ROTORCRAFT TRADESPACE EXPLORATION INCORPORATING RELIABILITY ENGINEERING

Sponsor: ARL

Saikath Bhattacharya, Vidhyashree Nagaraju, and Lance Fiondella

University of Massachusetts, Dartmouth, MA

Eric Spero and Anindya Ghoshal

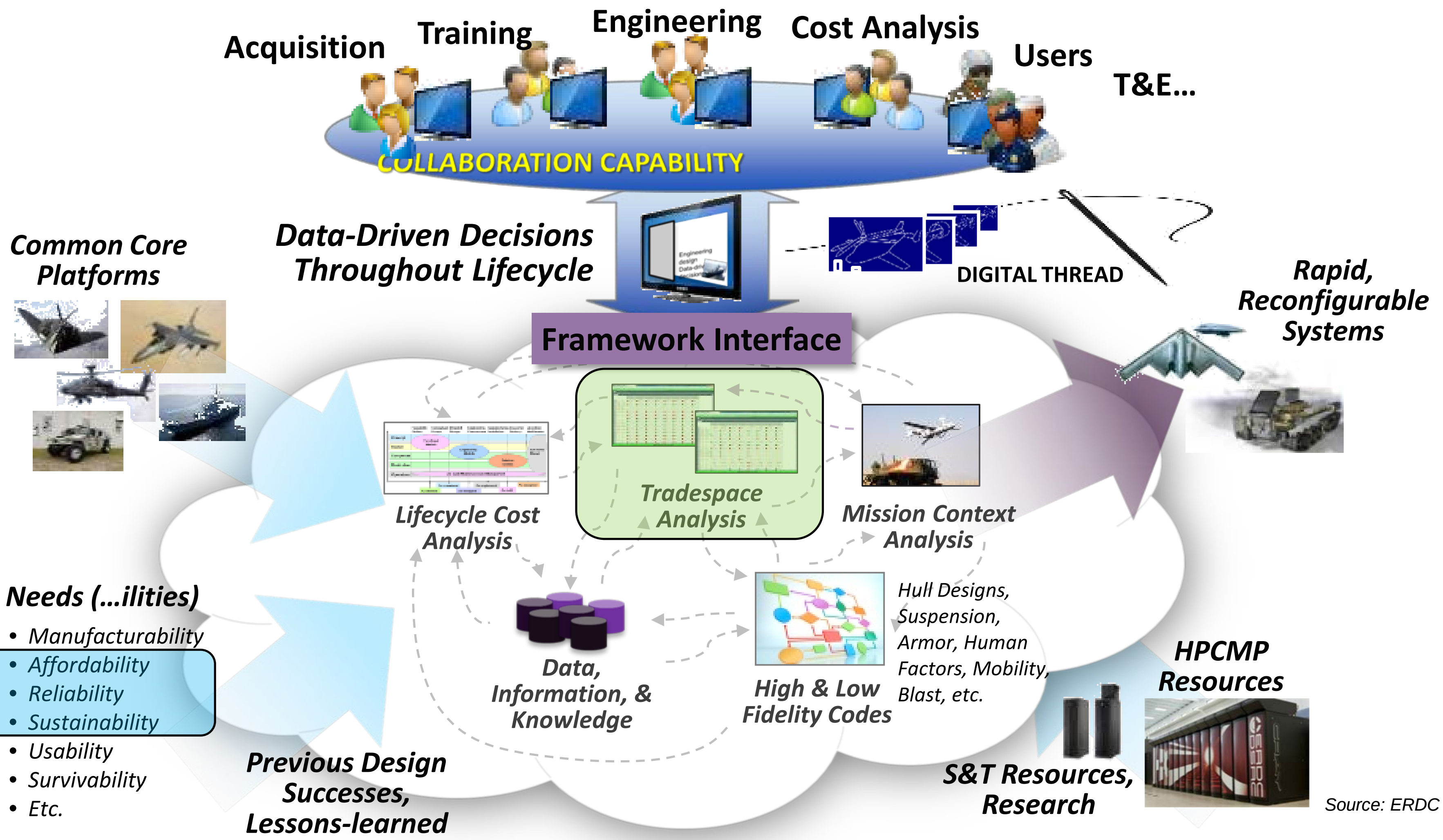
US Army Research Laboratory
Aberdeen Proving Ground, MD

5th Annual SERC Doctoral Students Forum
November 7, 2017
FHI 360 CONFERENCE CENTER
1825 Connecticut Avenue NW
8th Floor
Washington, DC 20009
www.sercuarc.org

Outline

- Background & Motivation
- Rotorcraft tradespace exploration
  - Performance covered; reliability missing
- Reliability modeling
  - —Assumptions and limitations
  - —Formulation
  - —Results
- Summary & Conclusions
- Future work

DOD Engineered Resilient Systems framework



Source: ERDC

Background (2)

- Operation and support (O&S) as well as affordability
  - —Impacted by non-functional requirements (reliability, availability, and maintainability (RAM))
  - —Receiving minimal tradespace consideration
- Propose strategy to incorporate reliability into tradespace exploration (TSE)
  - —Develop subsystem-level reliability investment model

Motivation

- Joint Multi-Role Rotorcraft Technology Demonstrator (JMR TD)
  - —Intends to reduce technology transfer risk of Future Vertical Lift (FVL) initiative
- Affordability
  - —Major concern in economic climate of flat and declining budgets
  - —DOD needs better information and guidance to more effectively manage and reduce O&S costs

Motivation (2)

- Majority of program costs consumed during O&S
  - Essential to reduce underlying causes
  - Design for reliability (DFR)
    - Reducing part replacement costs and logistics over decades can achieve significant savings
    - Recent DOD study indicates "Many programs may underinvest in reliability early in acquisition"
  - DOD Reliability, Availability, Maintainability, and Cost Rationale Report Manual
    - Notes cost risk prominently

Tradespace Analysis

- TSE processes and accompanying tools
  - Provide intuitive environment to explore alternatives
  - Assess designs for feasibility in multiple contexts
  - Promising methodology to
    - Facilitate effective designer/stakeholder communication
    - Ensure final product with mutually agreed set of capabilities
    - Support systems engineering tradeoffs during acquisition lifecycle

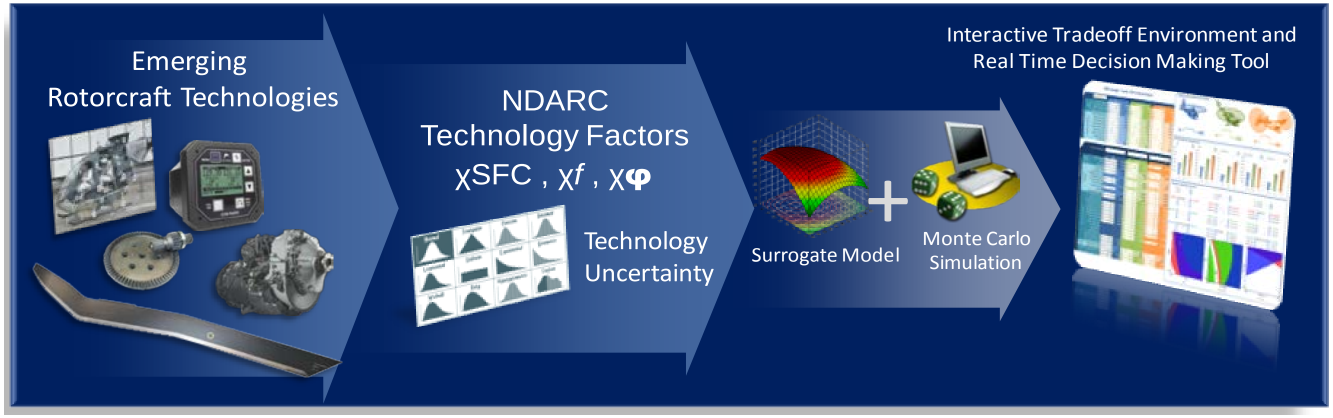
Value-based TSE best practices

- Best available TSE processes and tools research
  - —Finding: ERS pilot projects omitted subject matter expert measures and stakeholder value
- Prioritizing values can
  - —Enable decisions based on how well alternatives perform with respect to multidisciplinary objectives
  - —Focus TSE activities
  - —Achieve satisfaction within broader user-base

RAM and affordability are highly valued by stakeholders, but are missing from TSE

Rotorcraft tradespace analysis

- Rotorcraft Capability Assessment and Tradeoff Environment (CATE)
  - Uses NASA Design and Analysis of Rotorcraft (NDARC)
  - Interactive assessment of technology impacts across weight, design, performance, maintenance, and cost
  - Supports introduction and assessment of new candidate technologies



Source: ARL and Georgia Tech

CATE without Reliability

- Mission requirements determine vehicle size
- Configurations (single main rotor, compound, tilt rotor) assessed across 25 outputs
  - Grouped by weight, configuration, drag, propulsion, cost
  - Assess strengths and weaknesses
    - Compared to one another
    - Baseline vehicles for each category
- Lower and upper constraints on inputs reveal
  - What is possible with state of the art technologies
  - Additional logistical constraints

CATE with Reliability

- Execute CATE analysis
  - —Identifies designs that ensure operational effectiveness
- Vendor specific part selection
  - —Performed as stakeholders form consensus
  - —Makes design concepts more concrete
- High fidelity analysis
  - —Considers additional design constraints
  - —Quantifies performance more accurately
- Reliability analysis
  - —Can be performed while part selection is in progress
- Cost and tradespace analysis

Incorporating reliability into TSE ensures greater attentiveness to cost

Reliability Modeling

- Crow AMSAA model
  - —Strategy to achieve desired level of reliability growth over series of testing cycles
- System subject to developmental test
  - —Variety of failures discovered
    - o Not all of equal severity or importance
    - o Simplest method divides into two categories
      - —A-mode – no corrective action taken
      - —B-mode – corrective action taken

Model Assumptions

- B-mode failures
  - K – total number of failures (large unknown constant)
  - Each failure occurrence leads to system failure
    - Equivalent to series system
  - Failures discovered prior to end of testing cycle (T) subject to fix attempt by T

System failure rate and failure intensity

- System failure rate at time T

$$r(T) = \lambda_A + \sum_{i=1}^{K}(1-d_i)\lambda_i + (\lambda_B - \sum_{i=1}^{K}\lambda_i)$$

  - λ_A – Rate of A-mode failures
  - $\sum_{i=1}^{K}(1-d_i)\lambda_i$ – B-mode failure rate after corrective action
    - d_i – Fix effectiveness of i^{th} B-mode
  - $(\lambda_B - \sum_{i=1}^{K}\lambda_i)$ – unobserved B-mode failures

- As $K \to \infty$, expected failure intensity

$$\rho(T) = \lambda_A + \lambda_B\left((1-\mu_d) + \frac{\mu_d}{1+T}\right)$$

  - μ_d – Average success rate of corrective actions

Reliability Investment

- Essential function failures (EFF) prevent fully mission capable (FMC) system

$$FMC = \prod_{i=1}^{n} (1 - EFF_i)$$

—Similar to Crow's model of B-mode failures

- MTBEFF 1/expected failure intensity

$$M(T) \coloneqq \rho(T)^{-1}$$

Cost vs. Time

- Cost and time required to achieve MTBEFF

$$\gamma(T) = \frac{1}{CV^2(C_0 T + \mu_b \ln(1+T))}$$

  - CV – Coefficient of variation in B-mode failures
  - C_0 – Cost to operate test, analyze, and fix (TAAF)
  - μ_b – Average value of cost increments incurred by corrective action

Subsystem MTBEFF as function of reliability investment

- Solving cost equation and composing with MTBEFF provides direct relationship

$$M_i(T_i) = \frac{1}{1-\mu_{d,i}+\frac{C_{0,i}\mu_{d,i}}{\frac{1}{\lambda_{A,i}}+\frac{\mu_{b,i}\,F^{-1}\left(\frac{C_{0,i}+\frac{CV_i^2\gamma_i(T_i)}{\mu_{b,i}}}{\mu_{b,i}}\right)}{\lambda_{B,i}}}}$$

  - $F(W) = We^W$ - Lambert W-function

Maximizing fleet size through reliability improvement

$$\max \left\lfloor \frac{B - \sum_{i=1}^{n} \gamma_i(T_i)}{\sum_{i=1}^{n} \left(c_i \left(1 + \left\lfloor \frac{L}{M_i(T_i)} - \varepsilon \right\rfloor \right) \right)} \right\rfloor$$

subject to $T_i \geq 0, \forall i (1 \leq i \leq n)$

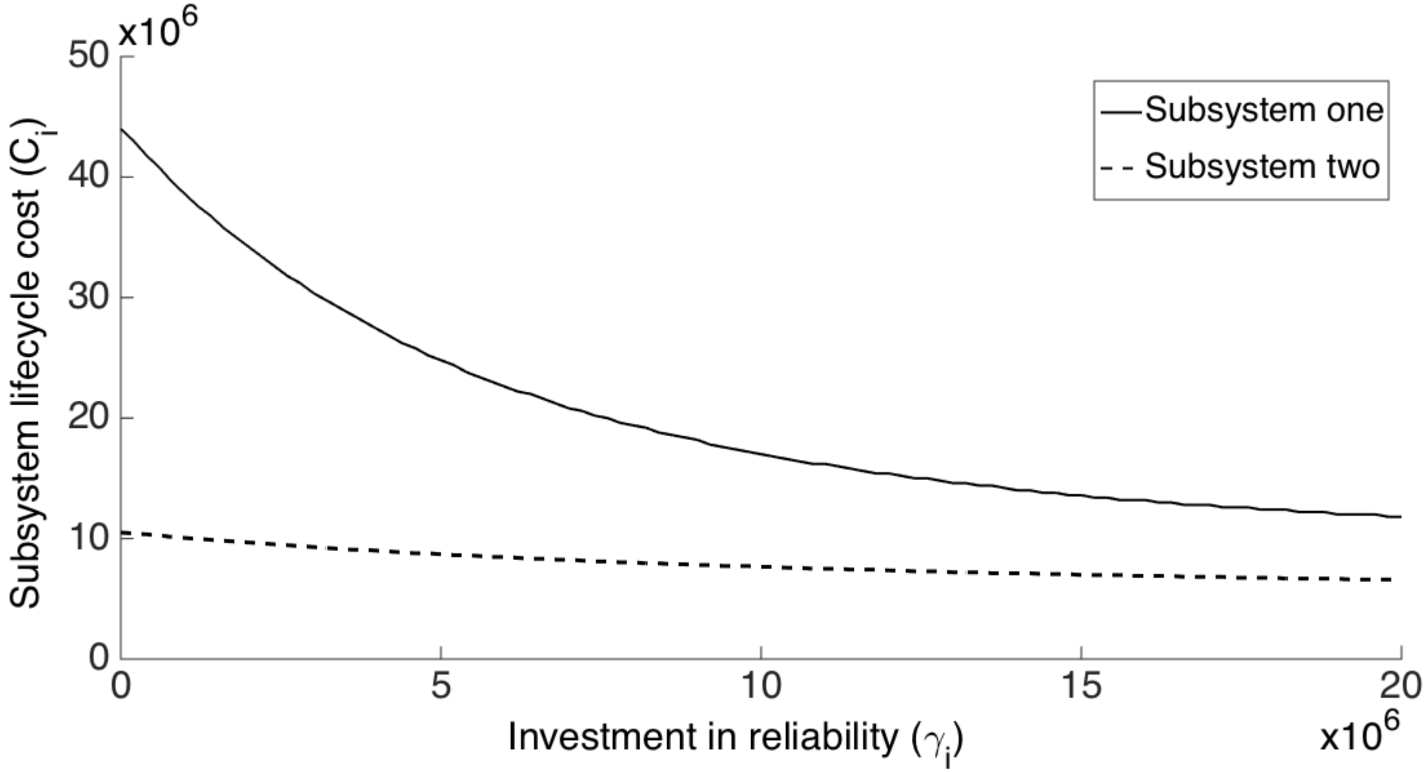
- B – Total budget
- $\sum_{i=1}^{n} \gamma_i(T_i)$ – Subsystem reliability investments
- c_i – Cost to replace subsystem i once
- L – Length of system lifecycle

Illustrations

- Parameters chosen for sake of illustration
  - $n = 2$ subsystems
  - $B = \$1,000,000,000$
  - $L = 20,000$ flight hours

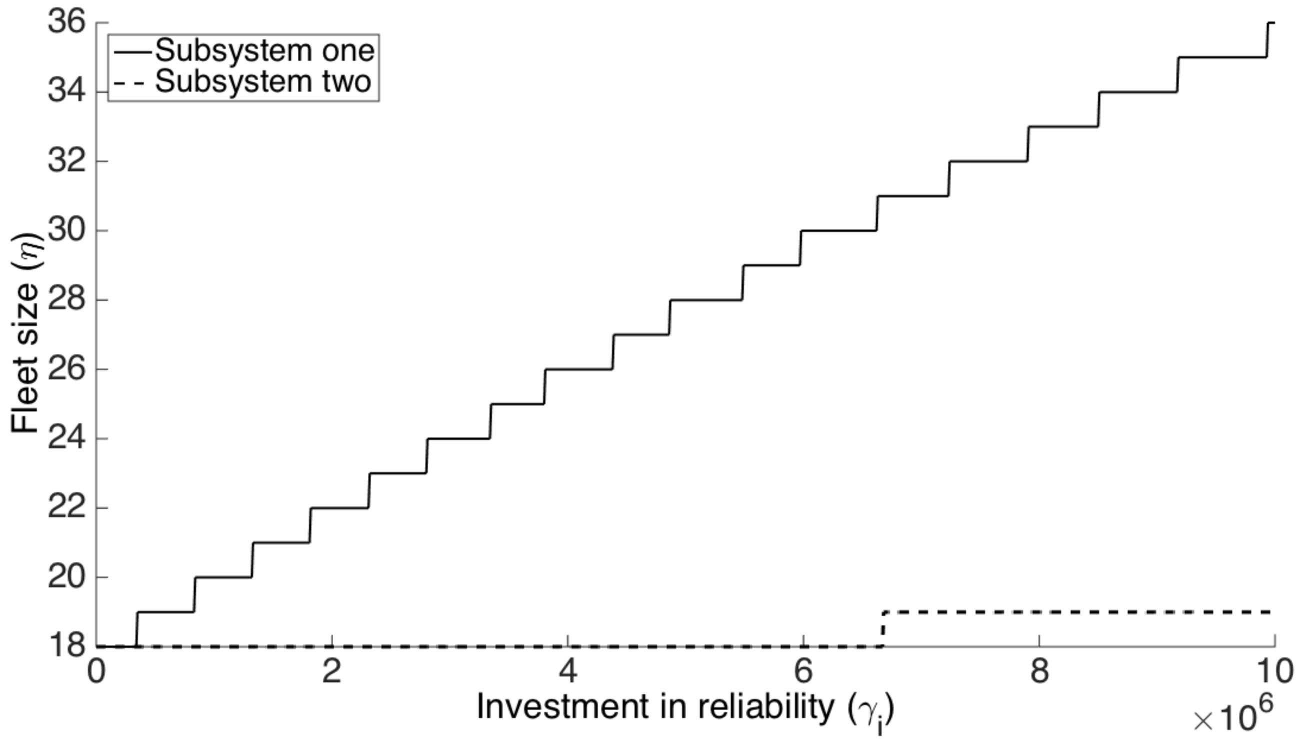
Parameters	Subsystem $i = 1$	Subsystem $i = 2$
$M_{A,i}$ (initial A-mode failure MTBF)	1,000	500
$M_{B,i}$ (initial B-mode failure MTBF)	100	200
$C_{0,i}$ (Cost of operating TAAF)	1,000,000	800,000
$\mu_{b,i}$ (Cost of corrective action)	5,000,000	4,000,000
$\mu_{d,i}$ (B-mode fix effectiveness factor)	0.9	0.8
c_i (Subsystem replacement cost)	20,000	75,000

Impact of reliability investment on lifecycle cost



Subsystem one could achieve significantly greater cost savings over system lifecycle

Marginal utility of reliability investment



Marginal investment required to improve subsystem one increases for each additional vehicle desired, but investment is preferred over subsystem two

Optimal reliability investment

Parameter	No Investment	Optimal Investment
M_1	90.92	444.66
M_2	142.86	270.39
P_1	219	44
P_2	139	73
C_1	44,000,000	9,000,000
C_2	10,500,000	5,550,000
C_s	54,500,000	14,550,000
η	18	62
Fleet Cost	981,000,000	902,100,000

- Reliability investment results in larger fleet at lower cost
- Optimal fleet size without reliability investment: \$3,379,000,000 (=62 × 54,500,000)
  —3.379x original budget

Consideration of reliability investment could make valuable contributions to long term program affordability

Summary and Conclusions

- Combine reliability engineering and TSE
  - Strategy considers investment over long term
- Studies linking reliability investment and improvement could promote
  - Compromise between performance and non-functional reliability and affordability attributes
  - Reduce lifecycle cost (LCC) and affordability

Future work

- Remove cost model assumptions
  - —Office of Cost Assessment and Program Evaluation (CAPE) methodologies and tools to estimate LCC
  - —LCC methodologies and tools limitations that may impede integration of tradespace methodologies and tools
- Assess fleet size and cost sensitivities to model assumptions (e.g., reliability, life, failure rate, fix effectiveness factor)

Acknowledgement

- Research supported by Cooperative Research and Development Agreement (ARL CRADA# 14-30) for Multi Task Technology Transfer between the U.S. Army Research Laboratory (ARL) and the University of Massachusetts Dartmouth (UMassD)
- Summer Research Fellowship Program grant from the Office of the Provost at the University of Massachusetts Dartmouth, Dartmouth, Massachusetts, USA