NASA Aeronautics Research Institute

# Adaptive Shape Parameterization for Aerodynamic Design

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# Motivation



*Goal: Use tools developed in the last two decades to dramatically simplify and automate aerodynamic shape design*

- Reduce labor for setup of design and geometric manipulation to automate and streamline design process
- Automation to reduce dependence on designer expertise
- Strengthen both designer-guided and automated approaches to design
- Capitalize on two decades of explosive growth in computer graphics and 3D modeling
- Capitalize on a decade of investment in sensitivity analysis, adjoint solvers and computational power

# Outline



- Background
- Summary of Innovations
- Technical Approach
- Results and examples
- Impact
- Current TRL
- Dissemination
- Summary and Next Steps

# Background



*While discipline-specific tools have improved, the design process itself has changed little in the past 20 years*

*How does the aerospace design process work?*

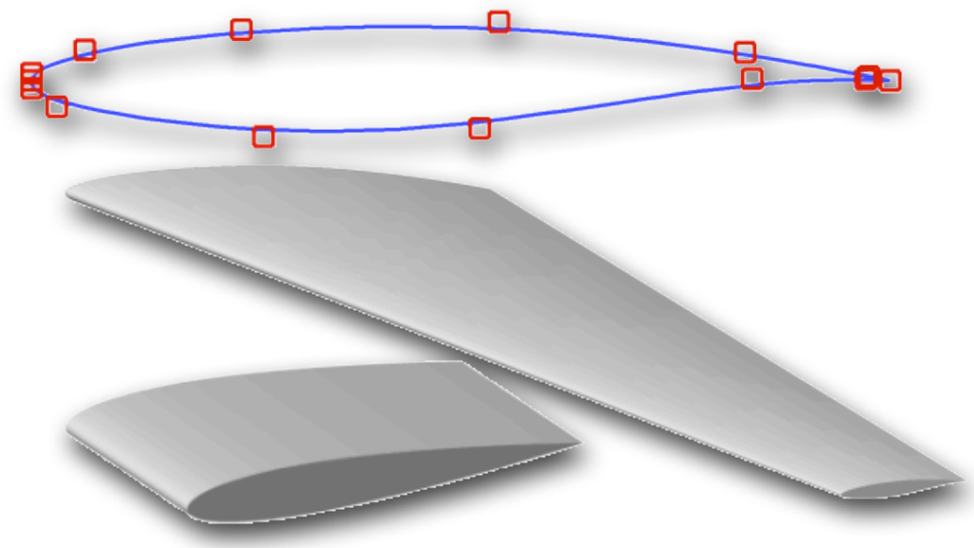
Seek an automated system that evolves a shape from “bad” to “good”. This requires:

- A method to manipulate geometry (the “modeler”)
- A design goal or “objective function” (aka “cost function”)
- A method for evaluating this objective (e.g. CFD, handbook methods, FEM etc..)
- An optimizer (GA, simplex method, gradient-based, SNOPT, NPSOL, KNITRO, DAKOTA, BFGS, steepest descent, etc..)

# Background



*Modelers, parameterization and design variables*



Constructive Modelers use a *recipe* to create a particular instance of a geometry

- **CAD-based** modelers, (*e.g.* Pro/E, Catia, NX, SolidWorks, Parasolid etc.)
- **Non-CAD** modelers, (*e.g.* VSP, Rage, ESP, Sumo, Jaguar, & many home-grown)
- Recipe uses parameters to control the shape of the object. e.g. Span, AR, thickness, taper-ratio, crank-location etc.
- Design Variables (*DVs*) are construction parameter that can be modified by the optimizer.
- **Note:** Parameters are built-in to model, "Legacy" discrete geometry is DoA

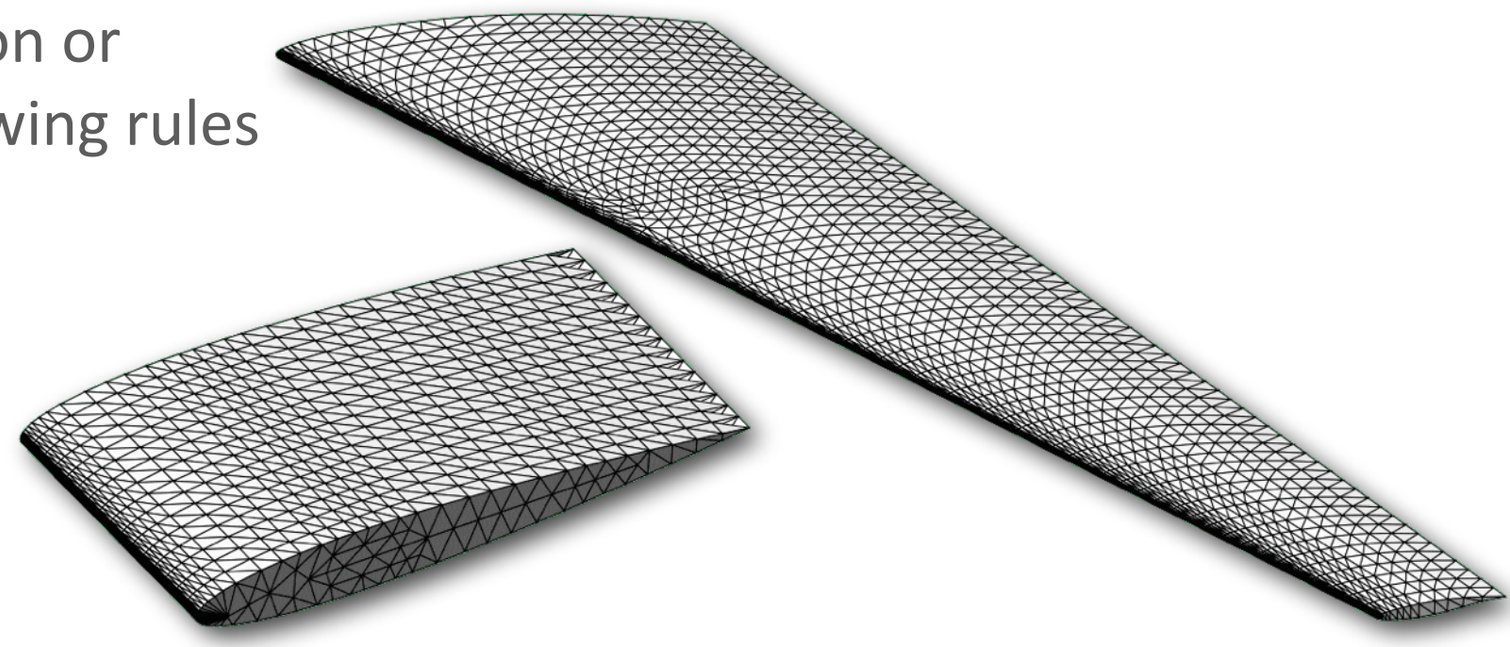

- Nemec, M., and Aftosmis, M., *Jol. Computational Physics* doi:10.10.16/j.jcp.2007.11.018, (2007)
- Nemec, M., and Aftosmis, M., "Adjoint Sensitivity Comp. for an Embedded-Boundary Cartesian Method and CAD Geom," *ICCFD4*, 2006.
- Nemec, M., and Aftosmis, M., "Aero. Shape Opt. Using a Cartesian Adjoint Method and CAD Geometry," *AIAA Paper 2006-3456*, June 2006
- Nemec, M., and Aftosmis, M., "Adjoint algorithm for CAD-based shape opt. using a Cartesian method." *AIAA Paper 2005-4987*, 2005
- Dannenhoffer, J.F., and Aftosmis, M.J., "Automatic creation of quadrilateral patches on boundary representations," *AIAA Paper 2008-0923*, Jan. 2008.
- Haimes, R., and Aftosmis M.J, "On generating high quality "water-tight" triangulations directly from CAD" Proc. 8th Intrn. Grid Conf., Jun. 2002

# Background



*Modelers, parameterization and design variables*

Discrete Modelers modify an existing discrete surface (*e.g.* triangulation or patches) and manipulate it following rules



- **Deformation Techniques:**
  - FFD
  - Lattices
  - Cages
  - Control Grids
  - Radial Basis Functions
  - Bump functions, etc..

- **Existing Software:** Sculptor, MASSOUD, BandAIDS, Blender, Maya, 3ds Max etc.

# Background



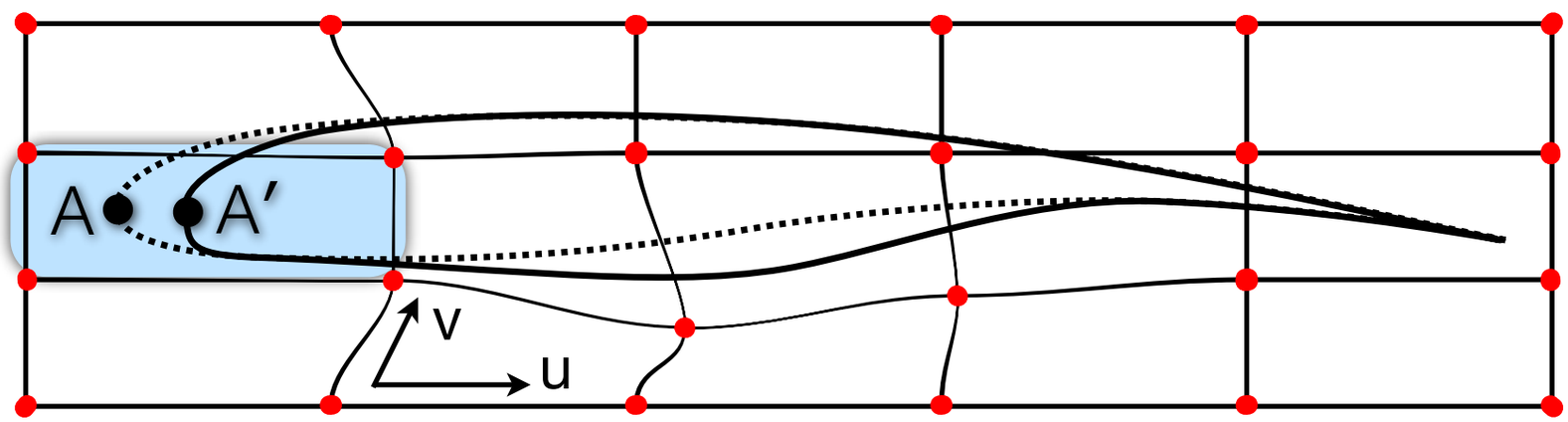
*Modelers, parameterization and design variables*

Discrete Modelers: Lattice Deformer or "FFD" (1986)

Enclose the geometry in regular lattice

- Moving a lattice vertex morphs the enclosed space
- Typically use 3D splines or NURBS for volumetric mapping function

Surfaces inside deform passively




Parameters (and DVs) are locations lattice vertices – non-intuitive and not on the surface of the geometry

Constraints can be challenging

# Background



*A few difficulties with traditional approaches*

Constructive modelers

- All possible design useful parameters must be anticipated and *built-in* at time of model construction ("gee, I'd really like to twist this wing")
- Additional parameters cannot be added without re-building model
- Constraints challenging if not explicitly built-in at construction

Discrete Modelers

- Large-scale deformation is challenging – orchestrate by linking lattice verts
- Constraints a challenge – again, orchestrate by parameter linking...

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Discrete Modelers

- Large-scale deformation is challenging – orchestrate by linking lattice verts
- Constraints a challenge – again, orchestrate by parameter linking...

*All a designer knows at design onset are objectives and constraints. The most useful parameters for a particular objective only become apparent as design progresses.*

# Summary of Innovations



*Meeting our goal of accelerating and automating shape design rests on three innovations developed during Phase I*

1. On-the-fly Reparameterization
   - *Constraint-based parameterization & deformation*
2. Automated Shape Parameter Selection
   - *Based on solution of the adjoint equation system*
3. Leverage Modern CG and 3D Modeling Tools
   - *From two decades of vigorous development in computer graphics and animation*

# Summary of Innovations



*Innovation #1: On-the-fly reparameterization*

Constraint-based parameterization - Designer chooses relevant parameters *at design time* not during model construction

- Parameters can be enriched or changed to incorporate discoveries made during optimization
- Model construction does not need to anticipate all possible useful parameters
- Opens design to use of "legacy" geometry, regardless of heritage
- Geometric constraints automatically satisfied – even when adding new parameters
- All permutations of geometry guaranteed to satisfy geometric constraints, no need for penalty functions

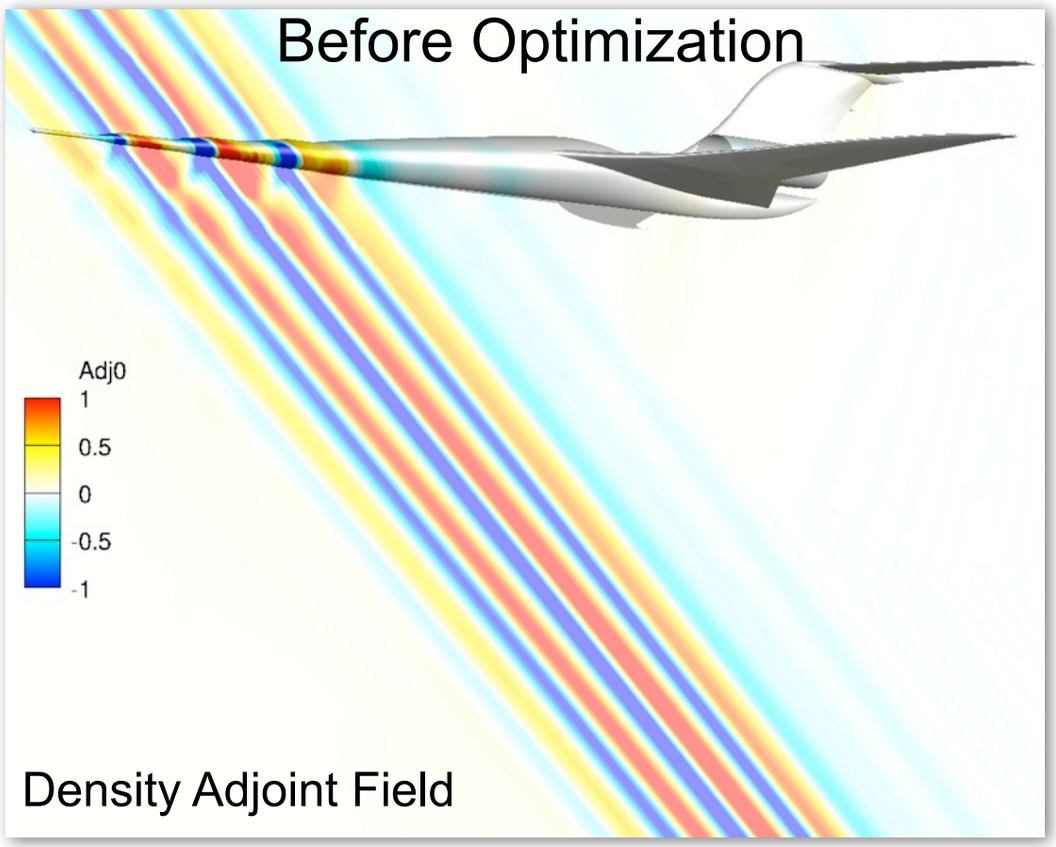
Anderson, G.R., Aftosmis, M.J., and Nemec, M., "Constraint-based Shape Parameterization for Aerodynamic Design". *ICCFD7 Paper-2001*. 7th International Conference on Computational Fluid Dynamics (ICCFD7), July 2012.

# Summary of Innovations



*Innovation #2: Automated shape parameter selection*

Adjoint-guided shape parameter selection - Use adjoint-based sensitivity analysis to highlight regions of the geometry that most directly affect the objective of a particular optimization




Example from low-boom design of forebody of supersonic aircraft (2011)

- Solution of the discrete adjoint equations directly link regions of the surface to the design objective.
- Capitalize on this information to chose the most important places to add shape control
- Adjoint already being solved for design gradients, thus no additional computation

Aftosmis, M. J., Nemec, M., and Cliff, S. E., "Adjoint-Based Low-Boom Design with Cart3D," *AIAA Paper 2011-3500*, 29th AIAA Applied Aerodynamics Conference, Honolulu, HI, June 2011. (Best paper award)

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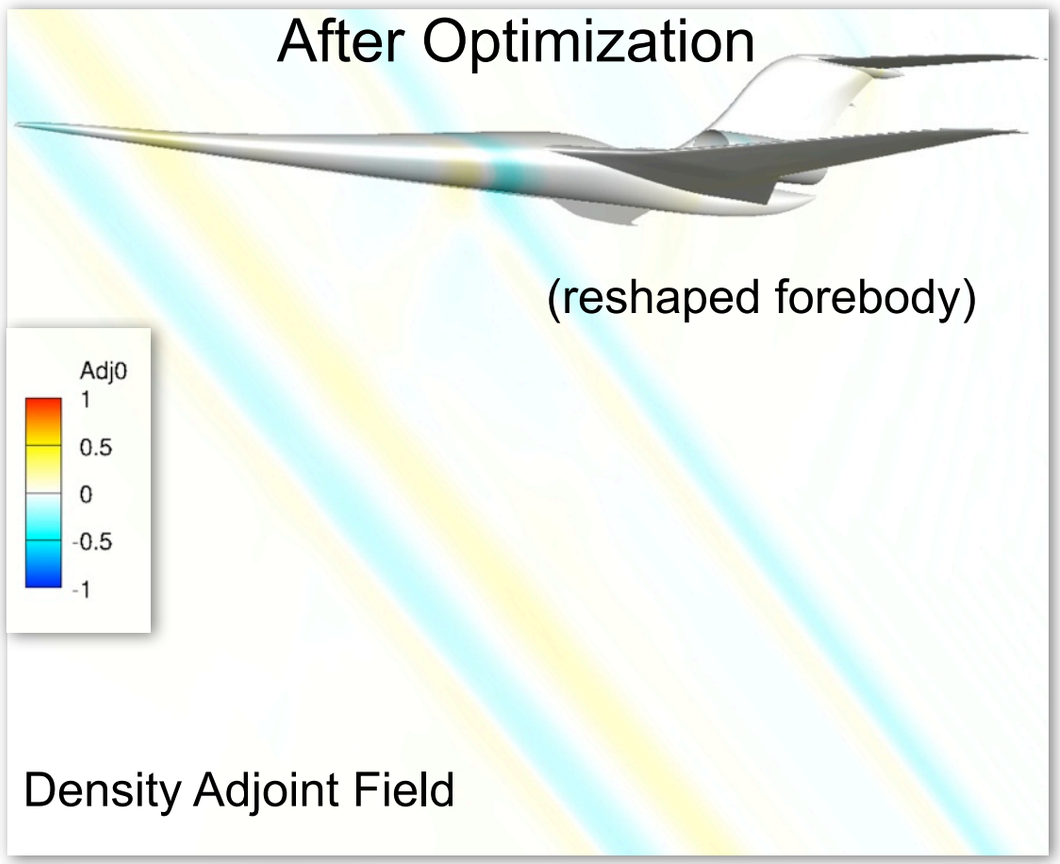


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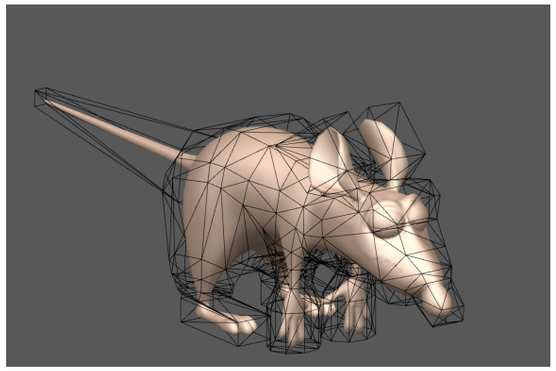
# Summary of Innovations



*Innovation #3: Leverage modern CG & 3D modeling tools*

Capitalize on investment in Computer Graphics and 3D modeling - explosive growth in CG for 3D animation and gaming has produced mature tools



- Offer flexible surface manipulation, batch processing, with natural deformation & control – these tools are unmatched in aerospace industry
- blender™ is a vigorously developed open-source software suite with 800k users worldwide & 15yrs of development

Anderson, G. R., Aftosmis, M. J., and Nemec, M., "Parametric Deformation of Discrete Geometry for Aerodynamic Shape Design," AIAA Paper 2012-0965, January 2012.

# Technical Approach



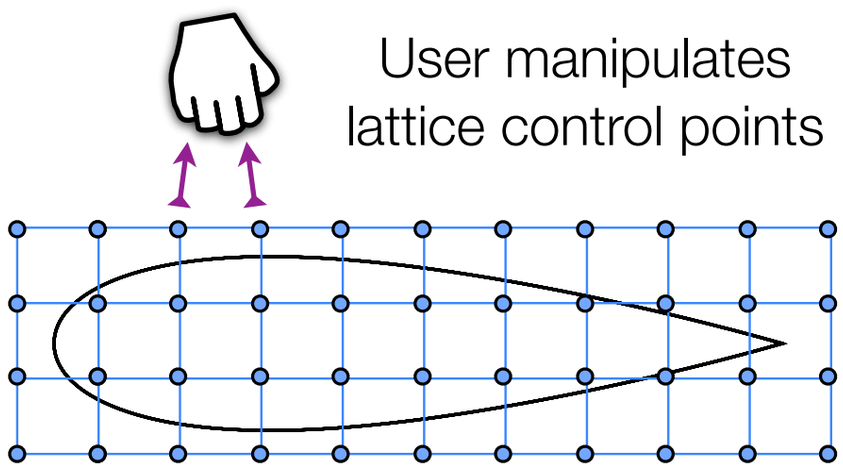
- ✓ Objective #1 – Constraint-Based Deformation
  - *Design parameters chosen at Design time and modified on-the-fly*
- ✓ Objective #2 – Framework for Automated Parameter Refinement
  - *Based on existing Cart3D Design Framework*
- ✓ Objective #3 – Develop Refinement Indicators
  - *Use adjoint-based sensitivity information*
- ☐ Objective #4 – Develop Comprehensive Refinement Strategy
  - *Determines **pacing** of introduction of new parameters for process efficiency, robustness, & automation*
  - *Currently prototyped, complete by end of Phase I*

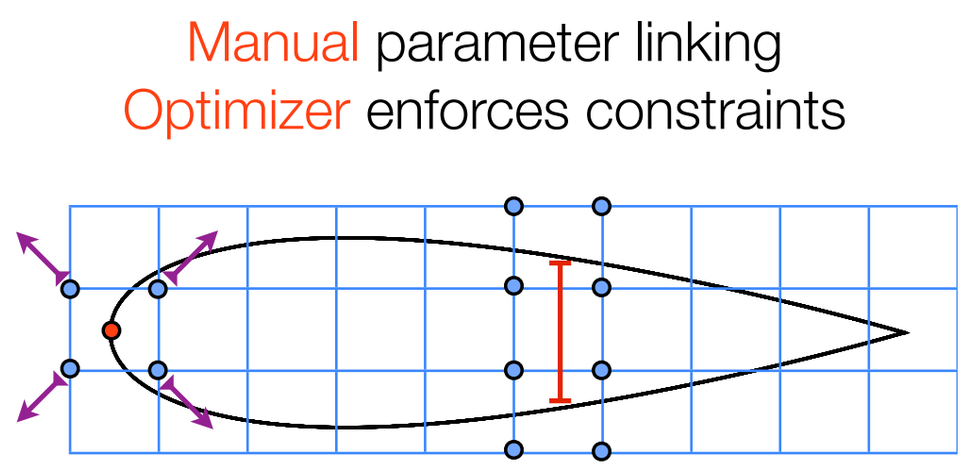
# Technical Approach



## *Objective 1: Constraint-based Deformation and Parameterization*

Traditional free-form deformation exposes lattice nodes as design variables



# Technical Approach



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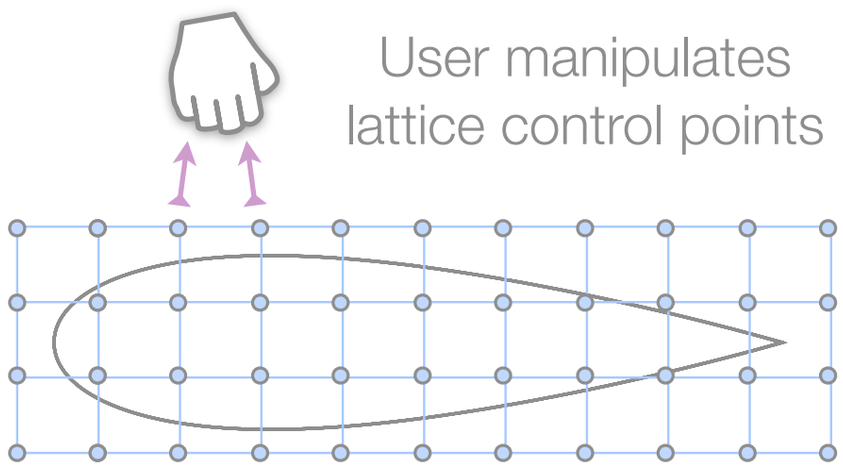
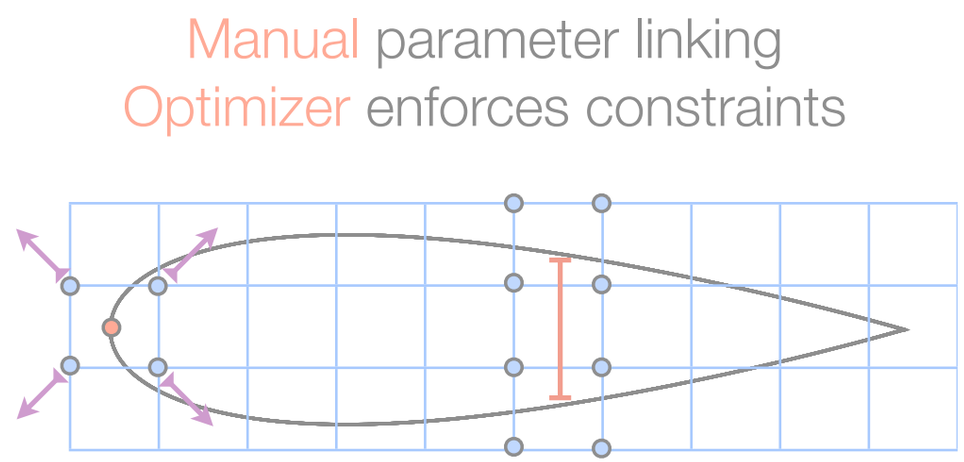
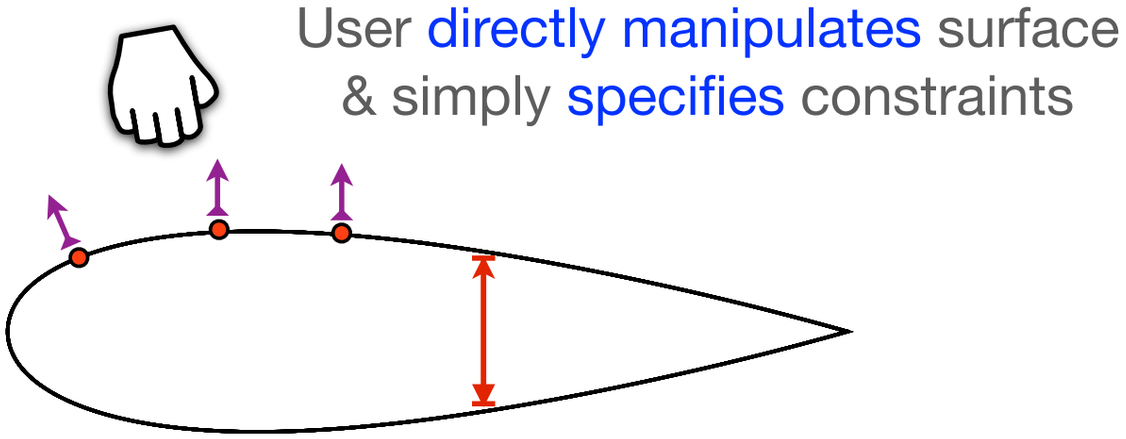
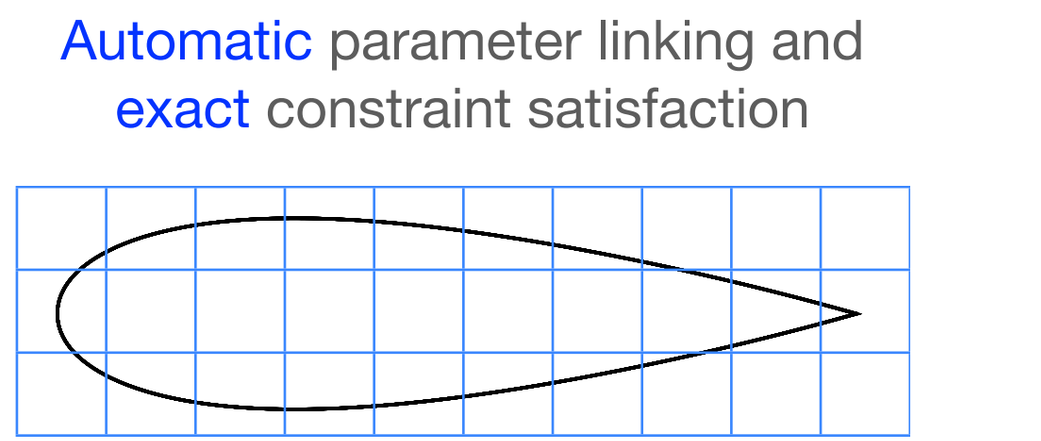



Constraint-based approach puts design variables directly on surface




(Lattice automatically managed in background)

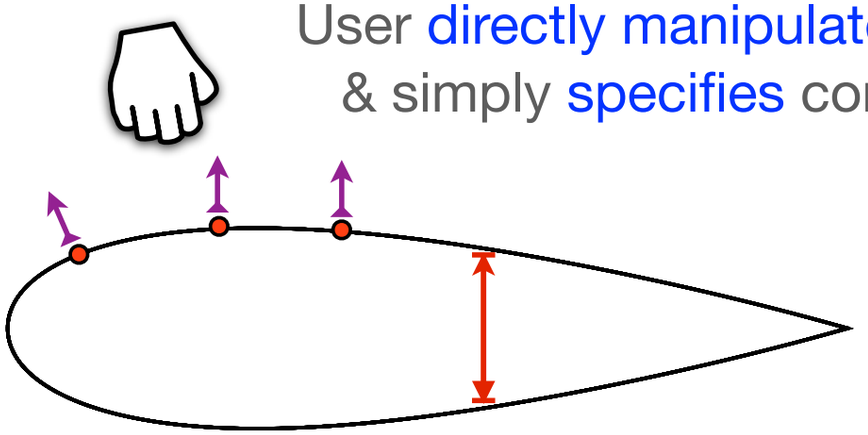
# Technical Approach



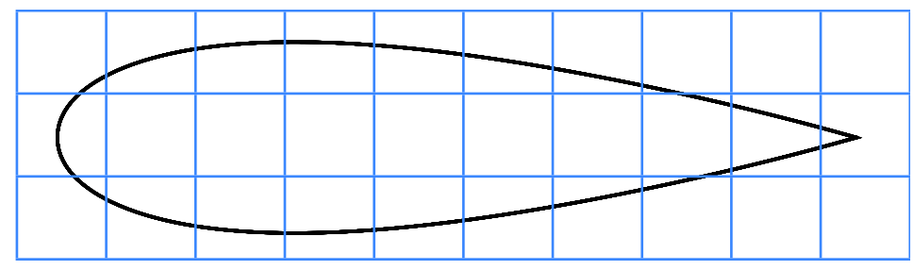
## *Objective 1: Constraint-based Deformation and Parameterization*

Constraint-based approach puts design variables directly on surface

User directly manipulates surface & simply specifies constraints



Automatic parameter linking and exact constraint satisfaction



(Lattice automatically managed in background)

$$\begin{pmatrix} f_1(\mathbf{L}) \\ f_2(\mathbf{L}) \\ \vdots \\ f_n(\mathbf{L}) \end{pmatrix} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

$$\mathbf{F}(\mathbf{L}) = \mathbf{X}$$

Lattice

Design variables and constraints

**Deformation Process:**

1. Modify design variables
2. Calculate exact constraints
3. Pseudo-inverse solve for new lattice

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# Technical Approach

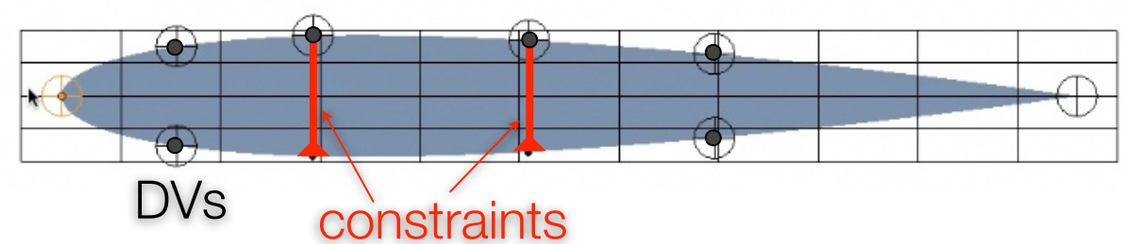


## *Objective 1: Constraint-based Deformation and Parameterization*

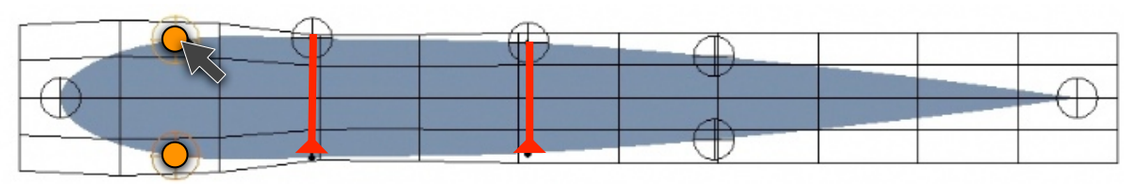
Constraint-based approach puts design variables directly on surface

- Get geometric smoothness and detailed control of lattice
- Constraints and DVs handled in identical manner
- Deformer can only produce shapes which satisfy constraints.

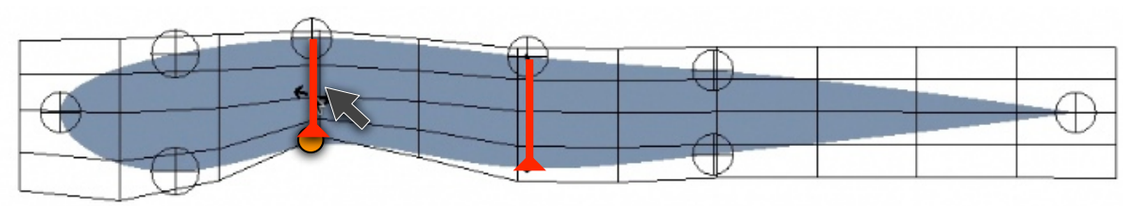
1. Initial geometry and lattice




2. Reposition DVs



3. Resize thickness constraints



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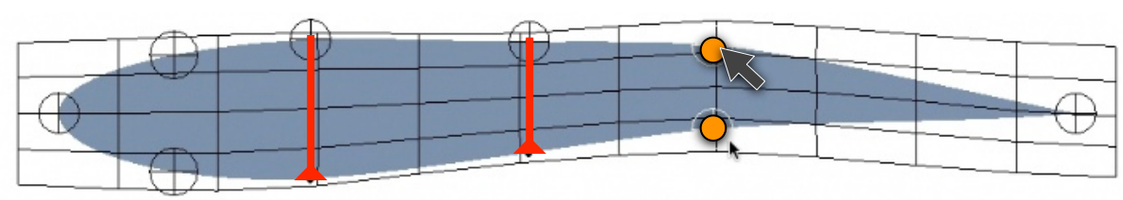

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# Technical Approach



*Review*

- Objective #1 – Constraint-Based Deformation
- Objective #2 – Framework for Automated Parameter Refinement
- Objective #3 – Develop Refinement Indicators
- Objective #4 – Develop Comprehensive Refinement Strategy

# Technical Approach



*Review*

- Objective #1 – Constraint-Based Deformation
- Objective #2 – Framework for Automated Parameter Refinement
- Objective #3 – Develop Refinement Indicators
- Objective #4 – Develop Comprehensive Refinement Strategy
- Objective #1 – *Mechanics* of deformer
- Objective #2 – ***How to add DVs?***
- Objective #3 – ***Where to add DVs?***
- Objective #4 – ***When to add DVs?***

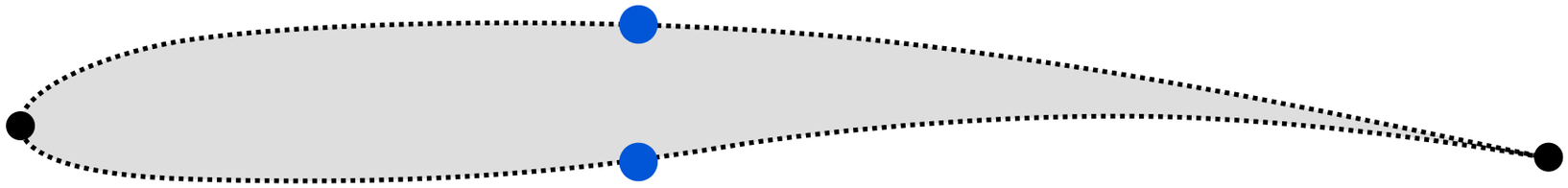
# Technical Approach



*Objective 2: On-the-fly enrichment of design space*

Modify existing Cart3D Design Framework for design-time addition of DVs

Current approach is classic *h*-refinement



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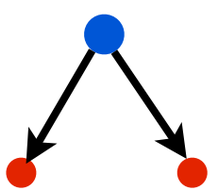

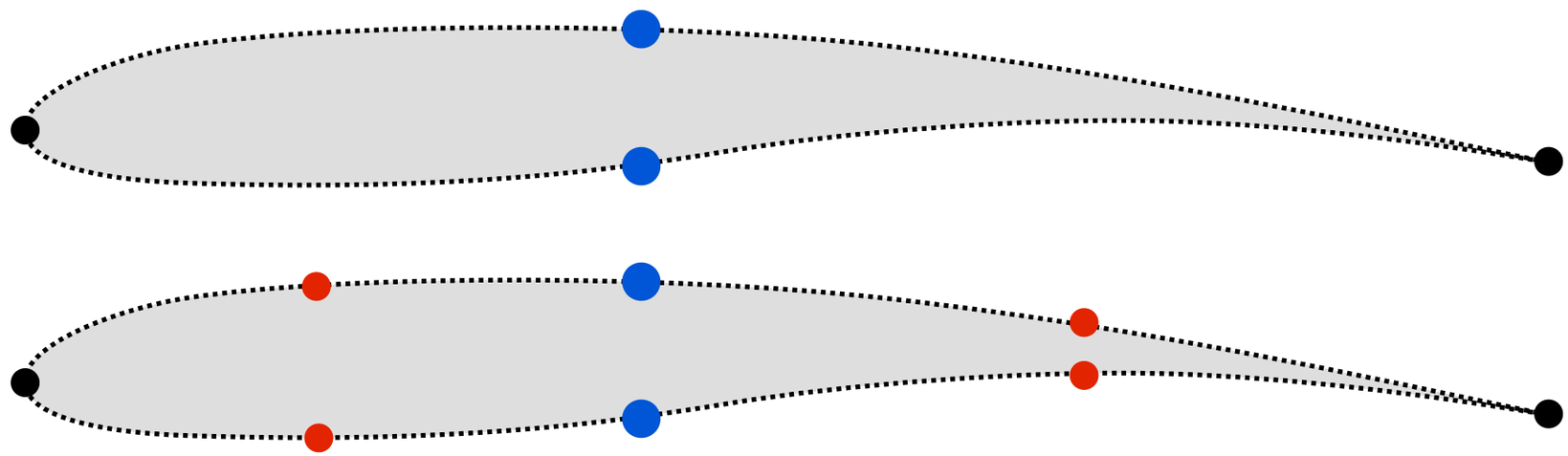

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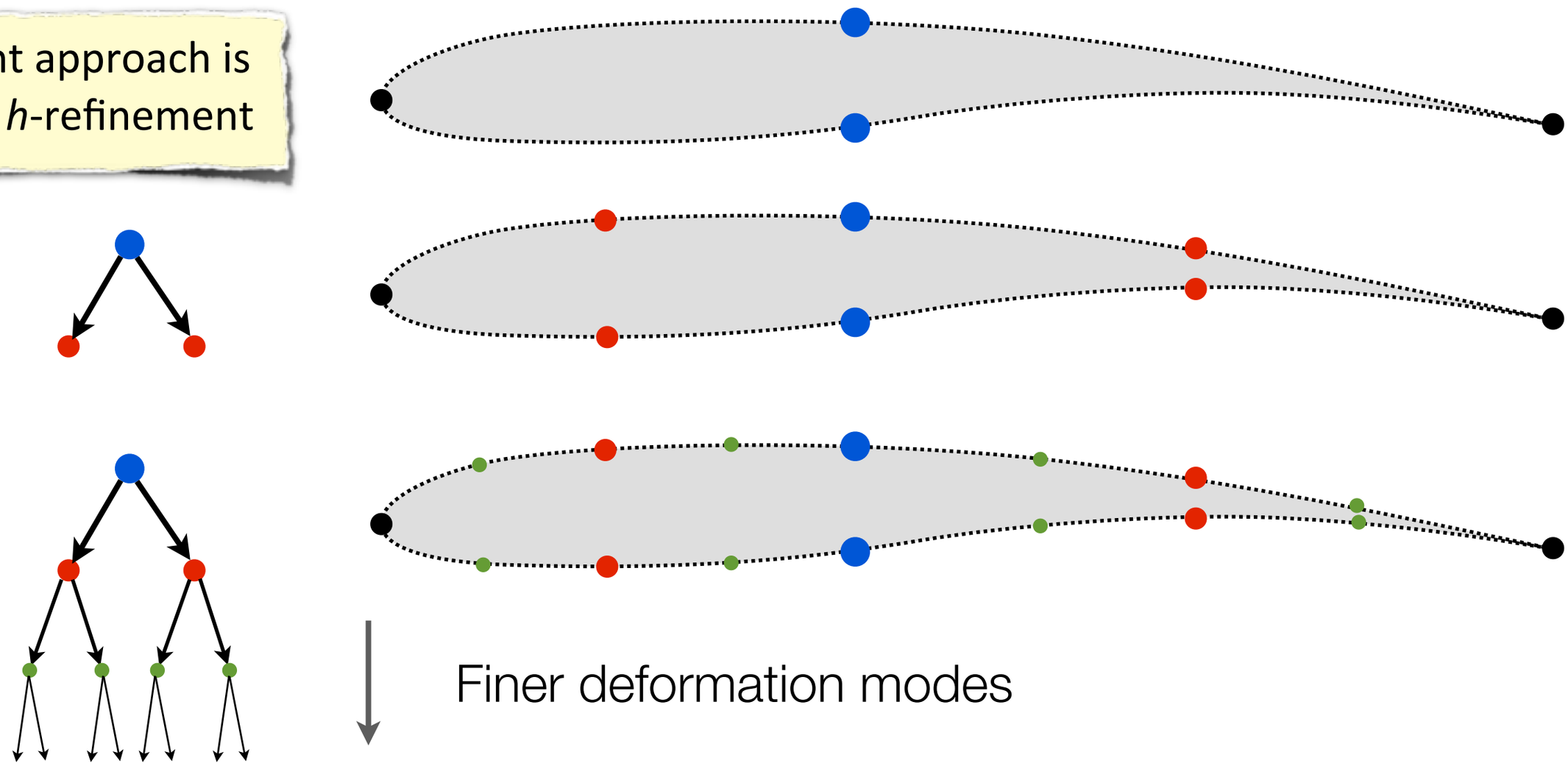


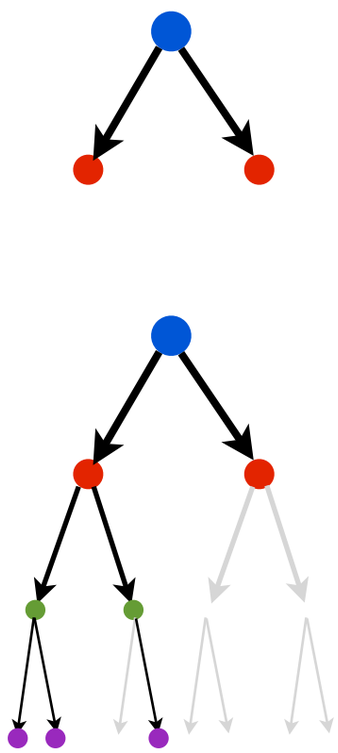
# Technical Approach

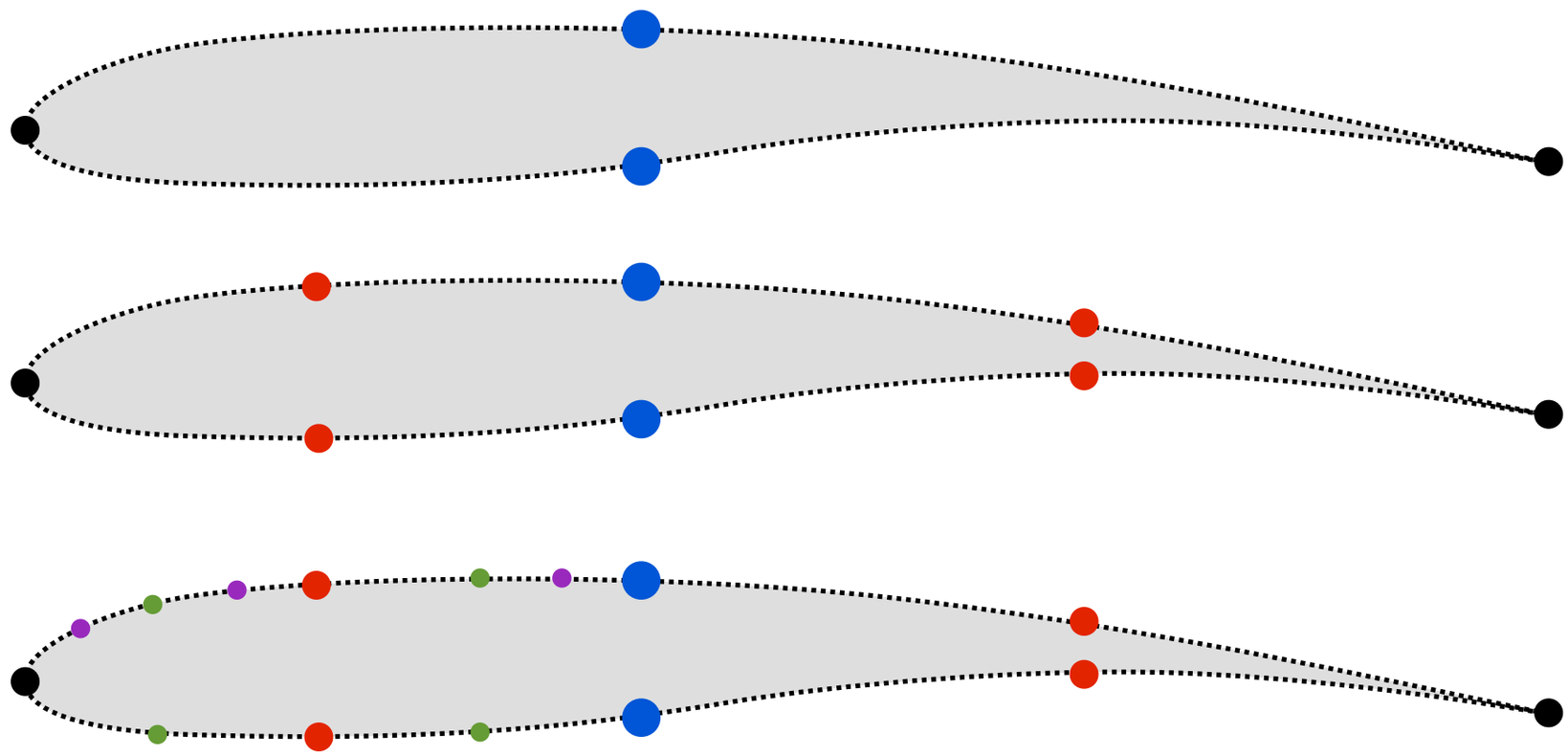


*Objective 2: On-the-fly enrichment of design space*

Modify existing Cart3D Design Framework for design-time addition of DVs

Also enables adaptive h-refinement





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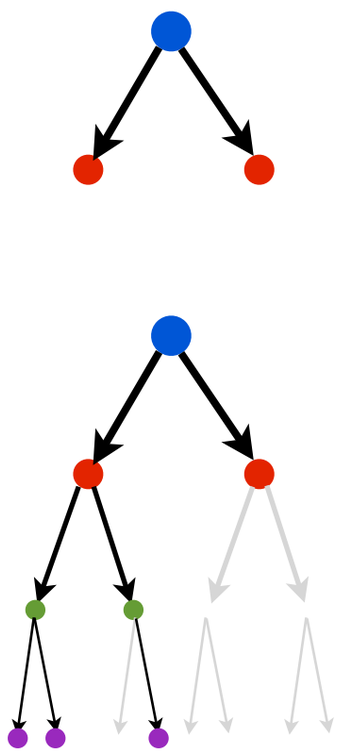

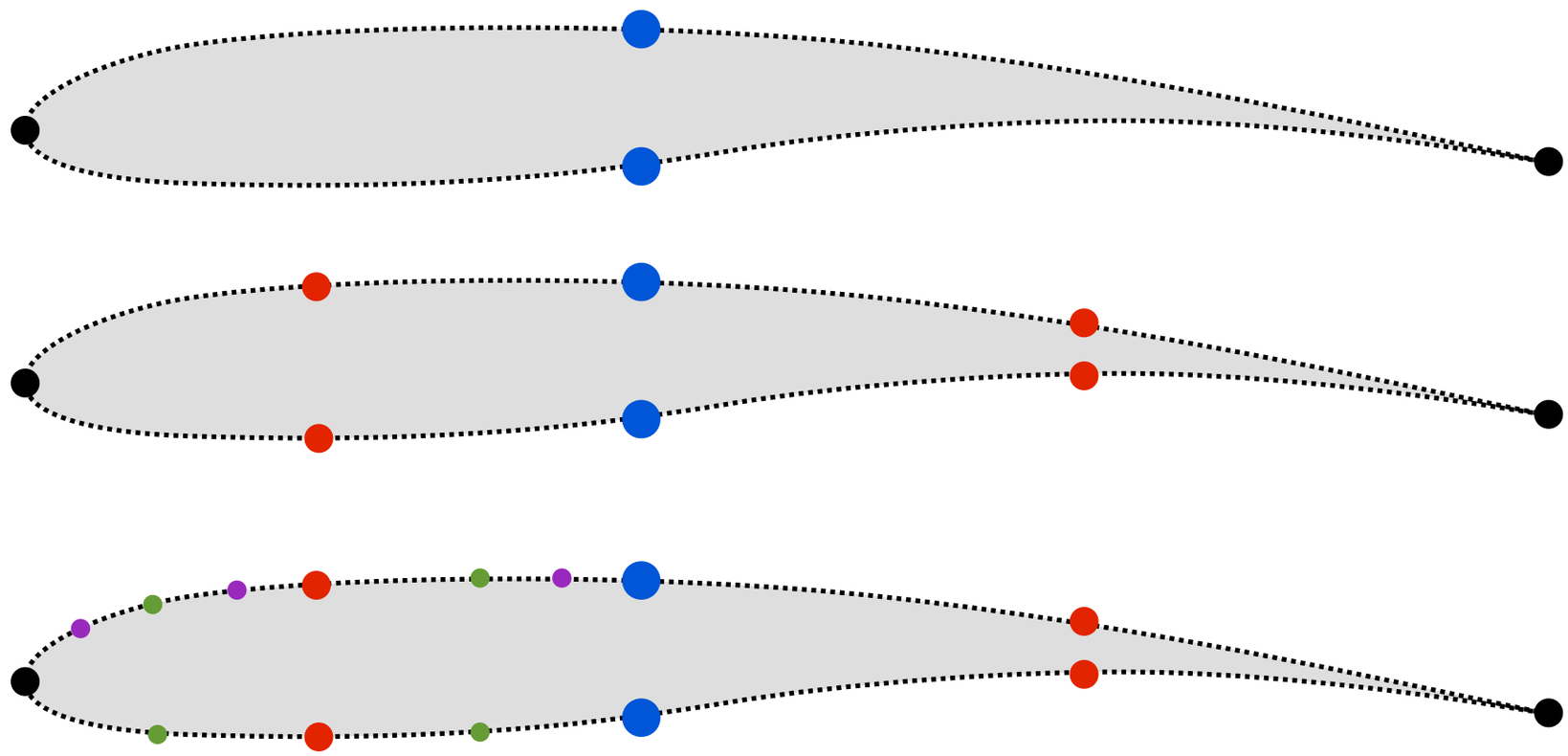

Adaptation requires an indicator to decide ***where*** DVs should be added

# Technical Approach



*Objective 3: Use adjoint to decide **where** to add DVs automatically?*

Already solving adjoint equation system as part of gradient-based design

Objective Function $\mathcal{J}(\mathbf{S}, Q)$

(Drag, Lift, sonic boom)

Adjoint

$\mathcal{J}(\mathbf{S})$

Project gradient

( the "sensitivities" )

Gradient $$\frac{\partial \mathcal{J}}{\partial X} = \frac{\partial \mathcal{J}}{\partial \mathbf{S}} \frac{\partial \mathbf{S}}{\partial X}$$

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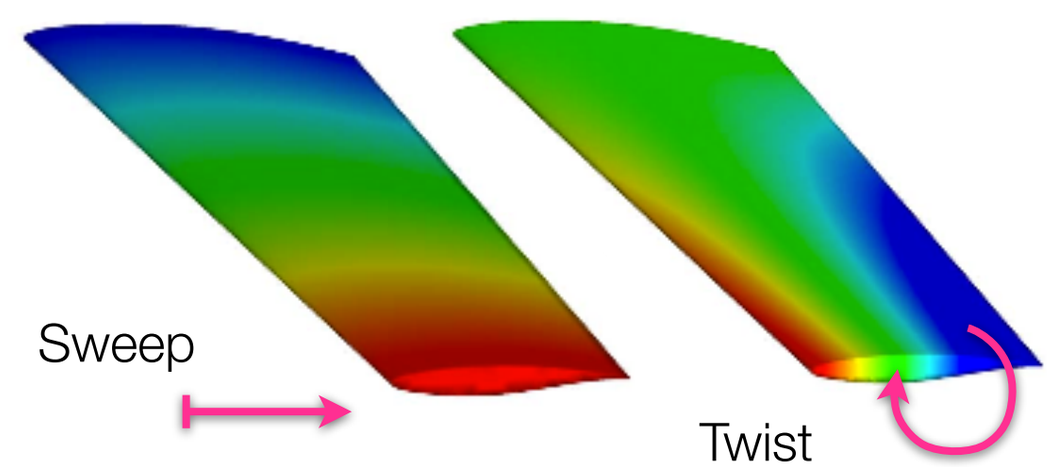
"shape sensitivities"



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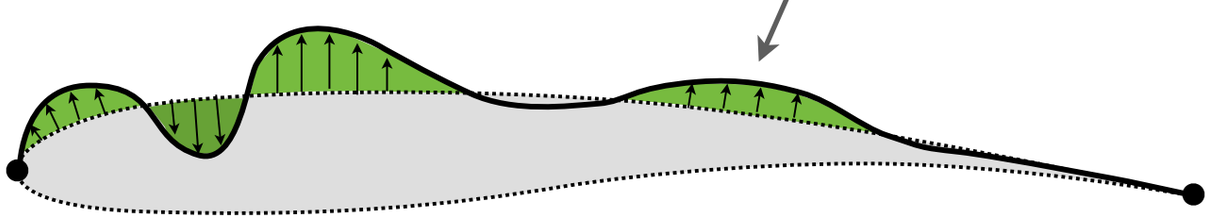
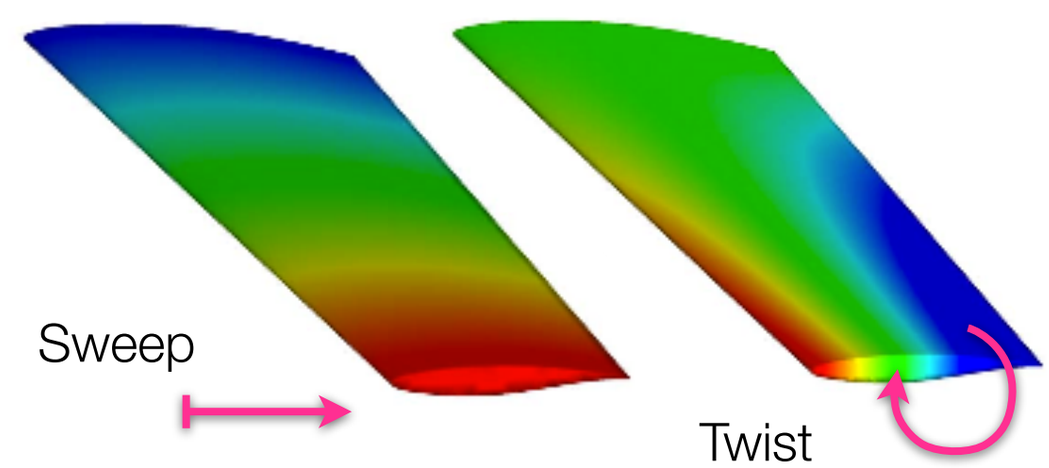


"Surface Objective Gradient"

"shape sensitivities"



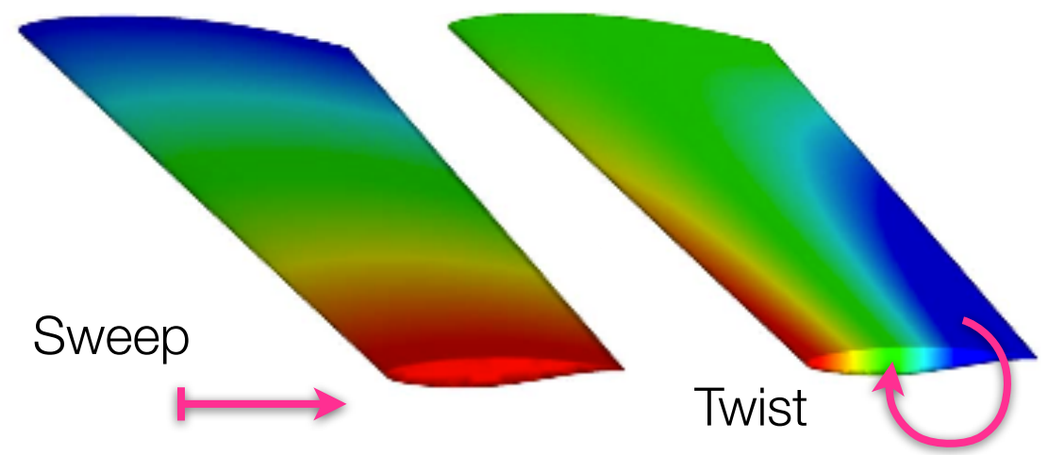
# Technical Approach



*Objective 3: Use adjoint to decide **where** to add DVs automatically?*

Gradient $$\frac{\partial \mathcal{J}}{\partial X} = \frac{\partial \mathcal{J}}{\partial \mathbf{S}} \frac{\partial \mathbf{S}}{\partial X}$$

The shape sensitivities come directly from the modeler



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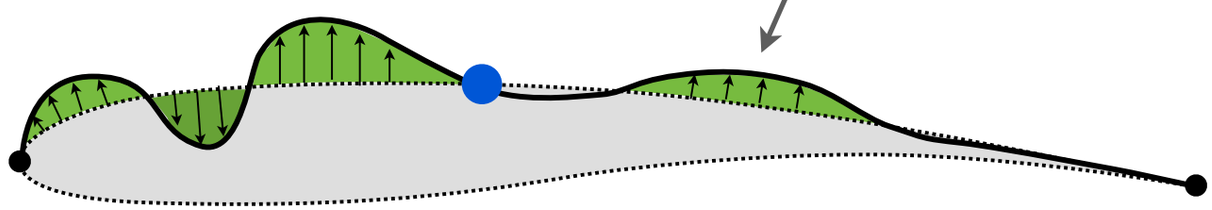


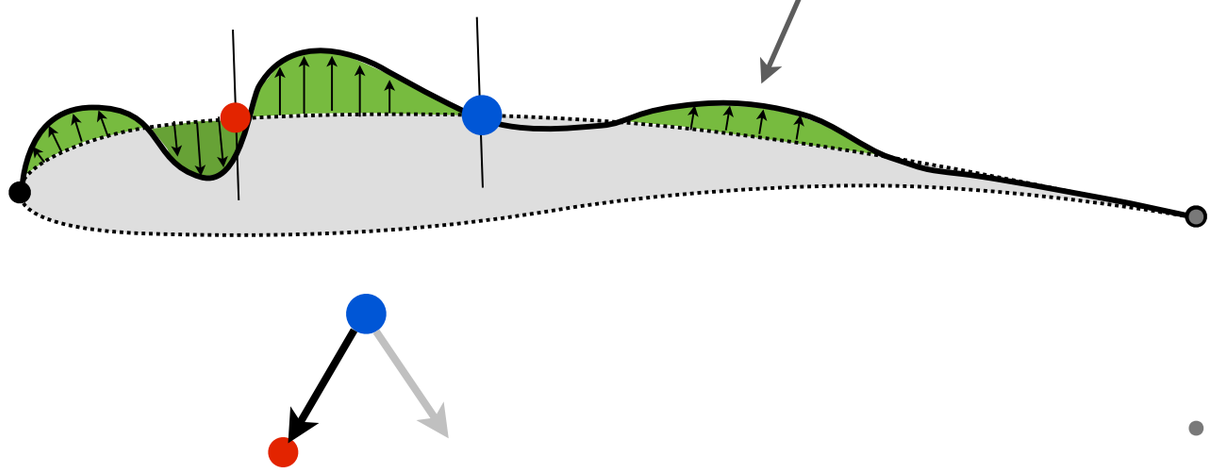
- The surface objective gradient comes from the adjoint and the derivative of the objective function
- Tells how sensitive the objective is to local changes in the surface
- We can just bin this up for regions of the surface associated with each DV

# Technical Approach



*Objective 3: Use adjoint to decide **where** to add DVs automatically?*

Gradient $$\frac{\partial \mathcal{J}}{\partial X} = \frac{\partial \mathcal{J}}{\partial \mathbf{S}} \frac{\partial \mathbf{S}}{\partial X}$$



- The surface objective gradient comes from the adjoint and the derivative of the objective function
- Tells how sensitive the objective is to local changes in the surface
- We can just bin this up for regions of the surface associated with each DV

- **Localize:** Refinement indicators are formed by aggregating the surface objective gradient on regions of the surface associated with each DV.
- Rank and **add DVs where indicators are the largest**

# Technical Approach



*Objective 4: Decide **when** to add DVs based on process metrics*

- Instrument the design framework to gather cpu and wall-clock time metrics
- Guard against over solving
- Monitor convergence rate of objective function
- Take into account wall-clock time, process robustness, process efficiency and number of successful design iterations

# Phase I Results



*Demonstrate accomplishments and Verification & Validation examples performed during Phase 1 research*

Inverse Design V&V Example in 2D (Objectives 1 & 2)

- Demonstrate correctness of results
- Demonstrates integration with complete Cart3D Design Framework including flow & adjoint solvers

Self-adaptive parameter refinement (Objective 3 & 4)

- Use adjoint-based surface sensitivities to prioritize introduction of new design variables
- Shape-matching model problem
- Compare to uniform refinement

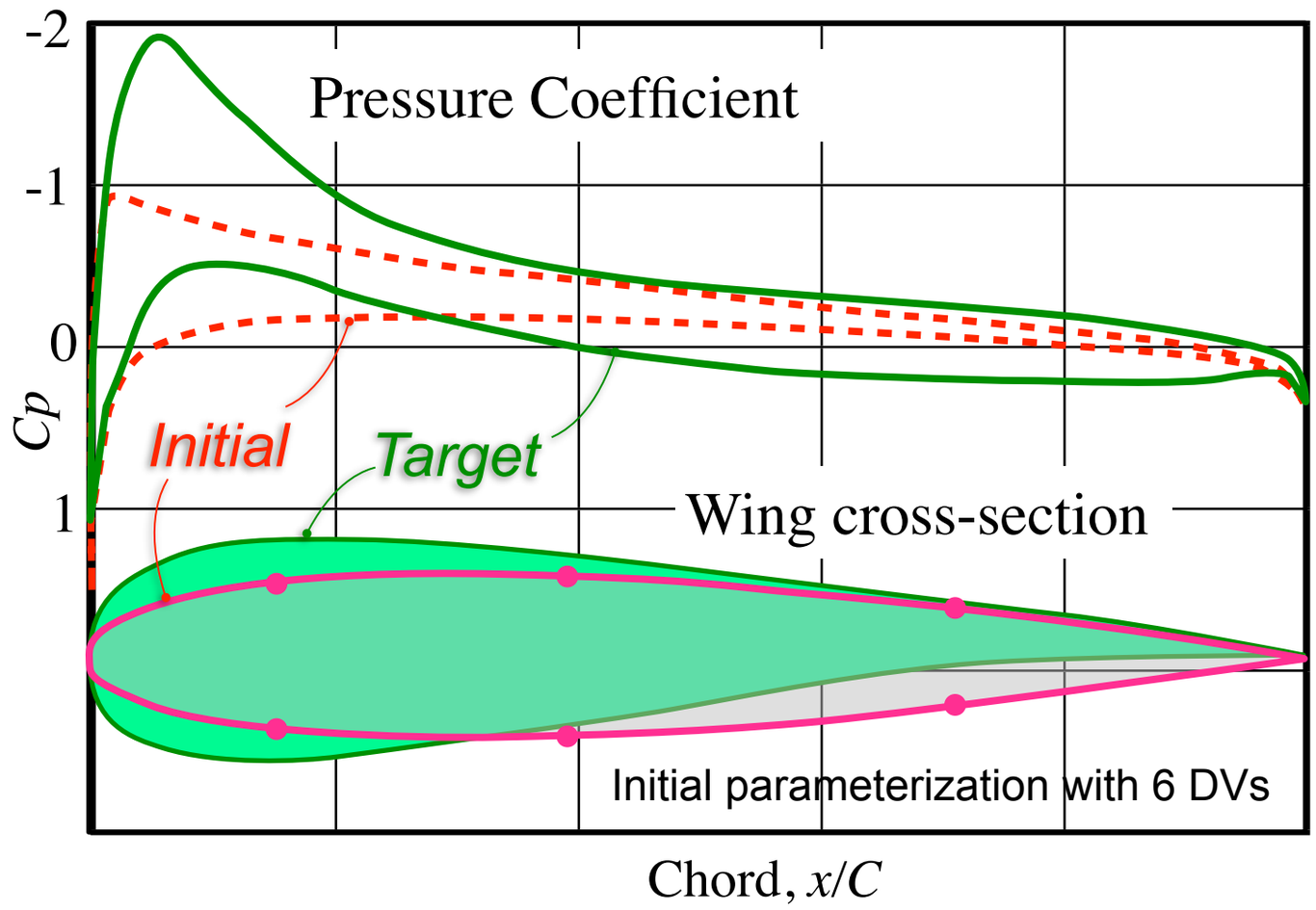
# Phase I Results



*Verification Example - Inverse design with uniform parameter refinement*

- Use complete Cart3D design framework & solvers
- Initial: NACA 0010 airfoil with 6 DVs on surface
- Target: Kulfan airfoil with known pressure distribution
- Objective Function:

$$J = \int (P - P_{\text{Target}}) dS$$



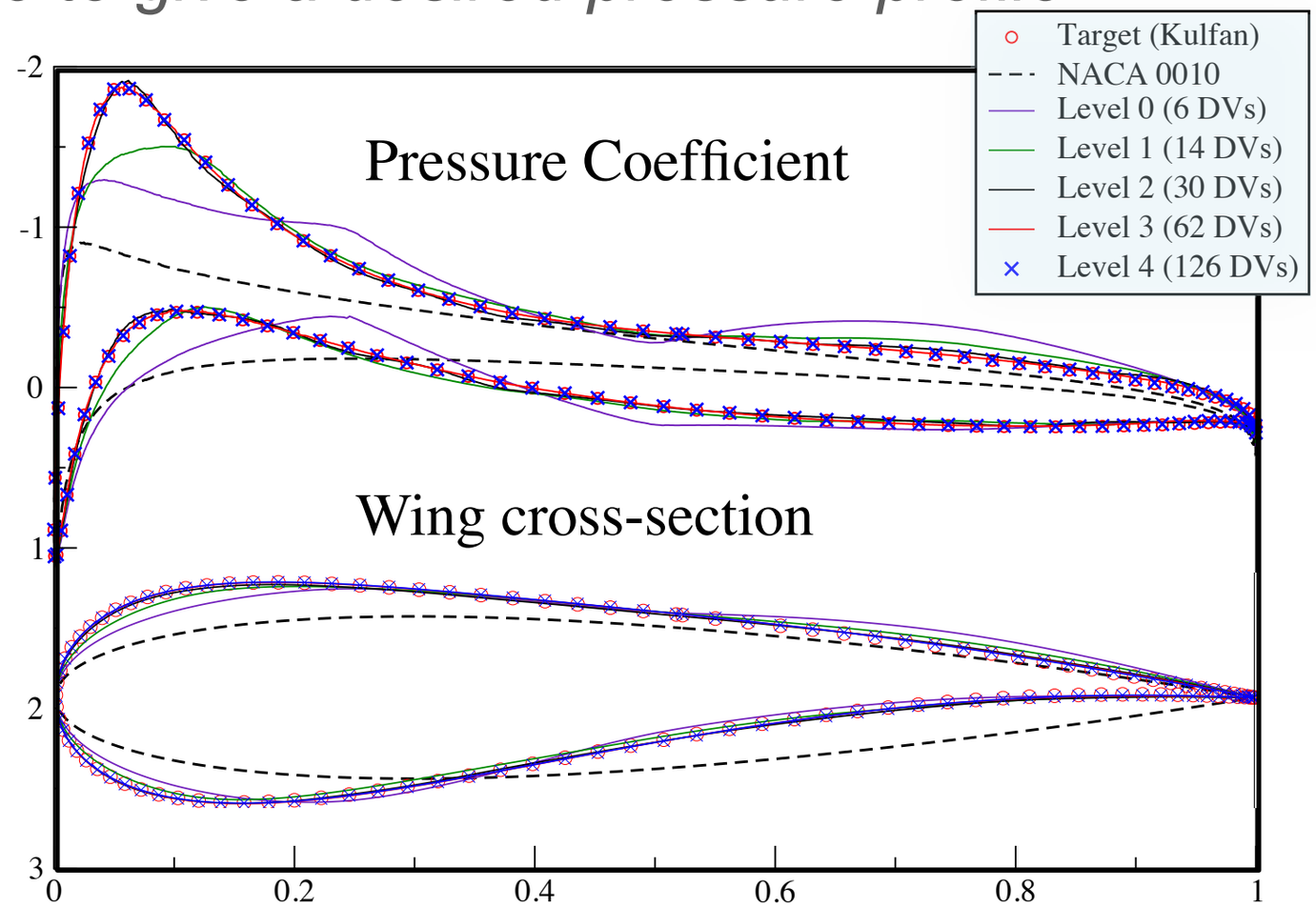

Problem Statement: *Advance design, automatically refining design variables as necessary to recover target using uniform refinement.*

# Phase I Results

NASA Aeronautics Research Institute

*Inverse Design - Discover shape to give a desired pressure profile*

- Uniform refinement to a total of 126 parameters
- Recovered pressure to plotting accuracy at 3rd refinement (30 DVs)
- Process *entirely automated*

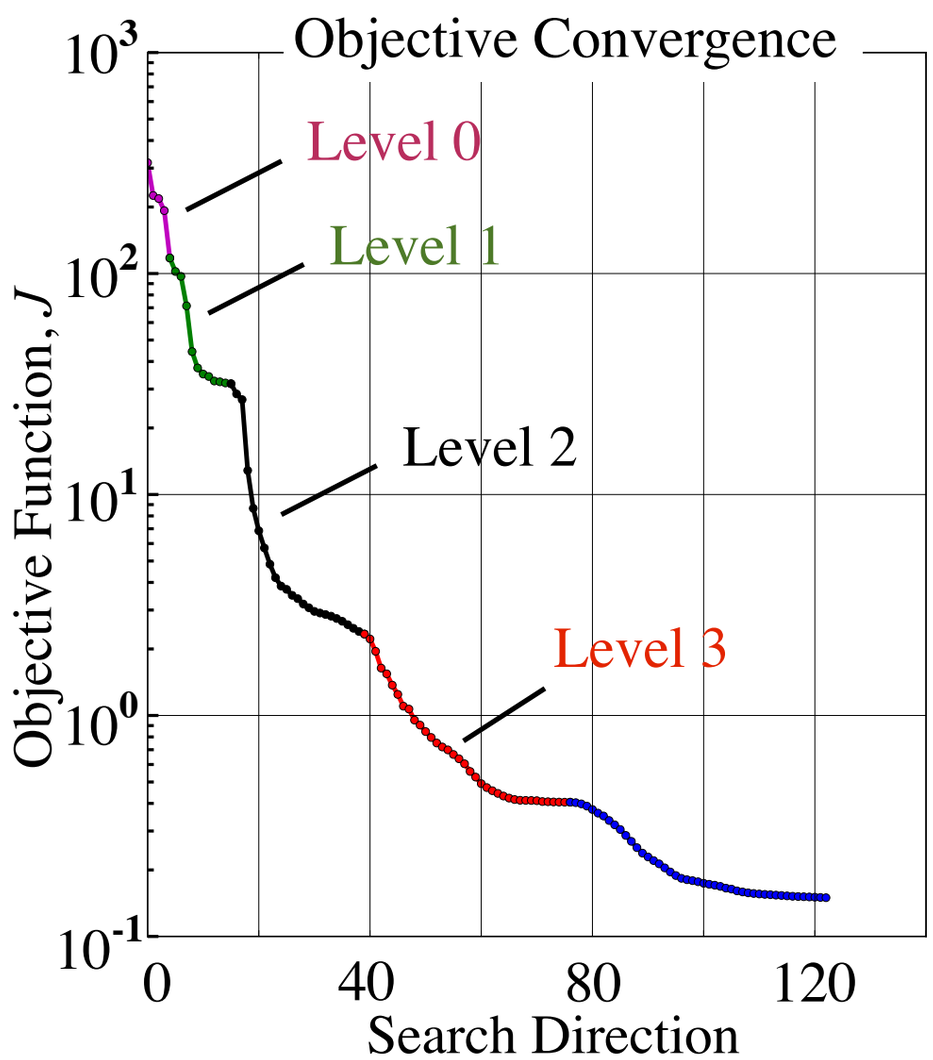



Problem Statement: *Advance design, automatically refining design variables as necessary to recover target using uniform refinement.*

# Phase I Results



*Inverse Design - Discover shape to give a desired pressure profile*



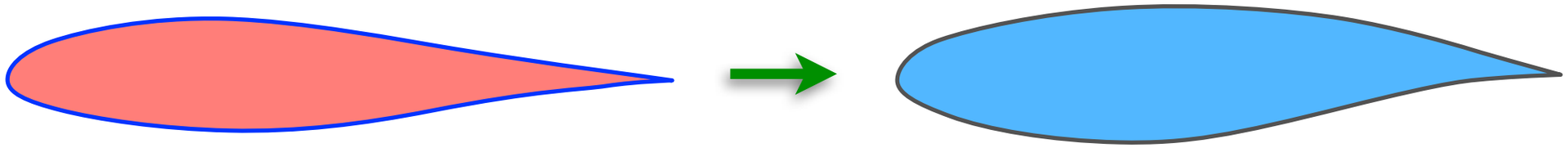

- Examine convergence of objective function
- Reduced objective function by 4 orders of magnitude in 120 design cycles
- Target recovered to plotting accuracy in 40 design cycles with 30 DVs
- New parameters introduced when improvement slows
- Final strategy for *pacing* refinement still in development

# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

Problem Statement: *Transform generic airfoil to RAE 2822 using self-adaptive parameter refinement:*



Initial airfoil

RAE 2822 airfoil

Objective function: *Point-wise difference between vertices*

$$\mathcal{J} = \sum_{i=1}^{nverts} (\mathbf{v} - \mathbf{v}^*)_i^2$$

Current coordinates

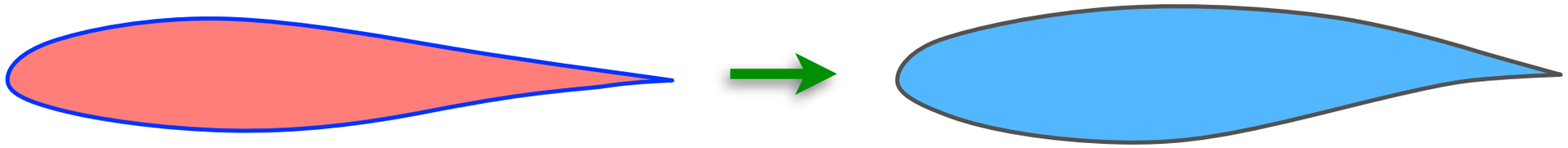
Target coordinates

# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

Problem Statement: *Transform generic airfoil to RAE 2822 using self-adaptive parameter refinement:*



Initial airfoil

RAE 2822 airfoil

## Objective function:

$$\mathcal{J} = \sum_{i=1}^{nverts} \left(\mathbf{v} - \mathbf{v}^*\right)_i^2$$

Current coordinates

Target coordinates

## Surface Gradient:

$$\frac{\partial \mathcal{J}}{\partial \mathbf{v}_i} = 2\left(\mathbf{v} - \mathbf{v}^*\right)_i$$

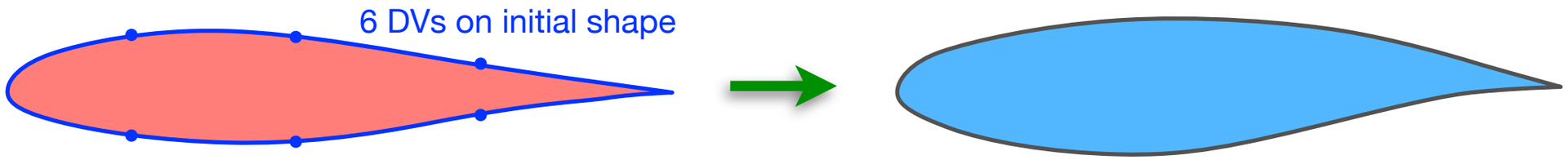
Differentiate objective function

# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

Problem Statement: *Transform generic airfoil to RAE 2822*




Initial airfoil RAE 2822 airfoil

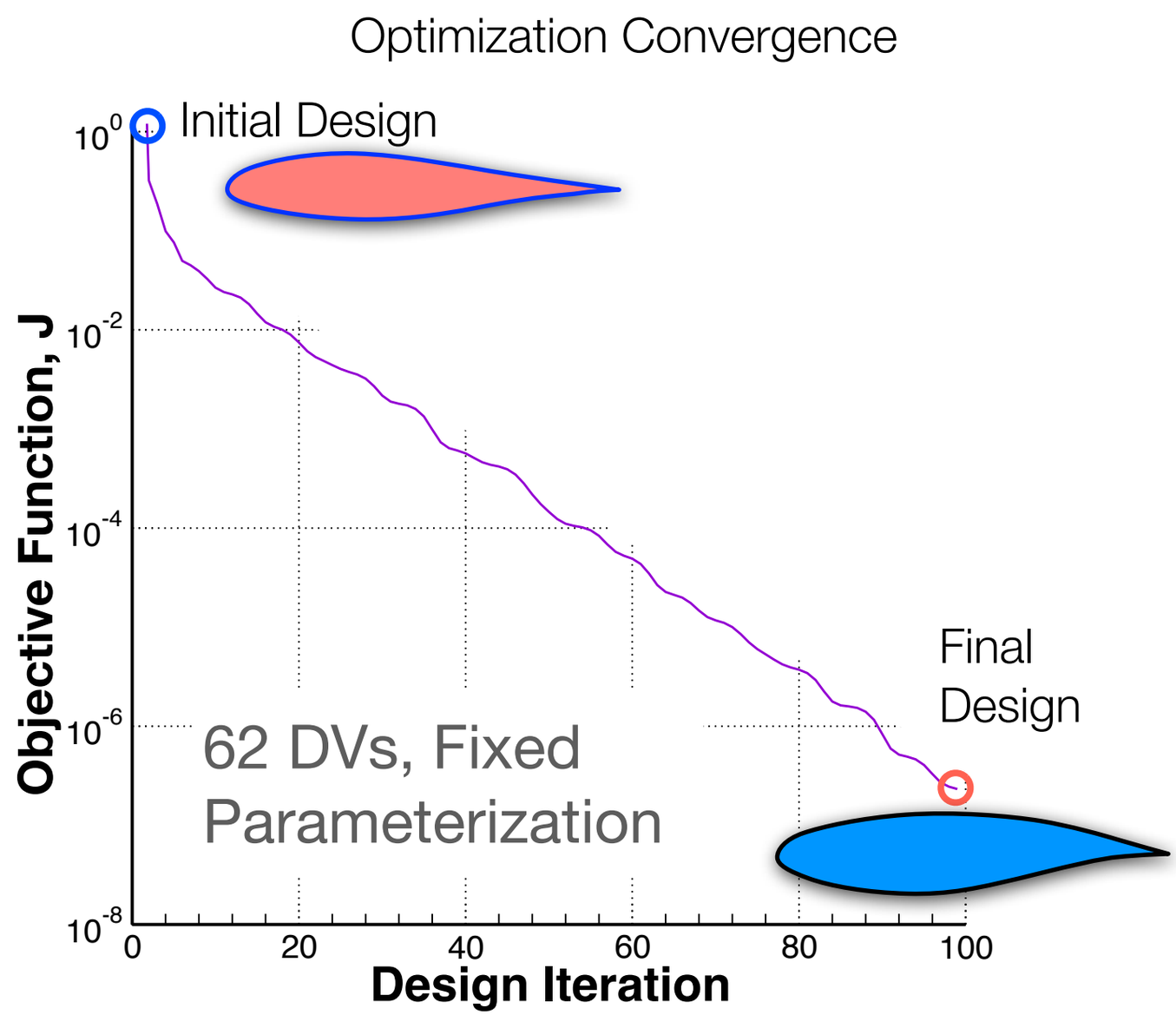
- Use constraint-based deformation for surface manipulation
- Form refinement indicator by aggregation of surface gradient
- Compare with uniform refinement of parameterization

# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

- Baseline convergence with uniform refinement (62 DVs)
- 7 orders of magnitude reduction in *J* in 100 design iterations.

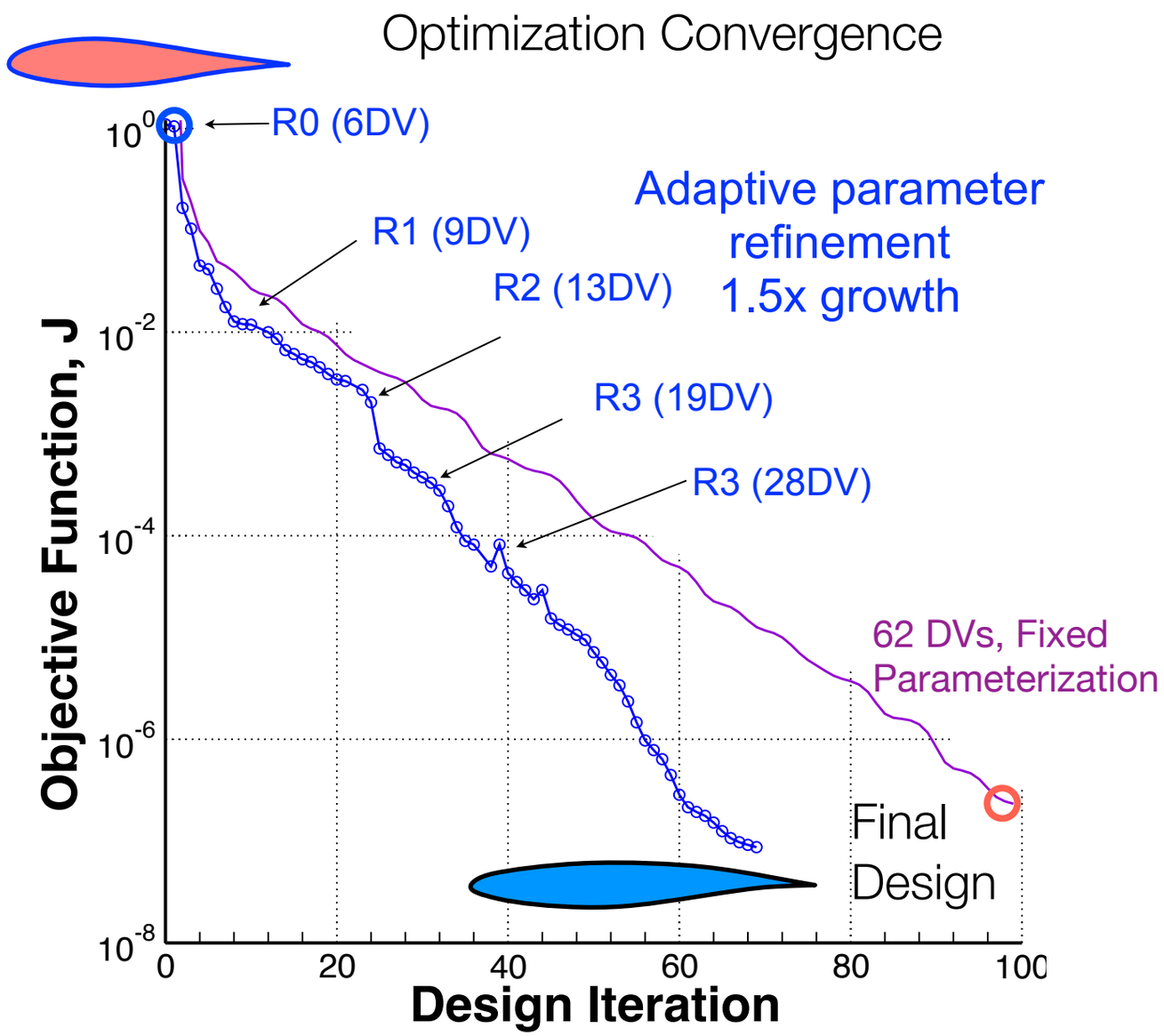


# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

- Repeat using adaptive parameterization
- 1.5x growth at each adaptation
- 35% fewer design iterations, with only 28 DVs on full set of 62DVs

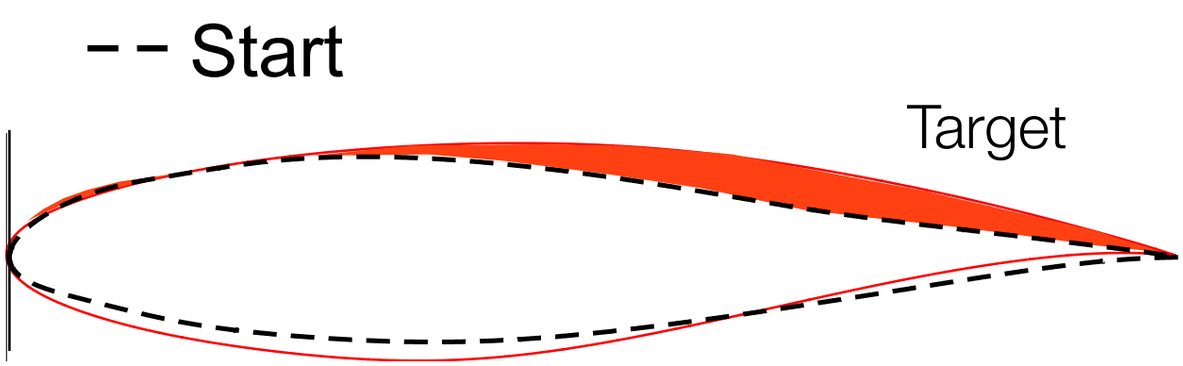


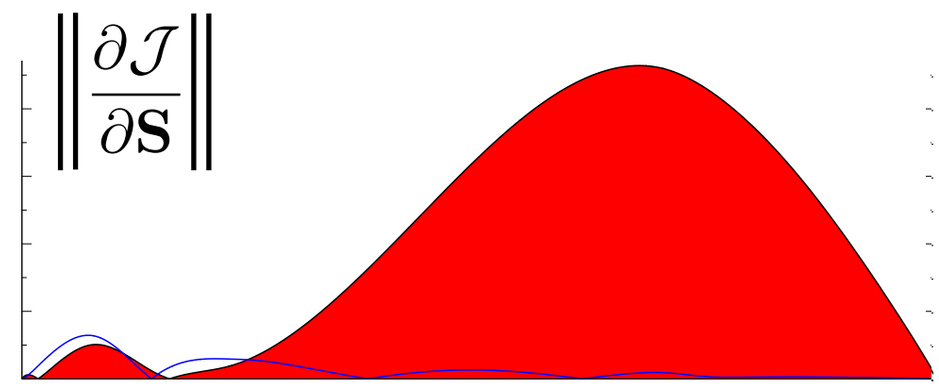
# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

## Initial parameterization “R0” (6DVs)




Top surface

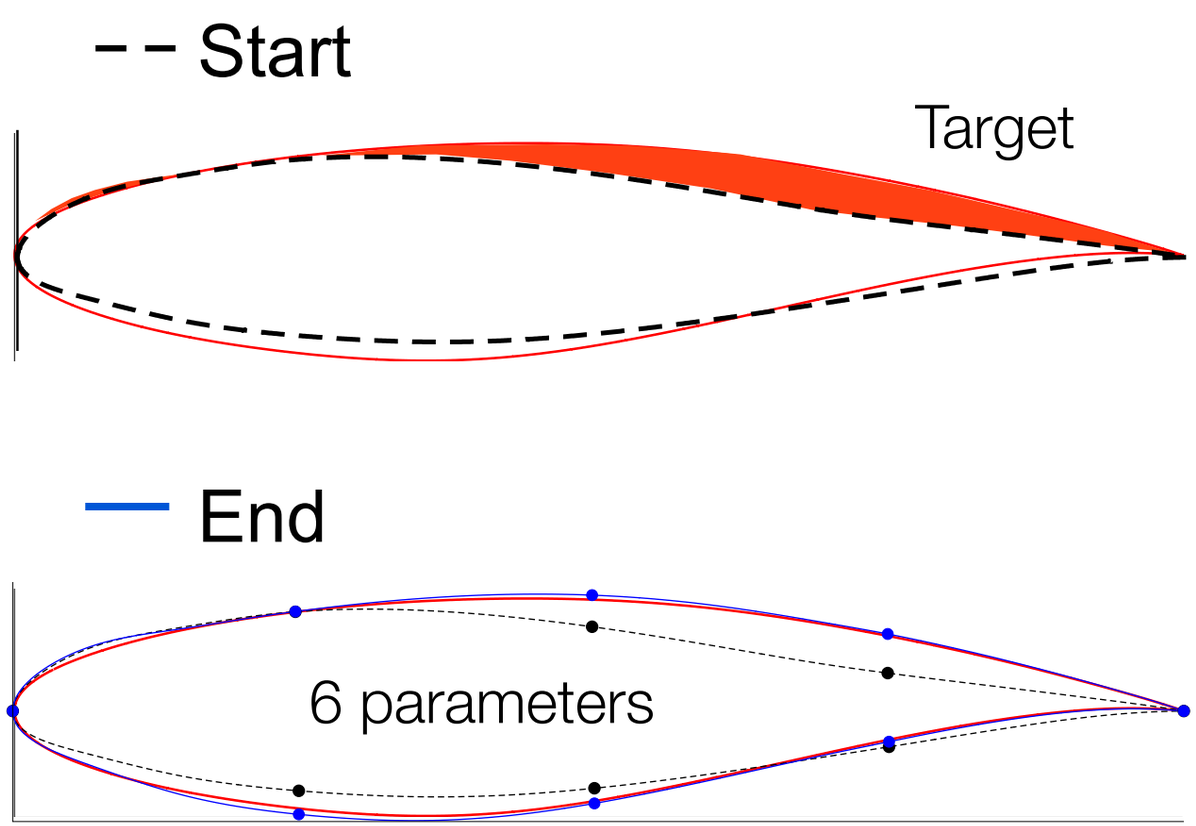
Design progress with initial parameterization

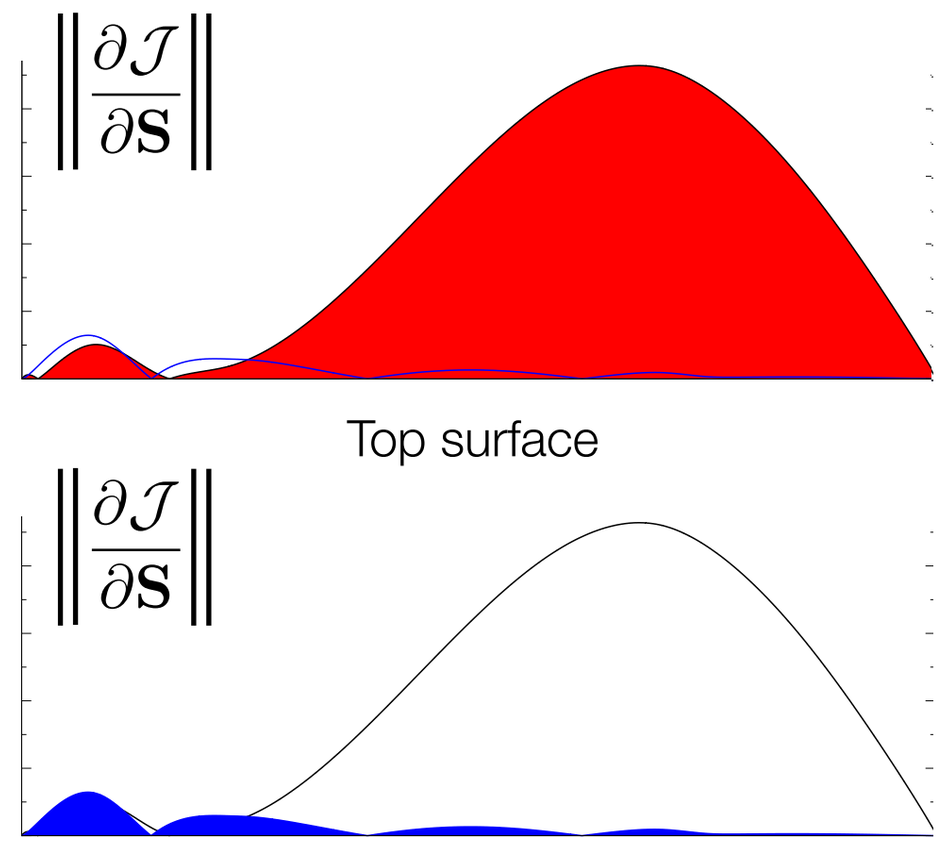
# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

## Initial parameterization “R0” (6DVs)



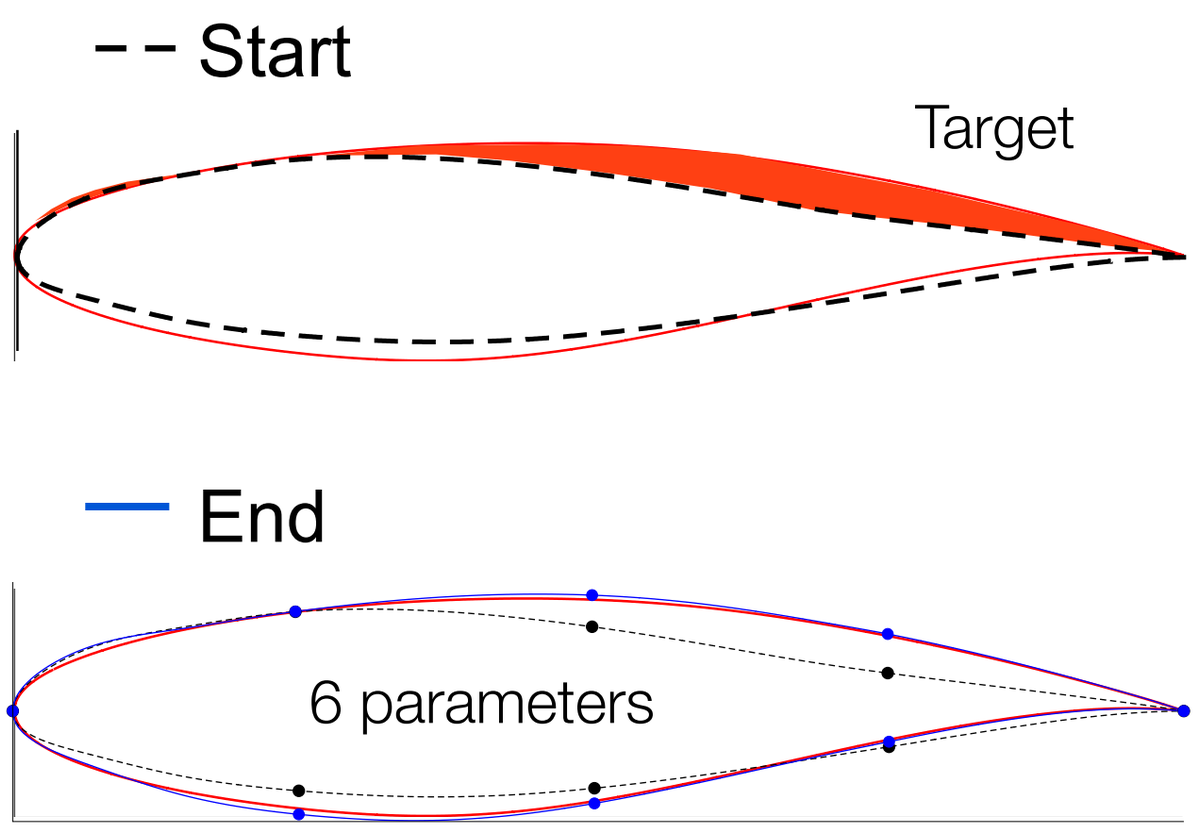

Design progress with initial parameterization

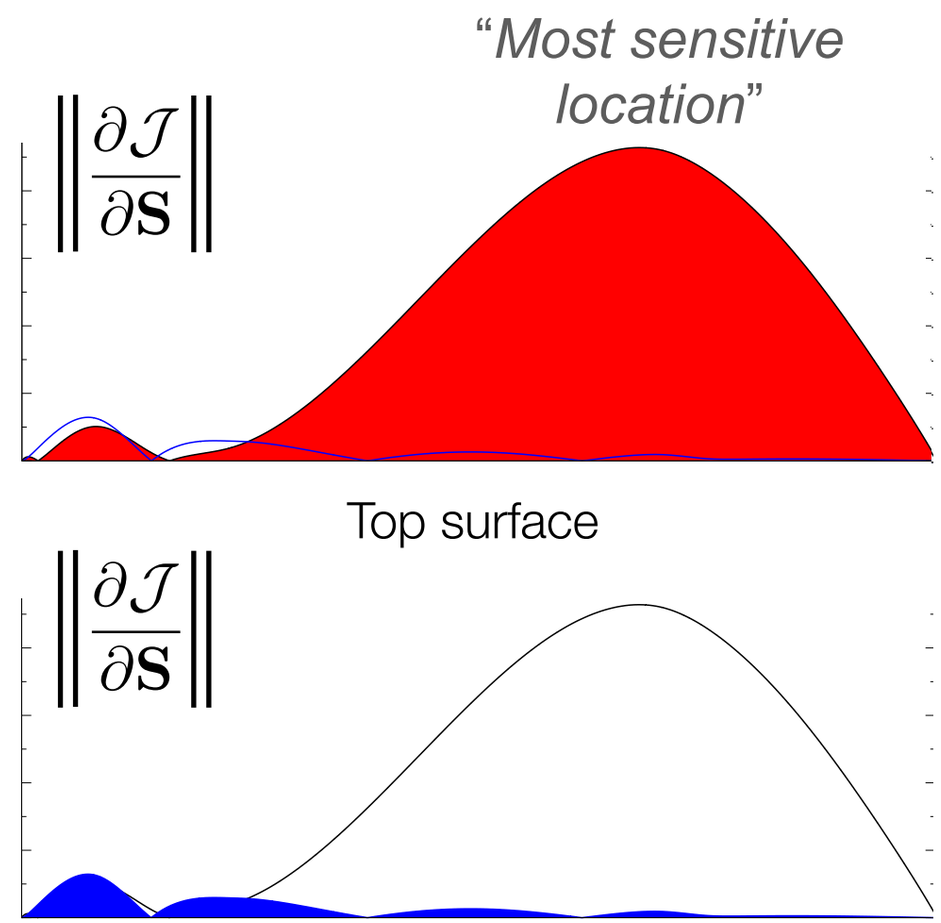
# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

## Initial parameterization "R0" (6DVs)



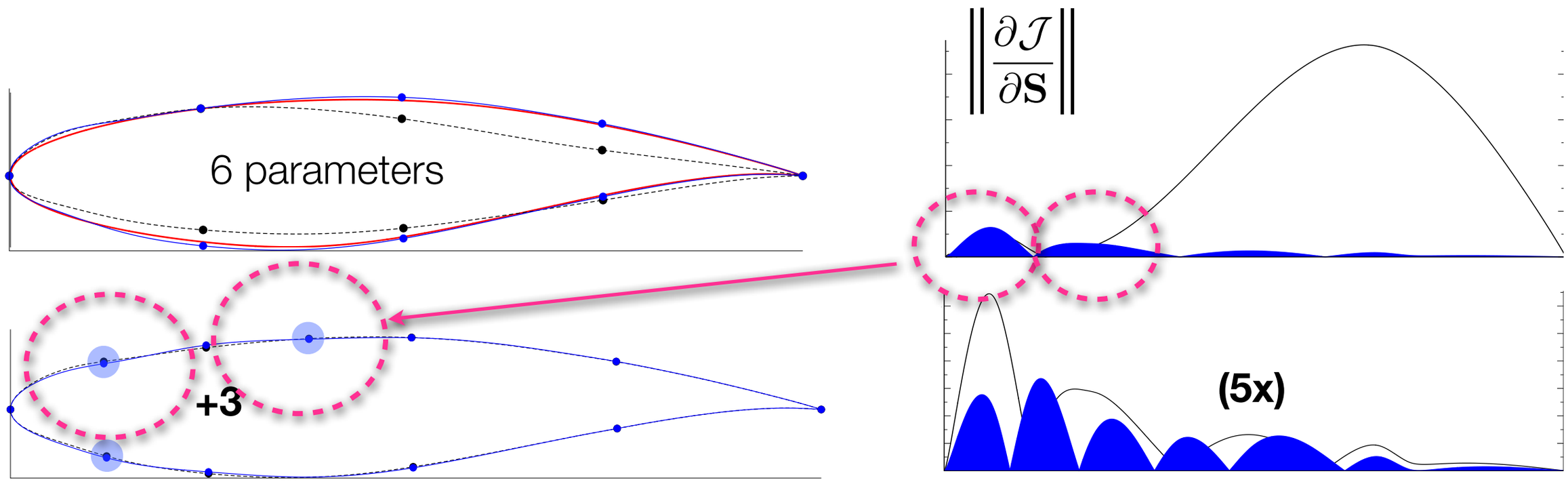

Design progress with initial parameterization
– 2 orders of magnitude reduction in Objective Function

# Phase I Results



*Self-adaptive parameter refinement: Shape-matching example*

## First Refinement "R1" (6DVs)




First refinement, add 3 new DVs (1.5x growth)

# Impact - ARMD Mission



*Impact on both ARMD mission-level goals and direct impact on specific programs and projects currently in ARMD portfolio*

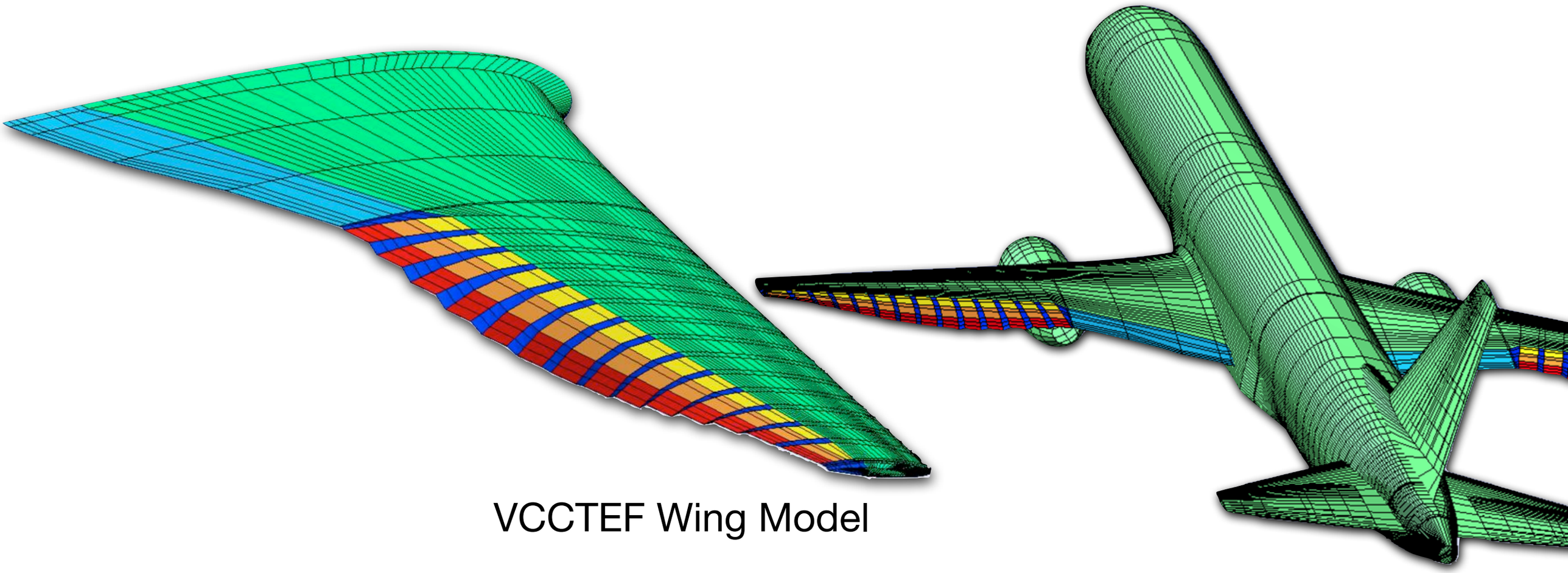
- Strategic Goals 3 & 4 – Develop better multidisciplinary design tools and advance aeronautics for societal benefit
- Outcome 4.1 – Provide design tools for vehicles with significantly improved performance. Working directly with efforts in
    - Environmentally Responsible Aviation (ERA) – Integration of ultra-high-bypass propulsion systems
    - FA: Sub-/Transonic aircraft – Flexible aircraft & VCCTEF
    - FA: High-Speed – Supersonic design for low-sonic boom
    - FA: Rotary Wing – Design tools for rotary wing
- Aeronautical Sciences – Improved tools for MDO

# Impact – Direct Impact



*Specific ARMD efforts directly supported during Phase I research*

*Adaptive Aeroelastic Shape Control* program & *Variable Camber Continuous Trailing Edge Flap* (VCCTEF) design



VCCTEF Wing Model

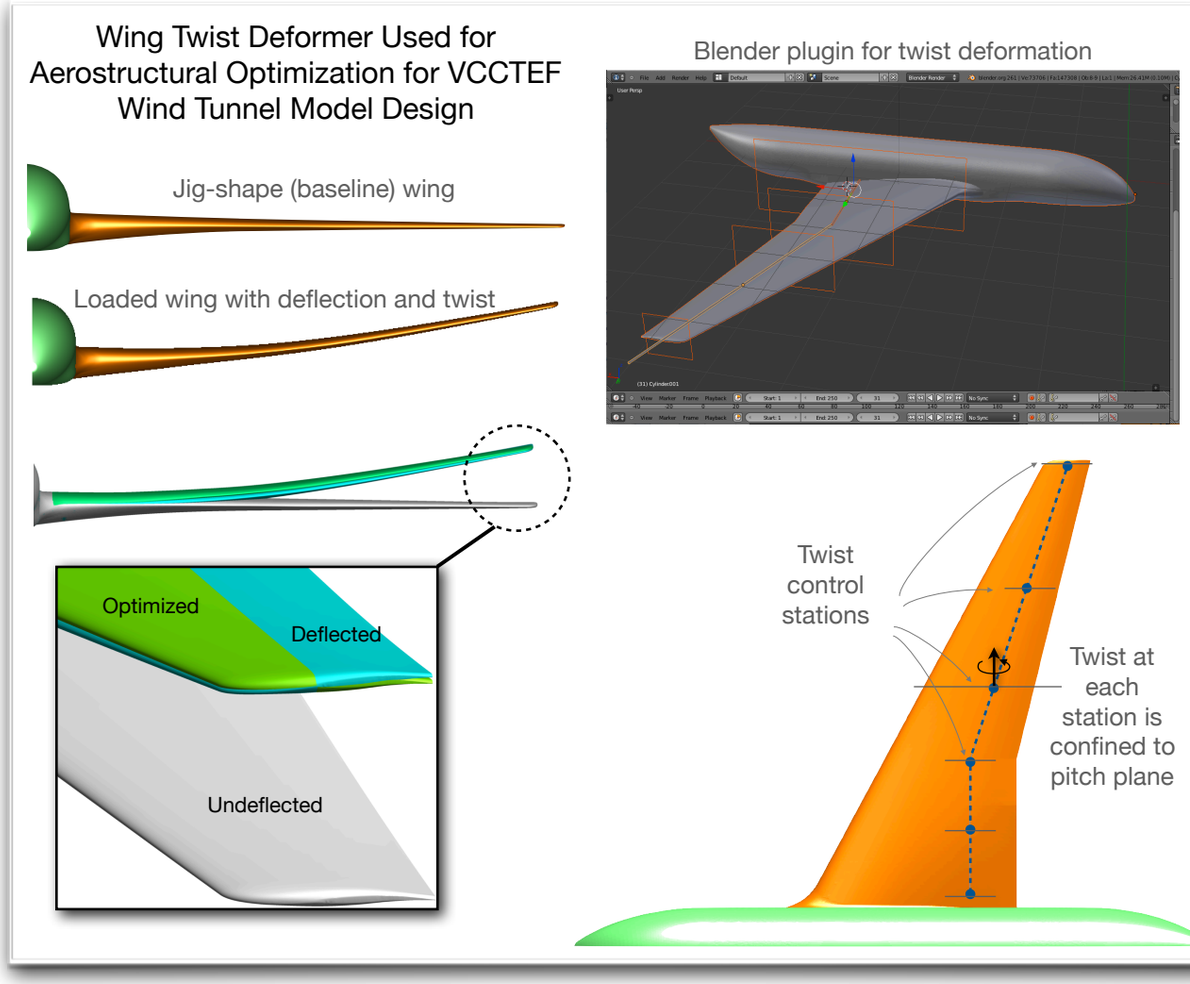
# Impact – Direct Impact

NASA Aeronautics Research Institute

*Specific ARMD efforts directly supported during Phase I research*

## *Adaptive Aeroelastic Shape Control* program & *Variable Camber Continuous Trailing Edge Flap* (VCCTEF) design

- Use Blender plug-in as geometry engine for enacting deformation of highly flexible VCCTEF wing
- Provided Blender plug-in for custom wing-twist parameterization
- Used Blender interface to Cart3D Design Framework for coupled aero-structural optimization of VCCTEF wind-tunnel model
- Enabled both bending & twist in design



# Impact – Direct Impact

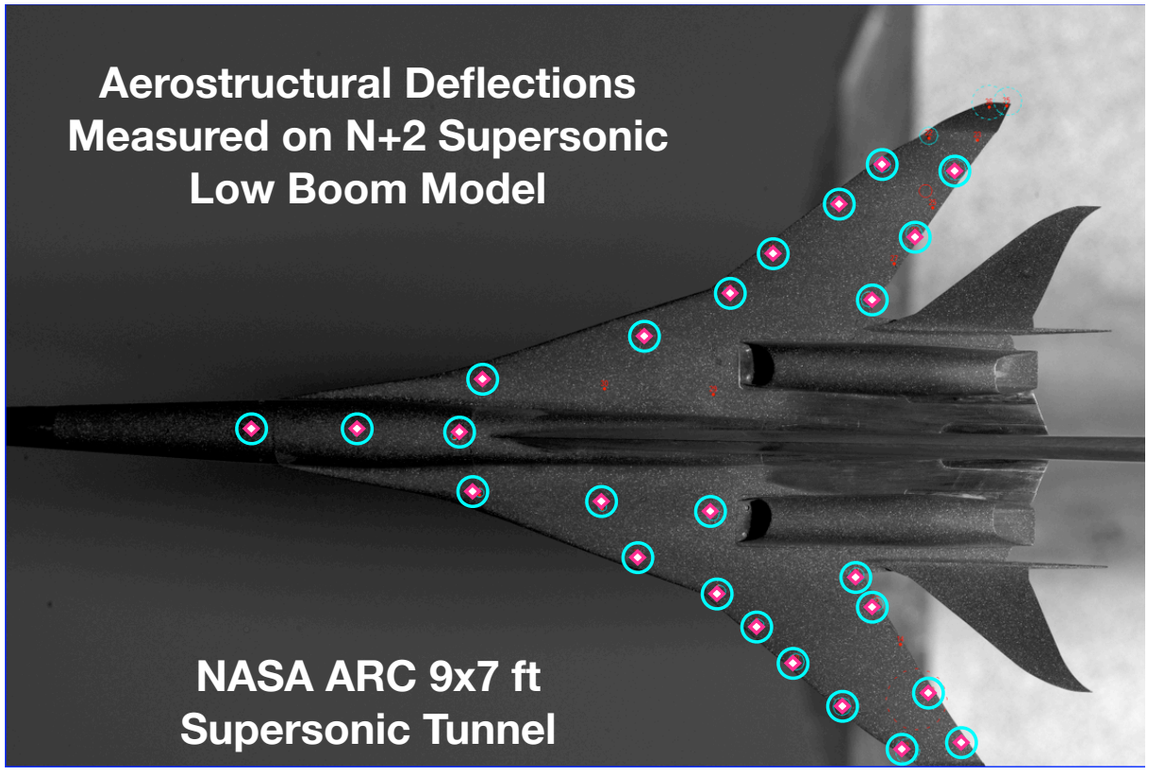


*Specific ARMD efforts directly supported during Phase I research*

*Fundamental Aeronautics: High-Speed Project*

*Low Sonic Boom Design Tools*

- Tunnel tests of N+2 low-boom models measured deflection due to air loads
- Plan is to compute sensitivity of boom signature to model deflections
- Constraint-based deformation developed in Phase I is best (and only) method for applying these deflections to the computational models
- This tool is production ready and will be applied to this problem in Aug 2013



# Impact – Direct Impact



*Joint work with AFRL on UAV Flight in Light Urban Landscapes*

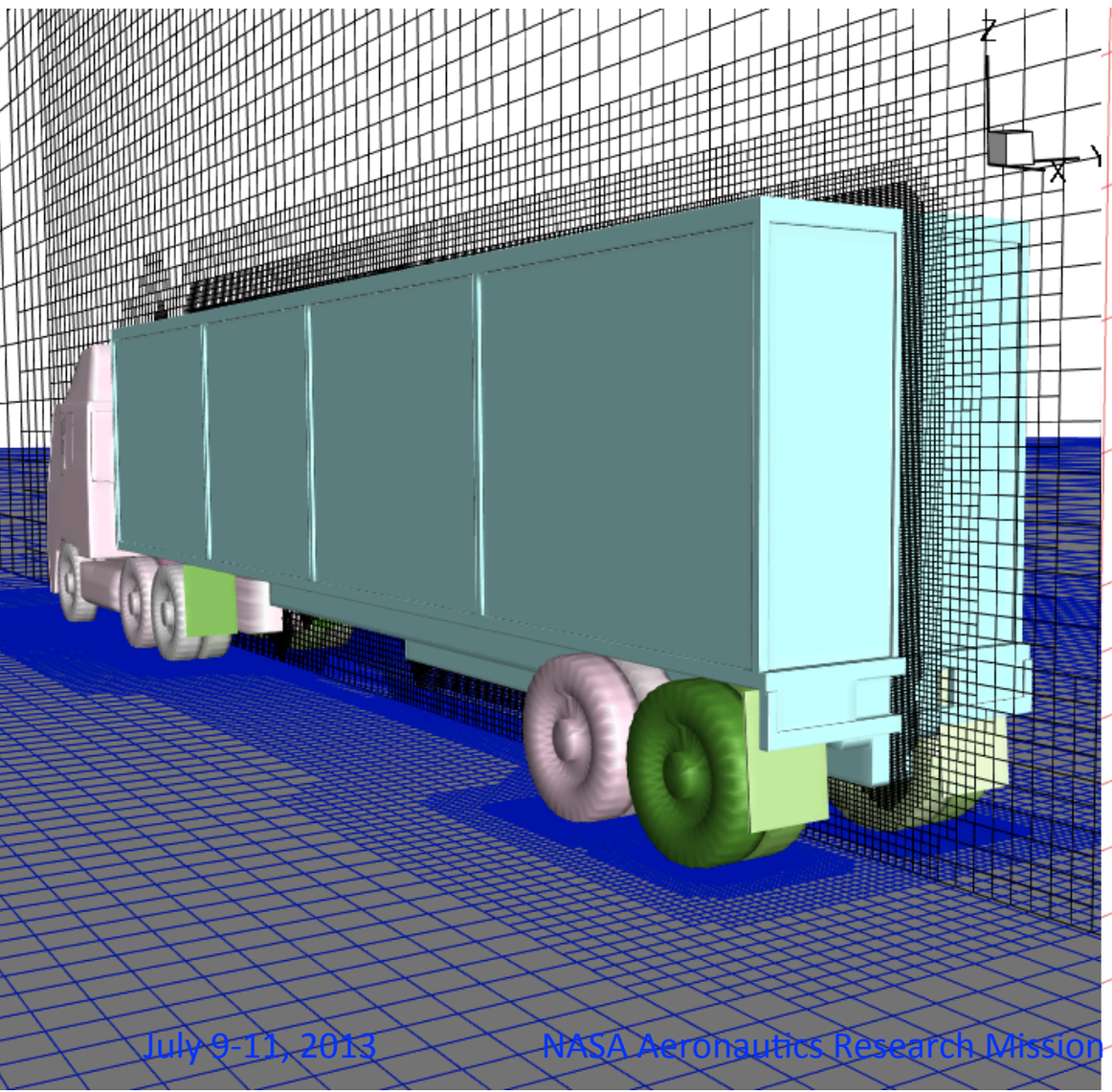
- All geometry for analysis produced using Cart3D plug-ins for Blender

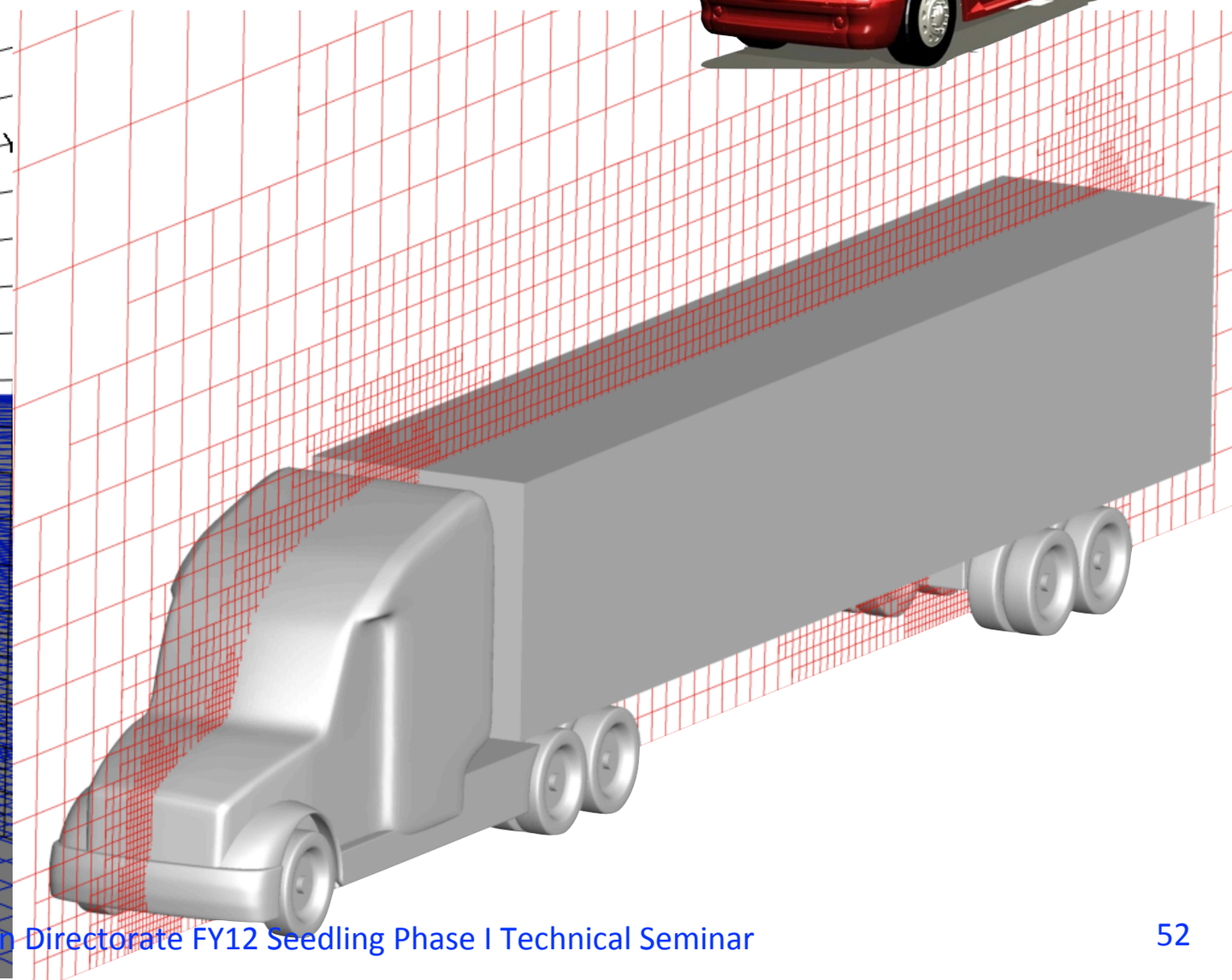
# Impact – Direct Impact

NASA Aeronautics Research Institute

*Support DOE study of aerodynamics of class 8 tractor-trailer trucks*

- Produced geometry for analysis using Cart3D plug-ins for Blender
- Tunnel tests done in ARC NFAC 80 x 120 ft



# Technology Readiness (TRL)



*TRL levels of various independent tools and components developed during Phase I*

- Cart3D design framework: TRL 8-9
  - Over 350 users supported
  - Design Framework in use in NASA, DoD, Industry and Academia
- Blender: TRL 9
  - Over 800,000 downloads from www.blender.org
- Constraint-Based Deformation Blender plugin: TRL 6
- Rigid-wing deformer for aeroelastic design: TRL 7
- Self-adaptive parameterization: TRL 4
  - Deployed in Cart3D Design Framework by end of Phase I

# Dissemination Plan



*Existing Cart3D user-base provides excellent path for dissemination*

- Over 350 users of Cart3D within NASA, DoD, DOE & Academia
- Support for adaptive parameterization built-into Cart3D Design Framework
- Blender user community has tremendous on-line support network (videos, tutorials, etc) for new users
  - Blender plug-ins will be distributed with Design Framework
- Detailed dissemination plan included in Phase II milestones
  - Includes alpha & beta-test programs
  - Includes workshop, tutorials and how-to videos
- Dissemination of technical developments through publication, seminars and professional meetings

# Technical Dissemination



## *Technical publications and presentations using this work*

- Anderson, G. R., Aftosmis, M. J., and Nemec, M., "Parametric Deformation of Discrete Geometry for Aerodynamic Shape Design," *AIAA Paper 2012-0965*, January 2012. also Presented at *AMS Seminar Series*, Invited Speaker, NASA ARC, Feb. 2012.
- Anderson, G.R., Aftosmis, M.J., and Nemec, M., "Constraint-based Shape Parameterization for Aerodynamic Design". *ICCFD7 Paper-2001*. 7th International Conference on Computational Fluid Dynamics (ICCFD7), July 2012.
- Anderson, G.R., Aftosmis, M.J., and Nemec, M. "Shape parameterization for Aerodynamic Design", Presented (Stanford University) March 2013.
- Aftosmis, M.J., Nemec, M., & Rodriguez, D., "*Twist Optimization of the VCCTEF Wind Tunnel Mode*l" Presented (NASA) May, 2013.
- Aftosmis, M.J., "*Inviscid Simulations of Light Urban Environments with Earth Boundary-Layers*", Presented (NASA) May 2013.
- Rodriguez, D.L., Aftosmis, M.J., Nemec, M., Smith, S.C., "Static Aeroelastic Analysis with an Inviscid Cartesian Method" submitted to 2014 AIAA Sci-Tech Meeting, Jan 2014.

- Stanford University Ph.D thesis (2014-15 academic year)
- Journal and conference papers planned under Phase II
- NASA TM Planned under Phase II

# Summary of Current Status



*No schedule issues, expect completion of all objectives by end of Phase I*

Objective 1: Constraint-based parameterization - [Complete] Implemented in 2 & 3 dimensions, Blender plug-ins in source repository. Presented at international ICCFD meeting.

Objective 2: Automated Parameter Refinement Framework - [Complete] Prototype running and available. Modified Cart3D Design Framework in source Repository.

Objective 3: Adjoint-based Refinement Indicators - [Prototyped] Various binning strategies working in two-dimensions using adjoint surface sensitivities. Leverages same discrete adjoint solve as shape design gradients. In source repository.

Objective 4: Refinement Strategy - [In Progress] Controls pacing of introduction of new parameters into optimization. Goal is robust strategy to maximize design improvement at fixed computational cost. Expected complete by end of Phase I.

# Next Steps



- Objective 1: Constraint-based parameterization - [Complete]
- Objective 2: Automated Parameter Refinement Framework - [Complete]
- Objective 3: Adjoint-based Refinement Indicators - [Prototyped] Finish evaluation and implement in production code-base.
- Objective 4: Refinement Strategy - [In Progress] Complete by end of Aug 2013.
- Release to alpha-testers, include:
  - Updated Cart3D Design Framework
  - Release Blender plug-ins for basic discrete geometry engine, constraint-based deformation, multi-segment twist plugin, adjoint-based refinement indicator
- Complete deformation of low-boom supersonic wind tunnel model – Aug 2013
- Submit Phase II NARI Seedling proposal with complete dissemination plan
- Submit Phase I final report & abstract to AIAA summer meeting

# Questions?

Michael Aftosmis

George Anderson