Quantifying and Incorporating Uncertainty in Aerospace Vehicle Design

AFOSR Workshop on Uncertainty in Analysis, Design and Certification of Engineering Systems

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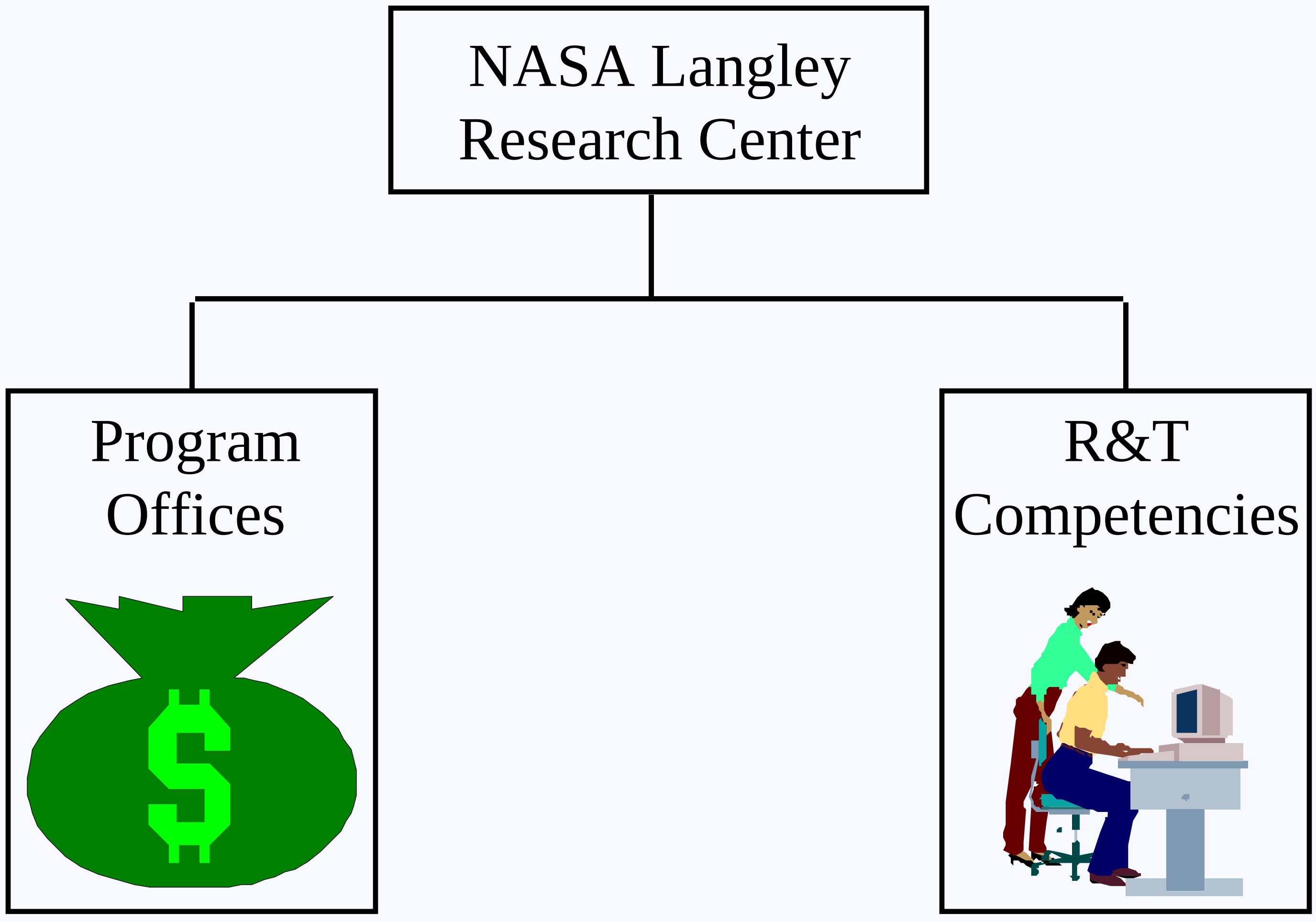
http://fmad-www.larc.nasa.gov/mdob/MDOB/

Objectives

- Describe the motivation for NASA Langley Research Center efforts on uncertainty quantification and design under uncertainty
- Describe current activities in the disciplines of
  - Aerodynamics
  - Structures
  - Controls
  - Systems Analysis
- Summarize technical challenges

Notional NASA Langley Organization

(http://www.larc.nasa.gov/)

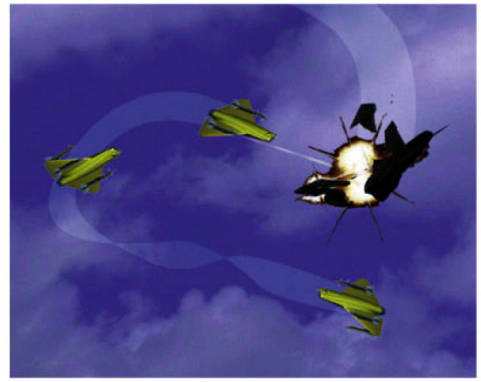


Aerospace Systems, Concepts and Analysis Competency

Space Transportation & Planetary Analysis

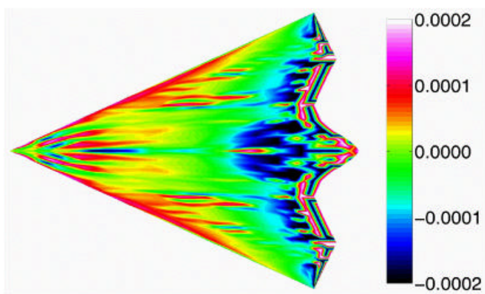
Advanced Civil Airplane & Transportation Systems Analysis

Survivable, Advanced, Military Vehicles

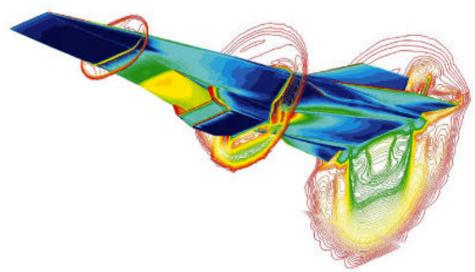


Space Mission Analyses

Multidisciplinary Design Optimization



Computational Aerosciences



NASA Advanced Space Transportation Goal

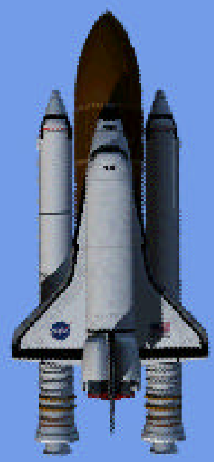
(http://www.aero-space.nasa.gov/goals/ast.htm)

- **Access to Space Objective**
  - Reduce the incidence of crew loss by an order of magnitude in 10 years and an additional two orders of magnitude in 25 years
  - Reduce the cost to low-Earth orbit by an order of magnitude in 10 years and another order of magnitude in 25 years
- **Medium/Heavy Payload Challenges**
  - Increase system reliability and performance margins through more robust designs and functional redundancy
  - Optimize system design cycle times
- **Small Payload Challenges**
  - Provide the capability for rapid development and production of highly reliable systems
  - Provide the capability for increased performance margins

NASA Space Launch Initiative
(http://astp.msfc.nasa.gov/)

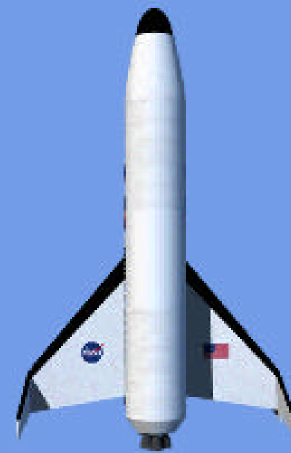
- **NASA's goals for the second generation RLV are to:**
  - **Improve the expected safety of launch so that by the year 2010 the probability of losing a crew is no worse than 1 in 10,000 missions**
  - **Reduce the cost of delivering a pound of payload to low Earth orbit from today's $10,000 down to $1000 by the year 2010**
- **NASA’s Intercenter Systems Analysis Team (ISAT) provides program managers with conceptual analyses**
  - **In late FY 02 the ISAT will have 3 months to evaluate 5 industry 2nd Generation RLV concepts**
  - **This will support the downselection to 2 concepts for further development**
  - **In FY 06 the ISAT will evaluate these 2 concepts to support a production decision on a shuttle replacement system**

Space Transportation Launch Vehicles



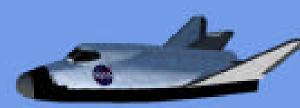
STS Upgrade

Shuttle Derived



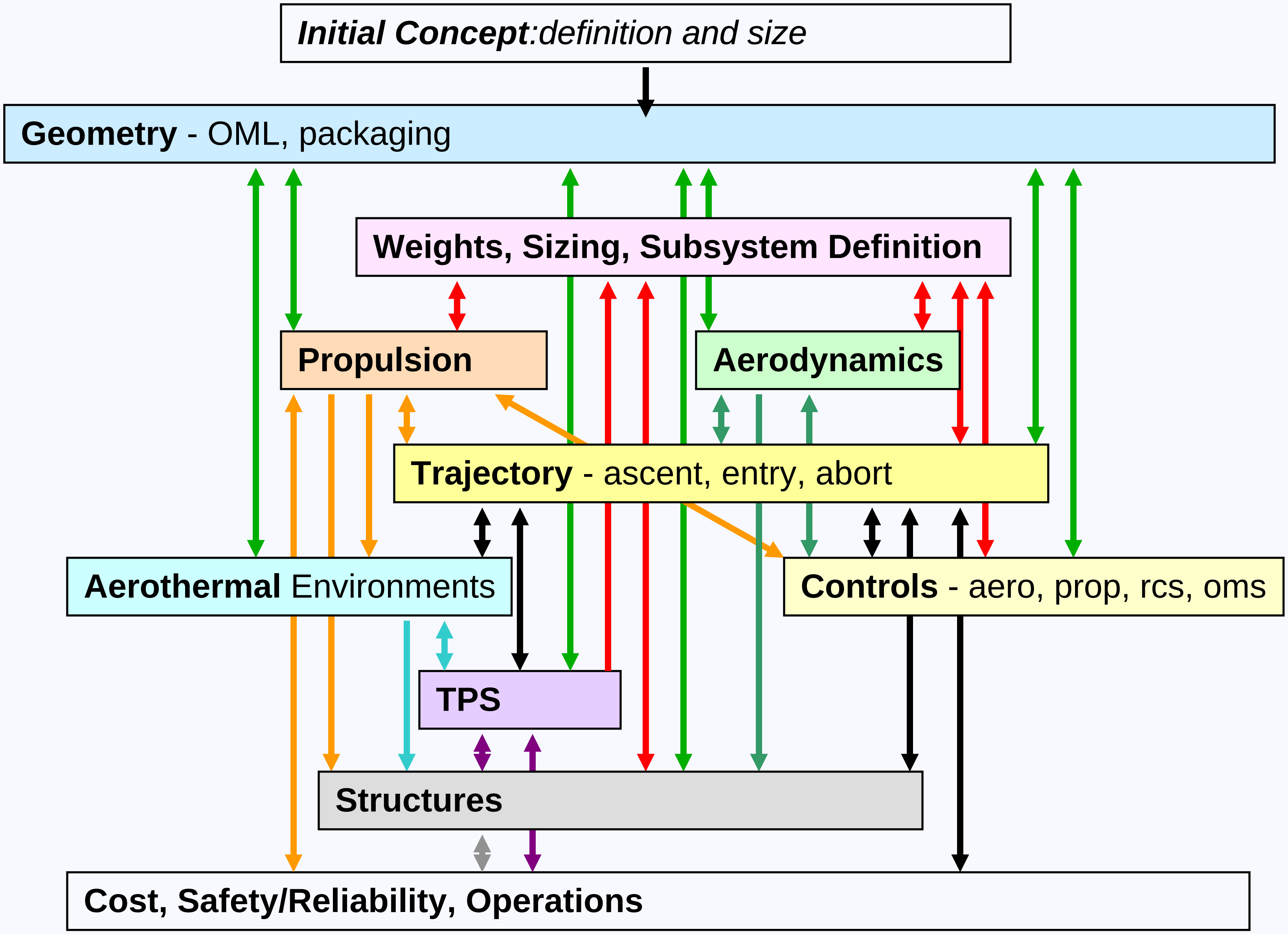
Single Stage to Orbit

Two Stage to Orbit
(Bimese)

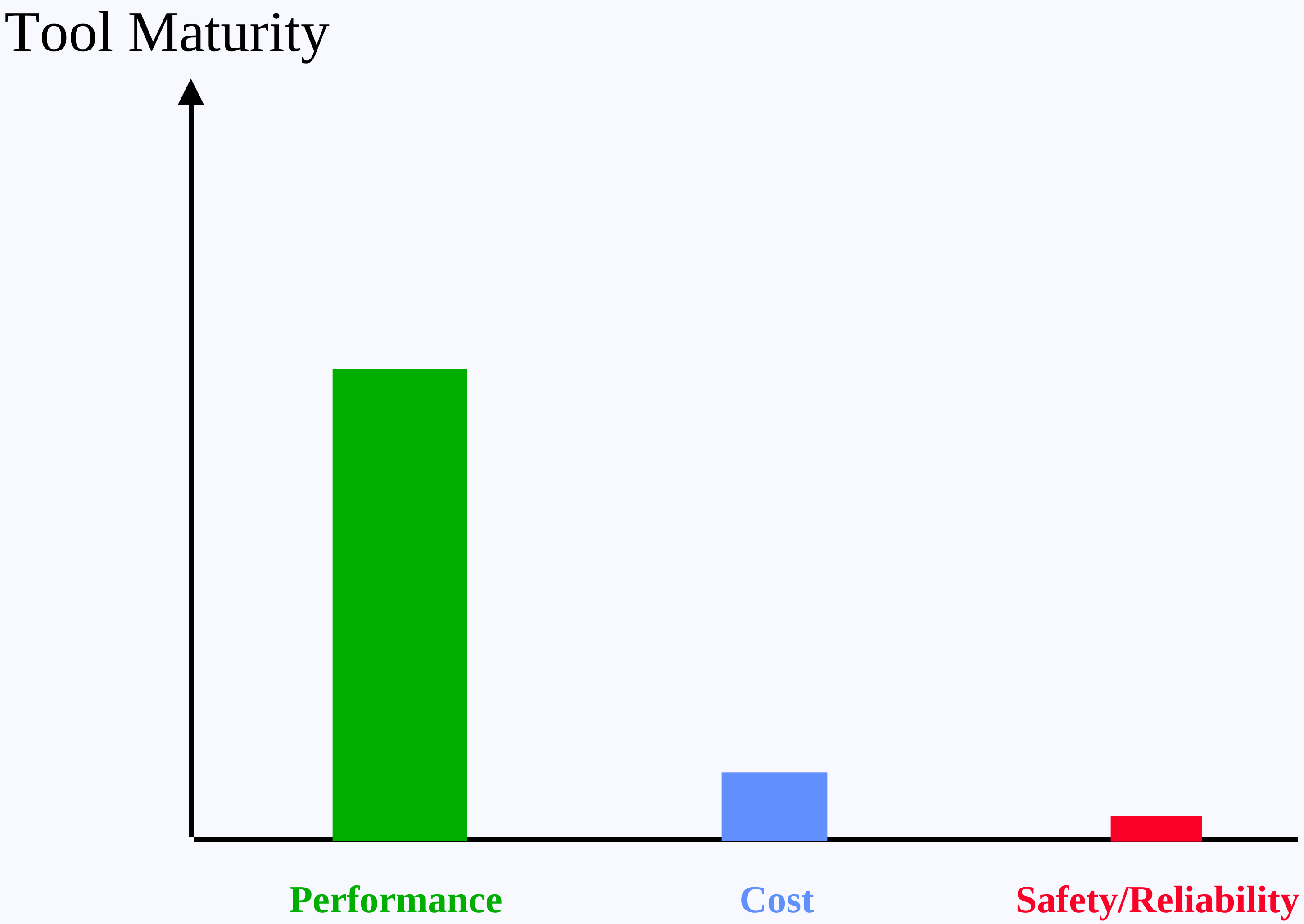


Crew Transfer
Vehicle

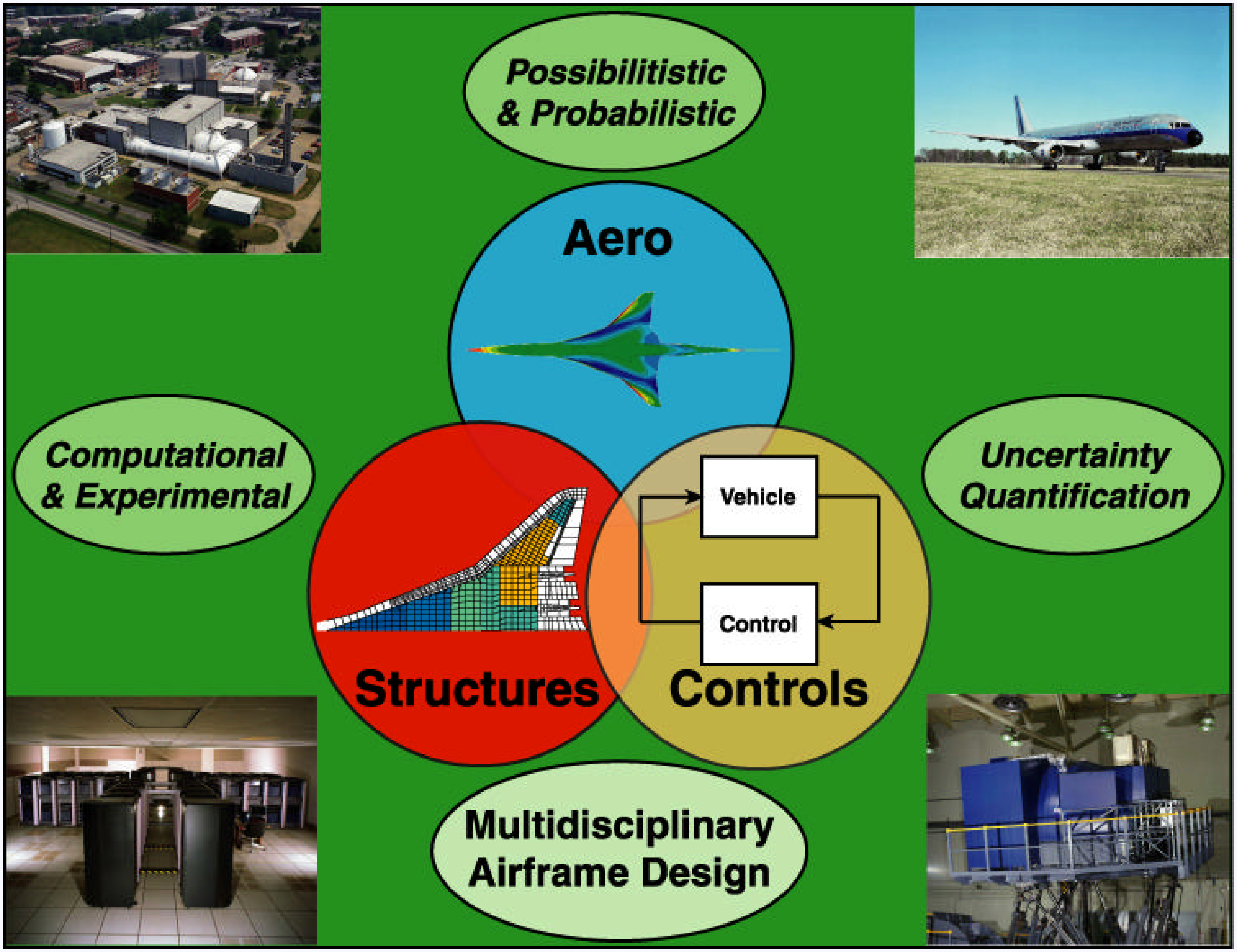
Systems Analysis for Launch Vehicles



RLV Systems Analysis Tools



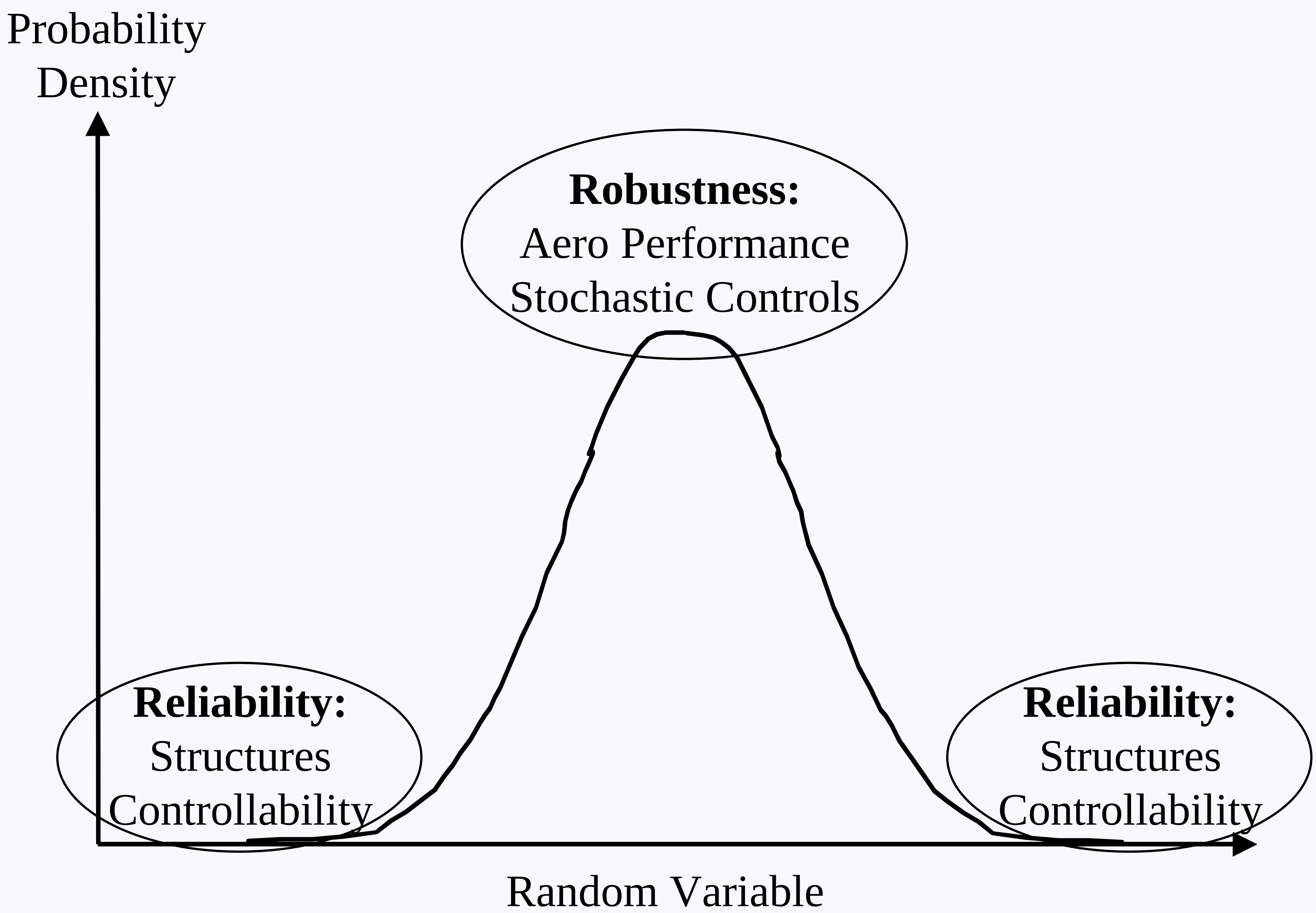
LaRC Risk-Based Design: Robustness & Reliability



Proposed LaRC Niche

- **Evaluate and improve methods for control of risk with applications to multidisciplinary airframe design by developing and validating strategies, algorithms, tools and data for**
  - **characterizing and controlling the uncertainties from the individual airframe design disciplines, esp. aerodynamics, structures and controls, based on the best available experimental and computational results**
  - **characterizing the norm and distribution of the resulting uncertainties in system metrics**
  - **accounting for uncertainties in the design of airframes at the conceptual through the detailed design stages**

Uncertainty Distribution vs. Problem Focus



Disciplinary Foci at LaRC

- **Aerodynamics**
  - Wind tunnel data quality
  - Robust design for performance
  - Reliability-based design for controllability
  - (Adjoint-based discretization error estimates)
- **Structures**
  - Reliability-based design using possibilistic & probabilistic methods
  - (Reliability-based design of an aeroelastically-tailored composite wet wing with advanced airfoils whose performance is predicted prior to flight)
- **Controls**
  - Stochastic control laws
- **Systems Analysis**
  - Safety/reliability predictions at the conceptual design stage
- **All**
  - Synergistic computational & experimental developments
  - Uncertainty quantification

Quantification of Uncertainty in Wind Tunnel Data

(http://wte.larc.nasa.gov/)

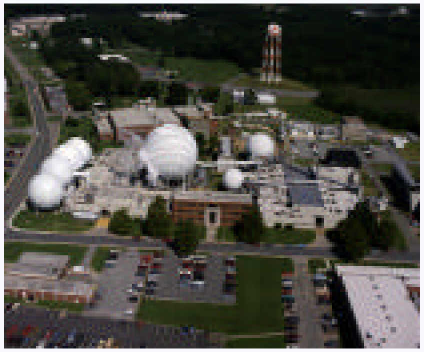
Subsonic

Transonic

- **NASA Langley has 40 wind tunnels, of which 6 are large-scale facilities**
- **NASA Langley's Wind Tunnel Enterprise has had a concerted effort to improve productivity and data quality since the mid-1990s**
- **Modern Design of Experiments (MDOE) is being applied to large-scale wind tunnel testing [Richard DeLoach]**
- **Statistical Quality Control (SQC) principles are used to measure data quality [Michael Hemsch]**

Supersonic

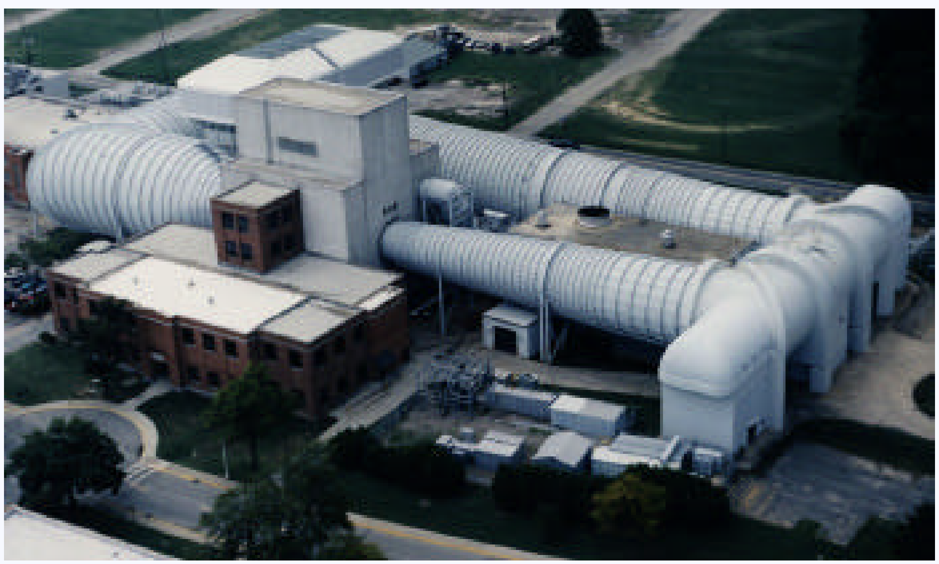
Hypersonic

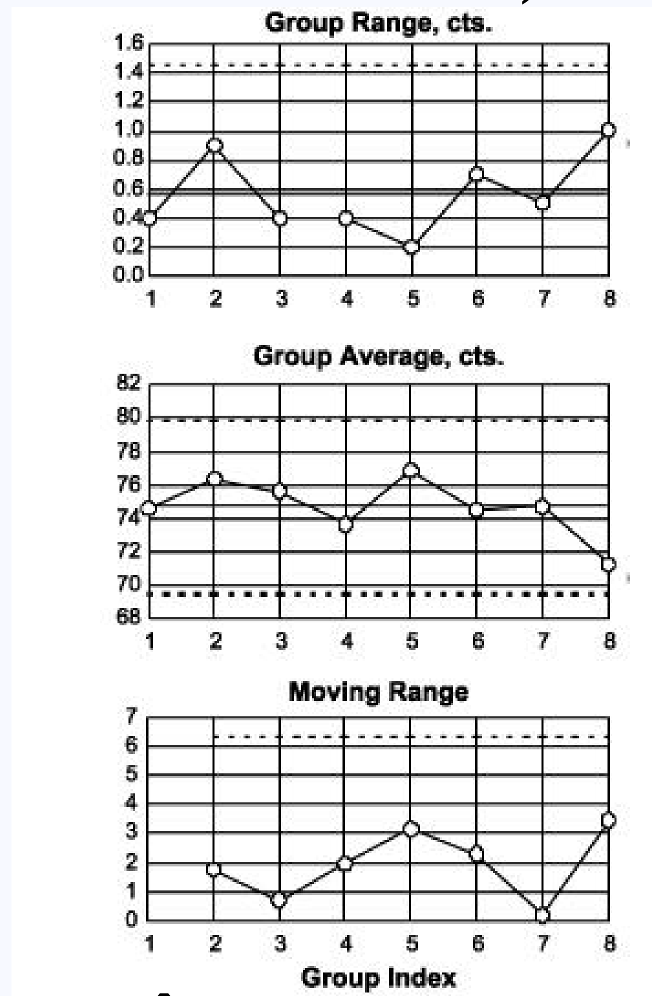


SQC Example: 16 Ft. Transonic Tunnel

(M. Hemsch, J. Grubb, W. Krieger, D. Cler: AIAA 2000-2201)

- Supersonic transport check standard
- M = 0.9
- AOA = 2°
- Axial-force coefficient





$\hat{\sigma}_{wg} = 0.33$ counts

$\hat{\sigma}_{bg} = 1.7$ counts

Uncertainty Propagation & Robust Optimization

(M. Putko, P. Newman, A. Taylor & L. Green: AIAA 2001-2528)

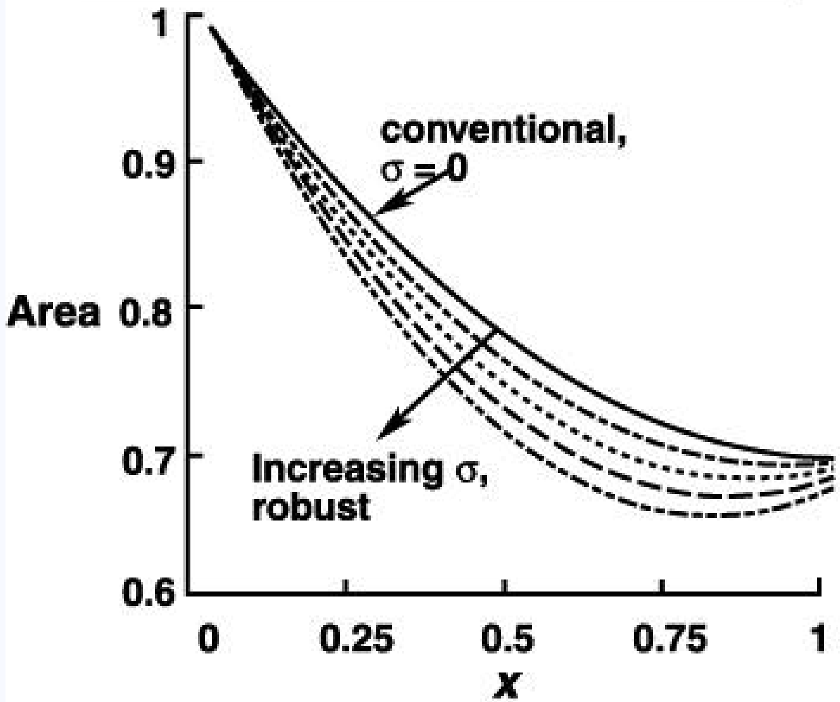
- **Objectives**
  - **Demonstrate efficient input uncertainty propagation through CFD code**
  - **Demonstrate robust design optimization for geometric and flow uncertainties**
- **Approach**
  - **Approximate statistical second-moment methods**
  - **Efficient calculations of first and second-order sensitivity derivatives**
  - **Moment matching formulation for probabilistic constraints**
- **Comparison**

	Conventional	Robust
Objective	$\min_{a,b} F(M;a,b)$	$\min_{\bar{a},\bar{b}} F(\bar{M},\sigma_M;\bar{a},\bar{b})$
State	$R(M;a,b)=0$	$R(\bar{M};\bar{a},\bar{b})=0$
Constraint	$V(M;a,b)\le 0$	$V(\bar{M};\bar{a},\bar{b})+k\sigma_V\le 0$

Robust Optimization for Geometric Uncertainties

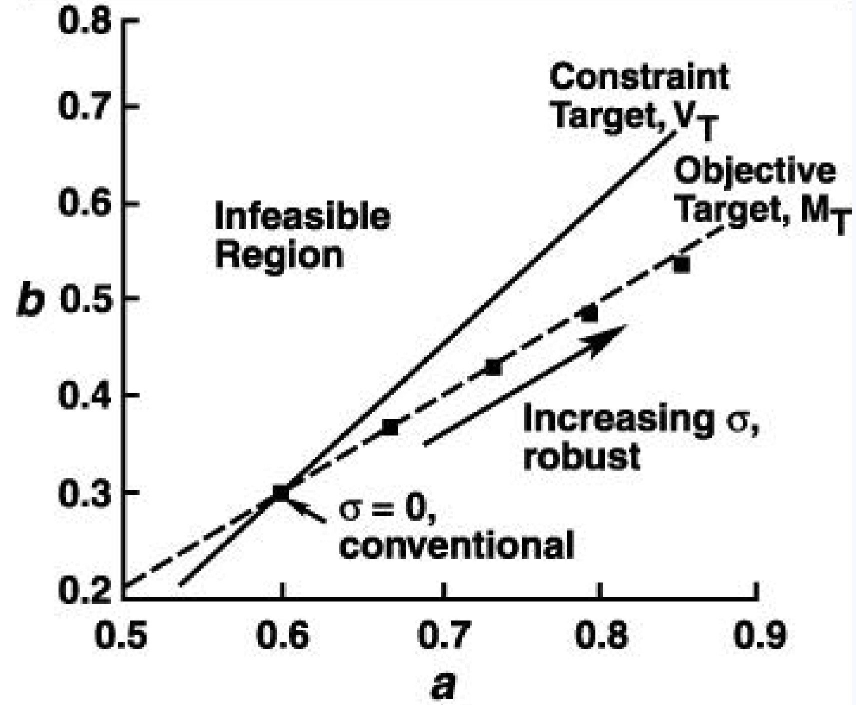
Quasi 1-D Subsonic Nozzle Flow With Fixed Exit Conditions

Optimization Results for Nozzle Area



Nozzle Area Distribution: $A(x)=1-ax+bx^2$

Optimization Results in Design Space (a,b)



Nozzle Volume: $V=1-a/2+b/3$

where a, b are probabilistic geometric design variables with standard deviation $\sigma_a = \sigma_b = \sigma$.

Robust Aerodynamic Shape Optimization

(Luc Huyse: AIAA 2001-1519)

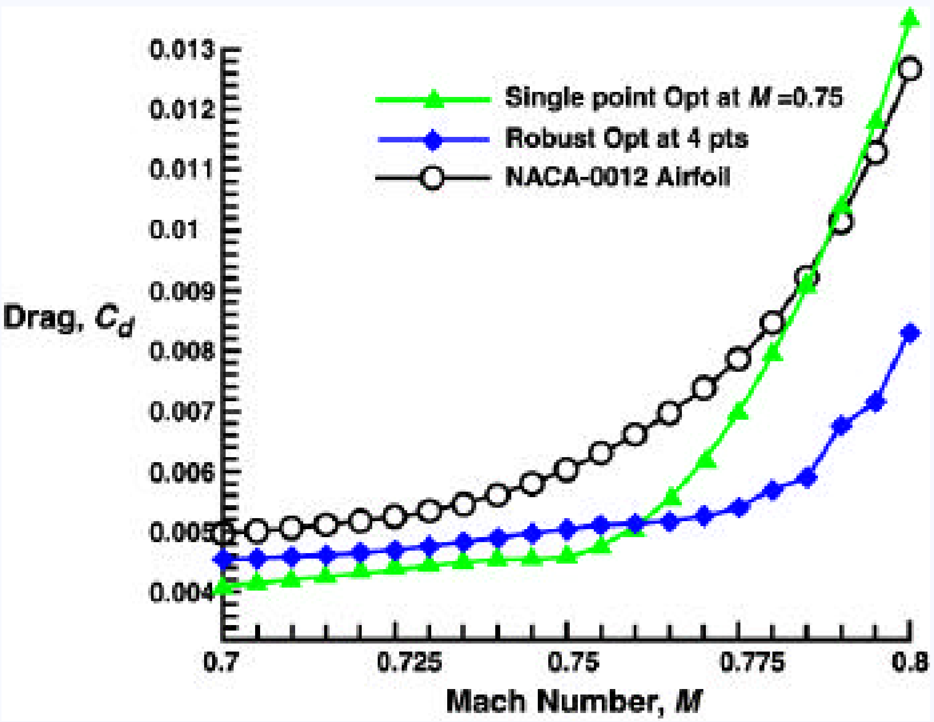
- **Objective**
  - **Minimize drag over a range of Mach numbers**
  - **Limit the number of aerodynamic analyses**
- **Approach**
  - **Use second-order, second-moment approximation to the expected value of drag:**

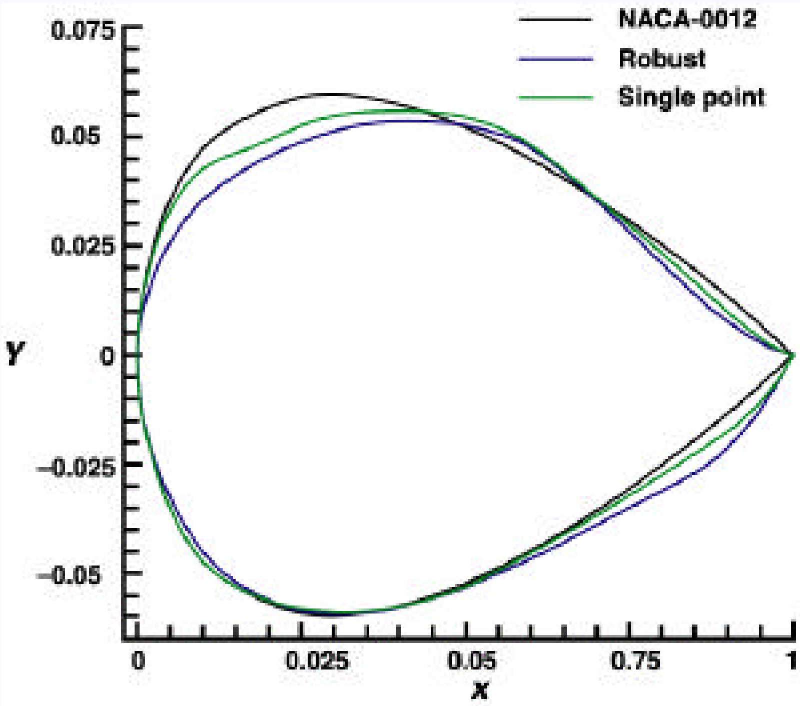
$$\rho^* = \min_{y\ \ \Omega} \left[C_d\left(y, M\right) + \frac{1}{2} Var\left(M\right) \frac{\partial^2 C_d}{\partial M^2}\bigg|_{d,\bar{M}} \right]$$

$$subject\ to: \quad C_l\left(y, M\right) \geq C_l^*$$

Robust Shape Optimization of a 2-D Airfoil

Feasibility Study using a Coarse Unstructured Grid





Improved Performance

Smooth Airfoil Shape

Probabilistic & Possibilistic Structural Design

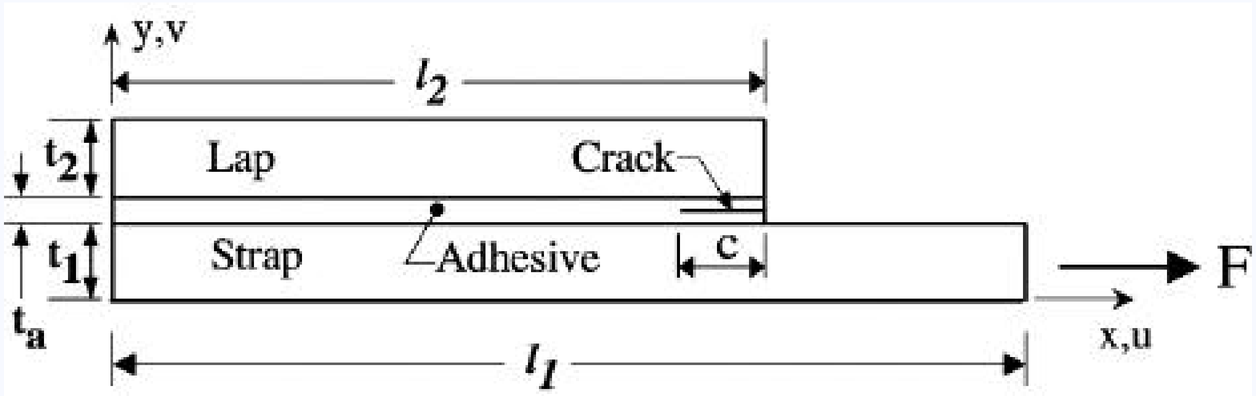
(W. J. Stroud, D. R. Ambur, M. W. Hilburger)

- **Objective**
  - **Develop verified uncertainty-based methodologies for both conceptual and preliminary structural design**
- **Approach**
  - **Develop and assess "possibilistic" analysis methods that account for uncertainties by bounding the uncertainties of the input parameters (e.g., loads) and by determining the corresponding bounds on the response quantities (e.g., stresses)**
  - **Identify structural imperfections that are specific to a manufacturing process for a given class of structures and determine their effect on structural performance through high-fidelity modeling, nonlinear analysis, and experimentation**
  - **Determine ways to transition from methods that make use of bounded uncertainties to methods that make use of a full reliability (probabilistic) analysis**

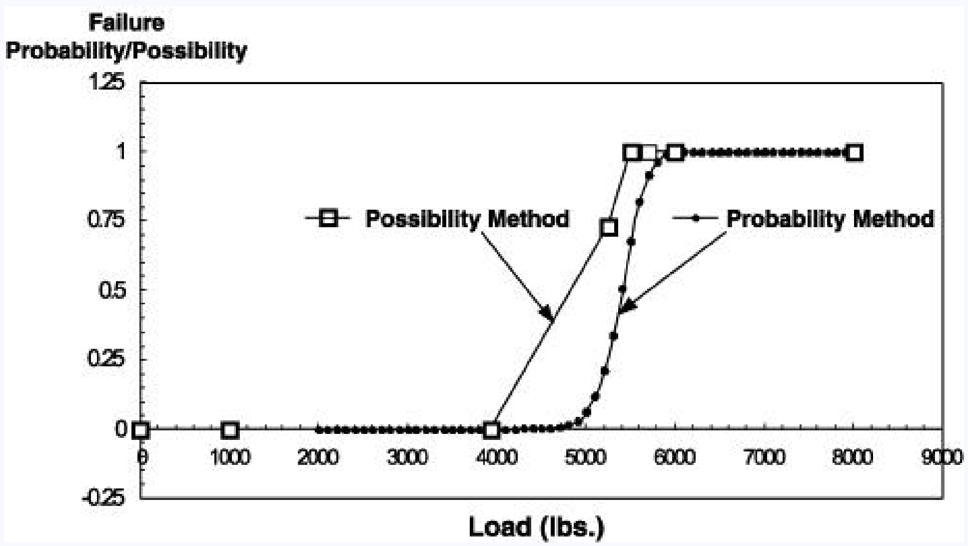
Probability & Possibility Analysis

(W. Stroud, T. Krishnamurthy, I. Raju & E. Glassgen: AIAA 2001-1239)

Lap Joint Model Problem



Nonlinear Analysis

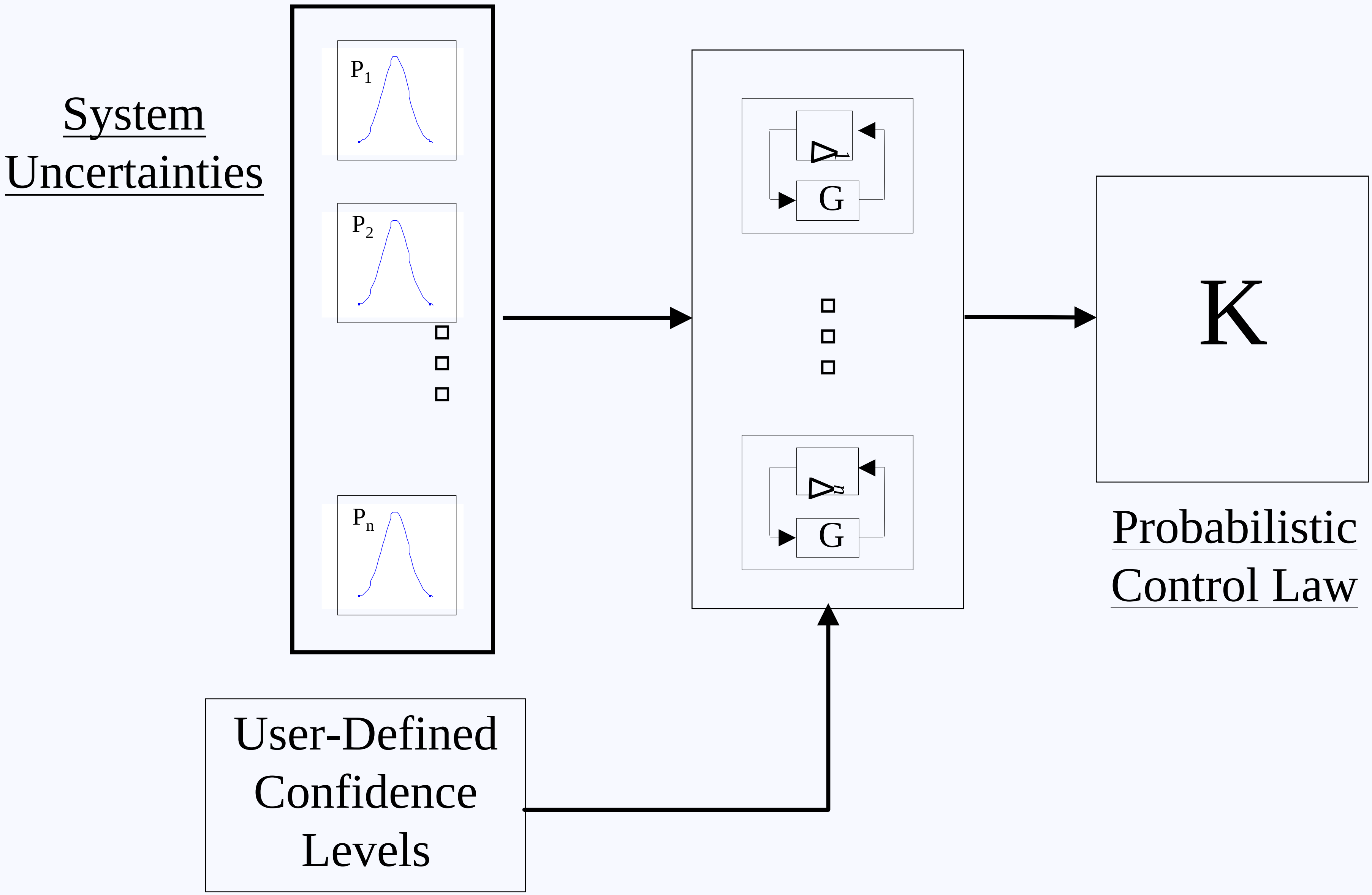


Stochastic Control Laws

(S. Kenny, P. Maghami, D. Miller)

- **Objective**
  - **Develop probabilistic-based methods and tools for robust control design and analysis of aerospace systems**
- **Approach**
  - **Dynamics and Control Analysis: Probabilistic and hypothesis-based software tools and methods for efficient analysis of uncertain systems**
  - **Robust Control Synthesis: Control design strategies for models that are parameterized in terms of probabilistic variables**

Robust Control Synthesis



Technical Challenges

- Rapid assessments of safety & reliability at the conceptual design stage
- Extending risk-based design methods beyond the structures discipline
- Next generation discipline analysis and design algorithms and tools that provide quantitative measures of uncertainties
- Sparse data on uncertainty distributions
- High computational burden of possibilitistic and probabilistic methods
- Strategies for predicting flight loads based on computational, wind tunnel and flight test data