# Protection Against Modeling and Simulation Uncertainties in Design Optimization

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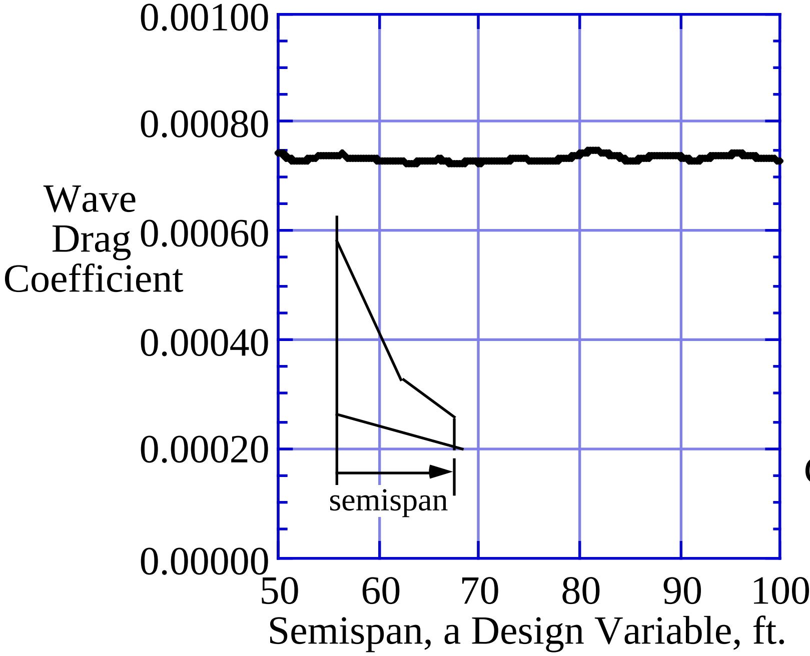
# The Problem

Unlike past generations, where design optimization was performed manually by seasoned designers, computational design relies on simulations that may be unreliable over portions of the design space and/or computationally expensive. Optimizers exploit weaknesses in simulation models. Computational design methods must be developed to overcome this problem.

# An Analysis Example: Wave Drag Variation for a Supersonic Transport

Harris Wave Drag Program results for 500 values of the semispan design variable

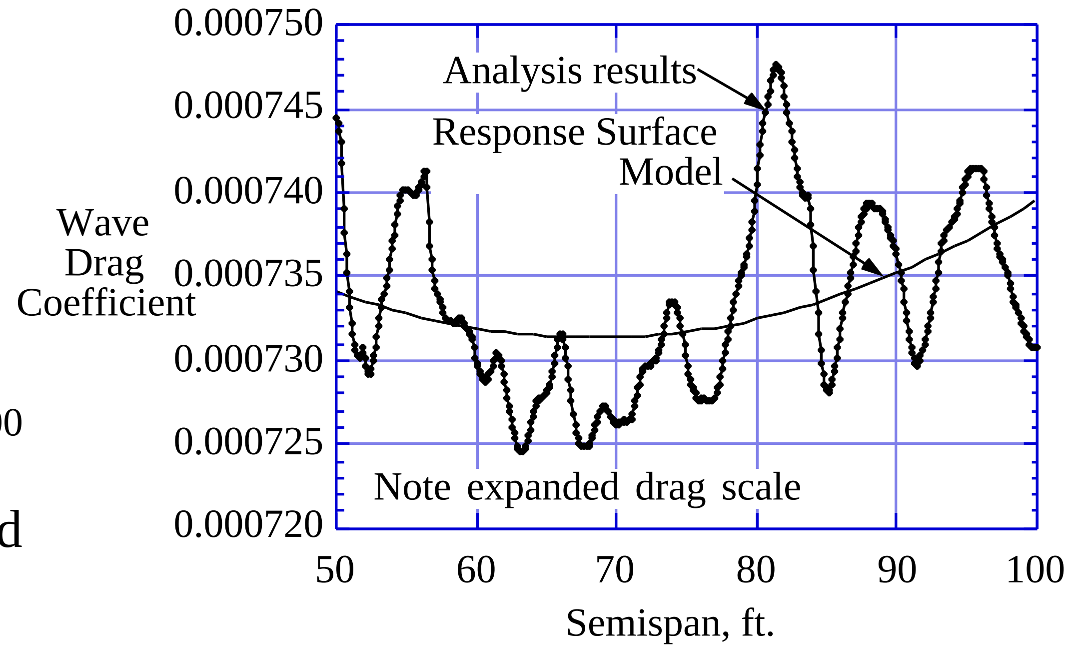
Plotted as an aerodynamicist would




An aerodynamicist was satisfied with these results

Automated design must cope with computer simulations that contain fine grain uncertainties that appear as “noise”

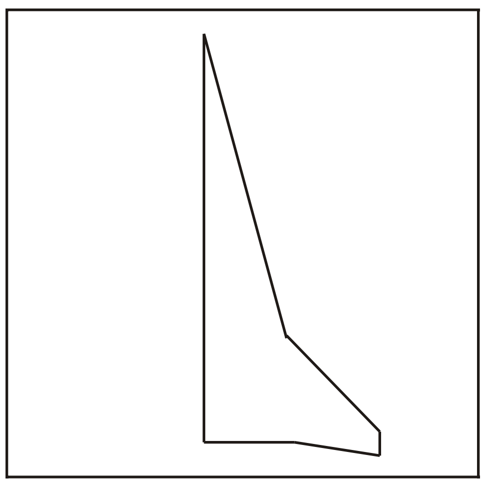
Results as seen by an optimizer during automated design



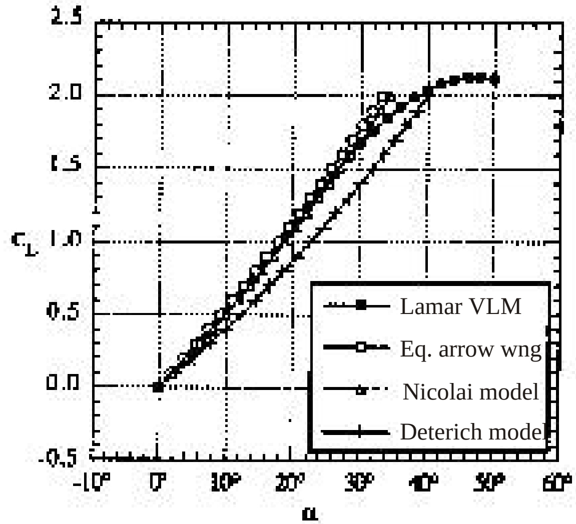
# Optimization exploits model weaknesses I

First calibrate simulation models against a "baseline"

"Baseline" wing planform



Lift of baseline planform as estimated by four different methods

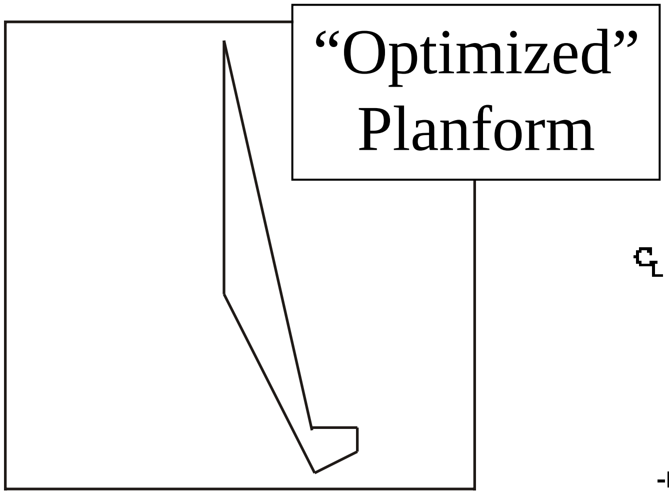


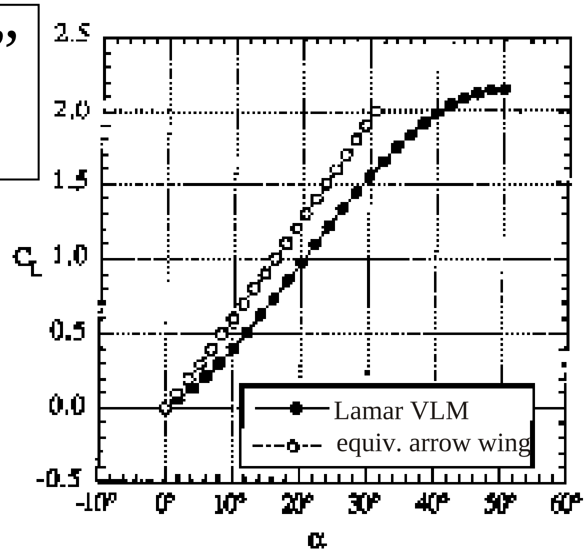

Conclusion: compared to the Lamar VLM results which are considered "truth", two approximate models appear to be accurate in the angle of attack range of interest, 10° to 20°.

Example from Hutchison, et al, AIAA Paper 92-4695, 1992

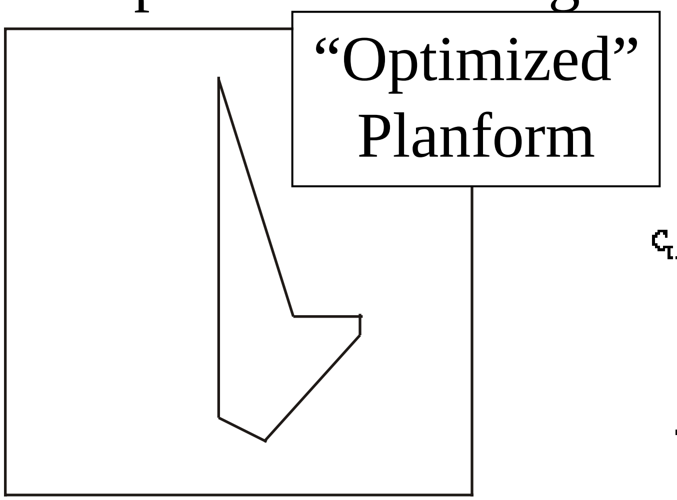
# Optimization exploits model weaknesses II

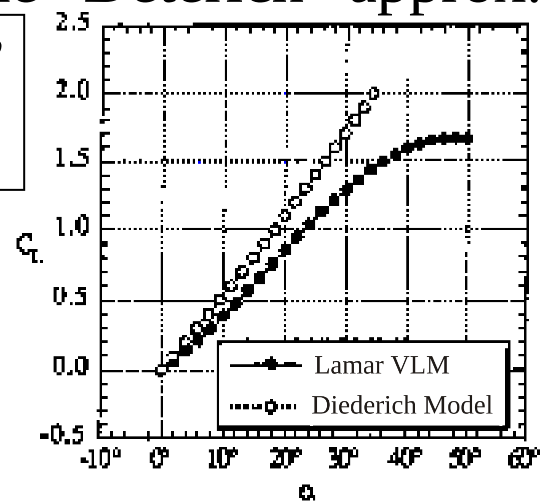
Optimization using the “equiv. arrow wing” approximation




Optimization using the “Deterich” approx.




Post optimization analysis clearly shows how the optimizer exploited the weakness of each model, producing nonsensical results.

Example from Hutchison, et al, AIAA Paper 92-4695, 1992

# Our Research Objective

By improving automated design procedures through use of a diagnostic methodology to help designers handle situations where computer simulations are not exact:

- provide an estimate of design uncertainty
- suggest "repairs" to improve simulations

*and thus*

- improve design quality/reduce uncertainty

# Our Approach

- Use discrepancies between simulations of varying fidelity and empirical data to identify when the design process is using poor simulations to make design decisions
  - Employ modern statistical methods
- Develop methods to repair the simulation information used in the design and indicate the level of uncertainty to the designer.

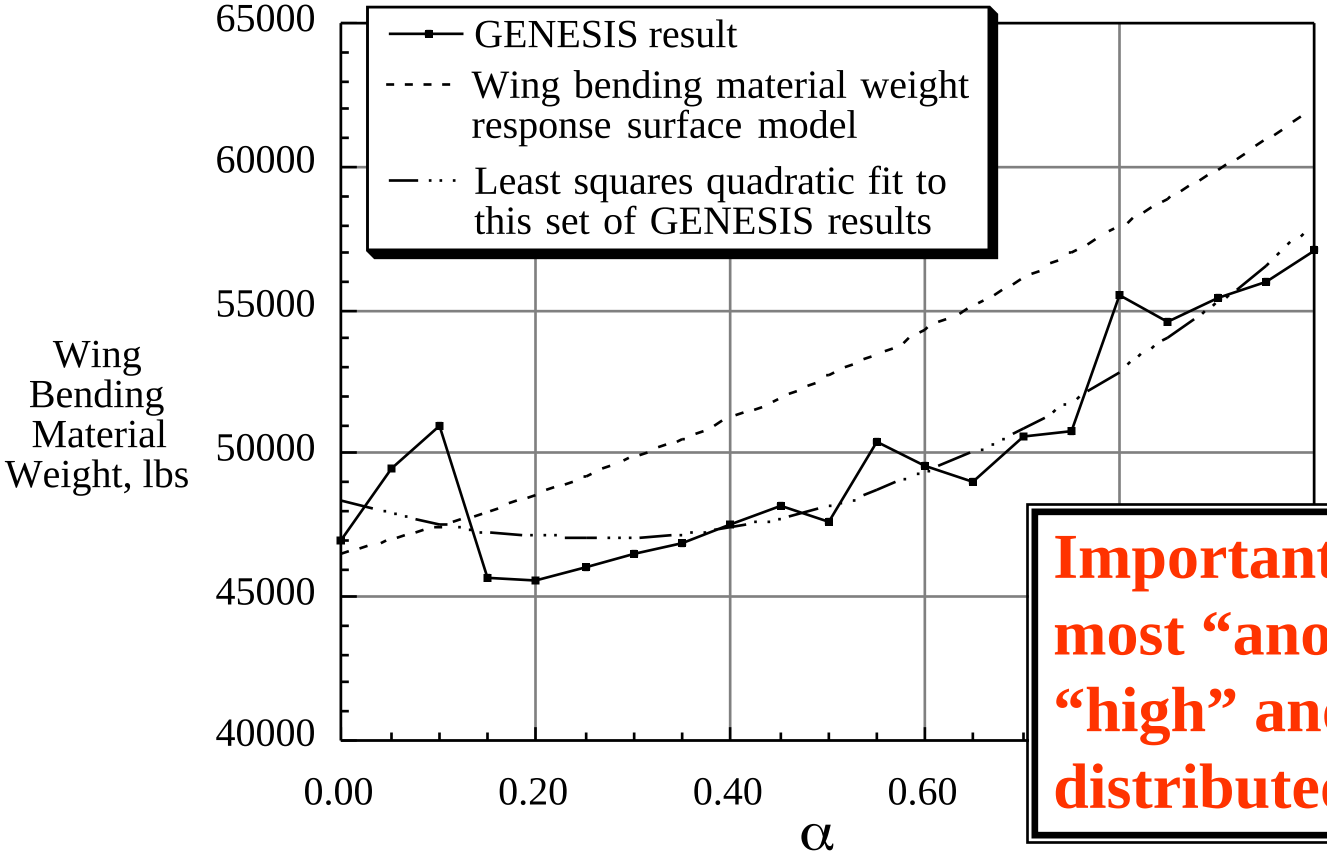
# Examples of initial/preliminary investigations carried out since the start of the grant (September 1999)

# A Model Problem to Identify Poor Simulation/Optimization

- Consider the minimization of wing structure bending material weight (WBMW) for a high speed airplane
- Generate a “database” of results to use in developing a model for multidisciplinary optimization (a response surface model)
- Use a commercial finite element structural optimization code

**Use statistical methods to remove bad optimization results (outliers)**

# Typical Results of WBMW Optimization over Design Space

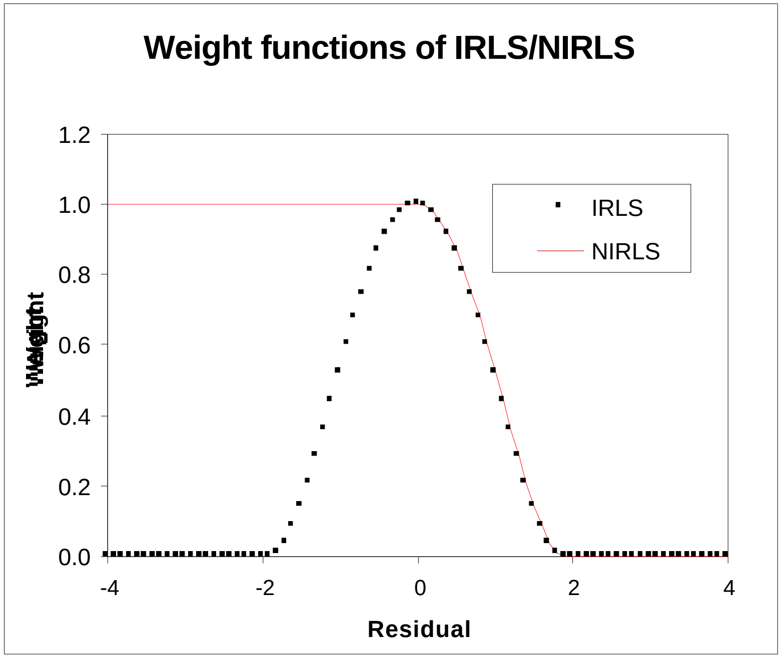



**Important to note that most "anomalies" are "high" and not normally distributed. A key insight.**

A "cut" across the design space

# Use of Statistical Methods to Remove Outliers in Computational Design

- *Robust Regression*
  - Ordinary least squares is heavily influenced by outliers
  - Use weighted least squares for non-Gaussian error
  - Allows outlier detection/correction
- *IRLS*
  - Fits *unbiased* noisy data
  - Down-weight points with large errors and refit the process until convergence




$$\mathbf{X}^T \langle w(\mathbf{r}) \rangle \mathbf{X}\beta = \mathbf{X}^T \langle w(\mathbf{r}) \rangle \mathbf{y}$$

$$\beta_{i+1} = \beta_i + \left[ \mathbf{X}^T \left\langle w\left( \frac{\mathbf{y} - \mathbf{X}\beta_i}{\sigma} \right) \right\rangle \mathbf{X} \right]^{-1} \mathbf{X}^T \left\langle w\left( \frac{\mathbf{y} - \mathbf{X}\beta_i}{\sigma} \right) \right\rangle (\mathbf{y} - \mathbf{X}\beta_i)$$

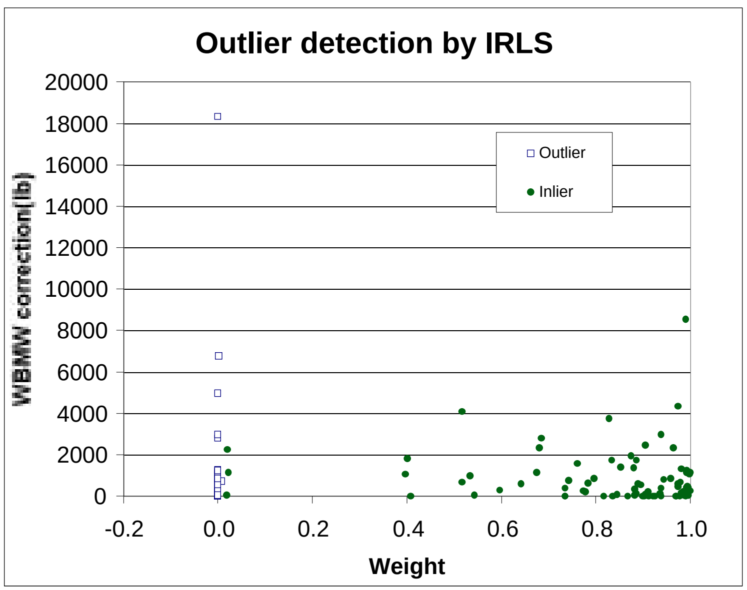
**NIRLS can identify results that appear to be "high" as outliers**

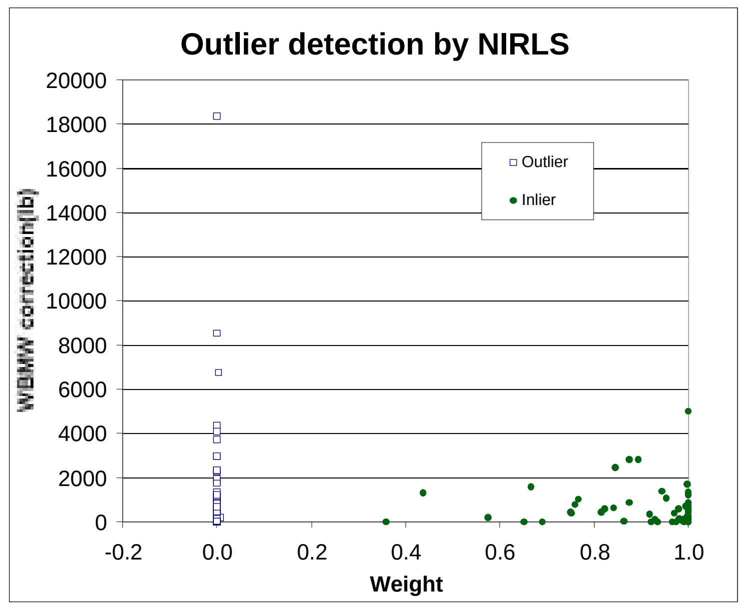
- ***Non-symmetric IRLS (NIRLS)***
  - Exploits idea that optimization error is biased
  - Reduces weighting of poor optimizations

# Results of Outlier Detection by IRLS/NIRLS for Model Problem

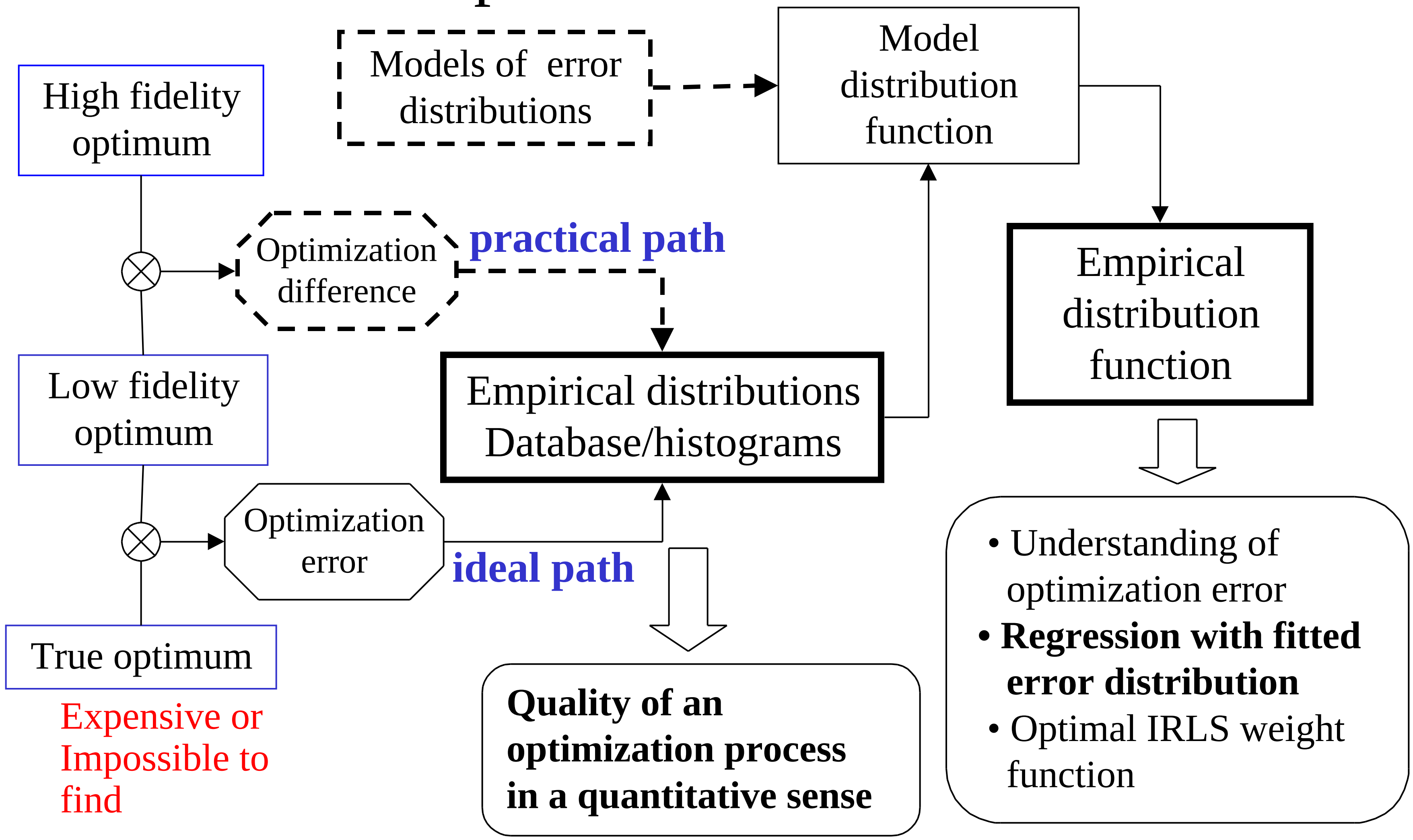
- 121 design points in 5 dimensions on which response surfaces of optimum wing bending material weight are fit
- Low-fidelity optimization corrected by high-fidelity optimization
- **NIRLS identifies more outliers, typically "corrects" results by 25%**

| | IRLS | NIRLS |
|---|---|---|
| Outliers corrected/detected | 37/41 | 51/55 |
| Mean of correction on outliers detected, lbs | 1200.1 | 1516.8 |

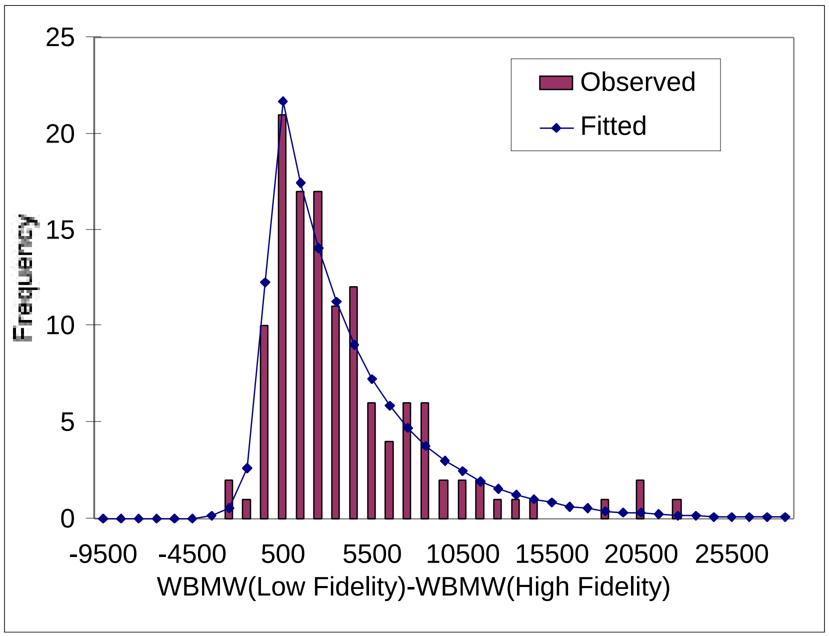


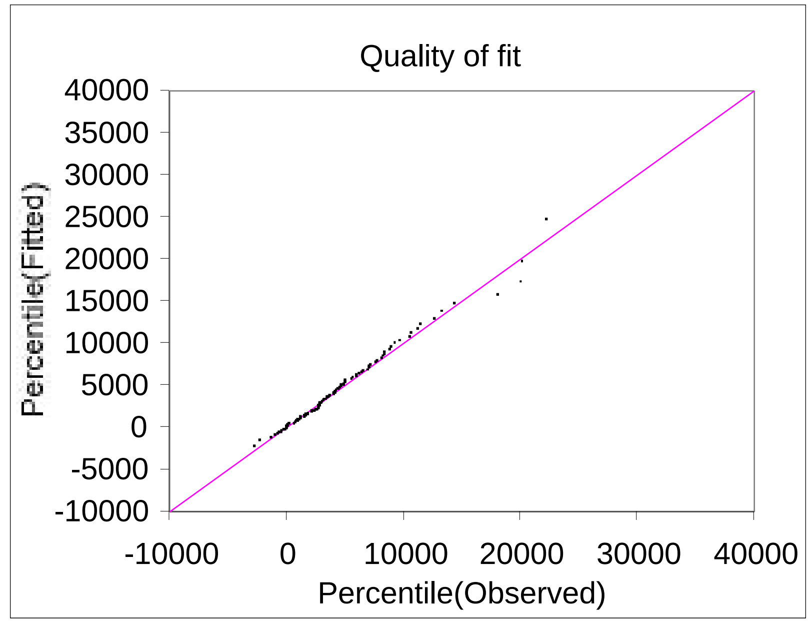



# Characterizing optimization uncertainty by modeling and fitting the distributions of optimization error



# Example of Optimization Differences Between High- and Low-Fidelity Optimization Results for the Model Problem




- **“Observation” is the histogram from the database**
- **“Fitted” is the expected frequency by the fitted distribution function**

# Method and Model Problem to Illustrate the Maximum Likelihood Estimate Method

For non-Gaussian error distribution, MLE is a general approach for regression fit:

- The structure of error distribution is fed back into regression
- Bias error is taken care of

MLE for linear regression

$$\text{Find } \mathbf{b} \text{ to Maximize}$$

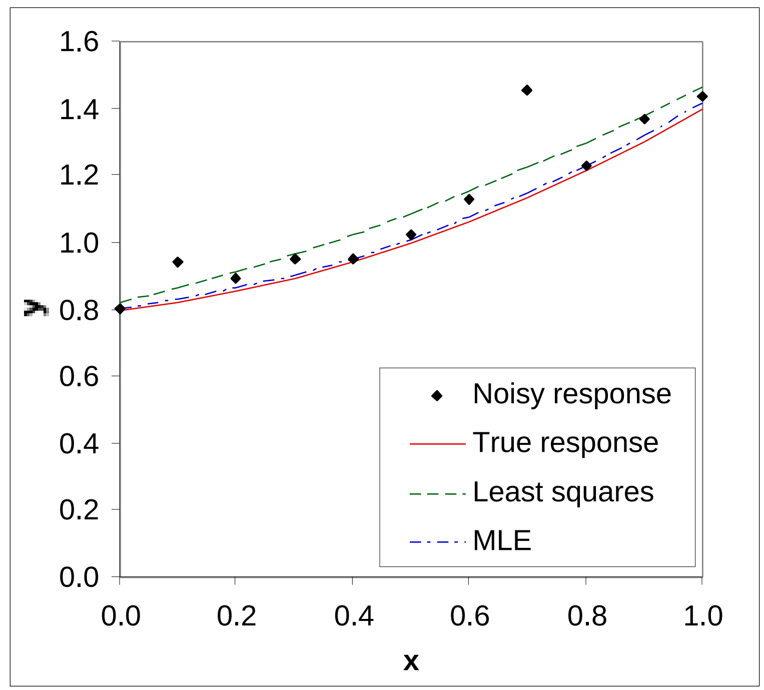
$$l(\mathbf{b}) = \prod_{i=1}^{n} f(e_i) = \prod_{i=1}^{n} f(y_i - b_0 - b_1 x_i)$$

**Note the excellent agreement between MLE and the true response in the model problem.**

*Model Problem:* Use a quadratic function and add random error following the exponential distribution

$$y_i = (y_{true})_i + e_i \text{ where } y_{true} = 0.8 + 0.2x + 0.4x^2$$

$$\text{random error } e_i \text{ follows } f(e_i) = \frac{1}{0.08}\exp\left(-\frac{e_i}{0.08}\right)$$



# Multidisciplinary Analysis and Design (MAD) Center for Advanced Vehicles

Virginia Polytechnic Institute and State University

Blacksburg, Virginia

# Research: MDO of Aircraft Configurations



- 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



- 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

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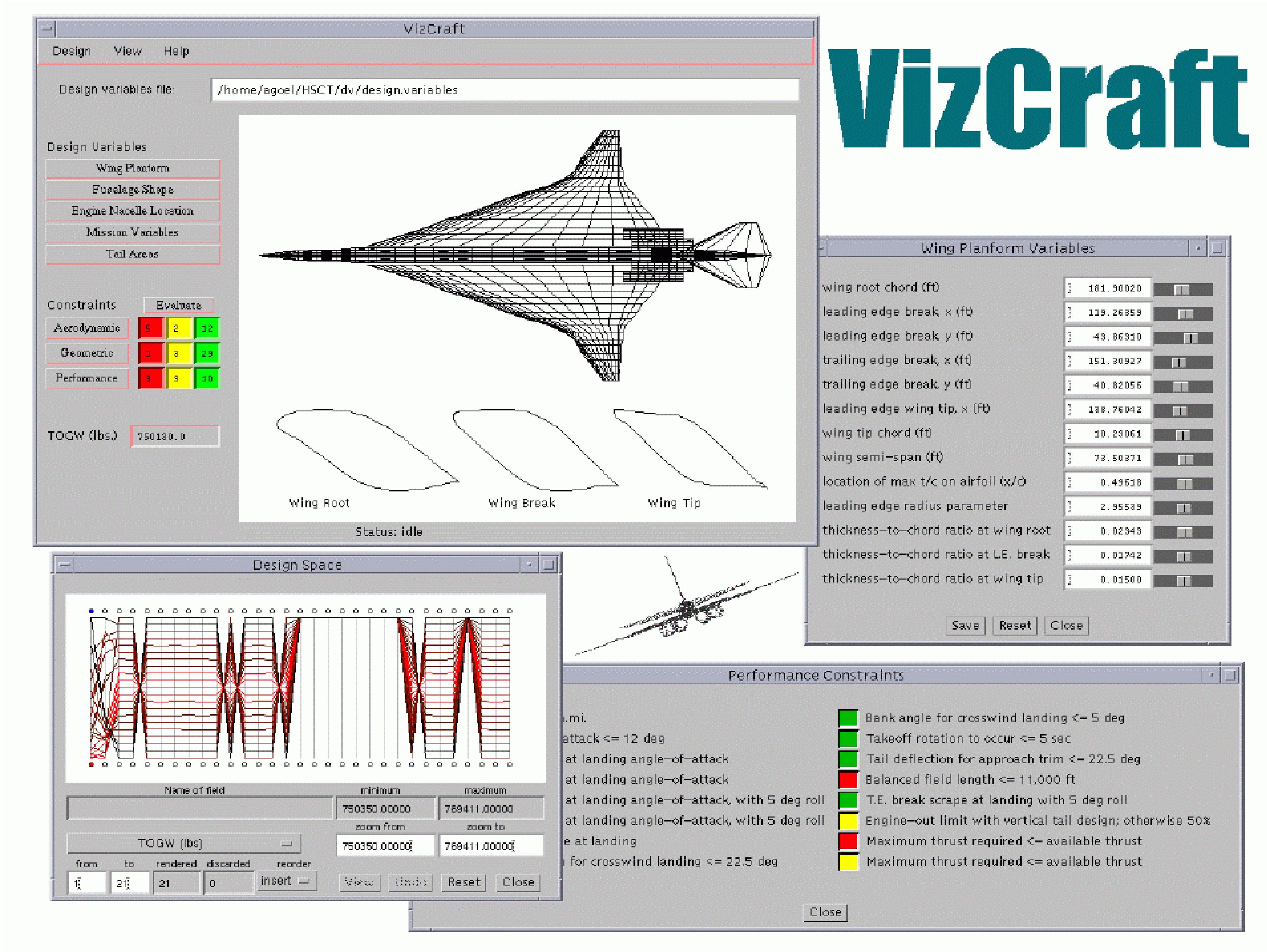
VizCraft
VizCraft
Design
View
Help
Design variables file:
/home/agoel/HSCT/dv/design.variables
Design Variables
Wing Planform
Fuselage Shape
Engine Nacelle Location
Mission Variables
Tail Areas
Constraints
Evaluate
Aerodynamic
Geometric
Performance
TOGW (lbs.)
Wing Root
Wing Break
Wing Tip
Status: idle
Wing Planform Variables
wing root chord (ft)
leading edge break, x (ft)
leading edge break, y (ft)
trailing edge break, x (ft)
trailing edge break, y (ft)
leading edge wing tip, x (ft)
wing tip chord (ft)
wing semi-span (ft)
location of max t/c on airfoil (x/c)
leading edge radius parameter
thickness-to-chord ratio at wing root
thickness-to-chord ratio at L.E. break
thickness-to-chord ratio at wing tip
Save
Reset
Close
Design Space
Name of field
minimum
maximum
750350.00000
769411.00000
zoom from
zoom to
TOGW (lbs)
from
to
rendered
discarded
reorder
21
0
insert
Reset
Close
Performance Constraints
Bank angle for crosswind landing <= 5 deg
Takeoff rotation to occur <= 5 sec
Tail deflection for approach trim <= 22.5 deg
Balanced field length <= 11,000 ft
T.E. break scrape at landing with 5 deg roll
Engine-out limit with vertical tail design; otherwise 50%
Maximum thrust required <= available thrust
Maximum thrust required <= available thrust
Close

# 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
- Reponse 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

Curriculum 21

SUCCEED

# Vertically Integrated and International Design Education at Virginia Tech

- We use freshmen in “senior” design teams
  - Freshmen added in Spring semester
  - Replaces their normal freshman project
- We have design teams composed of students at Loughborough University in the UK, working jointly with Virginia Tech undergraduates
  - One week “over there” in the Fall, one week “over here” in the Spring
  - Weekly web/telecon meetings in between, daily email

Curriculum 21

SUCCEED

# Fall 1999 Trip to England
# Giving up a Thanksgiving Meal

At Loughborough, in team meetings, and after the team presentation at the end of the week