

Multidisciplinary Design Optimization of Advanced Aircraft Configurations

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and students:

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Research: MDO of Aircraft Configurations

→ MAD Center

- MDO Design *philosophy*
 - impracticality of *brute-force* linking of high-fidelity codes
 - variable-complexity modelling (VCM)
 - response-surface methodology (RSM)
- Incorporating CFD and FE Structures into conceptual design
 - VCM reduces computational burden
 - RSM allows the study of design trade-offs
- Design space exploration
 - RSM in high-dimensional design spaces
 - design space visualization with local optima
- Parallel computing
 - Dynamic load balancing reqd. for evaluating millions of configurations
 - Distributed load control for scalability

Research (continued): MDO of Aircraft Configurations

→ MAD Center

- Global optimization
 - Number of processors and choice of algorithm
 - Preliminary results with multi-start local and global optimization
- Protection against modeling and simulation uncertainties in optimization
 - Discrepancies in simulations of varying fidelity and empirical data
 - Automated diagnostic methodology, robust statistics
- Problem solving environments
 - VRML based VIZCRAFT
 - parallel coordinates
- Design example: Strut-Braced Wing
 - MDO crucial to design
 - CFD and aeroelasticity still offline
 - Transonic transport (Boeing 777 mission): 19% TOGW reduction, 24% less fuel, 46% fewer emissions

Selected References

Response surface methodology:

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Design space exploration:

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Using detailed CFD in design:

- Knill, D. L., Balabanov, V., Golividov, O., Grossman, B., Mason, W. H., Haftka, R. T. and Watson, L. T., “Accuracy of Aerodynamic Predictions and Its Effects on Supersonic Transport Design,” MAD Center Report 96-12-01, Virginia Tech, AOE Dept., Blacksburg, VA, Dec. 1996.
- Mason, W. H., Knill, D. L., Giunta, A. A., Grossman, B., Haftka, R. T. and Watson, L. T., “Getting the Full Benefits of CFD in Conceptual Design,” AIAA 16th Applied Aerodynamics Conference, Paper No. 98-2513, Albuquerque, NM, June 1998.
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Using detailed structural analysis in design:

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Parallel computing:

- Burgee, S., Giunta, A. A., Balabanov, V., Grossman, B., Mason, W. H., Narducci, R., Haftka, R. T., and Watson, L. T., “A Coarse Grained Variable-Complexity Multidisciplinary Optimization Paradigm,” *Intl. J. Supercomputing Applications and High Performance Computing*, **10**, No. 4, 1996, pp. 269-299.
- Krasteva, D. T., Baker, C., Watson, L. T., Grossman, B., Mason, W. H. and Haftka, R. T., “Distributed Control Parallelism for Multidisciplinary Design of a High Speed Civil Transport”, in *Proc. 7th Symp. on the Frontiers of Massively Parallel Computation*, IEEE Computer Soc., Los Alamitos, CA, 1999, 166–173; also MAD Center Report 98-11-01, Virginia Tech, AOE Dept., Blacksburg, VA, Nov. 1998.
- Krasteva, D. T., Watson, L. T., Baker, C., Grossman, B., Mason, W. H. and Haftka, R. T., “Distributed control parallelism in multidisciplinary aircraft design”, *Concurrency, Practice Experience*, Vol. **11**(8), 1999, pp. 435–459.

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Global optimization:

- Cox, S. E., Haftka, R. T., Baker, C. A., Grossman, B., Mason, W. H. and Watson, L. T., “Global Optimization of a High Speed Civil Transport Configuration”, Proceedings of the Third World Congress on Structural and Multidisciplinary Optimization, Amherst, NY, May 1999.

Problem solving environments:

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HSCT design problem:

- MacMillin, P. E., Mason, W. H., Grossman, B. and Haftka, R. T., “An MDO Investigation of the Impact of Practical Constraints on an HSCT Configuration,” AIAA 35th Aerospace Sciences Meeting & Exhibit, Paper No. 97-0098, Reno, NV, Jan. 1997.

Selected References (continued)

MDO Application: strut-braced wing transport:

- Grasmeyer, J. M., Naghshineh-Pour, A., Tetrault, P.-A., Grossman, B., Haftka, R. T., Kapania, R. K., Mason, W. H. and Schetz, J. A., “Multidisciplinary Design Optimization of a Strut-Braced Wing Aircraft with Tip-Mounted Engines,” MAD Center Report 98-01-01, Virginia Tech, AOE Dept., Blacksburg, VA, Jan. 1998.
- Gern, F. H., Gundlach, J., Naghshineh-Pour, A., Sulaman, E., Tetrault, P., Grossman, B., Haftka, R. T., Kapania, R., Mason, W. H. and Schetz, J. A., “Multidisciplinary Design Optimization of a Transonic Commercial Transport with a Strut-Braced Wing,” Paper 1999-01-5621, World Aviation Congress and Exposition, San Francisco CA, Oct. 1999.
- Gundlach, J., Gern, F., Tetrault, P., Naghshineh-Pour, A., Ko, A., Grossman, B., Haftka, R. T., Kapania, R. K., Mason, W. H., and Schetz, J. A., “Multidisciplinary Optimization of a Strut-Braced Wing Transonic Transport,” AIAA 36th Aerospace Sciences Meeting & Exhibit, Paper No. 98-0420, Reno, NV, Jan. 2000.

MDO in Aircraft Design

Integrated Design

- Aerodynamics, Structures, Performance
- Controls, Propulsion
- Manufacturing, Costs

Conceptual Design Level

- Simple analysis methods
(algebraic, tables, FLOPS, ACSYNT)
- Traditionally multidisciplinary

Preliminary Design Level

- More detailed analysis methods
(panel codes, beam models)
- Usually disciplinary

Detailed Design

- State-of-the-art analysis methods
(Navier-Stokes, detailed finite-element)
- Disciplinary

Our Approach to MDO

Objective:

- Utilize detailed analysis methods in the early stages of a multidisciplinary design process
 - new concepts with weak historical database
 - market-driven efficient designs

Problem:

- Computational cost of hundreds of thousands of high-fidelity analyses
- Numerical noise due to discretization, incomplete convergence, shocks, irregular constraint boundaries, etc.
- Immense, non-convex design spaces

Approach:

- Variable-Complexity Modeling (VCM):
 - simultaneous use of several models (analyses) of different levels of complexity and fidelity
- Response Surface Models (RSM):
 - curve fitting (polynomial approximation) to the results of multiple analyses based on design of experiments theory

Variable-Complexity Modelling

VCM: simultaneously use both simple and detailed analysis methods

- simple models: hundreds of thousands of evaluations
 - detailed models: thousands of evaluations
 - very detailed models: ten to a hundred of evaluations
- Replace disciplinary, detailed model with simple model
 - e. g., weight equation instead of finite-element structural analysis
 - Use detailed model sparingly, by calibrating simple model
 - approximate (algebraic) solution $F_A(\vec{x})$.
 - detailed solution $F_D(\vec{x})$.

$$\sigma(\vec{x}_0) = F_D(\vec{x}_0) / F_A(\vec{x}_0)$$

$$F(\vec{x}) = \sigma(x_0) F_A(\vec{x})$$

- Explore design space with simple models and use detailed model in promising regions
- Use functional form of simple models to generate response surface models from detailed analyses.

Variable-Complexity Modelling: Experience

Variable-Complexity Modelling:

is an effective procedure to reduce the computational burden of multidisciplinary design optimization.

Problem Areas:

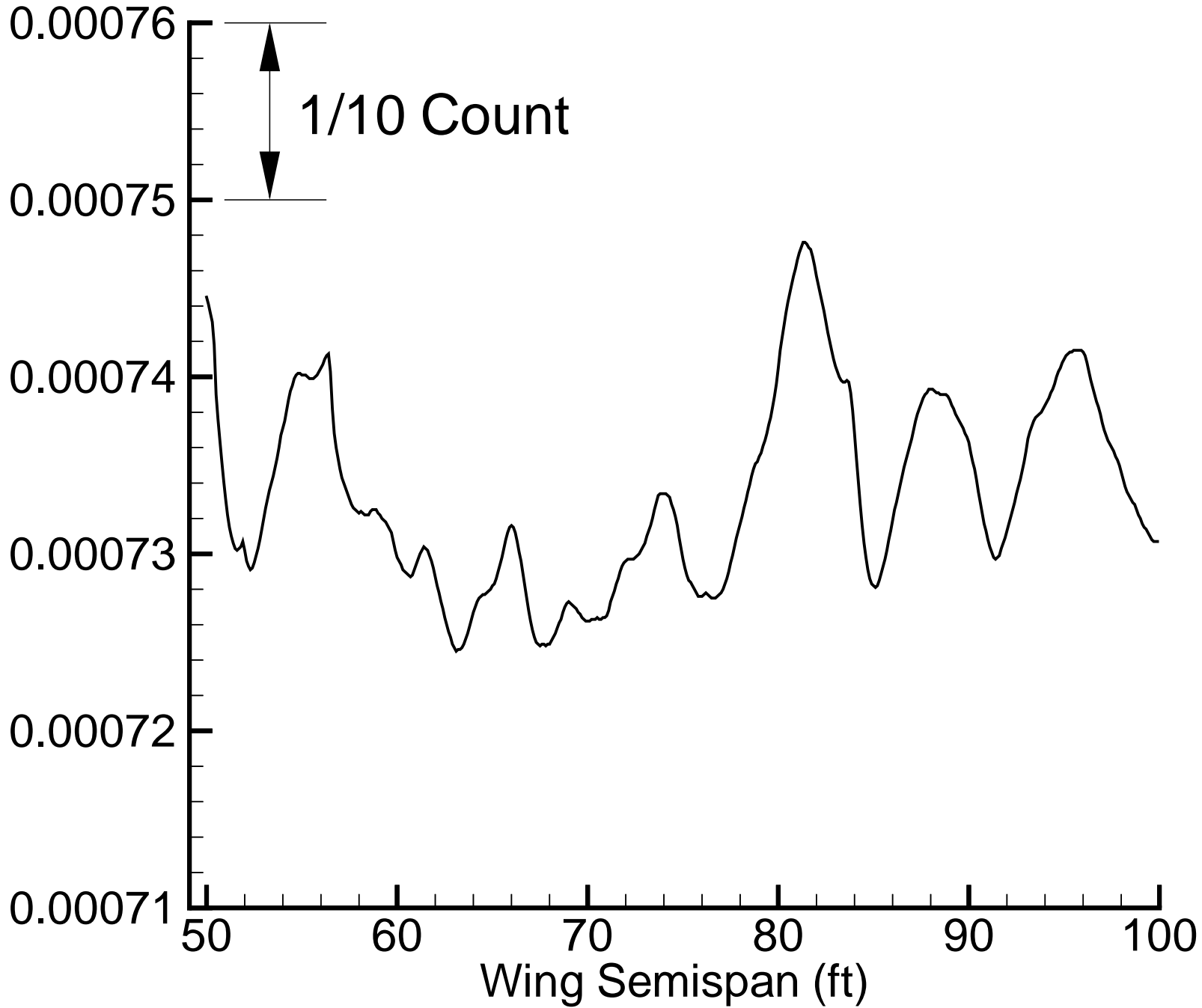
- Convergence difficulties due to noisy and non-smooth derivatives.
- Local minima in design space.
- Not adequate for very high-fidelity codes.
 - Euler/ Navier-Stokes
 - Detailed finite-element

The Next Step:

- Take advantage of the power of parallel computing.
- *Customized* response surface methodology.
- Use variable-complexity strategy to address *curse of dimensionality*.

C_{Dwave}

Noisy Analysis Example



Response Surface Modelling

Response Surface:

- Curve-fit, using polynomial approximation (typically quadratic), the *response* in terms of specified variables.

$$Y = c_0 + \sum_{1 \leq j \leq N} c_j x_j + \sum_{1 \leq j \leq k \leq N} c_{j,k} x_j x_k$$

- For HSCT design problem, response surfaces for drag and material bending weight.

Size of the model:

- For quadratic response surface in N variables, $(N + 1)(N + 2)/2$ coefficients.
for 10 variables, 66 coefficients, at least 100 analyses.
for 25 variables, 351 coefficients, at least 500 analyses.

Size of the design space:

- Candidate design at each corner of the design space, there will be 2^N candidate designs.
10 variables, 1,024 vertices.
25 variables, 33,500,000 vertices.
- *Curse of dimensionality.*

Customized Response Surfaces

- Use variable-complexity modelling to develop *customized* response surfaces.
- Preliminaries with simple analyses
 - From analytical form determine appropriate functional form (*e.g.*, log-log) and appropriate variables.
 - Analyze very large number of candidate designs.
 - Reduce design space by applying geometric constraints and approximate performance constraints.
 - Reduce design space by eliminating *nonsense* designs.
 - Use statistical techniques to determine the *best* locations to evaluate candidate designs.
- Response surface with detailed analyses.
 - Use coarse-grained parallel computing.
 - Fit response surface for the aerodynamic drag components and wing bending material weight.
- Perform MDO using response surfaces.

Issues Leading to the Use of Response Surfaces

Prehistoric (No Computers) Design Process:

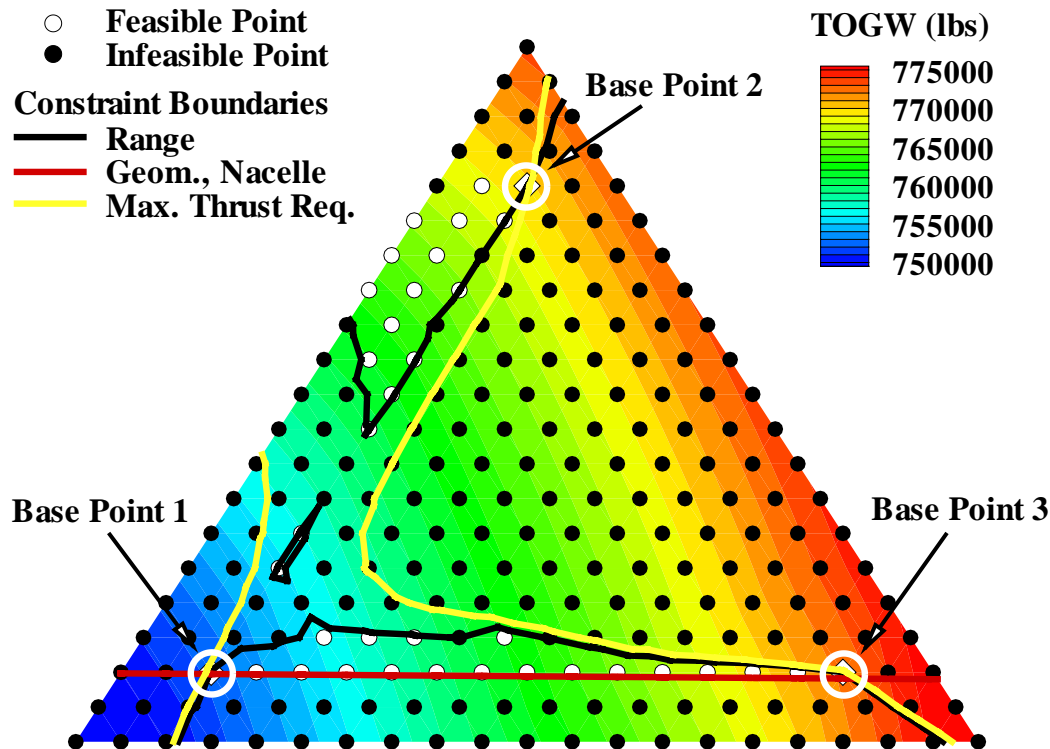
- Prehistoric integration problem:
 - Designers (generalists) lacked skills to exercise methods devised by analysts (specialists).
- Solution: Provide designers with RESULTS rather than tools.
- Requirement: Collapse information depending on a large number of parameters on two dimensional design charts.
 - Use experience and common sense to narrow down ranges of parameters.
 - Use similarity parameters to reduce number of variables.
 - Use appropriate scales (e.g., log-log).
- Experimentalists still use these approaches today.

Advantages of Response Surface Approach

- Disciplinary codes can be exercised independently by specialists rather than generalists.
- Errors reduced because designs analyzed in groups rather than singly.
- Computational efficiency through parallel computing.
- Response surface construction provides insight into design tradeoffs.
- Simplified MDO code integration.
- Noise filtered out.

- Optimization task becomes computationally trivial and permits:
 - Global optimization.
 - Multicriterion optimization.
 - Reliability based optimization.
- Design trade-offs, off-design performance, design space visualization, alternate objective functions greatly facilitated with response surfaces

The Design Space



Visualization Plot

- Choose 3 Feasible *Base Points*

- Connect *Base Points* to get Plane in 28-Dimensional Space

- Create Grid in Plane

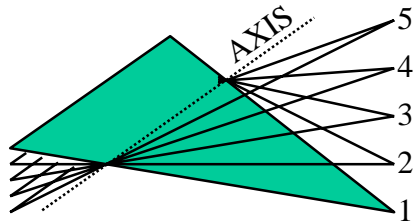
- Evaluate Objective Fn. and Constraints at Grid Points (with RS models)

Infeasible Points outside Constraint Boundaries on plot violate Side Constraints

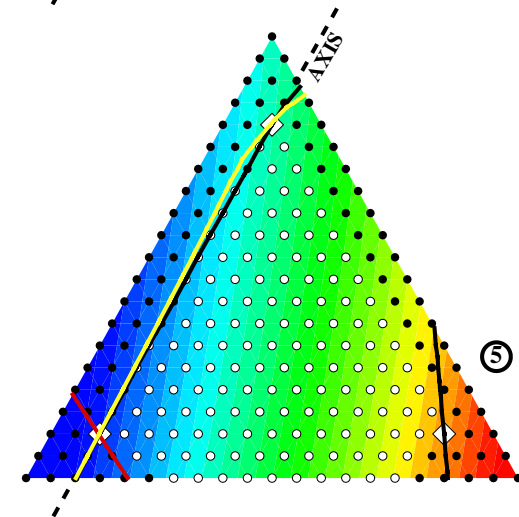
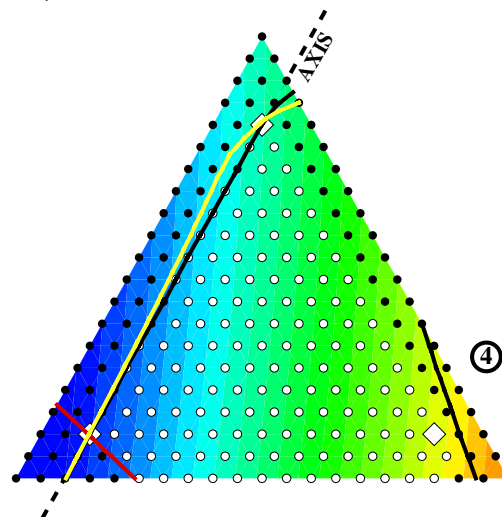
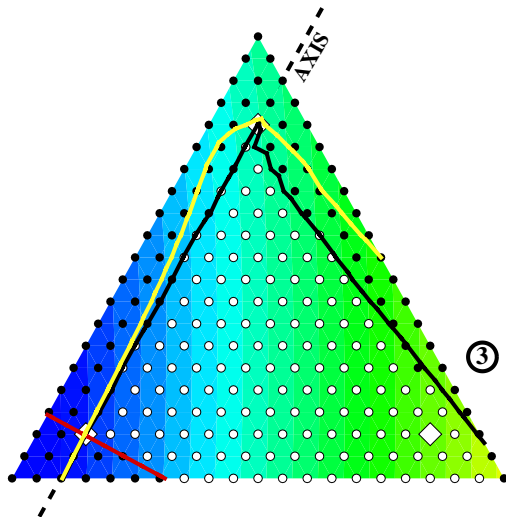
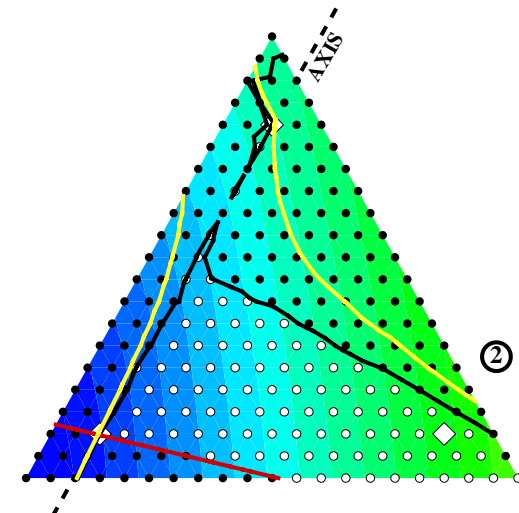
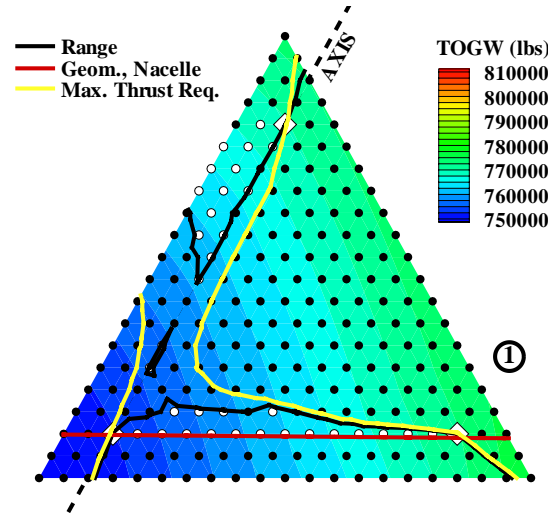
- Even in Simplified Plot, Design Space appears Complicated, Nonconvex

- Range Constraint is Multiply Connected even with Quadratic Drag RS Models

The Design Space, contd.



- *Base Points 1 & 2 are fixed*
- *Base Point 3 varies linearly*



VizCraft

VizCraft

Design View Help

Design variables file: /home/agoel/HSCT/dv/design.variables

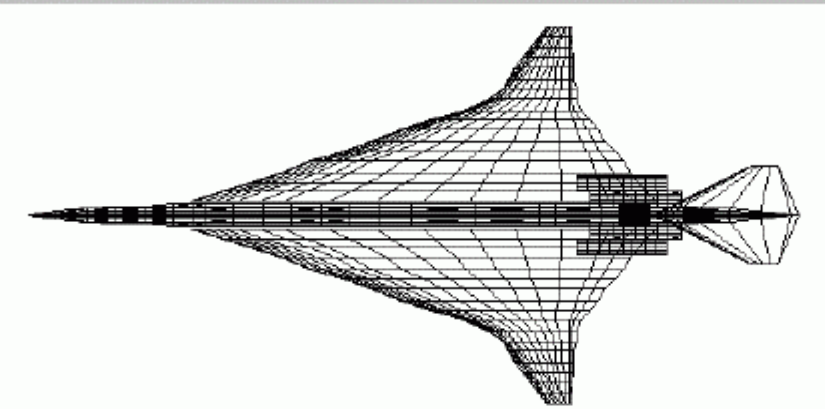

Design Variables

- Wing Platform
- Fuselage Shape
- Engine Nozzle Location
- Mission Variables
- Tail Area

Constraints Evaluate

Aerodynamic	5	2	32
Geometric	2	3	23
Performance	3	3	19

TOGW (lbs.) 750130.0

Wing Root Wing Break Wing Tip

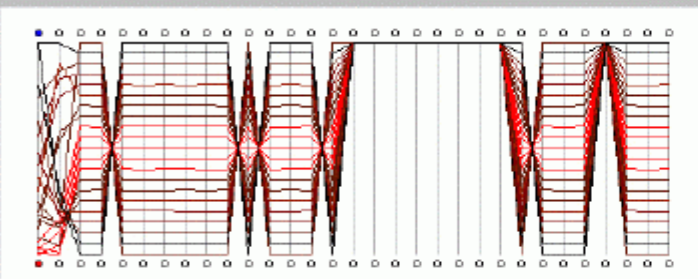
Status: idle

Wing Platform Variables

wing root chord (ft)	181.30020
leading edge break x (ft)	139.26359
leading edge break y (ft)	43.86310
trailing edge break x (ft)	151.30927
trailing edge break y (ft)	40.82056
leading edge wing tip, x (ft)	138.76042
wing tip chord (ft)	50.23061
wing semi-span (ft)	78.50371
location of max t/c on airfoil (x/D)	0.49518
leading edge radius parameter	2.95539
thickness-to-chord ratio at wing root	0.02343
thickness-to-chord ratio at LE break	0.02742
thickness-to-chord ratio at wing tip	0.01500

Save Reset Close

Design Space



Name of field	minimum	maximum
TOGW (lbs)	750350.00000	789411.00000
	zoom from	zoom to
	750350.00000	789411.00000

from to rendered discarded reorder

1 2 21 0 Insert

View Undo Reset Close

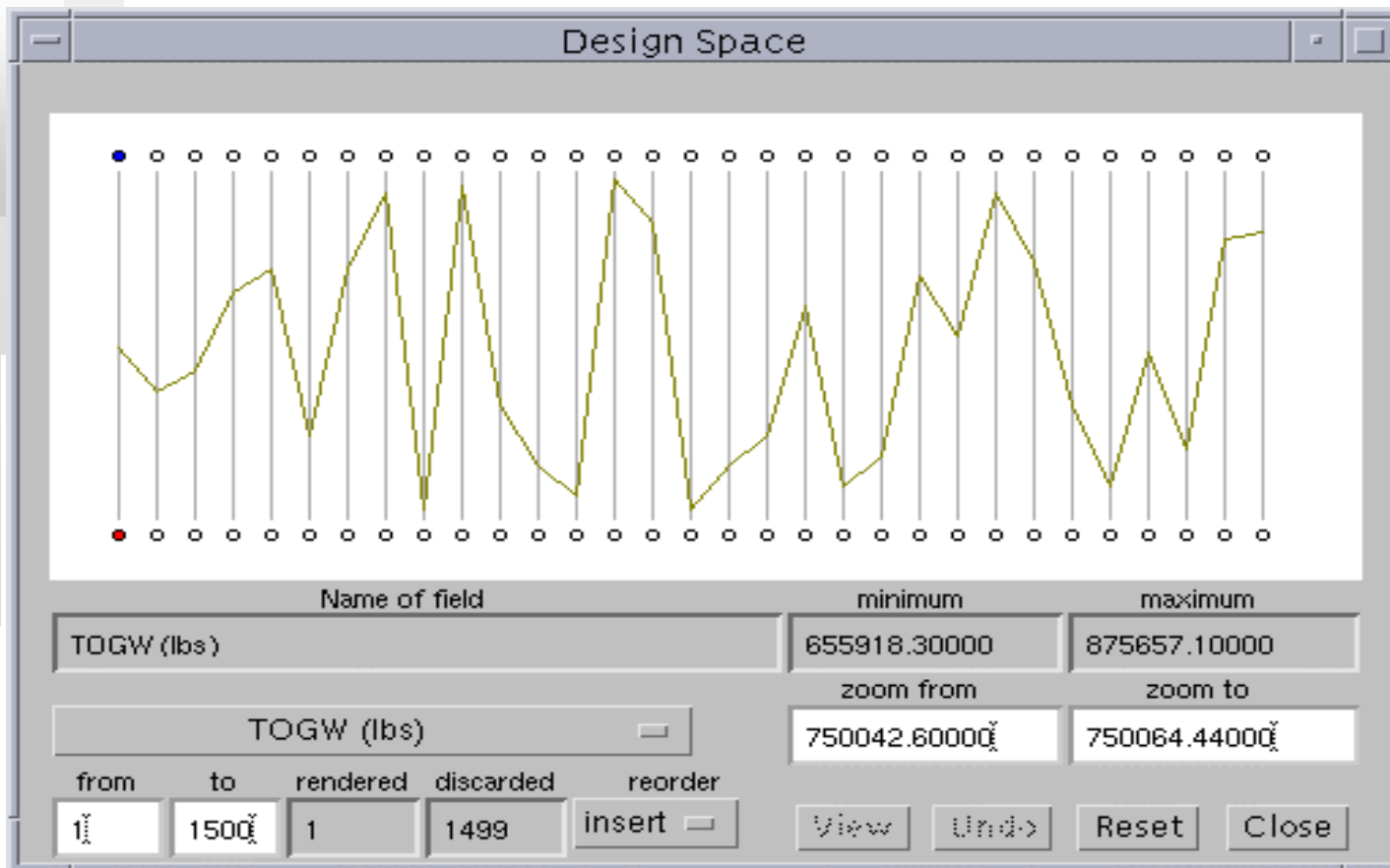


Performance Constraints

mi.	Bank angle for crosswind landing <= 5 deg
attack <= 12 deg	Takeoff rotation to occur <= 5 sec
at landing angle-of-attack	Tail deflection for approach trim <= 22.5 deg
at landing angle-of-attack	Balanced field length <= 11,000 ft
at landing angle-of-attack, with 5 deg roll	T.E. break scrape at landing with 5 deg roll
at landing angle-of-attack, with 5 deg roll	Engine-out limit with vertical tail design; otherwise 50%
e at landing	Maximum thrust required <= available thrust
for crosswind landing <= 22.5 deg	Maximum thrust required <= available thrust

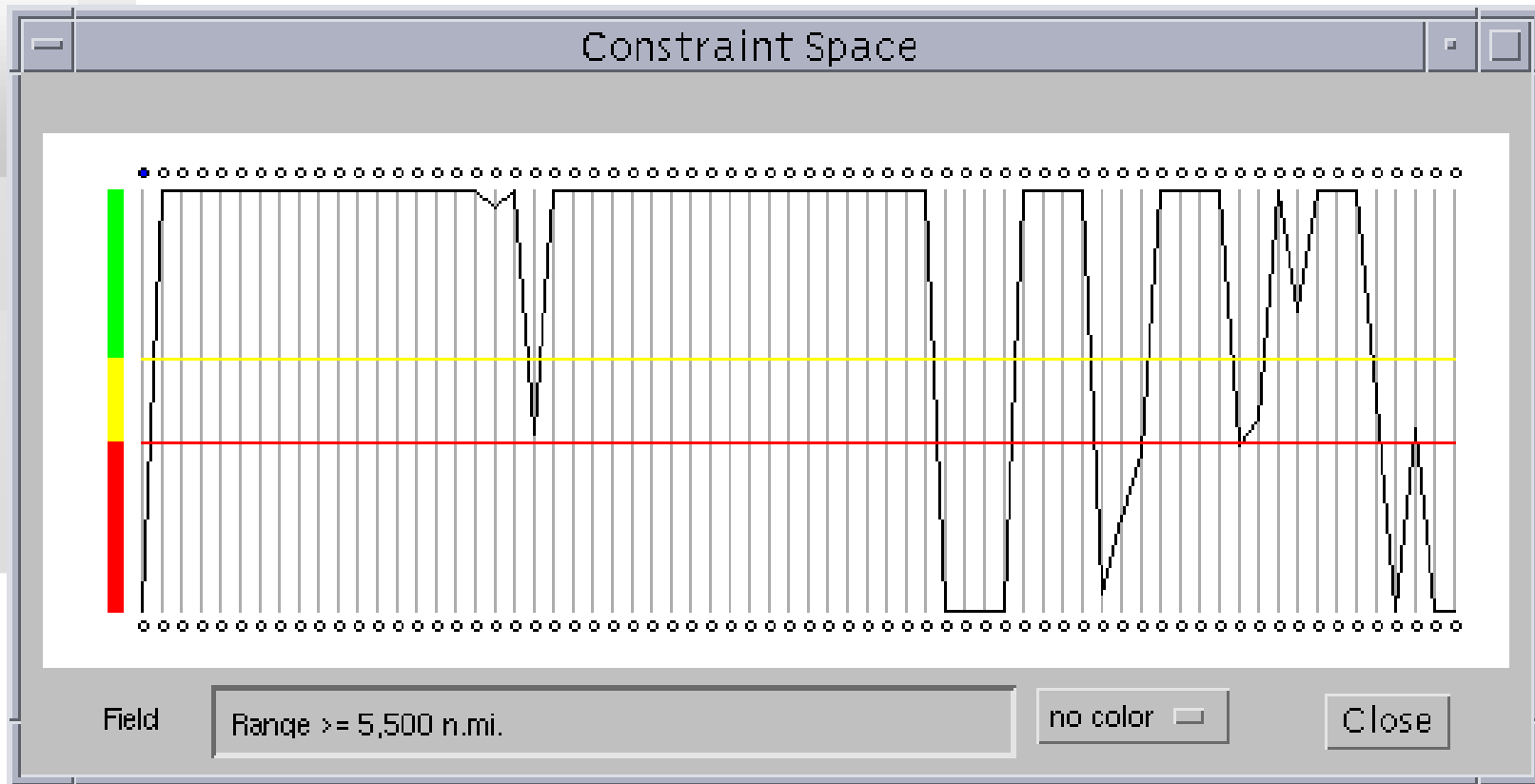
Close

Parallel Coordinates Example



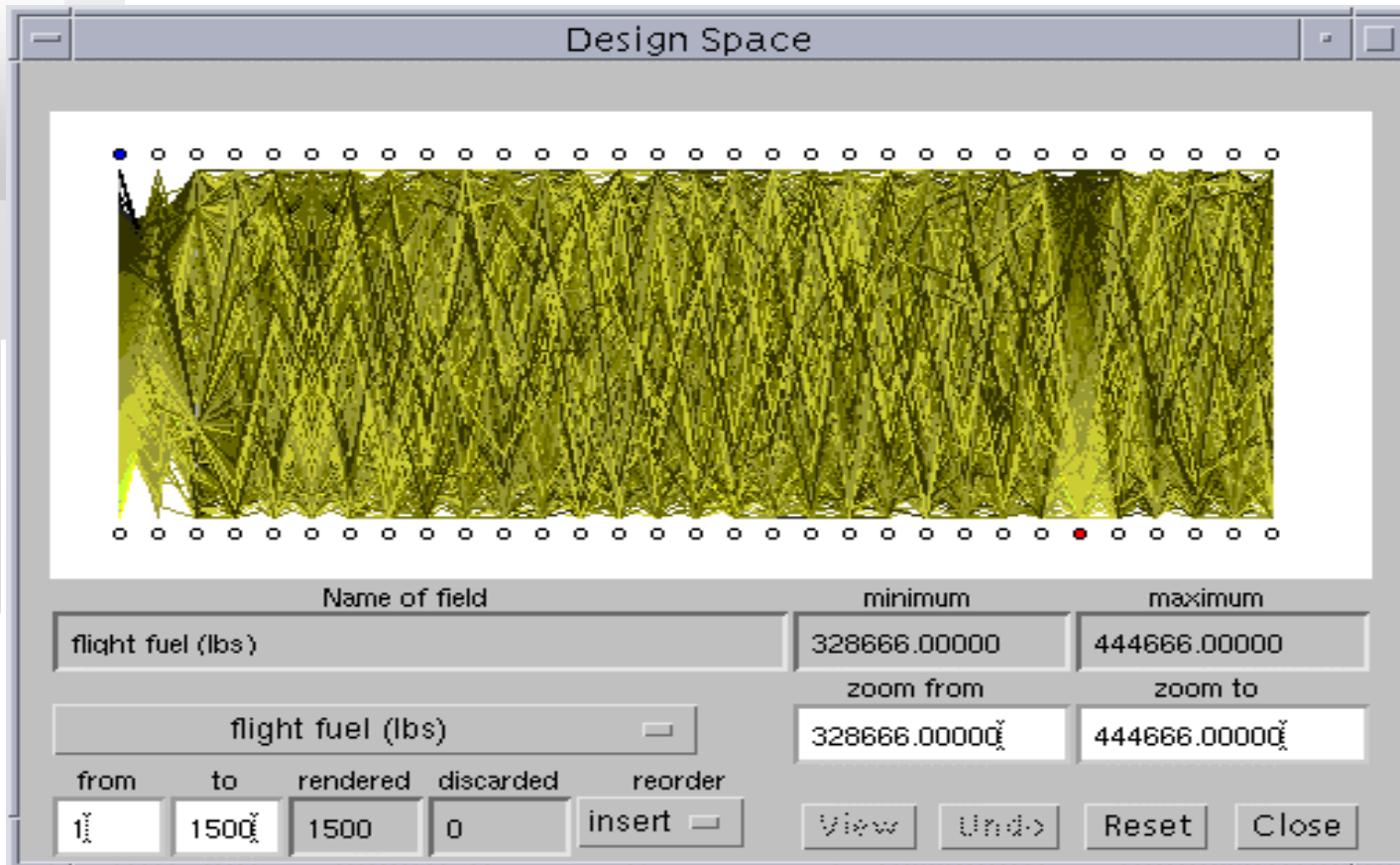
Single design point

Parallel Coordinates Example (contd.)



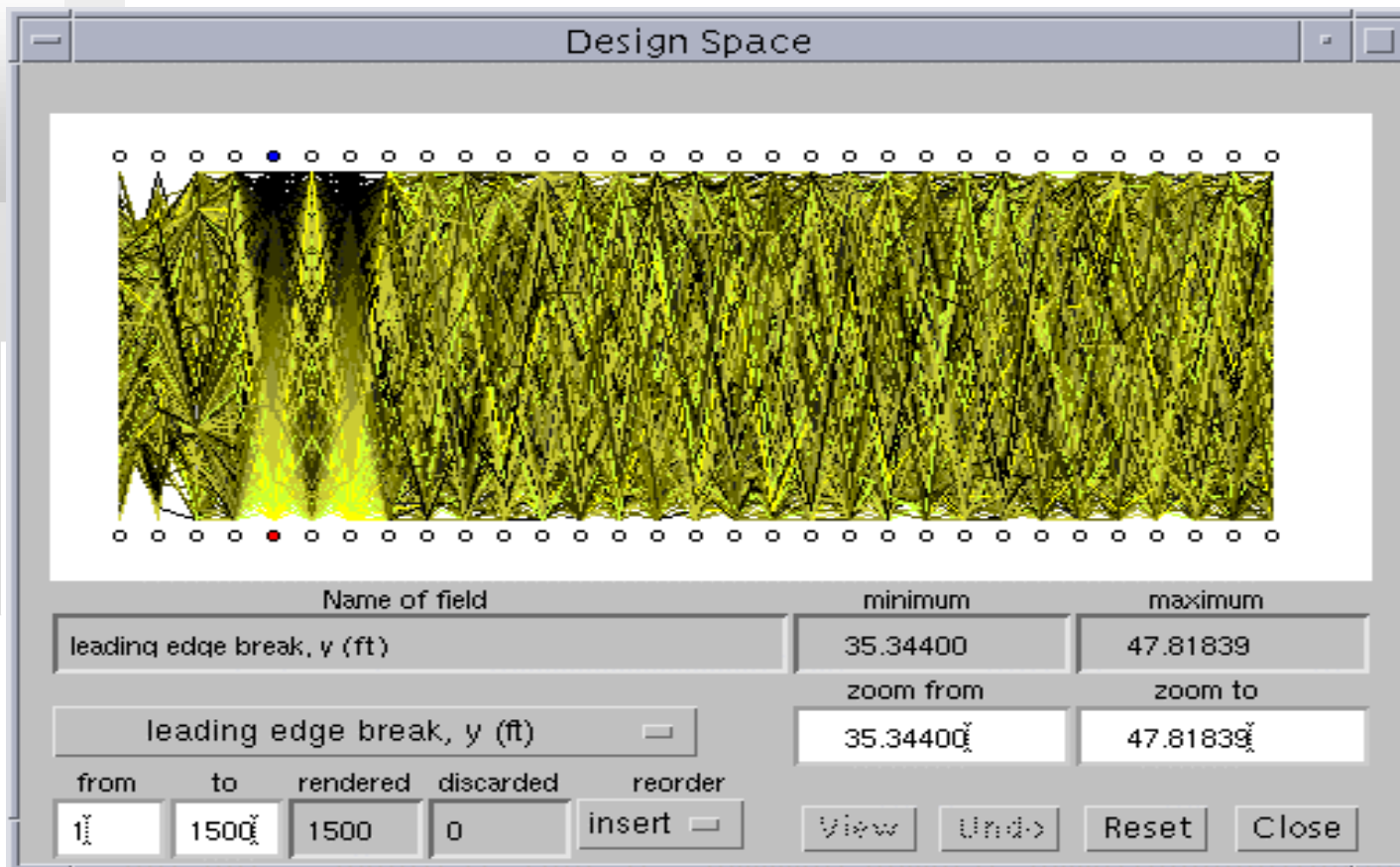
Constraint violations for a single design point

Parallel Coordinates Example (contd.)



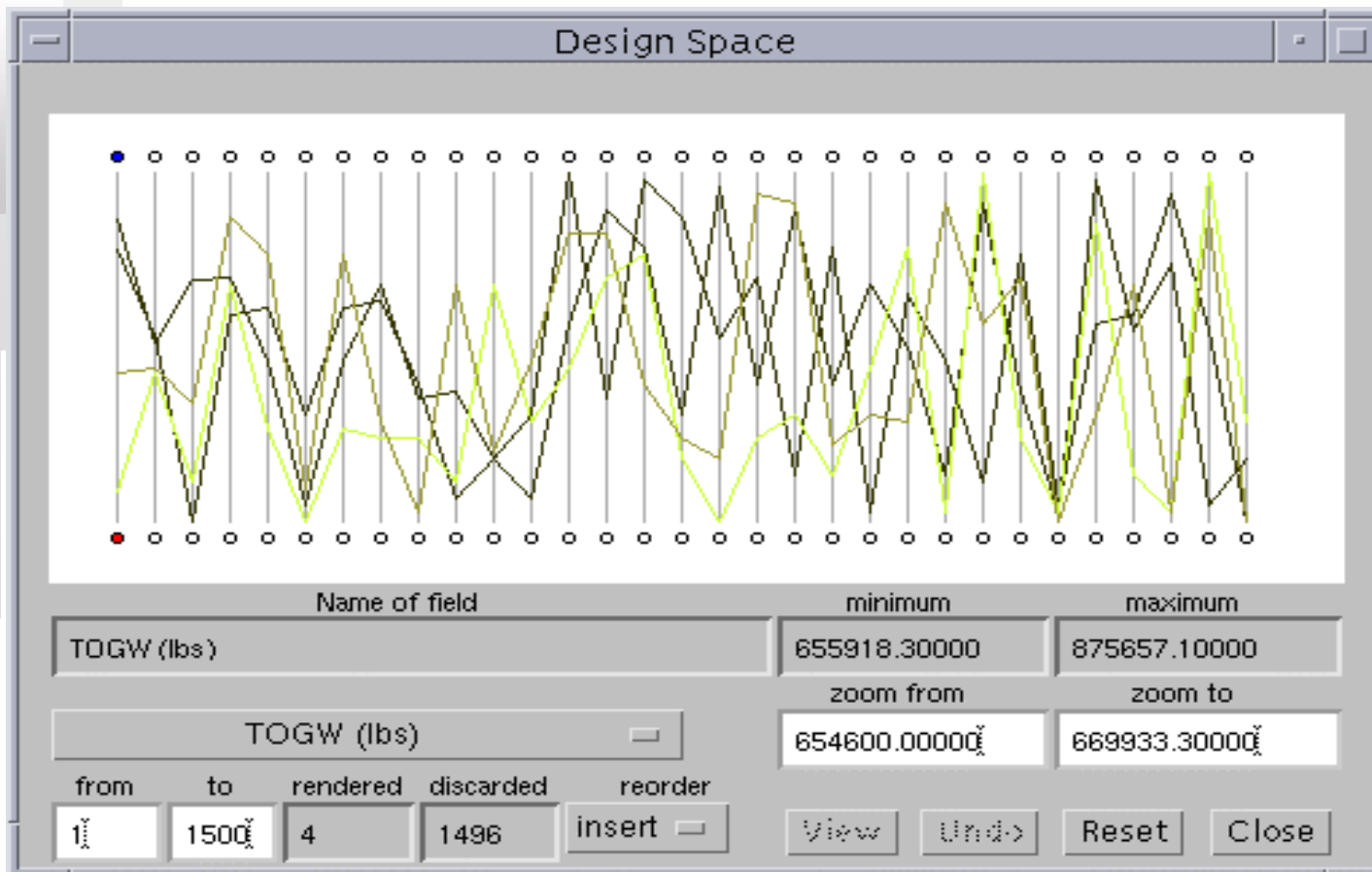
Visualizing a database of design points

Parallel Coordinates Example (contd.)

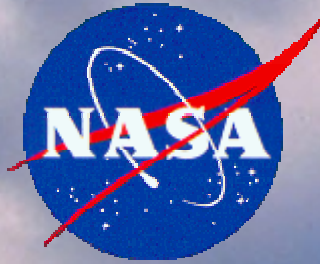


Recognizing patterns and relationships in a database

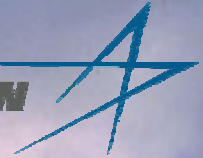
Parallel Coordinates Example (contd.)



Result of “brushing” out design points



LOCKHEED MARTIN



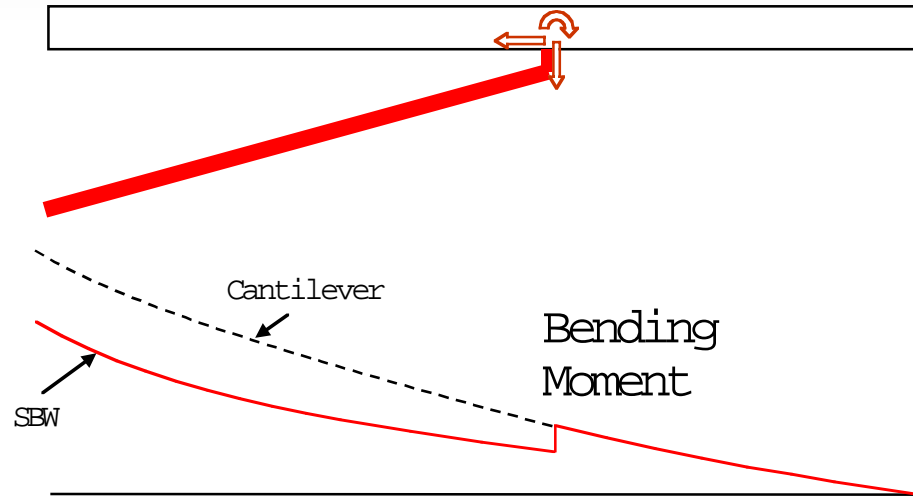
Virginia
Tech
VIRGINIA POLYTECHNIC INSTITUTE
AND STATE UNIVERSITY



NASA Langley
Research Center
October 16, 1998

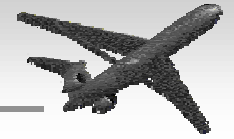
**A Structural and Aerodynamic
Investigation of a Strut-Braced Wing
Transport Aircraft Concept**

Why a Strut-Braced Wing?

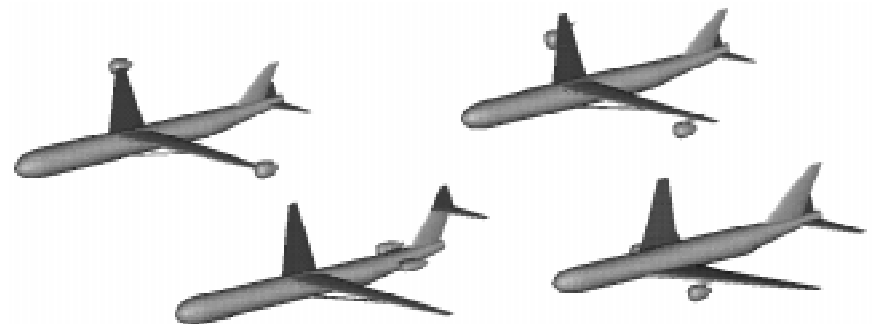
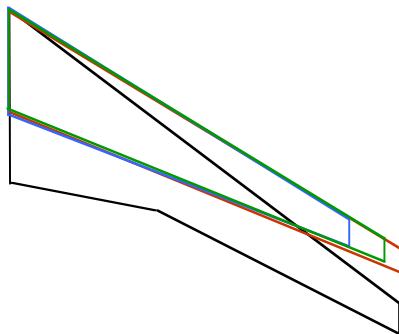


- ◆ Strut Allows Span Increase, t/c Reduction and/or Wing Bending Material Weight Reduction
- ◆ Small t/c Allows Wing to Unsweep for Same Transonic Wave Drag
- ◆ Reduced Sweep Permits More Natural Laminar Flow
 - Fuel Savings
 - Causes Additional Weight Savings

2010 Minimum-TOGW Optima



- ◆ Thrust Reduction of 21.5-31.6%
 - Lower Noise Pollution at Urban Airports
- ◆ Large SBW Sweep Reduction
- ◆ Less Wing Area
- ◆ SBW %TOGW Improvement = 9.2-17.4%
- ◆ SBW %Fuel Improvement = 14.3-21.8%
- ◆ Similar Wingspans Except for Wingtip-Engine Case
- ◆ Wingtip Deflection Constraint



Continuing Research: MDO of Aircraft Configurations

- Critical for detailed high-fidelity analyses early in the design process
- Impractical to link high-fidelity codes with an optimizer for an MDO tool
- Variable-complexity modelling has been shown to significantly reduce the computational burden
- Response surface modelling is an effective tool for performing MDO
 - code *disaggregation*
 - parallel computing efficiency
 - design trade-off studies

Further research needed in MDO to:

- Bring detailed costs and manufacturing into the design process
- Address global optimization and reliability-based optimization
- Fully incorporate advantages of parallel computing
- Effectively utilize problem solving environment in design