FUN3D v12.7 Training Session 8: Parameterization Tools

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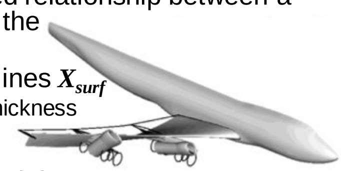
Setting

- 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?



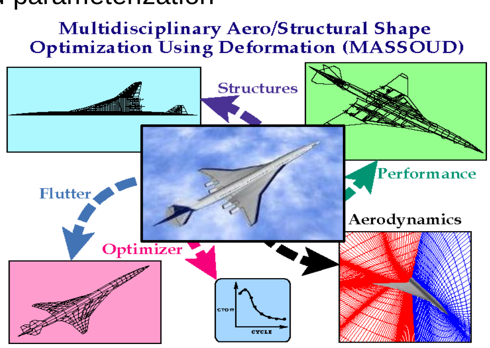
- This narrows down the number of design variables from hundreds of thousands (raw mesh points) to dozens or hundreds
  - Optimizers will perform more efficiently
  - Smoother design space
- An additional requirement of the parameterization package is that it provides the Jacobian of the relationship 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



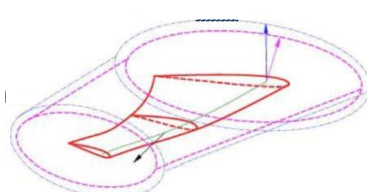
MASSOUD Key Ideas

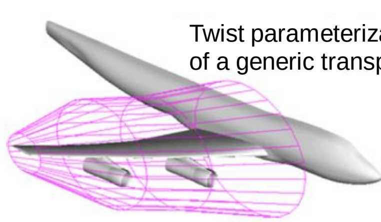
- Uses soft object animation algorithms for deforming meshes
  - Nonlinear global deformation (twist and dihedral)
  - NURBS surface (camber and thickness)
  - Free-form deformation (planform)
- Parameterizes the discipline meshes
  - Avoids mesh regeneration
- Parameterizes the changes in shape, not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

MASSOUD Twist and Shear

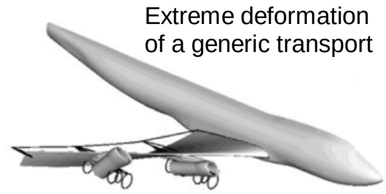
- Nonlinear Global Deformation
  - Wrapped in twist cylinder
    - Twisted and sheared in planes along span normal to twist vector

Twist parameterization of a generic wing





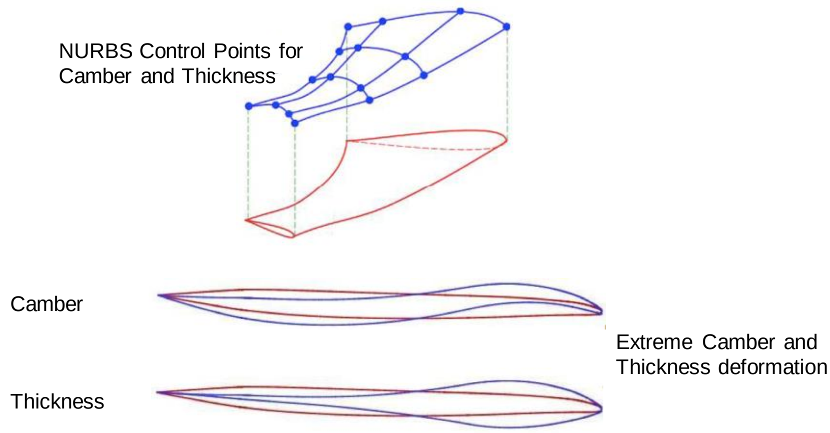
Twist parameterization of a generic transport



Extreme deformation of a generic transport

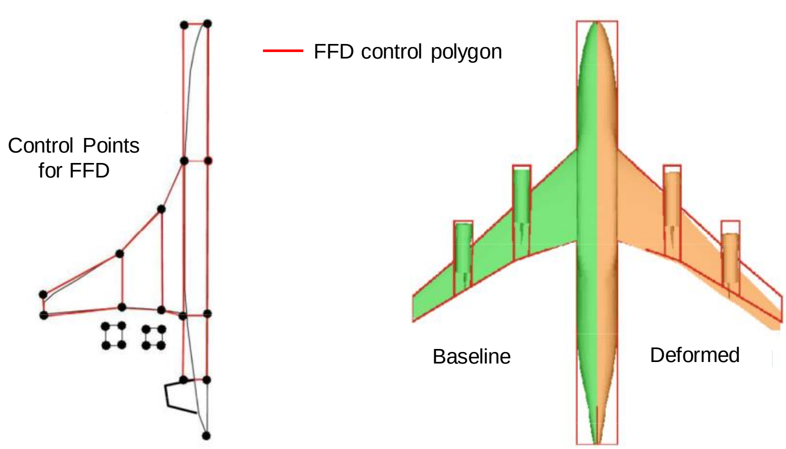
MASSOUD Camber and Thickness

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



MASSOUD Planform

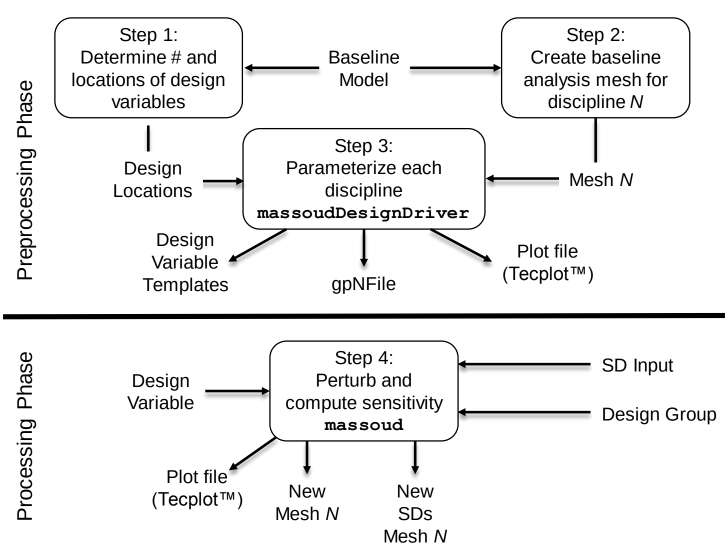
- Free-form Deformation (FFD)
  - Surround shapes with quadrilaterals



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

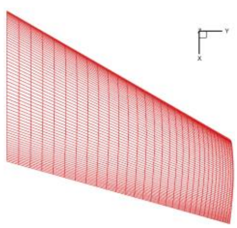
Leading and Trailing Edges

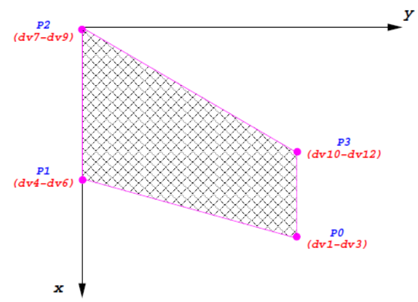
Thickness

Camber

MASSOUD Design Locations

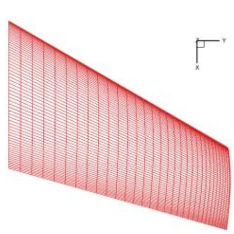
1. Planform
   - Cover planform with <u>5 point</u> quadrilaterals
     - Closed but orientation does not matter
   - 1 Curve per planform section
   - GridTool Family name “**`planform`**”

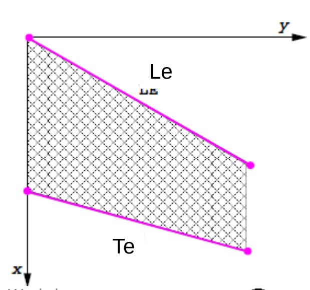




MASSOUD Design Locations

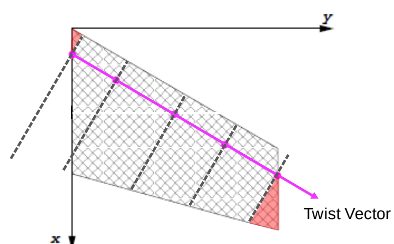
2. Leading Edge
   - Create an *n* point PWL curve defining the leading edge
     - Must bound all mesh nodes
     - May extend beyond actual geometry
   - GridTool Family name “**`le`**”
3. Trailing Edge
   - Create an *n* point PWL curve defining the trailing edge
     - Must bound all mesh nodes
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

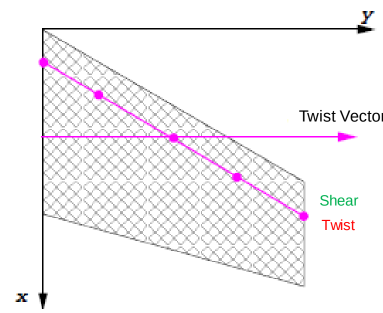




MASSOUD Design Locations

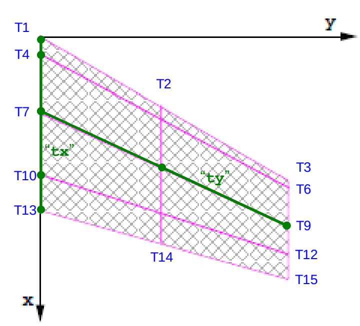
4. Twist Vector
   - Create a *2* point curve to represent the twist vector
     - Twist sections defined normal to this vector
   - GridTool Family name "**`twistv`**"
5. Twist Location
   - Create an *n* point PWL curve to represent the *n* twist locations
   - Airfoil sections defined at these points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





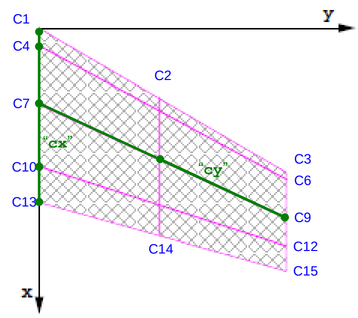
MASSOUD Design Locations

- 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

- 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_bndryN.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`"

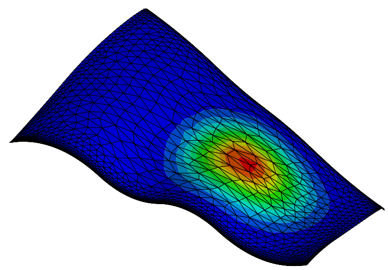
MASSOUD Step 4

- 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]
```

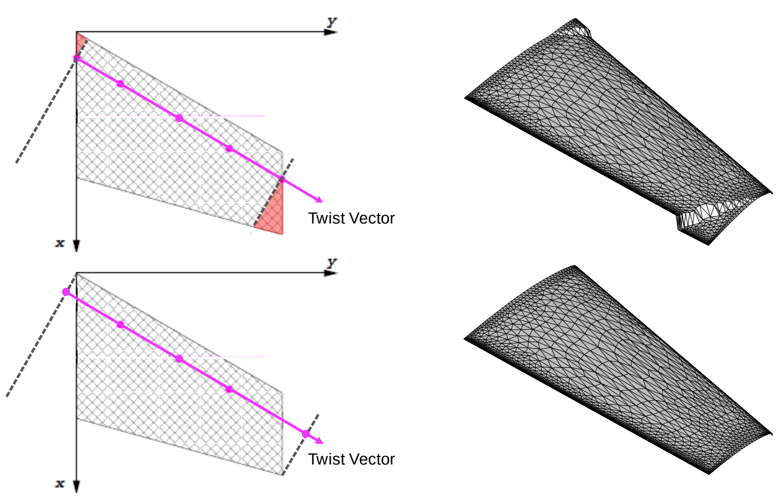
MASSOUD Results

- 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



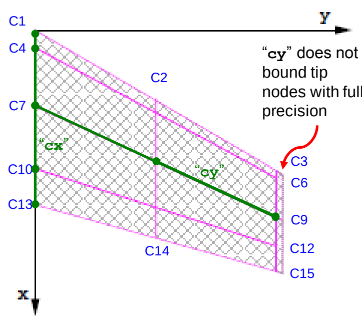
What Could Go Wrong (1 of 2)

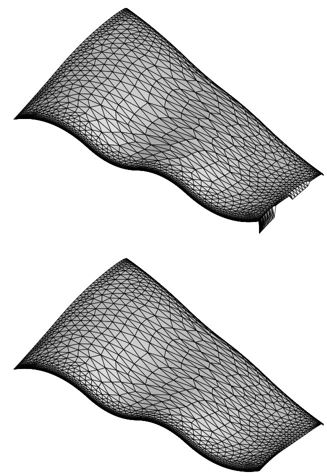
- Failure … check "`GP.log`"
- Design locations must be defined to bound all target mesh nodes



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

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

V_j MASSOUD Design Variables

P_i User-Defined Design Variables

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

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

$P_2 = (V_{10} + V_1)/2$ (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

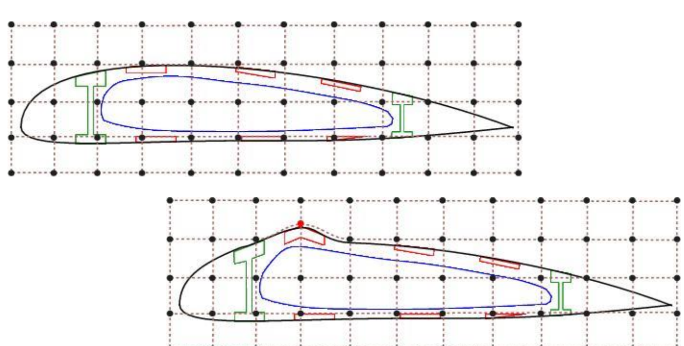
- Aerodynamic Shape Parameterization based on Free-Form Deformation
- General application based on free-form deformation
  - Handles complex shapes
  - DVs are not classic aerodynamic parameters

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

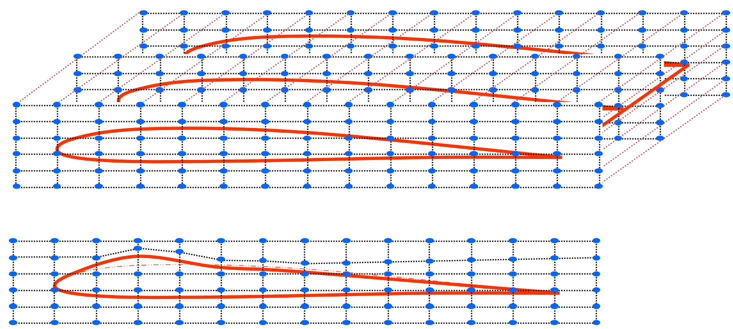
BandAids FFD (1 of 3)

- 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



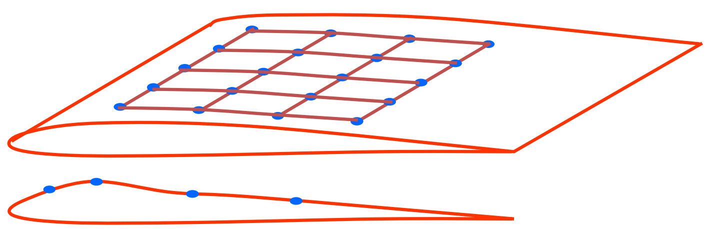
BandAids FFD (2 of 3)

- 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



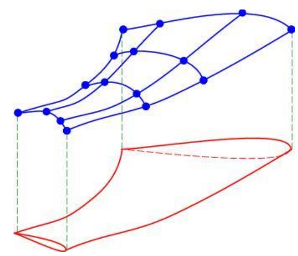
BandAids Parameterizes Changes

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

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

- r_n: Surface mesh point
- v: Design variable vector
- r_n^b: Baseline surface mesh
- $\Delta r_n(v)$: Shape changes

NURBS control points for camber & thickness

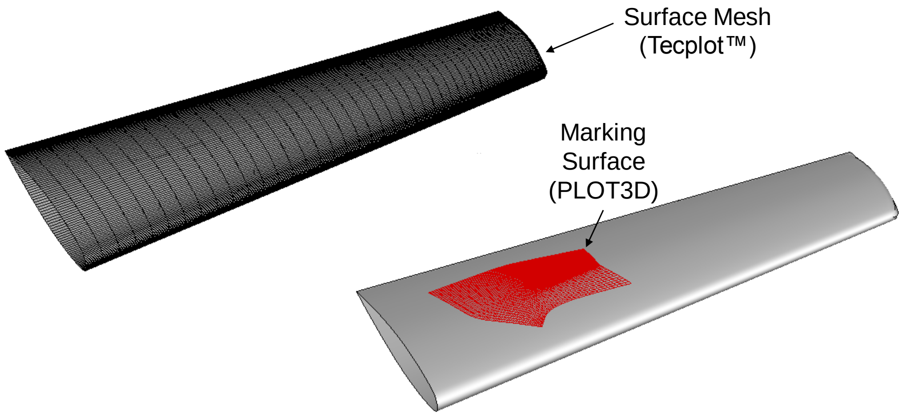


BandAids Installation

- 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

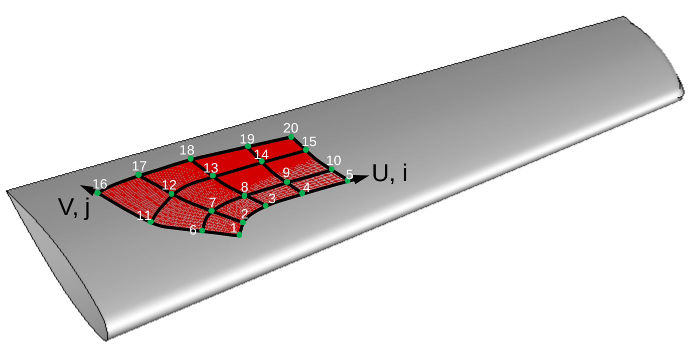
BandAids Marking Surfaces (1 of 2)

- 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