Agent Model of On-Orbit Servicing Based on Orbital Transfers

September 20, 2007
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Agenda

• On-Orbit Servicing (OOS) Overview
• Model Scope
• Agent Model Development
  – Agents
  – Behaviors
  – Assumptions
• Agent Model Results
  – Sample Run
  – Monte Carlo Analysis
• Key Findings
• Future Work
The process of improving a space-based capability through a combination of in-orbit activities which may include inspection; rendezvous and docking; and value-added modifications to a satellite’s position, orientation, and operational status.

**Missions of OOS**
- Inspection
- Relocation
- Rescue
- Refueling
- Upgrade
- Repair

**Example: DARPA Orbital Express**
- On-orbit validation of autonomous docking, refueling, component swapping
- Astro servicer, NextSat client

Servicing provides options to space missions, mitigates vulnerabilities to monolithic spacecraft, and enables a more robust space enterprise.
Research Opportunity

- Majority of robotic OOS studies are point designs on servicing provider architecture
- Some studies, mostly done at MIT, address customer valuation of servicing
  - Lamassoue (2001)
  - Saleh (2002)
  - Sullivan (2005)
  - Long (2005)
- Few studies address satellite architecture of the customer
  - e.g., DARPA’s NextSat of Orbital Express
  - However, work that does exist on serviceable spacecraft focused on implementing design changes in future satellites

Research opportunity: investigate physical amenability of satellites currently in orbit to OOS
Model Scope

• Investigate physical amenability of orbital slots to servicing
  – Primary outputs: mean $\Delta V$ expenditure, availability
  – Proximity operations treated as “black box”
• Context: five-year GEO servicing campaign
• Servicer CONOPS: multivariable optimization problem
  – $\Delta V$ expenditure
  – Transfer time

Focus on serviceability of target satellites, not provider architecture
Agent Model Overview

An agent model simulates a population of independent agents to observe aggregate emergent behavior

- **Target satellites**
  - Initiate servicing missions by issuing servicing “tickets” in a binomial process
  - States
    - Full health
    - Operational with request for scheduled servicing
    - Not operational with request for emergency servicing

- **Servicing vehicles**
  - Cooperate to complete servicing missions (minimize $\Delta V$ expenditure)
  - States
    - Parked in GEO
    - In transit to target satellite via circular coplanar phasing
    - Servicing target satellite
    - Out of fuel
Target Satellites

- Initialized based upon UCS Database
- 335 GEO satellites (on March 11, 2006)
- Assumptions:
  - Zero degree inclination
  - Identical failure modes
- Failure probabilities:

<table>
<thead>
<tr>
<th>Service</th>
<th>Average Annual Opportunities</th>
<th>Average Annual Opportunities in GEO</th>
<th>Predictable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refuel</td>
<td>20.0</td>
<td>8.9</td>
<td>yes</td>
</tr>
<tr>
<td>ORU Replacement</td>
<td>4.4</td>
<td>2.0</td>
<td>yes</td>
</tr>
<tr>
<td>General Repair</td>
<td>3.8</td>
<td>1.7</td>
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<tr>
<td>Relocation in GEO</td>
<td>13.0</td>
<td>13.0</td>
<td>yes and no</td>
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<tr>
<td>Deployment Assistance</td>
<td>0.3</td>
<td>0.1</td>
<td>no</td>
</tr>
</tbody>
</table>

Annual servicing opportunities based on empirical data (derived from comprehensive database of satellite failures)
Brook Sullivan, Ph.D. – University of Maryland Doctoral dissertation (2005)
Servicing Vehicles

- Four space tugs parked in GEO
- Bipropellant: 300 Isp
- Dry mass: 1200 kg
- Concept-of-Operations
  - Initially evenly spaced
  - Remains parked near orbital slot serviced
- Two-cases
  - Treat normal and urgent tickets the same (5 phasing revolutions)
  - Vary response time as a function of urgency (5 or 1 revolutions)

\[
\Delta V_{total} = g(I_{sp}) \ln \frac{M_p + M_f}{M_f} = 9.81(300) \ln \left(\frac{5076 + 1200}{1200}\right) \approx 4869 \text{ m/s}
\]
Tool Dashboard

![Bar chart showing the number of tickets per km/s for different space tug numbers.](chart)

- **km/s**: 1, 2, 3, 4
- **Space tug number**: 65

![Polar graph showing time and angles.](graph)

- **Time**: 30.4167
- **Angles**: ±180°, 135°, 90°, 75°, 60°, 45°, 30°, 15°, 0°, -15°, -30°, -45°, -60°, -75°, -90°, -105°, -120°, -135°, -150°, -165°, -180°
Monte Carlo Results: Median $\Delta V$ Expenditure for Orbital Slots

GEO satellite density (12° bins)
Key Findings

• **Demonstrated feasibility of using space tugs in GEO**
  – In terms of market, potential for 25 annual servicing opportunities
  – In terms of $\Delta V$, physical amenability of servicing GEO is high

• **Found high-level of servicing vehicle availability**
  – Very reliable spacecraft $\Rightarrow$ probability of 2+ servicing vehicles in simultaneous operation less than 1%
  – Opportunity for emergent uses $\Rightarrow$ infrastructure

OOS business models need to balance…
...the attraction of GEO due to the high concentration of high-value spacecraft and friendly orbital dynamics
...with the high-reliability of GEO satellites launched over the past two decades
Future Work

- Parameter study on reliability of spacecraft
  - At what level of reliability does servicing architecture become over-taxed?
  - Explore the trade between highly reliable space systems and lower cost systems that utilize an OOS system to achieve similar reliability

- Improve model fidelity
  - Differentiate between types of servicing missions
  - Refine astrodynamics model

- Design provider CONOPS

- Model economics / pricing
  - What is decision logic for target satellites initiating servicing tickets?
  - and for servicing vehicles accepting servicing requests?
Acknowledgements

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Why Service Satellites?

- **Reduce risk of mission failure**
  - Rescue satellites stranded by upper stage failures (e.g., Milstar 3)
  - Repair faulty spacecraft systems (e.g., Hubble Optical Assembly)
  - Mitigate beginning-of-life failures (e.g., solar array deployment)
  - Orbital debris removal (~100,000 objects currently, growing 175 metric tons/year)

- **Reduce mission cost**
  - Design for a shorter life with the option to service or abandon
  - Reduce need for on-orbit and launch-ready spares
  - Place high-value payload on EELVs and consumables on low-cost launch vehicles

- **Increase mission performance**
  - Option for lifetime extension
  - Option to upgrade to maximize revenue and prevent technological obsolescence
  - Improved fault detection and health monitoring

- **Improve mission flexibility**
  - Option to modify to meet different requirements
  - Capture emergent terrestrial market with constellation reconfiguration
  - Tactical maneuvering for military surveillance
  - Enable extremely low altitude orbits

Servicing provides options to space missions, mitigates vulnerabilities to monolithic spacecraft, and enables a more robust space enterprise
Circular Coplanar Rendezvous

Key equations

\[ \omega_{\text{target}} = \sqrt{\frac{\mu}{a_{\text{target}}^3}} \]

\[ T_{\text{phase}} = \frac{k_{\text{target}} (2\pi) + 9}{\omega_{\text{target}}} \]

\[ a_{\text{phase}} = \left( \frac{\mu}{2\pi k_{\text{servicer}}} \right)^{2/3} \]

\[ \Delta V_{\text{phase}} = 2|v_{\text{phase}} - v_{\text{servicer}}| = 2 \sqrt{\frac{2\mu}{a_{\text{target}}} - \frac{\mu}{a_{\text{phase}}} - \frac{\mu}{a_{\text{target}}}} \]
Multi-Objective Optimization

(a) 

\( \tau_{\text{phase}} \) (normalized) vs \( \Delta V \) (normalized)

(b) 

\( \frac{1}{\tau_{\text{phase}}} \) vs \( \frac{1}{\Delta V} \)

\( k \) (number of phasing revolutions) vs \( \frac{1}{\Delta V} \)