Space Systems Architecture
Lecture 3
Introduction to Tradespace Exploration

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A joint venture of MIT, Stanford, Caltech & the Naval War College
for the NRO

Tradespace Exploration

• A process for understanding complex solutions to complex problems
• Allows informed “upfront” decisions and planning

Most relevant to processes in these phases

Phases of Product Development

From Ulrich & Eppinger, Product Design and Development, 1995
**Architecture Trade Space Exploration**

A process for understanding complex solutions to complex problems

- Model-based high-level assessment of system capability
- Ideally, *many* architectures assessed
- Avoids optimized *point solutions* that will not support evolution in environment or user needs
- Provides a basis to explore technical and policy *uncertainties*
- Provides a way to assess the value of *potential* capabilities

Allows informed "upfront" decisions and planning

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**Integrated Concurrent Engineering**

A process creating preliminary designs very fast

- State-of-the-art rapid preliminary design method
- Design tools linked both electronically and by co-located humans
- Design sessions iterate/converge designs in hours
- Requires ready tools, well poised requirements

Allows rapid reality check on chosen architectures
Aids transition to detailed design
Emerging Capability

- Linked method for progressing from vague user needs to conceptual/preliminary design very quickly
- MANY architectures, several/many designs considered
- Understanding the trades allows selection of robust and adaptable concepts, consideration of policy, risk.

Months, not Years

What is an Architecture Trade Space?

X-TOS
- Small low-altitude science mission

Assessment of the utility and cost of a large space of possible system architectures

DESIGN VARIABLES: The architectural trade parameters
- Orbital Parameters
  - Apogee altitude (km) 150-1100
  - Perigee altitude (km) 150-1100
  - Orb inclination 0, 30, 60, 90
- Physical Spacecraft Parameters
  - Antenna gain
  - Communication architecture
  - Propulsion type
  - Power type
  - \( \Delta v \)
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

XTOS Tradespace Development

Concept
- Small low-altitude science mission
- Known instruments

Attributes
- Data Life Span
- Data Collection Altitude(s)
- Diversity of Latitude(s)
- Time Spent at Equator
- Data Latency

Design Vector
- Number of Vehicles and Mission Design
- Apogee Altitude
- Perigee Altitude
- Orbit Inclination
- Antenna Gain
- Communications Architecture
- Propulsion Type
- Power Type
- Maneuver Delta-V Capability
Continued

Total Lifecycle Cost ($M 2002)

- Orbit Calculations (STK)
- Spacecraft Estimations (SMAD)
- Launch Module

Calculate Utility
- Multi-Attribute Utility Theory

Estimate Cost
- SMAD/NASA mode

Understanding What Systems Do

- Transmit Information
- Collect Information
- Move Mass (inc. People)
- Others (Space Station…)

[Beichman et al, 1999]
Understanding who cares - Stakeholders

- Many interested parties in a complex system
- Each “customer” has a set of needs
- They are different, and can be contradictory

Concept Selection: Bounding

ATOS: Multi-vehicle Ionosphere Explorer

In Situ

- Topside Sounding
- Direct Scintillation Sensing
- GPS Occultation
- UV Sensing
**Scoping**

**A-TOS scope**

- **Spacecraft Instrument Control Center**
  - Ionosphere
  - Raw, commutated, uncalibrated data
  - Decommutated, calibrated instrument data

- **Physics Model**
  - Instrument to Local Ionosphere
  - Ionospheric characteristics

- **Global Ionospheric Model**
  - Current State
  - Predict Future State

- **Other Data Sources** (Various assets)

- **Hanscom Model**

- **Database**

- **User-Specific System Integration**

- **User Set**
  - "Scientist" User Set
  - "Space Weather" User Set
  - "Knowledgeable" User Set
  - "Warfighter" User Set

**Attributes**

- "what the decision makers need to consider"
- (and/or what the user truly cares about)
- Examples: Billable minutes = GINA metrics
- TPF Pictures =
  - camera performance metrics
- Rescue/move satellites =
  - mass moving, grappling capability, timeliness
  - Could have sub-cartoons for above

*Beichman et al, 1999*
XTOS Attributes

1) Data Life Span
2) Data Altitude
3) Maximum Latitude
4) Time Spent at Equator
5) Data Latency

Utilities

- “What the attributes are WORTH to the decision makers”
- Single Attribute utility maps attribute to utility
- Multi-attribute utility maps an architecture (as expressed by its attributes) to utility
### Single Attribute Utilities

- Utility vs. Data Collection Altitude (km)

### Multi-Attribute Utility

- Weight Factors of each Attribute (k values)
- \[ KU(X_i) + 1 = \sum_{k=1}^{N} (k_i U(X_i) + 1) \]

- Utility vs. Total Lifecycle Cost (SM 2002)
• “Parameters of the Trade Space”

<table>
<thead>
<tr>
<th>Variable:</th>
<th>First Order Effect:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Parameters:</td>
<td></td>
</tr>
<tr>
<td>• Apogee altitude (200 to 2000 km)</td>
<td>Lifetime, Altitude</td>
</tr>
<tr>
<td>• Perigee altitude (150 to 350 km)</td>
<td>Lifetime, Altitude</td>
</tr>
<tr>
<td>• Orbit inclination (0 to 90 degrees)</td>
<td>Lifetime, Altitude</td>
</tr>
<tr>
<td></td>
<td>Latitude Range</td>
</tr>
<tr>
<td></td>
<td>Time at Equator</td>
</tr>
<tr>
<td>Physical Spacecraft Parameters:</td>
<td></td>
</tr>
<tr>
<td>• Antenna gain (low/high)</td>
<td>Latency</td>
</tr>
<tr>
<td>• Comm Architecture (TDRSS/AFSCN)</td>
<td>Latency</td>
</tr>
<tr>
<td>• Propulsion type (Hall / Chemical)</td>
<td>Lifetime</td>
</tr>
<tr>
<td>• Power type (fuel / solar)</td>
<td>Lifetime</td>
</tr>
<tr>
<td>• Total ΔV capability (200 to 1000 m/s)</td>
<td>Lifetime</td>
</tr>
</tbody>
</table>

• Geometry of the Multi-vehicle Swarm
Scoping-QFDs

Identify key interactions for modeling

Sums identify attributes and Design Variables that are likely to be (or not be) distinguishers

Scoping-Iteration/evolution

TABLE II. EVOLUTION OF DESIGN VECTOR

<table>
<thead>
<tr>
<th>First Cut</th>
<th>After GINA exercise</th>
<th>After utility characterization and module progress</th>
<th>Schedule Crunch</th>
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<tbody>
<tr>
<td></td>
<td>10/20/00</td>
<td>10/31/00</td>
<td>1/15/01</td>
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<tr>
<td>Swarm type</td>
<td>Concept type</td>
<td>Swarm perigee altitude</td>
<td>Swarm apogee altitude</td>
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<td># sats/swarm</td>
<td># sats/swarm</td>
<td># sats/swarm</td>
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<td>Swarm orbit</td>
<td># orbital planes</td>
<td># subplanes/swarm</td>
<td># subplanes/swarm</td>
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<tr>
<td>Intra-swarm orbit</td>
<td>Swarm altitude</td>
<td># suborbits/subplane</td>
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<tr>
<td>Instrument type</td>
<td>Swarm orientation</td>
<td>Yaw angle of subplanes</td>
<td>Max sat separation</td>
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<tr>
<td># instruments/sat</td>
<td>Swarm geometry</td>
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<tr>
<td>TT&amp;C scheme</td>
<td>Separation within swarm</td>
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<tr>
<td>Ground station</td>
<td>Mothership (yes/no)</td>
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<tr>
<td>Mission lifetime</td>
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<td>Position control scheme</td>
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<tr>
<td>Latitude of interest</td>
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</table>
Mapping Design Vector to Attributes and Utilities - Simulation Models

XTOS Simulation Software Flow Chart

Orbits → Spacecraft → Launch → Mission Scenario → Cost (lifecycle) → Utility → Mission scenarios with acceptable satellites → Output

Techsat Models

Inputs (Design Vector)

MATLAB Models

Constellation → Radar → S/C Bus → Payload → Launch & Operations → System Analysis

Key Outputs

Lifecycle Cost, Availability, Probability of Detection, Revisit Rate, Resolution & MDV
**Exploring the Tradespace**

Each point is an evaluated architecture

Many good architectures at c. $0.5M/Image

**TPF: a science imaging system**

**The Pareto Front**

- Set of “best” solutions
- “Dominated” solutions are more expensive or less capable
Can look for the Pareto front using advanced optimization techniques

- **Pareto Front**
  - Multi-Objective SA Exploration of the TPF Trade Space

- **Using the Trade Space to Evaluate Point Designs**
  - TPF System Trade Space
  - **TPF**
    - Terrestrial Planet Finder - a large astronomy system
    - Design space: Apertures separated or connected, 2-D/3-D, sizes, orbits
    - Images vs. cost

- **Images vs. cost**
  - [Beichman et al, 1999]