Approved for Public Release, Distribution Unlimited

i-SAIRAS 2014

DARPA Phoenix Overview and Risk Reduction Plans

Glen Henshaw, PhD

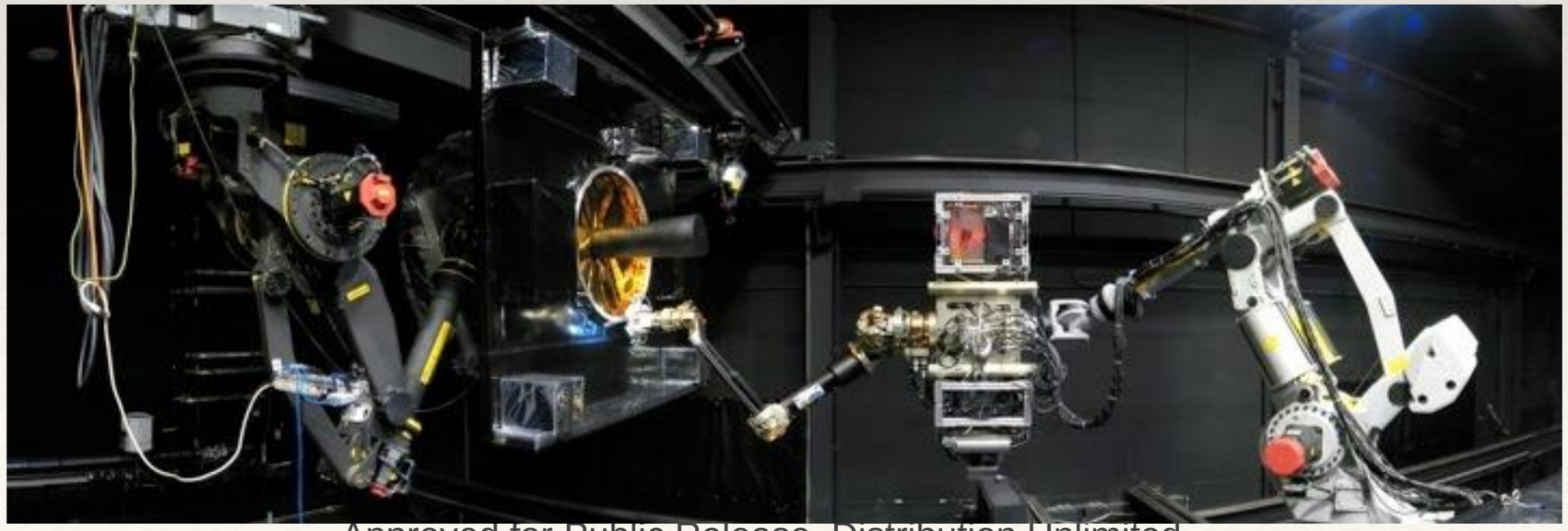
Bernard Kelm

US Naval Research Laboratory

Approved for Public Release, Distribution Unlimited

Background

- NRL was lead on prior DARPA robotic tug study efforts
- This effort included
  - Development of a GEO flight robotic arm
  - Work on flight-traceable algorithms
    - servo control, impedance control, inverse kinematics/obstacle avoidance, machine vision, RPO sensors and guidance laws
  - Demonstrated autonomous grapple of unmodified RSO in NRL proximity operations simulator, summer 2009



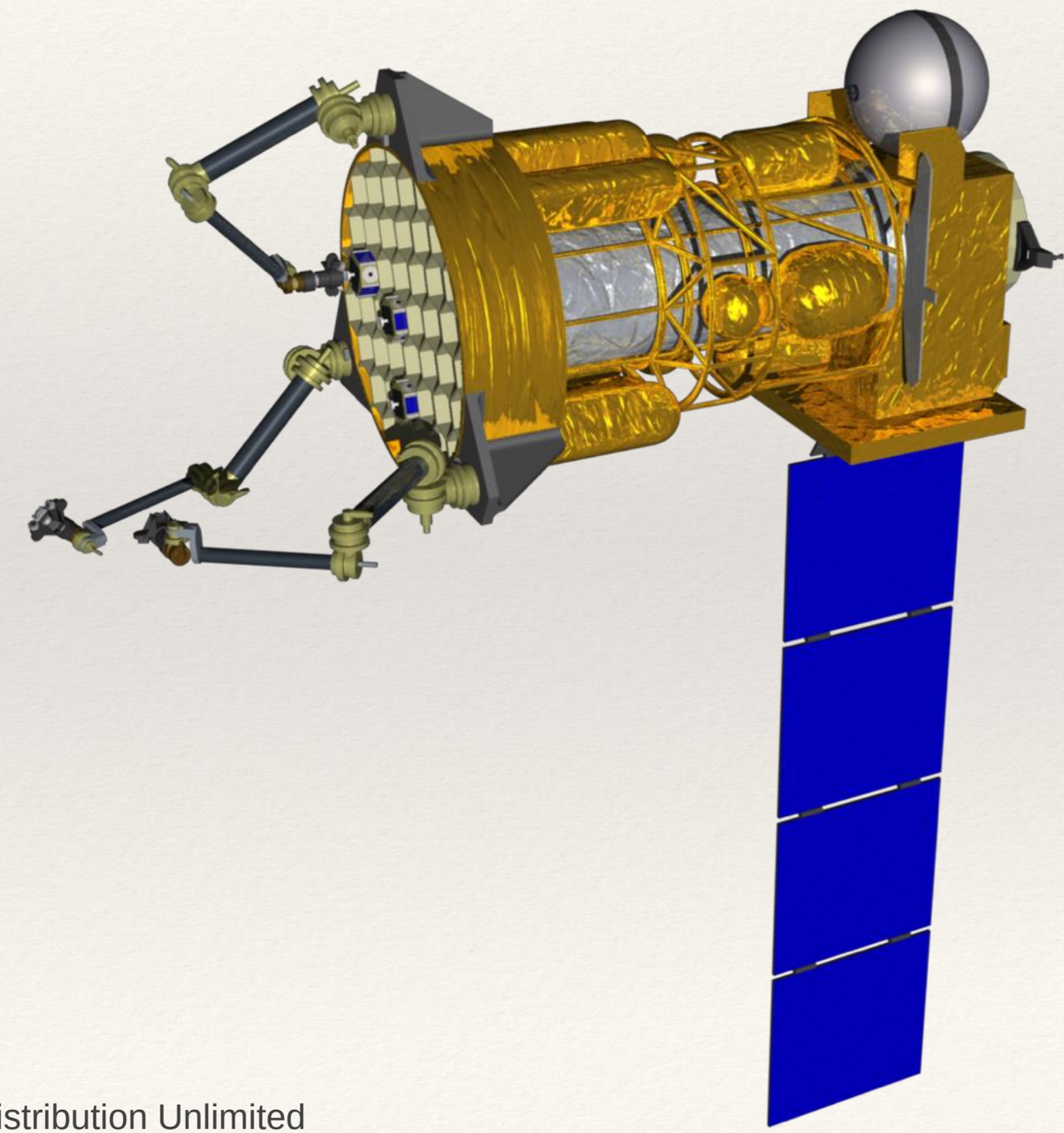
Approved for Public Release, Distribution Unlimited

FREND Demonstration circa 2009

Approved for Public Release, Distribution Unlimited

Original Phoenix Concept

- DARPA sponsored, NRL lead integrator
- Multipurpose robotic spacecraft
  - servicing
  - orbital assembly
- Geosynchronous orbit
- Two 7 DOF FREND arms
- One 4 meter camera arm
- Multiple end effectors
- Autonomous, partially autonomous, and tele-operated robotic control



Approved for Public Release, Distribution Unlimited

Phoenix — Today

- Continuing to execute risk reduction
- Developing hardware, software, and Concepts of Operations (ConOps), and validation techniques in preparation for a future GEO demonstration
- Planning to conduct ground verification and validation campaign through 2015
  - grapple of “POD” payload delivery system
  - assembly of new payloads from existing payloads
  - emplacement of payloads on unmodified customer S/C

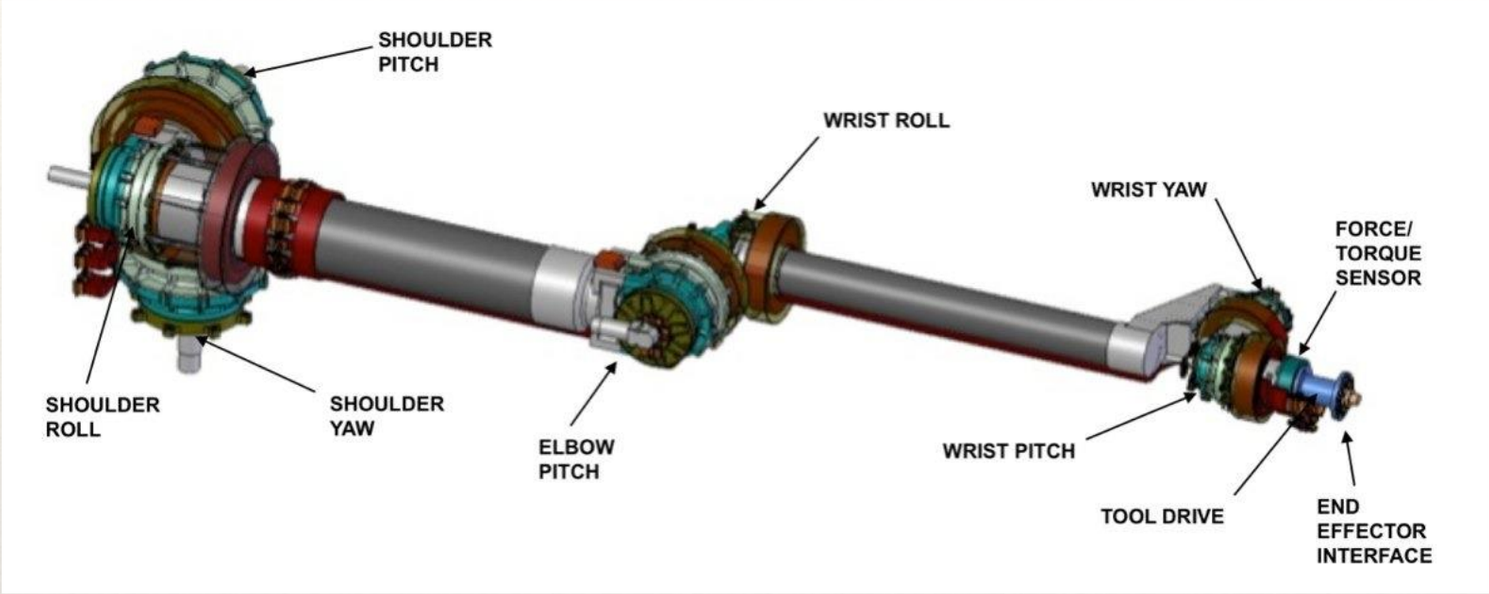
Approved for Public Release, Distribution Unlimited

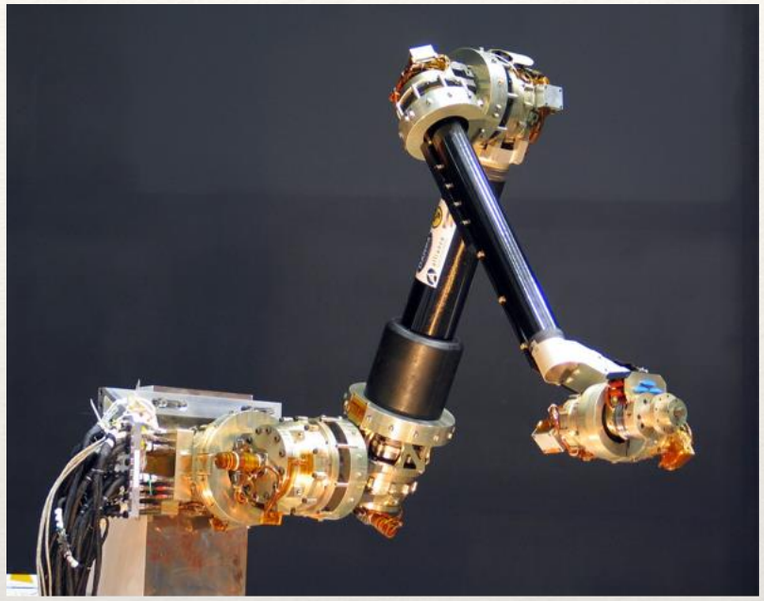
Payload Orbital Delivery system (POD)

- DARPA effort to increase up-mass tempo to GEO
- Would utilize hosted payload compartment on commercial satellites
- Would dispense a small (~50-150 kg) cargo carrier before or during final orbital maneuvers of host
- Would stabilize and support rendezvous and grapple with a Phoenix servicing vehicle
- Would allow delivery of new end effectors, parts, etc. without requiring new Phoenix servicer launch

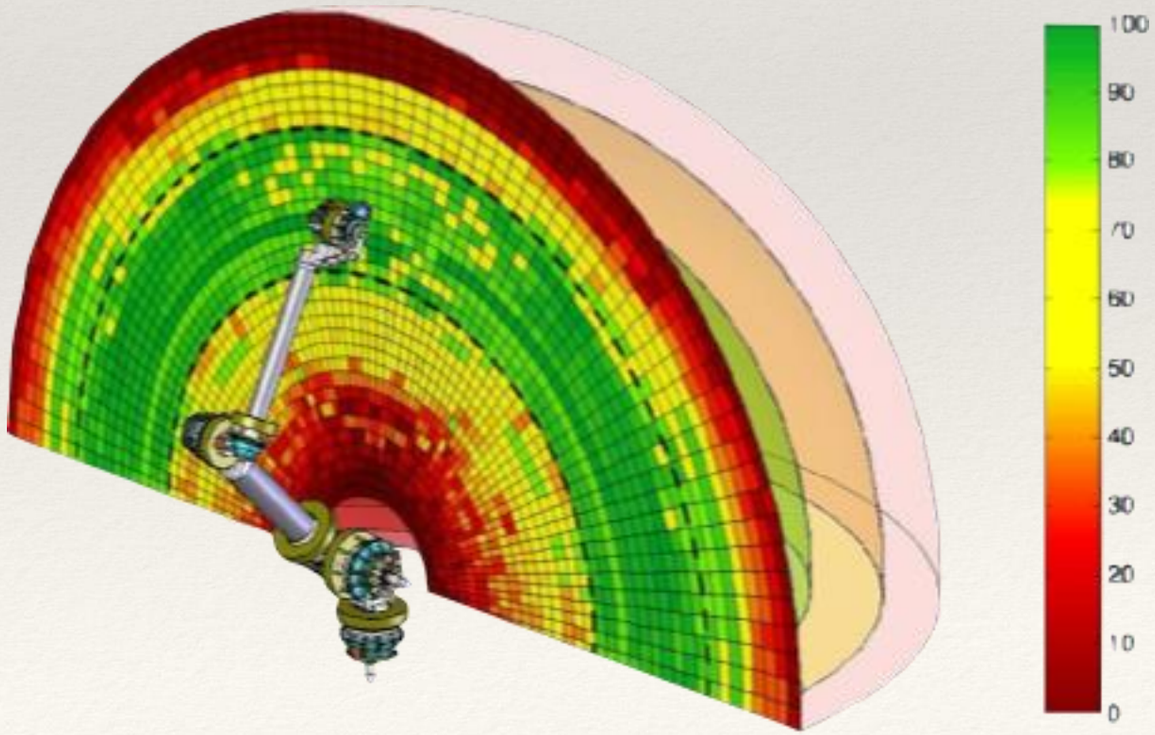
Approved for Public Release, Distribution Unlimited

FREND Arms





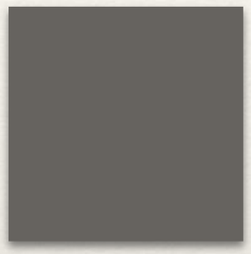
Degrees of Freedom	7 Joints + 1 Tool Drive
Length	1.8 m from shoulder pitch to wrist pitch
Mass	78 kg Arm + 10 kg Electronics
Operating Voltage	28.5 - 34V
Tip Velocity	Up to 15 cm/sec
Rotational Resolution	+/- 0.002 Degrees
Tracking Accuracy	+/- 5 mm
Tip Resolution	+/- 0.1 mm
Control Bandwidth	>1 Hz
Testability	Self Supporting & Full Performance in 1 G
Spaceflight Rating	1 year GEO Life, 100 krad Total Dose, Launch and Thermal Environments



Approved for Public Release, Distribution Unlimited

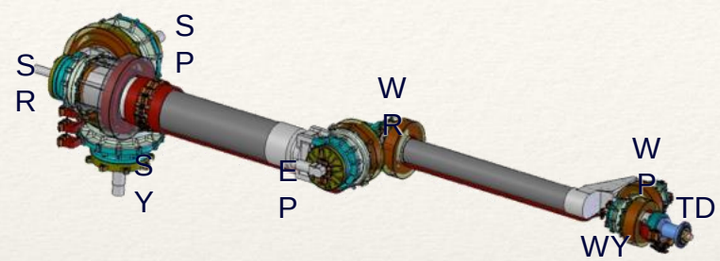
Servicer/Tender Component Development

SCL
Ground
Interface

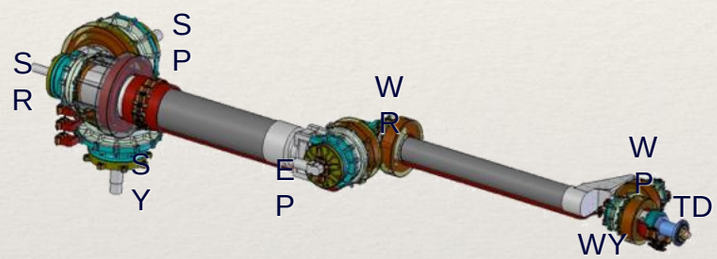


Flight
Controller Box
(“Rikishi”)

Flight



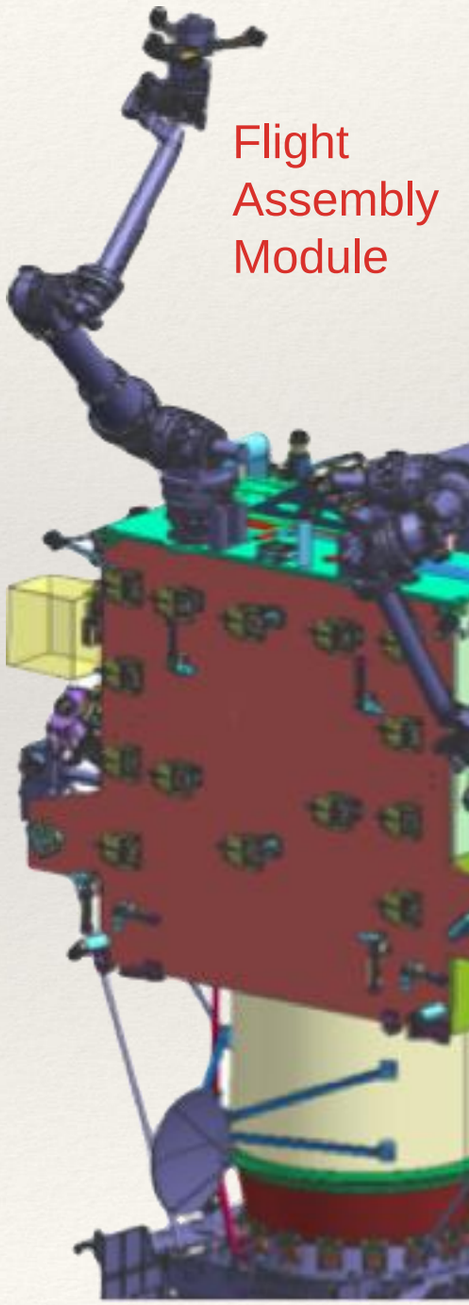
Flight



Flight
Marman Ring
Gripper

Flight
Bolt Hole
Gripper

Flight
Assembly
Module



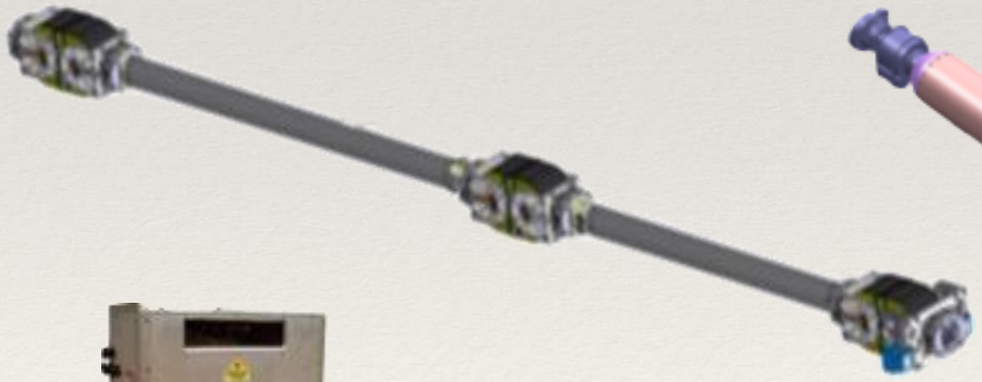
Flight
Tool Changer

Flight
Multipurpose
Gripper

Robotic Operator
Workstation

Flight
Controller Box
(“Rikishi”)

Flight



Flight
PODS Capture
Tool

Flight
Satlet Grasper
Tool

Flight Universal
Gripper/Anchor

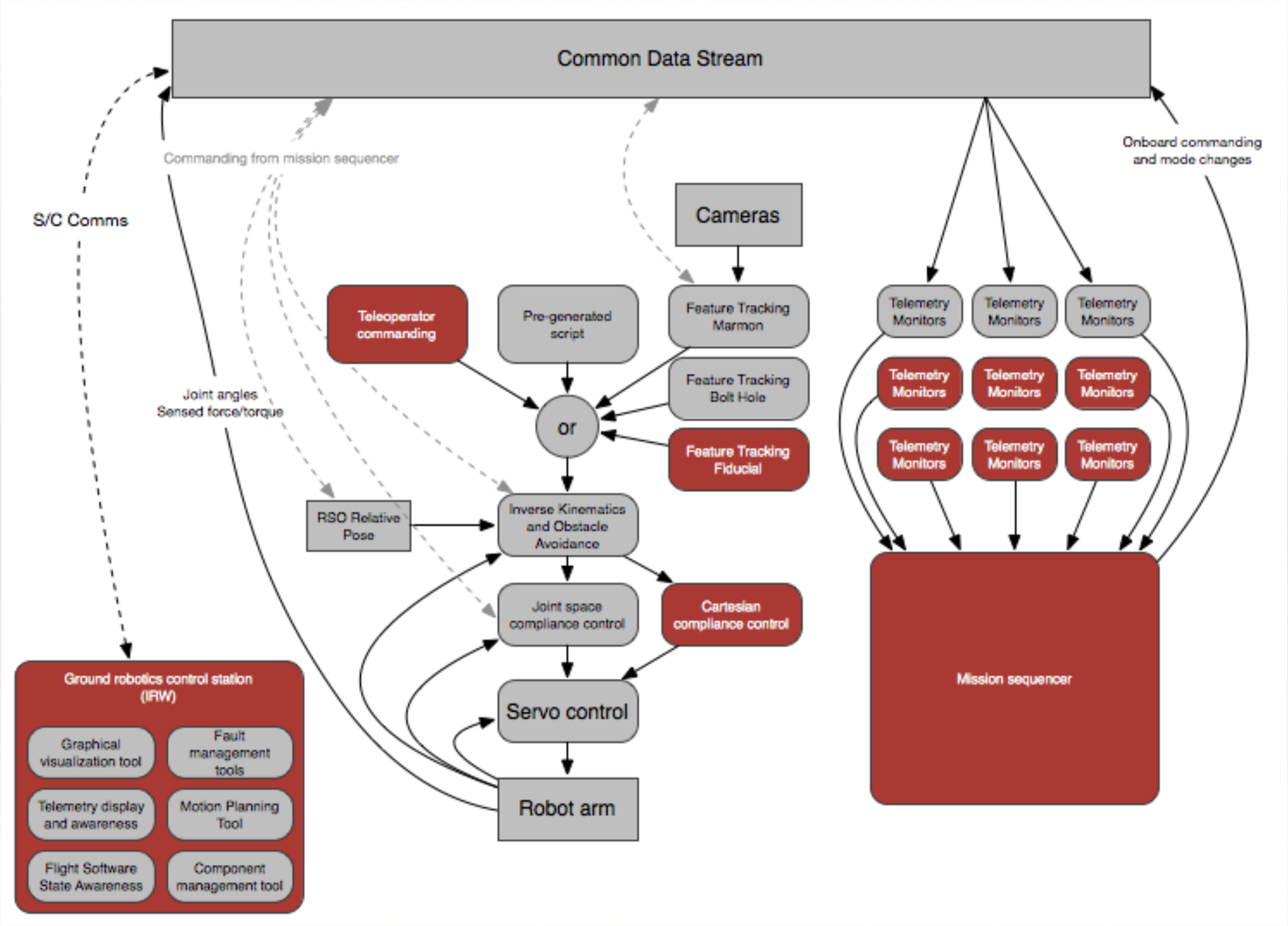
Flight
Spacecraft
Processor (PCU)

Flight
RPO LIDAR

Flight cameras

Approved for Public Release, Distribution Unlimited

Servicer Algorithm Development



Approved for Public Release, Distribution Unlimited

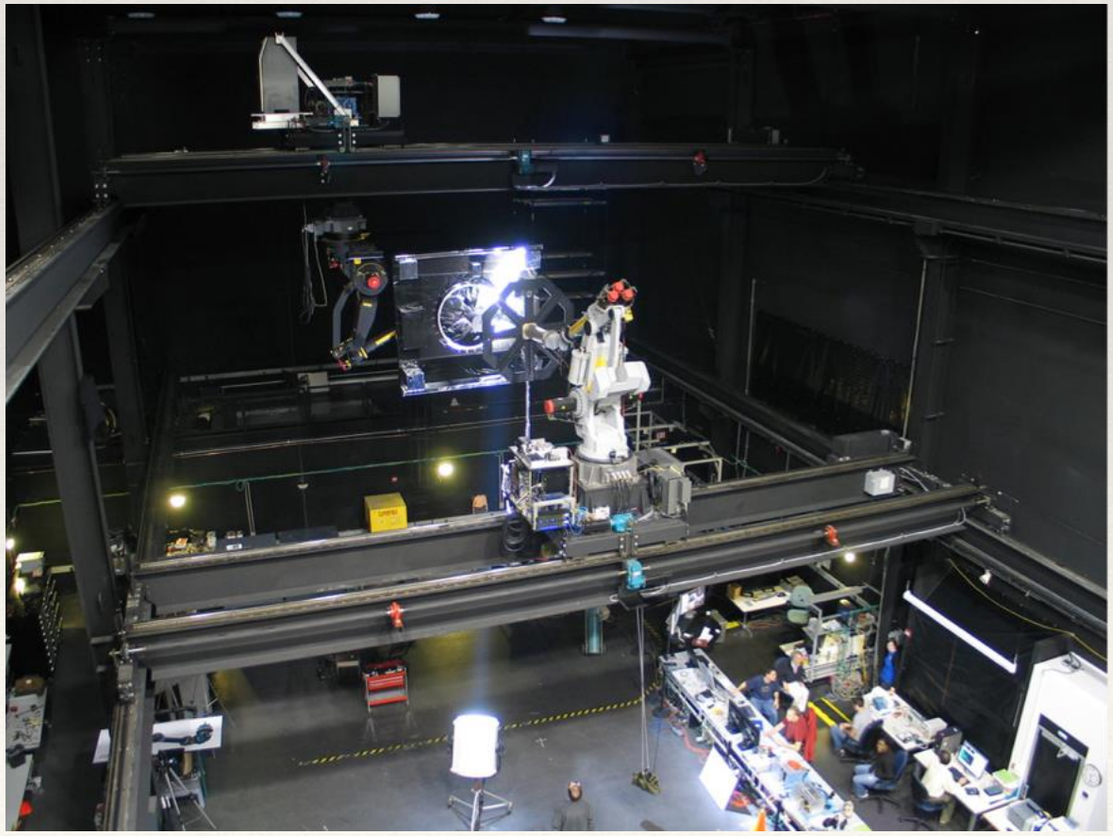
Robotic Control Methodologies

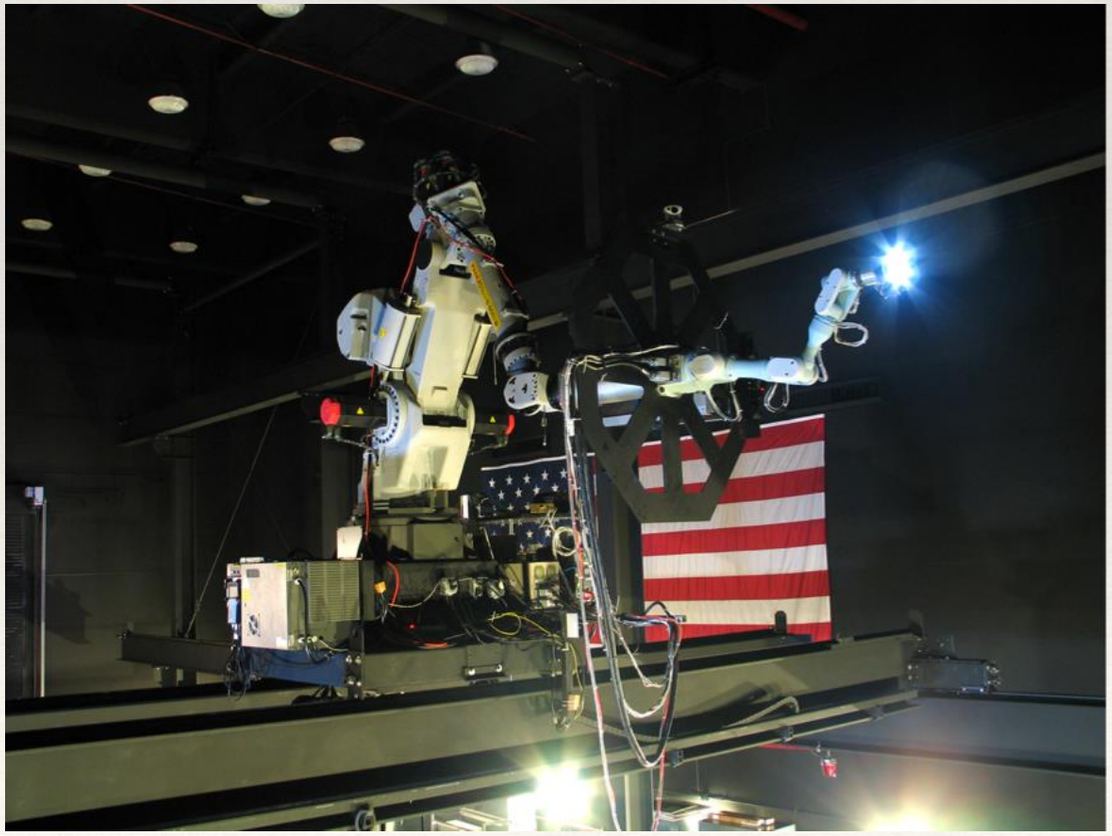
- Scripting
  - flight processor controls robot via precomputed trajectories that are cued by ground operators
  - used wherever possible
- Partial autonomy
  - flight processor controls robot via feedback from onboard sensors (EE cameras, F/T sensor, etc.)
  - includes supervision from ground via stop/go commanding
  - used during contact or fine alignment operations with engineered environment
- Full autonomy
  - same as partial autonomy except stop/go authority given by onboard software
  - used only during time–critical or communication–denied operations (e.g. robotic grapple or release)
- Tele–Operation
  - human operator controls robot in real time via hand controllers such as joysticks and “standard” telemetry/video displays
  - used only during manipulation of “non–engineered” environments, e.g. emplacing a new payload on an RSO or freeing a stuck deployable

Approved for Public Release, Distribution Unlimited

Proximity Operations Testbed

Specification	Pursuer Platform	Target Platform
Degrees of Freedom	6	6
Translational Range of Travel (X, Y, Z)	25, 10, 3 m	25, 10, 3 m
Rotational Range of Travel (ψ, θ, ϕ)	180, 180, 300 deg	180, 180, 360 deg
Absolute Positional Knowledge	1 cm	1 cm
Absolute Rotational Knowledge	0.01 deg	0.01 deg
Relative Positional Knowledge	0.003 cm	0.003 cm
Relative Rotational Knowledge	0.001 deg	0.001 deg
Relative Positional Control	0.5 cm	0.5 cm
Relative Rotational Control	0.001 deg	0.001 deg
Maximum Tanslational Velocity	45 cm/sec	45 cm/sec
Maximum Rotational Velocity	100 deg/sec	100 deg/sec
Maximum Payload Mass	400 kg	350 kg
Maximum Payload Moment	1372 N-m	1960 N-m

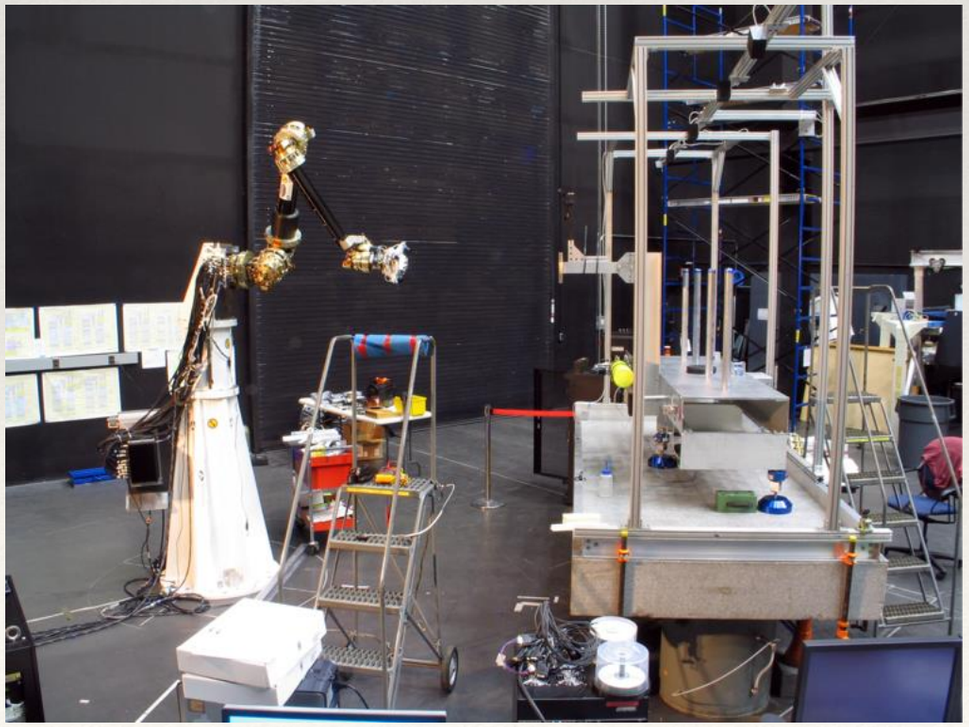


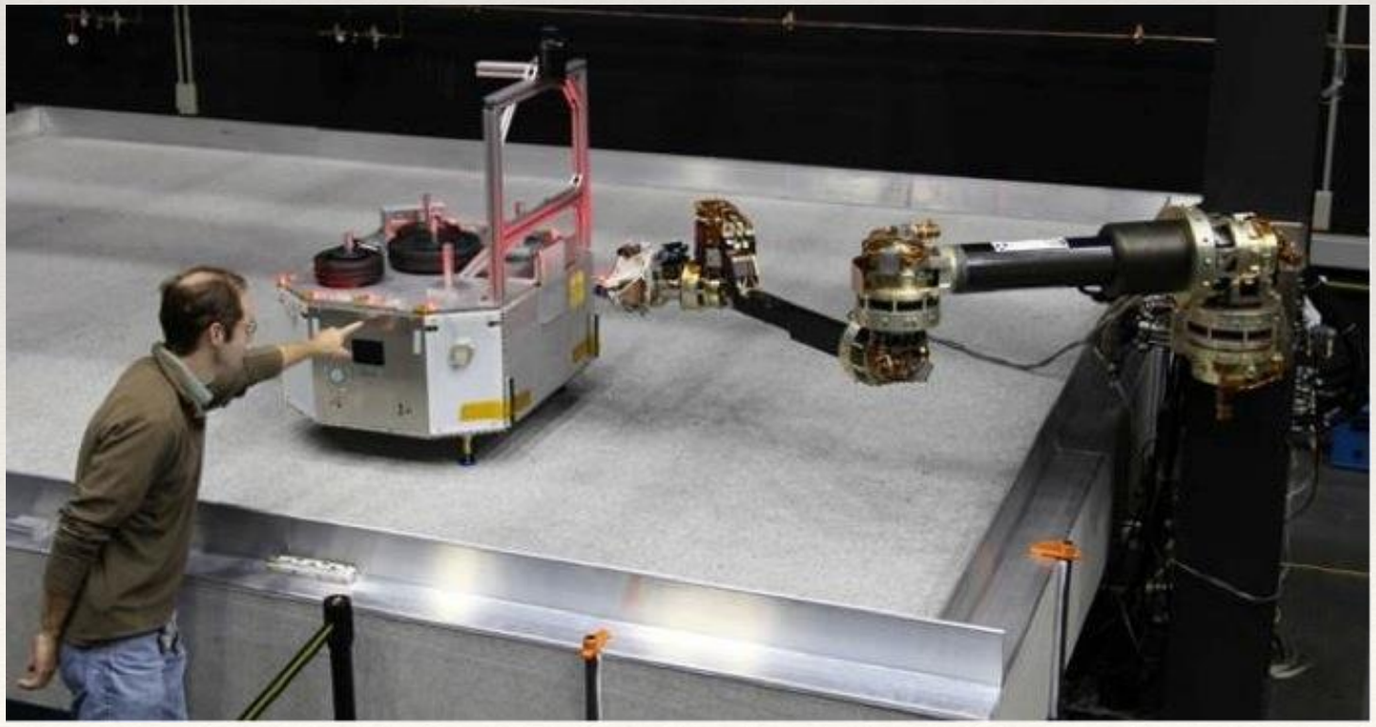


Approved for Public Release, Distribution Unlimited

Contact Dynamics Testbed

Size	4.5 x 6.1 m
Mass	25,000 kg
Grade	AAA (flat to <0.05 mm) granite
Bearing Capacity	13,000 kg
Sensing Resolution	+/- 0.1 mm
Sensing Rate	>400 Hz





Approved for Public Release, Distribution Unlimited

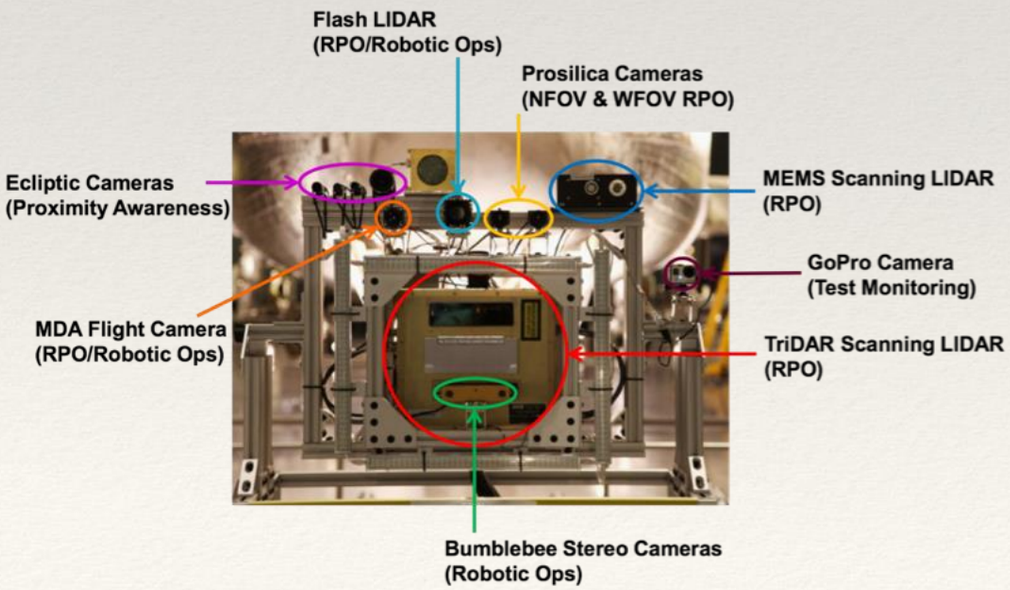
Engineering Tests

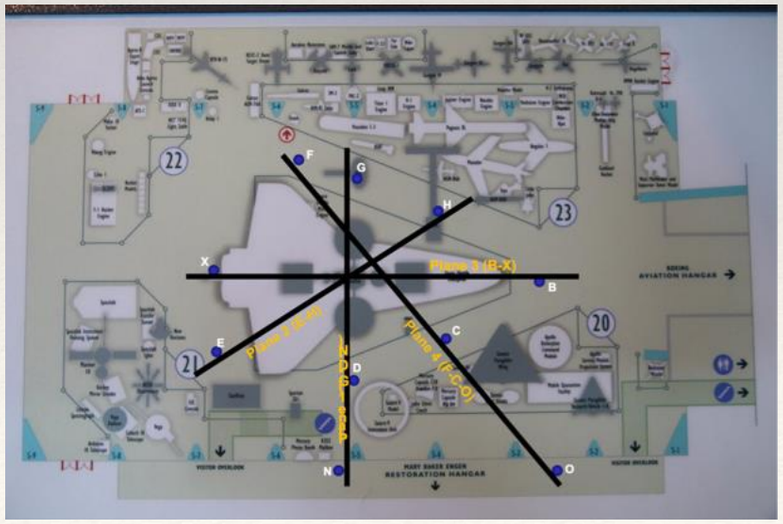
- Too numerous to list…
- include:
  - functional component tests (end effectors, tool changer, interfaces, cameras, force/torque sensors)
  - control algorithm stability and performance testing (servo control, joint space impedance control, Cartesian impedance control)
  - functional software tests
    - compliance control/tool interactions
    - rigid-body and flexible-body contact dynamics tests
    - nominal mission sequencer testing
    - fault detection and response validation
  - human operator interface tests
    - operator performing notional manipulation tasks using FREND arms, cameras, end effectors, mockups of customer spacecraft

Approved for Public Release, Distribution Unlimited

NASM RPO Sensor Test

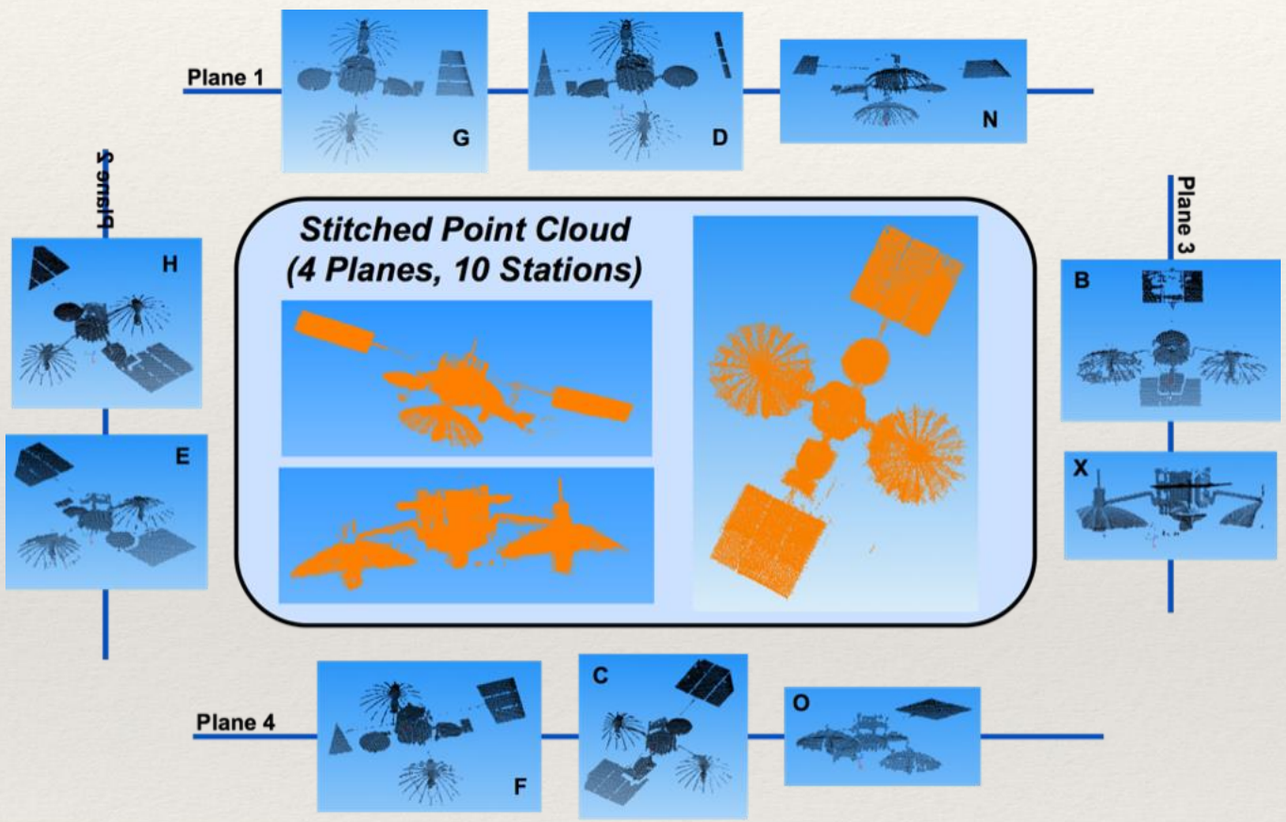
- Used TDRS satellite displayed at National Air & Space Museum Udvar–Hazy Center to test candidate RPO sensors





Approved for Public Release, Distribution Unlimited

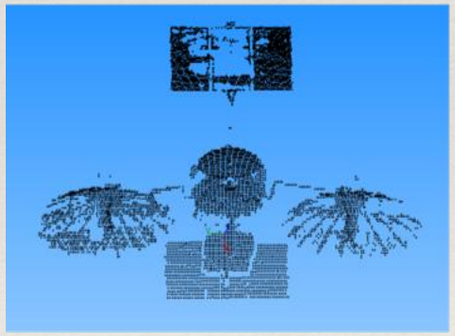
NASM RPO Sensor Test



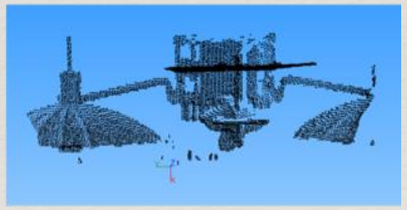
Station B Image @ 28 m

Station X Image @ 18 m

Station B Point Cloud



Station X Point Cloud



Approved for Public Release, Distribution Unlimited

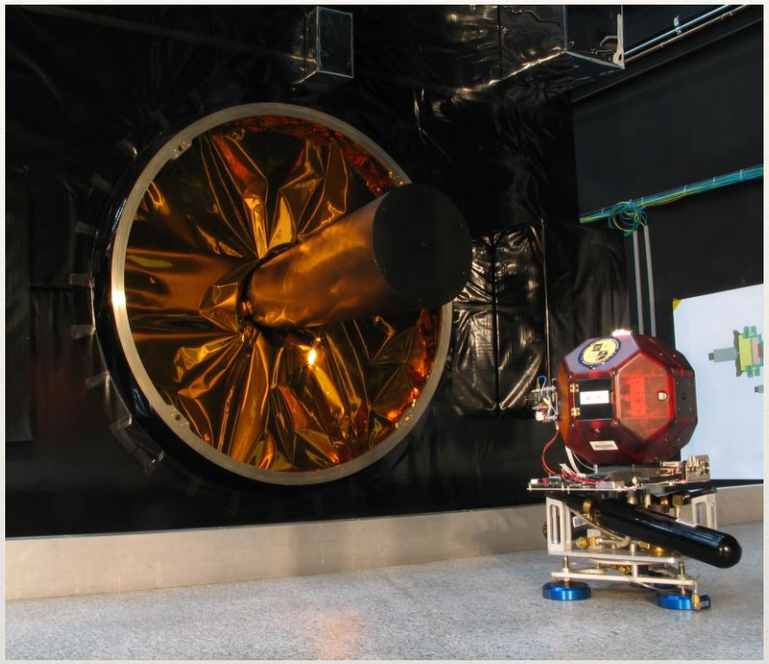
Summary

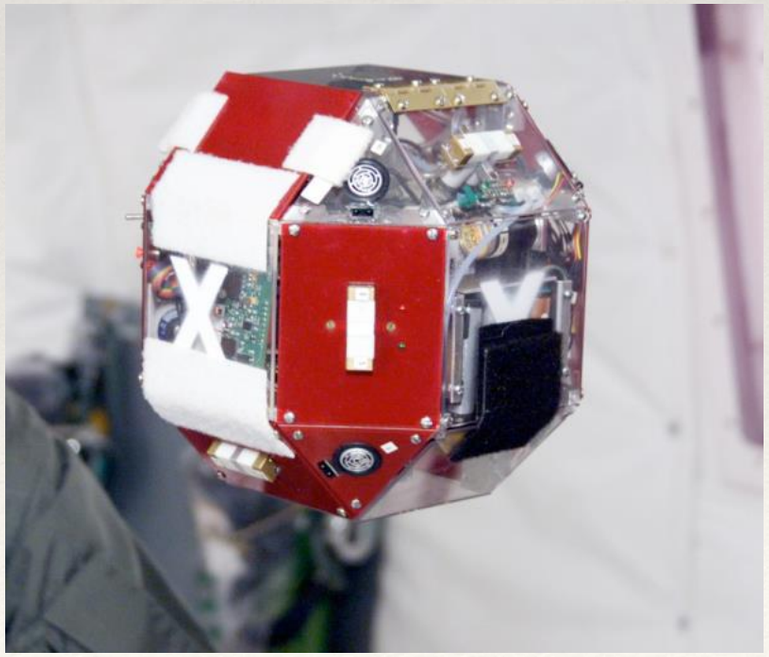
- Phoenix builds on decade–long work by DARPA, NRL
- Program plans to:
  - Utilize FREND hardware and software architecture
  - Add numerous pieces to enable very flexible, capable robotic servicing and orbital assembly missions
  - Incorporate PODs, rapid-mass-to-orbit using commercial satellite launches
- Current program phase working to execute three full–up ground based system demonstrations that lead to future GEO demonstration mission

Approved for Public Release, Distribution Unlimited

Low–design Impact Inspection Vehicle (LIIVe)

- LIIVe is an NRL 6.2 program to develop an autonomous proxops vehicle
- NRL has devoted $1.4M to demonstrating algorithms, sensors, and ConOps
- LIIVe is based on MIT's SPHERES vehicle
  - SPHERES vehicles are currently operating on ISS





Approved for Public Release, Distribution Unlimited

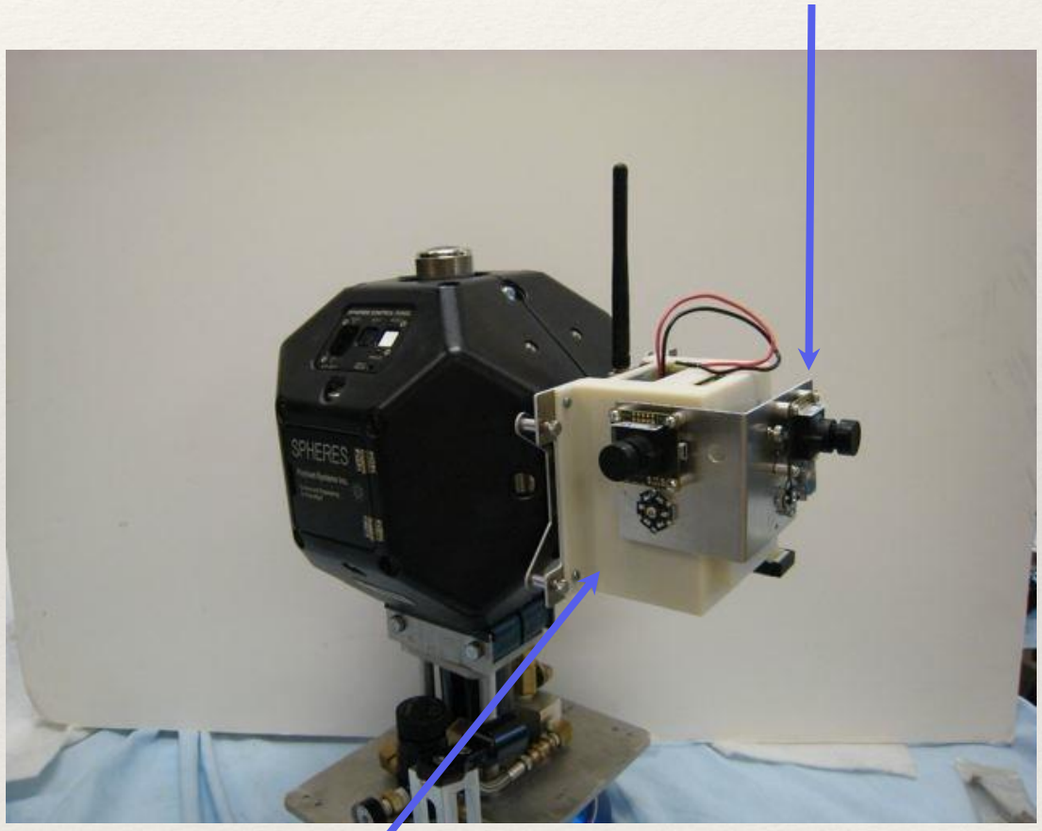
Concept of Operation

- Begin docked to host
- Deploy to stationkeeping point ~5 meters away
- Stationkeep using optical fiducial on docking mechanism
- 4π steradian local area inspection
- Stationkeep; transmit imagery to ground; wait for commands
- Circumnavigation
  - Patched natural–motion passively safe relative orbits, planned on ground
  - Maintain one camera along local velocity vector for collision avoidance, other pointed at host
  - In case of detected collision hazard, abort using pre–planned trajectories
- Stationkeep; transmit imagery to ground
- Redock/dispose

Approved for Public Release, Distribution Unlimited

LIIVe SPHERES Expansion Board

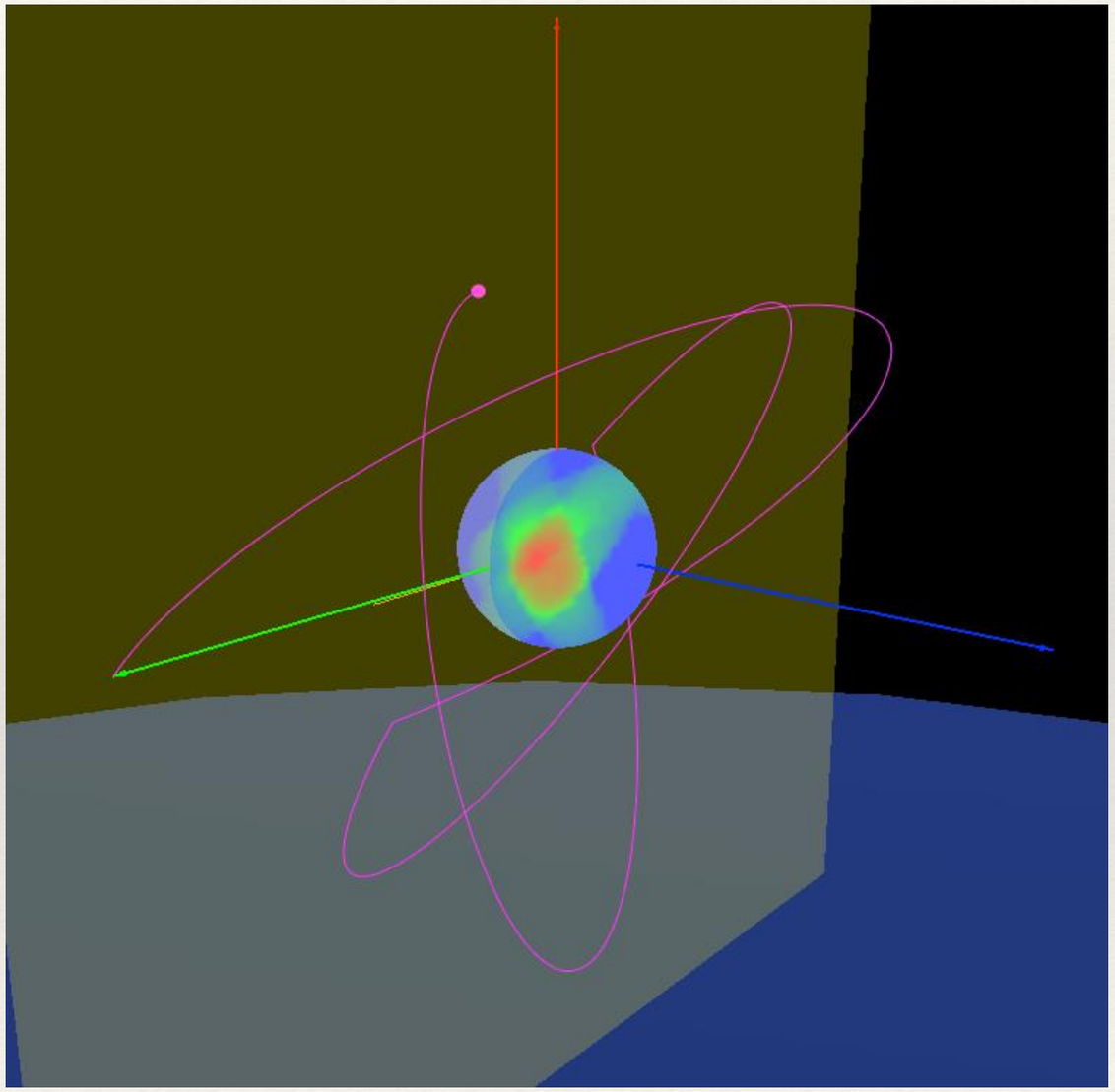
- Jointly designed by NRL, MIT, Aurora Flight Sciences
- Incorporates
  - 1 GHz Via C7 flight processor
  - 802.11g wireless connectivity (22 Mbits per second typical)
  - USB interface for piggyback sensor modules
- One sensor module currently designed: orthogonal visible–spectrum 752x480 cameras and fill lights



Approved for Public Release, Distribution Unlimited

Trajectory Planning

- Trajectories designed using NRL–developed ground tool
  - Relative orbital elements
  - Optimization software chooses patched segments to optimize camera coverage of points of interest, collision avoidance



Approved for Public Release, Distribution Unlimited