Transforming Systems Engineering to Take Advantage of the Digital Revolution

The Next Big Thing

1. Industrial Revolution
   Introduction of mechanical production plants using water and steam technology

2. Industrial Revolution
   Introduction of mass production based on division of labor using electrical power

3. Industrial Revolution
   Introduction of electronics and IT to increase the level of automation

4. Industrial Revolution
   Introduction of the cyber-physics world - Intelligent automation and integration of physical & virtual worlds

Digital Engineering

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Two key findings from GAO reports (06-66, 06-391, 06-110):

- Contractors not held accountable for achieving desired outcomes, including cost goals, schedule goals, and desired capabilities.
- Programs do not capture, early on, requisite knowledge needed to effectively manage program risks.

Not incompetence or malfeasance but a systemic problem.
DoD Digital Engineering Strategic Guidance (June 2018)

- 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

Authoritative Truth Sources – the Key to Shifting from a Design-Build-Test-Fix Paradigm to an Integrate-Analyze-Design-Build-Test-Operate-Learn Systems Engineering Paradigm
Authoritative Truth Sources

Develop, integrate, and curate models to digitally represent the system of interest over its lifecycle

- **Authoritative** connotes a governance process to assure the pedigree and provenance of the truth source and related models and data over the lifecycle
- **Truth** connotes a validated, verified source with quantified margins and uncertainties, particularly for epistemic uncertainties
- **Digital** connotes a calibrated emulator that can be used across all engineering functional domains

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Digital Surrogate Modeling Commons

Requires a Structured, Disciplined Integration of Model-Based Engineering, Testing, and Uncertainty Quantification
Using Truth Models to Support Engineering Activities and Decision Making Across the Lifecycle

**Risk – Uncertainty with Consequences**

**Prescriptive Analytics:**
- Used to understand what should be done or to recommend the best course of action for any pre-specified outcome
- Risk = \{Scenario, Probability, Consequence\}

**Predictive Analytics:**
- Probabilistic analysis of system state, used to forecast what might happen or could be accomplished – quantified margins and uncertainties

**Descriptive Analytics:**
- Application of Model Based Engineering analysis tools to transform technical data into system state technical information – the authoritative digital surrogate “truth source”.

**UQ – The Connective Tissue Between Analysis and Decisions - The Disruptive Transformation**
Develop, Integrate, and Calibrate an *Enduring* Digital Surrogate Truth Source

**Sources of Record**
- CAD Geometry File
- Operating Conditions Library
- Test Data
- Validated Models
- Reports

**High Fidelity Model**
- Enhanced Numerical Solutions
- Select Calibration / Training Points
- Minimize the Number of High Fidelity Modeling Computations
- Optimum Experimental DOE
- Calibrated Emulator

**Lower Fidelity Model**
- Design Variables
- DOE Latin Hypercube
- Space Filling Analysis
- Model Calibration
- Adaptive DOE
- Intermediate Emulator

**Testing and Operations**
- Select Calibration / Training Points
- Minimize the Number of Experiments / Tests
- Testing and Operations
- Enhanced Numerical Solutions
- Parametric Sensitivity Studies

**Parametric Sensitivity Studies**
- Engineering Design & Analysis
- Sensitivity / Trade Studies
- Design for Variation Reduction

**Mixed-Input Gaussian Process**
- $y(x_i, z_i) = m(x_i, z_i) + \varepsilon(x_i, z_i)$
- Calibration Points
- Posterior Mean
- 95% Confidence Level

**Updated with Additional Test and Operational Data Over the System Lifecycle**

**Calibrated Digital Surrogate Emulator**
- Enables Addition of Continuous or Discrete Heterogeneous Data

**SysML System Requirements**
- Pedigree, Provenance of All Records
Paradigm Shift in the Role of T&E in Model Validation and Integration Into the Authoritative Truth Source Emulator

Rethinking Model Validation and Data Uncertainty

- Comparisons with experimental data is insufficient to determine the validity of a model
- Both the model and the experiment contain epistemic and aleatory uncertainties
- Model still in its original format which is not conducive to statistical analysis for decision analytics
- A model can never be completely validated, it can only be invalidated by contrary experimental evidence – to determine if it is invalid for a particular application requires the modeler to quantify margins and uncertainties compared to quantities of interest
- An iterative Bayesian approach to assimilation of the experimental data with model data to form an authoritative digital surrogate is required

Figure 2. F-16C CFD (KeStrel and Cobalt, full-scale) with LEF = 0 degrees vs. LM Performance Data with LEF = 0 degrees for $C_L$, $C_D$ and $C_m$, Mach 0.9.

Truth Source
A single source of fully merged model and empirical data sets with quantified margins and uncertainties available to all stakeholders

Shifts the value of T&E to the production of knowledge required to provide the validated authoritative truth source to manage uncertainty
Typical DoD RDT&E Profile for an Air Vehicle

- **Lack of Design Closure at CDR**
- **Peak Burn Rate Occurs Around FF**
- **Standing Army Effect**
- **Ground Test Campaign** ~48 mos
- **Flight Test Campaign** ~24 mos
- **Nominally 14 Years**
- **First Flight**
- **Ground + Flight Test Campaigns Overlaps ~ 85% Cycle Time**
- **OT&E Pause Test Rate**
- **Non-Suitability**
- **Fewer Systems Delivered**
- **Higher PAUC**

**Are the Problems Created Out Here…**

- **RDT&E Overrun**
- **Nunn-McCurdy Breach**

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- **Late Delivery 1st Flight Vehicle**
- **Late Defect Discoveries**
- **OT&E Pause Test Rate**
- **Fewer Systems Delivered**

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- **MS B IOC**
- **First Flight CDR**

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- **Standing Army Effect ~48 mos to ~96 mos**
- **Nominally 14 Years**

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- **Are the Problems Created Out Here…**
- **Lack of Design Closure at CDR**
- **Peak Burn Rate Occurs Around FF**
- **Standing Army Effect**
- **Ground Test Campaign** ~48 mos
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Systemic Problem
Organization, tools, processes, and resourcing not conducive to creating requisite knowledge

Critical Factors Impacting Acquisition Occur Back Here

Decision Framework for Defense Systems

Can We Deploy Digital Engineering Practices to Quantify Better Decisions Earlier?

15% Critical Drawings released
TRL ≥ 4 for key technologies
MRL ≥ 4 new mfg technologies
IRL ≥ 4 to assure system integrability
SRL at 40% or better

• 80% Critical Drawings Released
• TRL ≥ 6 for key technologies
• MRL ≥ 6 new mfg technologies
• IRL ≥ 7 to assure system integrability
• SRL at 80% or better

Requisite Knowledge

Most Significant Cost/Capability Trade Opportunities
Operations & Sustainment Reviews
Post IOC Reviews
FRP
Need
80% Confidence System Meets Requirements
Selection of Preferred Concept
Draft CDD
A
B
C

System Requirements Defined in RFP for MS B Contract
CDR
RFP
Release decision
PDR
AoA
Study Plan
AoA Validation
ICD Validation
CDD Validation
CDR
CPD Validation
FF
IOT&E
DT&E
LRIP
IOC
FOC
FRP
FRP
Draft CDD
Selection of Preferred Concept

Expenditure Profile
Lifecycle Cost Committed
DMIL Decision

• 80% Critical Drawings Released
Definitions of Readiness Levels*

- **Technology Readiness Level (TRL)**
  - Maturity of a particular technology – cannot be higher than the TRL level for the least mature component

- **Manufacturing Readiness Level (MRL)**
  - Current level of manufacturing maturity, identifies maturity shortfalls and associated risks

- **Integration Readiness Level (IRL)**
  - Integration readiness of any two TRL-assessed technologies

- **System Readiness Level (SRL)**
  - Normalized matrix of pair-wise comparisons of TRLs and IRLs of a system

\[
[SRL]_{nx1} = [IRL]_{nxn} \times [TRL]_{nx1}
\]

Joseph A. Fernandez “Contextual Role of TRLs and MRLs in Technology Management” SANDIA REPORT SAND2010-7595, November 2010
**Systems Engineering Paradigm Shift**

**NASA Systems Engineering Process**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Purpose</th>
<th>Typical Outcomes</th>
</tr>
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<tbody>
<tr>
<td>Pre-Phase A</td>
<td>Concept Studies</td>
<td>To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs and scope.</td>
</tr>
<tr>
<td>Phase A</td>
<td>Concept and Technology Development</td>
<td>To determine the feasibility and desirability of a suggested new system and establish an initial baseline capability with NASA's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.</td>
</tr>
<tr>
<td>Phase B</td>
<td>Design and Technology Completion</td>
<td>To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure and product (and enabling product) requirements and generate a preliminary design for each system structure and product.</td>
</tr>
<tr>
<td>Phase C</td>
<td>Final Design and Fabrication</td>
<td>To complete the detailed design of the system (and its associated subsystems, including its operations system), fabricate hardware, and code software. Generate final designs for each system structure and product.</td>
</tr>
<tr>
<td>Phase D</td>
<td>System Assembly, Integration and Test, Launch</td>
<td>To assemble and integrate the system (hardware, software, and human) and, meanwhile developing confidence that it is able to meet the system requirements. Launch and operate for operations. Perform system and product implementation, assembly, integration and test, and transition to use.</td>
</tr>
<tr>
<td>Phase E</td>
<td>Operations and Sustainment</td>
<td>To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.</td>
</tr>
<tr>
<td>Phase F</td>
<td>Closeout</td>
<td>To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.</td>
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**Digital Engineering Paradigm**

**Integrate** – develop and apply digital surrogate truth source models at the component, subsystem, system level; validate surrogate models with higher fidelity models and empirical data; deploy subsystem surrogate models in an MDO analysis; perform trade and cost studies at the integrated system level.

**Analyze** – define subsystem and system level sensitivity to design variables; address uncertainty propagation across subsystems and impact on total system performance and costs; perform a probabilistic analysis to quantify margins and uncertainties on system meeting performance reqts.

**Design** – deploy design for variance reduction strategy for most sensitive design variables using updated digital surrogates; use mfg and sustainment digital surrogate models to design for manufacturing and sustainment.

**Build** – use surrogate truth source models to account for variations in mfg and assembly tolerances, precursor to the development of a digital twin.

**Test** – optimize tests to provide required knowledge to validate digital surrogate truth sources; use test to monitor and mitigate uncertainties in key technical performance parameters as a measure of progress toward requirements.

**Operate** – deploy a digital twin to monitor health, gain more knowledge about system performance, project optimum sustainment, and/or provide a reference model for adaptive control.

**Learn** – Accumulate knowledge and implement into digital surrogate models to improve the next system’s performance.

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Not in lieu of current SE processes but as an enhancement.
Quantifying and Managing Key Measures at Critical Decision Points

**Measures**
- Mission Needs or Critical Operating Issues
- Measures of Effectiveness (MOEs)
- Key Performance Measures (KPPs)
- Measures of Performance (MOPs)
- Technical Performance Measures (TPMs)

**Value Objective**
- Successful Achievement of Mission Objectives
- Measures of Effectiveness (MOEs)
- Key Performance Measures (KPPs)
- Measures of Performance (MOPs)
- Technical Performance Measures (TPMs)

**Value**
- Mission Utility
- Availability
- Affordability

**Mission Modeling**
- System Level Operational Performance
- IRL
- MRL
- SRL

**Reliability Modeling**
- TPM Measure of Progress Toward Meeting Requirements
- TPRI = f (% TPM Target Achieved, Degree of Difficulty)

**Manufacturing Modeling**
- Range
- Interactions with Surrogate Emulators to Balance Performance with Design Parameters that Drive Reliability and Affordability

**Calibrated TPM Surrogate Emulators**
- Range
- Interactions with Surrogate Emulators to Balance Performance with Design Parameters that Drive Reliability and Affordability

**TPM Measure of Progress Toward Meeting Requirements**
- Detailed Performance Measures
- TRL
- TPR

**Epistemic and Aleatory Uncertainties**
- Aero
- Propulsion
- Weight

**TPRI**
- Combined TPM Risk Index
- 90% Confidence Level

**CDF**
- Event
- Threshold
Decision Analytics – Moving to **Digital** Critical Decision Points

**Do**
- Quantify risks in achieving Mission Objectives
- Apply Bayesian Belief Network to evaluate potential scenarios to quantify probabilities of outcome and consequences
- Identify the Best Value option

**Think**
- Perform a probabilistic analysis to quantify margins and uncertainties for vital performance measures
- Assess the impact of margins and uncertainties on achieving military utility and affordability
- Assess the state of the system comparing calibrated Truth Source Models with required TPMs /QOIs

**See**
- Quantify TRL, MRL, IRL, SRL
- Optimize next steps to reduce uncertainties through additional modeling, testing, or identify necessity to redesign

All Stakeholders have a continuous digital view of progress toward meeting requirements, potential impacts on the program; *can iterate emulator sensitivities to assess “what if” for different outcomes*

Near real-time discovery of notable states or state changes allowing program actions before a staged critical decision event can take place.
Summary

The Digital Engineering strategy will enable a significant paradigm shift in Systems Engineering and T&E toward

• Early integrated analysis of a system using authoritative digital surrogates – better knowledge earlier
• Methodology for designing / executing tests to develop, calibrate, and curate the authoritative truth source emulators
• Adopting uncertainty quantification and risk mitigation for key Technical Performance Measures as the value proposition for T&E
• Enabling better informed Digital Critical Decisions by quantifying system performance, risk, and analyzing best courses of action

SE, MBE and T&E with UQ Provides Value to Digital Engineering as a Source of Knowledge for Risk Identification and Management