Metrics for Evaluating Survivability in Dynamic Multi-Attribute Tradespace Exploration

AIAA Space 2008

Matthew G. Richards
Research Assistant, Engineering Systems Division
Massachusetts Institute of Technology

Nirav B. Shah
Research Assistant, Aeronautics and Astronautics
Massachusetts Institute of Technology

Adam M. Ross, Ph.D.
Research Scientist, Engineering Systems Division
Massachusetts Institute of Technology

Daniel E. Hastings, Ph.D.
Professor, Aeronautics and Astronautics & Engineering Systems
Massachusetts Institute of Technology
Outline

1. Motivation
2. Survivability Definition
3. Survivability Metrics
   A. Existing
   B. Proposed
4. Application of Proposed Metrics
   A. Dynamic Tradespace Methodology
   B. Design Problem: Space Tug Survivability
   C. Results
5. Discussion
6. Conclusion
Motivation for Survivability

1. **Growth of military and commercial dependency on space systems**
   
   (Gonzales 1999; GAO 2002; Ballhaus 2005)

2. **Identified vulnerabilities in the U.S. space architecture**
   
   (Thomson 1995; Rumsfeld, Andrews et al. 2001; CRS 2004)

3. **Proliferation of threats**
   
   (Rumsfeld, Andrews et al. 2001; Joseph 2006)

4. **Weakening of the sanctuary view in military space policy**
   
   (Mowthorpe 2002; O’Hanlon 2004; Covault 2007)
Definition of Survivability

**Ability of a system to minimize the impact of a finite-duration disturbance on value delivery**
through (I) the reduction of the likelihood or magnitude of a disturbance, (II) the satisfaction of a minimally acceptable level of value delivery during and after a disturbance, and/or (III) timely recovery

**Epoch**: Time period with a fixed context; characterized by static constraints, design concepts, available technologies, and articulated attributes (Ross 2008)

## Limitations of Existing Metrics

| Engagement Survivability | \( P_S = 1 - P_K = 1 - P_H \cdot P_{K/H} \)  
| S = survive, K = kill, H = hit | • Binary assessment criteria 
| | fails to internalize graceful degradation |
| Campaign Survivability | \( CS = \left( P_S \right)^N = \left( 1 - P_K \right)^N \)  
| N = number of engagements | • Binary assessment criteria 
| | Assumes independence among shot and mission outcomes |
| Reliability Function (aka Survival Function) | \( R(t) = 1 - F(t) = e^{t/MTBF} \)  
| t = operating time  
| MTBF = mean time between failure | • Construct validity 
| | • Binary assessment criteria 
| | • Time to failure assumed as exponential density function |
| Inherent Availability | \( A_i = \frac{MTBF}{MTBF + MTTR} \)  
| MTTR = mean time to repair | • Construct validity 
| | • Binary assessment criteria |
| Mission Effectiveness | \( MoME = A_i \cdot P_S \cdot Capability \) | • Survivability preferences confounded with availability and capability |

(Ball 2003; Blanchard and Fabrycky 2006)
Proposed Survivability Metrics

Need to evaluate ability of system to (1) minimize utility losses and (2) meet critical value thresholds before, during, and after environmental disturbances.

desirable attributes: value-based, dynamic, continuous

<table>
<thead>
<tr>
<th>time-weighted average utility</th>
<th>threshold availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Difference between design utility and aggregate utility loss</td>
<td>• Ratio of time above critical value threshold ($V_x$ during baseline Epoch, $V_e$ during disturbance and recovery Epochs) to total time</td>
</tr>
<tr>
<td>• Internalizes lifecycle degradation</td>
<td>• Accommodates changing expectations during disturbances</td>
</tr>
<tr>
<td>• Based on Quality Adjusted Life Years (QALYs) in medicine*</td>
<td></td>
</tr>
</tbody>
</table>

$$\overline{U_t} = \frac{1}{T_{dl}} \cdot \int U(t) \, dt$$

$$A_T = \frac{MTAT}{T_{dl}}$$

Baseline Study: Space Tug

- Existing study of space tug tradespace*
  - Three attributes
    - Delta-V
    - Capability
    - Response time
  - Three design variables

Design Space
- 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

- Simple performance model
  - Delta-V → rocket equation
  - Binary response time
  - Capability solely dependent on manipulator mass
  - Cost calculated from vehicle wet and dry mass

### Adding Survivability to Design

#### Type I

**Susceptibility reduction**
- Active collision avoidance
- Reduced cross-sectional area (derived)

<table>
<thead>
<tr>
<th>Manipulator Mass</th>
<th>Fuel Load (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (300kg)</td>
<td>30</td>
</tr>
<tr>
<td>Medium (1000kg)</td>
<td>100</td>
</tr>
<tr>
<td>High (3000 kg)</td>
<td>300</td>
</tr>
<tr>
<td>Extreme (5000 kg)</td>
<td>600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propulsion Type</th>
<th>Shield Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storable bi-prop</td>
<td>30</td>
</tr>
<tr>
<td>Cryogenic bi-prop</td>
<td>100</td>
</tr>
<tr>
<td>Electric (NSTAR)</td>
<td>300</td>
</tr>
<tr>
<td>Nuclear Thermal</td>
<td>500</td>
</tr>
</tbody>
</table>

#### Type II

**Vulnerability reduction**
- Bumper shielding
- Increased capability margin (derived)

<table>
<thead>
<tr>
<th>Servicing</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
</tr>
</tbody>
</table>

#### Type III

**Resilience enhancement**
- On-orbit servicing insurance for timely repair

<table>
<thead>
<tr>
<th>Collision Avoidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
</tr>
</tbody>
</table>

#### Design Variables

- **Survivability features**
- 1 of 2560 possible design vectors (full-factorial)

- **45 m²**
- **5 m²**

(Lai 2002)
Model Overview

1. Design Vector
2. Space Tug Model
3. Conjunction event generator
4. Cross-sectional area
5. Shielding thickness
6. Dynamic state model
7. Statistics on Monte Carlo runs

Design Utility Cost
Survivability

Architecture Tradespace

>1mm debris flux (ORDEM2000)

25 m
500 Monte Carlo runs per satellite
# Impact Outcomes

<table>
<thead>
<tr>
<th>debris diameter</th>
<th>1 mm</th>
<th>→x cm←</th>
<th>10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>micro</td>
<td>degradation</td>
<td>damage</td>
<td>severe damage</td>
</tr>
<tr>
<td>small</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>medium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>large</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **impact outcome (Remo 2005)**
- **modeling assumption (7 km/s)**

- Threshold between satellite degradation and loss regime, x cm, is a function of bumper thickness
- Bumper thickness is a function of shield mass design variable and satellite body area

- 10% chance of loss in capability level
- end-of-life / collision avoidance with 99% success
Utility Trajectory Provides Data for Dynamic Survivability Assessment

Utility Trajectory - DV(1137)

Utility Trajectory - DV(1137) provides data for dynamic survivability assessment. The graph shows the utility trajectory over time, with impacts and servicing events marked. The utility is measured on a dimensionless scale, and the threshold is indicated by a red line. Mapping to survivability definition is also shown.
Need Measures of Central Tendency Across Runs
Pareto Surface of Cost, Utility, Utility Loss and Threshold Availability (n=594)

- Pareto Surface (Filtered)
- Design utility (dimensionless)
- Median time-weighted utility loss (dimensionless)
- Threshold availability (5th percentile)

The graph shows the relationship between cost ($M) and design utility (dimensionless), with threshold availability (5th percentile) as a color gradient on the right side.
Survivability Response Surfaces

- Threshold availability (5th percentile)
- Average time-weighted average utility (dimensionless)
- Cost ($M)

Legend:
- no avoidance, no servicing
- no avoidance, servicing
- avoidance, no servicing
- avoidance, servicing
- servicing response
- avoidance response
- shielding response

Number specifies baseline design vector.
Insights from Model

• Criticality of survivability derived from baseline design
  – Impact sometimes greater than dedicated survivability design variables
• Results highly sensitive to damage model
• Many highly survivable designs only slightly dominated in terms of cost and utility
  – Traditional Pareto-optimal designs exhibit poor survivability
  – Pareto surface of cost, utility, utility loss, and threshold availability increases size of optimal set by factor of 5
• Mixed impact of survivability design variables
  – Moderate shielding valuable only for mid-range and large tugs
  – Avoidance appropriate for only most risk-averse decision maker
  – Servicing has large positive impact
Conclusion

• Survivability engineering critical for U.S. space architecture

• Proposed metrics to operationalize dynamic, continuous, and value-centric definition of survivability

• Demonstrated metrics in dynamic tradespace study

• Developed survivability “tear” tradespace for integrated evaluation with cost and utility

• Future opportunities to improve model fidelity and incorporate environmental path-dependencies
Questions?