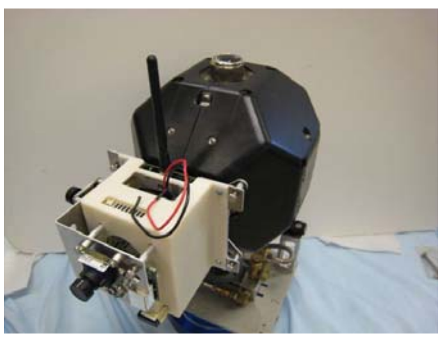
SPHERES VERTIGO Program: Vision Based Navigation Research onboard the International Space Station

ICRA 2011 Space Robotics Workshop



Brent Tweddle

tweddle@mit.edu

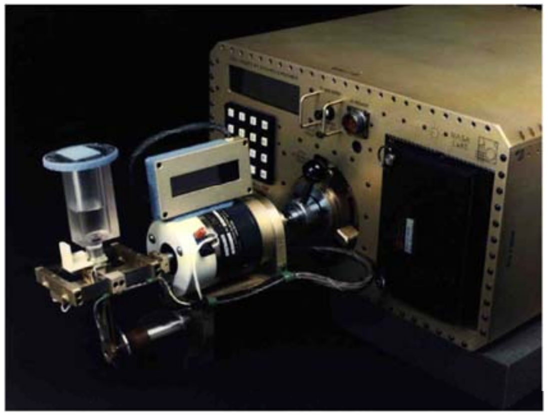
Ph.D. Candidate

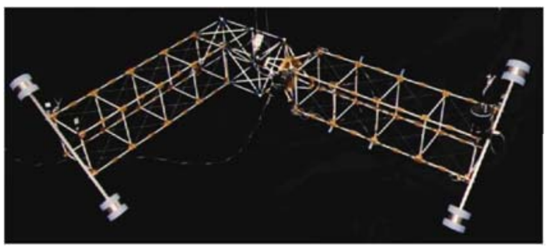
MIT Space Systems Laboratory

Presentation Outline

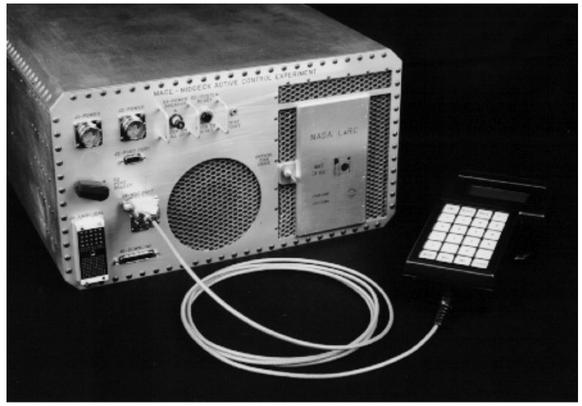
- Introduction to MIT Space Systems Laboratory and SPHERES Project
- SPHERES Goggles ground prototype
  - US Naval Research Laboratory LIIVe program
- SPHERES Goggles flight version
  - DARPA InSPIRE VERTIGO program
- Visual Navigation Algorithm Research

MIT SSL Research Laboratories in Space

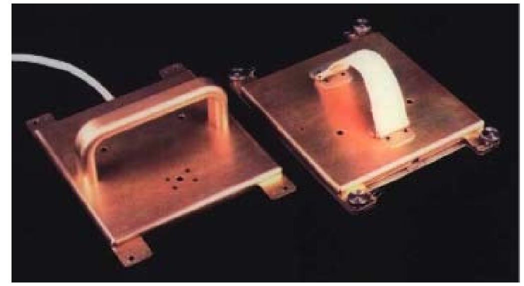




MODE
Shuttle 1991 & 1994



MACE
Shuttle 1995

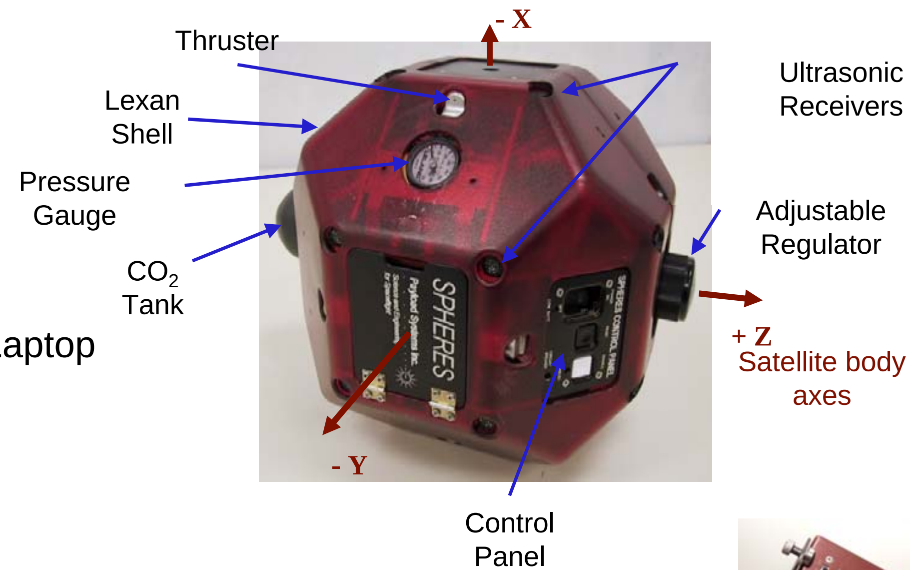


EDLS Mir 1996

MACE ISS 2000

SPHERES Hardware

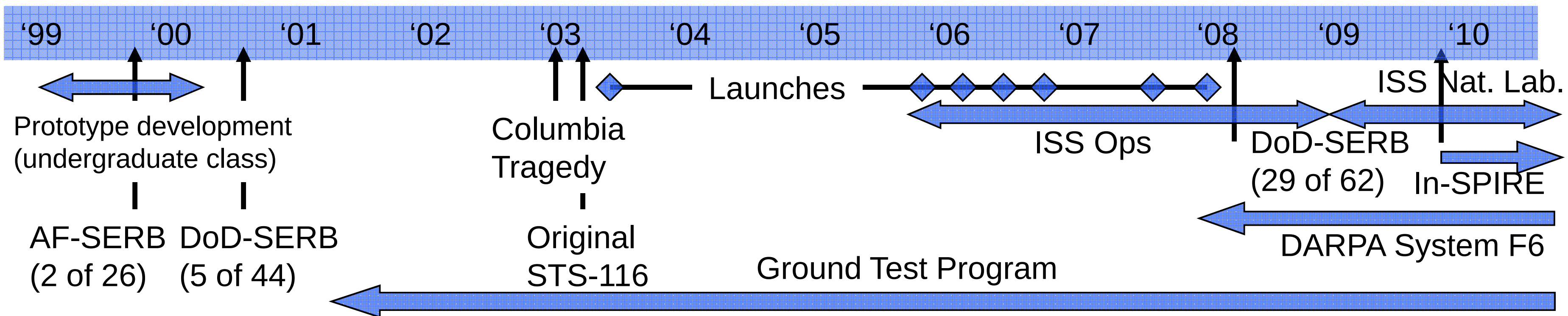
- Propulsion
  - 12 CO2 Thrusters
- Power
  - 16 AA Batteries
- Communications:
  - SPHERE to SPHERE and SPHERE to Laptop
  - 900 MHz TDMA 16kbps
- Processing
  - TI DSP C6701, 167MHz
  - 1 GFLOPS Theoretical Peak
  - 256 kB Flash ROM
  - C RTOS: DSP/BIOS
- Navigation
  - Pseudo-GPS Ultrasonic Metrology
  - Onboard IMU
  - Estimates 6DOF pose at 5Hz
  - Repeatability: ~1-5mm, ~1-2 degrees
- Astronaut Interface with ISS Laptop



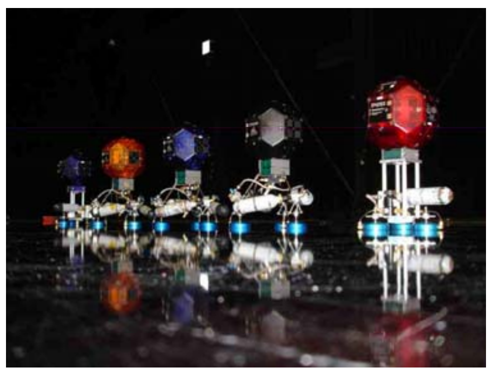
Ultrasonic Metrology Beacon

Diameter	0.22 m
Dry Mass	3.5 kg
Wet Mass	4.3 kg
Thrust (single thruster)	0.11 N
CO_2 Capacity	170g

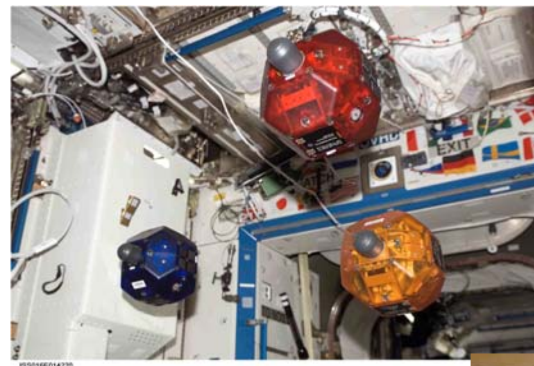
History of SPHERES



CDIO Capstone Class



Terrestrial Laboratory



ISS Laboratory

Zero-Robotics Student Competition
zerorobotics.mit.edu

Video: Collision Avoidance

Video: Docking to a Tumbling Target

Video: Decentralized Cyclic Pursuit

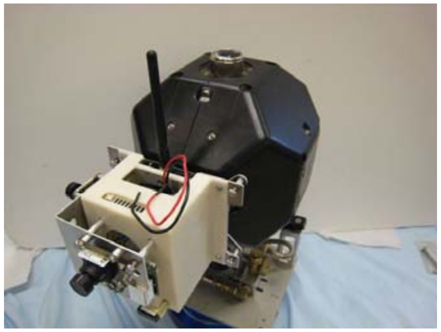
ISS Test Session Accomplishments

- Had a total of 26 science test sessions of ~4 hours each since launch in May 2006
- Conducted one, two, and three satellite operations in full 6DOF
- Accomplishments summary, including estimated percentage of task complete:

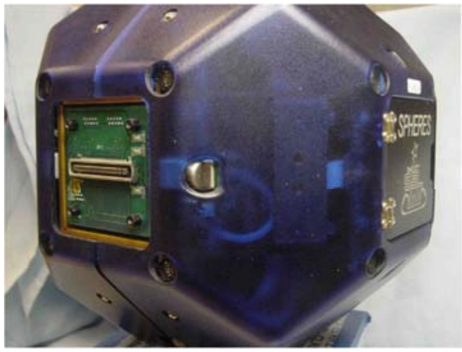
	Sessions	Completed	Pending	%
Docking				
- Traditional	2-5,8	Dock to tumbling target	None	100
- “Safe”	5-6,9-10,14	Basic “react to failure” tests	Obstacle avoidance (3 sats)	70
- Assembly	9-13, 17, 19	Basic maneuvers, Some Docking	Dock 2 “assembled” sats to 3rd	50
- Reconfiguration	5-13, 17, 19	Joint thruster firing, Sens. Rcfg	Fuel optimization	50
- Inspection	10-11, 18	Basic Maneuvers, Wall Avoidance	Full plane coverage tests	60
- On-line path planning	8,10,12	Docking to a fixed target	Docking to moving targets	60
- Obstacle Avoidance	9-11, 14	Virtual obstacles avoidance	Real obstacle avoidance	25
- Fuel slosh	13-14, 16, 18	Satellite excitation maneuvers	Addition of fluid tanks	30
Formation Flight				
- Precision Formations	7-8, 11-14, 18	Circles, plane change, Spiral	Fuel balancing, optical maneuvers	85
- Initialization	10-11,13-14, 19	3-sat with collision avoidance	3-Sat & integrated tests	40
- Scatter	10-11	2-Sat demonstration	3-Sat & integrated tests	40
- Path planning	10-11, 15	Real-time guidance algorithm	SPHERES-only path planning	10
- Distributed Control	14,15	Initial demonstrations	Cyclic Pursuit continuation	40
- Collision Avoidance	13, 15, 19	Head-On, 3-Sat, Integrated Tests	Multi-sat control law	80
- FDIR - Recovery	1-8, 14	Independent detection & recovery	Fully integrated FDIR	70
Common				
- Lost-in-Space	7, 18	2-Sat and 3-sat algorithms	3-Sat algorithms	60
- ΔV Control	10-12	Data collection and basic motion	Integration with estimator	70
- Advanced Controls (Hinf)	13-14	1 & 2 Sat basic maneuvers	Use on high-level tasks	50

Modularity-Enabled Upgrades

- Upgrade IVA hardware
- Prepare for EVA hardware
- Robotics competition



VISION-BASED NAVIGATION (Vertigo launch 2012)



EXPANSION PORT ENABLED …

ELECTRO-MAGNETIC ACTUATION (Rings launch 2012)

TETHERED FORMATIONS

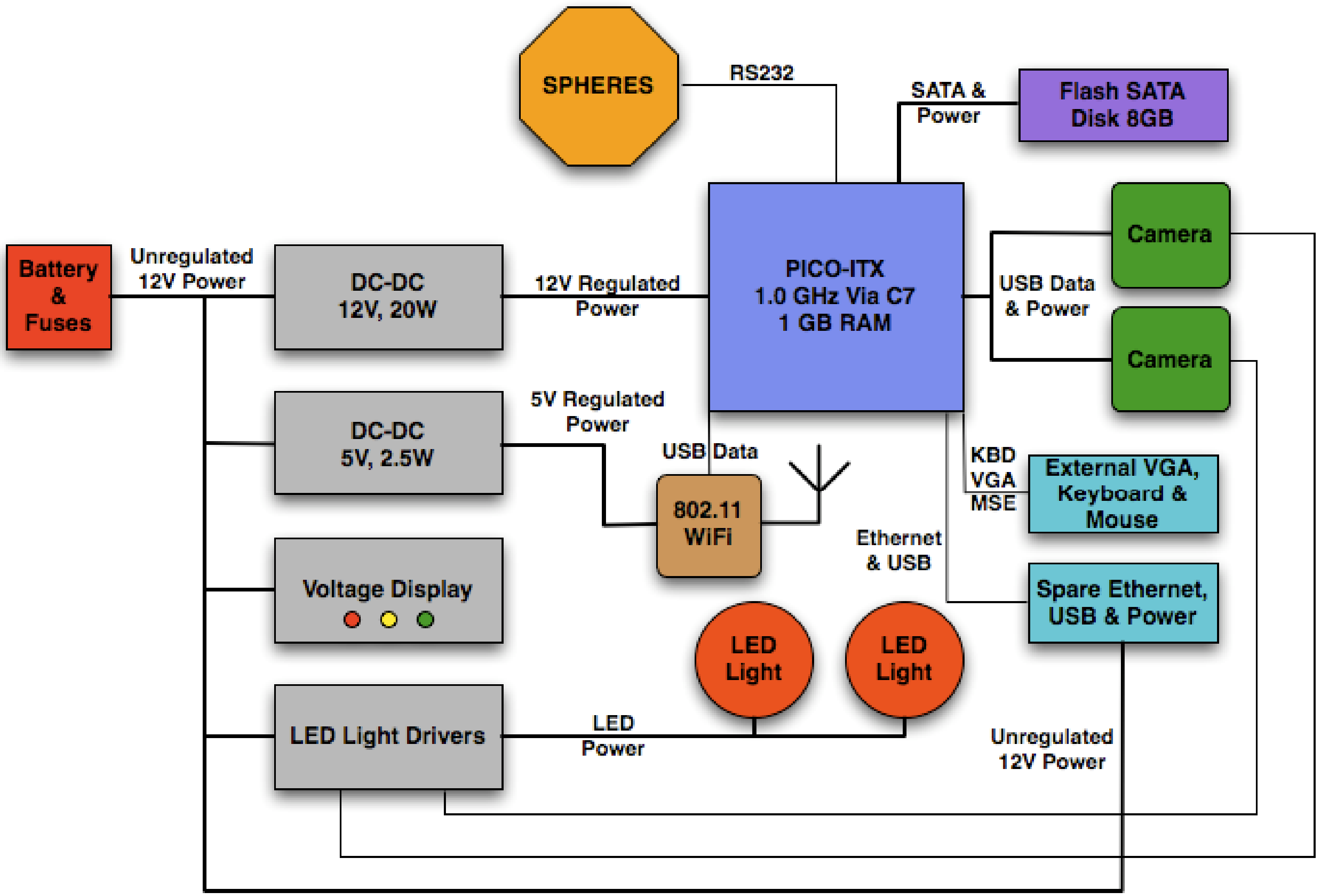
ROBOTIC ASSEMBLY (Spartan)

FLUID SLOSH

Vision Based Navigation on SPHERES

- Goal:
  - Upgrade hardware/software to enable vision based navigation research in a 6DOF micro-gravity environment
- Programs:
  - US Naval Research Laboratory LIIVe Program (2008-present)
    - SPHERES Goggles ground prototype
    - Flight traceable
  - DARPA InSPIRE/VERTIGO (2011 – 2013)
    - Manifested for Launch to ISS in 2012
    - Flight hardware delivery: May 2012
    - Current Status: PDR June 7, 2012

Overall Goggles Electronics Architecture



Processor

Single Board Computer	Processor	Thermal Design Power	Size	Instruction Set Architecture	Floating Point Unit
Lippert CoreExpress	Intel Atom 1.6 GHz	5W	5.8cm×6.5cm	x86	Yes
Via Pico-ITX	Via C7 1.0 GHz	12W	10cm×7.2cm	x86	Yes
Texas Instruments Beagle Board	OMAP3530 (600 MHz Cortex-A8)	2W	7.6cm×7.6cm	ARM	Yes
InHand Fingertip5	XScale PXA320 806 MHz	<1W	6.1cm×8.6cm	ARM	No

Table 2. Single Board Computer Comparison

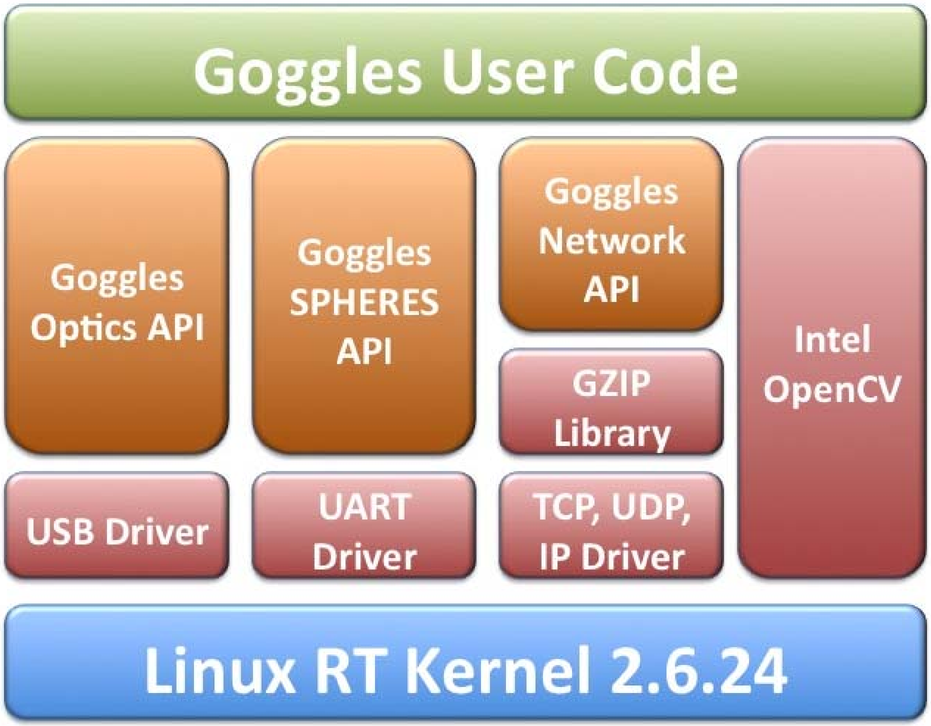
- Single Board Computer (SBC) drives power and size
- Intel Atom offered best specifications, but was not fully available at the beginning of the project
- Selected Via Pico-ITX for project due to schedule and familiarity

Goggles Software Architecture

- Designed for rapid development using publicly available open source software
  - Operating System:
    - Linux Ubuntu 8.04 Desktop Distribution with Real-Time Patches
  - C API provided for accessing hardware

Function	Description
initSPHERES()	This function initializes the SPHERES hardware including the RS232 port.
closeSPHERES()	This function deallocates all structures for the SPHERES interface.
waitGSPInitTest()	Blocks until a new SPHERES test is started.
checkTestTerminate()	Checks if a stop test message has been received.
sendCtrl()	This function sends control commands for the SPHERE to execute.

Function	Description
initTwoCameras()	This function initializes the cameras, sets frame rates, exposure, resolution and other parameters.
closeTwoCameras()	This function deallocates all structures for the cameras.
startTwoCameras()	This function starts the capturing process.
captureTwoImages()	This function blocks until a new image is captured, then returns a pointer to it.

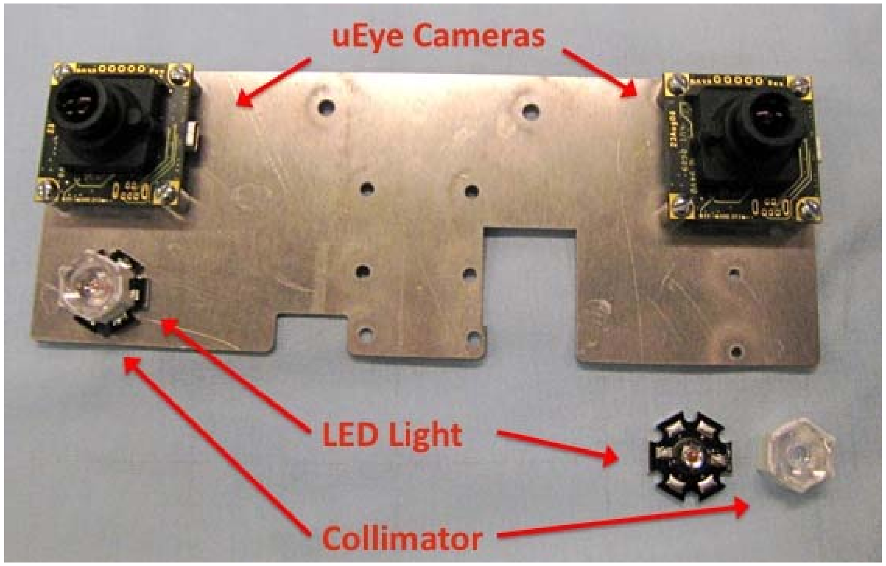


Cameras and Lights

- Simple selection process for optics
- Cameras: IDS Imaging uEye LE
- Lights: Luxeon III Star LED's

Sensor	1/3" CMOS with Global Shutter
Camera Resolution	640 x 480 pixels
Lens Mount	S-Mount, M12
Frame Rate	87 FPS (Camera Max), 10 FPS (Typical)
Exposure	80 μ s - 5.5 s
Power Consumption	0.65 W each
Size	3.6cm$\times$3.6cm$\times$2.0cm
Mass	12 g

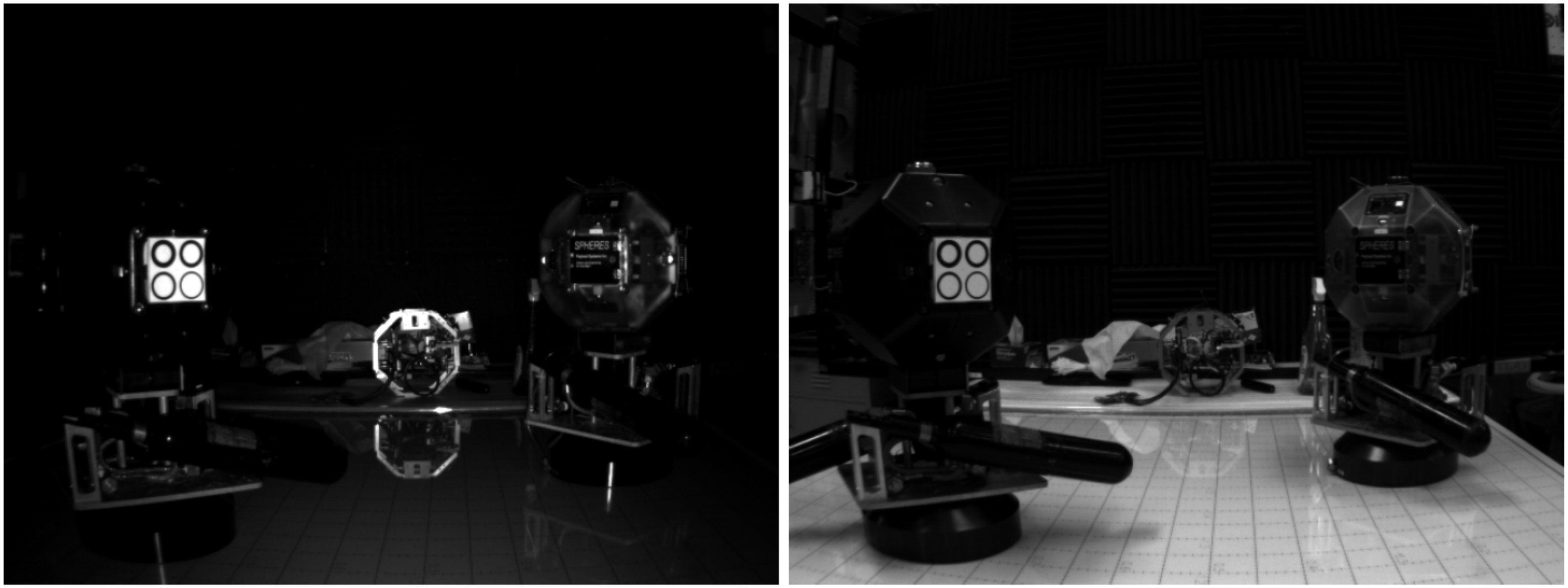
Table 3. IDS Imaging uEye LE



Model	Red-Orange Lambertian
Typical Luminous Flux	190 lm at 1400 mA
Typical Dominant Wavelength	617 nm (red-orange)
Typical Forward Voltage	2.95 V
Diameter	2 cm
Mass	5.5 g

Table 4. Luxeon III Star Specifications

Captured Camera Images



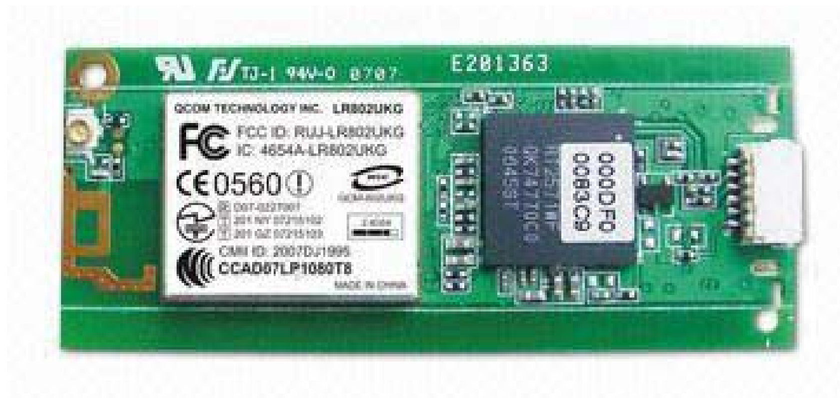
(a) Camera Image with Lights Off (LED Fill Lights On) (b) Camera Image with Lights On

Each LED consumes 2.95 W when on (1.0A current regulation).

LED's are flashed using hardware exposure trigger from camera with a 30% duty cycle.

2 LED's consume 1.8 W total (saves 4.1W).

Wireless Communications



- Required Data Rate:
  - 10 frames per second
  - 2 cameras
  - Lossless gzip compression (~50%)
  - 640 x 480 pixels per image
  - 8 bits per pixel
  - Total data rate: ~ 23 Megabits per second (Mbps)
- Available WiFi protocols:
  - 802.11g: 22 Mbps
  - 802.11n: 72 Mbps
- Selected a Qcom USB 2.0 device

Mode	Plug-In	FTP Transfer	FTP Receive
Average Power	0.90 W	2.65 W	2.60 W
Maximum Power	2.15 W	2.95 W	2.85 W
Data Rate	N/A	20.97 MBps	18.04 MBps

Table 5. QCom Device Characteristics

Power System

Item	Average Power Consumption
Pico-ITX	14 W
QCom Wireless Device	3 W
2 Cameras	1.3 W
LED Lights	2 W
Total	**20.3 W**

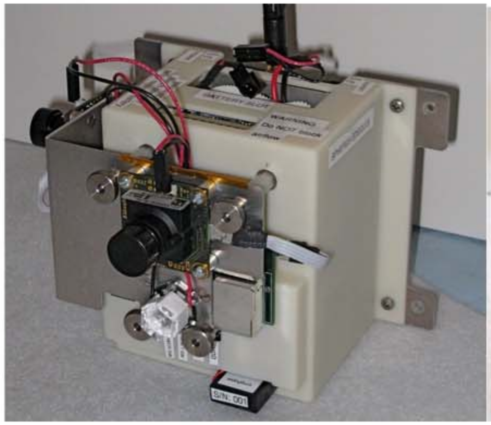
Table 2.5: Approximate Power Budget for Main Components

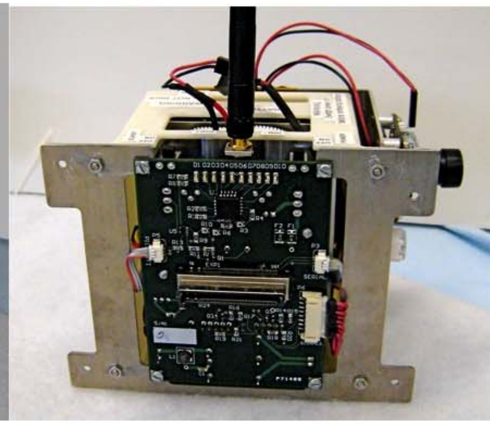
Battery Type	Lithium Polymer with built in protection circuitry
Regulation	DC-DC Converter Main: 12V 20W, 85% USB: 5V, 2.5W, 90%
Safety	Visible voltage display with audible low voltage alarm

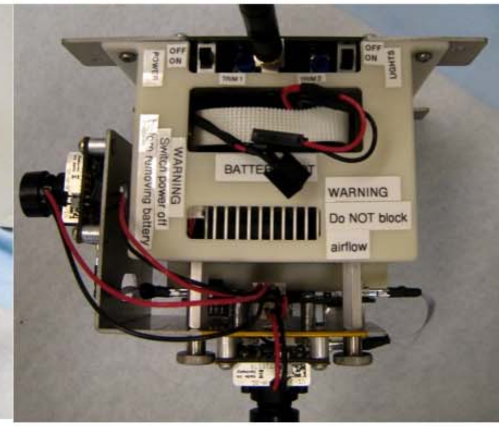
Nominal Voltage	11.1 V (3 cells in Series)
Capacity	2500 mAh
Mass	154 g
Energy Density	180 Wh/kg
Dimensions	104cm×5.0cm×1.8cm
Built in Protection	Over-current, Over-voltage, Over-Drain, Short-Circuit, Polarity

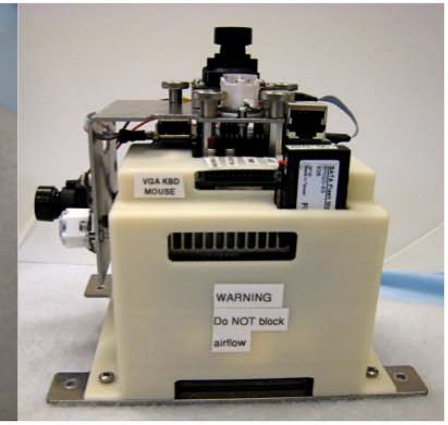
Table 2.6: Battery Specifications

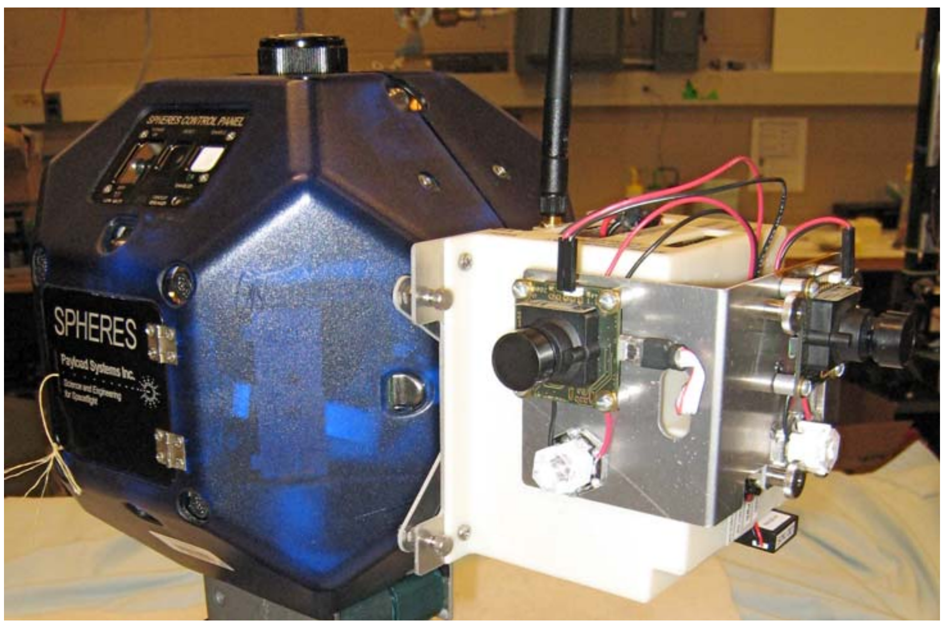
Integrated Goggles

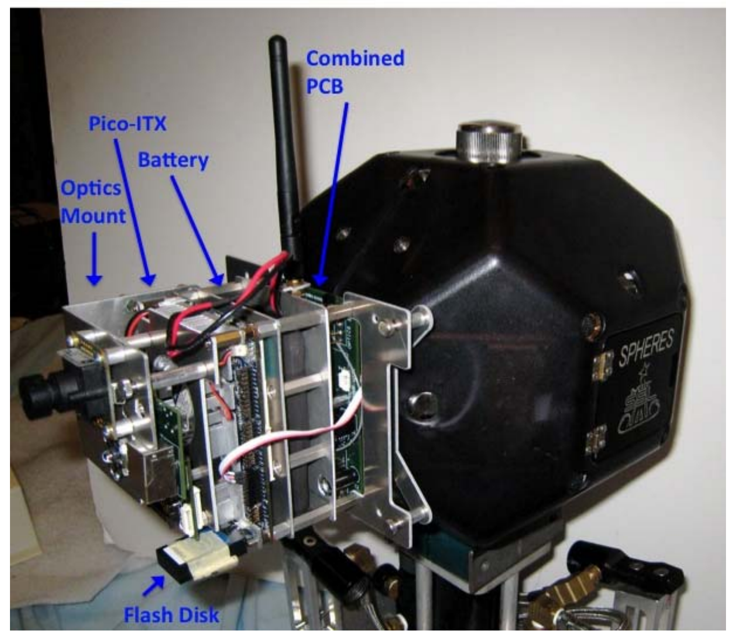












Hardware Modifications for Improved Performance

- Stereo Cameras for Depth Perception
- Launch “textured” 802.11n router
  - Use as calibration target
- Upgraded Processor
  - Retain PicoITX form factor
  - Via C7 to Via Nano
- Upgraded Wireless Communications
  - 802.11g to 802.11n
  - Improves throughput from ~ 20Mbps to ~60Mbps
- Power convertor replacement
  - Use more DC-DC convertors rather than Pico-ITX supplied linear regulators
  - Should reduce system power consumption
- Ultrasonic receivers to replace covered ones
  - Current LIIVe design disables ultrasonic receivers

LIIVe Processor	VERTIGO Processor
Via C7	Via Nano
1.0 GHz	1.2 GHz
128k L2 Cache	512k L2 cache
In-Order Execution	Out-of-Order Execution
	Speedup = ~2X

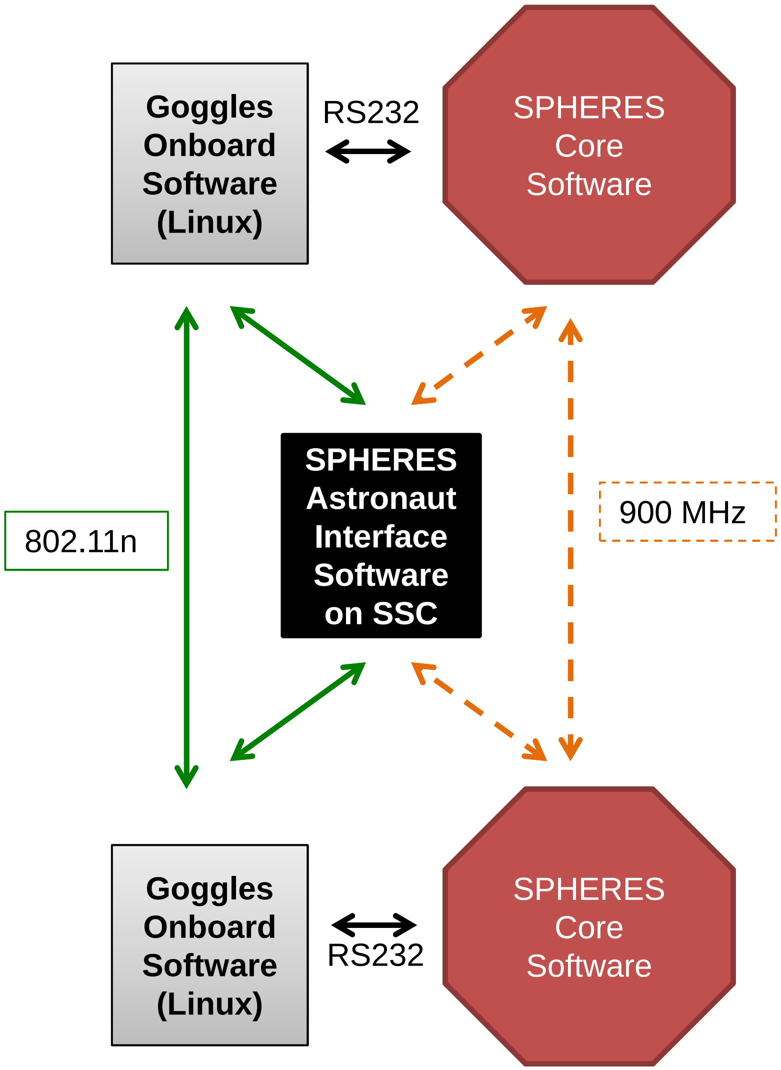
Hardware Modifications for Flight-Qualification

- Lithium-Ion Rechargeable Battery
  - Nikon EN-EL4a (already in use on ISS)
- LED Illuminating Lights
  - May require detailed integration effort

- Mechanical reinforcement for vibration survivability
- Manufacturing compliance with Human Factors Implementation Team (HFIT) and SSP 57000
  - Payload envelope requirements (on-orbit protrusions)
  - Push-off load test (125lbs over 4” x 4”)
  - Crew interface (buttons, LEDs, removable media etc)
  - Design for touch temp & heat dissipation limits, acoustic limits etc
- EMI/EMC compliance to SSP 30237
- Housing
  - ISS compliant materials
  - No Exposed PCBs

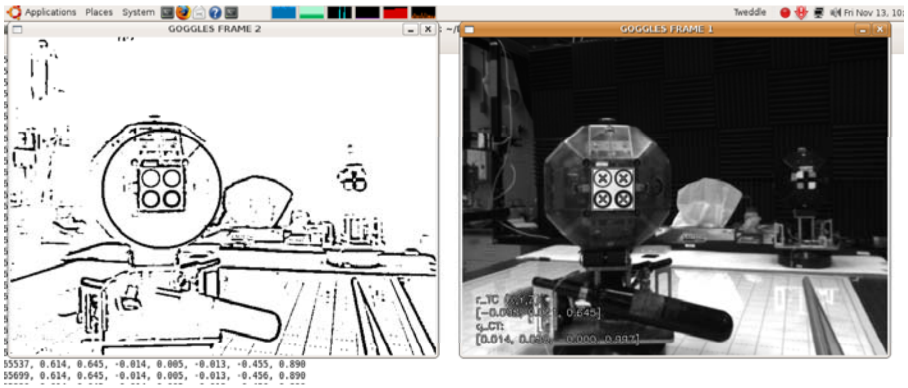
Operational Software Plan

- Operational Software (OS) Elements
  - SPHERES Software (TI DSP)
  - Goggles Onboard Software (Linux)
  - ISS Astronaut Interface Software (Windows SSC or Express Rack Laptop)
- OS Capabilities:
  - Program loading
  - Test running
  - Astronaut monitoring
  - Data download
  - Synchronization



Algorithm Research Areas

- Past and Continuing Research
  - NRL Spacecraft Inspection
    - C. G. Henshaw, L. Healy, and S. Roderick. **LIIVe: A Small, Low-Cost Autonomous Inspection Vehicle.** In AIAA SPACE 2009 Conference and Exposition, AIAA 2009-6544, 2009.
  - Fiducial Marker Tracking
    - B. E. Tweddle. **Relative Computer Vision Based Navigation for Small Inspection Spacecraft**. In AIAA Guidance, Navigation and Control 2011 Conference (accepted: Grad Student Competition Finalist)
  - Mars Orbital Sample Return Capture
    - B.E. Tweddle, J. McClellan, G. Vulikh, J. Francis, D. W. Miller. **Relative Vision Based Navigation and Control for the Mars Sample Return Mission: Capturing the Orbiting Sample**. Int. Conference on Spacecraft Formation Flying Mission and Technologies 2011



- Future Research
  - DARPA Research Mandate:
    - Visual SLAM problem for unknown target
    - Target may be tumbling and translating
    - Algorithms will be released via NASA Open Source Software
  - Many other possible areas
    - Guest Scientist Program/National Laboratory

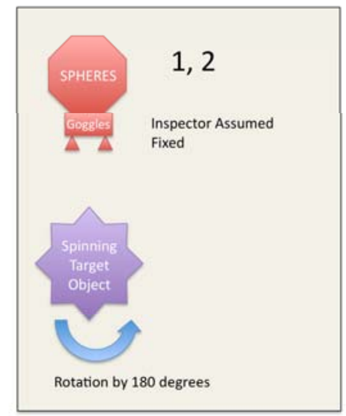
Primary Algorithm Overview

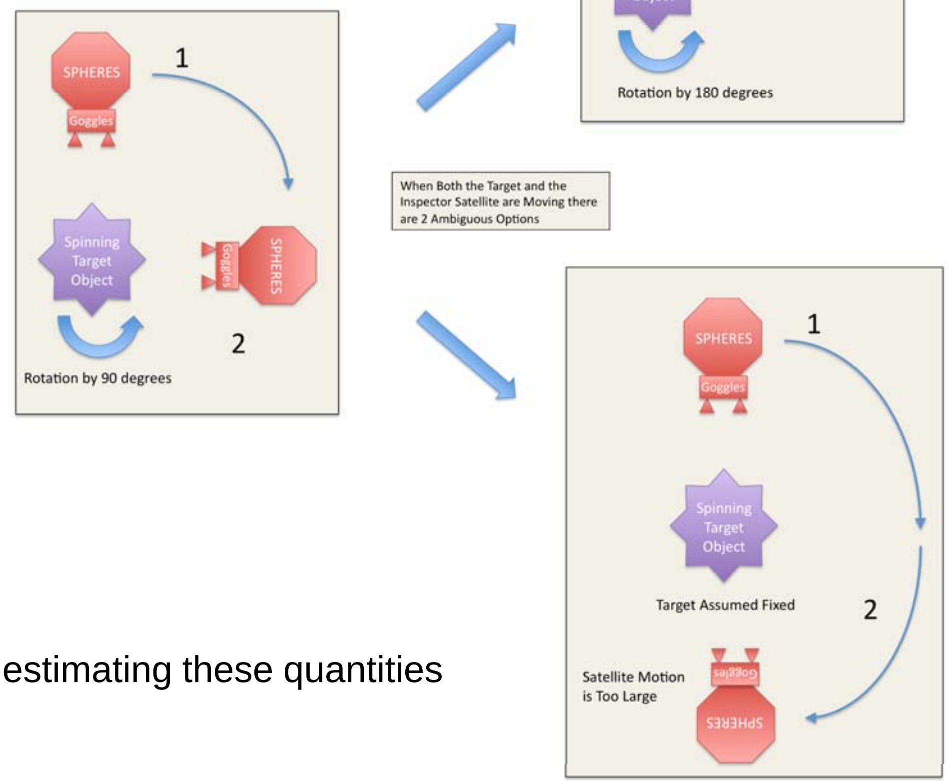
- Designed based on known working approaches and open source software
- Tradeoffs driven by computational constraints:
  - Camera Setup:
    - Monocular vs. Stereo vs. Trinocular
  - Map Type:
    - Point Features vs. Point Cloud vs. Occupancy Grid
  - Estimation Algorithm:
    - Offline Structure From Motion vs. FastSLAM vs. EKF-SLAM
- Assumptions:
  - Observer SPHERES will not have access to any information about the object’s state or appearance
  - The observer satellite begins with the target in view
  - The observer satellite can have an “in-view” but not “too close” starting position
  - The observer satellite has access to its own accelerometers, gyroscopes and high quality model of its own dynamics
- Experimental Validation:
  - Iterative testing procedure
  - Possible target objects: SPHERES, Textured Router, other ISS object?

Modified Primary Algorithm

Issue:

- Debris removal for decommissioned spin-stabilized GEO spacecraft
  - “Thus, in most cases expected angular rates should be low, but for over 100 GEO objects, they can be as high as roughly 40 rpm”
  - Kaplan et. al. “Engineering Issues for all Major Modes of In Situ Debris Capture, AIAA Space 2010
- With camera-only relative navigation there are unobservable degrees of freedom
  - Actual: 2 objects x 6 DOF = 12 DOF
  - Observable: 6 DOF
- Primary Algorithm can always build model, however the reconstructed trajectory may be inaccurate
  - Leads to sub-optimal or infeasible control





Solution:

- Add more measurements from a 3rd common reference frame
  - Inertial Measurement Unit
- Investigating best approach for simultaneously estimating these quantities
  - “Smoothing” is likely necessary

Summary

- SPHERES as a spacecraft testbed for guidance, navigation and controls
  - Astronaut interactive
- Discussed hardware upgrade for vision based navigation and plans to launch
- Overview of past, present and future of visual navigation algorithms

Questions and Discussion

SPHERES Datasheet

Spheres Fact Sheet

Synchronized **P**osition **H**old **E**ngage and **R**eorient **E**xperimental **S**atellites

Last Revision Date: 2007/05/20

SPHERES UNIT								
Mass		*Wet*	*Dry (no tank)*	*Dimension*		*X*	*Y*	*Z*
	kg	4.16	3.55	Maximum Span	cm	21.3	21.3	22.9
CO2 Mass	kg	0.17		*CM offset from GC (Wet)*	mm	0.48	-1.19	1.08
				CM offset from GC (Dry)	mm	0.49	-1.24	3.98
Inertia - Relative to CM		*Wet*	*Dry*		**Inertia - relative to GC**		*Wet*	*Dry*
I_{xx}	kg m^2	2.30E-02	2.19E-02		I_{xx}	kg m^2	2.29E-02	2.18E-02
I_{yy}	kg m^2	2.42E-02	2.31E-02		I_{yy}	kg m^2	2.42E-02	2.31E-02
I_{zz}	kg m^2	2.14E-02	2.13E-02		I_{zz}	kg m^2	2.14E-02	2.13E-02
I_{xy}	kg m^2	9.90E-05	9.90E-05		I_{xy}	kg m^2	9.65E-05	9.64E-05
I_{xz}	kg m^2	-2.95E-04	-2.95E-04		I_{xz}	kg m^2	-2.93E-04	-2.87E-04
I_{yz}	kg m^2	-2.54E-05	-2.54E-05		I_{yz}	kg m^2	-3.11E-05	-4.61E-05
Sensors								
Global Metrology			*IMU - Accelerometers*	No.	3	*IMU - Gyroscopes*	No.	3
Max Update Rate	Hz	5	Max Update Rate	Hz	1000	Max Update Rate	Hz	1000
Nom Update Rate	Hz	3-4	Range	mg	±25.6	Range	deg/s	±83
Max Range	m	3	Resolution	µg/count	12.5	Resolution	deg/s/count	0.0407
Position Accuracy	mm	tbd (~10)	Bandwidth	Hz	300	Bandwidth	Hz	50
Position Variability	mm	2	Noise (0 to 10 Hz) - 1 σ	µg rms	< 7	Noise (0 to 100 Hz) - 1 σ	deg/s/(Hz)$^{1/2}$	< 0.05
Angular Accuracy	deg	tbd (~3)	Noise (10 to 500 Hz) - 1 σ	µg rms	< 70			
Angular Variability	deg	1						
Thrusters	No.	12			**Communications**			
Thrust/Thruster	kgms^{-2}	0.11			Communication Scheme		TDMA	
Thrust variability	kgms^{-2}	0.01			Frame Length	ms	200	
					User Data	bytes/packet	32	
Processors								
DSP					Spacecraft to Spacecraft			
Speed	Mhz	167			Effective Data Rate	kbps	16	
FLOPS (std/peak)	MFLOPS	167 / 1000			*Available*	packets/s	62	
RAM - total	MB	16						
RAM - available	MB	9.7MB free, 6MB heap			Spacecraft to Laptop			
ROM - total	K Words (32bit)	57			Effective Data Rate	kbps	16	
ROM - available	K Words (32bit)	24			*Available*	packets/s	50	
BEACONS								
Fixed Beacons	No.	5		Onboard Beacons	No.	1 Per Sphere		
Timing from IR								
- Beacon No. 1	ms	10		Timing from IR	ms	Software Prog 10, 30, 50,		
- Beacon No. 2	ms	50	Hardware Programmable			70, 90, 110, 130, 150,		
- Beacon No. 3	ms	90	10, 30, 50, 70, 90, 110,			170, OFF		
- Beacon No. 4	ms	130	130, 150, 170	OnBoard Beacon Location		*X*	*Y*	*Z*
- Beacon No. 5	ms	170		(GC)	cm	-10.7	0	0

Final Specifications of LIIVe Goggles

Property	Value
Total Mass	895 g (with battery), 615 g (without battery)
Maximum Volume (Right Angle Optics Mount)	130 mm $\times$ 109 mm $\times$ 66 mm
Power Consumption	15 W (Idle), 18 W (Typical), 25 W (Max)
Processor	1 GHz Via C7, 128 kB L2 Cache
Chipset	VIA VX700
RAM	1GB DDR2 533 MHz
Flash Disk	8 GB SATA
Operating System	Real Time Ubuntu Linux 8.04 (Kernel 2.6.24-rt)
Cameras	2$\times$ IDS-Imaging uEye LE (1/3" CMOS with Global Shutter)
Camera Resolution	640 x 480 pixels
Lens Mount	S-Mount, M12
Frame Rate	87 FPS (Camera Max), 10 FPS (Typical)
Exposure	80 μ s - 5.5 s
Lights	2$\times$ Phillips Lumileds LXHL-LH3C (Red-Orange)
Lights Dominant Wavelength	617 nm
Lights Intensity SPHERES-to-Goggles Communications	140 lm @ 2.9 W (per LED) RS232 19.2 kbps
Wireless Communications	802.11g (54 Mbps)
Battery	Lithium Polymer 12V, 2.5Ah
External Ports	USB 2.0, Gigabit Ethernet, 12V Unregulated Power (2.0A Max)
Dongle Connector	Keyboard, Mouse and VGA

InSPIRE DARPA BAA
Problem Statement

Description:

The goal of this program thrust area is to develop hardware and software to enable one or two SPHERES to **construct a 3D model of another object** (likely a third SPHERE, but should be applicable to any object) and perform **relative navigation solely by reference to this 3D model**. The target object should be **assumed to be moving and possibly tumbling**, and its **state will not be a priori known** to the observer SPHERES (except through their own sensors). Once a 3D model of the object is constructed, the two observer SPHERES will perform relative navigation (as demonstrated through some test maneuver) solely by sensory reference to the target object and its 3D model. The observer SPHERES may communicate with each other, but not with the target object.

Metrics:

There is **no specific requirement for the accuracy** of the 3D model or the precision of the relative navigation solution. However, technical merit of the proposals will be based on the proposer's estimates and substantiation of these metrics and potential utility of their proposed solution. Ultimate experimental validation of the **3D model will be through reference to the actual target object**, while the accuracy of the relative navigation solution will be by **reference to the ultrasonic pseudo-GPS system** on the current SPHERES satellites.