Robust Aircraft Design Exploration through Integrated Parametric Modeling and Dynamic Simulation

Nick Borer
Draper Laboratory
nborer@draper.com
617 258 4655

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Outline

- Motivation
- Context for Robust System Design
- Case Studies in Multistate Design
  - Twin-Engine Aircraft
  - Long-Endurance UAV
  - Fleet of UAVs for Persistent Campaign
- Conclusions

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Motivation

If it's Going to Spend a Lot of Time Broken, Why Not Design it to Operate That Way?

- Conceptual design methodologies typically focus on optimizing nominal performance, with constraints for off-nominal conditions
  - Only guarantees *adequate*, not *best* performance in off-nominal conditions
- Yet, aerospace systems can spend significant time operating in off-nominal conditions


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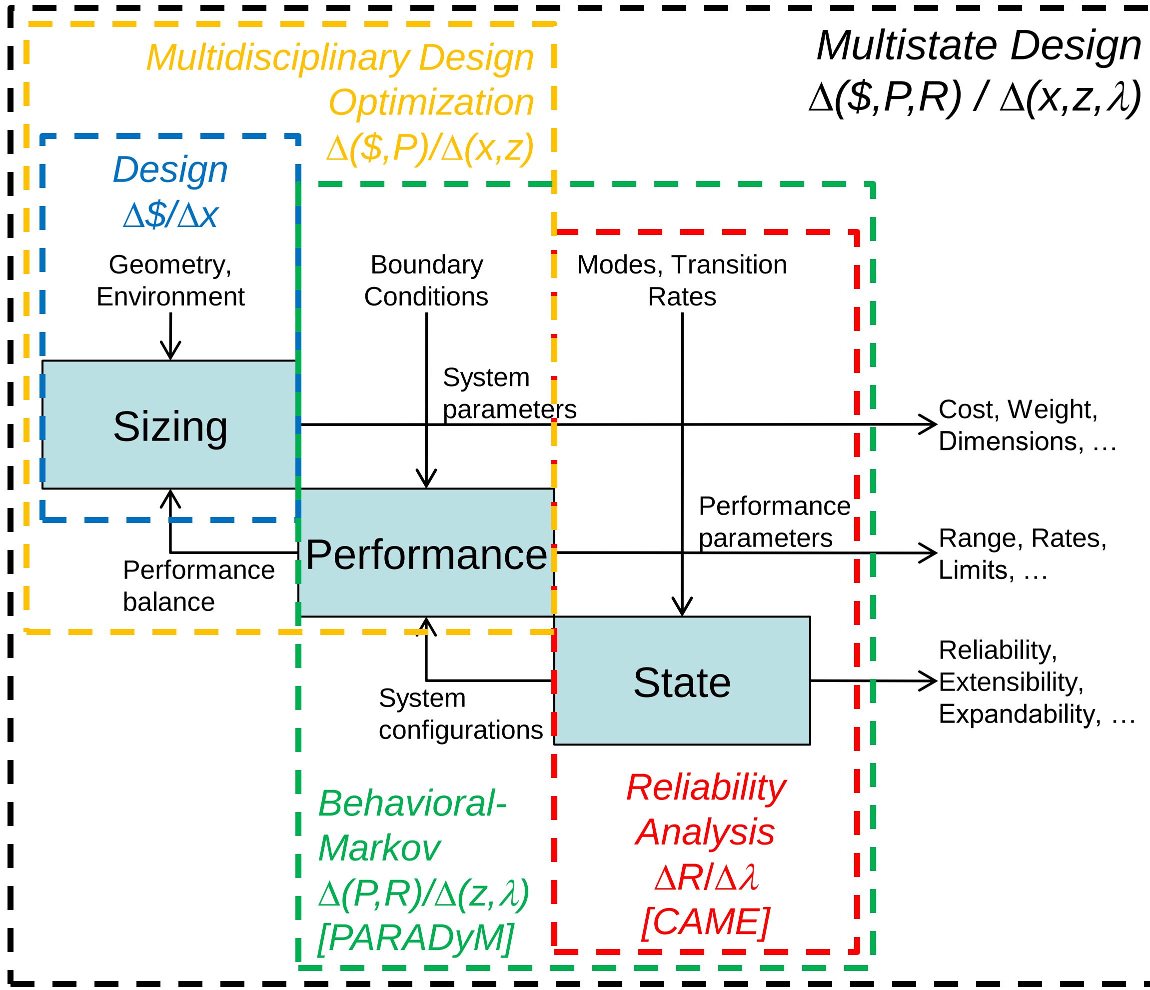
Robust System Design Context

Use All Available Means to Increase System Robustness

What is the best path to design for off-nominal events?

- Change the design
  - Increased margins
  - Cross-strapping, redundancy
- Change the performance requirements
  - Change operations (plan operation in favorable modes)
  - Remove operational requirements (e.g. do part of the mission with another system)
- Change the rate of state transition
  - Increased component testing, qualification
  - Use of higher-quality components



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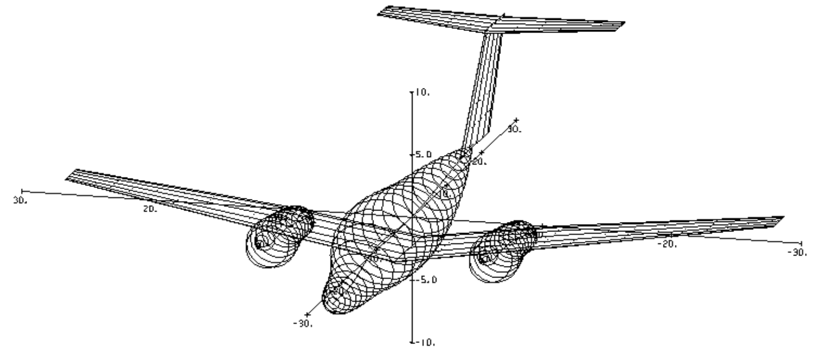
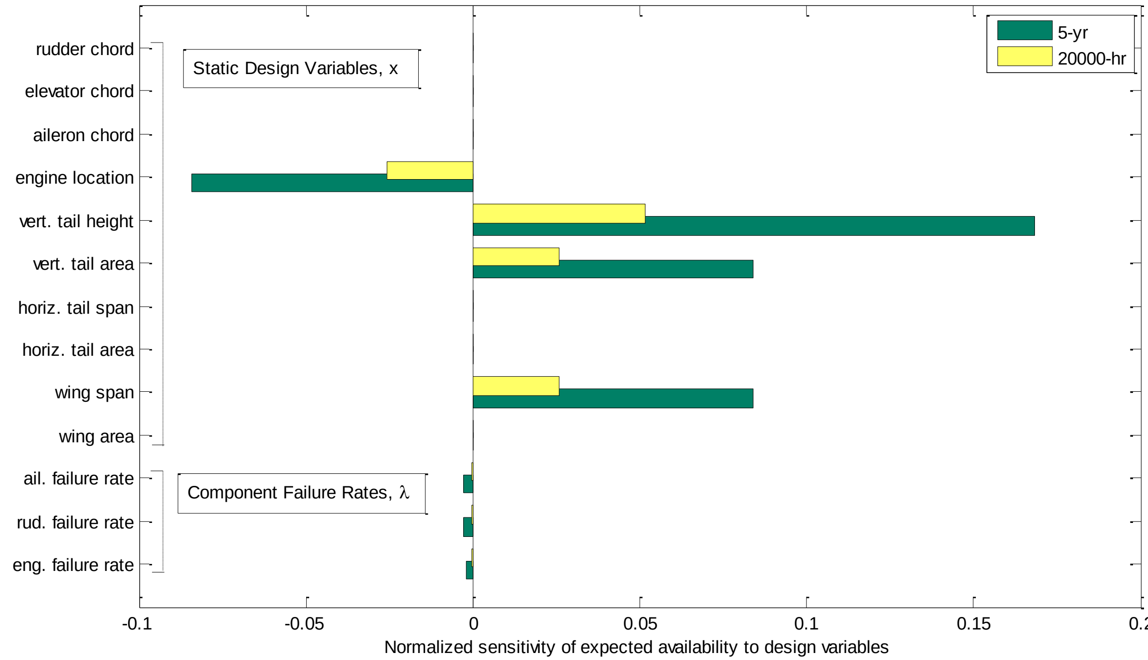
Multistate Sensitivity Analysis: Twin-Engine Aircraft

More Leverage Exists to Increase Availability through Design Variables, not Failure Rates

- Investigated the sensitivity of traditional aircraft design variables on reliability in addition to component failure rates for C-12 (Beech King Air)[1]
- Results showed that reliability was far more sensitive to vertical tail parameters than to component failure rates





1. J. S. Agte, N. K. Borer, O. de Weck, "Multistate Design Approach to the Analysis of Twin-Engine Aircraft Performance Robustness," *Journal of Aircraft,* 49(3) 781-793, 2012.

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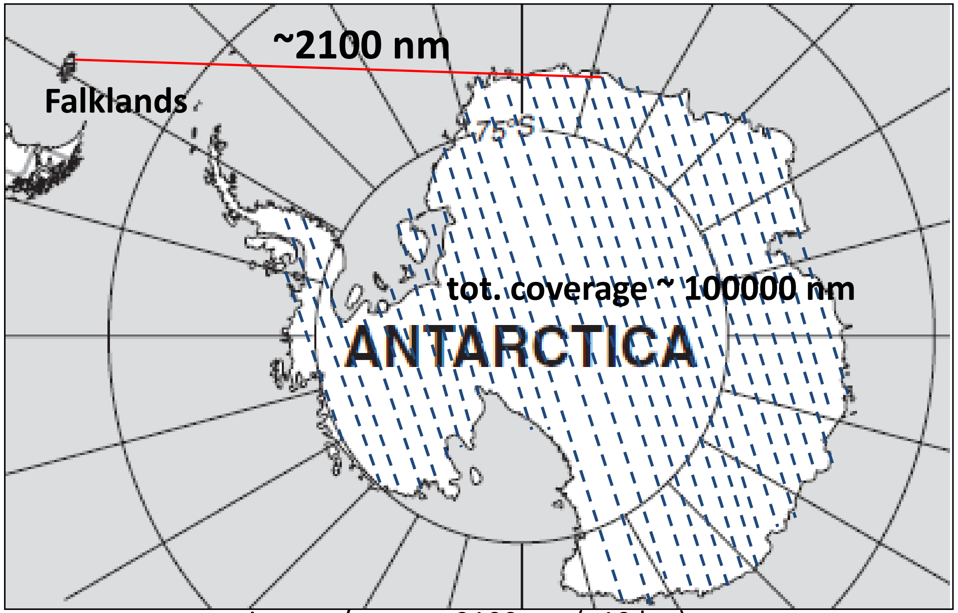
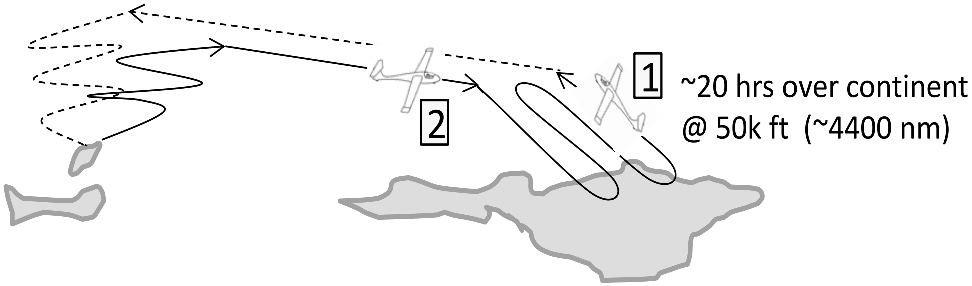
Multistate Tradespace Exploration: Long-Endurance UAS

Multistate Exploration Yields Reduced Cost, Increased Availability vs. Traditional Approach

- Investigated the tradespace of a long-endurance UAS
  - First considered a long-endurance system with a notional power system and three-month endurance[2]
  - Next considered a more conventionally-fueled “squadron” of systems operated to enable persistent coverage over five years[3]
- Both cases showed an increase in availability and reduction in cost over traditional approaches, as well as non-intuitive design features





2. J. S. Agte, N. K. Borer, O. de Weck, “Design of Long-Endurance Systems With Inherent Robustness to Partial Failures During Operations,” *Journal of Mechanical Design,* 134(10), 2012.
3. N. K. Borer, J. S. Agte, “Design of Robust Aircraft for Persistent Observation Campaigns Using Nested Multistate Design,” AIAA-2012-5452, AIAA Aviation Technology, Integration, and Operations Conference, September 2012.

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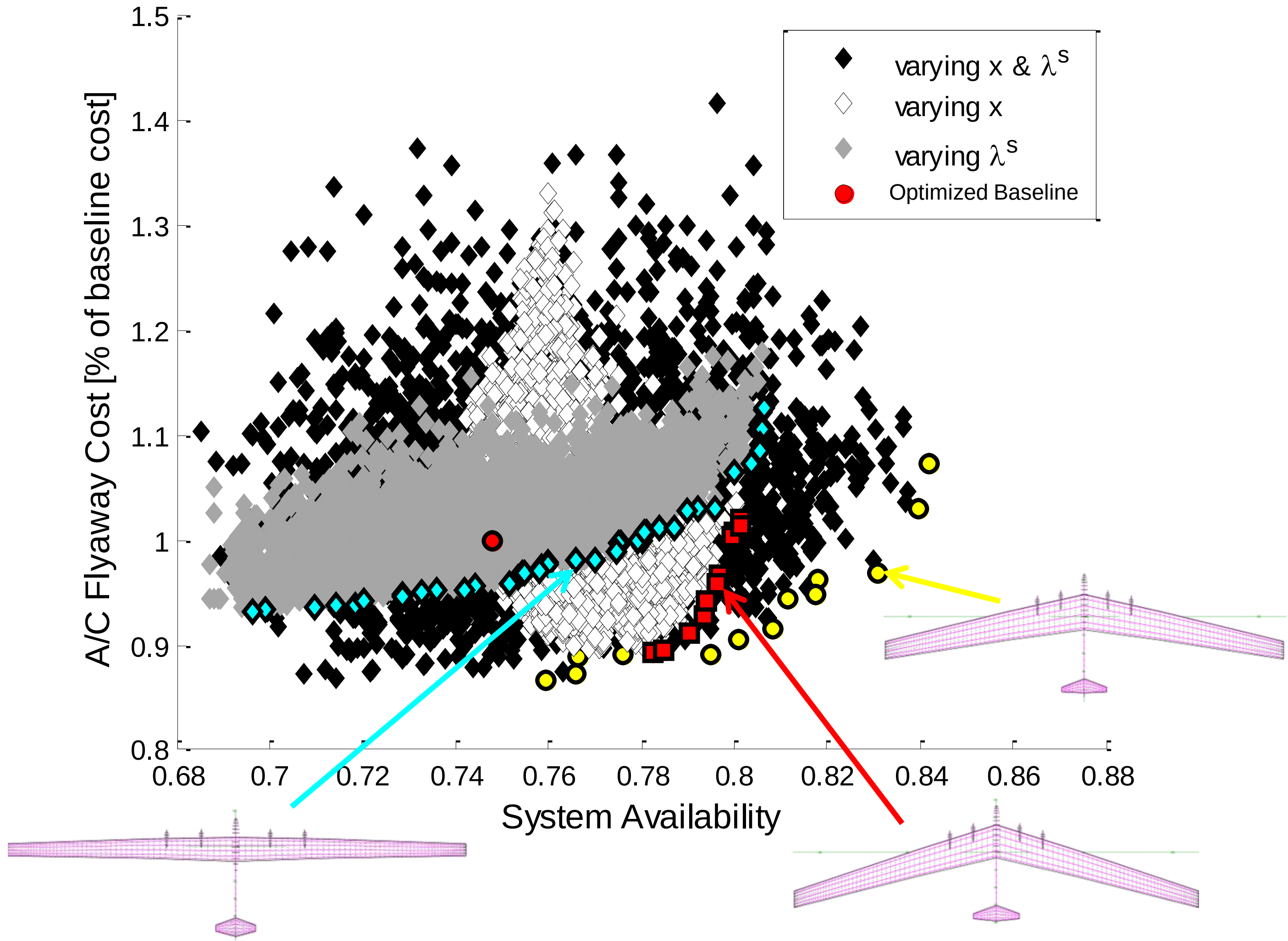
Acquisition Cost vs. Availability for 3-Month UAS

Multistate Approach Yields Lowest Cost, Highest Availability Solution



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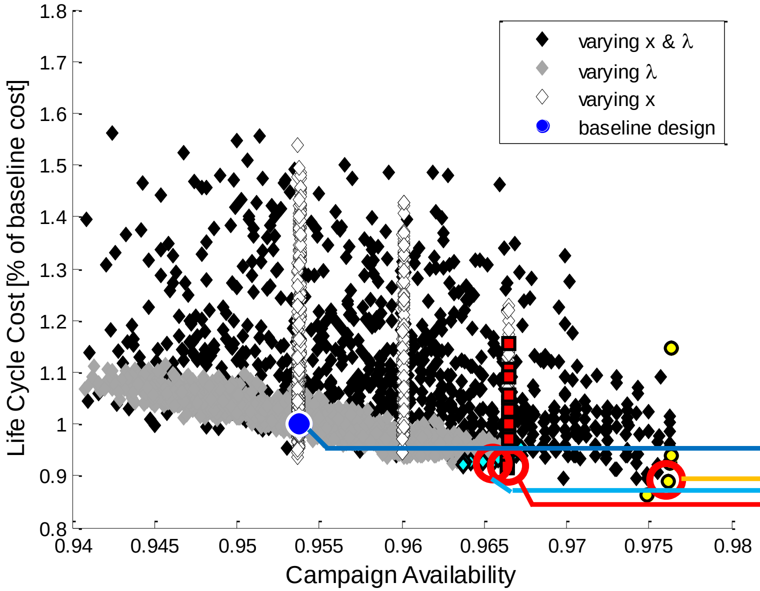
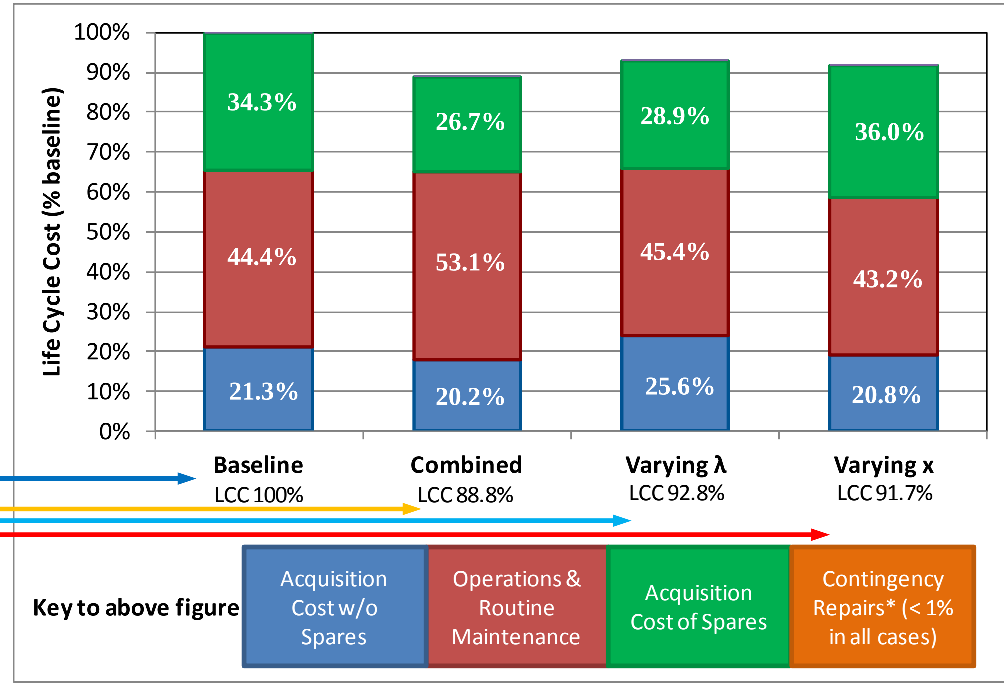
Life Cycle Cost vs. Availability for 5-year Campaign

Multistate Design Yields Lowest Life Cycle Cost, Least Attrition for Multiyear Persistent Campaign





- Multistate design – cheapest LCC, highest availability, highest O&M cost, lowest combined acquisition cost (initial + spares)

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Conclusions

It's Not Off-Nominal if You've Designed for it!

- Conceptual design of robust systems requires a change in perspective vs. traditional "design optimization"
  - Move away from constrained optimization of nominal performance to tradespace exploration across set of possible conditions
- Integrated modeling & simulation is key to this early exploration
  - Capture interactions between systems, operations, requirements, and disciplines
- Much to be gained by giving your reliability engineer a seat at the conceptual design table
  - Case studies show lower-cost, higher-availability designs are very possible

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- Multistate Sensitivity Analysis Case Study:
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- Multistate Design for Long Endurance UAV Case Study:
  - J. S. Agte, N. K. Borer, O. de Weck, "Design of Long-Endurance Systems With Inherent Robustness to Partial Failures During Operations," *Journal of Mechanical Design*, 134(10), 2012.
- Fleet of UAVs for Persistent Campaign Case Study:
  - N. K. Borer, J. S. Agte, "Design of Robust Aircraft for Persistent Observation Campaigns Using Nested Multistate Design," AIAA-2012-5452, AIAA Aviation Technology, Integration, and Operations Conference, September 2012.
- Behavioral-Markov Modeling for Reliability-Driven Design
  - N. K. Borer et al., "Model-Driven Development of Reliable Avionics Architectures for Lunar Surface Systems," IEEE Aerospace Conference, March 2010.
- Markov Modeling for Reliability-Driven Design
  - P. S. Babcock IV, "Development the two-fault tolerant attitude control function for the Space Station Freedom," 20th International Symposium on Space Technology and Science, Gifu, Japan, May 1996.

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Additional Information

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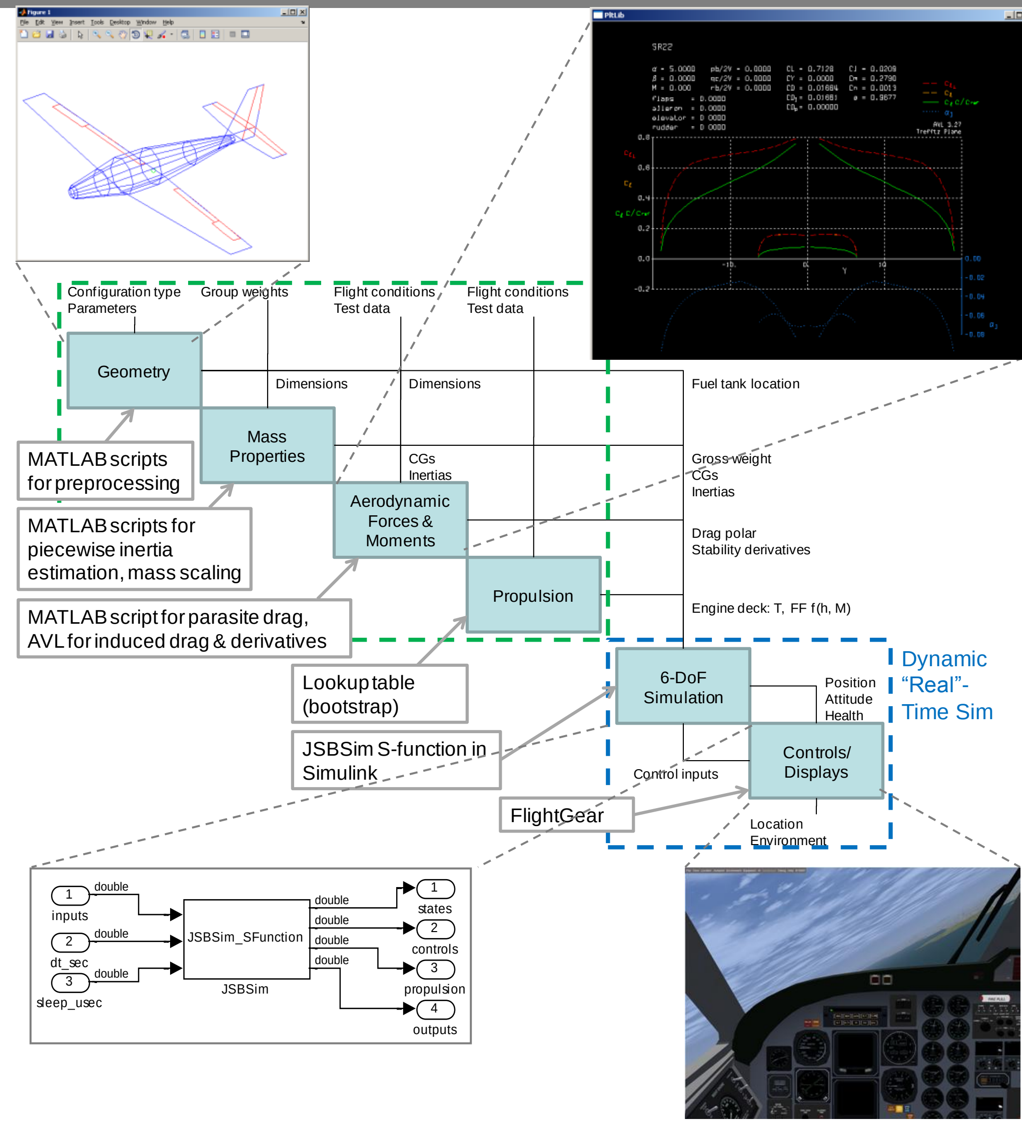
Integrated Parametric Flight Dynamics Model

- Built around MATLAB® and Simulink® for ease of integration with other analyses
  - MATLAB® calls to open-source aerodynamics module, custom-built analyses
- Flight dynamics model built as Simulink S-function from open-source flight dynamics engine
  - Allows for evaluation of control architectures, failure models in Simulink
- Outputs can be ported to quasi-real-time flight simulator for visualization and “pilot” operation



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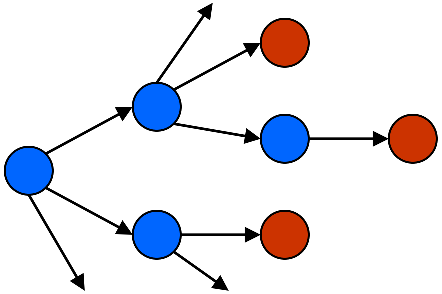
Behavioral-Markov Modeling

- Behavioral-Markov modeling offers an opportunity to predict and capture system behavior in an exhaustive combination of off-nominal events
  - Legacy: CAME (Computer Aided Markov Evaluator) used for fault-tolerant system development for high-reliability space and ground systems
    - Able to capture cascading failures through integrated system model
  - PARADyM (Performance and Reliability Analysis via Dynamic Modeling) enhances CAME's capabilities by directly simulating every Markov state with a behavioral model
    - System performance is captured for every Markov state
    - Status is determined directly from system performance



$$\frac{dP_1}{dt} = -(a+b)P_1(t)$$

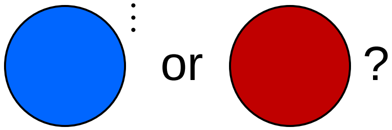
$$\frac{dP_2}{dt} = aP_1(t) - bP_2(t)$$

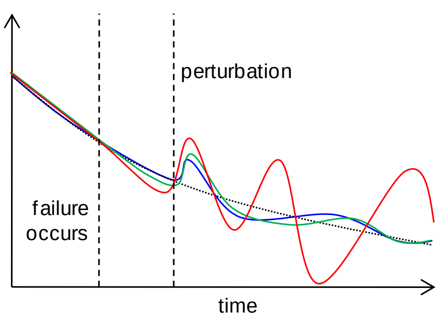
$$\vdots$$

$$P_1(t) = e^{-(a+b)t}$$

$$P_2(t) = e^{-bt} - e^{-(a+b)t}$$

$$\vdots$$





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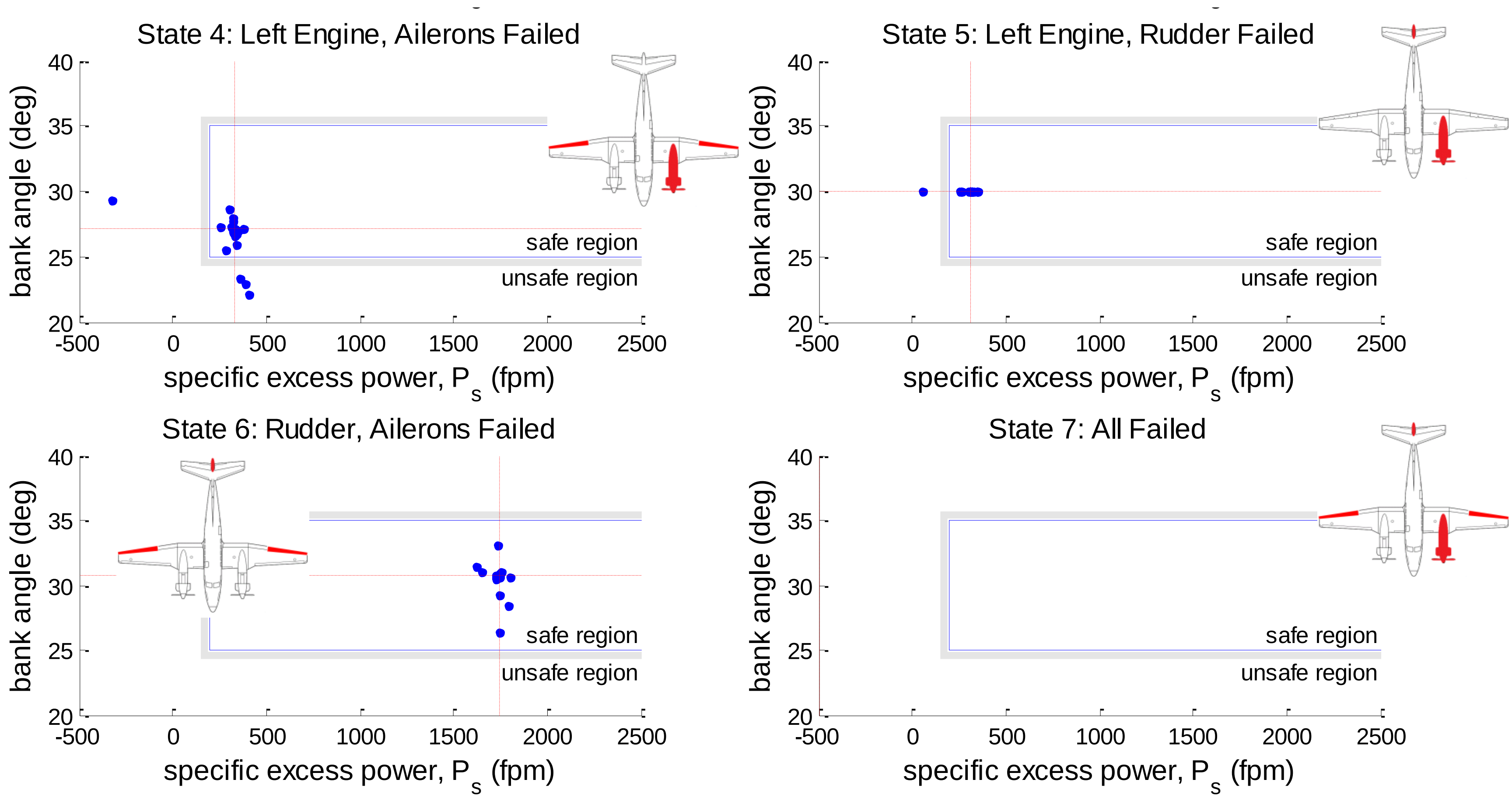
Effect of Geometry of Performance in Failed States

Actual (non-weighted) performance in each Markov state for the 23 geometry cases
Loss if P_s < 200 fpm, bank angle not held within 10 degrees



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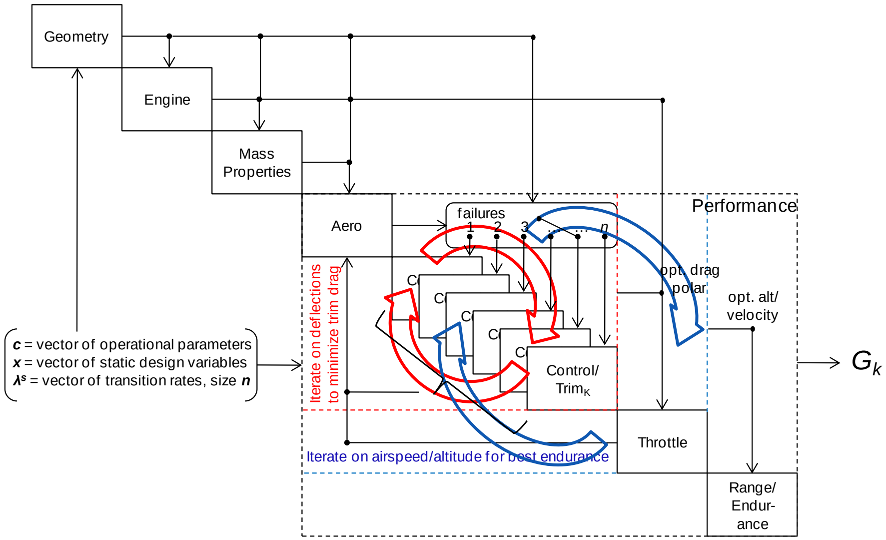
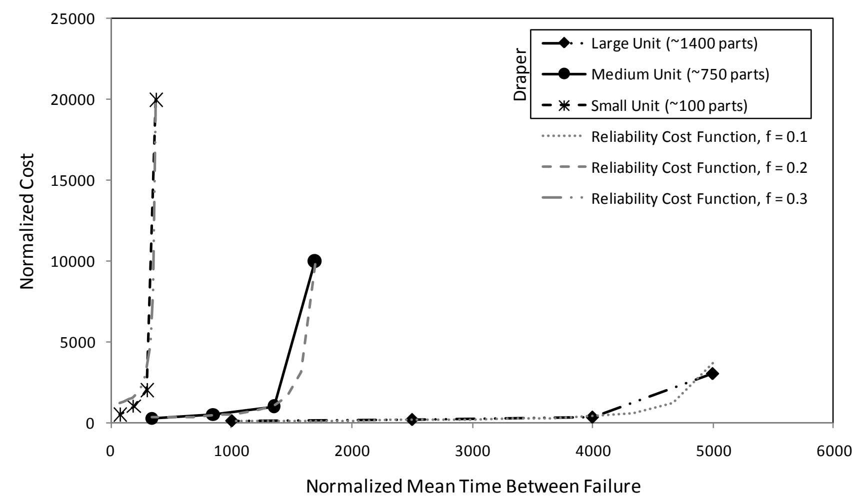
Aircraft Performance and Cost Model

- Aircraft sizing and performance
  - Added loop to optimize cruise operation for maximum endurance in each failure configuration
- Cost
  - Development and Procurement Cost of Aircraft model (DAPCA IV) updated for UAVs
  - Component reliability cost based on Draper/NASA study of cost vs. parts grades[4]





4. N. K. Borer et al., "Model-Driven Development of Reliable Avionics Architectures for Lunar Surface Systems," IEEE Aerospace Conference, March 2010.

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