Strategy Dynamics and System-of-Systems Tradespace Exploration

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Overview

• Research Objectives
• Background
• Methodology
• Application Case
• Results
• Discussion
• Future Work
Research Objectives

• Develop and demonstrate a conceptual design methodology incorporating collaborative system strategy dynamics in a tradespace exploration.
  — Yield constituent systems that are robust to SoS dissolutions and promote the formation and stability of the SoS.

• Determine how economic variables impact constituent system designs and the assess the suitability of the proposed methodology for such analyses.

• Determine the impacts of operational uncertainty on the expected value of designs generated using the proposed methodology.
Background

• A growing space economy creates opportunities for collaborative systems (SoS) that enhance value for constituent system owners.

• SoS formation requires investments to enable interoperation (Maier, 1998).

• Efficiency maximization goals create a temptation to eliminate redundant functionality.

• Failed SoS may result in non-recoverable interoperability costs and expensive modifications or delays to adapt systems for independent operation.

• Methods which objectively and consistently assess designs for suitability in a SoS context are required.
Background Continued

• Research in this area has focused on:
  — Combined and weighted constituent objectives (DiMario et al., 2009)
  — Global SoS objectives (DiMario et al., 2009, Fang et al., 2018)
  — Determining when a successful SoS is mutually beneficial (Baldwin et al., 2015, DiMario et al., 2009)
  — Discovering consensus/ compromise designs (Fitzgerald and Ross, 2013)

• These works do not consider the strategy dynamics induced by multiple decision makers.
  — Determination that an upside of collaboration exists for particular designs is not sufficient for rational selection of those designs.
Methodology

- Game theory provides tools for strategy selection in multi-decision maker problems (Selten, 1995).

- Games can be used to model multi-actor decisions in engineering design (Grogan & Valencia-Romero, 2019).

- Weighted average log measure of risk dominance, $R$, indicates the risk dominant strategy. $R < 0$ indicates dominance of collaborative strategy (Selten, 1995).
Methodology

<table>
<thead>
<tr>
<th>Actor 1</th>
<th>Actor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hare (\phi)</td>
</tr>
<tr>
<td>Hare (\phi)</td>
<td>( V^\phi \phi = 2 )</td>
</tr>
<tr>
<td>Stag (\psi)</td>
<td>( V^\psi \phi = 4 )</td>
</tr>
<tr>
<td>Stag (\psi)</td>
<td>( V^\psi \psi = 5 )</td>
</tr>
</tbody>
</table>

\[
 u_i(\phi, \psi) = \frac{V^\phi \phi - V^\psi \phi}{(V^\phi \phi - V^\psi \phi)} - \frac{V^\phi \psi - V^\psi \psi}{(V^\phi \psi - V^\psi \psi)} 
\]

\[
 R = \sum_{i=1}^{n} w_i(A) \ln \frac{u_i}{1 - u_i} 
\]

Where \( w_i(A) \) are the influence weights based on influence matrix \( A \).

- \( R = 0.69 \) for the example above, indicating that the independent (hare hunting) strategy is risk dominant.
Methodology

- Alternative designs change payoffs and strategy dynamics.

<table>
<thead>
<tr>
<th>Design</th>
<th>Hare, Hare</th>
<th>Hare, Stag</th>
<th>Stag, Hare</th>
<th>Stag, Stag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dogs</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spear</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Bow</td>
<td>1</td>
<td>1</td>
<td>1.75</td>
<td>4.5</td>
</tr>
</tbody>
</table>

- Adoption of the ‘bow’ design trades some upside potential for a reduction of downside loss.

- $R$ can be used in a SE context to guide trade space exploration towards strategically stable designs.
Methodology

- A two-phase trade space exploration implements the risk dominance criterion in a multi-attribute heuristic search
  - Objectives: Maximize NPV for each system, minimize $R$
Application Case

• Assesses collaboration between two, hypothetical, commercial space systems.
  — An earth observation system
  — A satellite communication system providing broadband internet services

• Each system can operate entirely independently of the other.

• Collaboration occurs when both systems implement interoperable inter-satellite links.
  — The SATCOM system performs EO command and data transport for a fee
  — EO system data value increases as latency decreases

• Evaluations performed for a five year mission duration for each system
Application Case

- Failure to coordinate on the collaborative system results in:
  - Unrecouped interoperability investments for both systems
  - Expensive ground station lease for EO if no organic ground stations are implemented
Application Case

EO System Evaluation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of planes</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Satellites per plane</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Aperture diameter (cm)</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>Altitude (km)</td>
<td>800</td>
<td>400</td>
</tr>
<tr>
<td>Number of ground stations</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

- System NPV assessed through simulation and analysis
  - Imagery revenue – a function of resolution and data latency
  - Cost – lifecycle cost based on parametric cost estimate
Application Case
SATCOM System Evaluation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of planes</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>Satellites per plane</td>
<td>80</td>
<td>8</td>
</tr>
<tr>
<td>User channels</td>
<td>32</td>
<td>1</td>
</tr>
<tr>
<td>Transmit power/channel (W)</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Min. user elevation (deg.)</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>Modulation scheme</td>
<td></td>
<td>22 options</td>
</tr>
</tbody>
</table>

- System NPV assessed through simulation and analysis
  - Communication revenue – a function of system capacity and customer base
  - Cost – lifecycle cost based on parametric cost estimate
Results

Fixed economic variables, deterministic schedule

• Data transport fee from EO to SATCOM fixed at $10M/month
  — Incurred only under collaboration when SATCOM service is available

• Top independent EO design
  — 3 planes, 3 satellites/plane, 1 m aperture, 400 km altitude, 3 ground stations; NPV = $346.75M

• Top independent SATCOM design
  — 41 planes, 80 satellites/plane, 40° min. elevation angle, 1 W/channel, 32 channels, 8PSK 2/3 rate; NPV = $9035.65M
Results Cont.

Fixed economic variables, deterministic schedule

- All Pareto efficient, collaborative, SATCOM system designs were the same as the best independent design.

- EO designs varied over a small range, trading maximum NPV for reductions to $R$ by decreasing investment cost and then adding organic communication paths.

<table>
<thead>
<tr>
<th>Design</th>
<th>Planes</th>
<th>Sats/ plane</th>
<th>Aperture</th>
<th>Alt. (km)</th>
<th>Ground Stations</th>
<th>NPV$_e$ ($M$)</th>
<th>NPV$_s$ ($M$)</th>
<th>$R$</th>
<th>$u_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>4</td>
<td>100</td>
<td>400</td>
<td>0</td>
<td>704.38</td>
<td>9332.78</td>
<td>-1.11</td>
<td>0.743</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>100</td>
<td>400</td>
<td>0</td>
<td>685.78</td>
<td>9332.78</td>
<td>-1.13</td>
<td>0.733</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>100</td>
<td>400</td>
<td>3</td>
<td>486.35</td>
<td>9332.78</td>
<td>-1.17</td>
<td>0.717</td>
</tr>
</tbody>
</table>
Results Cont.

Fixed economic variables, deterministic schedule

- Maximum value EO system design has a large downside risk and correspondingly high $u_e$.

- SATCOM downside is relatively low resulting in a low $u_s$. 

![Graph showing the relationship between $E[V_{eo}]$ and $p_{satcom}$ and $E[V_{satcom}]$ and $p_{eo}$]
Results Cont.

Fixed economic variables, deterministic schedule

- The success of a collaborative strategy is largely a function of EO design decisions

- EO Design 3 (solid magenta line) trades the efficiency gained by relying on SATCOM data transport, for robustness in the form of redundant communication paths.
Extended Application Case
Economic variables, schedule uncertainty

• The extended application case implements cost-share and data transport fee as economic design variables.
  — Cost-share - 0 to 100% of EO interoperability unique non-recurring costs
  — Fee - $1M to $20M/ month

• SATCOM’s portion of cost share is unrecoverable if they unilaterally select the independent strategy.

• Inclusion of economic variables results in many pareto efficient designs for a given technical implementation.
  — $R$ provides an objective criterion for discriminating between these solutions.

• Schedule uncertainty is modeled by Monte Carlo simulation with schedule delay applied to each system’s development cycle.
Results

Economic variables, schedule uncertainty

• A selection of designs on or near the Pareto frontier were selected for schedule uncertainty analysis.

  — Designs were selected for coverage of objective and design spaces.
    o min. $R$ – design with the minimum $R$ value
    o max. $\text{NPV}_e$ – design with the maximum EO NPV and negative $R$
    o max. $\text{NPV}_s$ – design with the maximum SATCOM NPV and negative $R$
    o max. up, min. $R$ – design with the maximum combined NPV and minimum $R$
    o $3 \times 4, 3\gamma$ – design with EO design of 3 planes, 4 satellites/ plane, and 3 ground stations and economic variables producing low $R$ and a moderate upside for each system
    o $2 \times 4$, min. $R$ – design with 2 EO planes and 4 EO satellites/plane and minimum $R$
    o $2 \times 4$ min. $\Delta$ – design with 2 EO planes and 4 EO satellites/plane and minimum delta upside between systems
    o $2 \times 3$, min. $R$
    o $2 \times 3, 1\gamma$ – low cost solution with negative $R$ and organic EO ground stations
Results
Economic variables, schedule uncertainty

Expected NPV for collaboration under schedule uncertainty.

Table 14  Monte Carlo Schedule Analysis Results

<table>
<thead>
<tr>
<th>Design</th>
<th>$E[NPV_v]$</th>
<th>$E[NPV_s]$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>min $R$</td>
<td>368.57</td>
<td>6191.82</td>
<td>undefined</td>
</tr>
<tr>
<td>max $NPV_v$</td>
<td>549.56</td>
<td>6167.81</td>
<td>undefined</td>
</tr>
<tr>
<td>max $NPV_s$</td>
<td>18.54</td>
<td>6697.23</td>
<td>undefined</td>
</tr>
<tr>
<td>max up, min $R$</td>
<td>445.13</td>
<td>6270.91</td>
<td>-1.66</td>
</tr>
<tr>
<td>max up, min $\Delta$</td>
<td>279.15</td>
<td>6436.60</td>
<td>-1.38</td>
</tr>
<tr>
<td>3x4, 3 $\gamma$</td>
<td>197.98</td>
<td>6349.57</td>
<td>-1.60</td>
</tr>
<tr>
<td>2x4, min $R$</td>
<td>361.54</td>
<td>6202.91</td>
<td>-2.63</td>
</tr>
<tr>
<td>2x4, min $\Delta$</td>
<td>198.08</td>
<td>6285.20</td>
<td>-1.66</td>
</tr>
<tr>
<td>2x3, min $R$</td>
<td>244.78</td>
<td>6355.75</td>
<td>-1.34</td>
</tr>
<tr>
<td>2x3, 1 $\gamma$</td>
<td>133.30</td>
<td>6354.33</td>
<td>-0.89</td>
</tr>
</tbody>
</table>
Discussion

• Results demonstrate a consistent trade between collective/ individual efficiency and system robustness

• Monte Carlo analysis reveals a limitation in the complete information game approach implemented in this work.
  — Strategy selection is dependent on payoffs - small payoff changes can have large impacts on equilibria selection
  — Design combinations which are very robust to strategic-level coordination failure may be fragile to operational uncertainty
    o The low downside risk for SATCOM exacerbates this phenomena in this research because only a slight upside is required for collaboration to be strongly favored by SATCOM, therefore a slight perturbation can flip the strategy selection criteria.
  — Future work will address this issue.
Future Work

• Future work will focus on the incorporation concepts from Bayesian games:
  — Model payoff uncertainty more efficiently than Monte Carlo.
  — Model varying degrees of managerial independence, teaming, and trust amongst decision-makers.


