Structuring T&E for Validation of Complex Systems Capabilities and Exploration of Emergent Behaviors

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Agenda

• SYSTEMS THEORY RELEVANT TO T&E
  – Complex Systems
  – Holism
  – Emergence

• STRUCTURING T&E FOR VALIDATION OF COMPLEX SYSTEMS
  – Complex System V&V
  – Complex System T&E
  – Considerations and Recommendations
    • Mission and Functional Analysis Based Test Planning
    • Risk Prioritized Integrated Testing across the Development Life-Cycle
    • Design of Experiments Based Test Planning and Analysis

• CONCLUSION
Systems Engineering
The way it really is?

How the user described it
How the requirement was understood
How the contractor designed it
How the programmer wrote it
How the PM/sponsor described it

How the project was documented
What was actually installed
How the Government was billed
How the helpdesk supported it
What the user really needed

Original Source Unknown
SYSTEMS THEORY RELEVANT TO T&E

– Complex Systems
– Holism
– Emergence
Complex Systems

- **Holistic**, hierarchal, transient, **emergent**, non-deterministic, large number of elements and states, etc...

- **Detail complexity**—hierarchical relationships dominate; complex in size and scope but straightforward causal relationships; somewhat predictable; risks in contributing parts (Calvano & John, 2004)

- **Dynamic complexity**—lateral interfaces dominate; complex integration and behaviors; unpredictable; system risks dominate; causal relationships difficult if not impossible to determine (Calvano & John, 2004)
Complex Systems Example: Naval Surface Fire Support

- Very Complex System; also possibly a System of Systems
- Dynamic Complexity – many parts, high degree of coupling and interaction across a large number of complex interfaces; integration challenge!
- Diverse, separated, component systems; transient states & deterministic behavior
- Variability and unpredictability of human behaviors and interaction w/ system
- Emergent behaviors from coupling of sensors, weapons, & employment methods
Holism

• “A system has holistic properties possessed by none of its parts. Each of the system parts has properties not possessed by the system as a whole.” Clemson (1984, p. 201)

• Holism emphasizes whole over parts; organizational level analysis ensuring elements function together to serve the purpose of the system. Jackson (2006, p. 650)

• Reductionism serves to help in building up a system design, but a holistic view is needed in order to evaluate complex systems.

Figure from Old Dominion University ENMA 640 and ENMA 715 Course Presentations
Emergence

• A systems principle that whole entities exhibit properties that are meaningful only when attributed to the whole, not its parts – e.g. the pungent smell of ammonia, which comes from the properties of the molecule, not those of the constituent nitrogen and hydrogen atoms. (Hitchens, 2003)

• Generally accepted aspects of emergence (see backup slides for references from literature):
  • Unpredictable / unexpected
  • Derives from integration, interfaces, and interaction of the systems’ elements
  • Not present in the systems’ elements nor can it be predicted by evaluating each of those – although can influence them

Figure from Old Dominion University ENMA 640 and ENMA 715 Course Presentations
Emergence?

Figure from www.despair.com
STRUCTURING T&E FOR VALIDATION OF COMPLEX SYSTEMS

- Complex System V&V
- Complex System T&E
- Considerations and Recommendations
Verification & Validation

• **Verification**: Confirmation by examination and provisions of objective evidence, that specified requirements have been fulfilled. (IEEE Std 1012, 1998, p.71)

  *Did you build what you said you were going to build?*

• **Validation**: Confirmation by examination and provisions of objective evidence that the particular requirements for a specific intended use are fulfilled. (IEEE Std 1012, 1998, p.71)

  *Did you build what the user needed?*

• V&V is a broad set of activities for software or whole systems applied across the life-cycle, supporting a variety of activities from assessing technical alternatives in conceptual design to ensuring the as-built system meets its specifications and the user’s need.
What encompasses a user’s needs?

Figure from DoD Acquisition Guidebook (2006). Washington, DC: OSD AT&L. p. 141.
Test & Evaluation

• Test = procedure to measure performance under various conditions. (Parker, 1994)

• Testing = linchpin, intelligence/feedback loop for systems engineering. (Laskey, 1999, p. 6)

• T&E at its best = goal to provide necessary info to ensure quality. At its worst = political game where programs fight for survival and money. (Laskey, 1999, p. 6)

• T&E ~ experiment & theory; predict outcome, validate points of doubt (Goode & Machol (1957, p. 509)
  – Unfortunately complex systems are often non-deterministic if not completely unpredictable
Focus of T&E

• “How well did the system actually perform, and did it accomplish its mission objective?” –
  – Mission accomplishment not just specs
  – System effectiveness + Support system capability (suitability)

• “Does the system meet all of the requirements as covered through the specified technical performance measures?”
  • Technical verification; developmental testing

• “Does the system meet all [user] requirements?”
  • Verification and validation?
  • Could a system meet the user’s requirements as stated and yet be not operationally effective/not suitable?

Blanchard (2008, p. 113)
### Complex Systems Engineering + V&V / T&E

<table>
<thead>
<tr>
<th>System/Program Milestones</th>
<th>System Management Plan</th>
<th>System Engineering Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional Baseline</td>
<td>System Engineering Management Plan</td>
<td>System Level</td>
</tr>
<tr>
<td>Allocated Baseline</td>
<td>Test and Evaluation Master Plan</td>
<td>Sub-System Level</td>
</tr>
<tr>
<td>Product Baseline</td>
<td>Conceptual Design Review</td>
<td>Component Level</td>
</tr>
<tr>
<td>Updated Product Baseline</td>
<td>System Design Review</td>
<td>Modification for Improvement</td>
</tr>
</tbody>
</table>

#### Need
- **Complex Systems Engineering + V&V / T&E**
- **NEED**
  - Functional Baseline
  - Allocated Baseline
  - Product Baseline
  - Updated Product Baseline

#### System Management Plan
- System Engineering Management Plan
- System Design Review
- Equipment/Software Design Reviews
- Critical Design Reviews

#### System Engineering Requirements
- System Level
- Sub-System Level
- Component Level
- Modification for Improvement

#### Get it right early!
- Importance of Conceptual Design
- Get testers involved (OT/DT/LFT)
- Understand mission environment
- Understand what constitutes operational effectiveness & suitability; what user really needs!
- Test early & often w/ honest assessment of risk to sustained mission capability

![Window of opportunity graph](image)

**Implications for complex system T&E**

- Understand mission environment and ensure testing explores those boundaries
- Evaluation of system/program performed in context of the program & many external and internal influences and drivers
- These also affect capabilities and limitations of T&E itself

Total Platform/System Mission Context

- Multiple, concurrent missions evaluated in complex scenarios

Implications for complex system T&E

- Multiple, concurrent missions evaluated in complex scenarios
Mission Based Testing
T&E Framework Toolset Architecture

• Describe discrete tasks to perform system missions in user’s language
• Define conditions affecting task outcome
• Extract attributes & measures from requirements & other references; correlate to tasks
• Assign test methods & data requirements to measures
• Group tasks w/ conditions & measures into testable/meaningful vignettes
• Repeat vignettes to account for variability due to conditions and settings
• Test vignettes grouped into scenarios run during test events
Integrated Testing

- Planning and development of individual test objectives;
- Coordinated integration of objectives over life-cycle
- Leveraged tests and data but independent evaluation
- Potential cost savings + better risk reduction; may reduce but cannot eliminate IOT&E
- Requires buy-in, strong T&E WIPT, rigorous and early planning and cooperations
Integrated Testing

**DT**
- Test to specifications
- Limited test environment
- Focused on a specific set of criteria.
- Test threshold values not capability
- Critical technical parameters
- Integration testing designed around min performance criteria and interface specs.
- May not address all threats or missions.
- CT adds contractual issues

**OT**
- Operational environment & threat with end users & support
- End-to-end mission perf. & support
- Production representative; system/family of systems
- Test overall capability of an item to meet user’s mission needs and value added for mission accomplishment.
- Test the limitations and capabilities of an item so that:
  - Employ and assess doctrine/TTP
  - Independent IOT&E & LFT&E mandates (Title X)

**THIS MUST TRANSFORM INTO A CONTINUUM OF TESTING**
- Increasing fidelity of technical and operational assessments
- Cooperating organizations
- Reduced budget and timeline?
- Team/IPT structure not competitive
Systems Engineering + T&E within the Acquisition Cycle

MORE THAN TESTING ... CONTINUOUS EVALUATION

RISK MANAGEMENT... MISSION CAPABILITY DELIVERY...

INTEGRATED T&E & SYSTEMS ENGINEERING

Ability to influence system design
System maturity & design/upgrade cost
Design of Experiments
Process Overview

Project description and process decomposition
- Problem statement and objective of experiment (test)
- Response variables, and potential causal variables – Ishikawa fish bone.

Plan test matrix
- Determine constraints, prioritize factors, and select statistical design \(2^K\) vs. \(3^K\) vs. mixed, Taguchi vs. classical arrays, full vs. fractional, non-linear effects?, replications?, blocking?)
- Write the test plan with sample matrices, profiles, and sample output; run sample analysis.

Produce observations
- Random run order & blocked against unknown effects
- Block runs to guard against uncontrollable unknown effects as needed.

Ponder the results
- Analyze and project data; draw conclusions, redesign test as necessary and assess results.
- Perform “salvo testing” (test-analyze-test); screen large # of factors then model
Design of Experiments
Test Matrix Development

• Partial or full matrix of varying settings for the factors (usually 2 or sometimes 3 level)
• Perform larger matrices in increments, eliminating factors that are shown to be non-factors through analysis
• Goal is to determine cause of variability in output based on input factors

<table>
<thead>
<tr>
<th>Run</th>
<th>Setting</th>
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<th>B</th>
<th>C</th>
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<tbody>
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<td>-1</td>
<td>-1</td>
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<tr>
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</tbody>
</table>

Adapted from USAF 53rd T&E Wing DOE Training Materials
Design of Experiments
Data Analysis

- Sample data analysis: produces regression model, predictions, response surface/curves as shown.
- Statistical analysis of the MOEs
- Exploration of mission performance variability across driving conditions

Design of Experiments

Benefits

- Better way to design and test complex systems
- Systematically explores system performance, effectiveness, and suitability – breadth and depth of testing across the performance envelope
- Challenge assumptions and demonstrate real performance across the expected environment
- Better justification for sample sizes; potentially significant reduction from case or one factor at a time testing
- Better linkage between M&S and live test
- DOE works well in Mission Based Testing/Integrated Testing and relies on proper task derivation and attributes and conditions selection
- DOE can improve testing across all programs – it is simply smarter testing!
Conclusion

• Complex Systems
  – Complex Systems – detail vs. dynamic complexity
  – Holism
  – Emergence

• Structuring T&E to Validate Complex Systems
  – Understand program context and system mission context
  – Test early, test often...
  – Mission Based Test Design
  – Integrated Testing
    • CT + DT + OT + LFT + ...
    • Integrated testing and data collection
    • But...Independent evaluation
    • T&E as part of SE life-cycle
    • Design of Experiments

• Questions