SPACETUG: Roles of MATE-CON and Traditional Design Methods

LAI PD Meeting
10/7/03

Dr. Hugh McManus
Metis Design
Space Tugs

• A vehicle or vehicles that can
  – Observe *in situ*
  – Change the orbit of
  – Eliminate (clean debris)
  – Retrieve
  – Otherwise interact with objects in orbit.

Potentially, an important national asset
Problem and opportunity

• Single-use missions for such a vehicle tend to be economically or physically infeasible

• Little work on the potential for a general-purpose vehicle and some of the key challenges associated with it

• Recognized difficulties include:
  – Unfriendly orbital dynamics and environment
  – Vehicle complexity
  – Market uncertainty

A new look at the problem:
Exploring the Architectural Tradespace with MATE-CON
AND defining point designs with more traditional mission analyses
MATE: Developing A Trade Space

- Understand the Mission
- Create a list of “Attributes”
- Interview the Customer
- Create Utility Curves
- Develop the design vector and system model
- Evaluate the potential Architectures
Spacetug System Attributes:

- Total Delta-V capability - where it can go
  - Calculated from simple model (rocket equation)
- Response time - how fast it can get there
  - Binary - electric is slow
- Mass of observation/manipulation equipment - what it can do when it gets there
  - Based solely on equipment mass (didn’t design observation or grappling equipment)
Utilities (parametric) and Cost

- Response time utility binary (electric bad)
- Total Utility a weighted sum
  - Examples will stress DV, then capability
- Cost estimated from wet and dry mass
Design Space

• Capability = Manipulator Mass
  – Low (300kg)
  – Medium (1000kg)
  – High (3000 kg)
  – Extreme (5000 kg)

• Propulsion Type
  – Storable bi-prop
  – Cryogenic bi-prop
  – Electric (NSTAR)
  – Nuclear Thermal

• Fuel Load - 8 levels

Other more detailed designs incorporated into study
  – Freebird (MIT class project)
  – SCADS (Aerospace)
  – GEO one-way or RT Tugs
  – GEO and LEO “tenders”

Most developed by ICE method

Exhaustive survey - 139+ designs
For each potential design:

- Calculate attributes
  - Total DV capability - rocket equation
  - Response time - electric is slow
  - Mass of observation/grappling equipment - specified
  - Vehicle wet and dry masses - simple models

- Calculate individual utilities for first three
  - Utility curves

- Calculate total utility
  - Weighted sum

- Calculate cost from wet and dry masses
Spacetug Tradespace
Propulsion System as a Discriminator

Highest performance systems require high ISP propulsion
Sensitivities to shifts in user needs

Unlimited DV demand favors high ISP propulsion
Key Physical Limits and Dangers

Hits a “wall” of either physics (can’t change!) or utility (can)
Tradespace Reveals Promising Designs

![Diagram showing tradespace analysis with cost and utility dimensions. The diagram includes categories such as Biprop, Cryo, Electric, Nuclear, Tenders, and Electric Cruisers. The data points are plotted on a cost versus utility graph, with Nuclear Monsters and Electric Cruisers highlighted.]
Traditional Analysis: Requirements developed for specific missions

- Target list developed
- Specific mission plans scoped
- Orbital mechanics and other analyses set requirements
- Possible product family built up from individual designs
1. Create a complete database (orbital elements, size, mass, type of control, data rates, etc.).

2. See if objects can be grouped in terms of similar orbital and physical characteristics.

3. Define specific target groups:
   a) Put reasonable constraints on altitude and inclination ranges.
   b) Identify predominant or average physical characteristics (length, height, span, mass).

4. Create mission scenarios for each target group.

Project led by MIT graduate student Kalina Galabov
Inclination[deg]

Altitude [km]

Number Of Satellites

Target Groups

Orbcomm

Globalstar

Iridium

miscellaneous

©2003 Massachusetts Institute of Technology
Target Group #1

Miscellaneous

- $i = 98.1$ to $99$ deg
- $h = 770.5$ to $861$ km
- Total: 345 satellites
- 1990-2001: 47 satellites
- US: 76 sat. (29 recent)
- Numerous rocket bodies

OR

- 600 kg
- 1.27 x 1.58 x 0.94 m
- 10.4 m solar array span
- 10 m deployed antennas span
- 3-axis stabilized

- 520 kg
- $D = 1.31$ m, $H = 3.96$ m
- Spin-stabilized
**GEO Target Group (#5)**

- Spin-stabilized
- ~55 rpm
- 750 kg / 850 kg
- \( D = 3 \text{ m}, H = 3.3 \text{ m} \)
- \( \text{Htot} = 7 \text{ m} \)

- 3-axis stabilized
- 1,880 kg / 2,200 kg
- \( 2.3 \times 2.2 \times 2.3 \text{ m} \)
- 25 m solar arrays span
- 8.3 m span of antennas

- \( i = 0 \) to 5.2 deg
- \( h = 35,662 \) to 36,667 km
- Total: 639 satellites
- 1990-2001: 333 satellites
- US: 280 sat. (103 recent)
Mission Scenario: LEO Tender I

Visit 5 satellites:
- 3 randomly within a 100 km altitude and 1 deg inclination box
- 2 in 200 km and 2.2 deg box

Example:
- any 3 satellites within h = 770 – 870 km and i = 98-99 deg
- one at h = 670.5 km and i = 98.2 deg (NASA’s Terra, 99-068A)
- one at h = 778 km and i = 100.2 deg (USAF Falconsat, 00-004D)

Targets Properties:
- 520 kg
- 1.27 x 1.58 x 0.94 m box
- 10.4 m solar array span
- 8 m deployed antennas span

Missions:
1) Orbit Change
2) Rendezvous – 100 m/s
3) Dispose (increase the altitude of 100 km to decay altitudes) or Move (ΔV = 167 m/s; 180 deg in one week)
4) Park (if disposal) and Return to LEO

Mission Life: 10 years

Assumptions:
1) The target properties are the same for all targets.
2) The tender is launched into a 99 deg orbit, h = 800 km.
Mission Scenario: GEO Tender

Visit 5 satellites:
- 3 randomly within a 400 km altitude and 5 deg inclination box
- 2 in 1500 km and 15 deg box

Example:
- any 3 satellites within $h = 35,600 – 36,000$ km and $i = 0 – 5$ deg
- one at about $h = 34,900$ km and $i = 0$ deg
- one at about $h = 35,800$ km and $i = 13$ deg

Targets Properties:
- 2,200 kg
- 2.3 x 2.2 x 2.3 m box
- 25 m solar array span
- 8.3 m deployed antennas span

Missions:
1) Orbit Change
2) Rendezvous – 100 m/s
3) Dispose (increase the altitude of 400 km) or Move ($\Delta V = 219$ m/s; 180 deg in one week)
4) Park (if disposal) and Return to GEO

Mission Life: 10 years

Assumptions:
1) The target properties are the same for all targets.
2) The tender is launched into a 28 deg GTO orbit.
ICE: Integrated Concurrent Engineering

- Rapid conceptual design of points in the tradespace
- CalTech/JPL/Aerospace Corp. Integrated Concurrent Engineering techniques used
- Analysis Team: MIT/Caltech/Cambridge Students
Results based on MATE tradespace: Bipropellant GEO Tug

- Approx. 1300 kg dry mass, 11700 kg wet mass
- Quite big (and therefore expensive); not very practical (?)

Scale for all images: black cylinder is 1 meter long by 1 meter in diameter

The “Rocket Equation Wall” explored
**Electric Propulsion RT GEO Tug**

- Approx. 700 kg dry mass, 1100 kg wet mass
- Includes return of tug to safe orbit
- A reasonable, versatile system

The “Electric Cruiser” on the knee of the tradespace
Results from Mission Analysis: Bi-prop Tender Designs

- Lower Utility, lower cost systems
- Can’t go to GEO (though can work there if inserted)
- 700-1000 kg dry mass; 1000-4000 kg wet mass
- A family of potential vehicles with reasonable sizes and mass fractions
Integration of Mission Analysis Results

- Modular family of possible vehicles
- Electric and conventional propulsion
- Varying fuel loads
- Variety of manipulators within fixed weight/volume/power envelope

<table>
<thead>
<tr>
<th>Tender</th>
<th>Grappling Module</th>
<th>Bus Module</th>
<th>Propulsion Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO (electric)</td>
<td><img src="image1" alt="GEO Module" /></td>
<td><img src="image2" alt="Bus Module" /></td>
<td><img src="image3" alt="Propulsion Module" /></td>
</tr>
<tr>
<td>LEO 1</td>
<td><img src="image4" alt="LEO 1 Module" /></td>
<td><img src="image2" alt="Bus Module" /></td>
<td><img src="image3" alt="Propulsion Module" /></td>
</tr>
<tr>
<td>LEO 2</td>
<td><img src="image5" alt="LEO 2 Module" /></td>
<td><img src="image2" alt="Bus Module" /></td>
<td><img src="image3" alt="Propulsion Module" /></td>
</tr>
<tr>
<td>LEO 3</td>
<td><img src="image6" alt="LEO 3 Module" /></td>
<td><img src="image2" alt="Bus Module" /></td>
<td><img src="image3" alt="Propulsion Module" /></td>
</tr>
<tr>
<td>LEO 4</td>
<td><img src="image7" alt="LEO 4 Module" /></td>
<td><img src="image2" alt="Bus Module" /></td>
<td><img src="image3" alt="Propulsion Module" /></td>
</tr>
</tbody>
</table>

- Targets: 1,500 – 3,500 kg
- Scaled for LEO 4A missions
- Scaled for LEO 4A missions
- NaOH
- NaHs
Bringing it all together:
Trade Space Check - GEO missions

The GEO mission is near the “wall” for conventional propulsion.
The Tender missions are feasible with conventional propulsion. General Tender is flexible (though not "optimal").
Synergies Between Methods Results in Powerful Conceptual Design Capability

Feasible mission concepts

Mission Analysis

ICE

Validation and understanding

Design point or attributes and sensitivities

Point design requirements

MATE

Mission Analysis
Synergies Between Methods Results in Powerful Conceptual Design Capability

**MATE**

Right Design(s) for the Right Mission(s)

**ICE**

General design

Point designs

Feasible mission concepts

Mission Analysis

Point design requirements
Synergies Between Methods Results in Powerful Conceptual Design Capability

**MATE**

- Feasible mission concepts
- Mission Analysis
  - Point design requirements
  - Validation and understanding
  - Design attributes & sensitivities

**ICE**

- Right Design(s) for the Right Mission(s)
- Family concepts, multi-mission tender