The FREND Robotic Arm

ICRA 2012 Workshop on Robotic Satellite Servicing
Sean Dougherty - Monday, May 14th
On-orbit Servicing
A long time coming

“Astrotug” Stations in Space. Donald Cox (1960)

DARPA Phoenix Mission Concept

NASA Servicing Mission Concept
Great Strides Recently

2007: Orbital Express

2008-present: FREND

2012: RRM

Credit: NRL
Credit: DARPA
Credit: NASA

FREND Full Scale Rendezvous and Autonomous Robotics Grapple Testing Using the Naval Research Laboratory’s Spacecraft Proximity Operations Testbed
Demonstrate the capability of autonomously executing unaided grapple of a variety of S/C interfaces

- Proximity Operation Testbed with dual platform motion simulator
- 7+ DOF Robotic Arm
- Scanning LiDAR with 6DOF Pose Algorithm
- Grapple Feature Tracking Algorithm
- Trajectory Planner, Compliance Algorithm
FRIEND Arm Overview

- 7DOF
- 2m
- 78Kg
- 10 Kg Payload
- 15 cm/s Tip Velocity
- ± 1mm Accuracy
- 5.2 Hz Natural Frequency
- F/T Sensing
- Tool Drive EE
- Custom MCBs
- 1g Testable
- Operate in GEO
Arm Optimized for Mission Success

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### Phoenix IDD FREND

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<tr>
<th>DOF</th>
<th>Length (m)</th>
<th>Mass (Kg)</th>
<th>Accuracy ( +/- cm)</th>
<th>Payload (Kg)</th>
<th>Tip Speed (cm/s)</th>
<th>Natural Frequency (Hz)</th>
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<td>3.5</td>
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<td>4.2</td>
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<td>2</td>
<td>1</td>
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<tr>
<td>7</td>
<td>2</td>
<td>78</td>
<td>0.1</td>
<td>10</td>
<td>15</td>
<td>5.2</td>
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FREND Arm Driving Requirements

1. Allow grappling of a cup-cone interface located 3” away from satellite structure
2. The arm must maximize dexterity
3. The arm must minimize its stowed volume
4. The arm must achieve a 15cm/s (6cm/s) velocity along its end-effector axis in 75% (95%) of its dexterous workspace
5. The arm must weigh less than 80Kg
6. The arm must support its own weight as well as a 5 Kg payload
7. The arm is required to position a tool tip with a tip linear accuracy of +/- 2mm and an angular accuracy of +/- 0.4 deg
8. The arm must achieve at least a 1Hz closed-loop bandwidth
9. The arm must survive launch loads
10. The arm must be able to operate in GEO
Good Tools Enable Rapid Iteration
Good Tools Enable Rapid Iteration

Gravity Sag Analysis

Launch Loads Analysis

Flexibility & Stability Analysis

Combined Stack Analysis
Testing & Validation

Eye-in-the-Sky Camera System

Floating Target

4DOF Capture Arm
Testing & Validation
Performance – Natural Frequency

5.2 Hz Natural Frequency in Extended Pose
- 1.7% Damping Ratio
- 7.2s Settling Time (2%)

6.4 Hz Natural Frequency in Nominal Pose

Measured vs. Simulated Responses

Experimental Data
Estimated Data
Performance – Arm Relative Accuracy

- Seven-Part Trajectory
  1. Self-Motion
  2. Wrist Yaw Motion
  3. Fast Approach
  4. Lateral Traverse
  5. Slow Plunge
  6. Wrist Elevation
  7. Combine Wrist Yaw-Roll

Augmented Trapezoidal Motion Planner
- Continuous Velocity
- In Track Error $\leq \pm 1\text{mm}$
- Cross Track Error $\leq \pm 0.5\text{ mm}$
Conclusions

The FREND robotic arm is a new benchmark for space technology

- High dexterity
- High accuracy, absolute position
- High stiffness, high bandwidth
- Novel set of electronics
- Integral FTS, thermal, cabling
- Flight ready
- 1-g testable

Additional Thoughts/Considerations:

- Multi-arm systems are worth the mass
  - If we adopt long-term, multi-target view
  - Arms are a reusable asset - only need to pay to get to orbit once
  - Refueling and high ISP propulsion worth considering
- Autonomous vision still a big challenge
  - Accuracy & bandwidth effect arm design
  - Getting better all the time but still computationally intensive and lighting conditions still challenging
  - Level of target preparedness worth considering