Gravity Offload Techniques Utilized at NASA’s Goddard Space Flight Center

Brian Roberts
Robotics Technologist
Satellite Servicing Projects Division
NASA Goddard Space Flight Center
Who We Are

• SSPD continues the legacy of the five successful Hubble Space Telescope Servicing Missions (1990-2009) and the Satellite Servicing Capabilities Office (2009-2016)

• Through our efforts, we are working to:
  - Advance the state of the art in robotic and human servicing technology to enable routine servicing of satellites that were not designed with servicing in mind
  - Position the U.S. to be the global leader in in-space repair, maintenance and satellite disposal
  - Help to enable a future U.S. industry for the servicing of satellites
NASA’s Rich Heritage of In-Orbit Satellite Servicing

- Robotic Refueling Mission 2011 - 2017
- Remote Robotic Oxidizer Transfer Test 2014
- Robotic External Leak Locator 2015
- Raven 2017 - 2019
- Restore-L 2020 (planned)
- Hubble Servicing Mission 4 2009
- Hubble Robotic Servicing and Deorbit Mission (HRSDM) 2005
- Hubble Servicing Mission 3B 2002
- Hubble Servicing Mission 3A 1999
- Solar Max 1984
- Hubble Servicing Mission 1 1993
- Hubble Servicing Mission 2 1997
- HST Orbiting Systems Test (HOST) 1998
SSPD is developing servicing technologies that support science and exploration. SSPD is responsible for the overall management, coordination, and implementation of satellite servicing technologies and capabilities for NASA.

**Study**
- Study point design notional missions with guidance from RFI responses

**Build**
- Build hardware & software for experiments in orbit and on the ground

**Test**
- Manage technology development campaign and servicing missions

**Advise**
- Design and advise cooperative servicing elements
Robotic Refueling Mission 1, 2, and 3

RRM is a multi-phased International Space Station technology demonstration that is testing tools, technologies and techniques to refuel and repair satellites in orbit - especially satellites not designed to be serviced.

RRM Phase 1
- **Storable propellants: steps required to refuel a legacy spacecraft**
  A. Take apart components (cut wire, manipulate thermal blankets and fasteners, remove caps)
  B. Connect refueling hardware and transfer fluid
  C. Reseal fuel port
- **Cryogen fluid: initial steps required to replenish cryogens in zero-g**
  1. Take apart components

RRM Phase 2
- **Cryogen fluid: intermediate steps required to replenish cryogens**
  2. Connect replenishment hardware

RRM Phase 3
- **Cryogen fluid: final steps required to replenish cryogens**
  3. Transfer and freeze cryogenic fluids in 0-g, maintain fluid mass for six months via zero boil-off
  4. Share technology data with Space Launch System (SLS), ISRU, Advanced ECLSS
- **Cooperative recharge of xenon propellant**

<table>
<thead>
<tr>
<th>Machine Vision Task</th>
<th>Cryogen Step 1 complete</th>
<th>Propellant Steps A, B, C complete</th>
<th>Cryogen Step 2 Complete</th>
<th>Cryogen Step 3 &amp; Xenon planned</th>
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<td>2011</td>
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Restore L Mission

- On orbit refueling of US government satellite in low Earth orbit
- Full scale technology demonstration mission to advance robotic satellite servicing technologies and enable systems for future robotic and human exploration of the solar system

Client: USGS Landsat 7

Vendor supplied spacecraft bus (Space Systems Loral)

NASA servicing payload

Autonomous Rendezvous

Autonomous Grasp

Telerobotic Refuel & Relocate
Technology Development Timeline

- **Relative Navigation System**
  - 2005-09: Real-time 6-DOF pose of HST
  - 2010: Proximity Sensors & Algorithms
  - 2011: Closed Loop Testing
  - 2012: Contact Dynamics Validation
  - 2013: Refueling Procedure Validation
  - 2014: Remote control w/ oxidizer
  - 2015: Receipt of 7-DoF Eng Arm
  - 2016: Engineering arm w/ flight-like algorithms
  - 2017: Receipt of 7-DoF – space qualified Arm

- **Robot System**
  - 2005-09: Gripper Tool
  - 2010: HST SM4 testing
  - 2011: 3-DOF Capture
  - 2012: 6-DOF auto tracking
  - 2013: SpaceCube 1.0 (MISSE-7) HST SM4 testing
  - 2014: Contact Dynamics Validation
  - 2015: Refueling Procedure Validation
  - 2016: Remote control w/ oxidizer
  - 2017: Flight processor executing robot control algorithms
  - 2018: Contact Dynamics Validation

- **Servicing Avionics and Software**
  - 2005-09: Real-time 6-DOF pose of HST
  - 2010: SpaceCube 2.0 STP-H4
  - 2011: SpaceCube 2.0 STP-H4
  - 2012: SpaceCube 2.0 STP-H4
  - 2013: RRM refueling demo
  - 2014: SpaceCube driving Eng. Arm
  - 2015: Comprehensive Refueling Tasks
  - 2016: Next-gen refueling tools
  - 2017: Real-time processing of natural feature vision algorithms on a SpaceCube 2.0 (Raven)

- **Tool Drive System and Tools**
  - 2005-09: Oxidizer seal-less pump evaluation
  - 2010: Ethanol refueling on orbit
  - 2011: Hose tests in zero-g, NBL
  - 2012: Oxidizer Transfer
  - 2013: Propellant Transfer system
  - 2014: Cryo & Xenon transfer (RRM3)

International Conference on Intelligent Robots and Systems Workshop (9/25/17)
1g Capable Robot with Gravity Compensation Algorithm

- Robot control software algorithm computes joint torques required to overcome gravity and provides them as torque feed forward to joint motor controllers; reduces arm sag in 1g and allows single set of joint controller tunings for 0g and 1g

- Another algorithm removes tool and payload gravity loads on force torque sensor; allows sensor to only “read” contact forces

- Every robot in 1g uses it (including the flight system) but not in 0g
Granite Table with Air Pads

• Air pads hover realistic payload mass and inertia on granite table to simulate 3 DOF motion

• Used for
  – Simulating high fidelity contact dynamics
  – Developing, characterizing, and validating
    • Robotics compliance control sensors and algorithms
    • End effector hardware design
    • Grapple control software
  – System integration and characterization of grapple related subsystems
  – Validating robot based contact dynamics simulations
Flat Floor with Air Pads

• Same concept as granite table only at larger scale
• Grapple arm uses this technique for evaluations
Helium Balloons

- Helium balloons offload hose being manipulated by robot
- Have used it a few times for RRM3 evaluations to offload hose
Industrial Robots as Proxy for Space Robot

• Close to 2 dozen 6- and 7-DOF industrial robots used to
  – Provide simulation platform for autonomous and teleoperation tasks
    • Tool engineering development
    • Procedure development
    • Training
    • On-orbit robot support
  – Simulate on-orbit robot kinematics and dynamics and robot to satellite contact dynamics
  – Validate algorithms and software functionality

• All tasks for the Robotic Refueling Mission were performed using a FANUC (and Motoman) robot and Motoman robots are being used now for Restore
• Industrial robots as kinematic simulators of space robots validated as part of RRM on the International Space Station (ISS)

• Lessons learned from simulating other aspects of 0g on the ground are being applied to Restore
Neutral Buoyancy

- Floats and weights are used on robots and hardware underwater to counter the buoyancy effects of water to closely simulate the weightlessness of space.
- Some Hubble Robotic Servicing and Deorbit Mission servicing tasks were performed this way.
- Also used to determine loads on the hose for Restore.
- Considering using it for berthing simulations for Restore.
Offload System

- Counterbalancing system to minimize effects of 1g environment
- SPDM Ground Testbed
  - Kinematic and dynamic hardware emulator of flight Special Purpose Dexterous Manipulator manipulator used on the ISS
  - Used to perform majority of Hubble Robotic Servicing and Deorbit Mission tasks and subset of tasks for Robotic Refueling Mission
Zero Gravity Flight

- Airplane flies “roller-coaster” parabolic arcs to provide 20 to 25 seconds of weightlessness
- Visual servo algorithm was used on one campaign and second flight provided lessons learned which are being applied to industrial robot-based contact dynamics simulators