DARPA Phoenix
Overview and Risk Reduction Plans

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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
FREND Demonstration circa 2009
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
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
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
# FREND Arms

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

Approved for Public Release, Distribution Unlimited
Servicer/Tender Component Development

SCL Ground Interface

Flight Controller Box ("Rikishi")

Robotic Operator Workstation

Flight Controller Box ("Rikishi")

Flight

Flight Spacecraft Processor (PCU)

Flight

Flight cameras

Flight RPO LIDAR

Flight Assembly Module

Flight cameras

Flight Universal Gripper/Anchor

Flight PODS Capture Tool

Flight Satlet Grasper Tool

Flight Tool Changer

Flight Multipurpose Gripper

Flight Marman Ring Gripper

Flight Bolt Hole Gripper
Servicer Algorithm Development
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
# Proximity Operations Testbed

<table>
<thead>
<tr>
<th>Specification</th>
<th>Pursuer Platform</th>
<th>Target Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degrees of Freedom</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Translational Range of Travel (X, Y, Z)</td>
<td>25, 10, 3 m</td>
<td>25, 10, 3 m</td>
</tr>
<tr>
<td>Rotational Range of Travel ((\psi, \beta, \phi))</td>
<td>180, 180, 300 deg</td>
<td>180, 180, 360 deg</td>
</tr>
<tr>
<td>Absolute Positional Knowledge</td>
<td>1 cm</td>
<td>1 cm</td>
</tr>
<tr>
<td>Absolute Rotational Knowledge</td>
<td>0.01 deg</td>
<td>0.01 deg</td>
</tr>
<tr>
<td>Relative Positional Knowledge</td>
<td>0.003 cm</td>
<td>0.003 cm</td>
</tr>
<tr>
<td>Relative Rotational Knowledge</td>
<td>0.001 deg</td>
<td>0.001 deg</td>
</tr>
<tr>
<td>Relative Positional Control</td>
<td>0.5 cm</td>
<td>0.5 cm</td>
</tr>
<tr>
<td>Relative Rotational Control</td>
<td>0.001 deg</td>
<td>0.001 deg</td>
</tr>
<tr>
<td>Maximum Translational Velocity</td>
<td>45 cm/sec</td>
<td>45 cm/sec</td>
</tr>
<tr>
<td>Maximum Rotational Velocity</td>
<td>100 deg/sec</td>
<td>100 deg/sec</td>
</tr>
<tr>
<td>Maximum Payload Mass</td>
<td>400 kg</td>
<td>350 kg</td>
</tr>
<tr>
<td>Maximum Payload Moment</td>
<td>1372 N-m</td>
<td>1960 N-m</td>
</tr>
</tbody>
</table>
Contact Dynamics Testbed

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>4.5 x 6.1 m</td>
</tr>
<tr>
<td>Mass</td>
<td>25,000 kg</td>
</tr>
<tr>
<td>Grade</td>
<td>AAA (flat to &lt;0.05 mm) granite</td>
</tr>
<tr>
<td>Bearing Capacity</td>
<td>13,000 kg</td>
</tr>
<tr>
<td>Sensing Resolution</td>
<td>+/- 0.1 mm</td>
</tr>
<tr>
<td>Sensing Rate</td>
<td>&gt;400 Hz</td>
</tr>
</tbody>
</table>
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
NASM RPO Sensor Test

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

Stitched Point Cloud
(4 Planes, 10 Stations)

Station B Image @ 28 m
Station X Image @ 18 m

Station B Point Cloud
Station X Point Cloud
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
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
Concept of Operation

- Begin docked to host
- Deploy to stationkeeping point ~5 meters away
- Stationkeep using optical fiducial on docking mechanism
- $4\pi$ 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
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
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