FUN3D v13.4 Training

Session 10: Parameterization Tools

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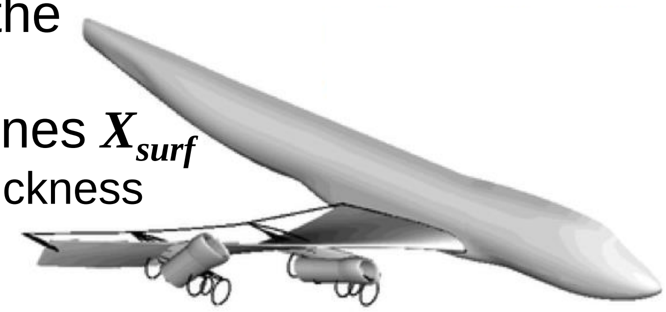
Setting

- FUN3D shape design relies on a pre-defined relationship between a set of parameters, or design variables, and the discrete surface mesh coordinates
- Given $\boldsymbol{DV}$, surface parameterization determines $\boldsymbol{X_{surf}}$
  - For example, given the current value of wing thickness at a location, what are the corresponding xyz-coordinates of the mesh?



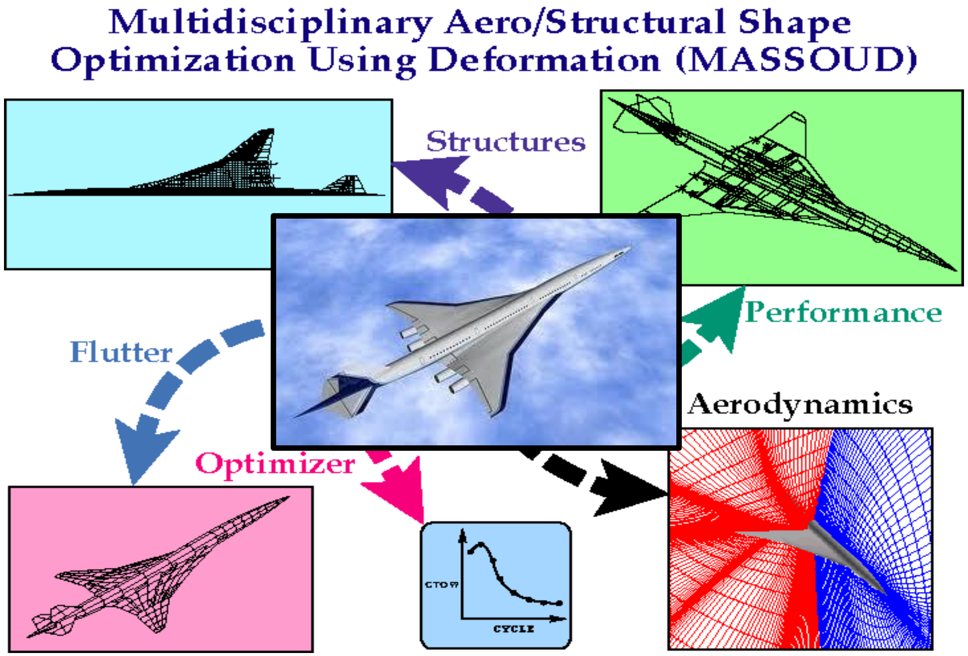
- This narrows down the number of design variables from hundreds of thousands (raw mesh points) to dozens or hundreds
  - Optimizers will perform more efficiently
  - Smoother design space
- An additional requirement of the parameterization package is that it provides the Jacobian of the relationship between the design variables and the surface mesh, $\partial X_{surf}/\partial DV$
- While users may provide their own parameterization scheme, FUN3D is set up to handle three common packages:
  - MASSOUD: Aircraft-centric design variables (thickness, camber, planform, twist, etc)
  - BandAids: General FFD based tool
  - Sculptor®: Commercial package from Optimal Solutions

Learning Goals

- Parameterize geometry with respect to DVs to control shape
  - MASSOUD
  - BandAids
- Generate perturbed surface mesh and SDs for FUN3D design
  - Visual validation
- What we will not cover
  - Body transformations
  - How to use the data in FUN3D
    - That will be covered in the next session

MASSOUD

- **M**ultidisciplinary **A**erodynamic-**S**tructural **S**hape **O**ptimization **U**sing **D**eformation
  - AIAA-2000-4911 (Jamshid Samareh)
- Used to generate consistent models for MDAO
  - Same shape changes communicated across all disciplines
- Highly tailored for aerodynamic shapes
  - Parameters familiar to engineer
- Mesh based parameterization



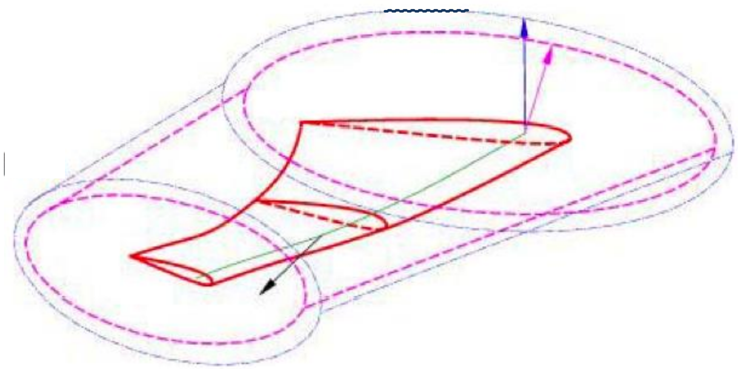
MASSOUD Key Ideas

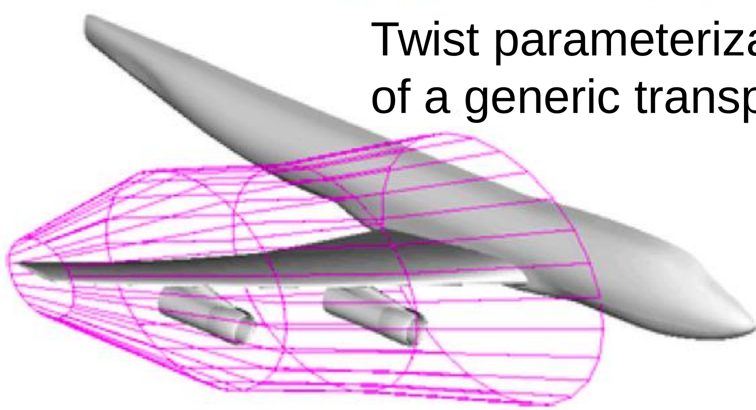
- Uses soft object animation algorithms for deforming meshes
  - Nonlinear global deformation (twist and dihedral)
  - NURBS surface (camber and thickness)
  - Free-form deformation (planform)
- Parameterizes the discipline meshes
  - Avoids mesh regeneration
- Parameterizes the changes in shape, not the shape itself
  - No need to reproduce shape
    - Reduces the number of design variables

MASSOUD Twist and Shear

- Nonlinear Global Deformation
  - Wrapped in twist cylinder
    - Twisted and sheared in planes along span normal to twist vector

Twist parameterization of a generic wing





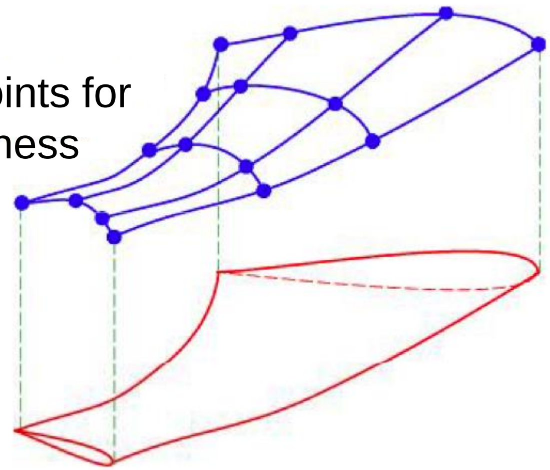
Twist parameterization of a generic transport

Extreme deformation of a generic transport

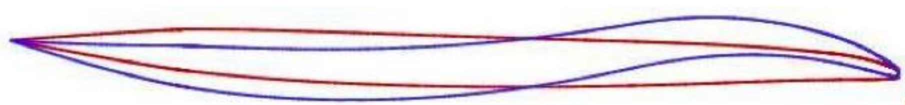
MASSOUD Camber and Thickness

- Non-Uniform Rational B-Spline (NURBS)
  - Represents the shape changes not the shape

NURBS Control Points for Camber and Thickness

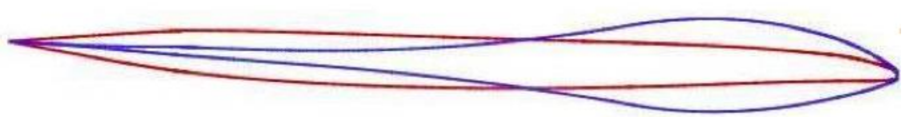


Camber



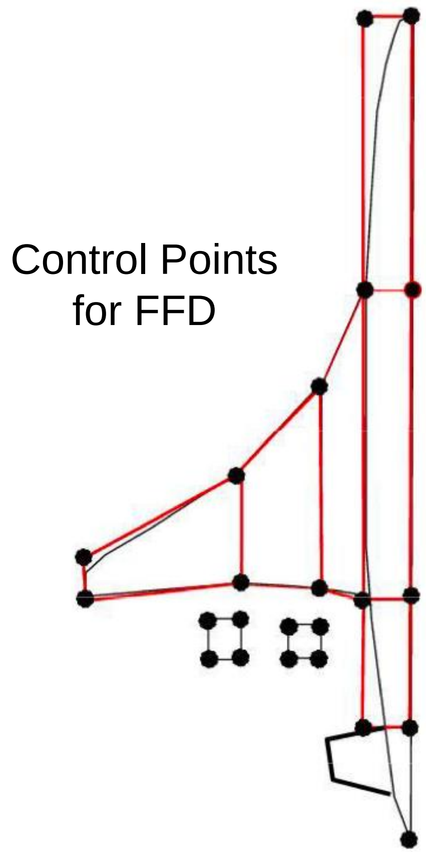
Extreme Camber and Thickness deformation

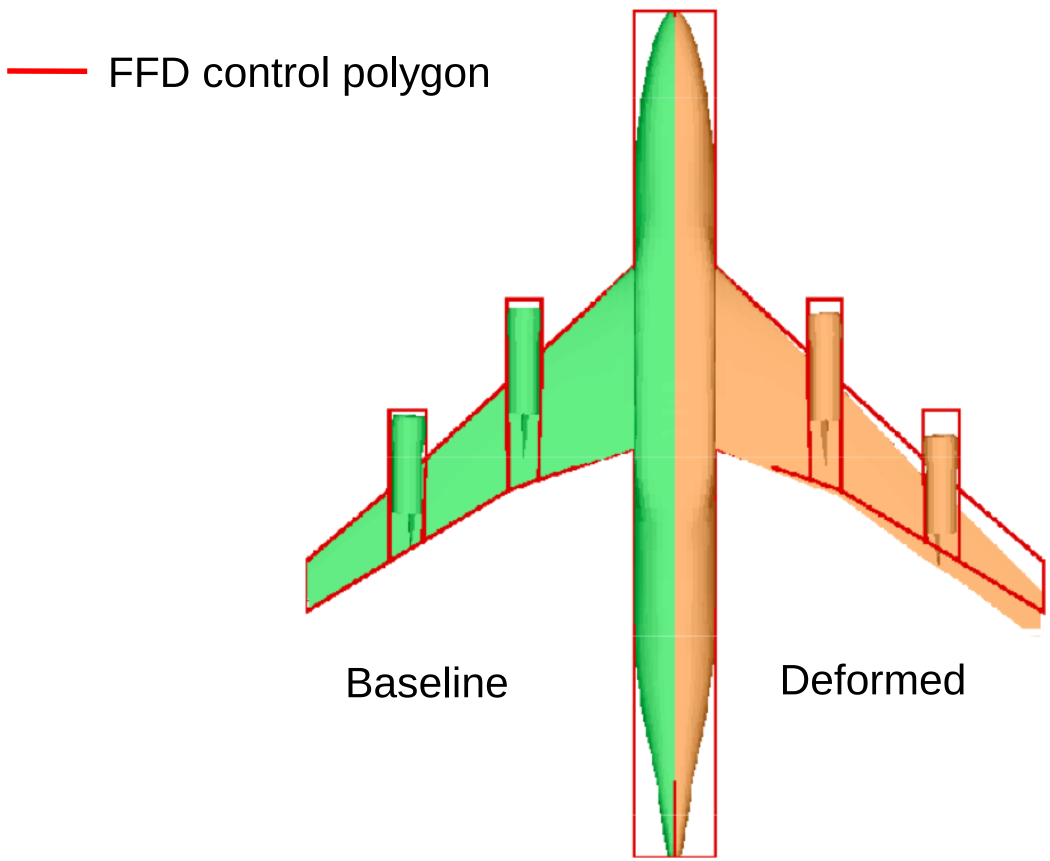
Thickness



MASSOUD Planform

- Free-form Deformation (FFD)
  - Surround shapes with quadrilaterals

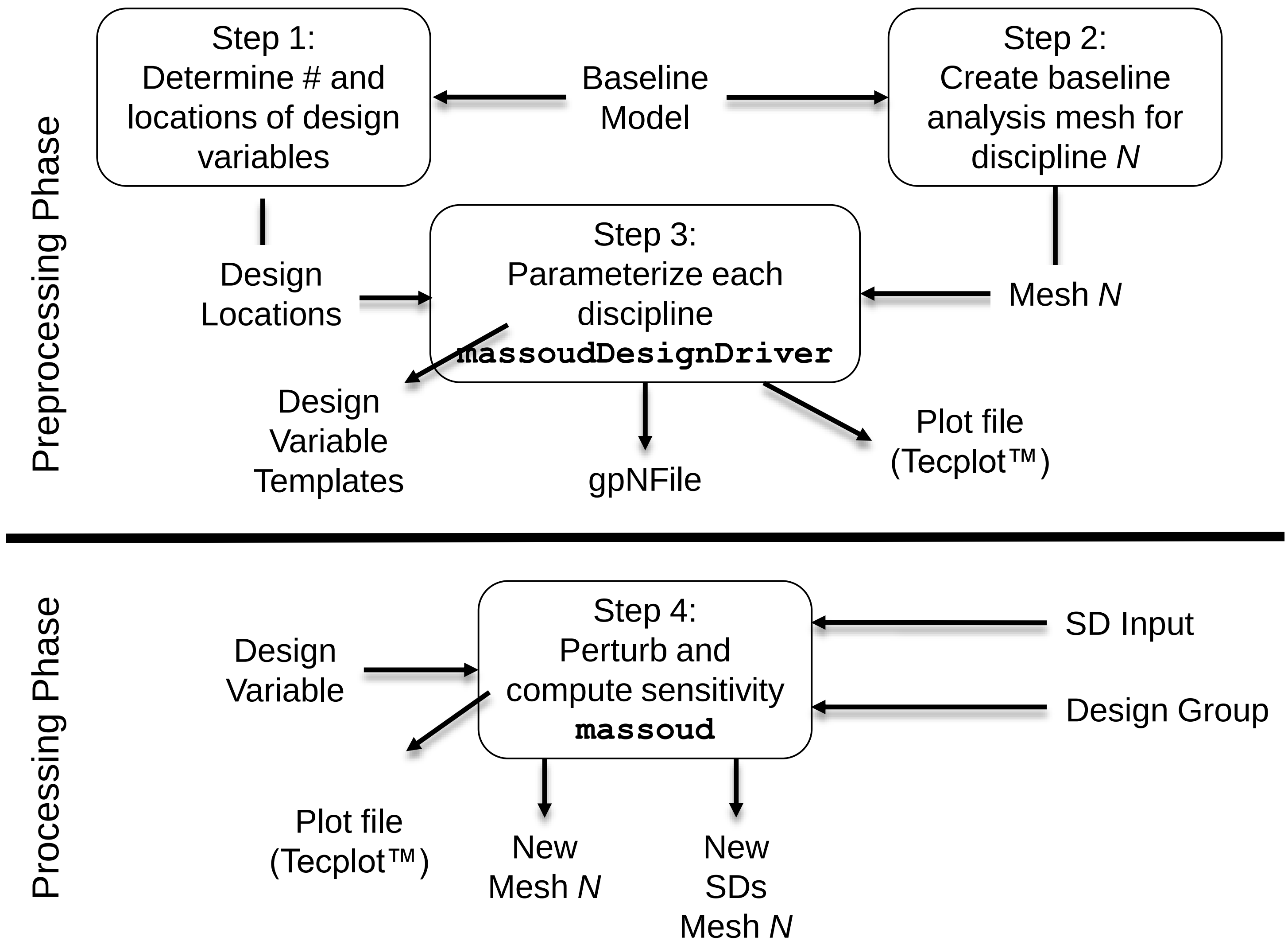




MASSOUD Installation

- Distributed as source code
  - Single **`Makefile`** uses GNU C compiler (**`gcc`**)
    - Any localization must be done manually
  - Creates two executables
    - `**massoudDesignDriver**` creates parameterization
    - `**massoud**` surface mesh perturbation with sensitivity data

MASSOUD Process



MASSOUD Step 1

- Parameterization requires input to define DV locations
  - Small ASCII file
  - Contains 7 groups of oriented curves
    - X axis is positive downstream
    - Y is positive out the wing span
      - Y should be positive with curves monotonically increasing
  - GridTool can be used to create the file

MASSOUD Design Locations File

```
Design location file Case Name Title (SECTION 1)
np    ne    ntwist  ncmax
4     1     2    100   0 1 2
Pt      X              Y                    Z (SECTION 2)
0        -0.0010000     -1.0010000e+00       0.0000000e+00
1         1.0010000     -1.0010000e+00       0.0000000e+00
2         1.0010000      0.0000000e+00       0.0000000e+00
3        -0.0010000      0.0000000e+00       0.0000000e+00
0         1         2              3
#Twist Vector (SECTION 3)
#        Ax            Ay               Az
0.0000000e+00  1.0000000e+00  0.0000000e+00
#        x             y                z                 ir              or
2.5000000e-01  -1.0000000e+00  0.0000000e+00     1000.0    10000.0
2.5000000e-01   0.0000000e+00  0.0000000e+00     1000.0    10000.0
# Le/Te definitions (SECTION 4)
2
0.0000000e+00  -1.0010000e+00  0.0000000e+00
0.0000000e+00   0.0000000e+00  0.0000000e+00
2
1.0000000e+00  -1.0010000e+00  0.0000000e+00
1.0000000e+00   0.0000000e+00  0.0000000e+00
5    2  0.000000e+00-1.001000e+00        0.000000e+00        1.000000e+00        # Thickness (SECTION 5)
 0.0    0.000000e+000.000000e+00
 0.1    0.000000e+000.000000e+00
 0.5    0.000000e+000.000000e+00
 0.75   0.000000e+000.000000e+00
 1.0    0.000000e+000.000000e+00
3    2
0.000000e+00  -1.001000e+00  0.000000e+00
0.000000e+00  -0.500000e+00  0.000000e+00
0.000000e+00   0.000000e+00  0.000000e+00
5    2  0.000000e+00-1.001000e+00        0.000000e+00        1.000000e+00        # Camber (SECTION 6)
 0.0    0.000000e+000.000000e+00
 0.1    0.000000e+000.000000e+00
 0.5    0.000000e+000.000000e+00
 0.75   0.000000e+000.000000e+00
 1.0    0.000000e+000.000000e+00
3    2
0.000000e+00  -1.001000e+00  0.000000e+00
0.000000e+00  -0.500000e+00  0.000000e+00
0.000000e+00   0.000000e+00  0.000000e+00
```

Planform

Twist vector and Twist

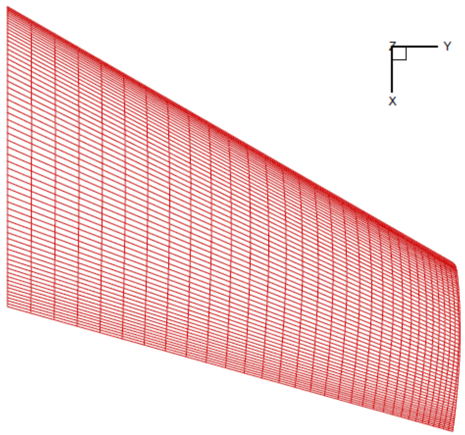
Leading and Trailing Edges

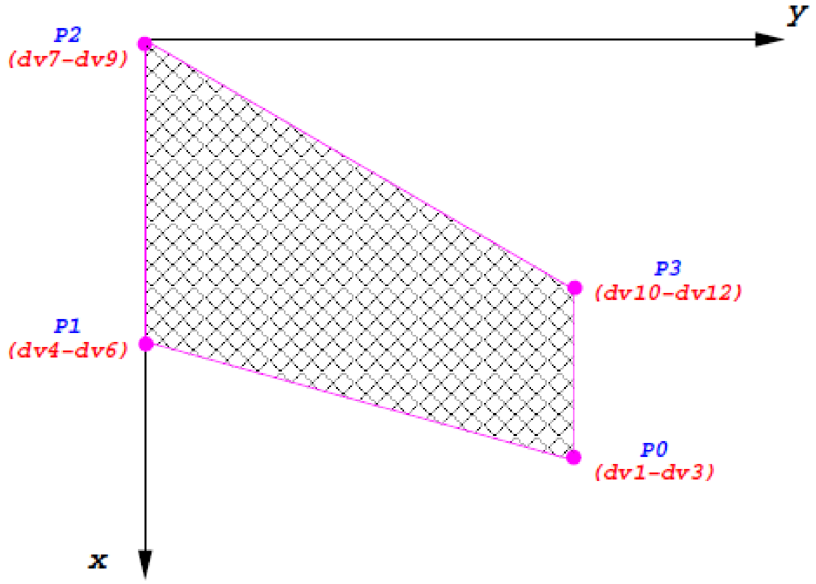
Thickness

Camber

MASSOUD Design Locations

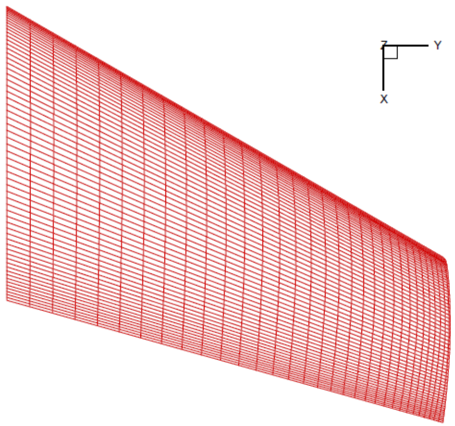
1. Planform
   - Cover planform with 5 point quadrilaterals
     - Closed but orientation does not matter
   - 1 Curve per planform section
   - GridTool Family name "**`planform`**"

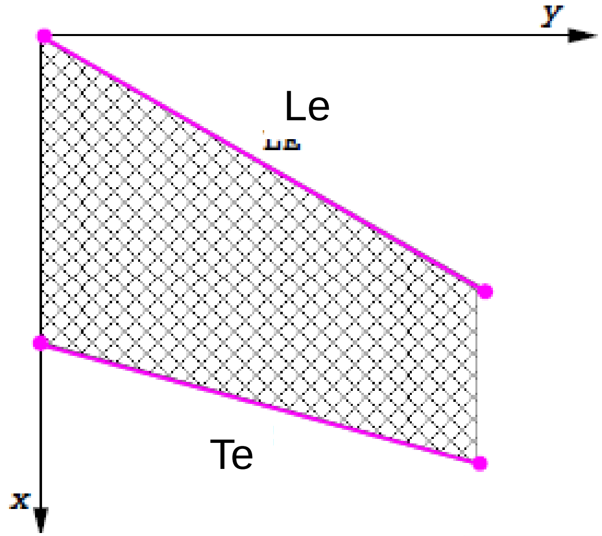




MASSOUD Design Locations

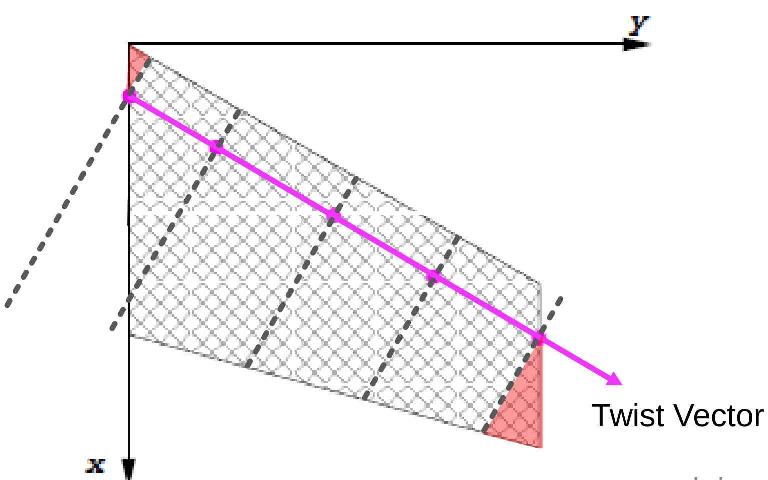
2. Leading Edge
   - Create an *n* point PWL curve defining the leading edge
     - Must bound all mesh nodes
     - May extend beyond actual geometry
   - GridTool Family name "**`le`**"
3. Trailing Edge
   - Create an *n* point PWL curve defining the trailing edge
     - Must bound all mesh nodes
     - GridTool Family name "**`te`**"

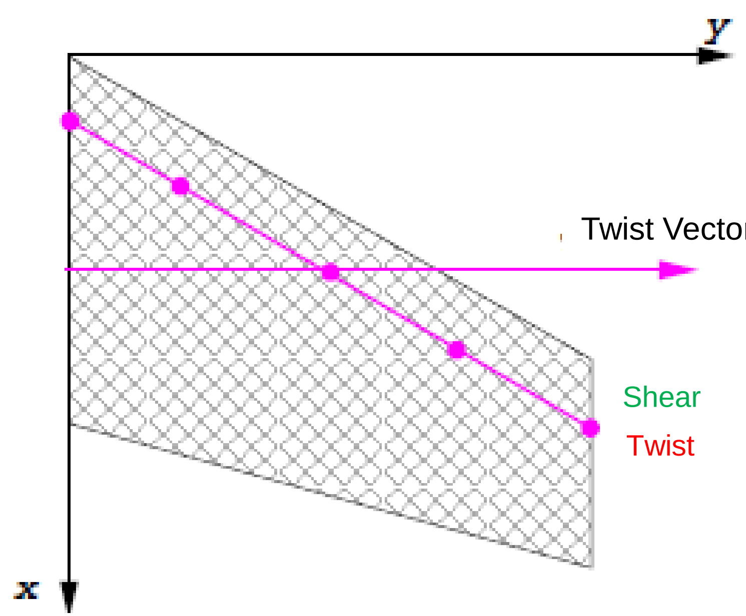




MASSOUD Design Locations

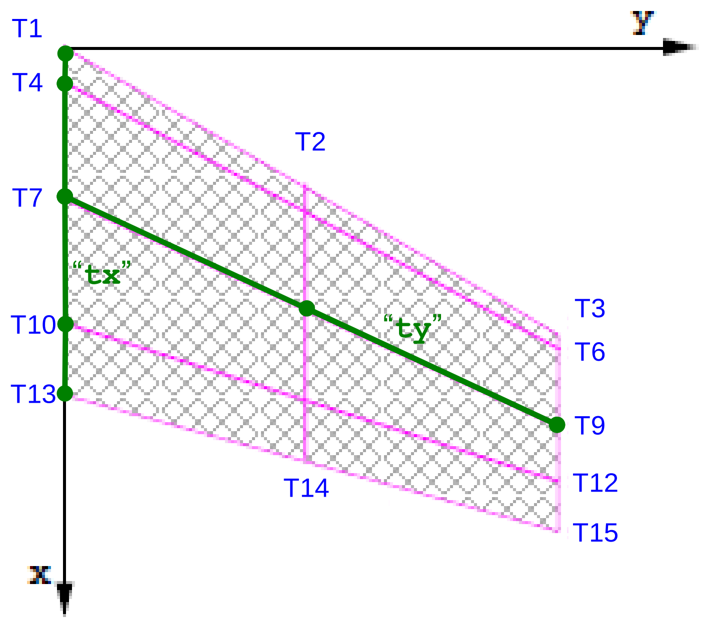
4. Twist Vector
   - Create a *2* point curve to represent the twist vector
     - Twist sections defined normal to this vector
   - GridTool Family name "**`twistv`**"
5. Twist Location
   - Create an *n* point PWL curve to represent the *n* twist locations
   - Airfoil sections defined at these points normal to "**`twistv`**"
     - First and last section must bound the Y coordinates of the target mesh
   - GridTool family name "**`twist`**"





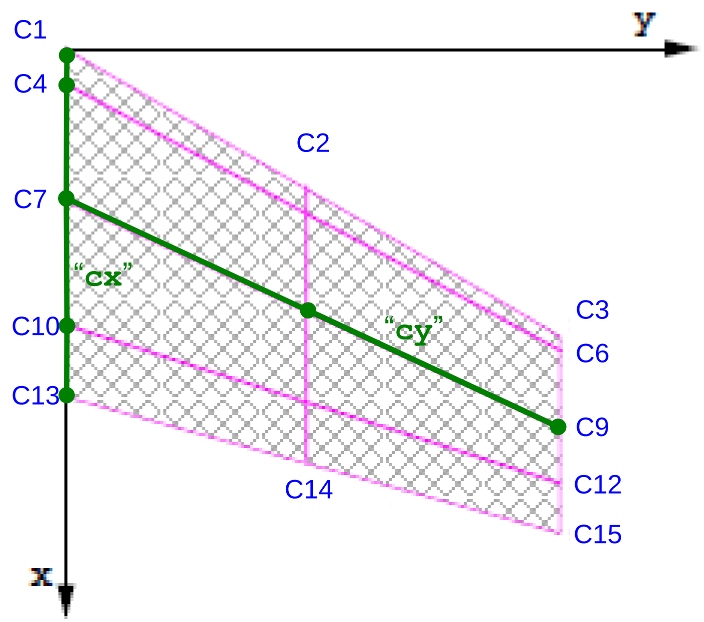
MASSOUD Design Locations

6. Thickness
   - Chordwise
     - Create an n point PWL curve to represent the *n* chordwise thickness locations
     - Start, length, and %
     - GridTool family name "**`tx`**"
   - Spanwise
     - Create an *m* point PWL curve to represent the *m* spanwise thickness locations
     - Should bound Y values of all target mesh nodes
     - Beginning and ending Y coordinates must be bounded by the Y coordinates of **both** the "**`le`**" and "**`te`**" curves
     - May be a duplicate of the "**`twist`**" curve
     - GridTool family name "**`ty`**"
   - *n x m* set of DVs



MASSOUD Design Locations

7. Camber
   - Same as for Thickness but with GridTool family names "**`cx`**" and "**`cy`**" respectively
   - May be duplicates of "**`tx`**" and "**`ty`**"
   - Two curves define *n x m* set of DVs



MASSOUD Step 2

- Dump out surface meshes of interest in a Tecplot™ format
  - Includes the surface node coordinates
  - Global ID of the surface nodes wrt the volume mesh
  - FUN3D flow solver CLO '**`--write_massoud_file`**'
    - Produces "**`[project]_massoud_bodyN.dat`**" file for body *N*
  - Default extracts all viscous boundary surfaces as separate bodies
- FUN3D Namelist controls

```
&massoud_output
  n_bodies = 2     ! Parameterize 2 bodies
  nbndry(1)        = 6     ! 1st body has 6 boundaries
  boundary_list(1)       = '3-8'         ! Boundaries in
  1st body
  nbndry(2)        = 3     ! 2nd body has 3 boundaries
  boundary_list(2)       = '9,10,12'   ! Boundaries in
  2nd body
/
```

- **`boundary_list`**() indices should reflect boundary lumping

MASSOUD Step 3

- Generate geometry parameterization

```
% massoudDesignDriver -t input_massoud_bndry1.dat \
                          designLocations \
                          design.gp.1
```

- Geometry parameterization is output in "**`design.gp.1`**"
  - Used as input to `**`massoud`**`
- Additional output
  - "**`designVariableTemplate`**"
    - Reference for "**`design.1`**" file with zero perturbations
  - "**`designTemplate.usd`**"
    - Reference for "**`design.usd.1`**" user defined variable links
  - "**`designVariableTemplateNumber`**"
    - Lists the DV indices by DV type (planform, twist, etc.)
  - "**`baselineShape.plt`**"
    - Tecplot™ readable zero perturbation reference
  - Errors in "**`GP.log`**"

MASSOUD Step 4

- Mesh deformation `% massoud massoud.N`
  - Where MASSOUD input is in "**massoud.N**"
  - FUN3D design will utilize "**customDV.N**" for perturbations

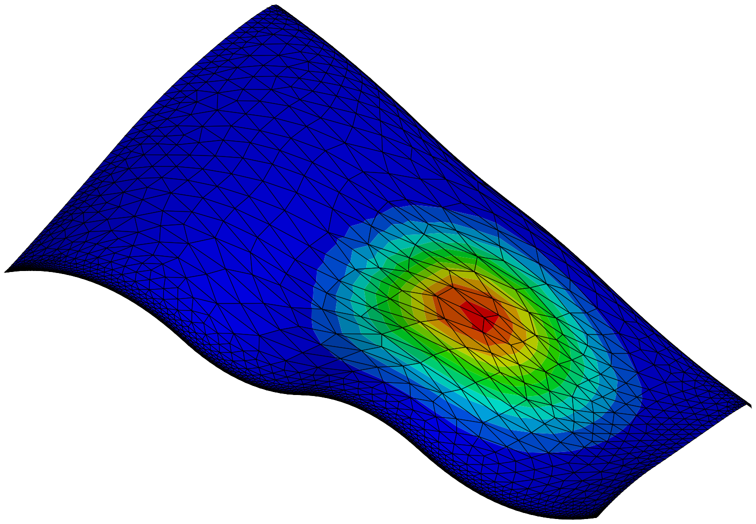
```
#MASSOUD INPUT FILE
# Option (0 analysis), (> 0 sd using user dvs ) (-1, sd using massoud dvs)
-1
# core (0 incore solution)  (1 out of core solution)
0
# input parameterized file
design.gp.1
# design variable input file
design.1
# input sensitivity file (used for Option > 0)
design.usd.1
# output file mesh file
new1.plt
# output tecplot file for viewing
model.tec.1
# file containing the design variables group
designVariableGroups.1
# user design variable file
[customDV.1]
```

MASSOUD Results

- Visual inspection
  - Tecplot™
    - "**`model.tec.1.sd1`**" contains mesh and SDs
      - (e.g. XD1, YD1, ZD1… XDndv, YDndv, ZDndv)
  - GridTool

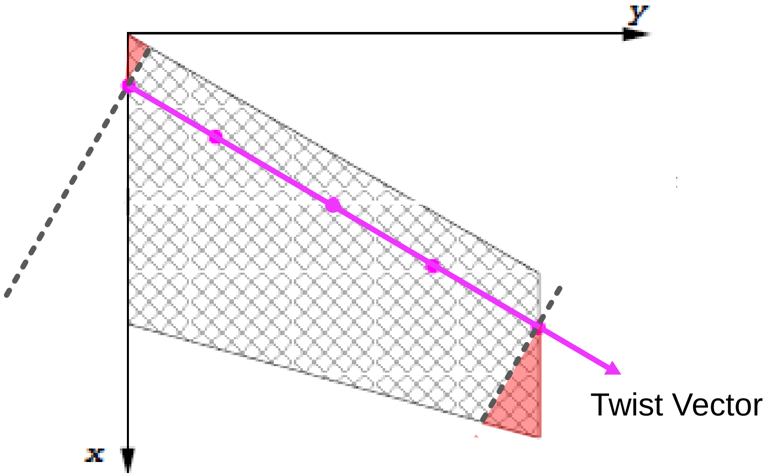
    `% GridTool -d model.tec.1.sd1`

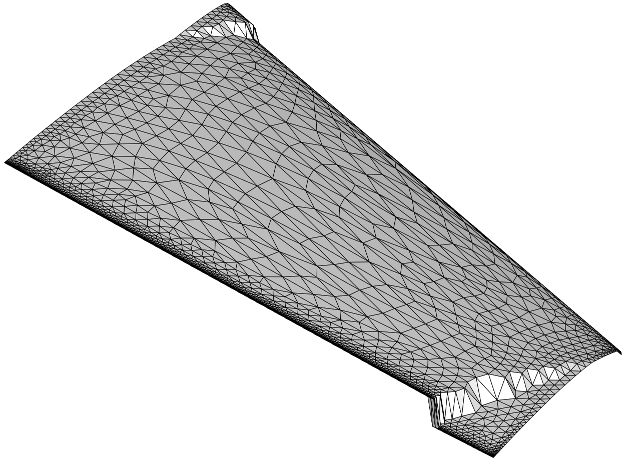
    - Sliders to interactively perturb DVs
    - Twist is non-linear and is only indication of change

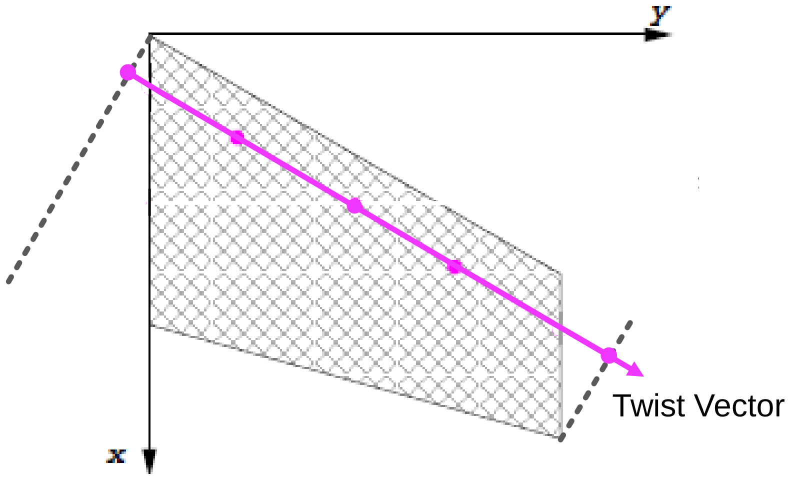


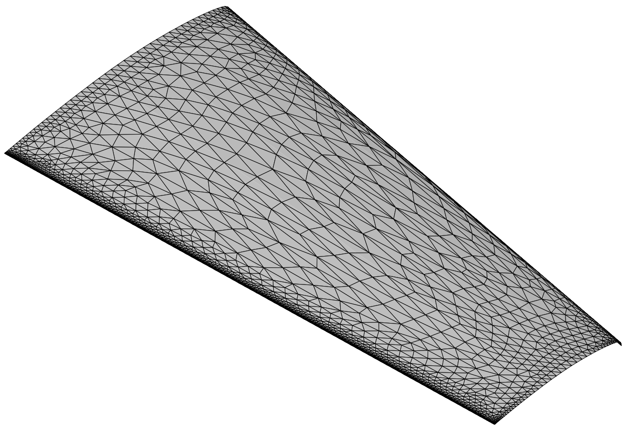
What Could Go Wrong (1 of 2)

- Failure … check "`GP.log`"
- Design locations must be defined to bound all target mesh nodes



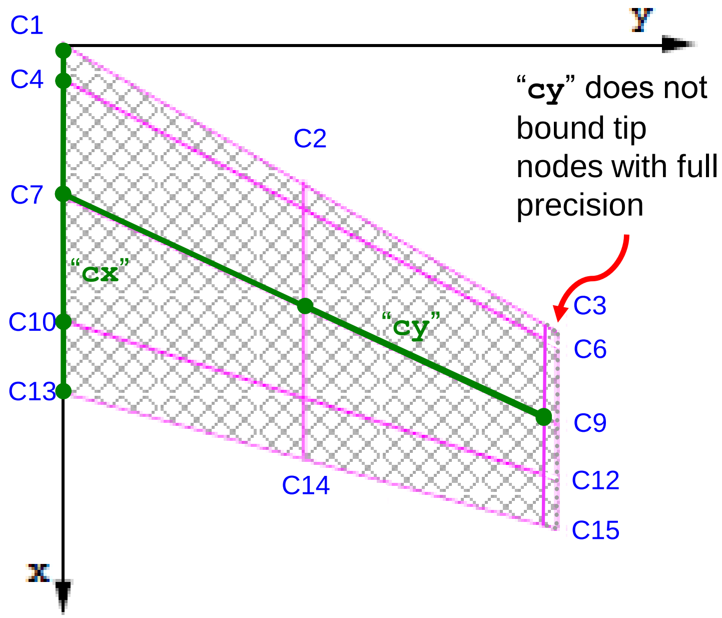


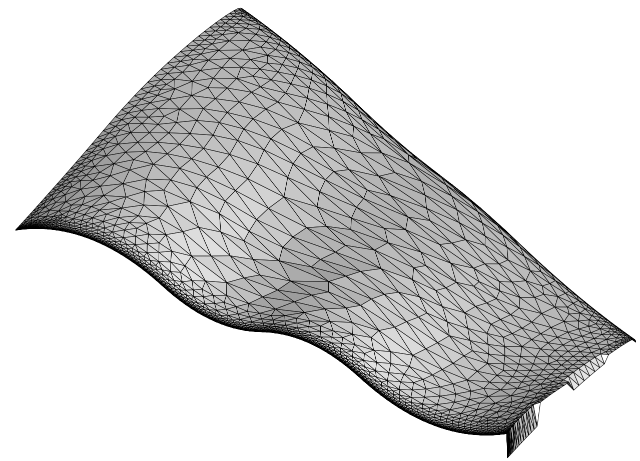


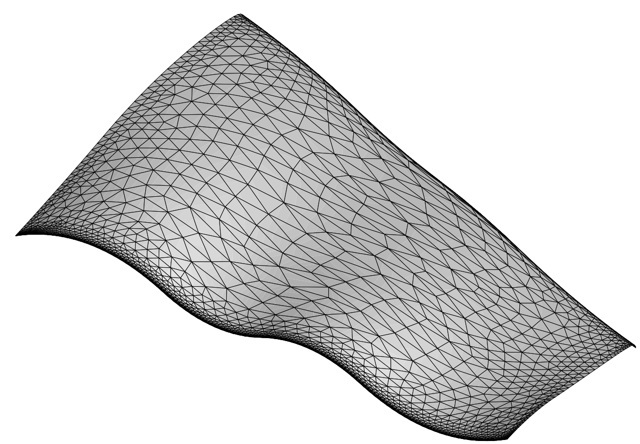


What Could Go Wrong (2 of 2)

- Design locations must be defined to bound all target mesh nodes







MASSOUD User Defined Variables

- New variables as linear combination of MASSOUD variables

$$\frac{\partial \overline{R}}{\partial V_j} = \frac{\partial \overline{R}}{\partial P_i} \frac{\partial P_i}{\partial V_j}$$

V_j MASSOUD Design Variables

P_i User - Defined Design Variables

$$\begin{bmatrix} \frac{\partial P_1}{\partial V_1} & \frac{\partial P_2}{\partial V_1} & \cdots & \frac{\partial P_{i\max}}{\partial V_1} \\ \frac{\partial P_1}{\partial V_2} & \frac{\partial P_2}{\partial V_2} & \cdots & \frac{\partial P_{i\max}}{\partial V_2} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial P_1}{\partial V_{j\max}} & \frac{\partial P_2}{\partial V_{j\max}} & \cdots & \frac{\partial P_{i\max}}{\partial V_{j\max}} \end{bmatrix}$$

$$P_1 = V_{10} - V_1 \quad \text{(Chord)}$$

$$P_2 = (V_{10} + V_1)/2 \text{ (Mid - Chord Location)}$$

$$P_3 = V_2 = V_{11}$$

	P_1	P_2	P_3
V_1	-1	0.5	0
V_2	0	0	1
V_{10}	1	0.5	0
V_{11}	0	0	1

M6.usd

```
# this is input sd file for MASSOUD
# number of row == number dvs within MASSOUD
# number of col == final number  dvs
#(row) (col) (#of nonzero rows)
52 3 4
    d    1d    2d    3d
    1    -1   0.5    0
    2     0     0    1
   10     1   0.5    0
   11     0     0    1
```

MASSOUD Pros and Cons

Pros

- Consistent Meshes
- No need for mesh generation
- Easy to setup (hours)
- Parameterization is fast
- Analytic sensitivity
- Compact set of DVs
- Suitable for high- and low-fidelity application

Cons

- Limited to small shape changes
- Fixed topology
- No built-in geometry constraints
- No direct CAD connection

BandAids

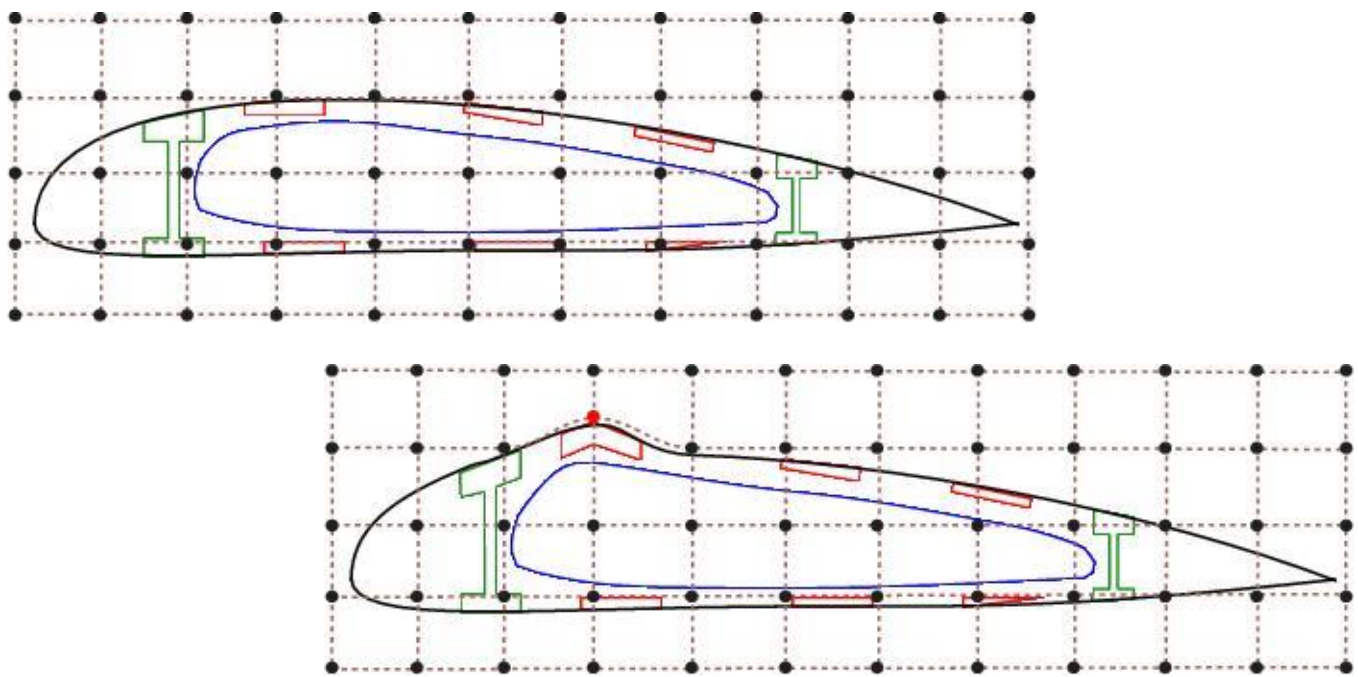
- Aerodynamic Shape Parameterization based on Free-Form Deformation
- General application based on free-form deformation
  - Handles complex shapes
  - DVs are not classic aerodynamic parameters

BandAids Key Ideas

1. Parameterize surface mesh
   - Avoids mesh regeneration
2. Use FFD to represent shape perturbations
   - Automates surface parameterization
3. Parameterize changes in shape perturbation, not the shape itself
   - Reduces the number of design variables

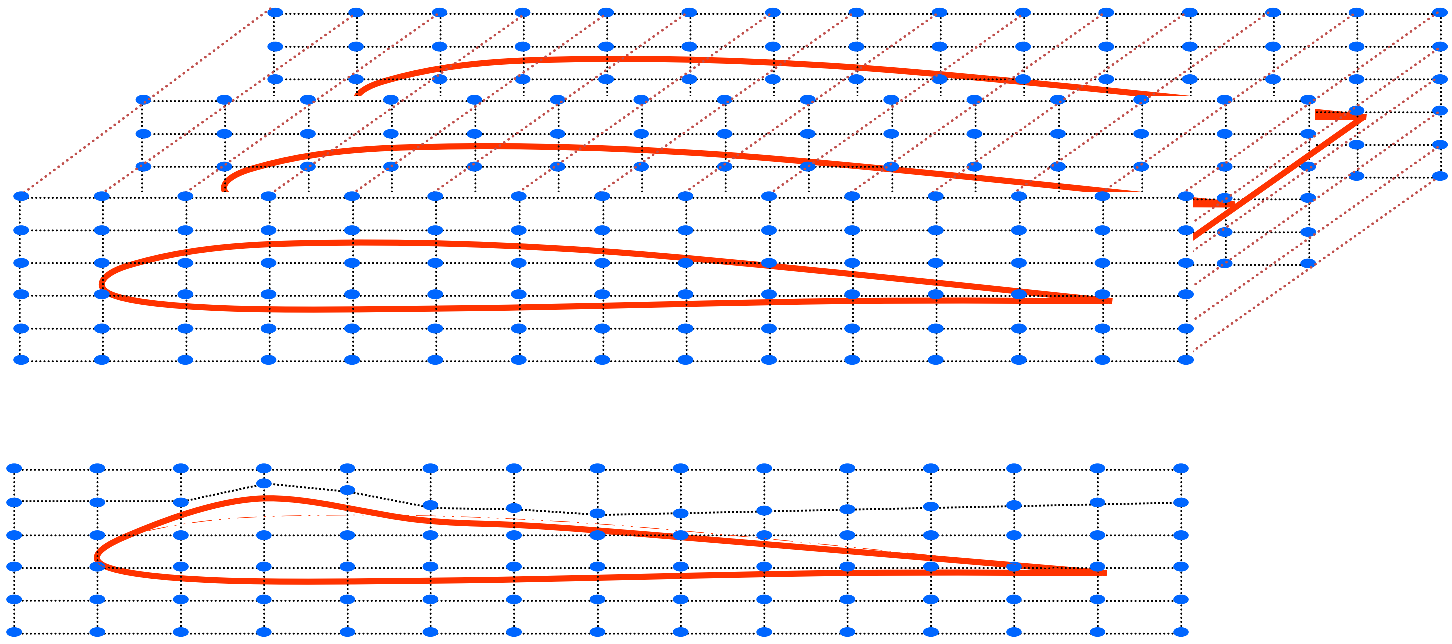
BandAids FFD (1 of 3)

- Based on algorithm used in computer animation
  - Control points are DVs
  - Immersed in Jell-O®
- Design variables have no aerodynamic significance
  - Only those near surface have significant impact



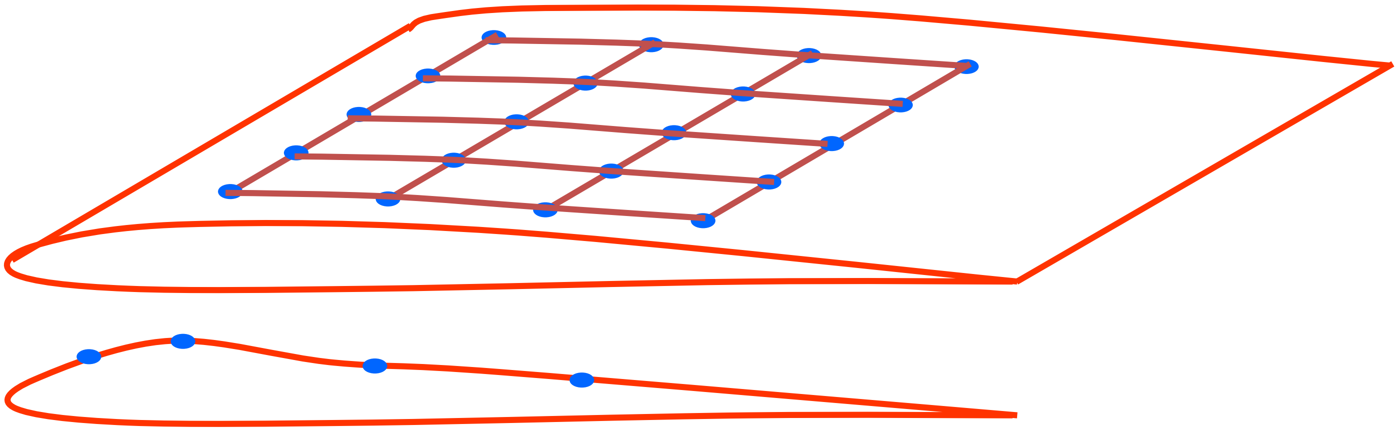
BandAids FFD (2 of 3)

- Many more control points in 3D
  - Only those near surface have impact on surface



BandAids FFD (3 of 3)

- Equivalent 3D bi-variant form of tri-variant FFD
  - Collapse CPs onto surface
    - Move CP moves surface underneath
  - Number of DVs reduced from N^3 to N^2
  - 4 sided Bandaid marking surface over geometry
    - Moves only surface to which it is collapsed
    - No MDO



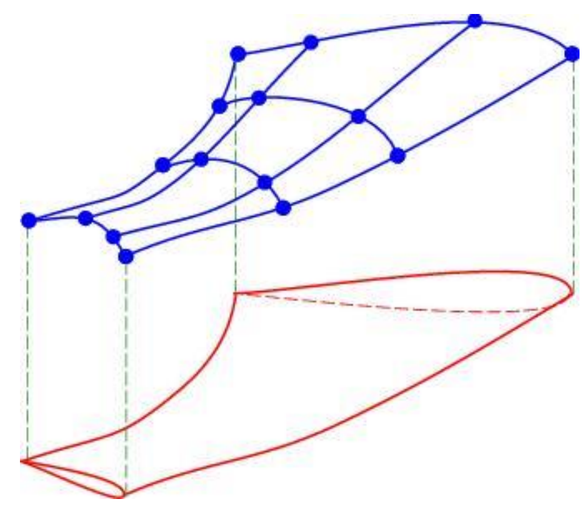
BandAids Parameterizes Changes

- Shape changes are small
  - Can be represented with fewer CPs than surface
- Maintains surface mesh character/quality

$$r_n(v) = r_n^b + \Delta r_n(v)$$

Surface mesh point — Design variable vector — Baseline surface mesh — Shape changes

NURBS control points for camber & thickness

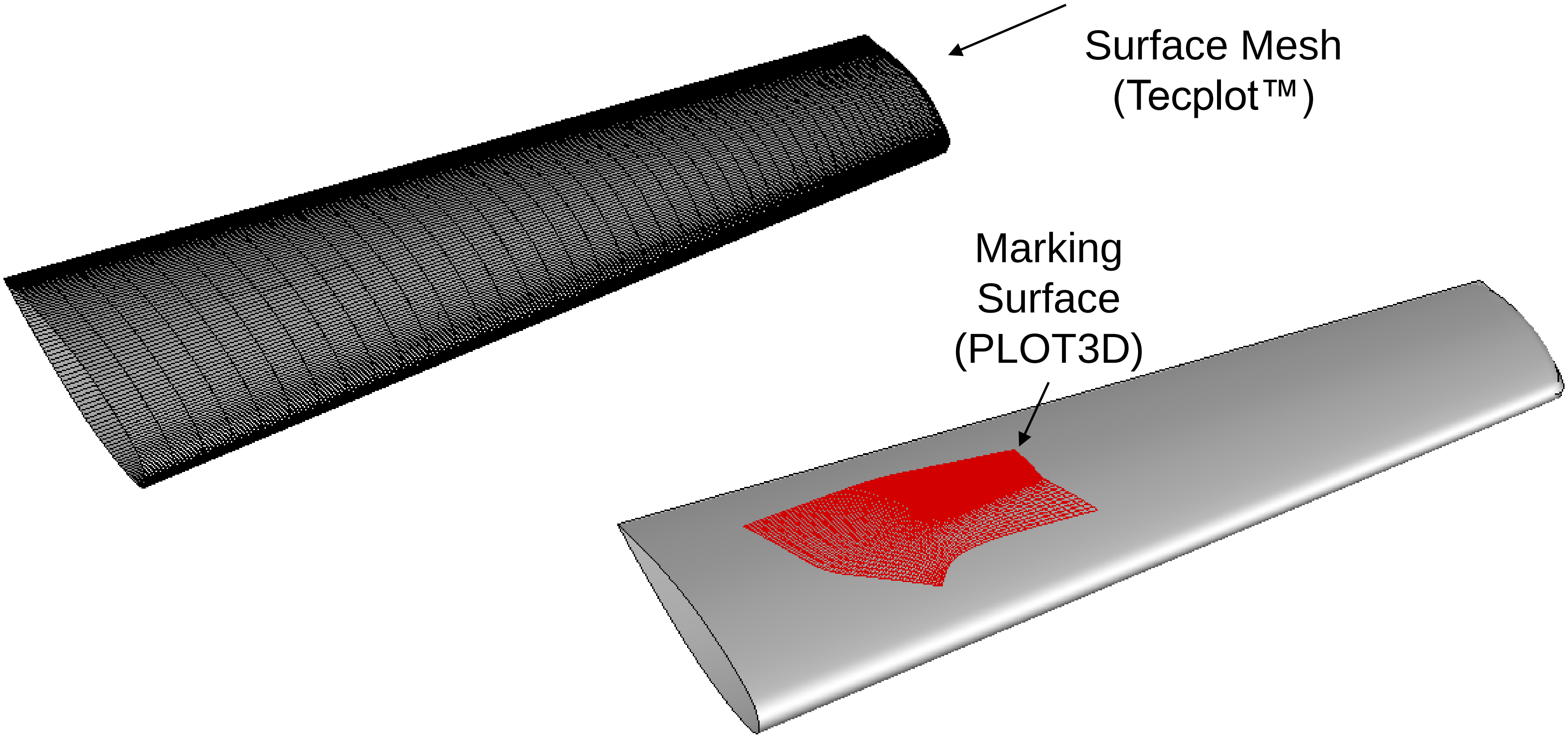


BandAids Installation

- Distributed as source code
  - Single **`Makefile`** uses GNU C compiler (**`gcc`**)
    - Any localization must be done manually
  - Creates a single executable
    - \`**`bandAids`**\` parameterization and deformation

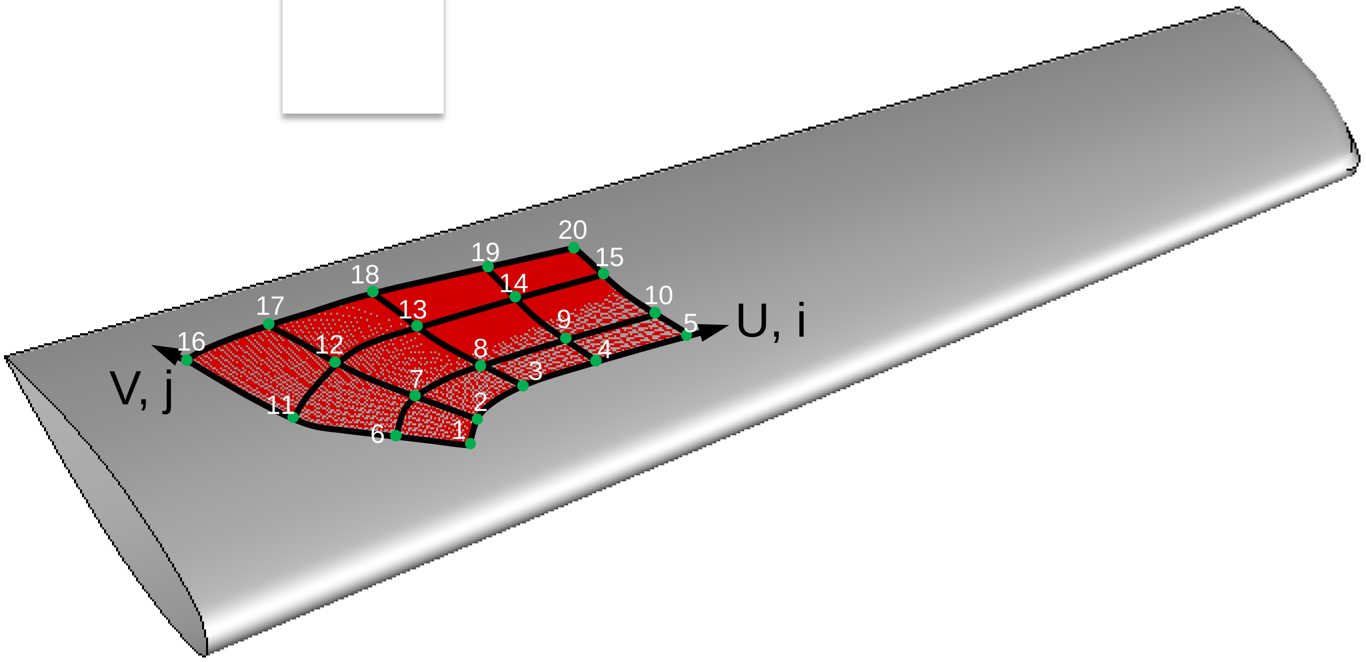
BandAids Marking Surfaces (1 of 2)

- Create structured marking surface
  - Marks portion of geometry to parameterize
  - Can span multiple geometry surfaces



BandAids Marking Surfaces (2 of 2)

- Marking surface interpolated by reference with *n x m* CPs
  - *n x m* DVs



BandAids Execution

```
% bandAids inMesh.plt \
           inDesignSurf.p3d \
           output \
           numDesignInU \
           numDesignInV \
           [tol]
```

- "`inMesh.plt`" target mesh in Tecplot™ format
- "`inDesignSurf.p3d`" marking surface in PLOT3D format
- "`outfile`" output file name prefix
- "`numDesignInU`" number of design variables in U-direction
- "`numDesignInV`" number of design variables in V-direction
- "`tol`" optional, max gap between mesh and marking surface
- User defined variables are created if a "**`bandaids.usd`**" file exists at execution

BandAids Output

- Execution produces seven files:
  - "**output.bandaid**"
    - All non-zero shape information
    - Read directly by FUN3D
  - "**output.distance.plt**"
    - Tecplot™ file with the surface mesh including the distance between the surface mesh and marking surface
  - "**output.distanceSD.plt**"
    - Tecplot™ file containing surface mesh and sensitivity data
  - "**bandAidsSample.dvs**"
    - Template for input design variable file
  - "**bandAidsAll.usd**", "**bandAidsCol.usd**", and "**bandAidsRow.usd**"
    - Templates to base "**bandaids.usd**" used for DV linking
    - Requires a subsequent \`**bandaids**\` run for linked variables

BandAids Deformation

- Not necessary with FUN3D as all deformation is linear
  - Useful for validation
- Execute **bandAids** with –**deformMesh**

```
% bandAids -deformMesh \
             output.distanceSD.plt \
             my.dvs \
             new.plt
```

- "**output.distanceSD.plt**"
  - Tecplot™ file containing surface mesh and sensitivity data
- "**my.dvs**"
  - Input DV perturbations
- "**new.plt**"
  - Deformed surface mesh

BandAids Results

- Visual inspection
  - Tecplot™
    - "`output.distanceSD.plt`" contains mesh and SDs
      - (e.g. XD1, YD1, ZD1… XDndv, YDndv, ZDndv)
  - GridTool

```
% GridTool -d output.distanceSD.plt
```

    - Sliders to interactively perturb DVs

BandAids Pros and Cons

Pros

- General Application
- Consistent Meshes
- No need for mesh generation
- Easy to setup (hours)
- Parameterization is fast
- Analytic sensitivity
- Compact set of DVs
- Suitable for high- and low- fidelity application

Cons

- Non-intuitive DVs
- Limited to small shape changes
- No built-in geometry constraints
- No direct CAD connection

What We Learned

- MASSOUD parameterizes with aerodynamic parameters
  - Best applied to aerodynamic shapes
- BandAids provides general application
  - Albeit w/o intuitive parameters
- Both mesh based parameterization
- Both tools parameterize shape changes not shape
  - Reduces number of DVs
- Both provide mesh perturbation with SDs suitable for FUN3D