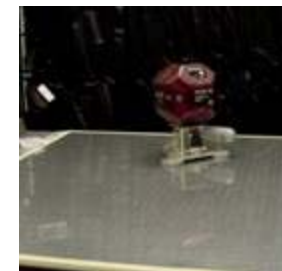
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- Laboratory environment aboard the ISS
  - 3 6-DOF free-flyer, self-contained nano-satellites; 3 support satellites in ground operations
  - Satellite-to-ground (laptop) and inter-satellite communications
  - Custom pseudo-GPS metrology system
  - Guest Scientist Program supports multiple investigators and includes in-house simulator
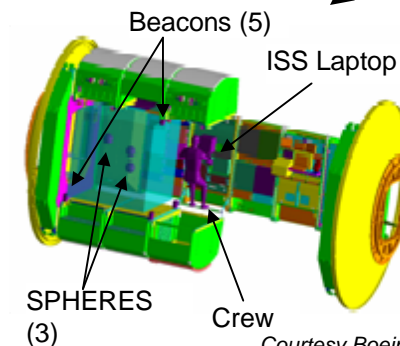
Simulation

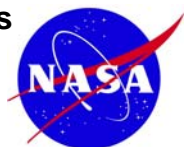**2D Ground Tests**

Pressure Regulator
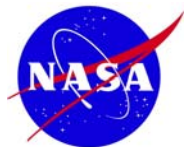
Control Panel

Ultrasound Sensors

Pressure Gauge

Thrusters

Battery

SPHERES nano-satellite

Beacons (5)

ISS Laptop

SPHERES (3)

Crew

Courtesy Boeing Co

SPHERES expected ISS Operations

SPHERES

SPHERES CDIO Class

- 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

http://ssl.mit.edu/spheres/videos/mitnewsoffice/712MITPR.MOV
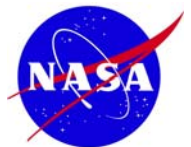
- Diameter
  - 0.2 m
- Mass
  - 3.4 kg
- Max acceleration
  - Linear: 0.17 m/s2
  - Angular: 3.5 rad/s2
- Battery Life
  - 60 - 90 min
- Power
  - 6.2 W
- Baud Rate
  - 19200 bps
- Metrology Resolution
  - 2.0 cm
- Tank Life
  - Ranges from 20 s - 30 min

- 13 Students SP99/FA99/SP00
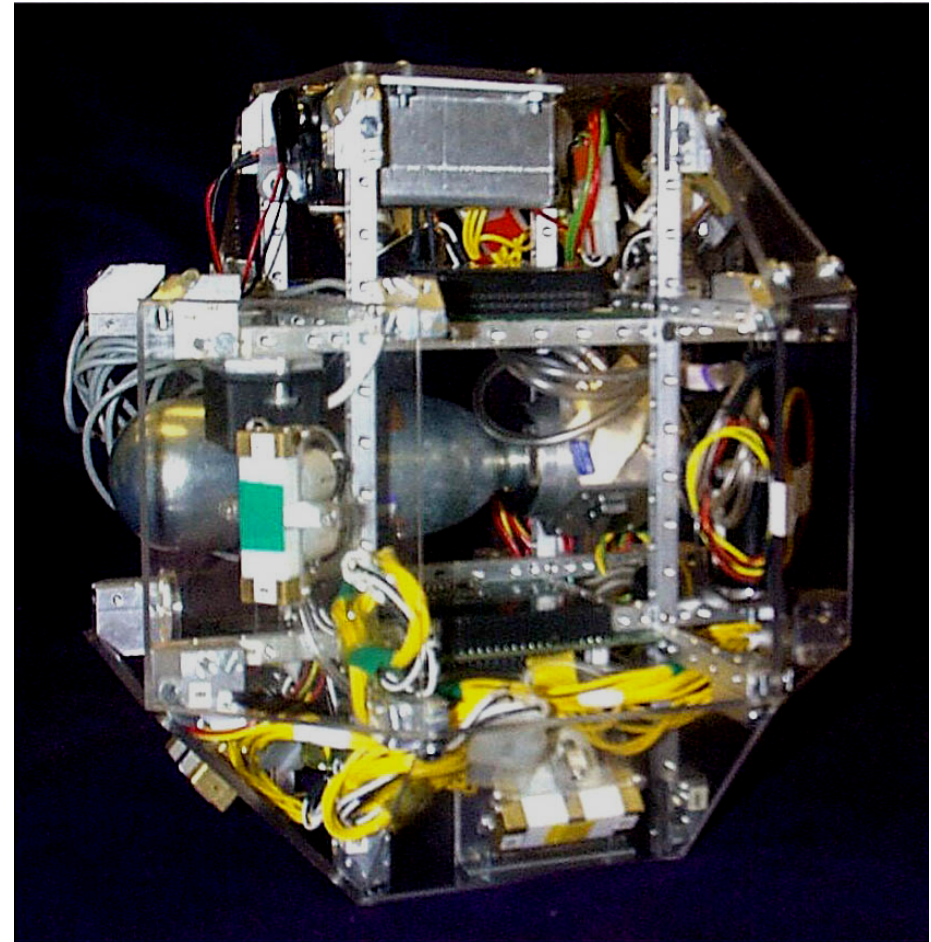
- KC-135 Reduced Gravity Airplane
  - Full 6DOF dynamics
  - Short duration
- Tests Performed (2/01 and 3/01)
  - System checkouts
  - Single SPHERE attitude control
  - Master/Slave formation flight

- 2D Laboratory Experiments
  - Long duration 2D tests (3DOF)
  - Can use fixed supplies instead of consumables
  - Preliminary low-cost testing prior to KC or ISS deployment
- Tests Performed
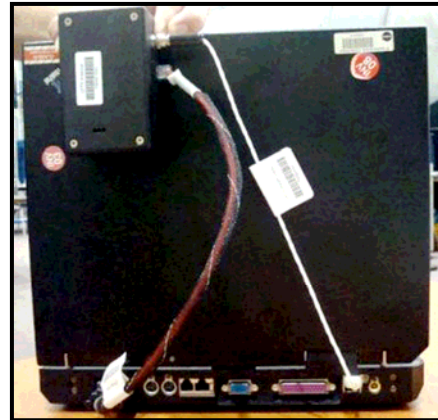 - Master/Slave formation flight
  - Docking algorithms

http://ssl.mit.edu/spheres/videos/kc/
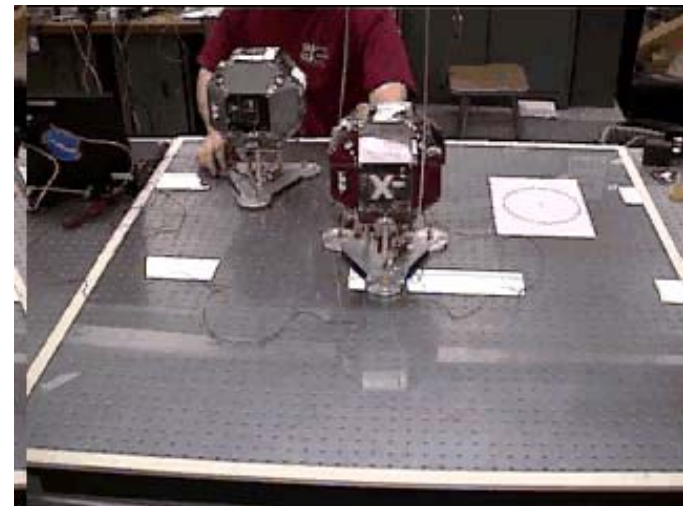
SPHERES

SPHERES ISS Facility

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SPHERES Satellite (up to 3)

SSC with SPHERES LPTX
(shown on laptop lid)

Beacon (with mount)

Battery Pack
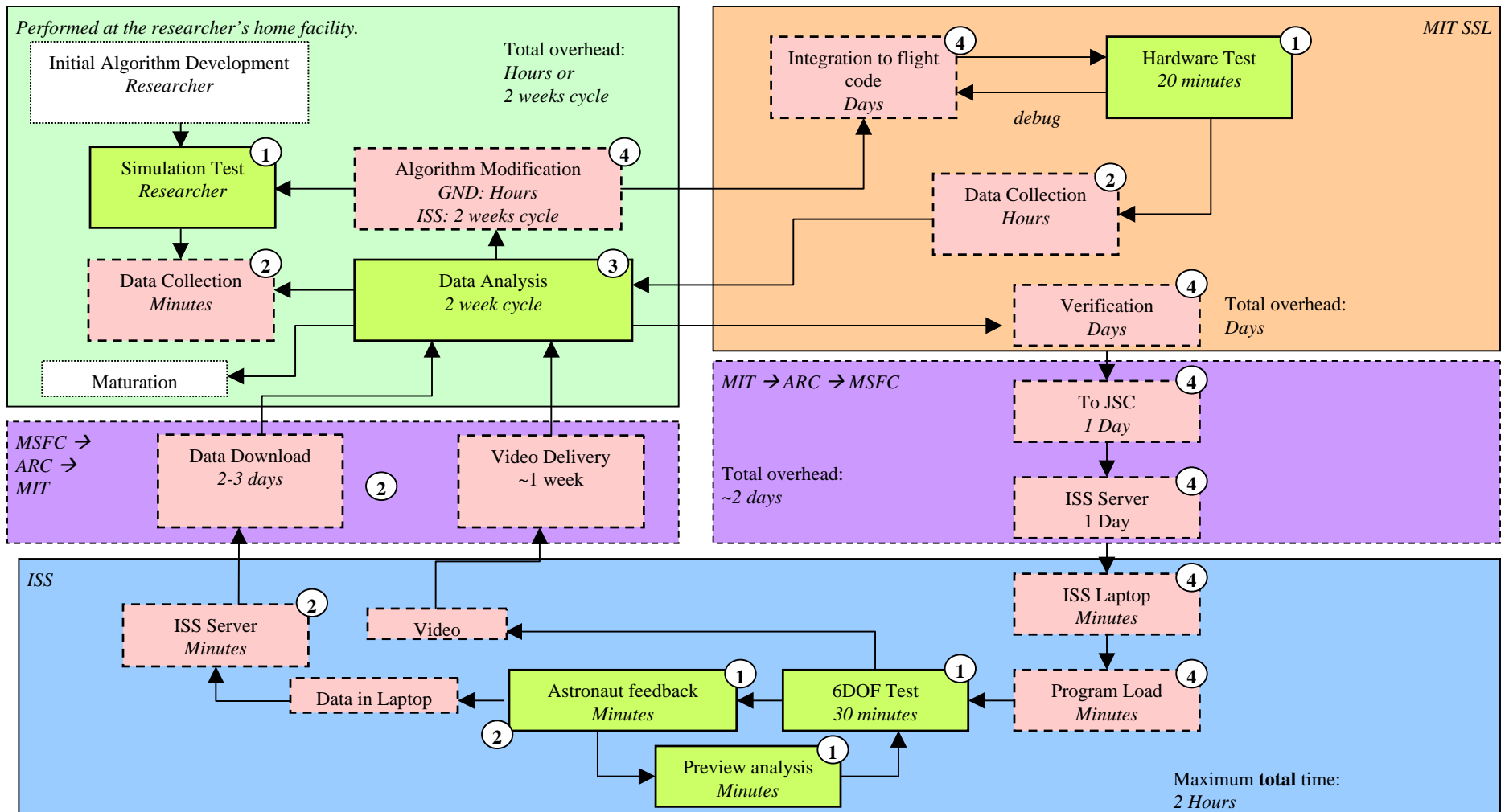(2 per sat)

CO2
Tanks
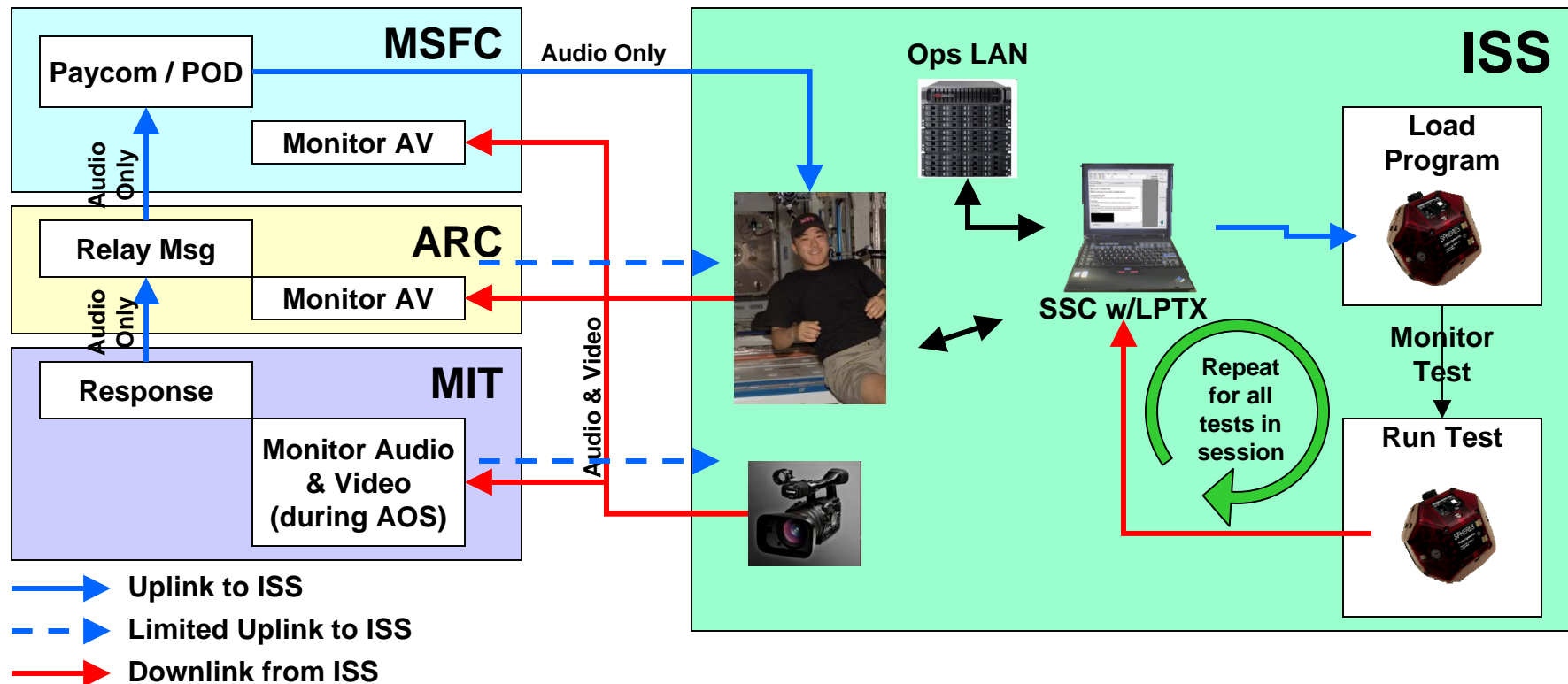(1 per sat)

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Performed at the researcher's home facility.

Total overhead:
*Hours or
2 weeks cycle*

Initial Algorithm Development
Researcher

Simulation Test
Researcher (1)

Algorithm Modification
*GND: Hours
ISS: 2 weeks cycle* (4)

Data Collection
Minutes (2)

Data Analysis
2 week cycle (3)

Maturation

MIT SSL

Integration to flight code
Days (4)

Hardware Test
20 minutes (1)

debug

Data Collection
Hours (2)

Verification
Days (4)

Total overhead:
Days

MSFC → ARC → MIT

Data Download
2-3 days (2)

Video Delivery
~1 week

MIT → ARC → MSFC

To JSC
1 Day (4)

Total overhead:
~2 days

ISS Server
1 Day (4)

ISS

ISS Server
Minutes (2)

Video

Data in Laptop

Astronaut feedback
Minutes (1) (2)

6DOF Test
30 minutes (1)

Preview analysis
Minutes (1)

ISS Laptop
Minutes (4)

Program Load
Minutes (4)

Maximum **total** time:
2 Hours

MSFC

Paycom / POD

Audio Only

Audio Only

Monitor AV

ARC

Relay Msg

Audio Only

Monitor AV

MIT

Response

Monitor Audio & Video (during AOS)

Audio & Video

Ops LAN

SSC w/LPTX

ISS

Load Program

Monitor Test

Run Test

Repeat for all tests in session

→ Uplink to ISS

⇢ Limited Uplink to ISS

→ Downlink from ISS

- During a test session crew controls the satellites:
  - Step 1: Setup the work area
  - Step 2: Load a program into the satellites

  - Step 3: Run & monitor the test
  - Step 4: Move to next text based on Test Plan or feedback from the ground (if available)

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SPHERES ISS Research

SPHERES

- Develop a platform to demonstrate and validate *metrology, control, autonomy, and artificial intelligence algorithms* for **distributed satellite systems (DSS)**

- Demonstrate different configurations of DSS
  - **Rendezvous and docking algorithms**
    - Servicing missions
    - Space assembly
  - **Autonomous formation flight**
    - Optical telescopes (Stellar Imager), space based radar
    - *Approved by SERB May 2008: Fractionated Spacecraft* (DARPA)

- Provide a *representative* environment for the demonstrations
  - 6 DOF
  - Long duration m-g
  - Full satellite simulation
  - Allow science "payloads"
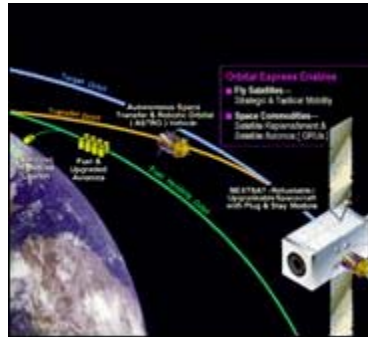
JPL   DARPA   ESA

TPF   **Orbital Express**   **Darwin**

SPHERES

- Phase 1 Final Objective
  - Mature autonomous docking algorithms to a semi-cooperative docking target tumbling with nutating motion to TRL 6 to aid with servicing and assembly missions
  - Autonomous
    - No human intervention with high success rates
  - Semi-cooperative
    - Target can communicate but has no actuation capabilities (simulated)
  - Nutating
    - Two rotational vectors at different periods
  - TRL 6
    - System demonstration in a representative environment
  - Servicing
    - Dock precisely to enable the transfer of consumables and/or rendezvous closely to enable satellite inspeciation
  - Assembly
    - Demonstrate autonomous systematic assembly of a complex spacecraft using multiple components with some s/c acting as "tugs"
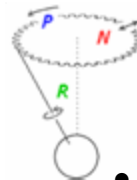
wikipedia.com

- Performed
  - Global estimation complete
  - Docking to a *tumbling cooperative* target
  - Initial Path Planning completed
    - Docked to a fixed target
  - Robust controllers (LQR, Hinf, etc)
  - Path planning & collision avoidance
    - To rotating and semi-cooperative targets
    - Nutating target
  - Obstacle avoidance
    - On-line autonomous avoidance
    - Reaction maneuver planning
  - Inspection
    - Full plane capture sequencing
- Ongoing
  - Direct relative estimation
  - Further plume impingement work
  - Assembly
    - Assembly sequence with cooperative targets
    - Assembly with unknown initial conditions

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

- Method
  - Two satellites
  - Target satellite began rotating at controlled -2.25deg/sec after initialization
  - Global estimator provides full 6-DOF state estimate

Docking Approach Trajectory

Tangential Alignment
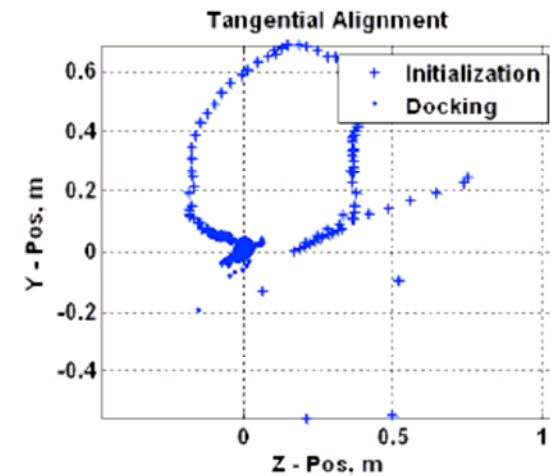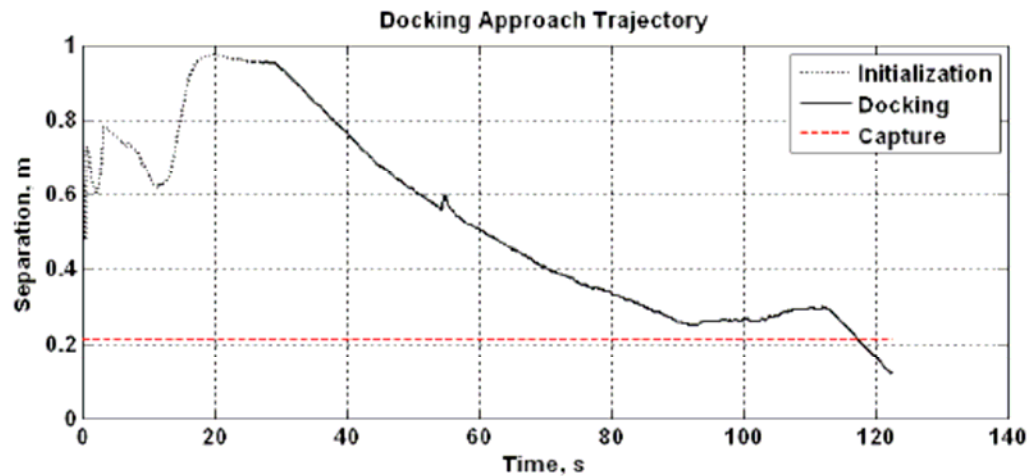
http://ssl.mit.edu/spheres/videos/ISS/ISS_TS05/TS05_P141_T6_2_Handheld_5xspeed.mp4

- Scenario: Target spacecraft front docking port faces away from the chaser spacecraft. Chaser has to plan a path to go around the target (obstacle).

- Science:
  - Docking GN&C architecture
  - Online path planning with obstacle avoidance
  - PID and LQR tracking control
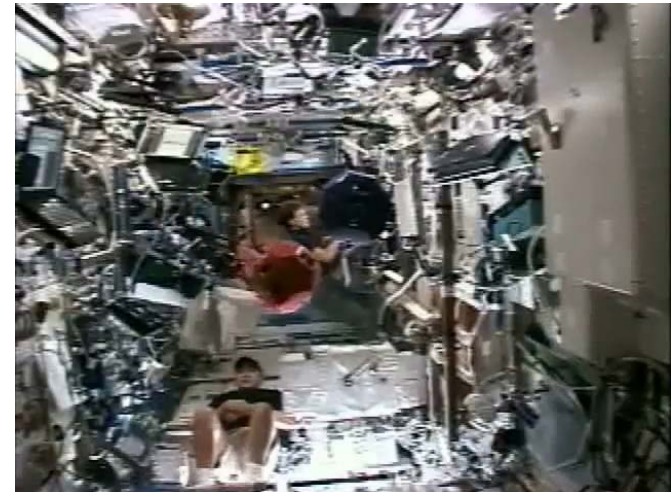
Blue – Planned, Magenta – Actual
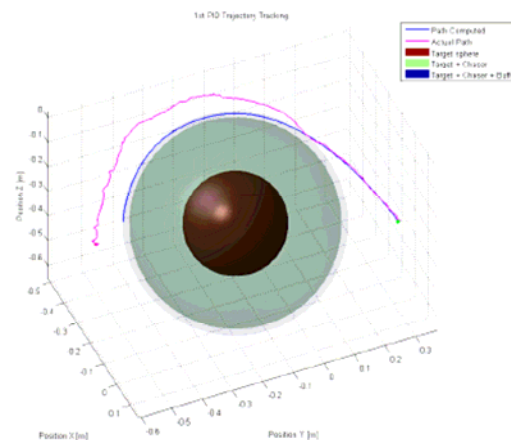
PID Control: ~10 cm tracking error
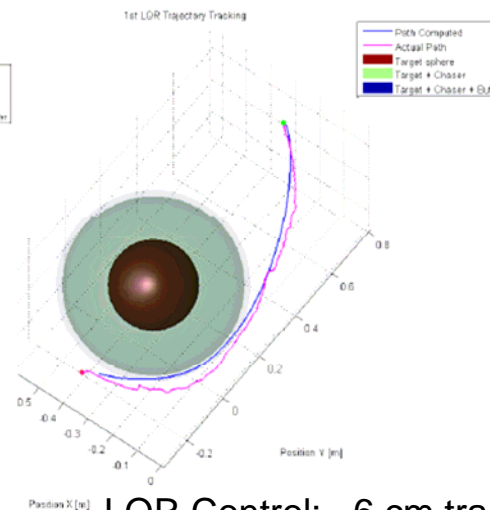
LQR Control: ~6 cm tracking error

http://ssl.mit.edu/spheres/videos/ISS/ISS_TS10/Docking_Fixed_Online_Path_Planning_4_AFT_5x(P192T05).mp4

SPHERES

- Phase 1 Final Objective
  - Demonstrate feasibility of coarse formation flight control for separated space telescopes and radar
  - Create an architecture of distributed modules that enable all major spacecraft hardware to function as network-addressable and shareable devices.
  - Coarse control
    - Thruster based relative position and attitude control of the spacecraft to within ±5 millimeters
    - Later to be coupled with precision optical control for space telescopes
  - Separated space telescopes & radar
    - Telescopes: TPF/DARWIN and SI designs
    - Usually rotating formations
    - Either maximize coverage or resolution
    - Allow re-shape of formation to switch between coverage/resolution modes
  - Distributed Modules
    - Demonstrate the ability of multiple modules to create a virtual single spacecraft by autonomously aligning themselves, showing the ability to change their geometry, and avoid collision between each other, while maintaining communications and sharing their devices.

- Progress
  - 3-Satellite formation flight demonstrations
    - Rotations and plane changes
    - Off-line path planning maneuvers
    - Initial communications design
  - 2-Sat fractionation demos
  - Advanced controls
    - Non-linear and fuel-optimized
    - Fuel balancing
  - Space telescope & Radar
    - Off-axis combiner demonstration
    - Capture maneuvers
    - Control optimized for optical capture
  - Fractionation
    - 3-Satellite tests (all parts)
    - Optimal initialization
    - Reconfiguration (geometry, metrology, architecture)
    - Obstacle Avoidance

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- Objective
  - Simulate formation initialization from a launch vehicle deployment
  - Initialize with unknown attitude and limited line of sight information
- Method
  - 3 SPHERES use relative measurements from an onboard beacon
  - All 3 SPHERES begin pointing away from each other and perform a search maneuver to locate the other
  - Final configuration has each satellite pointing to a partner to form a ring

$\longrightarrow$ = beacon face

SPHERES

- Results: Success
  - Demonstrated ability of 3 satellites to describe a synchronized circular formation within 2cm error
    - Tested communications synchronization algorithms
    - Used basic PID control

- Future
  - Staged formation flight with interferometry
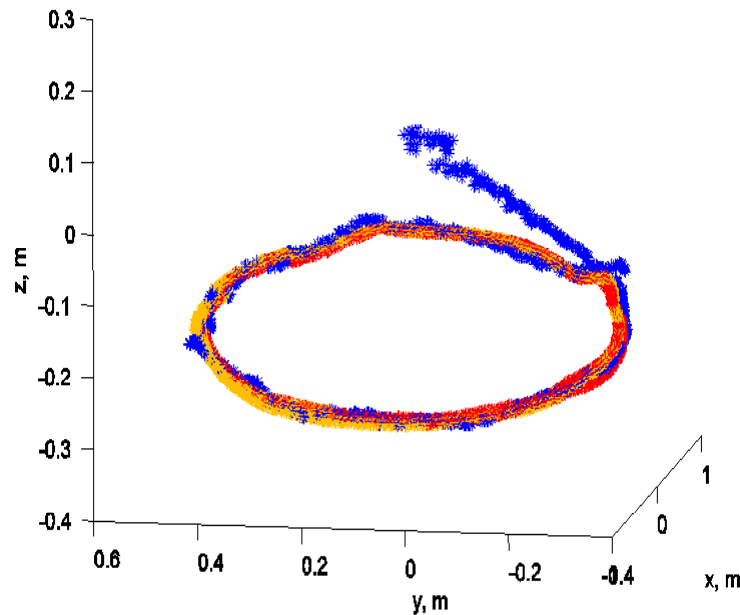
http://ssl.mit.edu/spheres/videos/ISS/ISS_TS07/3SatCircle_1_AFT_4x(P163T2).mov

SPHERES

- **Objective**
  - Perform a tightly coordinated spiral maneuver that could be used for synthetic imaging

- **Method**
  - 2 SPHERES start 27 cm apart and perform 2 revolutions of a spiral, expanding to 133 cm
  - 180 sec. per revolution to match previous circular tests
  - PID control with added feed-forward forces

- **Results**
  - Largest error is at the start of the maneuver – not enough time to reach starting point
  - S1 RMS Error: 0.92 cm
  - S2 RMS Error: 0.85 cm
  - Relative Error: 1.23 cm

Targets

ISS

SPHERES
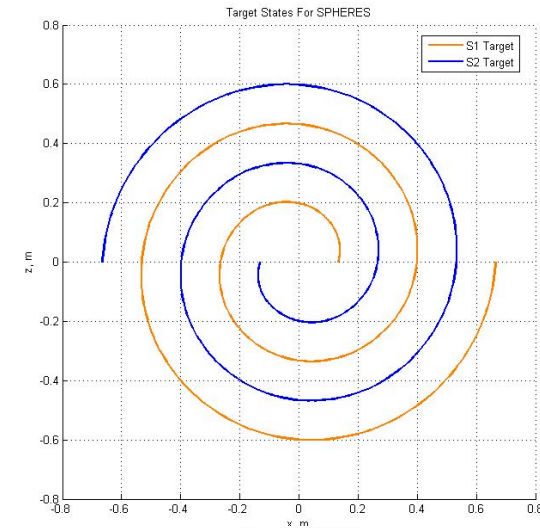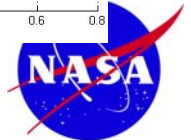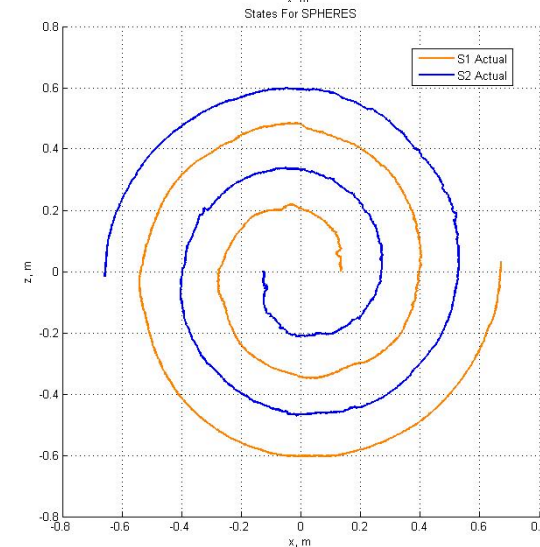
- Objective:
  - Create a formation using a completely decentralized control scheme
- Method
  - Decentralized cyclic pursuit algorithm
  - Global convergence (Random Initialization)
  - Capability of using only relative information
  - Synchronization
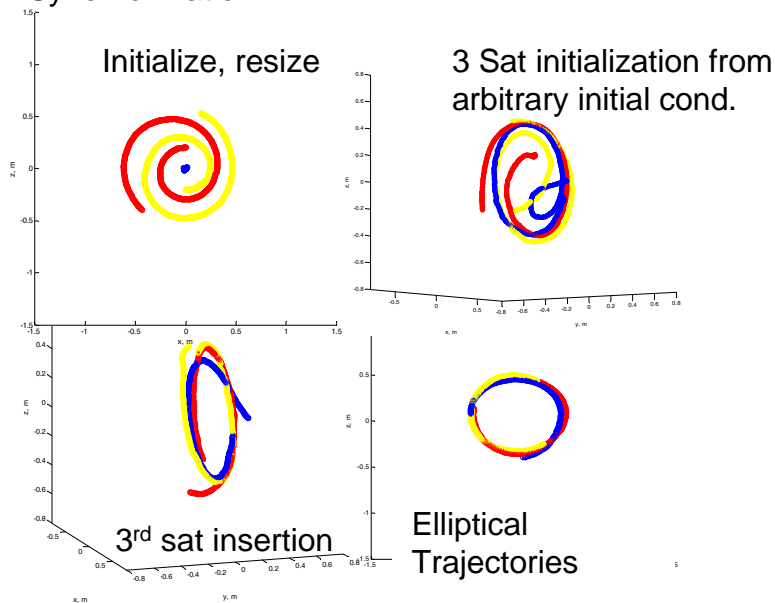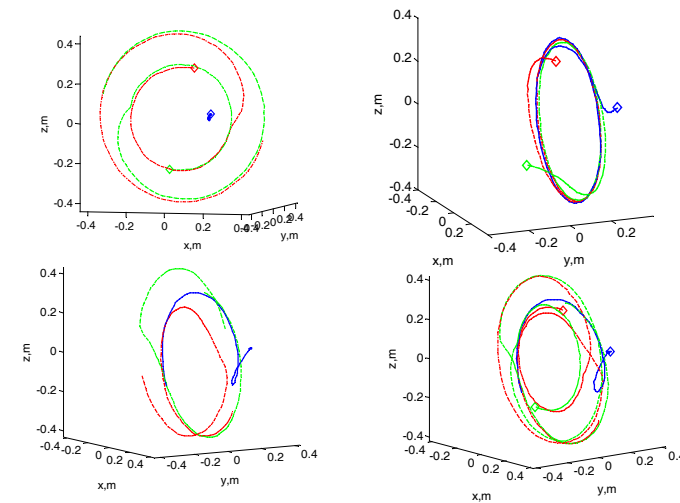
Initialize, resize

3 Sat initialization from arbitrary initial cond.

3rd sat insertion

Elliptical Trajectories

Simulation

ISS

SPHERES

- Objective
  - Demonstrate collision avoidance for formation flying satellites

- Description
  - Target trajectory forces collision avoidance at test volume center
  - Behavior-based avoidance maneuver runs independently on each satellite

start

Target Trajectory

ISS Avoidance Results

Legend:
- SPH1
- SPH1 Avoid
- SPH2
- SPH2 Avoid
- SPH3
- SPH3 Avoid
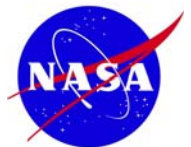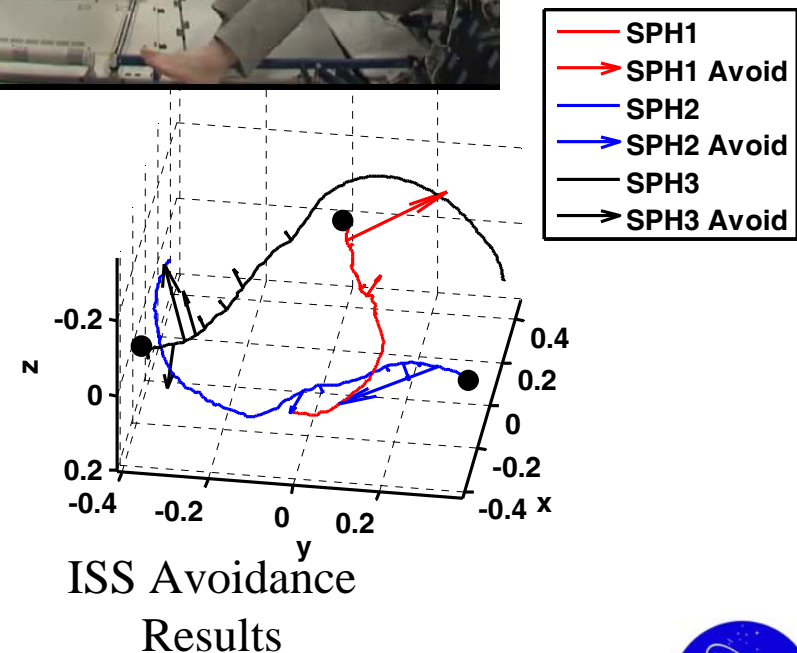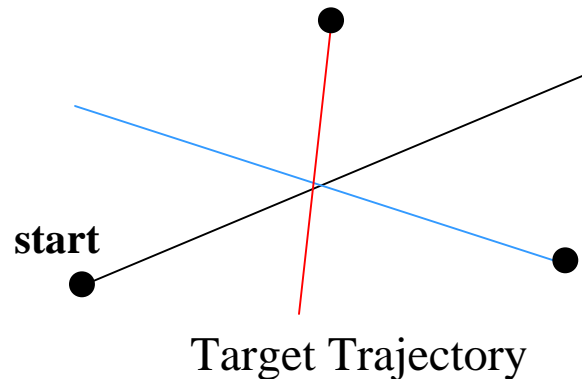
- VERTIGO - 2012-Oct

  - Vision Based Navigation

- RINGS - 2012-Dec

  - Electro Magnetic Formation Flight)

- Slosh - 2013-Jul

  - Fluid Slosh CFD model validation

- InSPIRE 2 - 2013-Jul, 2014-Jan, 2015-Jan

  - Docking Ports

  - Multi-port adapter

  - Manipulator Arms

VERTIGO

SPHERES
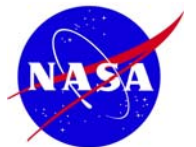
- **Visual Estimation and Relative Tracking for Inspection of Generic Objects**

  - Perform spacecraft **vision based navigation** in a microgravity environment
  - Enable other researchers to perform follow on vision based navigation research

- What are the Goggles?

  - A hardware upgrade to the SPHERES satellites:
    - 2 Stereo Cameras
    - 1.2 GHz Linux CPU
    - Illuminating LED Lights
    - 802.11 WiFi Connection
    - Lithium Battery (ISS Nikon Camera battery)
    - Textured stickers to "simplify" image processing

SPHERES

- LED Power Switch
- Cameras
- Ultrasound/IR Board
- Support Structure
- 1 of 4 Captive Thumbscrews
- Ultrasound Sensors
- Red LEDs
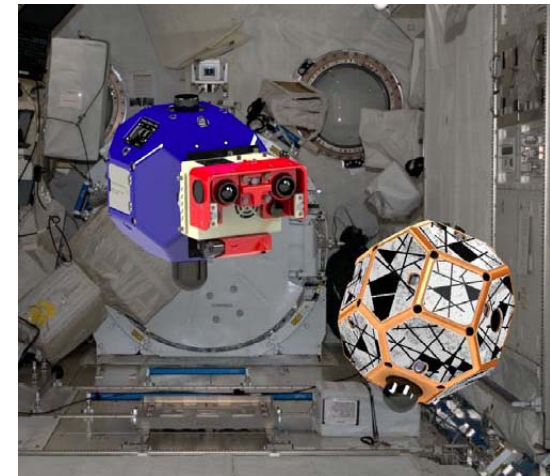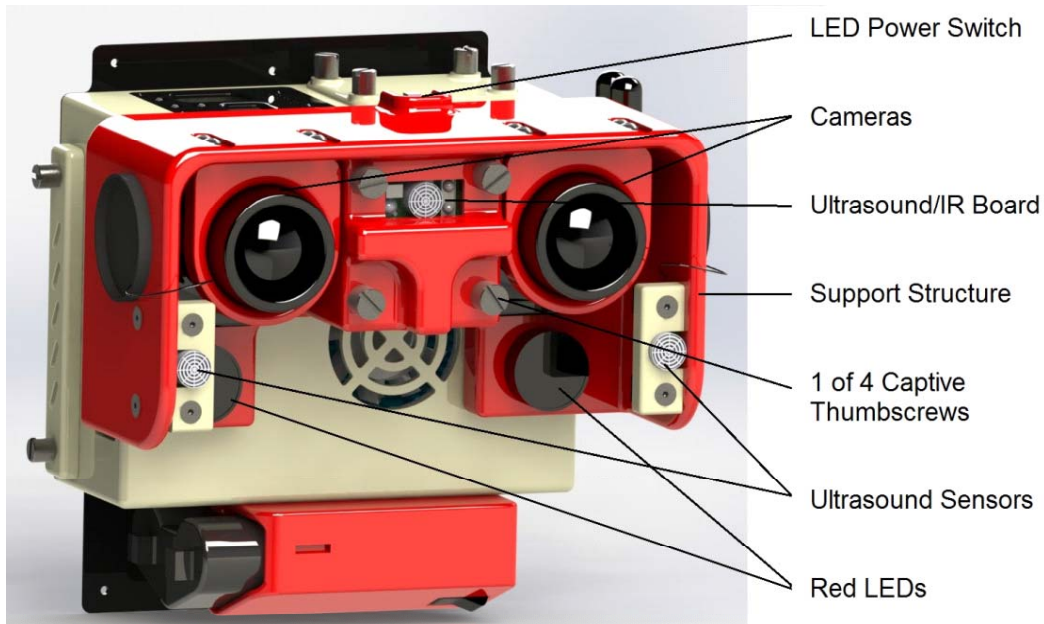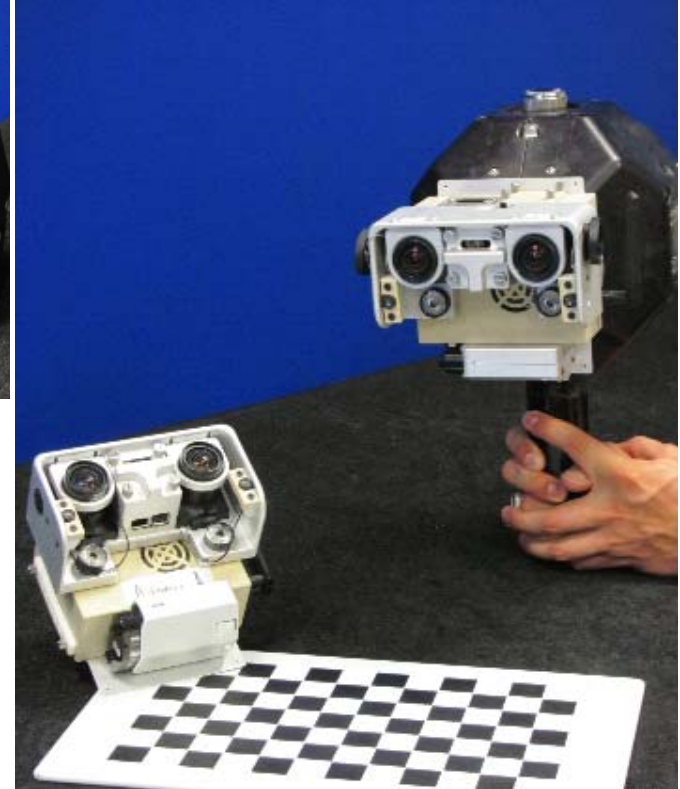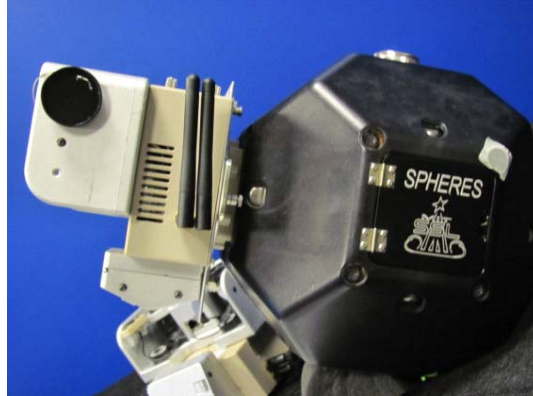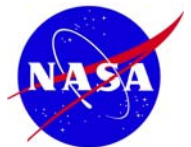
Expansion Possibilities

- – Removable Optics Mount
  - • Interface: USB 2.0, 12V Unregulated, RS232 x2, 1Gbps Ethernet
- – 802.11n USB WiFi Card
  - • Offboard processing, communications and sensor resources

- ***Inspection*** of an ***unknown***, ***uncooperative***, possibly ***tumbling*** and ***moving*** target object
- Estimate inspector trajectory and build a 3D map of the target object. Estimate linear and angular velocities as well as inertial properties of a tumbling/spinning target
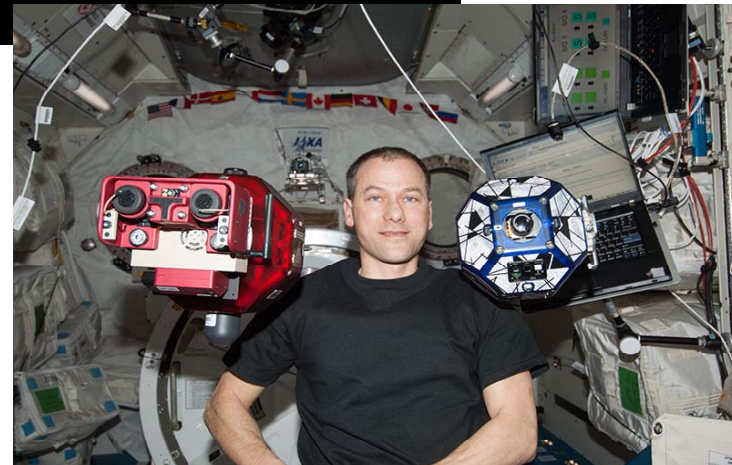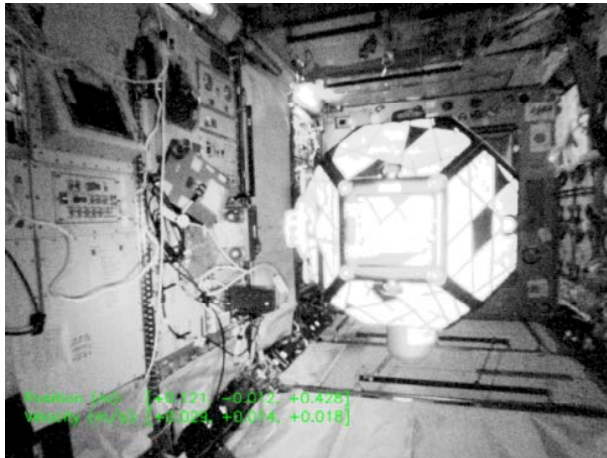
RINGS

- Purpose of RINGS:
  - Demonstrate EMFF for the first time in full 6 DOF micro-gravity
  - Mature EMFF control algorithms in 6 DOF
  - Demonstrate a hybrid EMFF/Wireless Power Coupling Design

- Electromagnetic Formation Flight (EMFF)
  - Apply force and torque on SPHERES
  - Use electromagnetic interactions modeled as magnetic dipoles

- Wireless Power Transfer (WPT)
  - Inductively coupled coils at resonance to improve power coupling
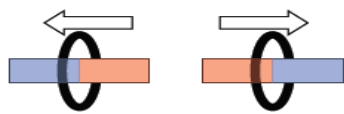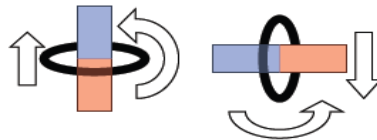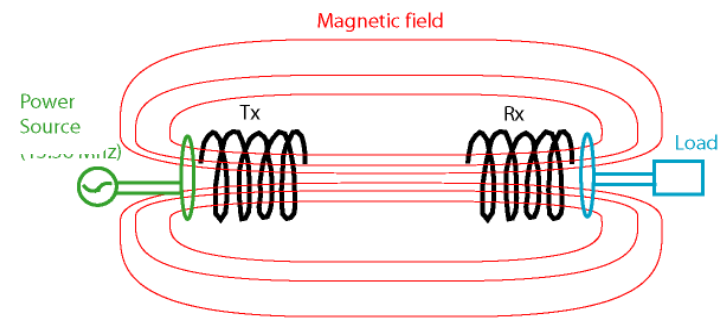
Force   Torque
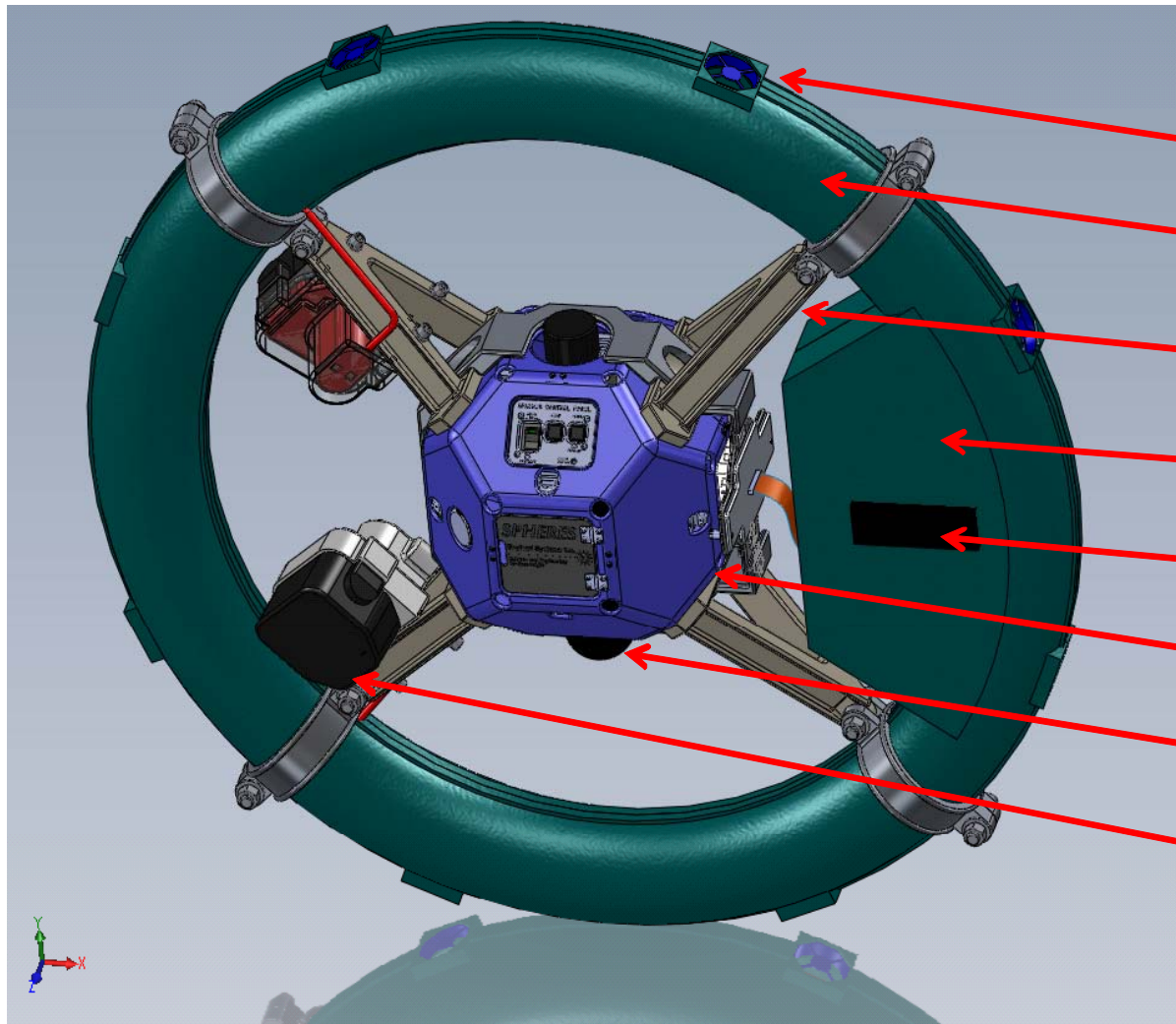
Fan

Ring Housing

Support Structure

Electronics Box

LCD Display

SPHERE

CO_2 Tank

Battery
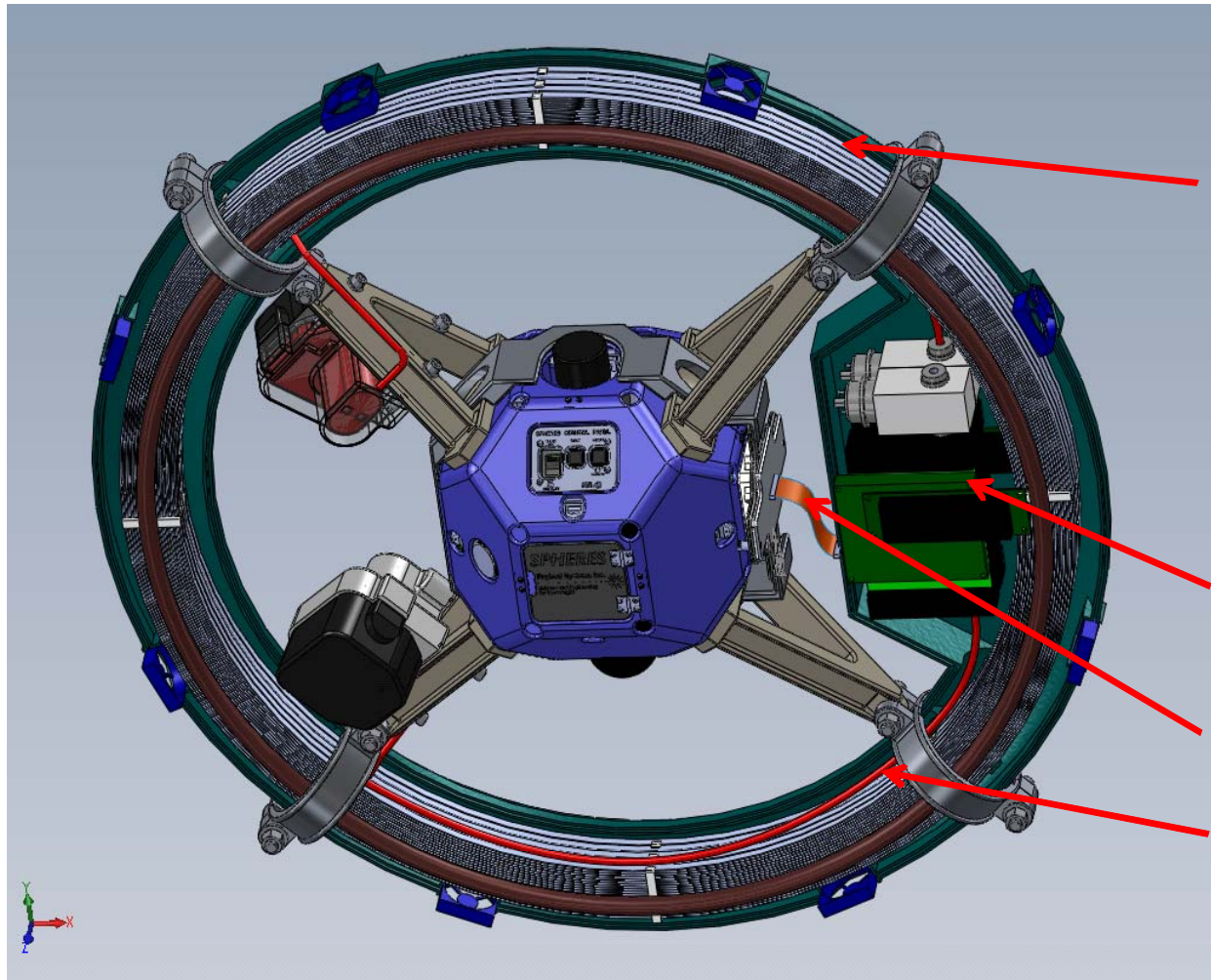
SPHERES

5-layer Resonant Coil
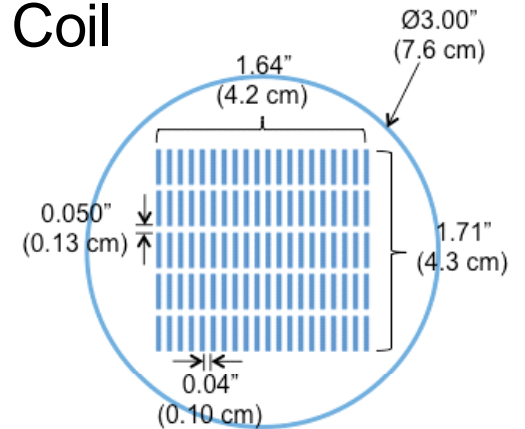
Power Electronics

Expansion board interface & cable
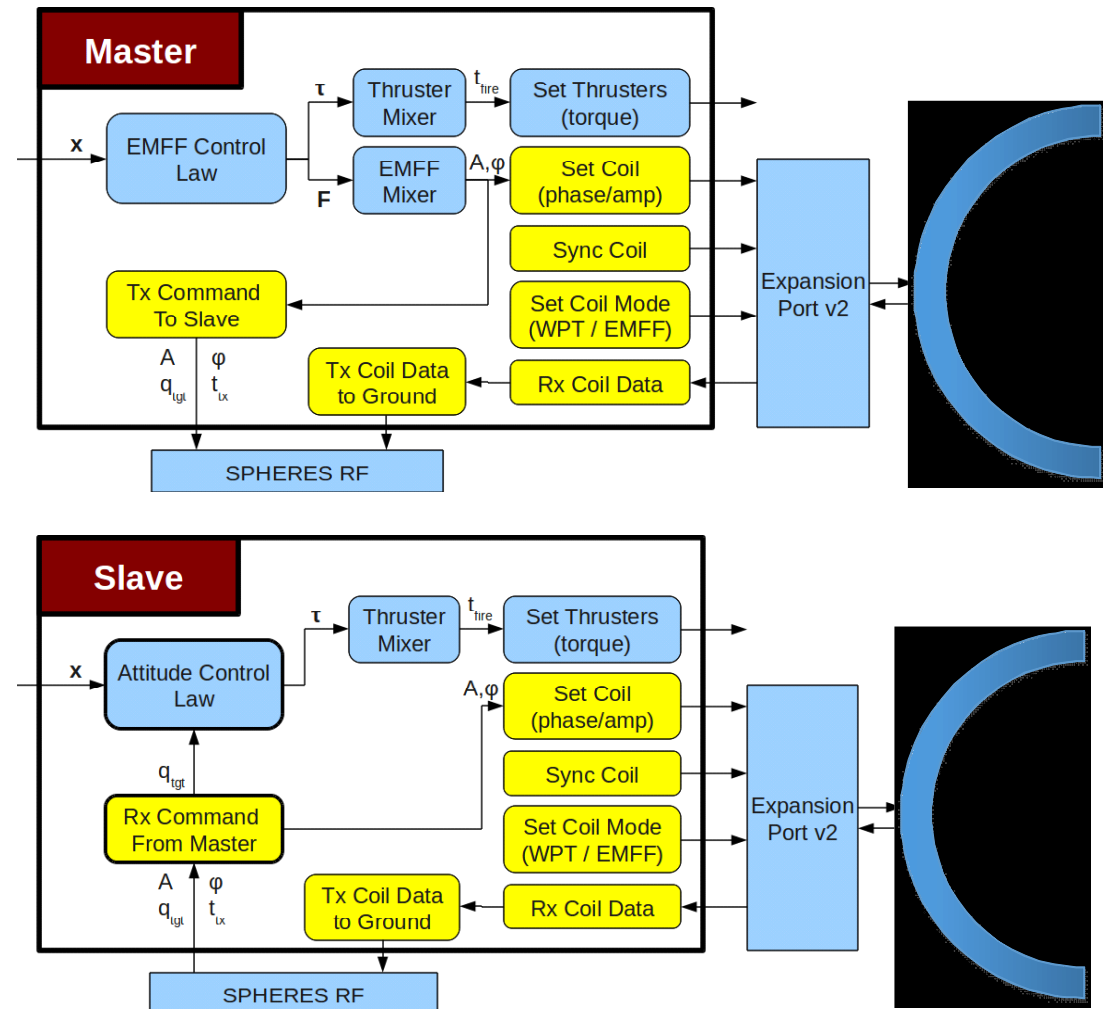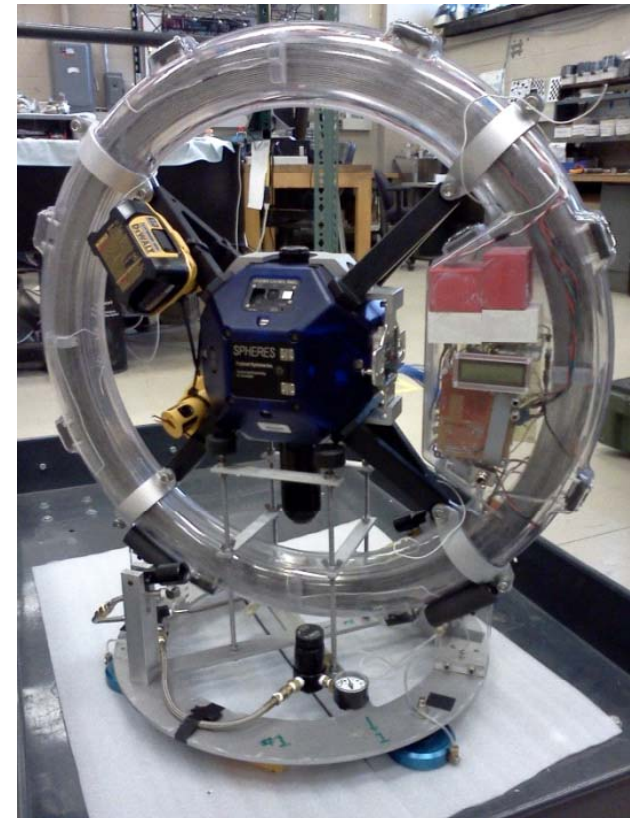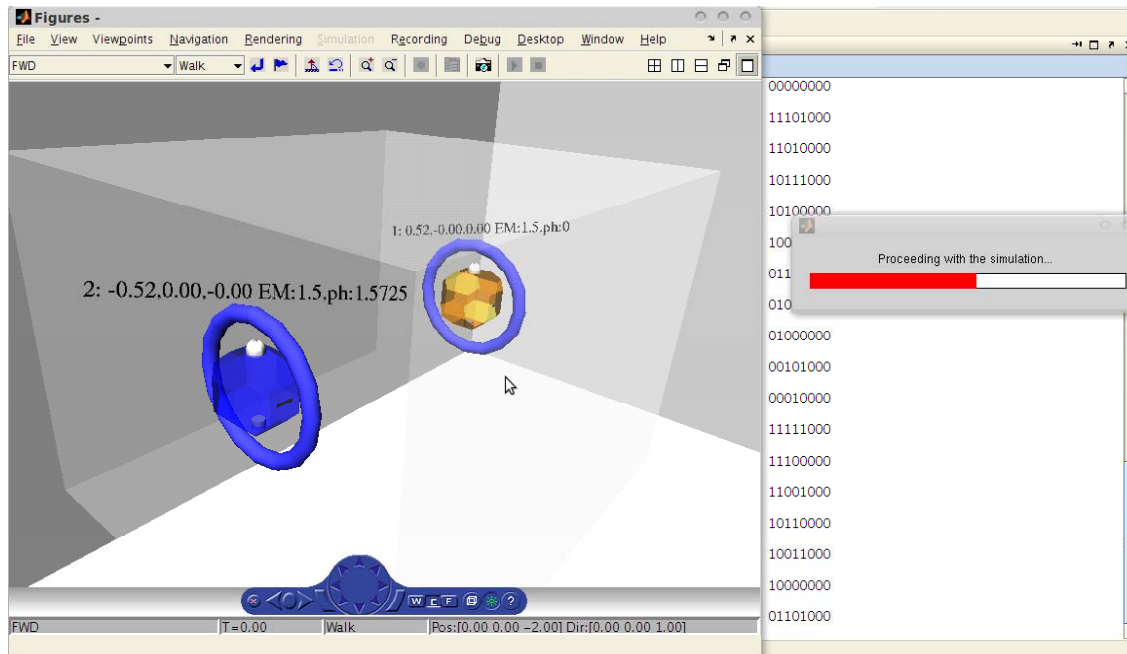
Battery Power Cable

SPHERES

- SPHERE 1 is the master satellite and controls SPHERE 2, the slave

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- Updated SPHERES Simulation

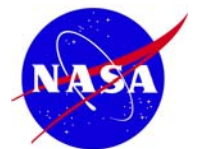- Ground hardware development complete; now integrating flight HW

SPHERES

- Determination of mass & inertia properties of the full assembly
- Preliminary validation/measurement of EMFF forces & WPT ability

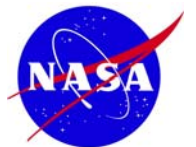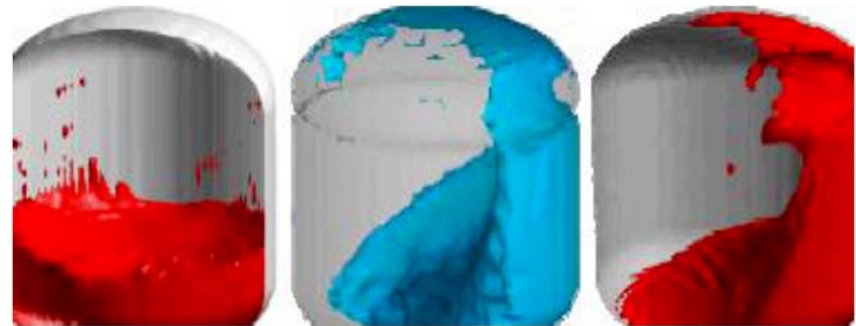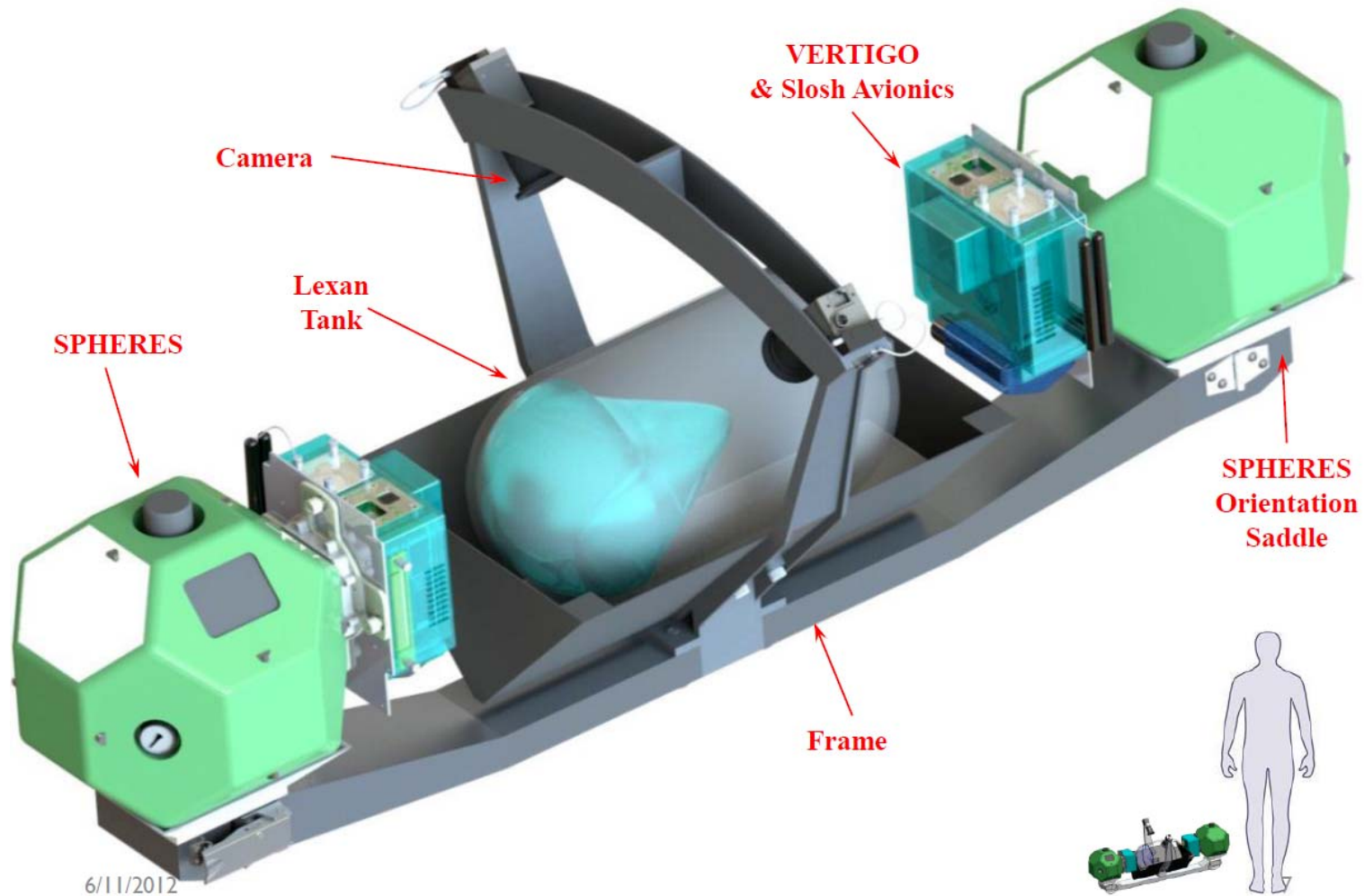**Launch on HTV-4 in SU/FA '13!**

SLOSH

- Acquire long-duration, low-gravity slosh data for calibration of detailed Computational Fluid Dynamics (CFD) models of coupled fluid-vehicle behavior

- Why?
  - Predicting spacecraft and launch vehicle slosh dynamics is critical for mission success
  - Current CFD models lack long-duration data
  - Better models = more reliable, safer systems

- How:
  - Utilize existing SPHERES satellites to propel transparent fluid-filled tank
  - Acquire system and liquid position data for known applied forces using IMU and imaging systems
 - Benchmark CFD model predictions

VERTIGO & Slosh Avionics

Camera

Lexan Tank

SPHERES

SPHERES Orientation Saddle

Frame

6/11/2012

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- Uses VERTIGO computer
  - 64 GB of SDD for data storage
  - CPU tested: 85% utilization while streaming data at max rate (14/frames/sec at 5 MP/frame)
  - Sync. of two units w/comm
- New cameras
  - 2 high-res monochrome gigabit-Ethernet cameras (5.1 MP, 14.6 frames/sec)
  - High aperture lens
- Additional IMU
  - Four 6DOF inertial measurement sensors (3x accelerometer, 3x gyroscopes) for up to +/- 2g slosh maneuvers
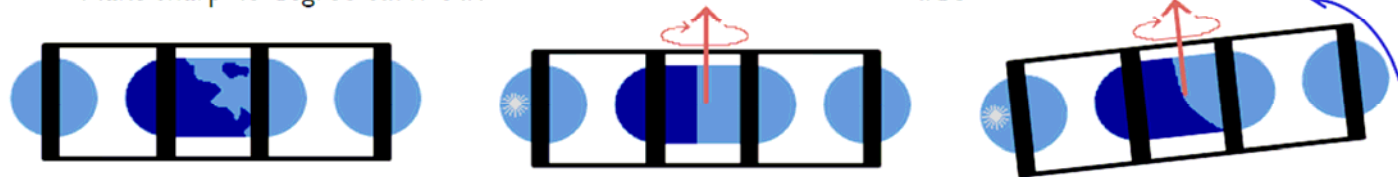
SPHERES
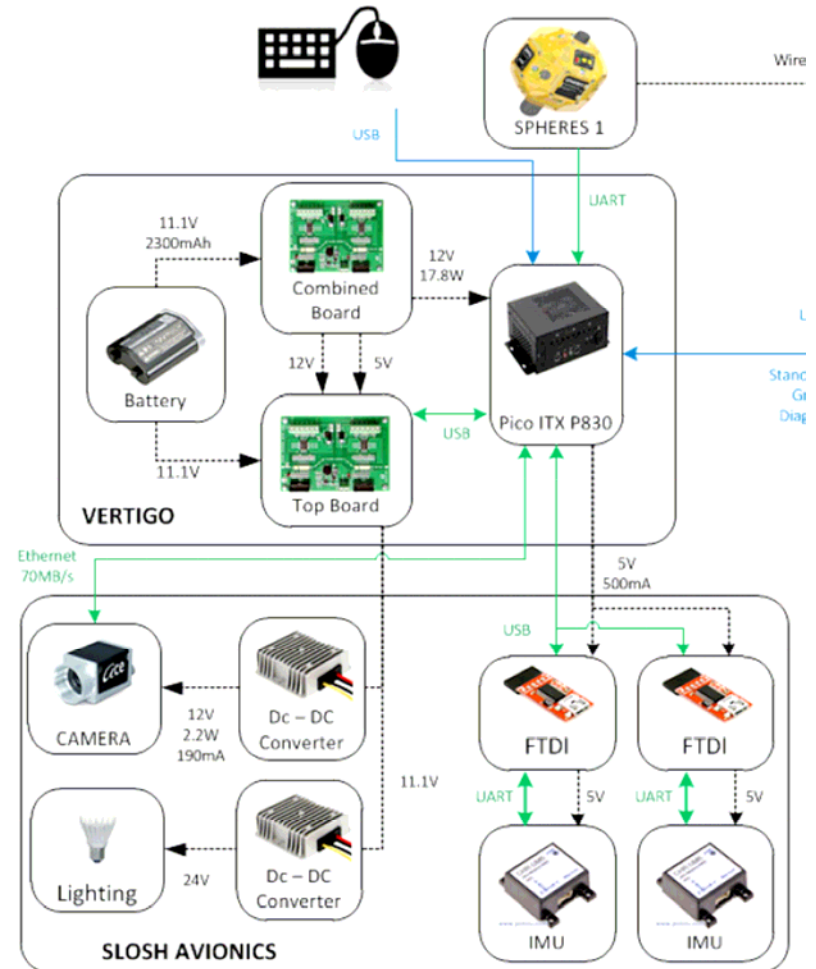
- ## Maneuver 1: Simulate an engine shut down
  - Accelerate system along major axis of tank for a fixed duration
 - Apply reverse thrust to accelerate system in opposite direction for a fixed duration
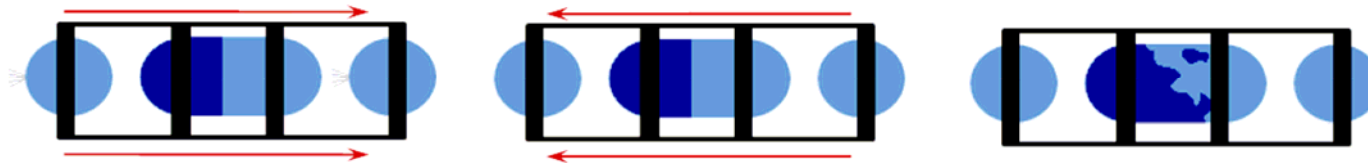
- ## Maneuver 2: Simulate a turn to attitude
  - Spin tank about a minor axis to settle all propellants
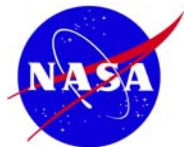 - Make sharp 45 degree turn out of spin plane to 2nd burn attitude

- ## Maneuver 3: Simulate a thermal roll
  - Slowly spin tank about minor axis to attain constant spin rate and settle fluid
  - Thermal roll about major axis while maintaining constant major axis spin rate
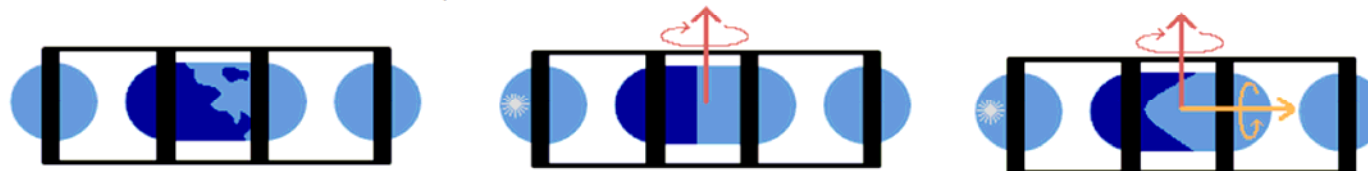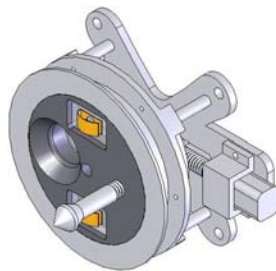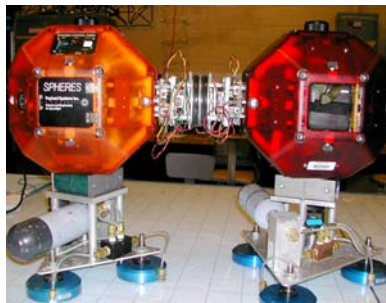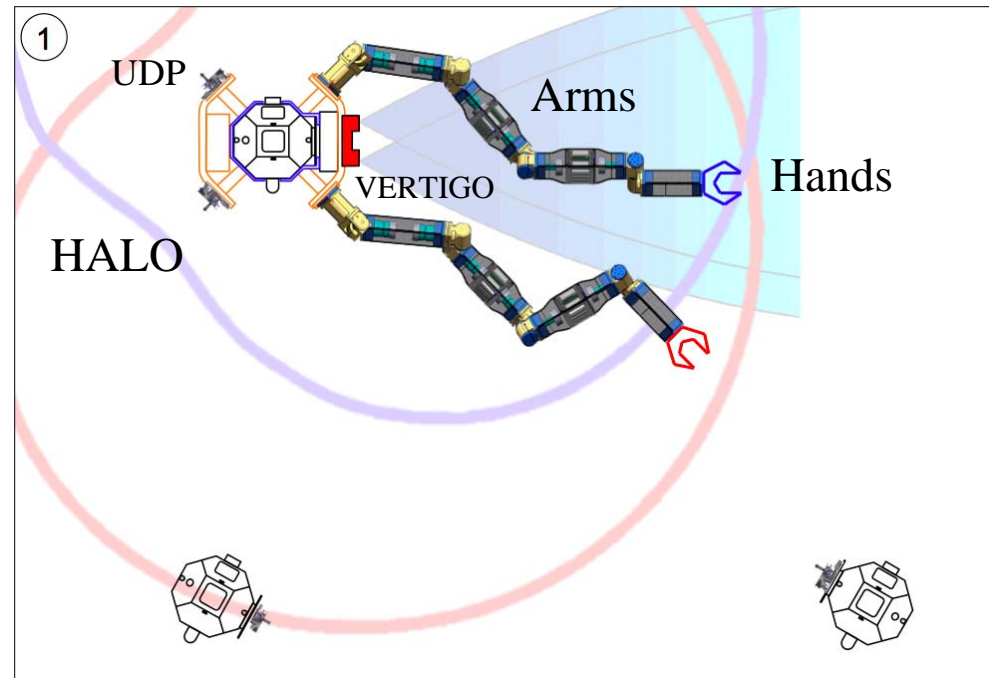
InSPIRE-2: "Medusa"

- **Hardware Upgrades**
  - 2013: UDP
  - 2014: HALO "multiport"
  - 2015: NRL arms
  - 2016: NRL hands

- **Software Development**
  - Proximity operations
  - Docking / reconfiguration
  - Robotic arm manipulation

- **Zero Robotics Competitions**
  - Partial funding for 2013 HS Tournament
  - Potential partial funding for 2014 and 2015 HS Tournament
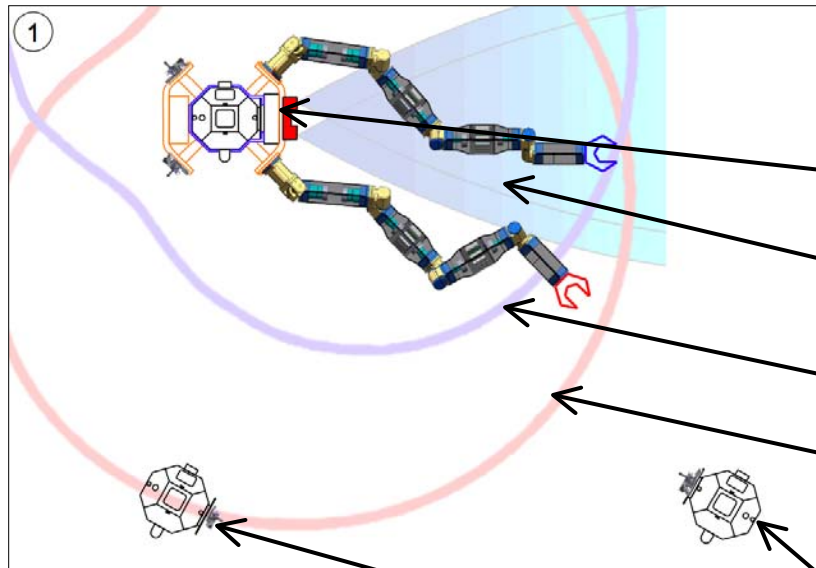

UDP

1

UDP

Arms

Hands

VERTIGO

HALO

Inspire 2 - adds new HW to ISS and maintains ZR alive

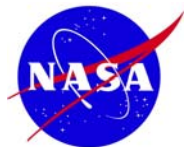Initial
<u>Positions</u>

Servicer/tender

VERTIGO Workspace

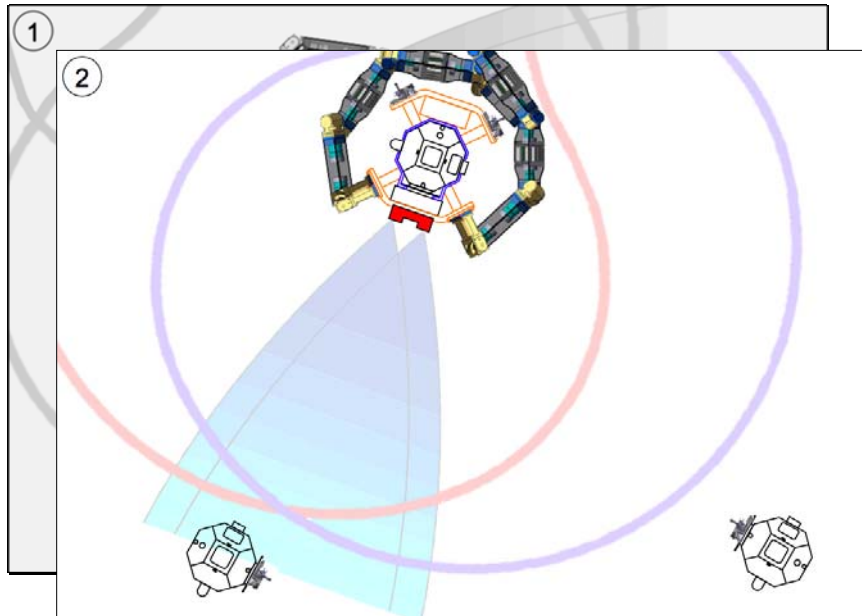Blue Arm Workspace Boundary

Red Arm Workspace Boundary

SPHERES/Satlets

SPHERES

<u>Target Search and Location</u>
- Servicer/tender reconfigures arms
- Uses VBN to find 1st Sphere
- Plans path to Sphere
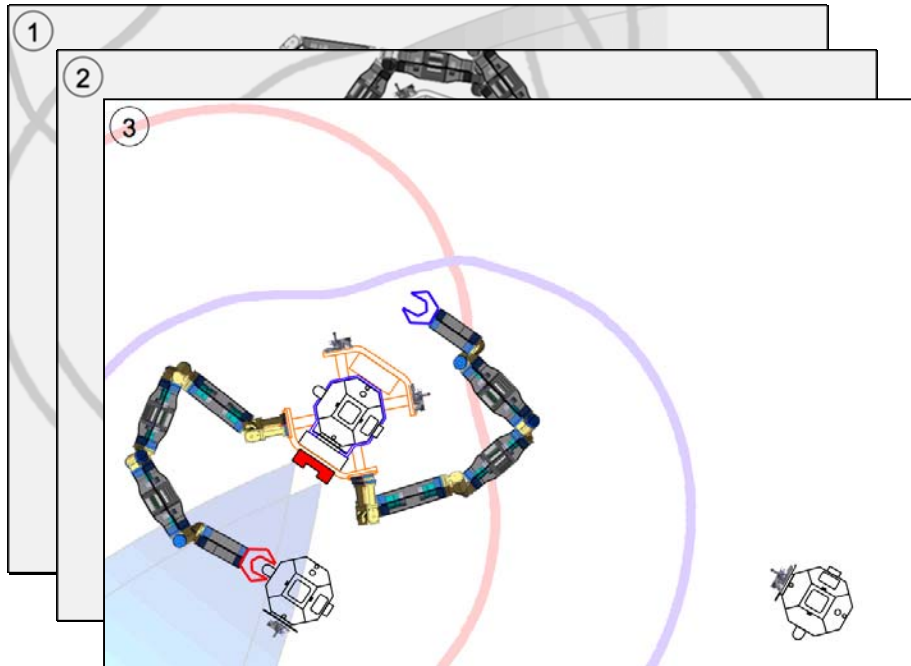
Target Approach and Acquisition

- Servicer/tender travels to 1st Sphere
- Determines Sphere's state using VBN
- Grasps Sphere using arm and end effector

Target Berthing and Docking

- Servicer/tender uses arm to dock Sphere to HALO
- UDPs activate and close
- End effector releases Sphere
- Reconfigure arms
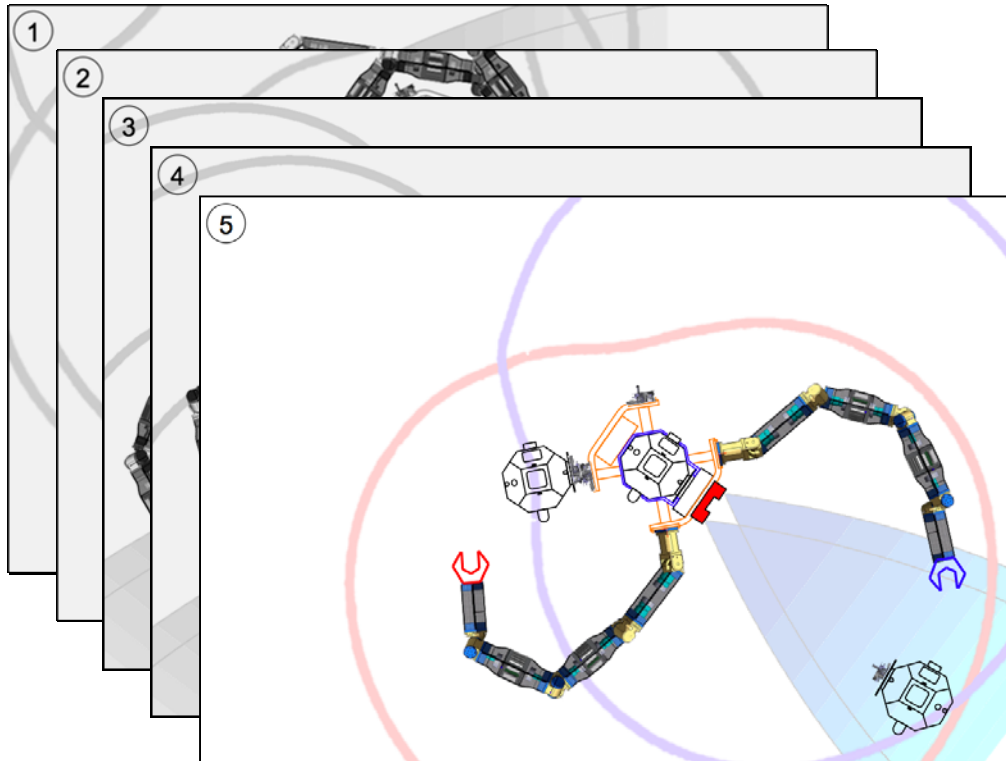
Target Search and Acquisition

- Servicer/tender finds 2nd Sphere using VBN
- Plans path and travels
- Grasps 2nd Sphere with arm
- Berths with 2nd Sphere
- Plans path to final location
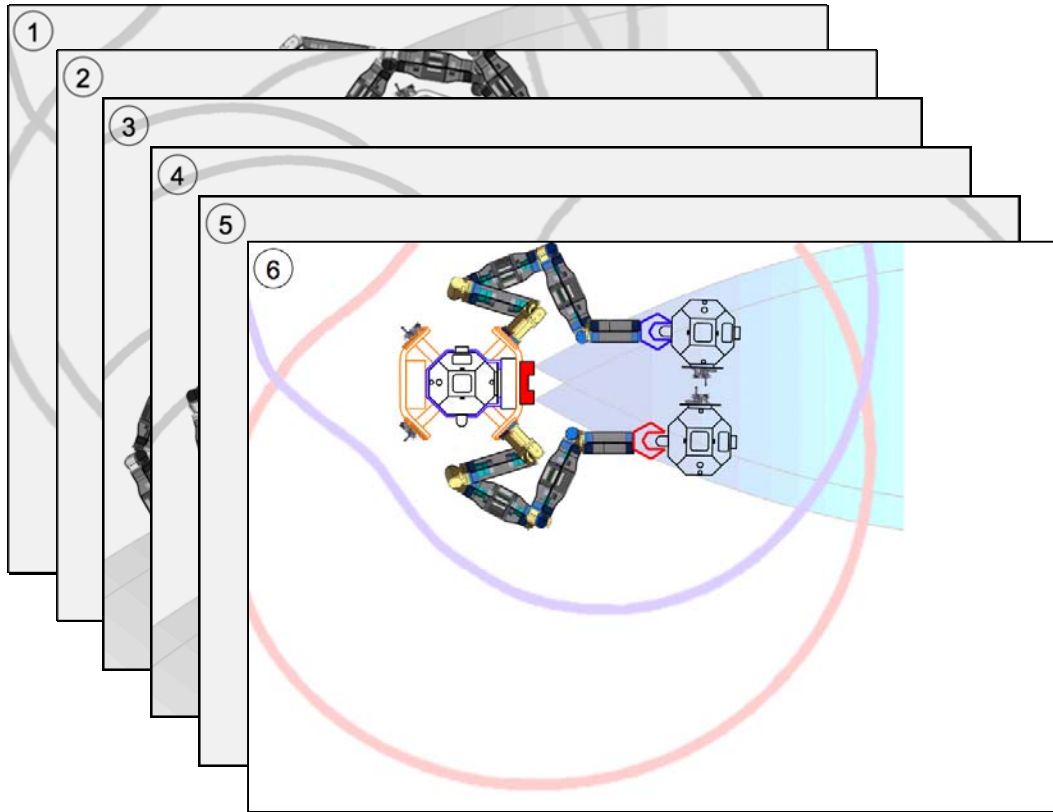
Assembly

- Servicer/tender travels to final location
- Retrieves Spheres from HALO with arm
- Docks 2 Spheres together using arms and VBN

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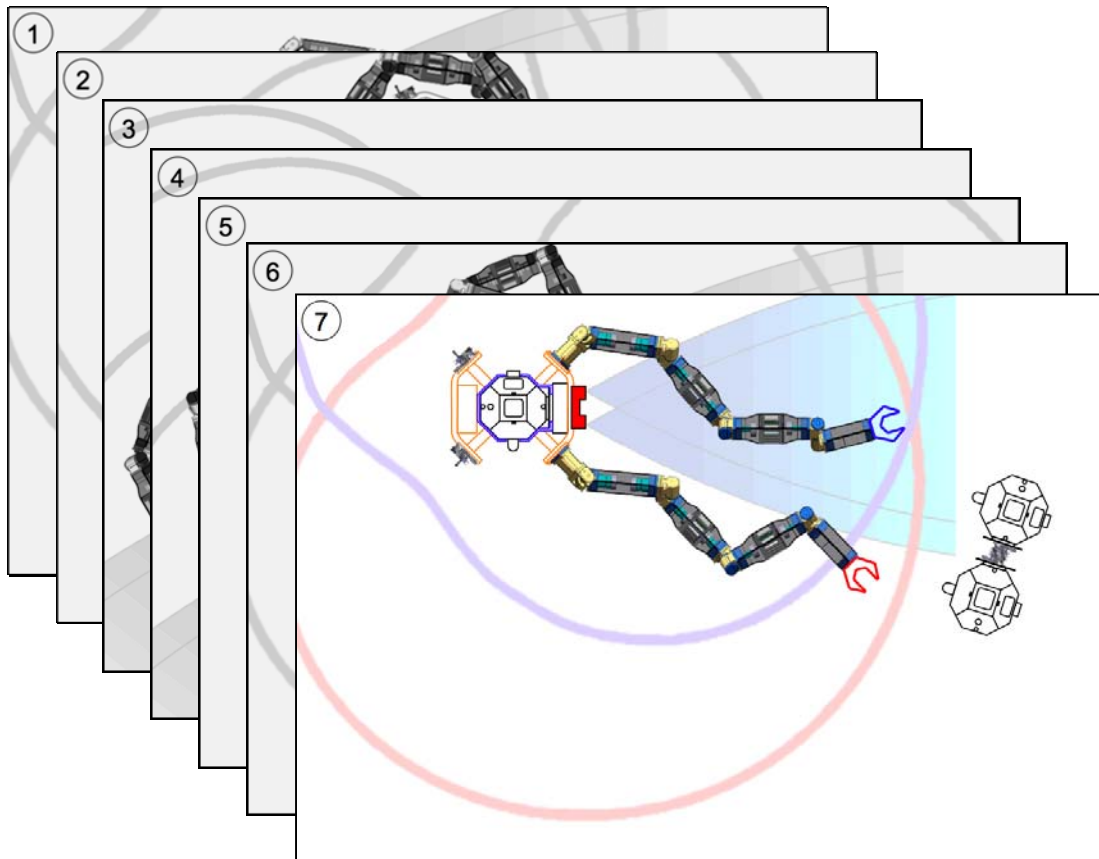
Release

- Extends arms
- Releases docked configuration
- Reconfigures arms
- Awaits next mission

SPHERES

- Previous tests in the ground with the docking ports and flexible structures
  - MEDUSA will *not* have flexible structures, at least not yet...
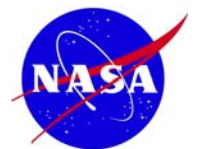
ZERO ROBOTICS
ISS PROGRAMING CHALLENGE

http://zerorobotics.mit.edu
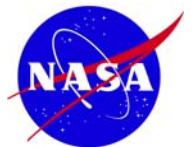
- A competition designed to allow Middle- and High-school students unprecedented access to the International Space Station

- Teams of students work to program the SPHERES satellite to win an MIT-designed game

- The teams go through multiple elimination rounds; the top teams see their code tested aboard the ISS

A "complementary" software Competition in the Fall, similar to the FIRST Robotics HW in Spring.

- The teams go through multiple elimination rounds; the top teams see their code tested aboard the ISS
- Full programming experience
- ZR Team supports online only

- Middle School Summer Program
  - Assumes teachers do not know programing: created new **curriculum** which helps "any" teacher run Zero Robotics
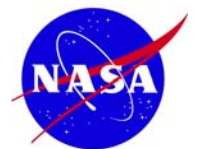   - Curriculum "deployed" and currently under use!
  - Game can be programmed using a "Graphical User Interface"

  - Expanded to: CA (near ARC), FL (near KSC), GA (near GeorgiaTech), and ID (near Lorna Finman / Barbara Morgan)
  - June: web-based (webex) training of Middle School summer teachers
  - July+August: 5-week summer program
  - August 12-13: ISS Finals

- High School Fall Tournament
  - Mostly an "afterschool club"
  - Will integrate some of MS tutorials during SU13
    - Mentors are the Science/Math/Computer teachers and local engineer volunteers

  - Mid-April: registration opens
  - Summer: publicity campaign
  - September: Kick-off
  - October/November: 2D & 3D Runs
  - December: semi-finals
  - January '14: ISS finals

2010 MS ISS Finals interviews quotes:
"It turned out to be easy."
"The best part was seeing people cheering for you."
*"I learned about velocity and gravity."*
"If you keep doing it, it's easy!"

SPHERES

- Step 1: Team Registration (Apr - Sep)
  - Teams submit a proposal for their programming plan, including student written essay
- Step 2: 2D Simulation Programming (Sep/Oct)
  - Test in online simulation; 2D motion
  - Thousands of sim matches per team
- Step 3: 3D Simulation Programming (Oct/Nov)
  - Full 6DOF motion
  - Thousands of sim matches per team
- Step 4: "Semi-Finals"
  - Create "alliances" of 3 teams each
  - Final 3D simulation competitions
- Step 4: Finals
  - Finalists invited to MIT/ESTEC to view a live feed of the event
 - Astronauts operate the satellites aboard the ISS in real-time
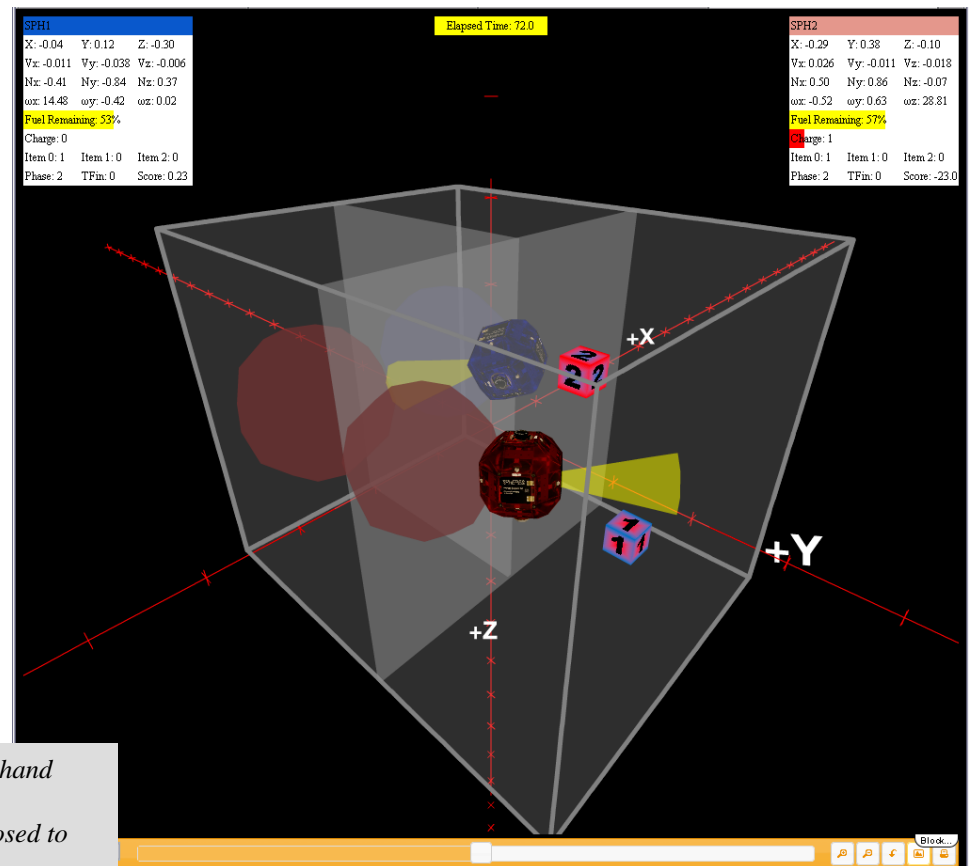
"We realize how rare an opportunity it is to work hand in hand with some of the leaders in programming and aerospace engineering and can not be more grateful that we are exposed to this possibility as high schoolers" **Team *Pirate Squad***

SPHERES

	2009	2010	2011	2011 ESA Pilot	2012
Schools	2	24	122	21	143 (USA + ESA)
Students	13	> 200	> 1000	> 150	> 1500
Structure	No elimination	2 Eliminations ISS: 10 teams	2 Eliminations Alliances ISS: 27 teams	1 Elimination Alliances ISS: 9 teams	2 Eliminations Alliances ISS: 27 USA + 18 ESA

2009   **2010**   **2011**   **2012**
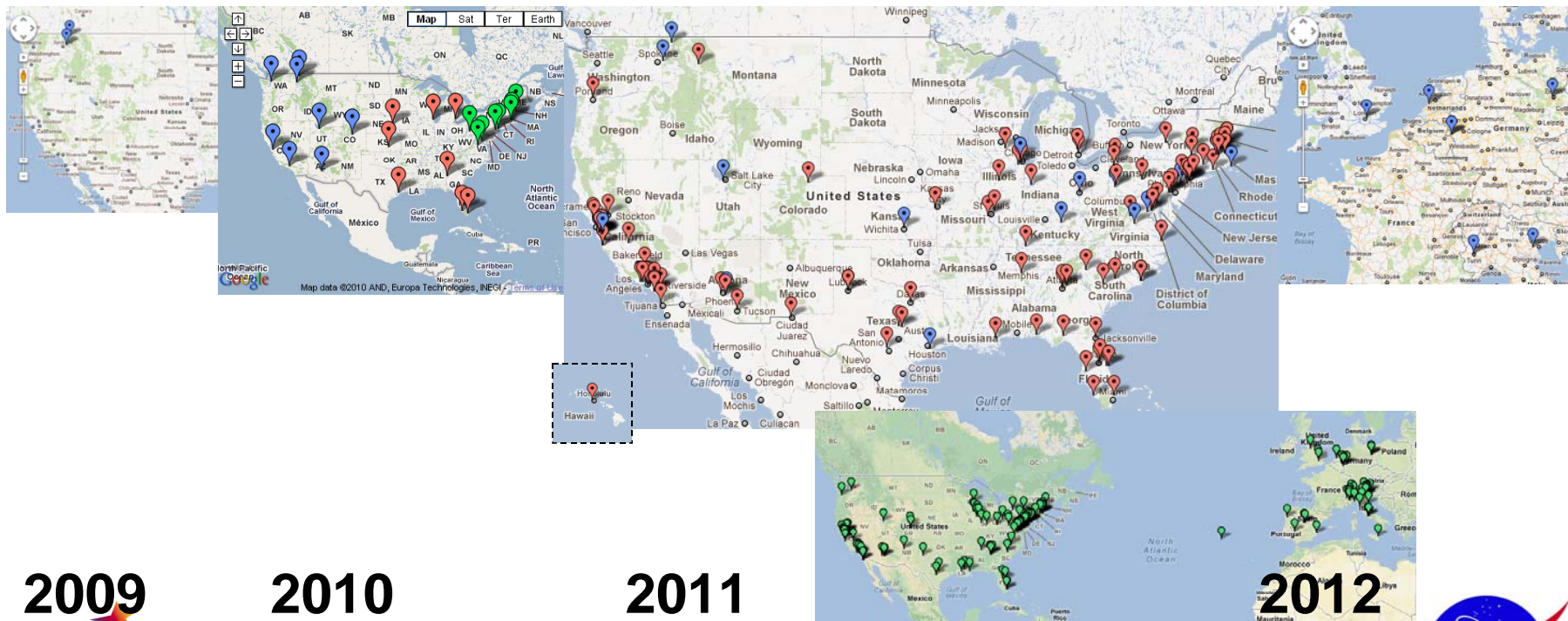
"The students by the end were asking how they get into MIT and I hope many of them begin working towards that goal." **STEM Curriculum Specialist, East End House**

"The awesomeness factor of [the ZR] competition goes well beyond that of [sports]… afterall, [Tiger] Woods is hitting a dinky ball on earth, while we are racing big balls in space" **Team Because Racing**

http://ssl.mit.edu/spheres/videos/zerorobotics/

SPHERES

spheres@mit.edu

http://ssl.mit.edu/spheres

- NASA ARC
  - Andres Martinez, Program Manager
  - Steve Ormsby, Operations Lead
  - Mark Micire, Engineering Lead
- MIT Investigators
  - Prof. David W. Miller, PI
  - Alvar Saenz Otero, Lead Scientist
- MIT Science Team (FA '13)
  - Brent Tweddle (PhD)
  - 10 Masters Students (Bruno Alvisio, Dustin Hayhurst, Chris Jewison, Bryan McCarthy, David Sternberg; Andrew Hilton, Jenny Liu, Duncan Miller, Katherine Reising, Tim Setterfield)
- AFS Hardware Integration & Program Management
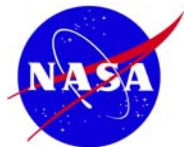 - John Merk
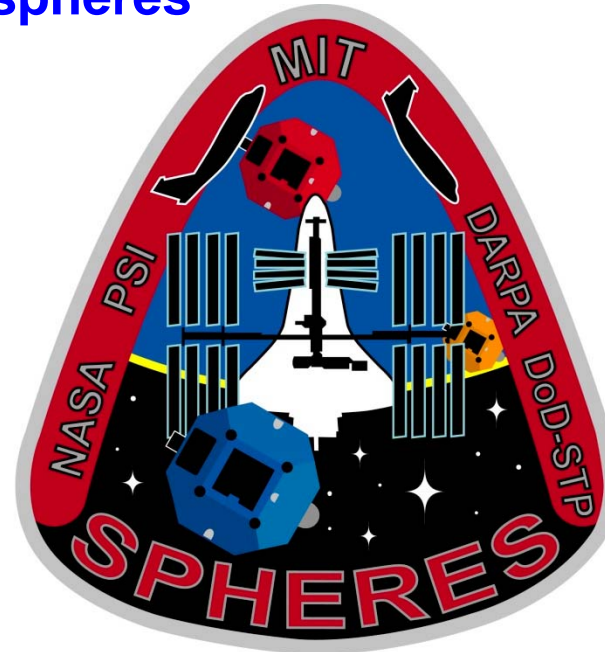
Alumns showcased in presentation:
Jacob Katz (PhD)
Swati Mohan (PhD)
Alexander Buck
Greg Eslinger
Christophe Mandy
Amer Fejzic
Christopher Pong
Sreeja Nag
Michael O'Connor

SPHERES

Questions?

SPHERES

SPHERES Overview

Dr. Alvar Saenz-Otero

MIT SPHERES Lead Scientist
MIT SSL Associate Director

http://ssl.mit.edu/spheres