Systems Geometry: A Dimensional Approach to T&E Systems of Systems Understanding

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Presentation Overview

• Introduction, Problem and Background
• Systems of Systems
• Test and Evaluation SoS Characteristics
• Systems Geometry
• CAGE II Case Study
• Future Research
Systems of Systems

• What are Systems of Systems?
  – “An SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities.” (DAG 2004)

• Five Characteristics (Sage & Cuppan, 2001)
  – Operational Independence of Constituents
  – Managerial Independence of Constituents
  – Geographic Distribution
  – Emergent Behavior
  – Evolutionary Development
The Challenge of Systems of Systems

- Connectivity
- Common “language”
- Coordination

- Multiple developers
- Emergent behaviors
### Characteristics of Distributed SoS in T&E (1 of 2)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Explanation</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic location</td>
<td>This is the location of the component system of interest. This could also account for multiple “sites” at a particular location.</td>
<td>Military post, laboratory, city, country</td>
</tr>
<tr>
<td>Participants / Stakeholders</td>
<td>There are many “sub” dimensions of stakeholders within an event. It could represent a particular service, command, or division. It could also represent a particular lab, program, or company. It includes funding sources, sponsors, users, developers, etc.</td>
<td>Army, Navy, Air Force, Marines, Canadian Forces, UK Forces, TRADOC, ARL, Contractors, Universities, etc.</td>
</tr>
<tr>
<td>Purpose / Mission</td>
<td>Each event or capability has a specific mission or purpose. There is some overlap between capabilities – but not in the resources. There is also overlap in the resources used but not the proposed mission (reuse). This represents the motivation for the desired emergent SoS behaviors.</td>
<td>Training, developmental testing, operational testing, research, network evaluation, etc.</td>
</tr>
<tr>
<td>Constituent Systems</td>
<td>Systems can consist of many types. Operational equipment represents constituent systems that are typically used in the field by a warfighter in a real warfare situation. Modeling and simulation is used to explore concepts, augment a SoS environment containing operational equipment, or develop courses of action. A variety of tools are used for operating and monitoring the SoS environment, collection of data for analysis, assessment of the event activities, and so on.</td>
<td>Live, virtual and constructive simulations, command and control equipment, network monitoring tools, test tools, statistical tools, data loggers, etc.</td>
</tr>
<tr>
<td>Capabilities – Functional</td>
<td>Functional capabilities highlight the role that an event participant plays in the overall SoS event. These may be tied at a very high level to operational activities but only in overall role. These functional capabilities are more at the event level.</td>
<td>Technical operation and control, blue ground maneuver, engineering support, communication effects, etc.</td>
</tr>
</tbody>
</table>
## Characteristics of Distributed SoS in T&E (2 of 2)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Explanation</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capabilities – Operational</strong></td>
<td>Operational capabilities directly address the military or operational scenario represented in the event while designating which components of the scenario are represented by which systems.</td>
<td>Air defense, logistics support, blue ground forces, etc.</td>
</tr>
</tbody>
</table>
| **Network Connectivity**       | There are several types of networks supporting SoS events – these include:  
  - Physical networks – the actual networking infrastructure (hardware, routers, etc.) used to link the component systems  
  - Operational communications – this represents the operational network that is used for scenario connectivity.  
  - Support / Coordination communications – this network allows the functional teams to coordinate efforts for the system. | Physical: SIPR/NIPRnet, SDREN/DREN, etc.  
Operational: various tactical networks  
Support: chat, text, VOIP |
| **Interoperability (layers)**  | This addresses the ability of the constituent systems to interact in a valid and meaningful way during an event. There are levels of interoperability from simple exchange of raw data to common interpretation of received information. This consists of a number of interoperability architectures and integrating capability (such as gateways) that address interoperability at the various layers. | DIS, HLA, TENA, CTIA, IP, etc. |
System Dimensions

- Geometrically, we understand 1, 2 or 3 dimensions – maybe 4 or more
- Systems, particularly SoS have many dimensions that define them
- SG defines 3: Operational, Functional, and Technical
Operational Dimension
Functional Dimension

Analysts / Experiment Support

Engineer / Infrastructure Support

Warfighters / Mission Support
Technical Dimension

CAGE II Distributed M&S Architecture

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Canada
Canadian Forces Warfare Centre (CFWC)
3701 Carling Ave, Ottawa (Shirleys Bay), ON
Distributed Mission Operations Centre (DMOC)

Australia
Battle Simulation Centre - Enoggera
Building M14, Chermside Ridge Rd
Gallipoli Barracks, Enoggera QLD 4051

United States
Redstone Test Center (RTC)
Building 4500, Martin Road
Distributed Test Control Center (DTCC)

Exercise Control and Data Tools

Live Radios
C5ISR
Tactical Apps
Systems Geometry

- Adjusting one or more dimensions changes the geometric definition
Systems Geometry is defined as a methodology for exploring emergent system behaviors (planned and unplanned) of multi-dimensional SoS through the capture and analysis of intra- and cross-dimensional characteristics of a targeted SoS.

Purpose of SG:
• Help SoS developers understand and address emergent SoS behaviors
• Support better planning for SoS development
• Assist in proactive mitigation of SoS behaviors that are not intended (risk)
The Problem

• Current system engineering methods fail to address the all the ‘dimensions’ of these complex SoS
  – Particularly the interactions between the dimensions which impact the resulting emergent behavior

• Major issues are uncovered when integrating these SoS – this is much too late in the development cycle

• A methodology is needed to address the emergence of these ‘unintended’ SoS behaviors early in the system development lifecycle to allow for proactive mitigation of these behaviors.
# The SG Methodology

## SG Architecture Framework

<table>
<thead>
<tr>
<th>System Geometry Dimensions</th>
<th>Operational</th>
<th>Functional</th>
<th>Technical</th>
<th>Network</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Social</strong></td>
<td>Organizations and role players participating in a scenario</td>
<td>Organizations and participants supporting component systems - engineering support</td>
<td>Organizations and engineering staff supporting technical execution of event</td>
<td>Relationships between organizations participating from an operational, functional or technical perspective. Collaboration.</td>
</tr>
<tr>
<td><strong>Geographic</strong></td>
<td>Location of functional, technical systems supporting an operational scenario.</td>
<td>Location of technical systems supporting functional activities.</td>
<td>Location of component systems supporting the event. Also location of engineering specific support</td>
<td>Physical networks connecting virtual and physical component systems.</td>
</tr>
<tr>
<td><strong>Business Process</strong></td>
<td>Scenario or mission threads.</td>
<td>Describes how component systems support the operational process. Also includes processes for using the component systems.</td>
<td>Process for conducting the event to include scheduling, system set up, system start up, network connectivity, etc.</td>
<td>Flow of information over the physical network to support operational activities and support activities. Also physical flow of information between sites from both operational and technical view.</td>
</tr>
<tr>
<td><strong>Experiment Design / Data Collection</strong></td>
<td>Experiment design and data collection related to the operational scenario activities.</td>
<td>Experiment design and data collection related to the use of component systems and how data is collected with these systems to support operational data collection.</td>
<td>Experiment design and data collection regarding the use of the physical infrastructure and how data is collected to support functional and operational needs.</td>
<td>Flow of data collected to support event experimentation activities. Includes local / site flows as well as inter-site data flows.</td>
</tr>
</tbody>
</table>
The SG Methodology
SG Process Definition

- Identify Areas for Analysis
- Identify SG Dimensions
- Use an AF to Capture Dimensional Information
- Develop SoS Models and SoS component Models
- Perform Dimensional and Cross Dimensional Analysis

Review Results
### The SG Methodology

#### SG Methods Definition (2 of 2)

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SysML</strong></td>
<td>- Identification of SoS components, attributes and interactions</td>
</tr>
<tr>
<td></td>
<td>- Exploration of operational, functional and technical business processes</td>
</tr>
<tr>
<td></td>
<td>supported by the SoS</td>
</tr>
<tr>
<td><strong>Matrix methods</strong></td>
<td>- Interoperability and system interactions</td>
</tr>
<tr>
<td></td>
<td>- Operational support mapped to specific systems</td>
</tr>
<tr>
<td></td>
<td>- Identification of redundancies of function and systems</td>
</tr>
<tr>
<td></td>
<td>- Implementation to analyze experimentation needs; Objectives mapped to</td>
</tr>
<tr>
<td></td>
<td>Hypothesis mapped to Metrics allowing an exploration of which metrics</td>
</tr>
<tr>
<td></td>
<td>are most important (mentioned on some of the SE for SoS material)</td>
</tr>
<tr>
<td><strong>Network analysis</strong></td>
<td>- Bottlenecks in interfaces or networks</td>
</tr>
<tr>
<td><strong>methods</strong></td>
<td>- Critical systems that interface with many others</td>
</tr>
<tr>
<td></td>
<td>- Analysis of alternative configurations</td>
</tr>
<tr>
<td></td>
<td>- Stakeholder analysis</td>
</tr>
</tbody>
</table>
Case Study: Coalition Attack Guidance Experiment

- Series of experiments exploring coalition coordination
- CAGE I served as the “lessons learned” basis for focusing analysis
- CAGE II was the focus of SG implementation
- Exhibited all the characteristics of SoS and the SG dimensions
CAGE I Issue Areas To Be Considered

• Constituent System (interface) Maturity
  – Coordination throughout planning critical
  – Pre-event testing is vital
  – Configuration management needs to be maintained

• Integration and Interoperability
  – Clear path for integration needed
  – Consistent use of proper standards well in advance of event

• Experimentation Support
  – Better collaboration of experiment and data collection activities with other event areas
### System x System Interaction Matrix

|---|----------|-------------|-------------------|------------------|----------------|------------------|------------------|------------------|----------------|------------------|------------------|----------------|---------------------|---------------------|---------------------|---------------------|---------------------|----------------|----------------|----------------|------------------|------------------|------------------|------------------|----------------|------------------|------------------|------------------|------------------|----------------|----------------|----------------|------------------|------------------|----------------|----------------|----------------|------------------|
System Analysis – Degree Centrality

### Panel A: Ranking for Degree Centrality

<table>
<thead>
<tr>
<th>Rank</th>
<th>Id</th>
<th>Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CA-CFWC-Bender</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>CA-CFWC-RTI-S RTI</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>CA-CFWC-JCATS Server</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>US-RTC-TENA-DIS GW</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>CA-CFWC-TENA-DIS GW</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>AU-TENA-DIS GW</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>CA-CFMWC-RTI-S RTI</td>
<td>6</td>
</tr>
<tr>
<td>8</td>
<td>AU-RTI-S RTI</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>US-OneSAF</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>CA-CFWC-JSAF-DIS GW</td>
<td>4</td>
</tr>
</tbody>
</table>

\[
y = 13.637x^{-1.077} \\
R^2 = 0.8521
\]
Operational vs Functional Analysis:
Importance of Objectives

Identify Most Critical Objective

Operations
Analysis
Technical

Obj 1
Obj 2
Obj 3
Obj 4
Obj 5
Obj 6

Expert Choice
Experimental Design Analysis: Metrics Mapping to Objectives

Significant influence of Metrics 3, 8 and 9

High dependency on many metrics for Objective 4
SG Observations & Potential Issues

- **Observation**: System x System network analysis highlighted systems with high centrality measures, indicating significance of proper operation of those nodes.

- **Potential Issue**: Major SoS execution problems can occur if system nodes with high centrality measures have problems.
  - There is a need to ensure such nodes are well tested and configuration controlled before an event.

Actual Problems in CAGE II

- During the exercise, the routing tables were changed on one of the network routers causing connectivity issues with conference room calls and malfunction in Sim Radios.

- Incompatibility of one of the TENA gateways with one of the OneSAF simulations caused failure of the simulation and required isolating the simulation on a separate network to allow for its continued its participation in the exercise.

- TENA gateway required five updates during the conduct of the experiment, interfering with the timely conduct of experiment activities.
Case Study Review Results: Issues (2 of 2)

SG Observations & Potential Issues

- **Observation**: Network analysis of experimental design (metrics vs obj) highlighted complexity with metrics use and objective evaluation.
- **Potential Issue**: Overly complex experiment design (too many hypotheses with too many metrics) could make it difficult to evaluate achievement of objectives if certain metrics are unavailable.

Actual Problems in CAGE II

- Overlapping hypotheses and metrics where multiple hypotheses had numerous metrics and many metrics were associated with multiple hypotheses led to confusion and also trouble with assigning causality to observed behavior.
Case Study Review Results: Opportunities

SG Observations & Potential Opportunities

• **Observation**: Operational System x Operational System network analysis highlighted systems with high centrality measures, indicating significance of those nodes.

• **Potential Opportunity**: Stable nodes with high centrality measures can contribute to successful execution of the experiment.
  – JADOCS was identified as a highly central C2 node in the network.

Actual Advantages in CAGE II

• JADOCS provided an excellent integration of the tactical air picture from all partners.
• JADOCs operated well across all the objective areas.
Why Should We Care?

• There is great cost associated with the development of complex distributed SoS which grows significantly when issues are not discovered until systems integration.

• Understanding SoS from an emergence standpoint highlights shortcomings of traditional system analysis techniques and opens the door to implementing new approaches.

• New techniques and tools for effective engineering analysis need wider adoption.
  – Engineering education needs to target these tools and techniques to better equip today’s systems engineer.
Future Research – Near term

• Implement SG using DoDAF as the architecture framework, fine tuning the methodology with real system development activity
• Perform a multi-dimensional analysis of the relationship between the operational and technical domains – relating scenarios to system configurations or objectives (training, testing, etc.) to system configurations.
• Investigate the use of options analysis for configuration selection in a T&E technical infrastructure (Purdue)
• Conduct a comparative study of SoS modeling methods to determine what types are most appropriate for different dimensional analyses
• Explore network analysis statistics for values that may characterize particular types of configurations of SoS
• Expand the study of emergence and complexity to explore additional analysis methods
## The SG Methodology

### SG Methods Definition (1 of 2)

<table>
<thead>
<tr>
<th><strong>SoS Issues</strong></th>
<th><strong>Recommended Methods for T&amp;E</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interoperability &amp; Integration</td>
<td>SysML sequence diagrams along with interface attribute information for all three dimensions will provide important insight into the SoS needs for integration and interoperability.</td>
</tr>
<tr>
<td>Constituent System Maturity</td>
<td>Matrix and network methods to show stakeholder relationships with one another and with candidate constituent relationships. Capability analysis (and other SoS configuration alternative techniques) will consider maturity when providing constituent system options to the SoS developer.</td>
</tr>
<tr>
<td>Collaboration</td>
<td>Matrix and network methods showing stakeholder relationships along various collaborative areas to include operational collaboration, functional and technical.</td>
</tr>
<tr>
<td>Training</td>
<td>Matrix methods mapping processes, systems and stakeholders can determine what kind of training is needed and who needs to be trained. Traditional project management methods of planning and tasking can ensure that proper training takes place.</td>
</tr>
<tr>
<td>Resource Assessment / Utilization</td>
<td>Matrix methods help to identify system resources required to support operational and functional activities. Network methods could be used to examine which resources are most critical to the success of the event.</td>
</tr>
<tr>
<td>Analysis &amp; Experimentation Support</td>
<td>SysML use case and sequence diagrams can be used to show the business process for analysis and experimentation activities, ensuring that they are supported. Matrix methods will relate the needed capabilities with specific systems for implementation. Network analysis methods can reveal the importance of certain metrics or hypotheses for performing capability analysis.</td>
</tr>
<tr>
<td>Implementing Architectural Views</td>
<td>Utilize DoDAF which is recommended for use in the DoD T&amp;E environment and can capture the information required for other analysis techniques.</td>
</tr>
</tbody>
</table>
# The SG Methodology

**SG Tools Definition (1 of 2)**

<table>
<thead>
<tr>
<th>SG Process Step</th>
<th>SG Analysis Methods</th>
<th>Tool Features</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify Areas for Analysis</td>
<td>Review lessons learned and capability requirements through stakeholder meetings</td>
<td>Brainstorming tools, office products for documentation, desktop sharing, whiteboard applications, audio and video teleconferencing</td>
<td>MindManager, <a href="#">Text 2 Mindmap</a>, Skype, WebEx, Adobe Connect, Sharepoint</td>
</tr>
<tr>
<td>Identify SG Dimensions</td>
<td>Discussion with stakeholders, review of analysis areas, previous experience</td>
<td>Brainstorming tools, office products for documentation, desktop sharing, whiteboard applications, audio and video teleconferencing</td>
<td>MindManager, <a href="#">Text 2 Mindmap</a>, Skype, WebEx, Adobe Connect, Sharepoint</td>
</tr>
<tr>
<td>Use an Arch Framework to Capture Dimensional Information</td>
<td>Use DoDAF and/or ESM to capture key dimensional information.</td>
<td>Office products for documentation, tools for developing architecture views</td>
<td>Office products (<a href="#">MS Excel</a>, <a href="#">MS Word</a>, Innoslate, Genesys, IBM Rational Tools, MagicDraw, Open System Engineering Environment)</td>
</tr>
</tbody>
</table>
## The SG Methodology
### SG Tools Definition (2 of 2)

<table>
<thead>
<tr>
<th>SG Process Step</th>
<th>SG Analysis Methods</th>
<th>Tool Features</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Develop SoS Models and Functional Models</td>
<td>Use SysML, AB and SD to model SoS and key SoS functional areas</td>
<td>System level models development supporting model-based systems engineering to include UML, SysML, discrete event simulation, system dynamic and agent based models</td>
<td>IBM Rational Tools, MagicDraw, Arena, AnyLogic, NetLogo, Expert Choice</td>
</tr>
<tr>
<td>Perform Dimensional and Cross Dimensional Analysis</td>
<td>Use previous experience and network analysis methods to explore cross dimensional relationships</td>
<td>Functional block diagrams, data flow diagrams, N2 Charts, IDEF Diagrams, UML diagrams, SysML diagrams Tools for generating network graphs and calculating node and network statistics</td>
<td>Office products (MS Excel, MS Word, etc.), Innoslate, Genesys, IBM Rational Tools, MagicDraw, Open System Engineering Environment</td>
</tr>
<tr>
<td>Review Results</td>
<td>Meet with stakeholders to review results and update dimensional information and methods as needed</td>
<td>Brainstorming tools, office products for documentation, desktop sharing, whiteboard applications, audio and video teleconferencing</td>
<td>MindManager, Text 2 Mindmap, Skype, WebEx, Adobe Connect</td>
</tr>
</tbody>
</table>

### Tool Features
- IBM Rational Tools
- MagicDraw
- Arena
- AnyLogic
- NetLogo
- Expert Choice
- MS Excel
- Gephi
- ORA (CASOS tool)
- Statistical tools
- MS Excel, Gephi, ORA (CASOS tool)
- IBM Rational Tools
- MagicDraw
- Office products (MS Excel, MS Word, etc.)
- Innoslate
- Genesys
- IBM Rational Tools
- MagicDraw
- Open System Engineering Environment
- Gephi, Ora, Pajek, NetLogo, NodeXL, UCinet, R
- MindManager, Text 2 Mindmap, Skype, WebEx, Adobe Connect
The Case Study: Coalition Attack Guidance Experiment

- **Operational Independence:** Standalone simulations and operational systems
- **Managerial Independence:** Developed in different countries and by different groups in each country.
- **Geographic Distribution:** US, Canada and Australia locations
- **Emergent Behavior:** Coalition operations only possible using combination of systems.
- **Evolutionary Development:** Evolving constituent participation over time as the SoS event was developed
SG Observations & Potential Issues

- Observation: Analysis of interactions between functional groups highlights dependencies and constraints that can cause decisions by one group to impact other groups.

- Potential Issue: Lack of collaboration between functional groups working on a SoS could lead to systems not integrating in a timely manner because they were selected for use late in the development process.

Actual Problems in CAGE II

- Not enough time or resources were devoted to the integration spirals to properly checkout and debug the entire simulation environment and its interoperability with the C2 systems.

- Significant technical issues were encountered due to lack of attention to critical integration spirals which were used as “dress rehearsals” for the event.

- Collaboration issues led to conflicting goals regarding the overall purpose of the event: training vs testing. The main focus of a training event runs counter to the focus of a testing event. This led to major disagreements between stakeholders.