System Architecting for Survivability:
Limitations of Existing Methods for Aerospace Systems

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Agenda

• Survivability Definition

• Literature Review
  – Research Context
  – Motivation: Space System Fragility
  – Limitations of Survivability Methods

• Future Work

• Conclusion
Definition of Survivability

*Ability of a system to minimize the impact of a finite disturbance on value delivery* through either (I) the reduction of the likelihood or magnitude of a disturbance or (II) the satisfaction of a minimally acceptable level of value delivery during and after a finite disturbance.

**Epoch:**
Time period with a fixed context; characterized by static constraints, design concepts, available technologies, and articulated attributes (Ross 2006).

![Diagram](image-url)

Ulrich and Eppinger (2004) have a six-phase model of product development. Research addresses product architecture, spanning Phases 1 and 2:

- **Concept Development**
  - Identification of stakeholders
  - Enumeration and evaluation of design alternatives
  - Selection of one or more concepts for further development

- **System-Level Design**
  - Definition of the architecture, including subsystem decompositions and functional specifications

Phase 0: Planning
Phase 1: Concept Development
Phase 2: System-Level Design
Phase 3: Detail Design
Phase 4: Testing and Refinement
Phase 5: Production Ramp-Up

Critical front-end in complex system design

(Gruhl 1992; Blanchard and Fabrycky 2006)

(Ulrich and Eppinger 2004)
Value-Based Conceptual Design Through Tradespace Exploration

Value is a measure of net benefit specified by a stakeholder

• Value-centric perspective enables unified evaluation of technically diverse system concepts
• Operationalized through the application of decision theory to engineering design
  – Quantifies benefits, costs, and risks
    (Thurston 1990; Keeney and Raiffa 1993)

• Tradespace exploration uses computer-based models to compare thousands of architectures
  – Avoids limits of local point solutions
  – Maps decision maker preference structure to potential designs
    (McManus, Hastings and Warmkessel 2004; Ross et al. 2004; Walton and Hastings 2004; Weigel and Hastings 2004)
Incorporating Survivability into Tradespace Studies

Ilities are temporal system properties that specify the degree to which systems are able to maintain or even improve value in the presence of change*

- Ilities are increasingly regarded as critical system properties for delivering stakeholder value
  (Moses 2004; Rhodes 2004; McManus and Hastings 2006)
- Ongoing research seeks to establish prescriptive methods for incorporating ilities in system design
  (de Neufville 2004; de Weck, de Neufville and Chaize 2004; Fricke and Schulz 2005; Rajan, Van Wie et al. 2005; Ross and Hastings 2006; Nilchiani and Hastings 2007; Silver and de Weck 2007)
- Challenges for incorporating ilities in tradespace studies
  - Taxonomic uniformity
  - Characterizing temporal constructs in traditional tradespaces
  - Disaggregating from traditional attributes in Multi-Attribute Utility Theory
  - Investing in uncertain future

*Definition excludes some non-operational ilities, such as manufacturability

Motivation: Need for “ilities” in Space Architecture

1960’s Paradigm

- CORONA: 30-45 day missions
- 144 spacecraft launched between 1959-1972 (Wheelon 1997)

Evolution to Current State

- Inability to adapt to uncertain future environments, including disturbances

“Our spacecraft, which take 5 to 10 years to build, and then last up to 20 in a static hardware condition, will be configured to solve tomorrow’s problems using yesterday’s technologies.” (Dr. Owen Brown, DARPA Program Manager, 2007)
Criticality of Survivability for U.S. Space Architectures

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)

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Chinese Anti-satellite Test Creates Most Severe Orbital Debris Cloud in History

The debris cloud created by a successful test of a Chinese anti-satellite (ASAT) system on 11 January 2007 represents the single worst contamination of low Earth orbit (LEO) during the past 50 years. Extending from 300 km to more than 4000 km in altitude, the debris frequently transits the orbits of hundreds of operational spacecraft, including the human space flight regime, posing near-collisions to current and future space systems. Moreover, the majority of the debris were thrown into long-duration orbits, with lifetimes measured in decades and even centuries.

The target of the test was an old Chinese meteorological spacecraft, Pengyun-1C (International Designator 1999-025A, U.S. Space Surveillance Network (SSN)) and nearly 100 additional debris were being tracked, making permanent catalog numbers (Figure 1). While the final tally of large (> 5 cm size) debris could well exceed 2000, the number of objects with a size of 1 cm or more is estimated to be as large as 35,000. Both values represent an increase of more than 15% of the known debris environment at the start of 2007.

More than half the identified debris were thrown into orbits with mean altitudes in excess of 850 km. Consequently, the debris will remain scattered throughout LEO for many, many years to come. Initially confined to a disk about the Earth, the orbital planes of the debris are rapidly dispersing and will encircle the globe before the rain of debris spreads.

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Figure 1. By 31 March 2007 more than 1000 debris from the Chinese ASAT test had been identified and were being tracked by the U.S. Space Surveillance Network.

Figure 2. Known orbits planes of Pengyun-1C debris one month after its disintegration by a Chinese Interceptor. The white solid represents the International Space Station.
Current Response: Survivability Engineering

• Survivability engineering discipline emerged in 1960’s
  – Survivability requirements derived early in conceptual design from System Threat Assessment Report (STAR)
  – Survivability evaluated using Probabilistic Risk Assessment
    (Ball 2003; USAF 2005)

• Survivability of individual systems well addressed
  (Nordin and Kong 1999, Paterson 1999)

• However, architecting for survivability is poorly understood
  – e.g., survivability of triad of U.S. strategic forces
    (Bracken 1983; Blair 1985)
  – Criticality of whole product system
    (Leveson 2002; Sheffi 2005; Baldwin et al. 2006; Hollnagel, Woods and Leveson 2006)

How to evaluate survivability as an emergent architectural property?
### Kill Chain for Engagement-Level Survivability Assessment

\[ P_S = 1 - P_K = 1 - P_H \cdot P_{K/H} \]

<table>
<thead>
<tr>
<th>Kill Chain</th>
<th>Description</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_A )</td>
<td>Probability the threat site is Active</td>
<td>Operational Scenario definition</td>
</tr>
<tr>
<td>( P_{D</td>
<td>A} )</td>
<td>Probability of Detecting the aircraft given the threat site is Active</td>
</tr>
<tr>
<td>( P_{L</td>
<td>D} )</td>
<td>Probability of a firing solution and Launch given a Detection</td>
</tr>
<tr>
<td>( P_{I</td>
<td>L} )</td>
<td>Probability of threat Intercepting the aircraft given a Launch</td>
</tr>
<tr>
<td>( P_{H</td>
<td>I} )</td>
<td>Probability of a Hit or warhead fuzing given a threat Intercept</td>
</tr>
<tr>
<td>( P_{K</td>
<td>H} )</td>
<td>Probability of a Kill given a Hit</td>
</tr>
</tbody>
</table>

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### Problems with Existing Metrics

<table>
<thead>
<tr>
<th>Engagement Survivability</th>
<th>$P_S = 1 - P_K = 1 - P_H \cdot P_{K/H}$</th>
<th>• Binary assessment criteria fails to internalize graceful degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S = \text{survive}, K = \text{kill}, H = \text{hit}$</td>
<td></td>
</tr>
</tbody>
</table>
| Campaign Survivability   | $CS = (P_S)^N = (1 - P_K)^N$ | • Binary assessment criteria  
                          | $N = \text{number of engagements}$ | • Assumes independence among shot and mission outcomes |
| Reliability Function     | $R(t) = 1 - F(t) = e^{t/\text{MTBF}}$ | • Construct validity  
                          | $t = \text{operating time}$ | • Binary assessment criteria  
                          | $\text{MTBF} = \text{mean time between failure}$ | • Time to failure assumed as exponential density function |
| Inherent Availability    | $A_i = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$ | • Construct validity  
                          | $\text{MTTR} = \text{mean time to repair}$ | • Binary assessment criteria |

*Ball 2003; Blanchard and Fabrycky 2006*
Limitations of Survivability Engineering

1. Treatment of survivability as a constraint rather than an active trade in the design process
   (Wheelon 1997; Walker 2007)

2. Static nature of System Threat Assessment Reports
   (Ball 2003; Anderson and Williamsen 2007)

3. Reliance on probabilistic risk assessment and the assumption of independent failures
   (Leveson 1995; Perrow 1999; Leveson 2002; Pate-Cornell, Dillon and Guikema 2004)

4. Limited scope of survivability design and analysis
   (Neumann 2000; USAF 2005; Walker 2007)

5. Lack of value-centric perspective
   (Keeney 1992; Ross 2006)
Future Work:
Dynamic Modeling of Survivability

Multi-Attribute Tradespace Exploration (MATE) (McManus, Hastings and Warmkessel 2004; Ross et al. 2004)

Epoch-Era Analysis
(Ross 2006)

Two aspects to an Epoch:
1. Needs (expectations)
2. Context (constraints including resources, technology, etc.)
Future Case Application: Operationally Responsive Space

Operationally Responsive Space (ORS) purportedly enhances survivability of current national space architecture

- **Goal**: reduce time constants associated with space system acquisition, design, and operation (*DoD 2007*)
- **Fundamental idea**: trade off reliability and performance of “big space” for speed, responsiveness, and customization potentially offered by small tactical spacecraft (TACSATs)
- **Problem**: uncertain value proposition (*Tomme 2006; Fram 2007*)

“ORS deserves, yet has not received, our analytic due diligence.”
(*Mr. Gil Klinger, Former Director of Space Policy, U.S. National Security Council, 22 August 2007*)
Conclusion

• Given limitations of survivability engineering for aerospace systems, need design methodology that:

  1. incorporates survivability as an **active trade** throughout design process
  2. reflects **dynamics** of operational environments over entire lifecycle
  3. captures **path dependencies** of system susceptibility and vulnerability
  4. extends in scope to **architecture-level** survivability assessments
  5. takes a **value-centric** perspective

• Opportunity to build on recent research on dynamic tradespace exploration

• Application of emergent survivability design method may aid in resolution of critical issue in national space architecture
  - Existing analytic frameworks not well-suited to evaluating purported survivability benefits of Operationally Responsive Space (ORS)*

* Small spacecraft paradigm emphasizing timely launch, tactical control, and customization
Thank You / Questions?
References (1/4)

References (2/4)

References (3/4)

References (4/4)

Terminology

- **Architecture**
  - the structure of components, their relationships, and the principles governing their design and evolution over time (DoD 2003)

- **Architecting**
  - the process of creating and building architectures; those aspects of a system development most concerned with conceptualization, objective definition, and certification for use (Maier and Rechtin 2002)

- **Design**
  - [V] the process of devising a system, component or process to meet desired needs…. [includes] the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation (Accreditation Board for Engineering and Technology)
  - [N] the detailed formulation of the plans or instructions for making a defined system element (Maier and Rechtin 2002)

- **Tradespace**
  - the potential solution space spanned by completely enumerated design variables; enables cross-design comparisons (Ross and Hastings et al. 2004)
Survivability Mapping to Related Disciplines

<table>
<thead>
<tr>
<th>Type of Disturbance</th>
<th>Internal Origin of Disturbance</th>
<th>External Origin of Disturbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural / Accidental</td>
<td>Reliability</td>
<td>Security</td>
</tr>
<tr>
<td>Malevolent</td>
<td>Survivability</td>
<td></td>
</tr>
</tbody>
</table>

- **Reliability**: probability of functioning for a prescribed time under stipulated environmental conditions
- **Safety**: freedom from accidents or losses
- **Security**: protection of a system’s informational, operational, and physical elements from malicious intent
- **Survivability**: capability to avoid or withstand hostile natural and synthetic environments

*(Leveson 1995; USAF 2005)*

Porous boundaries!
Resilience Engineering

- Drive for efficiency has led to global, lean supply chains that are extremely fragile to disasters
- Empirical data indicates need for balance between security, redundancy, and short-term profits
- Resilient design principles include standardization, modular design, and collaborative relationships with suppliers

Research Agenda for Systems of Systems (SoS) Architecting

1. Resilience
2. Illustration of Success
3. System vs. SoS Attributes
4. Model Driven Architecting
5. Multiple SoS Architectural Views
6. Human Limits to Handling Complexity
7. Net-Centric Vulnerability
8. Evolution
9. Guided Emergence
10. No Single Owner SoS

USC Center for Systems and Software Engineering, October 2006