Analysis Driven Shape Design using Free-form Deformation of Parametric CAD Geometry

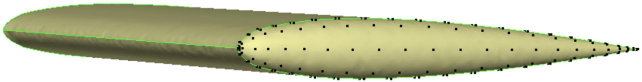
Marlena C. Gomez and Marshall C. Galbraith
Aerospace Computational Design Laboratory
Department of Aeronautics & Astronautics
Massachusetts Institute of Technology

AIAA SciTech January 2024

Motivation

Preliminary Design

- Traditional Parameters
  - chord, sweep, aspect ratio
- Do not capture detailed features



Local Shape Modification

- Fine-tune only detail areas after preliminary design
  - wingtip, wing-fuselage junction, strut, fairing
- Use Free-form Deformation to morph underlying B-spline geometry
- Geometry generated with Engineering Sketch Pad (ESP)
- Analysis and optimization using pyCAPS framework

Outline

Previous Work

Limitations

Free-form Deformation

Morphing Airfoil

Penalty Function

Optimization Results

Drag Minimization of a Symmetric Airfoil

Drag Minimization of an Asymmetric Airfoil

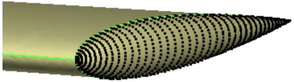
Conclusion

Outline

3D Shape Optimization: Wingtip B-Spline Surface

Wingtip B-Spline Surface

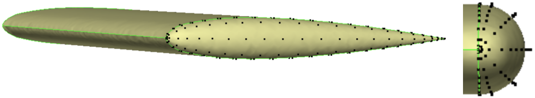
- NACA 0012 unit chord and span
- Rounded wingtip with radius 1



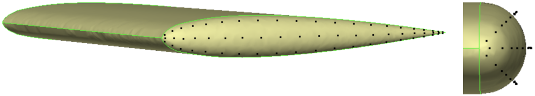
All 1175 control points defining surface by default.

Design Parameters

- Fixed control points
  - First opens up geometry
  - Second breaks tangency
- 63 control points
  - 21 in u-direction
  - 3 in v-direction
- Move by offset value outward up to 0.3 in normal direction



All 175 control points defining reduced surface.

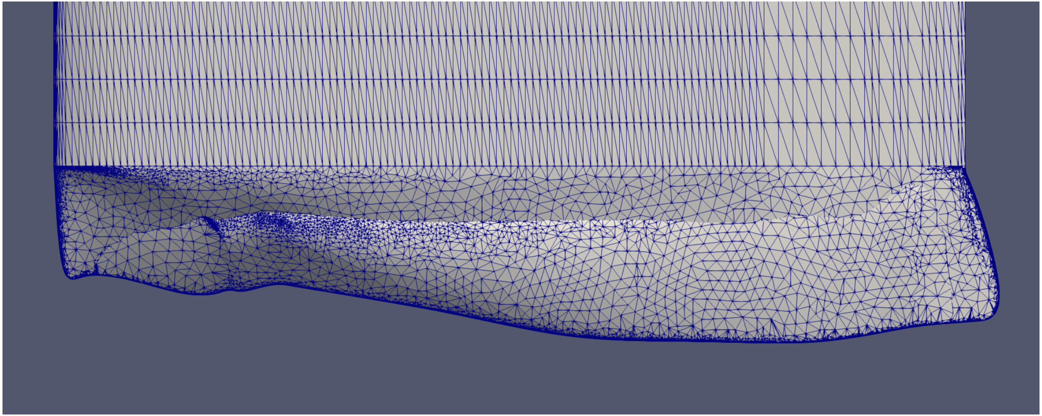


Design variable control points

FFD: Motivation

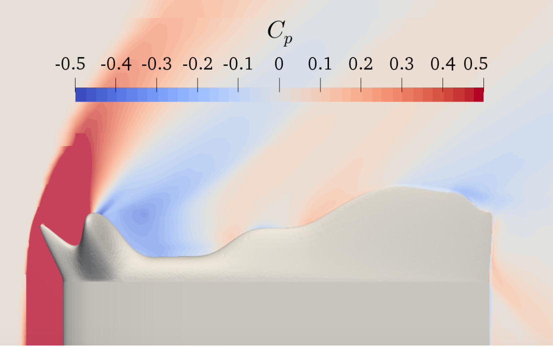
Using B-spline control points as design parameters

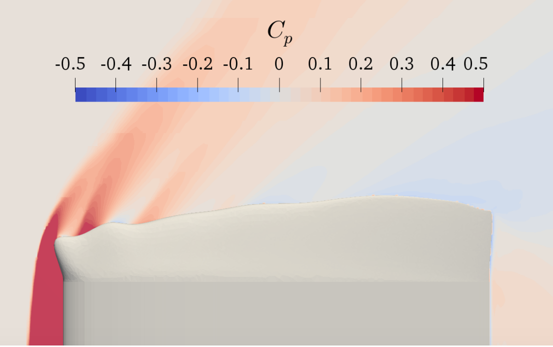
- Issue: Expressed shapes limited by constraints on control point movement, which is the normal direction because otherwise geometry self-intersects



Using B-spline control points as design parameters

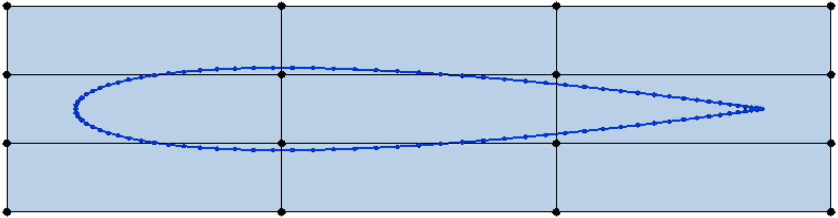
- Issue: wiggles in geometry





Outline

FFD: Morphing Airfoil

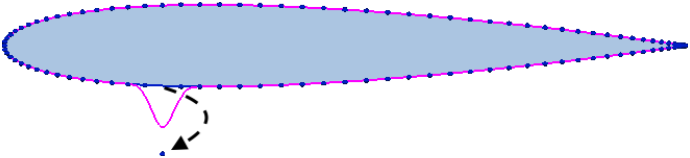


FFD grid and surface with embedded NACA 0012 and control points

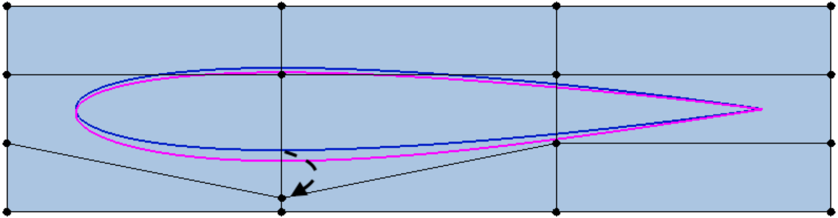
Free-form Deformation

- Control points of FFD grid are design variables to move underlying B-spline geometry
- Advantages:
  - Successfully used to morph mesh points in design
  - Smoother shapes
  - Control over number of DoFs

FFD: Morphing Airfoil

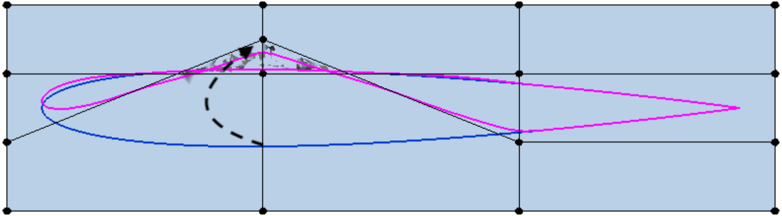


Movement of one control point of a B-spline curve. The undeformed geometry is shown in blue, and the deformed geometry is shown in pink.



Result of deforming one control point in cubic FFD surface.

FFD: Penalty Function



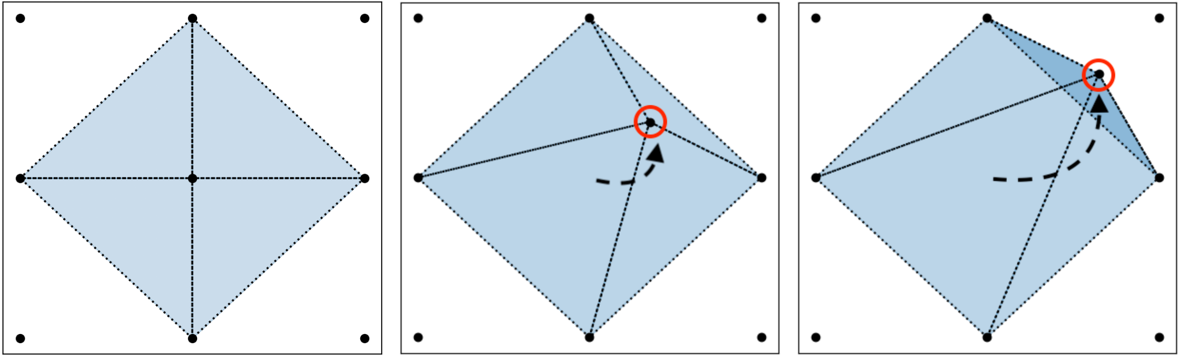
Invalid geometry outline.

Penalty function

- Prevent invalid geometry by constricting FFD control points from moving outside of the bounds of its neighbors
- If FFD surface does not have folds, embedded geometry also will not have folds

Outline

FFD: Penalty Function



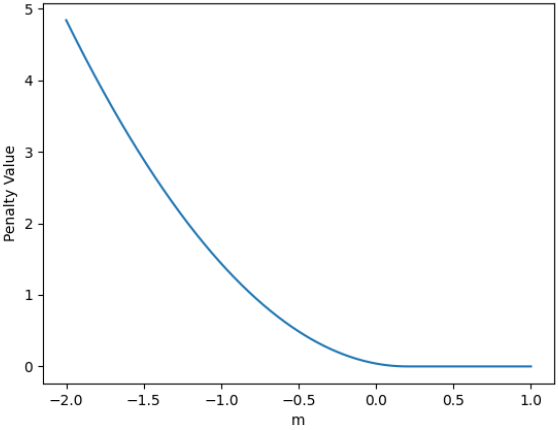
Interior control point | Penalty = 0 | Penalty > 0

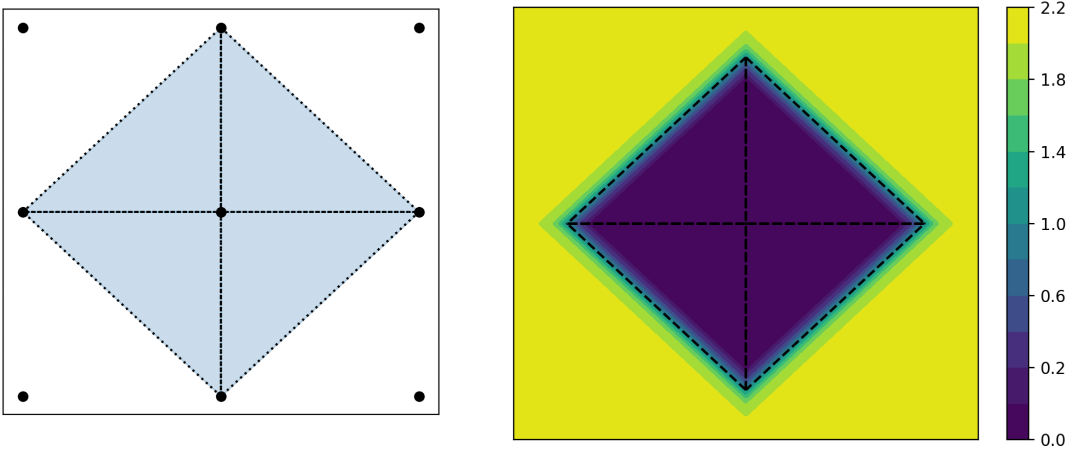
Penalty Function

- Zero only when control point moves withing area of triangles formed by neighbors

FFD: Penalty Function

- Penalty Function Cost:
  $\eta(m) = \mathrm{erfc}(10 \cdot \mathrm{m}) \cdot (\frac{1}{4} - \frac{1}{2} \cdot \mathrm{m})$
- $m = 4 \cdot \frac{\mathrm{smoothmin(A_i)}}{\sum_{i=1}^{4} A_i}$
- Minimum function is not differentiable, use smoothmin function





- Colormap of penalty function for an interior control point

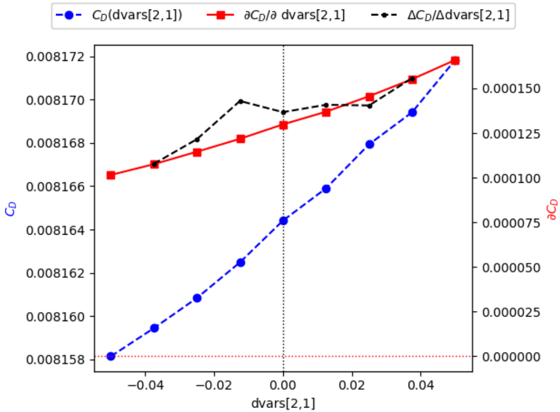
Outline

FFD: Optimization

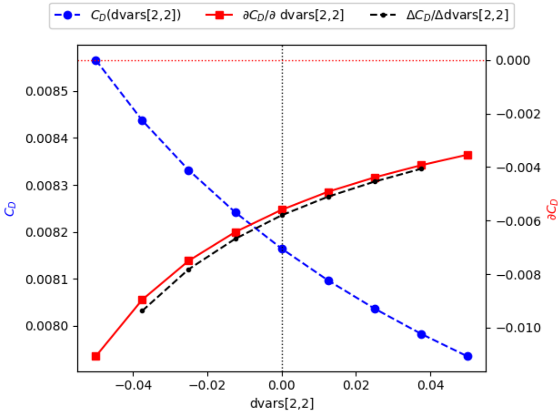
Optimization Driven by Analysis

- pyCAPS framework used to get analysis and derivative values
  - Python-based interface for Computational Aircraft Prototype Syntheses (CAPS)
- MSES used for analysis
  - Tool for design and analyses of 2D airfoils
  - Flow model solves Euler equations with an integral boundary layer method
- OpenMDAO framework used for optimization
  - Gradient-based Sequential Least Squares Programming (SLSQP) algorithm used for optimization

FFD: Sensitivity Verification



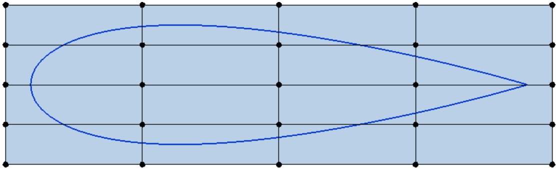
x-component



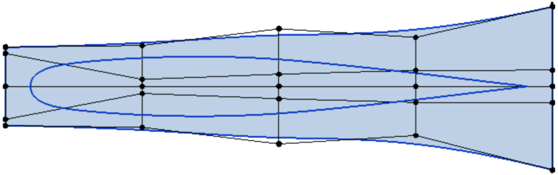
y-component

- Automatic differentiation and finite differentiation comparison of FFD control point for C_D

Drag Minimization of a Symmetric Airfoil



Initial



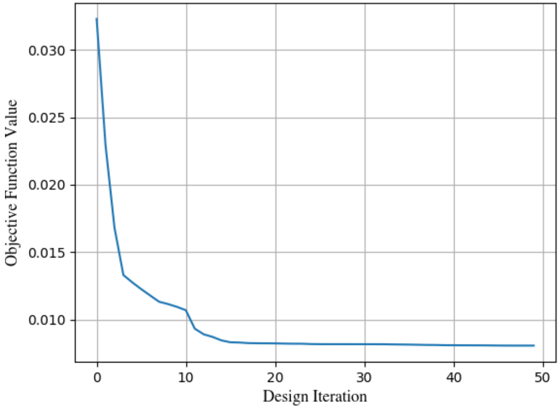
Final

A drag minimization of a NACA 0024 with a 5 × 5 cubic FFD grid using MSES

$$\begin{aligned} \underset{\Delta \mathbf{P}}{\text{minimize}} \quad & C_D + \eta(\Delta \mathbf{P}) \\ \text{subject to} \quad & A_{\text{airfoil}} \geq \frac{1}{2} \cdot A_{\text{NACA0024}} \end{aligned}$$

- Mach = 0.7
- Re = 5×10^6
- $\alpha = 0°$
- X-range: [-0.001, 1.0015]
- Y-range: [-0.14, 0.14]
- Degrees of Freedom: 10

Drag Minimization of a Symmetric Airfoil

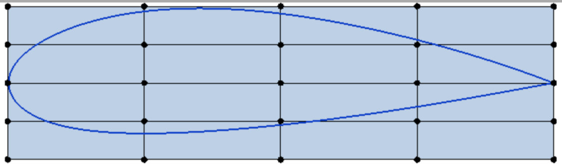


Objective Function History

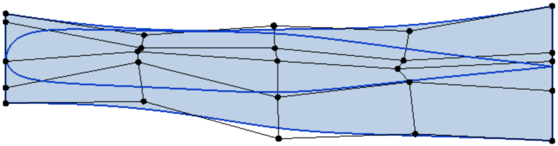
- Number of Iterations: 50
- Initial Obj Fn Value: 0.032
- Best Obj Fn Value: 0.008

Outline

Drag Minimization of an Asymmetric Airfoil



Initial



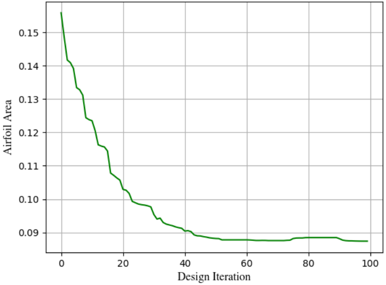
Final

A drag minimization of a Kulfan airfoil with a 5×5 cubic FFD grid using MSES

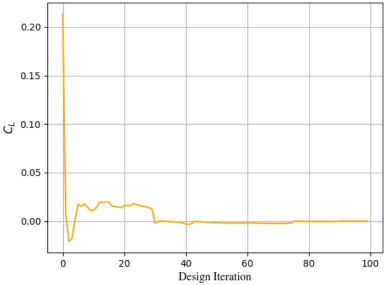
$$\begin{aligned} \underset{\Delta \mathbf{P}}{\text{minimize}} \quad & C_D + \eta(\Delta \mathbf{P}) \\ \text{subject to} \quad & A_{\text{airfoil}} \geq \frac{1}{2} \cdot A_{\text{initial}} \\ & C_L = 0 \end{aligned}$$

- Mach = 0.2
- Re = 5×10^6
- $\alpha = 0^\circ$
- X-range: [-0.05, 1.05]
- Y-range: [-0.16, 0.16]
- Degrees of Freedom: 38

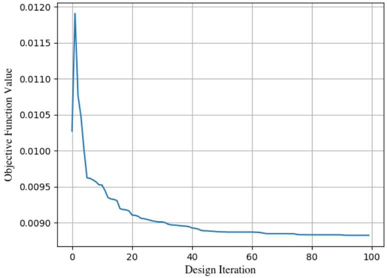
Drag Minimization of an Asymmetric Airfoil



Airfoil Area History



C_L History



Objective Function History

- Initial Area: 0.156
- Best area: 0.078
- Initial C_L: 0.213
- Best C_L: 0.001
- Initial Obj Fn Value: 0.010
- Best Obj Fn Value: 0.0075

Conclusion

Method for using FFD to morph B-splines for shape optimization

- View as beginnings of fine-tuning after preliminary traditional parametric design
- Use control point locations of FFD box as free parameters, which morph underlying B-spline surfaces and edges
- Self-intersections of geometry prevented by penalty function
- Demonstrated using gradient-based optimization to minimize drag for symmetric and asymmetric airfoils using MSES

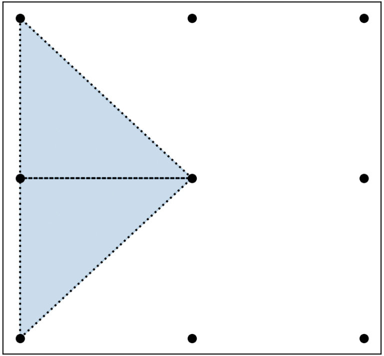
Future Work

- In the future, look at 3D CFD analyses cases
- Incorporate as a UDF in ESP

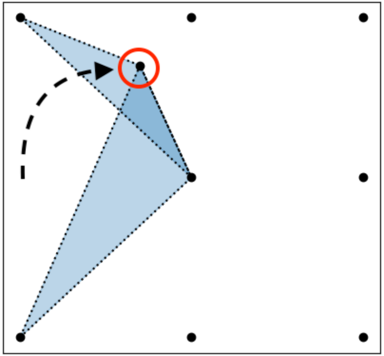
Thank you!
Questions?

This work was funded by the EnCAPS project, AFRL Contract FA8650–20–2–2002: "EnCAPS: Enhanced Computational Aircraft Prototype Syntheses", with Dr. Richard Snyder as the Technical Monitor.

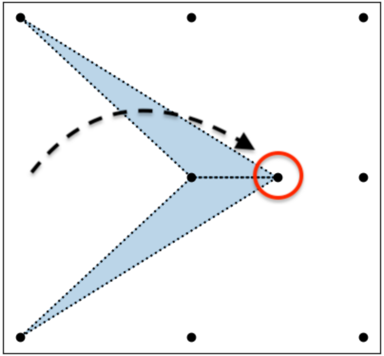
Additional Slides: Penalty Function



Edge control point



Penalty > 0

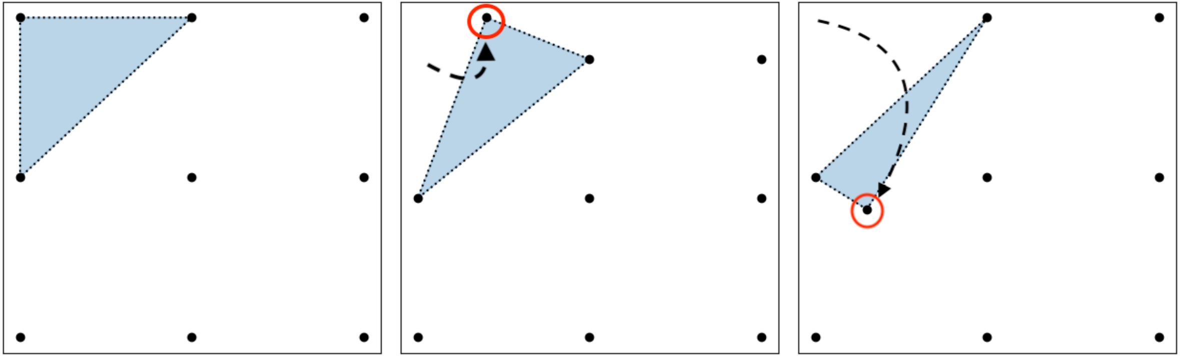


Penalty > 0

Penalty Function

- Zero only when control point moves withing area of triangles formed by neighbors

Additional Slides: Penalty Function



Corner control point | Penalty = 0 | Penalty > 0

Penalty Function

- Zero only when control point moves withing area of triangles formed by neighbors