Engineering for Resilience
January 6, 2016

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A Resilient System

- Reliable and effective in a wide range of contexts
- Adaptable to many others through reconfiguration or replacement
- Predictable degradation of function

**C-130 Hercules**
Main tactical airlifter for many military forces worldwide

**B-52 Bomber**
Pre-eminent American Heavy bomber for the last 54 years

**AC-130A**
Drone Control

**EC-130E**
Airborne battlefield command and control & electronic warfare

**HC-130H**
Maritime and Ice Patrol

**JC-130**
Mid-air Retrieval

**Boeing B-52B**
1st USAF Version, Recon pod

**B-52 D**
Big Belly mod 500 LB bombs

**B-52 G**
Major redesign, Advanced Avionics to aft

**B-52 F**
Larger capacity engine

**B-52H**
Display with weapons Barksdale AFB 2006

**B-52 H**
Carrying 2 D21 drones

Images, text from public domain.
21st Century: Shifting Engineering Processes

The changing characteristics of a “system” require a new vision for the future of engineering, design and manufacturing.

20th Century Systems Engineering

- Custom hierarchy
- Stand-alone, stove-piped
- Physical components
- Physical flows and interfaces
- Hardware control
- Human control

21st Century Systems Engineering

- Open architectures
- Collaborative environments
- HPC & physics-based resources
- Digital data & engineering
- Deep Analytics and Trades
- Automatic processes

Requirements / Architecture

Moving from custom build to Composability and Integration

D. Long, INCOSE President
Analysis Drives Design, Engineering, and Decisions

**Requirements Drive Design**

Previous 10-15 years
*Fixed, focused, governed*

- Highly specialized platforms
- Fixed capabilities
- Costly
- Focused mission portfolio
- Long development time

Point Solutions for Asymmetric Warfare

**Data & Analyses Drive Design**

Now.....The Future
*Modular, adaptable, autonomous*

- Flexible platforms
- Adaptable to capabilities
- Affordable
- Resilient to new threats
- Short development time

Composable, Agile Solutions for Multiple Missions and Threats
ERS Goal: Quantify and Buy Down Acquisition Risk

Problems

- Increasing Costs
- Rate of change and uncertainty
- Rapid, emergent threat
- Requirements creep
- Adaptability deficiency
- Life extension demand
- Technology disruptors
- Workforce decline/expertise

New Technology Approach

Empower rigorous risk analysis

- Requirements Generation
- Analysis of Alternatives
- Lifecycle Intelligence
- Virtual Prototyping

Mitigate Issue:
28% Life Cycle Cost vs. 72% Life Cycle Cost

GROWING COMPLEXITY

BUDGET CONSTRAINTS
Problem – the last 50 years:
Design Engineering - A Linear, Process-heavy Environment

- Fixed 75% Lifecycle Costs
- Material Solution

- Evolving Threat
- Technology Disruption

- Unstable Performance
- Cost & Schedule Overrun

- Limited Effectiveness

Operational Overview:

- Linear acquisition process
- Lacks adaptability to changes
- Stove-piped workforce and data sources
- Information shared via static documents
- Limited Reuse

User Needs:
- Technology Changes
- Materiel Changes
- Design Changes
- Requirements Changes
- Other Changes

Negatively impacts:
- Response time
- Time & delivery
- Budget
- …etc.

Distribution Statement A – Approved for public release by DOPSR. Distribution is unlimited.
ERS Leverages 50 Years of S&T Investments

ERS LEVERAGES YEARS OF MAJOR DOD S&T INVESTMENTS

- ADVANCED MODELING
- CONTEXT SIMULATION
- HIGH PERFORMANCE COMPUTING
- MATHEMATICAL OPTIMIZATION
- OPEN & TRUSTED SYSTEMS

ERS INTEGRATED CAPABILITY

- OPEN ARCHITECTURE IMPLEMENTATION
- LIFECYCLE INTELLIGENCE & MODELING
- DATA ACCESS & RETENTION
- KNOWLEDGE MANAGEMENT
- SECURITY

- MODELS
- MULTI-DIMENSIONAL TRADESPACE ANALYTICS
- HIGH PERFORMANCE COMPUTING
- BIG DATA ANALYTICS & VISUALIZATION
- IP PROTECTION

ERS is the first integration of modern computational engineering tools and technologies that directly impact DoD Acquisition environments.
Components of a New Design Environment

**Tradespace Tools & Analytics**
- Decision Support
- Big Data Analytics & Visualization
- Open Architecture
- Knowledge Management
- Data Retention
- HPCMP & S&T Resources

**Integrated Capability and Workflow**
- ERS Cloud
  - 10,000X Productivity Improvement In AoA
- ERS Env
- Tradespace Tools & Analytics
- Analytics
- Rapid Prototyping & Evaluation
- Virtual Warfighting, Reduce Prototyping Time & Costs

**Requirements Generation**
- Fully Explore & Identify KPPs
- MOV ENGINEERING LEFT

**Analysis of Alternatives**
- Reduces alternatives from thousands to tens or less
- Design Req
- Analytic Tools
- Feedback
- Adv M&S

**Virtual Prototyping & Evaluation**
- Rapidly Distill Many More Alternatives

**Policy / Regulation**
- ARCHITECTURE TRADE ANALYSIS
- ADVANCED MODELING
- ENV REPRESENTATION
- MISSION CONTEXT
- other

**ERS Cloud**

**Integrated Capability and Workflow**

**HPCMP & S&T Resources**
ERS Layered Architecture

- Reduction to manageable pieces
- Isolates complexity
- Organizes development
- Abstracts details
- Promotes reusability
- Clear frame of reference
ERS Powerful Tradespace Approach

ERS Tradespace Concept

- Architecture
- Tradespace Analytics
- Advanced Modeling
- Environmental Rep.
- Mission Context

ERS CLOUD COMPUTING ENVIRONMENT (CCE)

10,000x Improvement in productivity in Analysis of Alternatives

Efficiently discover key performance parameters (KPPs)

Currently Applied ERS Advanced Tradespace Analytics

- **TRADE lite**
  - Early concept tool
  - Functional / component breakdown
  - Explore tradespace edges

- **TRADE Studio**
  - Highly computational
  - Sifts through millions of designs
  - Refined set of specifications for viable design solutions

**Expand Tradespace Fully**

- Performance Assessments
- Performance Metrics
- High-fidelity Models
- Parameter Sweeps: Design Variations
Organization of Tradespace Capability

** DEFINE **
Define the system and its requirements in SysML.

** MODEL **
Construct accurate and complete tradespaces.

** TRADESTUDIO **

** ANALYZE **
Visualize and explore the tradespace.

- SysML Authoring Tool
- ERSTAT Data Analytics
- Environmental Simulation
- CREATE
- Large Data Analysis
- Select and Compare
- Analysis of Alternatives
- Mission Context Analysis
- Statistical & Predictive Analysis
ERS Infrastructure

Systems engineers collaborate on design decisions

DoD Supercomputing Resources

ERS Cloud Services

HTML5 access to ERS products

TradeStudio

ERS Infrastructure

DoD Web Services

Model API: Soap/REST Interface

Challenges:
- Protect IP
- Access Control
- System Admin. Rights
- Scaling

Industry Interfacing
Enable Cost Reduction, Agility and Early Performance Feedback

Simulate Any Environment…Anywhere…Anytime

Rapid Prototyping: More Designs, Less Time
Support Testing & Evaluation

Mission Test: Both Notional & Actual
Employ Variable-Fidelity
Current DoD Acquisition Application
DoD Acquisition Impact

**US Navy NSWCCD**
**ERS Ship Design Projects**

*LX(R) AoA*
22,000 alternatives analyzed in 6 weeks

~16 Billion Decision

**Small Surface Combatant (SSC)**
19M designs analyzed in 3 months resulting in 270K feasible alternatives

~12 Billion Decision

**Submarine Class**
Virginia-class replacement Currently preparing analysis tools


**US Army AMRDEC**
**ERS Rotorcraft Projects**

Evaluated Boeing’s IRAD-produced, CH-47 rotor blades

**Full, accurate assessments achieved with ERS tools & CREATE Helios models.**

ERS and CREATE tools ready for transition to Future Vertical Lift program


**US Air Force**
**Trades Analysis & Virtual Prototyping**

**Low Cost Attritable Aircraft Technology (LCAAT)**

**Trades Analysis (Air Force)**
Design Trades, Mission Trades

**Virtual Prototyping (OSD ECP)**
Virtually Test & Warfight Designs

ERS and CREATE tools ready for transition to Future Vertical Lift program
Computational Research & Engineering Acquisition Tools and Environments (CREATE) Program

Air:  
- **Fixed-wing aircraft, rotorcraft, conceptual design, and operational testing and transition**

Ground Vehicle (GV):  
- **Autonomous navigation and operational testing**

Meshing and Geometry (MG) Support:  
- **CREATE MG improves the ease, speed, flexibility, and quality of geometry and mesh generation**

**CREATE**  
**Fully Validated on Real Problems**

- **CREATE-AV**  
  Aircraft (AV) Design Tools

- **CREATE-SHIPS**  
  Ship Design Tools

- **CREATE-RF**  
  Radio Frequency (RF) Antenna Design and Integration Tools

- **CREATE-MG**  
  Meshing and Geometry (MG) Support

- **CREATE-GV**  
  Ground Vehicle (GV) Design Tools

**Ship Design Tools:**  
- **Shock/damage, hydrodynamics and early-stage design, and operational testing and transition**

**Radio Frequency (RF) Antenna:**  
- **Conceptual design and detailed analysis tools for myriad DoD platforms**
CREATE AV Tools
Concept design, High Fidelity Fixed-Wing and Rotary-Wing

Kestrel and Helios: *Air frame (Aerodynamics & Structural Mechanics), Control, Propulsion*

**Fixed Wing**
- Virtual Prototyping
- Design Verification
- Operational Use Evaluation
- Planning/rehearsal of Flight Tests
- Performance Certification

Simulates A-10 baseline & alternative wing leading-edge configs

Virtual airframe-propulsion system integration assessment early in design decision.

Multi-body static/dynamic motion w/moving control surfaces & aero-elastic aircraft

**Rotorcraft**

Virtual testing of integrated CH-47F new rotor

Holistic Analysis of Platform Dynamics

Rapidly, accurately model H-60 main/tail rotor in multiple configurations & conditions in context of dynamic system performance

**DaVinci: Rapid Conceptual Design**

Simulates A-10 baseline & alternative wing leading-edge configs
Current ERS Rotorcraft Efforts

**Initial experiment demonstrating value of virtual prototyping using validated, high-fidelity models**

**FY14 and Prior**
- Boeing proposed new CH-47 rotor blade
- CREATE-AV Helios validated on old blade design
- CREATE-AV Helios confirmed added lift of new blade design in hover
- Paved way for larger projects in virtual prototyping (potential: Future Vertical Lift)

**FY15: CREATE-AV Helios**
- Analyzed payload allowance and maximum forward velocity characteristics
- Pre-flight test validation
- ERSTAT (ERS-built tradespace) generated and analyzed 1000’s of missions in a matter of minutes

**FY16 and Beyond:**
- Live flight tests with new rotor blade will be informed by early computational analyses
- Integrate Rotor Performance Maps into real-time mission planning tools from ERS work

**ERS AIAA SCITECH – Jan 2016**
Distribution Statement A – Approved for public release by DOPSR. Distribution is unlimited.
ERS Approach Supports Integrated Turbine Engine Program (ITEP) Analysis

- ERS success on Blackhawk prompted application to Apache attack helicopter
  - ERS provides employment of a *highly computational and integrated approach*
  - System-based, design-trade assessments made possible with ERS tradespace analysis tools
  - Physics-based, system performance reduces time, cost and error in new or upgraded designs

"More engine power to the Black Hawk and the Apache means farther range, more time on the objective … all resulting in a more lethal, more effective mission,"

"….new engine that would make current choppers more fuel-efficient, give them longer duration and additional power to carry extra weight."

ERS Major Industry Partnerships

Industry Partners are formally engaged in ERS development.

Government-Industry-Academia Architecture Working Group

Analysis of very big data

ERS tradespace analytics in the context of decision-making: AoA, scoring, bias elimination, “openness”…

Access to HPC Resources for design projects

Industry “sandboxes” for testing ERS architecture/tools

Nov. 18-19, 2015
Software Engineering Institute
ERS Adoption Strategy

2012 – 2014
TECHNOLOGY DEVELOPMENT & EXPERIMENTATION
Continuous Technology Advances, Insertions and Improvements

- Initial Tradespace Tools
- Prototype Knowledge Management Environment
- Initial Integrating Architecture
- Linked Physics-based Models

2015 – 2016
IMPLEMENTATION WITHIN DOD PROJECTS

- 2nd Gen Tradespace Tools - Ships, GV, AV
- Industry Linked to Architecture
- Initial Cost Modeling
- Initial Mission Tools

2017 – 2019
CAPABILITY INTEGRATION TESTING AND FIELDING

- User-configured Analytics
- Risk Representation and Mitigation
- Environmental Simulation Anywhere on Earth
- Manufacturability, Producing & Life Cost Tools
- Mission Context Tools

2020 – 2024
FULL TRANSITION TO ACQUISITION PROCESSES

- Modeling of entire acquisition cycle
- Validated cost representation
- Virtual prototyping of all materiel alternatives
- Cognitive computing

ERS V1.X          ERS V1.0          ERS V2.0          ERS V3.0          ERS V4.0

Q1FY16

Trade Analysis at Increasing Echelons →

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# Future Work Investments

## Significant Challenges

<table>
<thead>
<tr>
<th>Technical Area</th>
<th>Challenges 2016 - 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual Prototyping</td>
<td>Physics-based modeling, environmental influences and variations, Universal Task List (UTL) unit and system behaviors, mission immersion</td>
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<tr>
<td>Modeling Sub-systems</td>
<td>Dependencies, category theory, composition, reconfigurable and dynamic design</td>
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<tr>
<td>Material Life and Failure</td>
<td>Material models, material strength, thermal models, etc.</td>
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<tr>
<td>Lifecycle Cost Modeling</td>
<td>True cost analysis over sustainment</td>
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<tr>
<td>System-of-system Analysis</td>
<td>Identify and describe system of systems behaviors, components, structures, and contribution to joint and universal tasks</td>
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<tr>
<td>Modeling Manufacturing</td>
<td>Identify and generate manufacturing processes and assembly operations capable of predicting time and cost of manufacturing</td>
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</tbody>
</table>
Questions & Answers