Cumulative Global Metamodels with Uncertainty: A Tool for Aerospace Integration

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Introduction / Motivation

- Aerospace products require integration of multidisciplinary data
- Need for high-level representation based on
  - Limited experimental or numerical data
  - Data from heterogeneous sources
- Multidimensional response surface technology
  - Can handle
    - Multiple fidelity levels
    - Multiple disciplines
    - Technical and nontechnical data
  - Characteristics:
    - Analytical representation
    - Constructed on-the-fly
    - Cumulatively enriched
  - Applications:
    - Design optimization
    - Mutual data set enrichment via data fusion

Background

- Response surface (RS) technology
  - increasingly used:
    - Structural reliability
    - Instrument calibration
    - Aerodynamic and trajectory optimization
  - well-suited for
    - Automated searches
    - Acceleration of optimization tasks, rapid strategy evaluation
- Curse of dimensionality
  - Precludes
    - Polynomial, finite-element approximations
  - Candidates:
    - Neural networks
    - Support vector machines
    - Multidimensional splines
    - Self-training radial basis function networks (NEAR RS)

NEAR RS

- Two modules
  - Metamodel (response surface) identification
  - Metamodel evaluation/interrogation
    - Graphical user interface / multidimensional viewer
- Ability to estimate further sampling needs / model quality
  - Uncertainty estimation

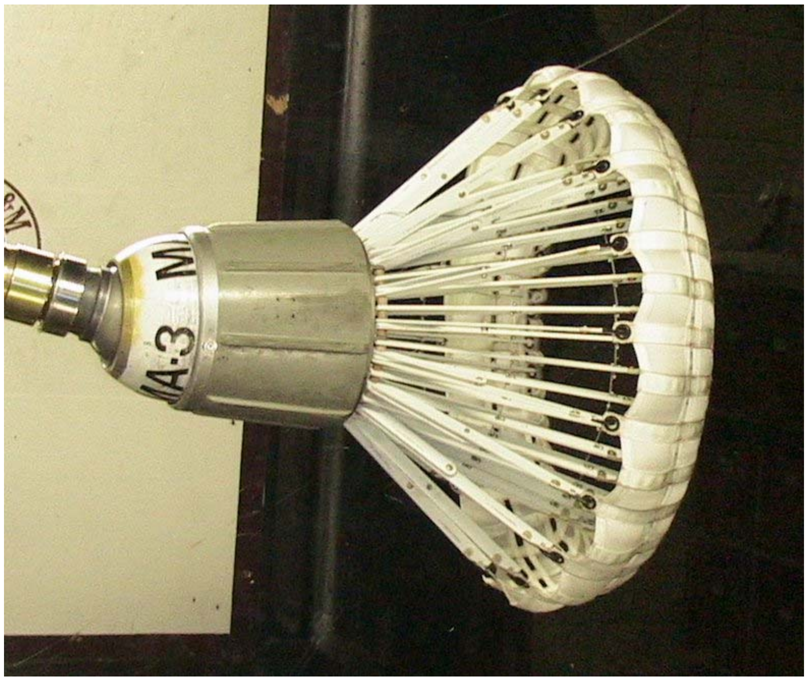
Four Examples

- Design optimization
  - Refueling drogue canopy
  - Large asymmetric launch vehicle payload fairing
- Mutual enhancement of data sets
  - Correction of aerodynamic data base using experimental data
- Uncertainty prediction
  - X-38 forebody aerodynamics

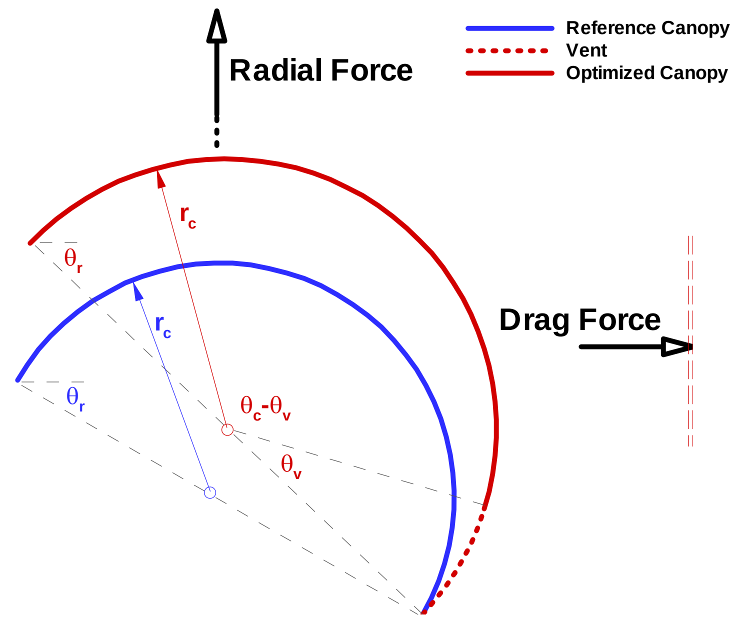
⇨ **Significant acceleration of optimization tasks**
  - CFD usable in preliminary design

⇨ **Data fusion**

Refueling Drogue Canopy Design



Standard C-130 refueling drogue

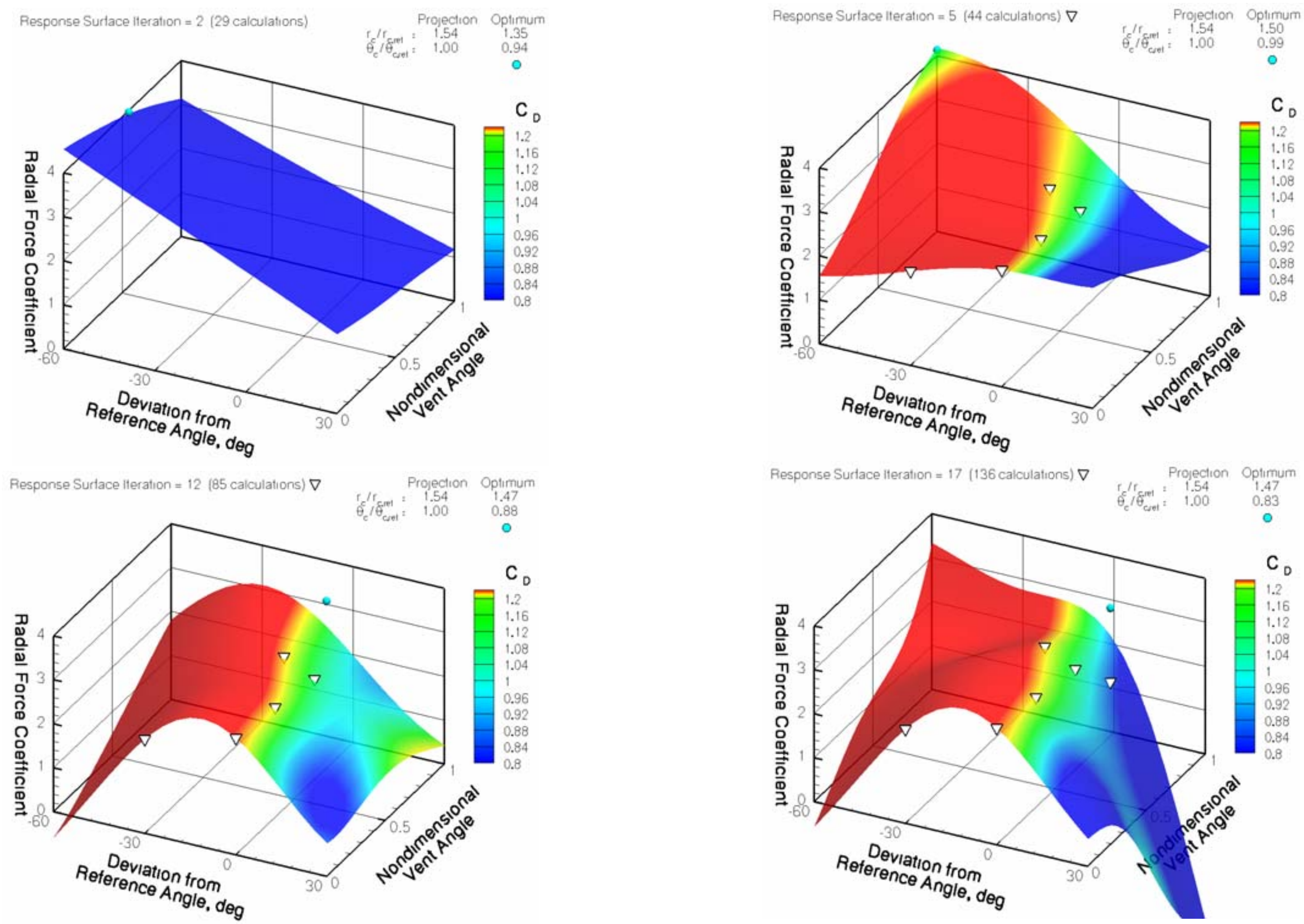


Geometric parameters

Canopy Optimization

- 4 independent variables (θ_r, r_c, θ_c, θ_v), 2 dependent variables (C_R, C_D)
- Constraints via objective function specification
- Procedure:
  - Seed the design space / Design of Experiments
  - Response surfaces identification
  - Global search
  - Add new points to the design space
    - Allow for dynamic strategy
  - Stop criterion

Radial Force Response Surface Evolution



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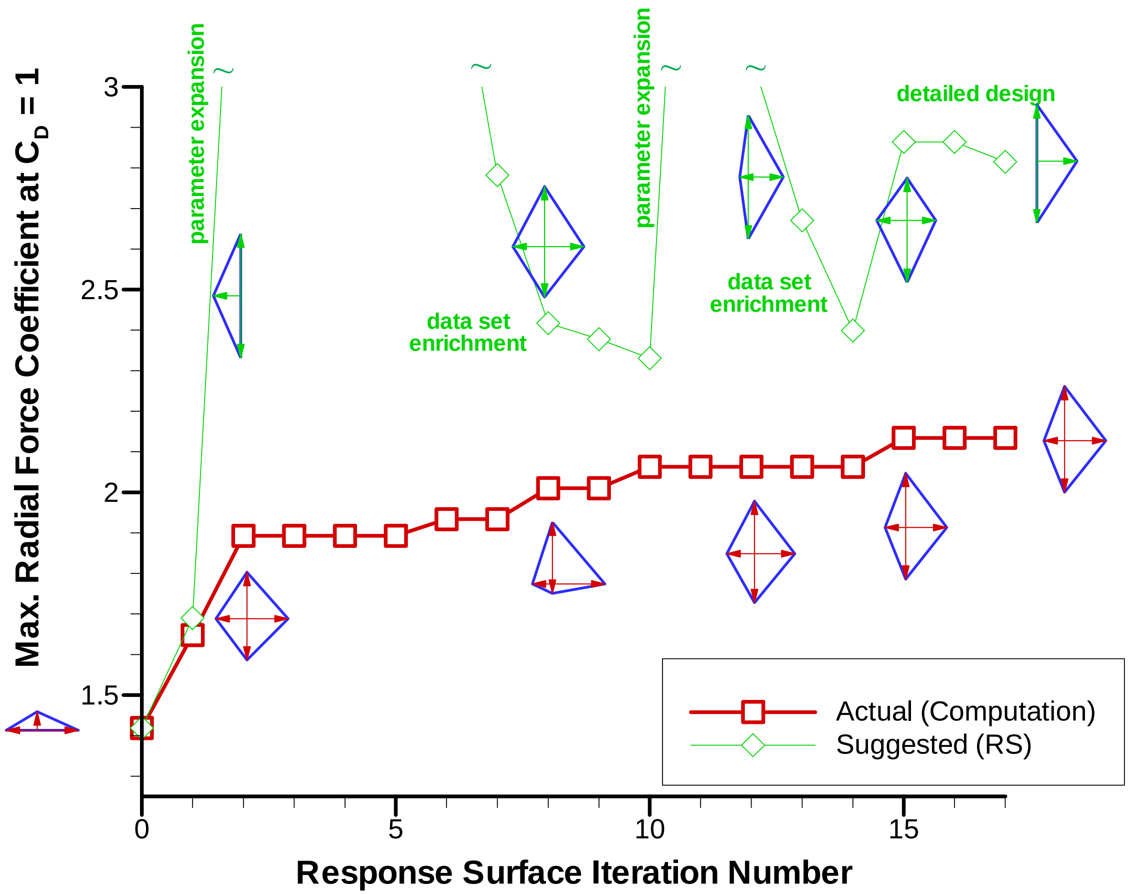
Canopy Design Evolution



surrogate
=
driver

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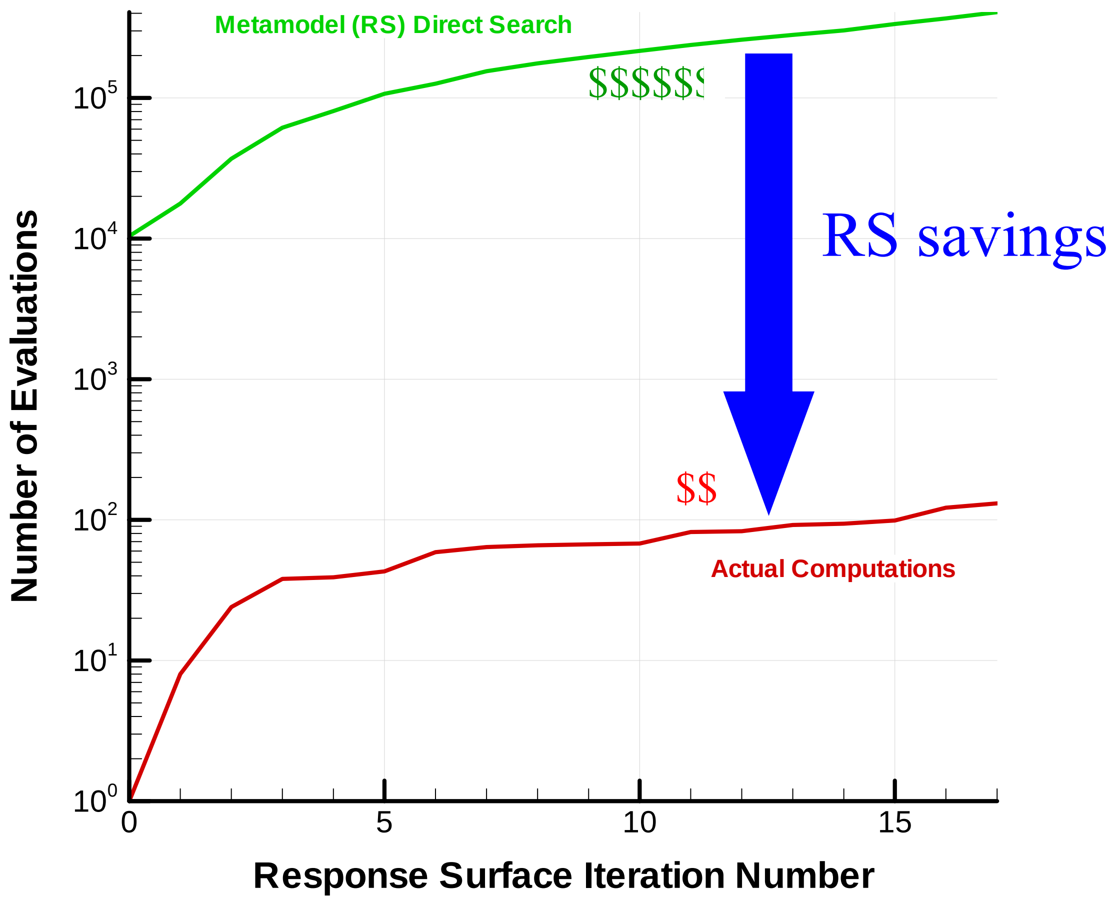
Performance Gain



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Large Asymmetric Launch Vehicle Payload Fairing Design

Thom Baur © The Boeing Company

- Aerodynamic and structural design of payload fairing
  - Spacecraft with optical mirror up to twice the diameter of an EELV
- Reference vehicle: Boeing Delta 4 Heavy

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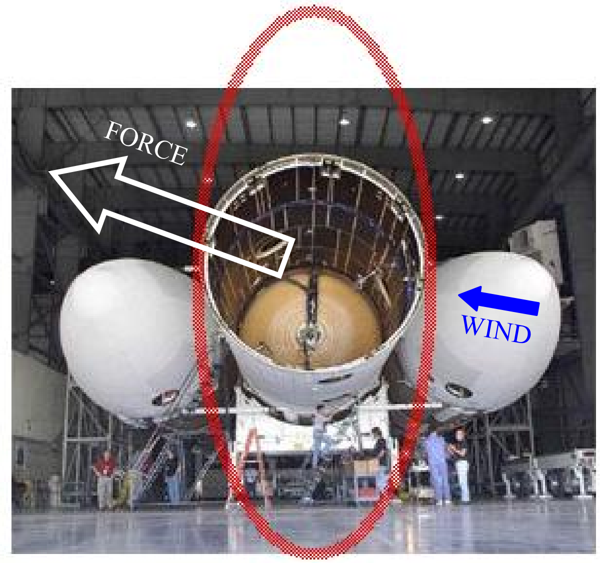
Aerodynamic Design

- Preliminary design goals
  - Stability and control
  - Mass
- Methods
  - Optimization
  - Computational Fluid Dynamics
- Aerodynamic objectives
  - Low lateral force (C_m)
  - Smooth variation with respect to angle of attack near Mach 1.0



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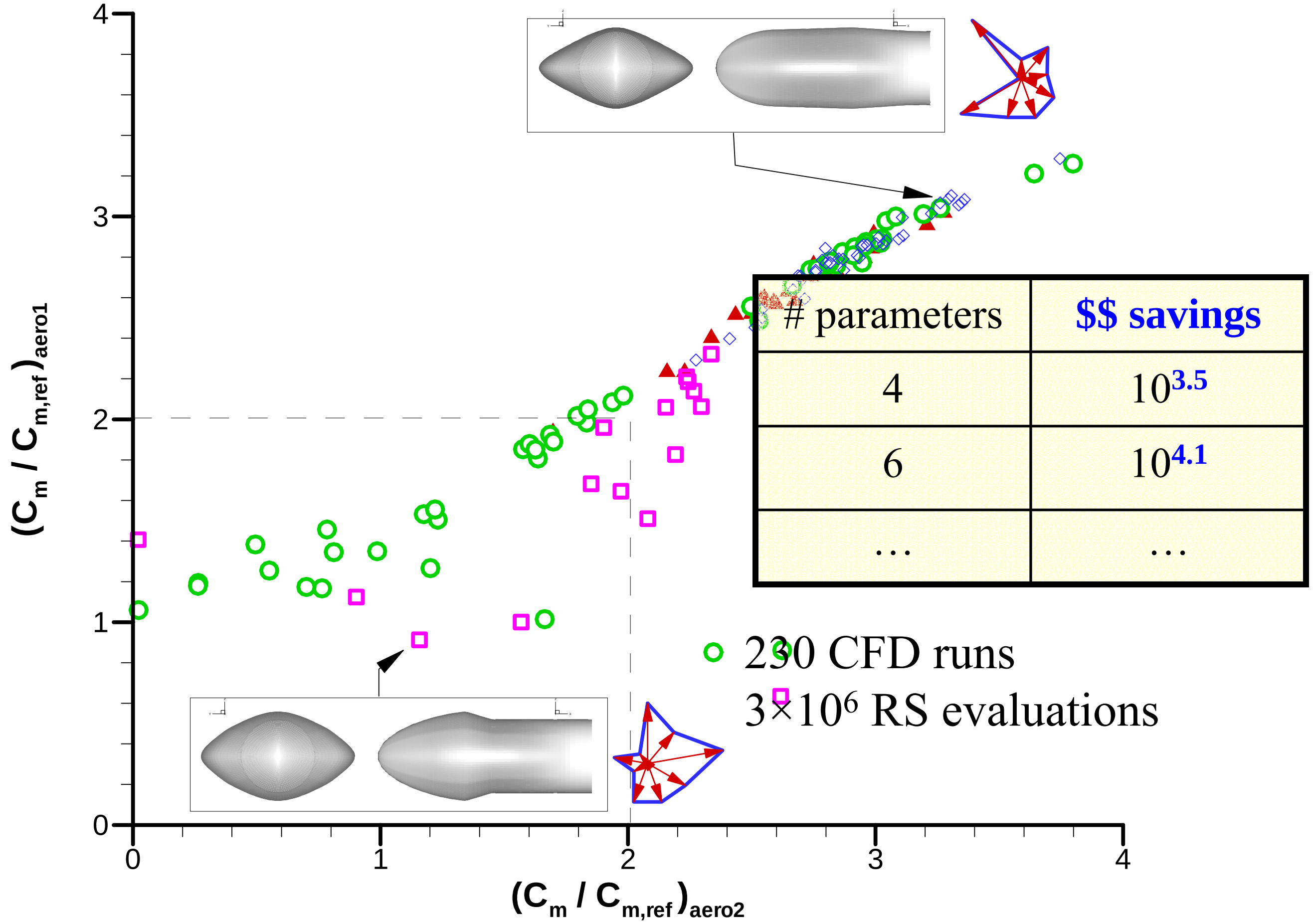
Payload Fairing Optimization

- 9 independent variables (6 active for parameterization of shape), up to 4 dependent variables $C_m(\alpha_i,M_i)_{\ i=1..4} \equiv C_{m,i}$
- Objective function specification = $F(C_{m,1}, C_{m,2}, C_{m,3}, C_{m,4})$
- Procedure:
  - Seed the design space / Design of Experiments $$$$
  - Response surfaces identification $
  - Global search
  - Add new points to the design space (strategy)
    - Automatic remeshing / Overflow / Postprocessing $$$$
  - Stop criterion
  - Verification

Multipoint Fairing Optimization



# parameters	$$ savings
4	$10^{3.5}$
6	$10^{4.1}$
…	…

Mutual Enhancement of Data Sets

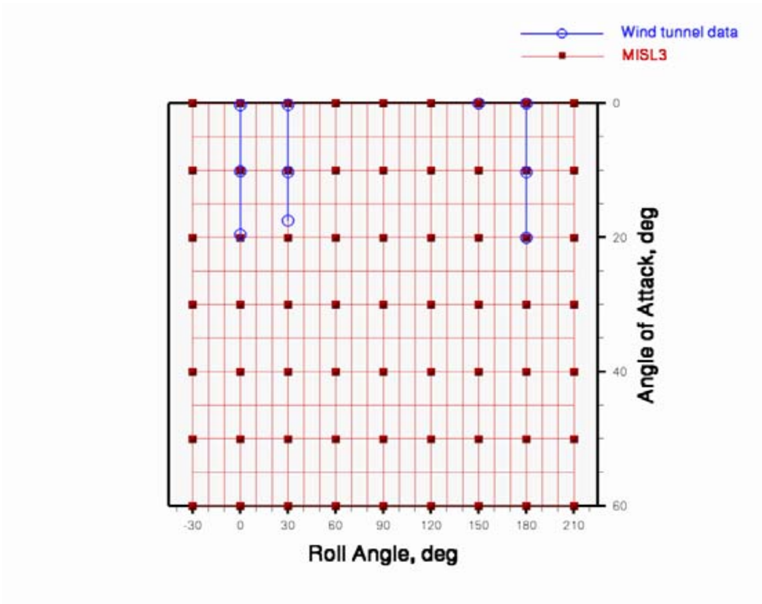
- Global metamodels can be used to
  - perform data fusion operations
  - enhance the usefulness of limited experimental data
- Interpolation / Extrapolation / Data generalization
  - ill-posed problem
  - regularizing assumptions
    - physics based models
    - mathematical equations
    - smoothness assumptions
    - empiricism
    - **hypersurface**
      - going through the experimental data
      - “supported” by additional computational constraints

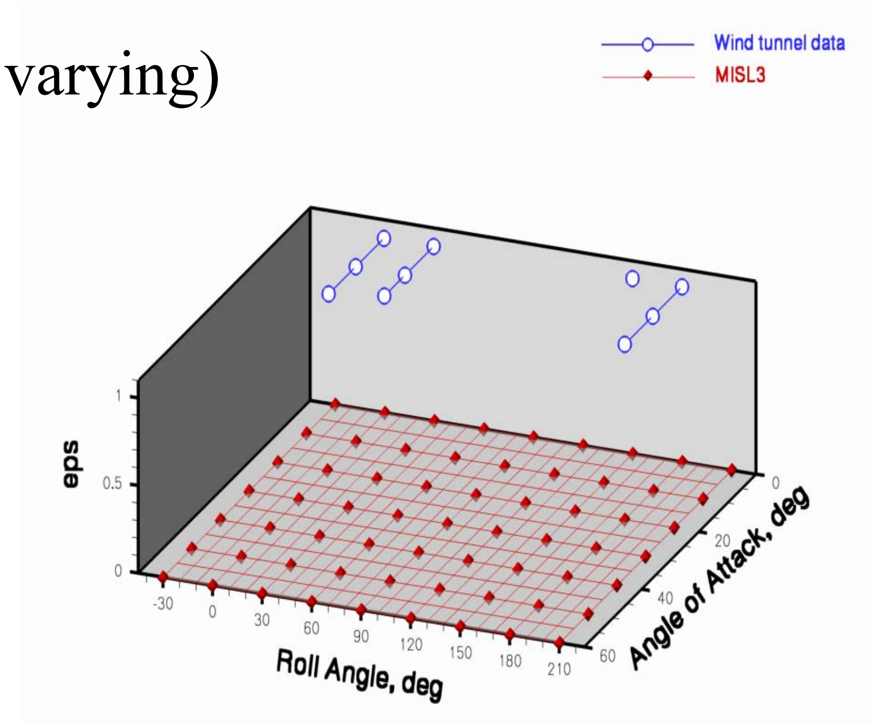
Correction of Aerodynamic Databases Using Experimental Data

- Wind-tunnel data assimilation for use in flight simulations
- Generic body-tail configuration
- Two data sets
    - experimental (wind tunnel) data
    - “computational” data (MISL3 database)
        - Forces and moments
        - Wide range of angles of attack, roll angles, and Mach numbers
- “Error database”

Error database

- Defined as difference between two fits
  - Four-dimensional
  - Analytic (smoothly varying)

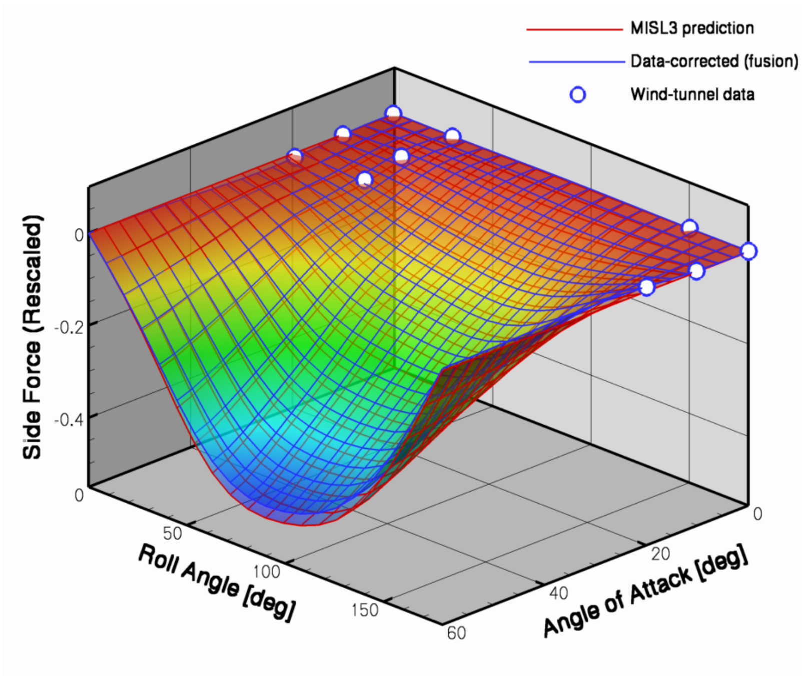




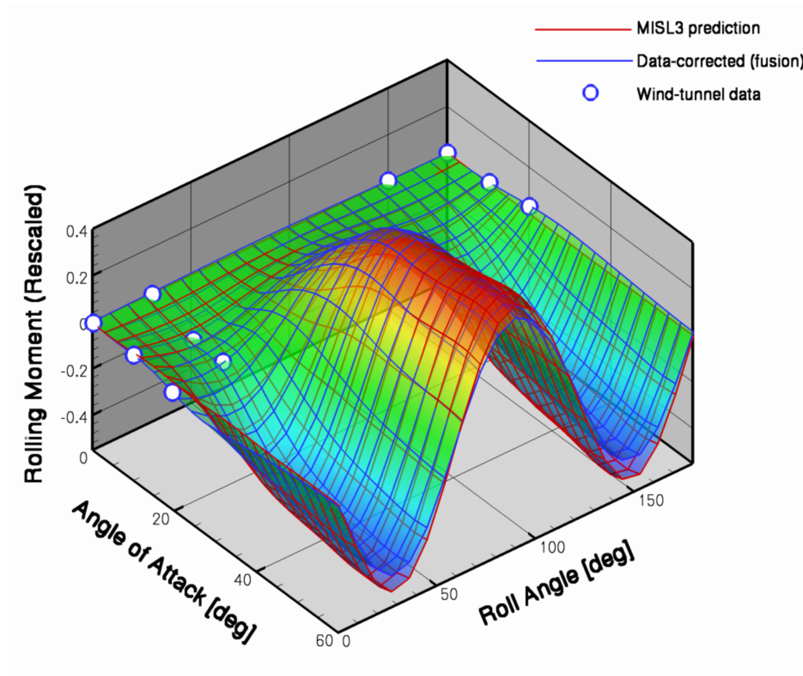
Error database

- Used to “correct” MISL3 database
    - Takes into account experimental measurements
- Smart interpolation/extrapolation
    - Process is automatic
    - No equations specified

Wind Tunnel Data Enhancement of MISL3 Database



Side Force



Rolling Moment

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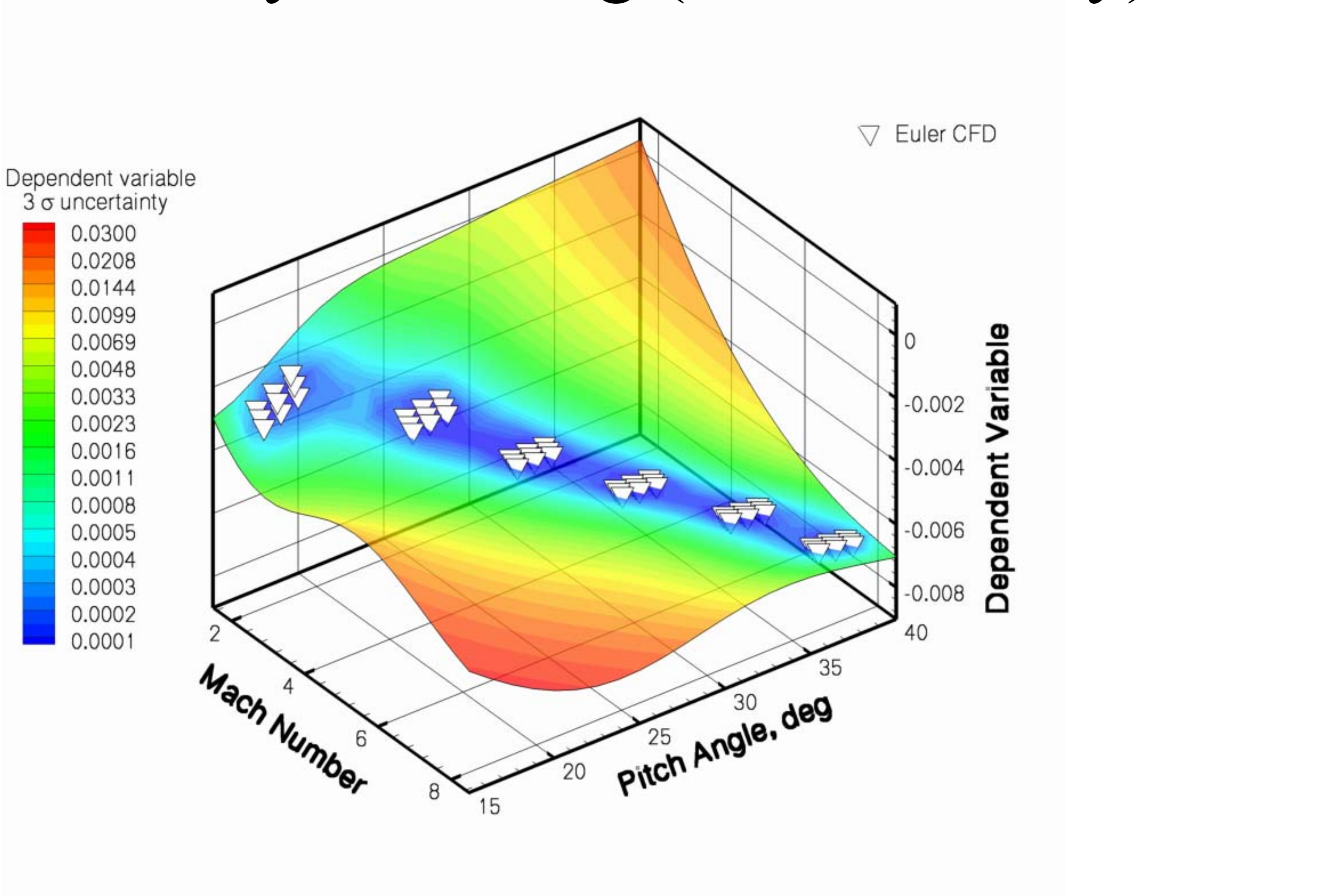
Uncertainty Prediction in NEAR RS

- Uncertainty estimation based on propagating statistical descriptions of uncertainty in measurements (input data) to uncertainty in the response surface coefficients.
- Approach
  - uses the covariance of the output measurements
  - based on theory of best linear unbiased estimation

Uncertainty Modeling (X-38 Reentry)

- 3D Euler solutions (NASA Ames)
- Each CFD solution = 1 point in multidimensional space
- Solution space parameterized by
    - Mach number
    - pitch angle
    - grid resolution
    - algorithm

Uncertainty Modeling (X-38 Reentry)



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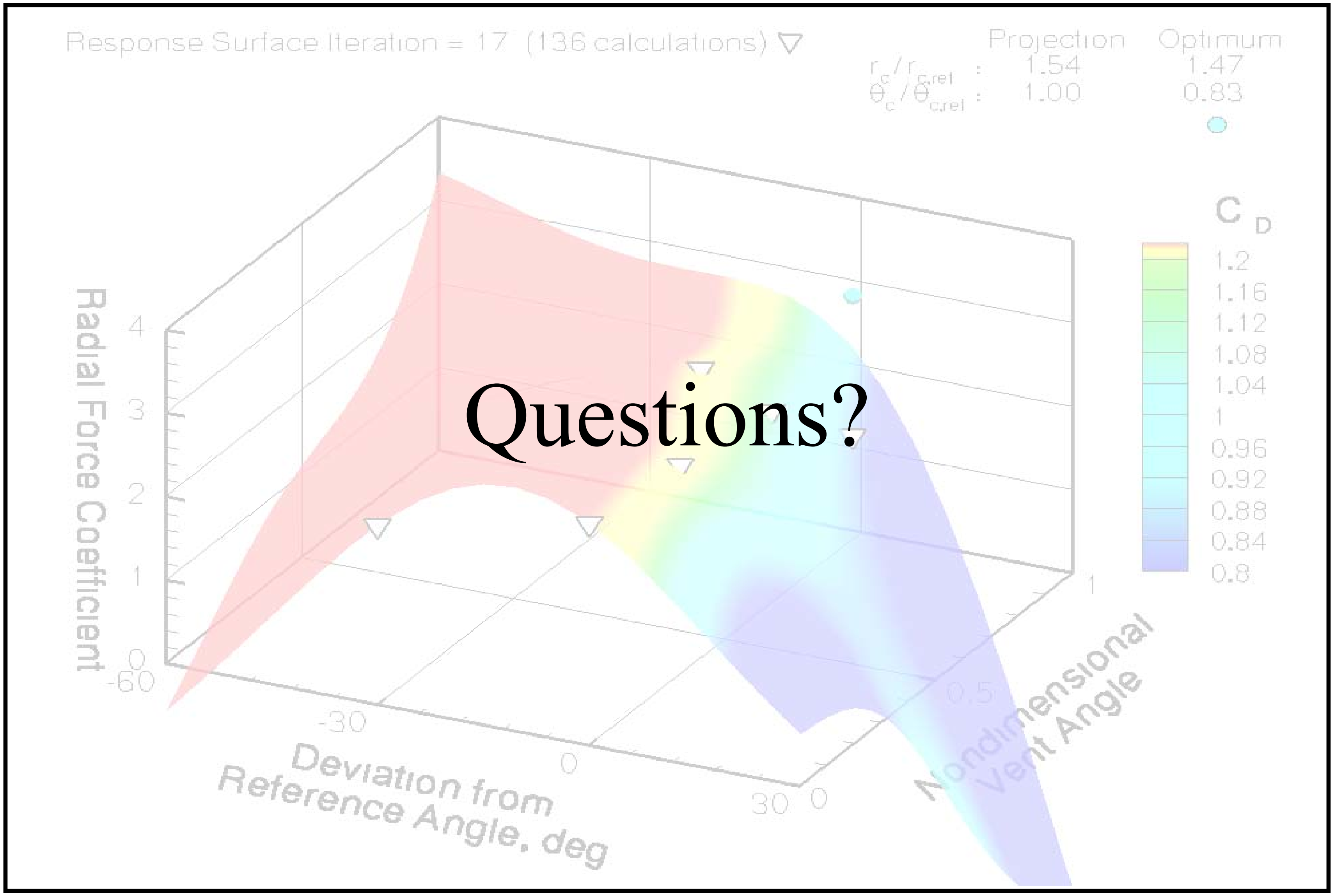
Cumulative Global Metamodels: Conclusion

- Significant cost savings in design optimization tasks
- Fully analytic, mathematical description
  - easily manipulated and shared
  - Data structure flexibility / use of heterogeneous data sets
- Rational basis for propagating uncertainty estimates
  - suitable for risk assessment
- Metamodel uncertainty can be used as a driver for decision making, further populating data sets.



Questions?

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