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 ($\theta_r$, $r_c$, $\theta_c$, $\theta_v$), 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
Canopy Design Evolution

Max. Radial Force Coefficient at $C_D = 1$

Parameter expansion

Data set enrichment

Detailed design

Surrogate = driver

Response Surface Iteration Number

Actual (Computation)

Suggested (RS)
Performance Gain

- **Response Surface Iteration Number**
- **Number of Evaluations**

Metamodel (RS) Direct Search

RS savings

Actual Computations

- **$$$$$$**
- **$$**

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Large Asymmetric Launch Vehicle Payload Fairing Design

- 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
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
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 $\$

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Multipoint Fairing Optimization

![Diagram of multipoint fairing optimization with data points and parameters listed in a table]

- **# parameters** | **$$ savings**
  - 4 | $$10^{3.5}$$
  - 6 | $$10^{4.1}$$
  - ... | ...

- 230 CFD runs
- 3 x 10^6 RS evaluations
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” MISP3 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
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)
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?