SoSECIE Webinar

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NDIA System of Systems SE Committee

Mission

- To provide a forum where government, industry, and academia can share lessons learned, promote best practices, address issues, and advocate systems engineering for Systems of Systems (SoS)
- To identify successful strategies for applying systems engineering principles to systems engineering of SoS

• Operating Practices

 Face to face and virtual SoS Committee meetings are held in conjunction with NDIA SE Division meetings that occur in February, April, June, and August

NDIA SE Division SoS Committee Industry Chairs:

Mr. Rick Poel, Boeing Ms. Jennie Horne, Raytheon

OSD Liaison:

Dr. Judith Dahmann, MITRE

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- If a question requires more discussion, the speaker(s) contact info is in the brief.

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2020-2021 System of Systems Engineering Collaborators Information Exchange Webinars Sponsored by MITRE and NDIA SE Division

June 2, 2020 SERC: Methods to Evaluate Cost/Technical Risk and Opportunity Thomas McDermott and Cody Fleming

> May 19, 2020 Digital Engineering Toolchain Dr. Aleksandra Markina-Khusid

July 28, 2020 Addressing Mission Engineering from a Lead Systems Integration Perspective Dr. Warren Vaneman

More coming soon!

New Digital Engineering Enabled Systems and Mission Engineering Performance Measures

Dr. Ed Kraft

Systems of Systems Engineering Collaborators Information Exchange Webinar May 5, 2020

Edmkraft, Inc

Introduction

- Traditional Systems Engineering measures (TRL, IRL, SRL, MRL) are adequate for prescribing systems engineering stages, configuration management, and interface control documentation but do not provide essential knowledge to support quantified Risk Informed Decision Analytics (RIDA).
- Any technology or design feature introduced into a component, subsystem, system, or system of systems should have *measurable technical performance* which impacts the Value of the system.
- Digital Engineering enabled development, calibration, and use of model-based engineering and authoritative truth sources provides a formal, structured approach to quantifying and tracing maturation of technical performance measures (TPMs) and their impact on support to RIDA and Value creation.

The Revolutionary Idea Separating the Future from the Past is the Collaborative use of Knowledge to Master Risk at the Speed of Relevance

DoD Digital Engineering Strategic Guidance (June 2018)

- 1. Formalize the development, integration, and use of models to inform enterprise and program decision making
- 2. Provide an *enduring, authoritative source of* truth
- 3. Incorporate technological innovation to *improve the engineering practice*
- 4. Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders
- 5. Transform the culture and work



DoD defines Digital Engineering as an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal

Authoritative Decisioning The Focal Point for Digital Engineering

- Authoritative Decisioning is the quantifiable use of knowledge, research, and analysis to support decisions — from big strategic choices to thousands of operational micro-choices.
- Digital Engineering enables Authoritative Decisioning by providing digital continuous intelligence in which real-time analytics are integrated within enterprise functional operations, processing current and historical data to prescribe actions in response to events.
- Digital Engineering accelerates the use of knowledge through analytics to produce value.
- Authoritative Decisioning is the organizing focal point for a Digital Engineering Ecosystem – all tools, processes, and practices need to lead to value-added, risk-informed decisions at the speed of relevance

"... if analytics does not lead to more informed decisions and more effective actions, then why do it at all?" — Mike Gualtieri, Forrester

Digital Engineering Enabled Authoritative Decisioning OV-1



Value Mapping in a Digital Engineering Environment The Centerpiece of Lifecycle Decision Analytics

Value Objective = Mission Utility • Robustness / Total Ownership Cost

- <u>Mission (or Military) Utility</u> set of required technical attributes of the system that provides a distinct advantage over competitors in the marketplace
- <u>Robustness</u> normalized measures of how well the system performs over time (Reliability, Availability, Maintainability), in unanticipated circumstances, and in alternate uses (Resiliency)
- <u>Total Ownership Costs</u> lifecycle cost of development, production, fielding, operations, sustainment, and demilitarization

Purpose of the Value Objective

- Provides the "North Star" for all decision analytics at any phase and any level (e.g., component to system-of-systems)
- Key elements are measurable and can be dynamically coupled to time varying Requirements and Stakeholder Expectations
- Enables quantification of risks and decision impacts on delivering the Value Objective at every phase
- Digital Engineering enables forward projection of optimum sequential development of Value vs localized value decisions

A Value Objective is Essential for Guiding Desired Quantified Knowledge at Critical Decision Points Using Digital Engineering

Mastering Risk

- Mastering risk using digital engineering principles may be the single most important aspect that separates the future of systems engineering from the past
- Using statistical methods to determine probabilities of the state of a system is a quantification of incomplete information or uncertainty at a time instant
- A current measure of uncertainty should not be conceived in terms of disorder, but rather as a measure of the probability distribution that characterizes the amount of missing information
- Employing authoritative digital surrogate models with uncertainty quantification methods can project the best means to obtain the missing information to achieve an acceptable level of uncertainty and maximize Value – the mastery of risk



"The revolutionary idea that defines the boundary between modern times and the past is the mastery of risk: the notion that the future is more than a whim of the gods and that men and women are not passive before nature."

Peter Bernstein, "Against the Gods: The remarkable story of risk"

Discovery of defects or insufficient performance that negatively impact a program late in the lifecycle is not bad luck – it is a failure to properly quantify and master the³risks associated with each decision along the way

Strategy 1 – Use of Models to Support Decisions Developing an Authoritative Digital Surrogate Reduced Order Model



Adaptive DOE, Added Training Data

Edward M. Kraft, "Development and Application of a Digital Thread / Digital Twin Aerodynamic Performance Authoritative Truth Source," AIAA-2018-4003. Aviation Systems Conference, Atlanta, GA, June 25-29, 2018

Strategy 2 - The Essence of Digital Engineering Enduring, Authoritative Truth Sources and Digital Surrogates

- Shifts primary means of communication from documents to digital models and data
- Provides the technical elements for creating, updating, retrieving, and integrating models and data
- Enables access, management, analysis, use, and distribution of information from a common set of models and data
- Provides authorized stakeholders current, authoritative, and consistent information for use over the lifecycle
- Essential for making decisions under risk across the lifecycle

Measures of the Maturity and *Credibility* of Authoritative Truth Sources Will Enable a More Knowledge-Based Informative Understanding of the Risks of Achieving the Value Objective

Risk Informed Decision Analytics (RIDA)

- Every useful question one can ask at a critical decision point is one in which there is a of lack information to some degree
- When faced with a lack of information, the only thing one can do is to reason by induction
- Essential to RIDA is the *credible* quantification of margins and uncertainties (QMU) at critical decision points
- The QMU provides the prior probability as the basis for a Bayesian inference process to select the next best course of action to master risk

Quantified Margins and Uncertainty (QMU) Key to Mastering Risks

QMU is a technical framework for producing, combining, and communicating information about performance margins of complex systems to support risk-informed decision making

QMU Requires:

- **Performance Threshold** –a specification of a necessary performance achievement, typically in quantitative form.
- **Performance Margin** difference between the required performance of a system and the demonstrated performance of a system
- Uncertainty begins with the requirements that provide a foundation for the definition of performance thresholds, accumulates and transforms as the various science and engineering activities that lead from design to qualification to evaluation are executed.
- Credibility requires a consistent, disciplined approach to the validation and calibration of models used to develop the probability and cumulative distribution functions



QMU, System Robustness / Reliability, and Decision Analytics



Prescriptive Analytics - Risk Informed Decision Analytics to Master Risk



Ρ

TPM, QOI

Sensitivity Analysis MC or Sobol Methods to determine which input parameters influence the mean and variance the most For a TPM/QOI related variable *Y* with a probability density function *p(y), Shannon's* information entropy is

 $H(Y) = -\sum_{i} p(y_i) \log p(y_i)$

which is the average amount of information contained in P the random variable Y, it is also the uncertainty removed after the actual outcome of Y is revealed

Digital Surrogate Model Projection of QMU'



TPM, QOI

Entropy Based Inference •Kullback-Lieber Divergence or relative entropy •Bayesian Inference •Maximum Entropy



<u>Resource Allocation</u>
Budget / Schedule Constraints
Stakeholder Preference
Impact on Value Objective

Directly relates current measures of uncertainty to determining an activity that produces a new probable state that will move the system closer to meeting the Value Objective

Digital Thread – Connected Available Knowledge for Decisions

Digital Thread at Any Time Increment, t

 $D_t \in I_t \subseteq P_t \times T_t \times \mathcal{D}_t$

Optimization is performed on a Value Objective statement – not just current knowledge but potential future information

Design information

• Geometries, Materials, Design, Manufacturing, Testing and Operating Specifications; 3-D CAD, eBOM, Critical Drawings; Digital Surrogate Models

Tools, methods, and processes

• Information and protocols of methods, tools, processes, and algorithms

Statistics of uncertain inputs

• Probability space associated with uncertain variables; sources of epistemic and aleatory uncertainties: QMU

Source of available information

• Curated assembly of all agreed upon single sources of information - the Authoritative Truth Sources

Strategy 3 - Rethinking Systems Engineering Maturity/Readiness Levels



Digital Surrogate Model Readiness Level (DSMRL) for Performance Models

- •Introduce a readiness level associated with the very essence of Digital Engineering – the Authoritative Truth Source
- •A Digital Surrogate Model Truth Source enables Quantification of Margins and Uncertainties (QMU) of performance at the component, assembly, subsystem, system, and mission level
- •Applications of calibrated Digital Surrogate Performance Models will enable a quantification of performance levels and provide knowledge for decision analytics to determine the best course of action to meet Stakeholder expectations

DSMRL Provides a Consistent, Disciplined Approach to Assuring the Credibility of Surrogate Models Used for QMU Analyses

h	DSMRL	Maturity of MBE Derived Digital Surrogate Performance Models
	1	Un-validated, deterministic models of basic physical principles, no geometry details
	2	Validated models using generic legacy data for class of problems, notional geometries; material / component level reduced order models (RSM)
,	3	Low-fidelity, model-generated, calibrated RSM digital surrogates using set-based inputs, parametric sensitivity studies, design for variations; initial UQ sensitivity analysis; initial program model-based performance truth source curation
e	4	Recalibrated RSM using high-fidelity models and/or laboratory data for system of interest parameters; closer to final component, subsystem geometry; identification of epistemic- (EU) and aleatory- (AU) uncertainties
0	5	Recalibrated RSM using empirical data generated from component / breadboard tests in a relevant environment; EU/AU uncertainties propagated
	6	Recalibrated RSM using developmental test data from system/subsystem prototype or in a relevant environment; as-prototyped geometry; EU/AU accounted for
	7	Recalibrated RSM using data from operational testing; as-built, as-flown geometry; comprehensive set of managed RSM models from material/component to system
	8	Recalibrated RSM using data from operations; as-built, as-operated geometry; lifecycle curation of comprehensive digital surrogates in a PLM system
	9	Recalibrated RSM using data from a digital twin and artificial intelligence gathered from an as-built, as-operated, as-optimized system

Develop, Integrate, and Calibrate an Enduring Digital Surrogate Truth Source

B Digital Surrogate Model Readiness Level (DSMRL)



Edward M. Kraft, "Development and Application of a Digital Thread / Digital Twin Aerodynamic Performance Authoritative Truth Source," AIAA-2018-4003. Aviation Systems Conference, Atlanta, GA, June 25-29, 2018

QMU Maturity Levels



*William L. Oberkampf, Martin Pilch, and Timothy G. Trucano "Predictive Capability Maturity Model for Computational Modeling and Simulation" Sandia Report SAND 2007-5948, October 2007

Determining and Mitigating Risk Over the Lifecycle



TPM, a Technology Performance Index (TPI), and a Technology Performance Risk Index (TPRI)

- At each stage in the technology maturation process should be able to provide a quantified assessment of the impact of a technology on specific TPM measures, the uncertainty in the technology performance, and the related influence on System and Mission performance – will the technology provide the required impact on Mission Utility?
- A Technology Performance Index (TPI) for each Technology is the measure of the achieved performance of a Technology or design feature at time *i* as the percentage of the threshold TPM for component *j* relative to its measured performance, *m_{jj}*, or

$$TPI_{ij} = \min\left\{\frac{m_{ij}}{TPM \ threshold}, 1\right\}$$

 A Technology Performance Risk Index (TPRI) * to link technical performance risk measures to the readiness of a technology to be transitioned into a system can be defined as

$$TPRI = 1 - \frac{TPI}{1 + (1 - TPI) * DD}$$

and *DD* is the Degree of Difficulty

^{*}Sherica S. Holloman, Steven M. Stuban, and Jason Dever "Validating the Use of Performance Risk Indices for System-Level Risk and Maturity Assessment" Engineering Management Journal, Vol 28, No. 2, 2016.

Degree of Difficulty – an Additional Risk Assessment

- Enables an assessment of the challenges to maturing a technology to desirable levels at pending critical decision points
- The challenges include technical and non-technical factors that at a minimum could impact the cost and schedule of the program to achieve the required technology maturity or even include the possibility the technology required for full system implementation cannot be achieved
- Some non-technology factors could include changing budgets, non-availability of material or critical development facilities, skill capacity, and the difficulty in obtaining appropriate certifications
- Shannon's Entropy could provide a more quantitative measure of Degree of Difficulty

Degree of Difficulty*

0	No Risk
0.1	Very Low Risk
0.3	Moderate
0.5	High
0.7	Very High
0.9	Extremely High Risk
1.0	Guaranteed Failure

^{*}Sherica S. Holloman, Steven M. Stuban, and Jason Dever "Validating the Use of Performance Risk Indices for System-Level Risk and Maturity Assessment" Engineering Management Journal, Vol 28, No. 2, 2016.

Quantifying and Managing Key Measures at Critical Decision Points



Digital Engineering Enabled Transformation of T&E

DoD Digital Engineering Strategy

Formalize the development, integration, and use of models to inform enterprise and program decision making

Provide an enduring, authoritative source of truth

Incorporate technological innovation to improve the engineering practice

Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders

Transform the culture and work

T&E Transformations

Transform T&E from a data source for validating a code to a knowledge source for developing and calibrating an authoritative digital surrogate model

2. Use T&E calibrated surrogates to provide credible Quantified Margins and Uncertainties (QMU) to support Risk Informed Decision Analytics

3. Define the value of T&E in terms of quantified and managed progression of TPMs to meet requirements

4. Use Bayesian inference to determine best course of testing to master risk and optimize value

 5. Transform from linear, calendar- and documentdriven processes to dynamic, model-based, processes
 including a Digital Test & Evaluation Master Plan (TEMP) and "Digital Critical Decisions"

Purpose of T&E (DoDD 5000.1 E1.11)

Integrate with M&S to facilitate learning, assess technology maturity and interoperability, facilitate integration into fielded forces

Provide essential information to decision makers

Assess attainment of technical performance parameters (TPMs)

Confirm performance against documented capability needs and adversary capabilities

Determine whether systems are operationally effective and suitable, survivable, and safe for intended use

The key to transforming T&E through Digital Engineering is to think *DIGITALLY*, not digitized

Digital Thread Enabled Multi-Phase Decision Analytics



Adapted from: Singh, Victor and Willcox, Karen E. "Engineering Design with Digital Thread," 2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 8–12 January 2018, Kissimmee, Florida.

Connecting Digital Engineering to Mission Engineering Enhanced Mission Means Framework (MMF) Metrics



Summary

•A systematic translation of the Digital Engineering into value added processes is outlined requiring

- Well defined Value Objective to frame decision analytics
- Early and persistent integrated analyses of a system using calibrated authoritative digital surrogates
- Designing / executing tests to validate calibrated authoritative truth sources
- Optimizing SE processes and T&E campaigns to identify and mitigate uncertainty in Technical Performance Measures and Quantities of Interest
- Comprehensive Uncertainty Quantification is essential to the paradigm shift
- A culture transformation of this scale will require a shift in perspective requiring Education and Training to incorporate the Digital Engineering principles

SE, MBE and T&E with UQ Provides Value through Digital Engineering by Providing Knowledge to Master Risk at the Speed of Relevance 32

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Questions?



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