RECENT DEVELOPMENTS ON AUTOMATION OF OVERSET STRUCTURED MESH GENERATION

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NASA Ames Research Center

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OUTLINE

- Motivation, objectives, challenges
- Automation procedure

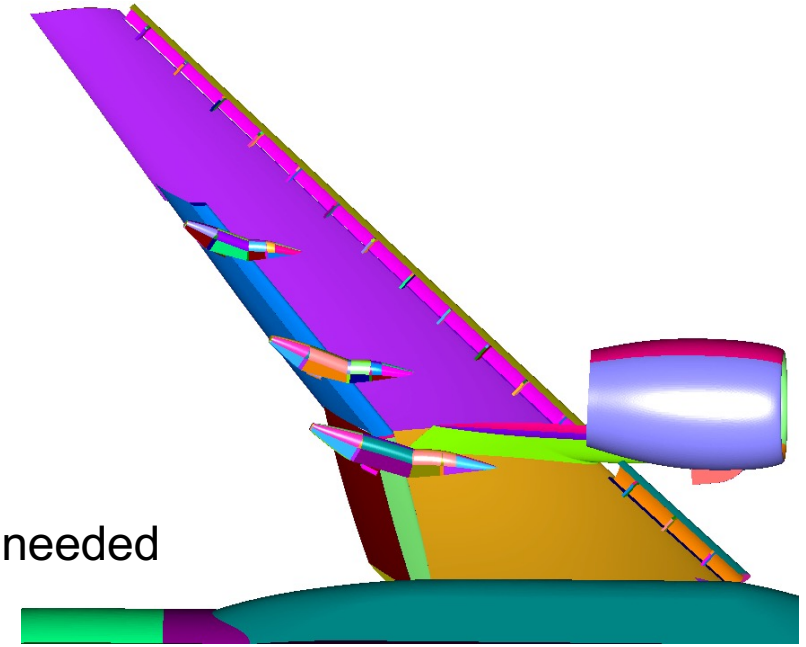
  …

  ⋯⋯► Loosely-Coupled Boundary Conditions
- Software modules
- Test cases
- Concluding remarks

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MOTIVATION AND OBJECTIVES

- Structured overset viscous flow solvers are highly accurate and efficient compared to other methods
- High-fidelity overset mesh generation requires significant user expertise and effort (weeks/months, surface grids ~80% time)
- Develop tools to reduce expertise and effort needed for overset mesh generation
- Goal: 100% automation
- Significant time saving with 80 - 99% automation



CHALLENGES (1, 2, 3)

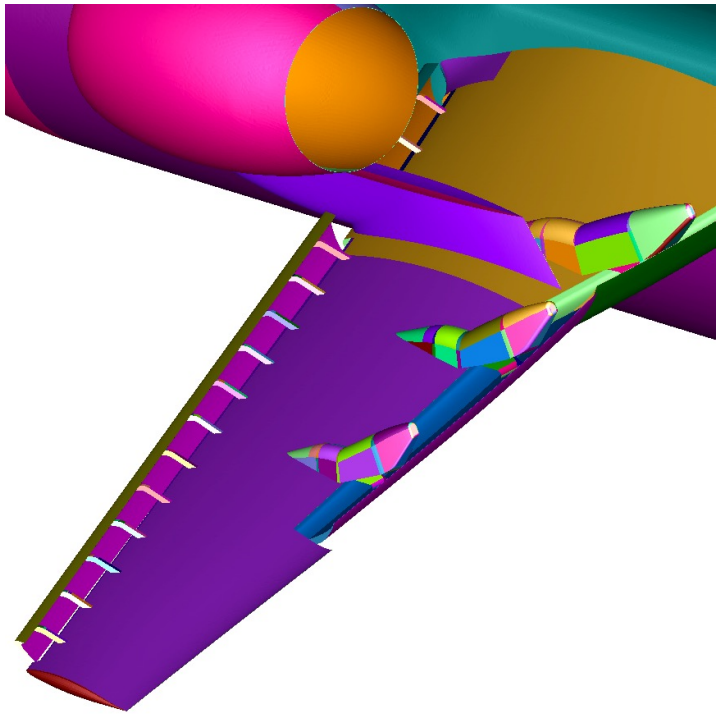
1. Surface domain decomposition *

2. Grid point distribution *

- Geometry
- Flow solution
- Controlled by global parameters
  (max grid spacing, max turning angle,
  max stretching ratio)

3. Marching scheme *

- Method selection (hyperbolic / algebraic)
- Marching distance estimate



* Addressed in current work and in following paper

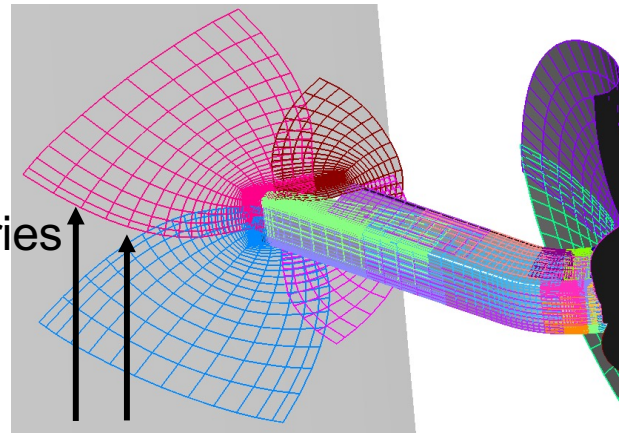
Chan, W. M., Pandya, S. A., Haimes, R., Automation of Overset Structured Surface Mesh Generation on Complex Geometries, AIAA Paper 2019-3671, AIAA Aviation Forum, Dallas, Texas, June, 2019.

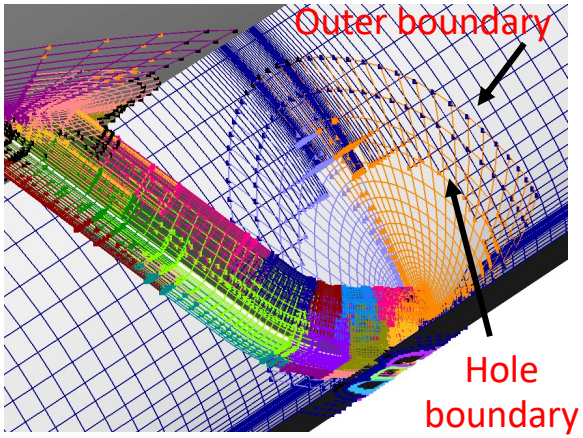
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CHALLENGES (4, 5)

4. Mesh overlap *

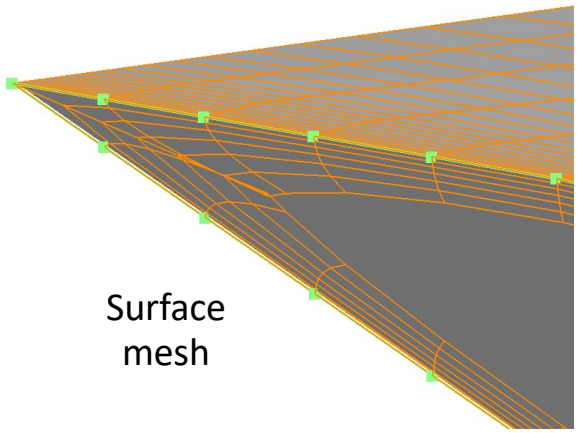
- 2 x Nf cells
  Nf = # fringe point layers
- Adjacent mesh side boundaries
- Outer boundaries
- Hole boundaries

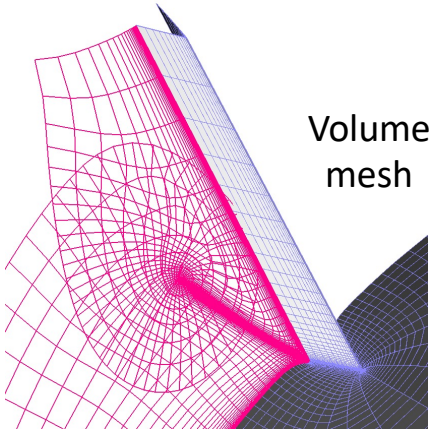




5. Hyperbolic mesh with concave regions **

- Negative cell areas (surface)
- Negative Jacobians (volume)
- Eliminate manual iterations on smoothing parameters



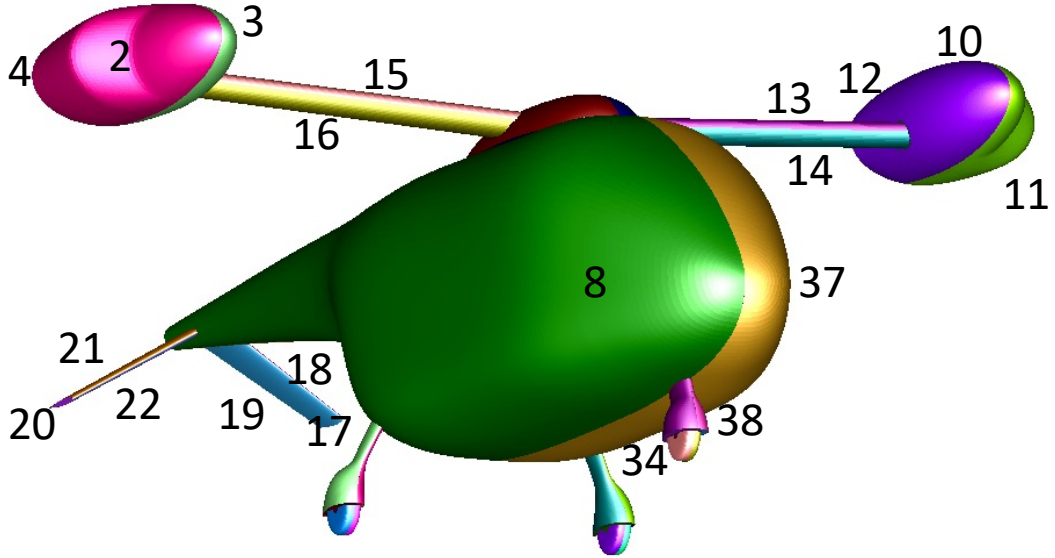


** To be addressed in future work

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GEOMETRIC COMPONENTS SPECIFICATION

- Text file: component name + list of face numbers
- Information usually not available from geometry file (STEP/IGES)
- Manual construction with OVERGRID + Text Editor
  (< 10 minutes for example below)
- Enables:
  - Local component characteristic length -> local max grid spacing
  - Auto construction of input file for component aero loads computation
  - Enables single component meshing option



Geometric Components Data File

Right_LandGear 1,23:27	Left_Wing 13:14
Rotor_1_Cowling 2:4	Right_Wing 15:16
Main_Fuselage 5:6,8,37	Left_Tail 17:19
Fuselage_Fairing 7,9	Right_Tail 20:22
Rotor_2_Cowling 10:12	Left_LandGear 28:33
	Front_LandGear 34:36,38:40

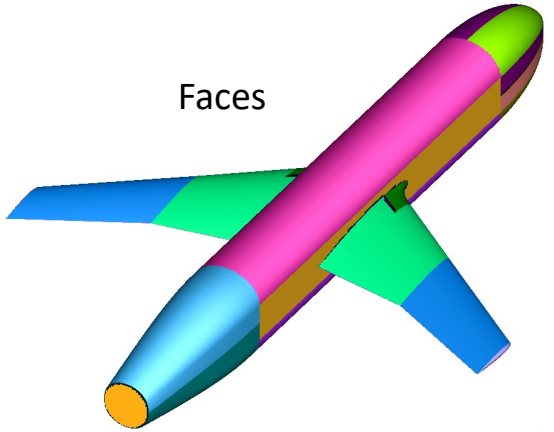
SURFACE DOMAIN DECOMPOSITION

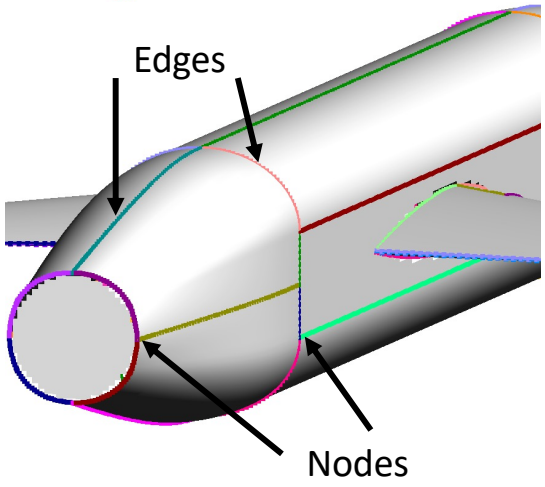
Input Geometry

- Boundary Representation (BRep) solid
- Basic entity types: Faces, Edges, and Nodes
- Topological relationship between Faces, Edges, Nodes
- Interface: Engineering Sketch Pad (ESP) from MIT

Strategy

- Construct meshes based on Faces, Edges and Nodes
- Total number of meshes bounded by
  (# Faces + # Edges + # Nodes)
- Actual number is less from
  - Face mesh elimination if completely covered by Edge & Node meshes
  - Merging of thin Face meshes with neighboring meshes





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AUTOMATION FLOW CHART

Surface mesh generation → **Volume mesh generation** → *** Volume mesh domain connectivity** → **Flow solver + aero-loads input generation**

BRep Geometry

- Determine grid spacing at Nodes
- Discretize Edges
- Construct Face meshes with iblanks
- Construct Node meshes
- Construct Edge meshes
- Retract Face mesh hole boundaries

} Algebraic/hyperbolic methods Loosely-Coupled B.C.

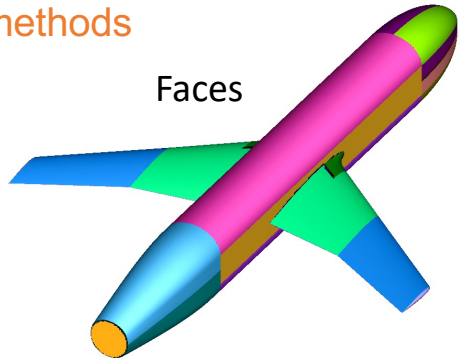
Surface meshes + connectivity data

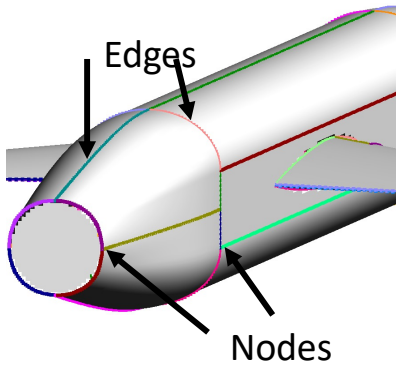
Volume meshes + connectivity data

Input files for flow solver + aero-loads computation

Flow Solver

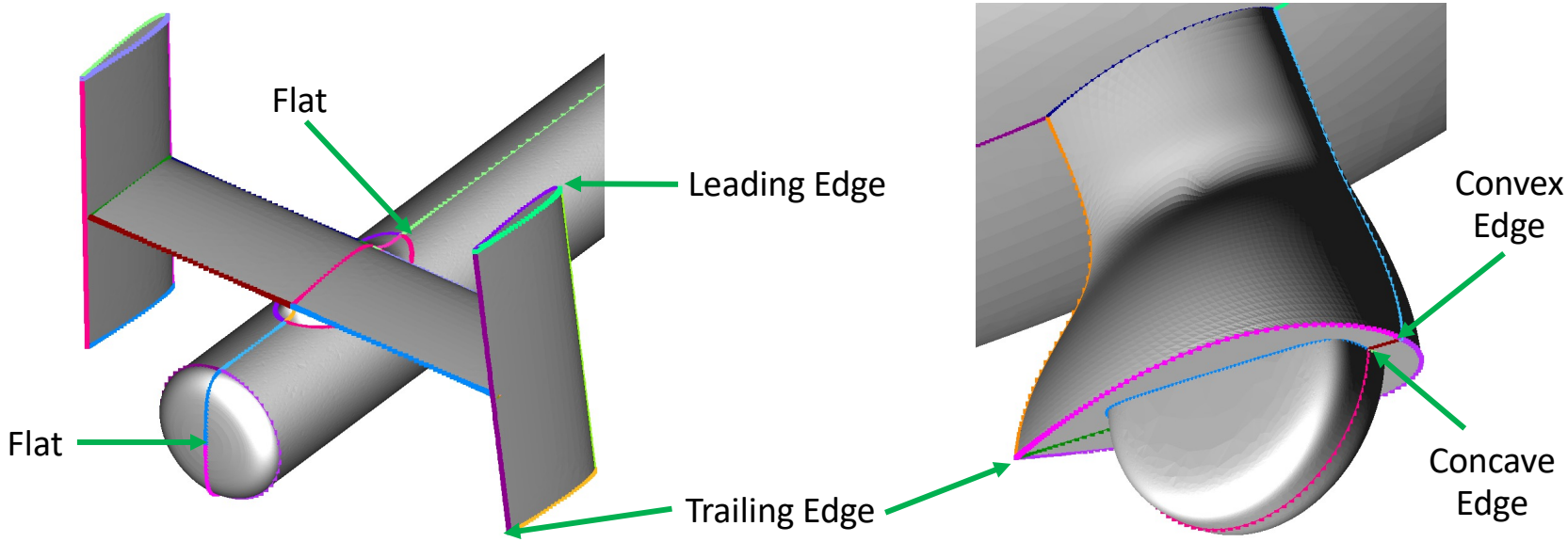
** Work in progress*





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GRID POINT DISTRIBUTION



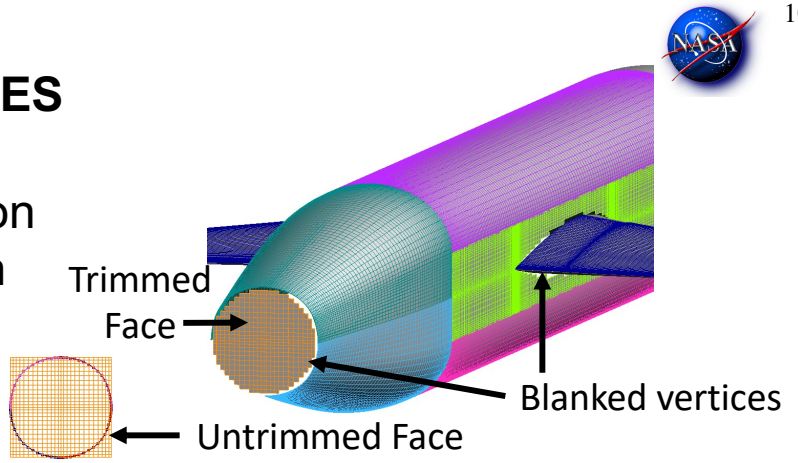
- Determine appropriate grid spacing at Nodes based on geometric features
- Discretize Edges - hyperbolic tangent stretching function
  End grid spacings = Node grid spacing
  Max grid spacing = Global param. scaled by local component characteristic length
  Max stretching ratio = Global param.

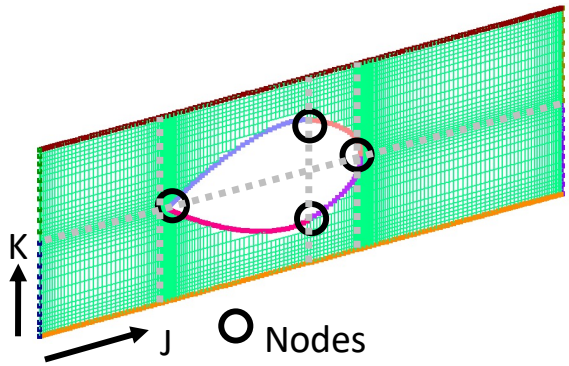
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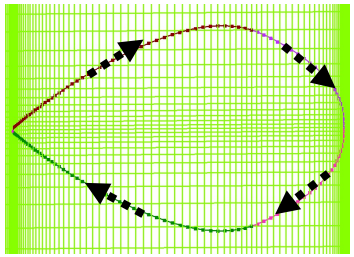
FACE MESHES

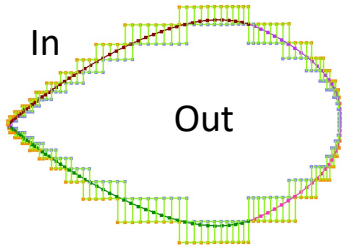
Grid point distribution on Face mesh

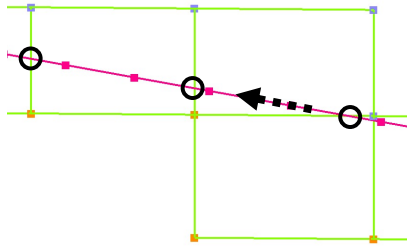
- Nodes divide face into zones in J and K direction
- Construct stretched grid in each zone based on
  - end spacings (Nodes)
  - max spacing (global param.)
  - max stretching ratio (global param.)











Iblank array

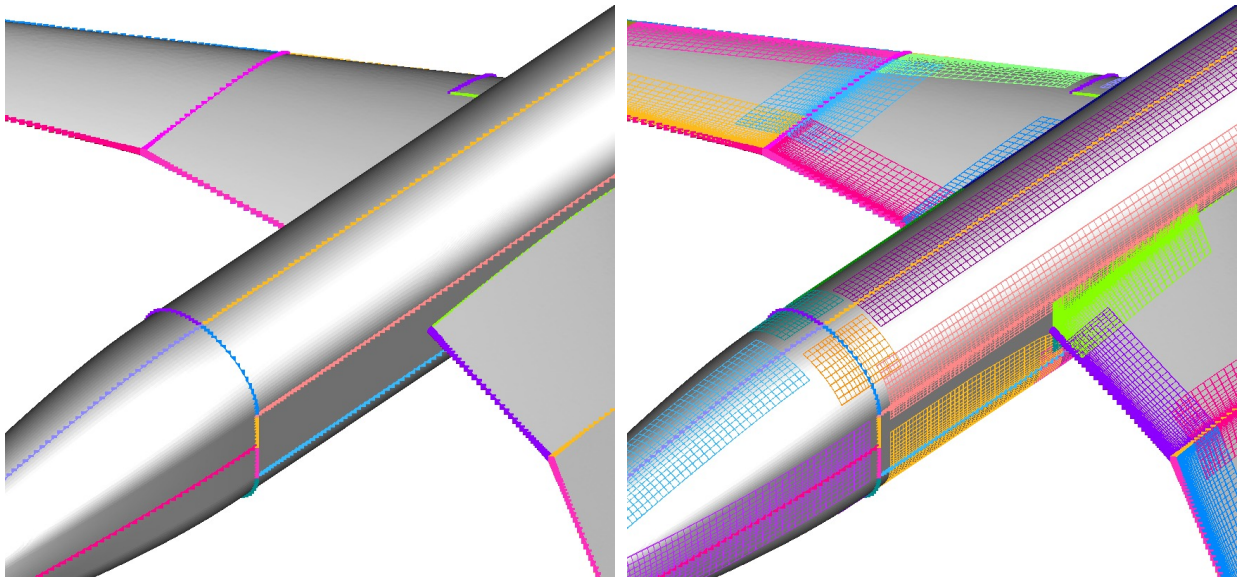
- 1 = on geometry, 0 = outside geometry
- Marks minimum hole cut on face meshes

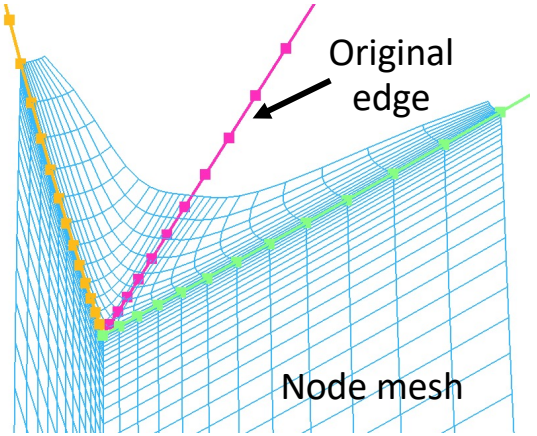
In/out test in discrete space

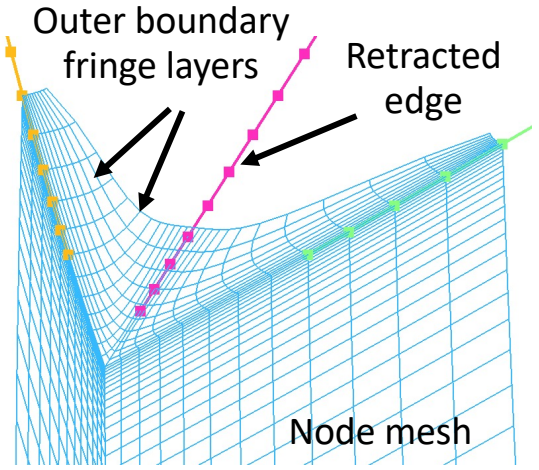
- Directed Edge line segments
- Cut Face mesh quadrilateral cells
- Left side in, right side out
- Paint to fill all Face mesh vertices

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EDGE MESHES





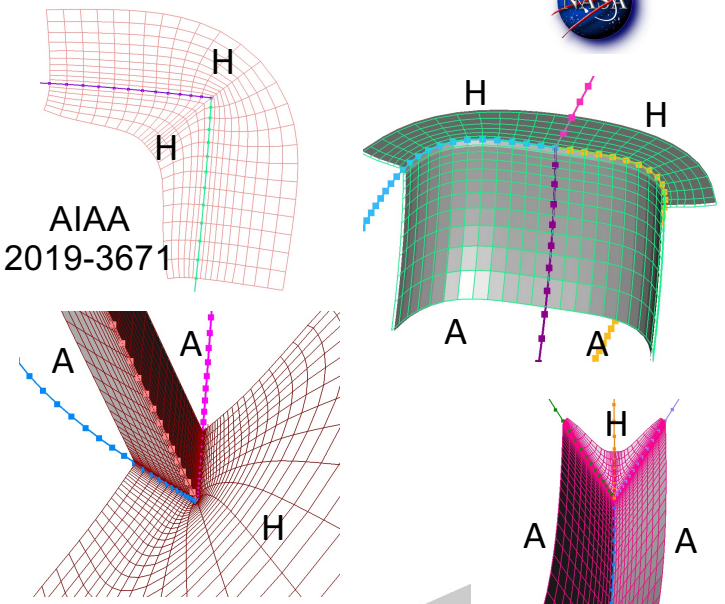


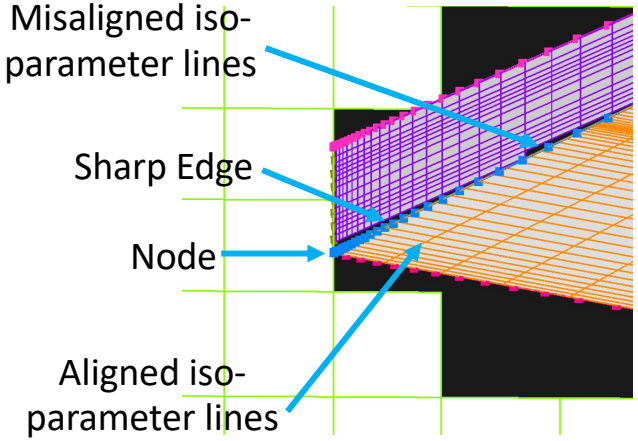
- Retract discretized Edges from Nodes
- Variable retraction to achieve (2 x Nf) cell overlap with Node mesh at end points
- Generate Edge meshes by hyperbolic/algebraic marching

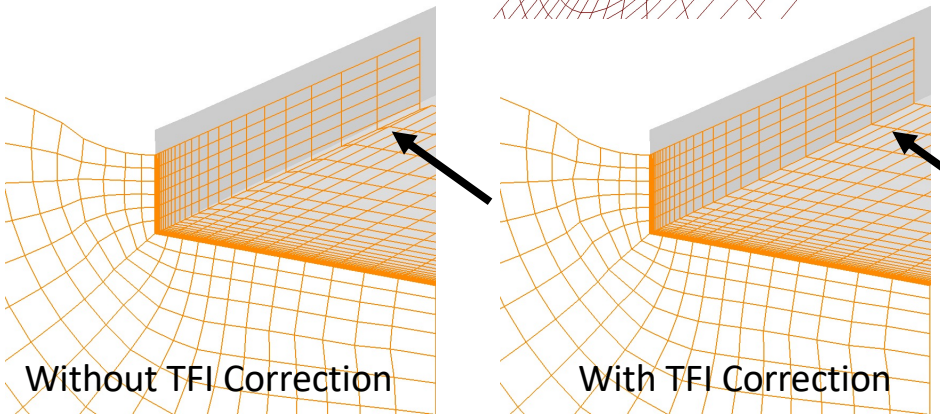
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NODE MESHES

- Construct initial curve to straddle Node by concatenating “best” two Edges meeting at Node
- Two, three or four parts created by hyperbolic or algebraic marching
- Switch to TFI for algebraic meshes with non-aligned iso-parameter lines relative to sharp dividing Edge at Node



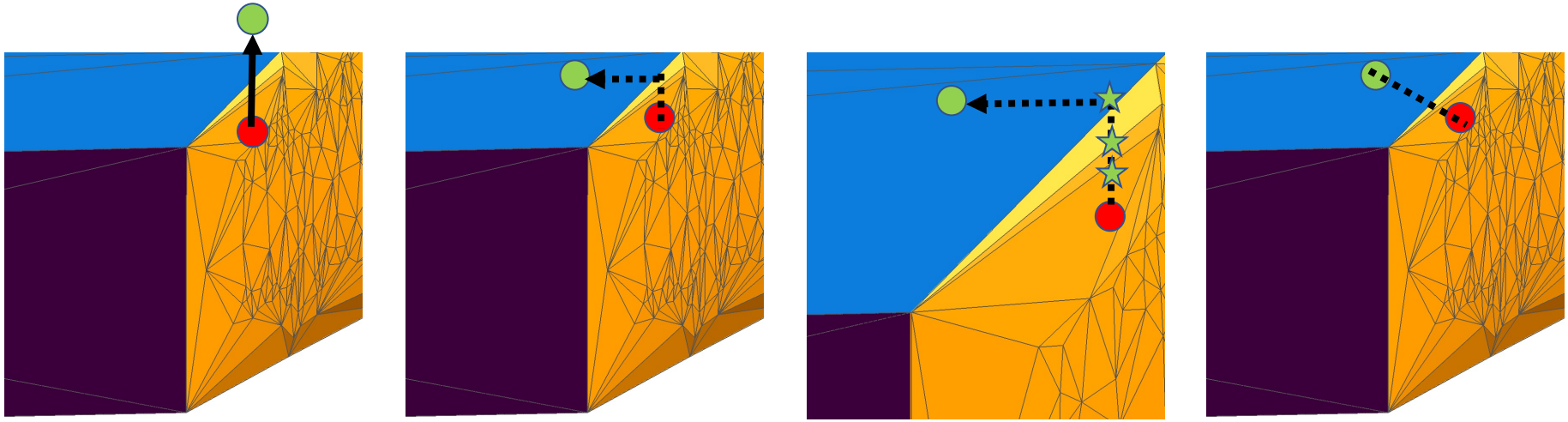




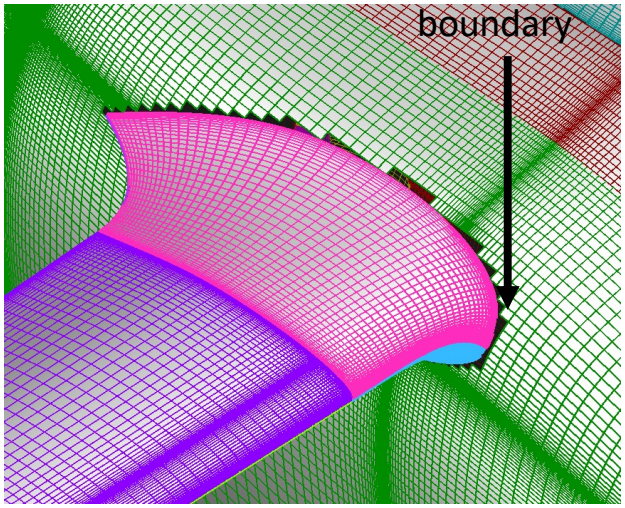
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HYPERBOLIC MARCHING WITH SURFACE WALKING

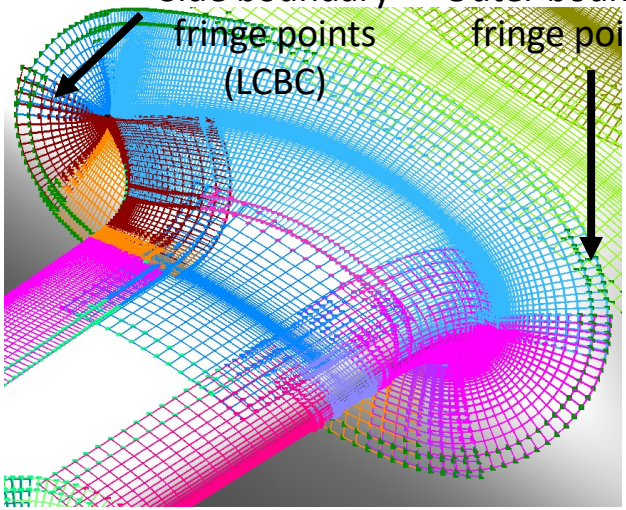
- Previous projection scheme can run into difficulty near sharp edges (e.g., trailing edges)
- Replace with walking scheme on triangulation
- Take step from triangle interior, edge or vertex using step vector predicted by hyperbolic marching equations



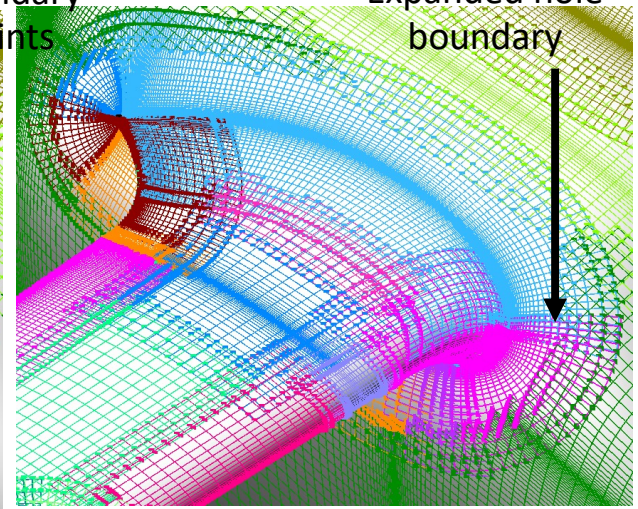
FACE MESH RETRACTION & REDUCTION



Face meshes with minimum hole



Edge and Node meshes

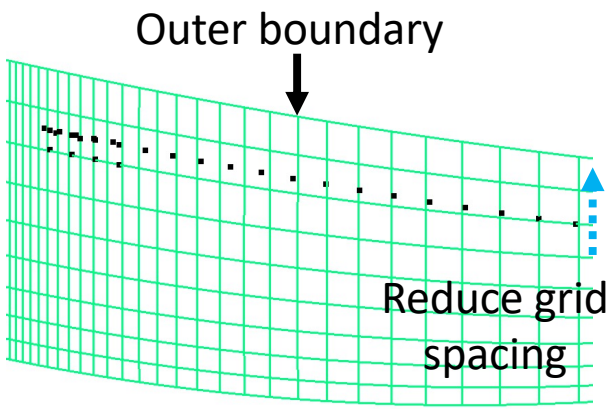


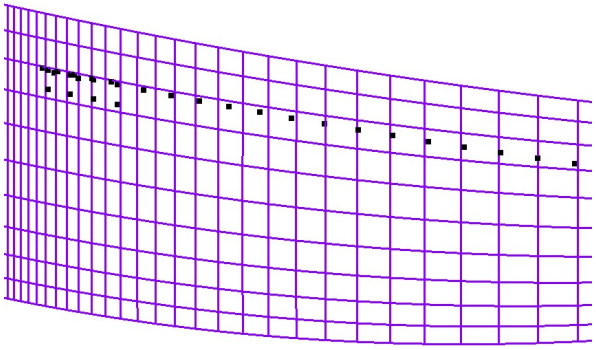
Retracted Face meshes with expanded hole

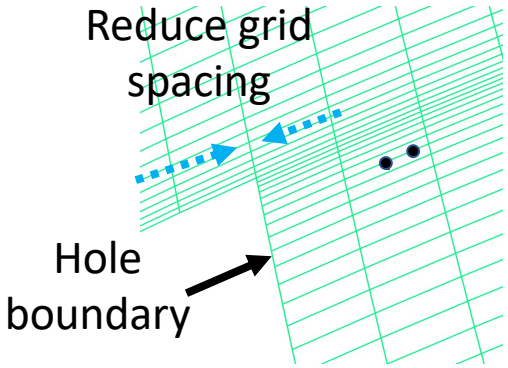
- Expand minimum hole
- Remove face meshes that are completely covered by Edge/Node meshes
- Reduce dimensions on meshes with one or more layers of blanked points
- Blanked vertices and donor stencils for fringe points identified => surface domain connectivity completed

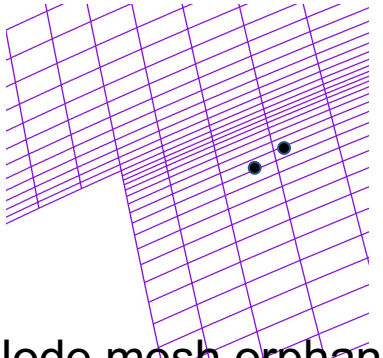
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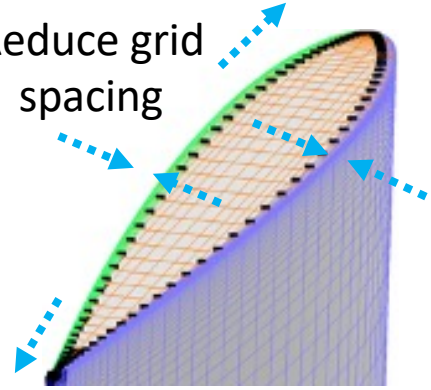
FACE MESH REFINEMENT
(work in progress)

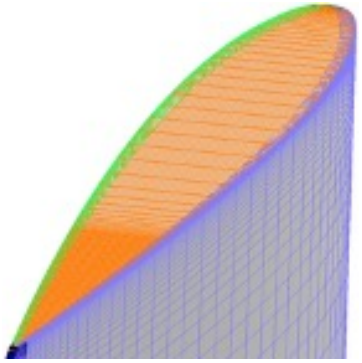












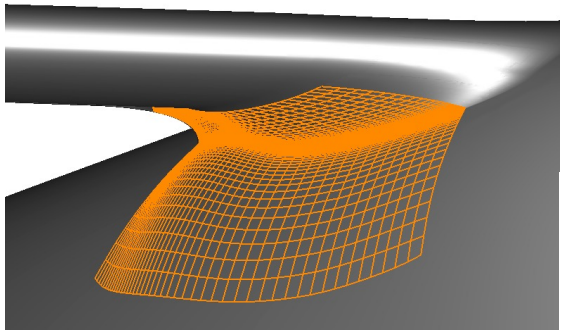
- Identify cells that contain Edge/Node mesh orphan points (black symbols)
- Split into zones in J and K direction for local refinement

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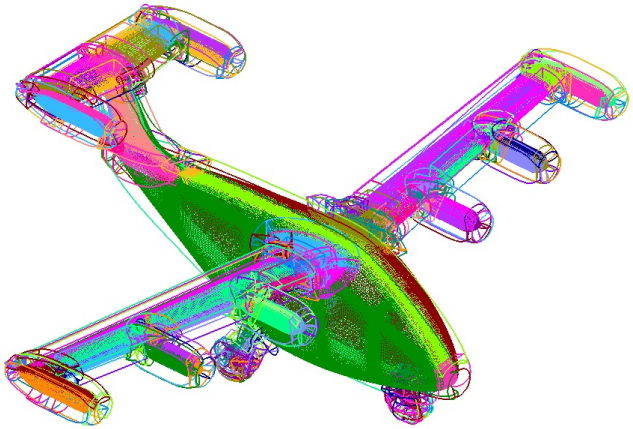
VOLUME MESH GENERATION

Near-Body Curvilinear

- Hyperbolic meshes
- All meshes use same wall spacing, marching distance, stretching ratio
- Auto selection of smoothing parameters and splay boundary conditions based on concave region detection

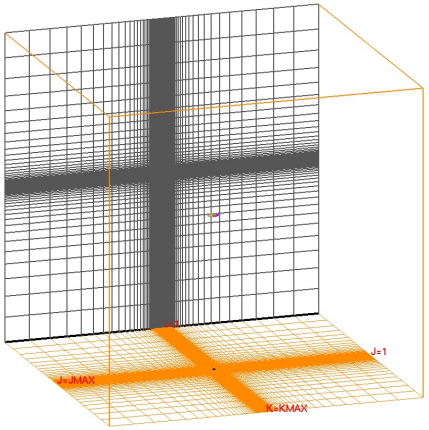


Concave region



Off-Body Cartesian

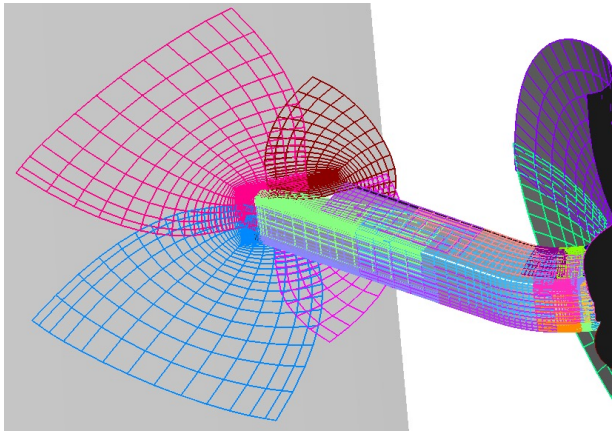
- Simple stretched Cartesian



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LOOSELY-COUPLED BOUNDARY CONDITIONS FOR HYPERBOLIC MESHES

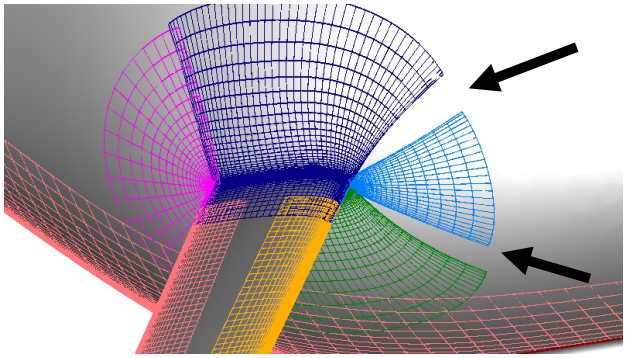
- Overview of Loosely Coupled Boundary Conditions (LCBC)
  - Motivation
  - Loose-coupling algorithm
  - Implementation in surface and volume meshing
- Examples
  - 6-Pax Quadrotor
  - NASA Juncture Flow Experiment Model 0015
- Conclusions



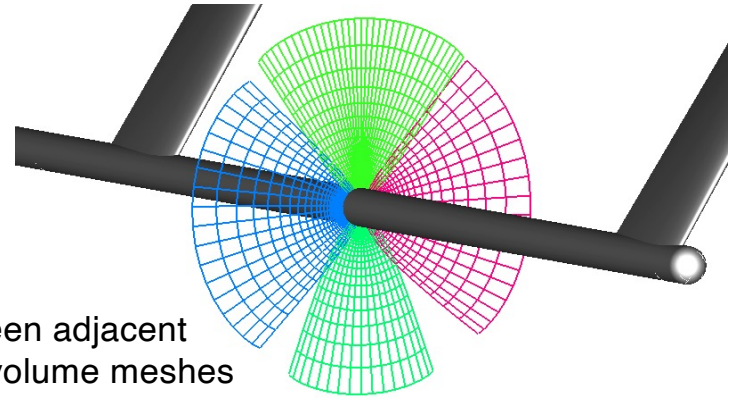
Chuen, A. M., Chan, W. M., Overlap Preservation Using Loosely-Coupled Boundary Conditions for Body-Fitted Structured Overset Grids, AIAA Paper 2022-0216, AIAA SciTech Forum, San Diego, CA, Jan., 2022.

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OVERLAP ISSUES IN HYPERBOLIC SURFACE AND VOLUME MESHES

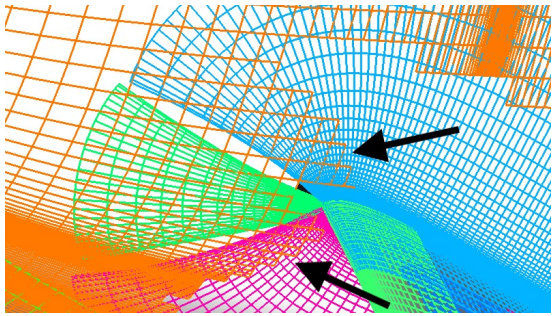


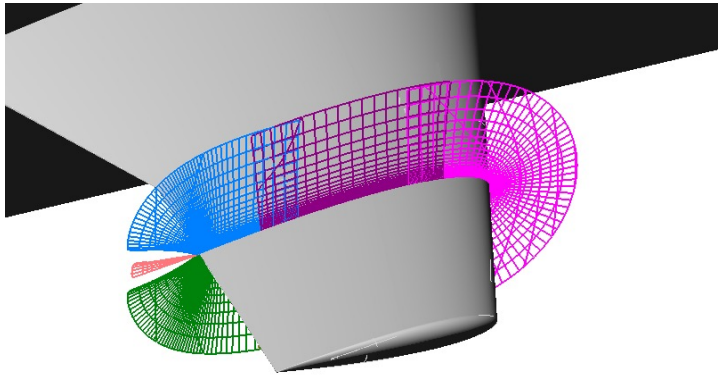
Gaps between adjacent (edge/node) hyperbolic meshes with overlapping initial curves



Gaps between adjacent hyperbolic volume meshes

Face mesh (orange) filling in gaps between adjacent meshes

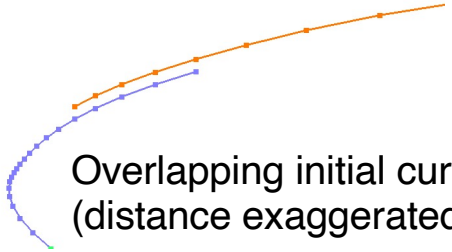




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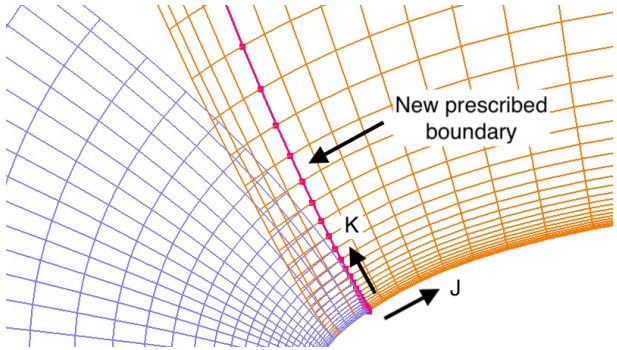
LOOSELY COUPLED BOUNDARY CONDITIONS (1)

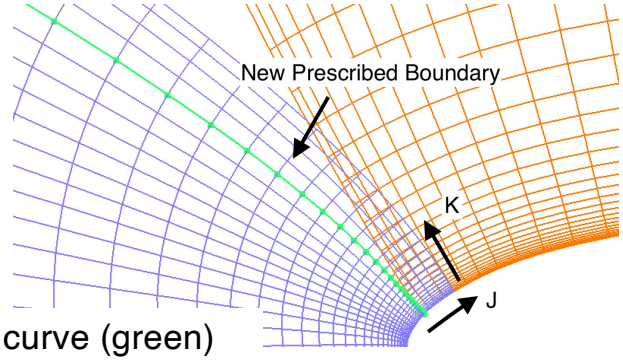
- Need to enforce different boundary conditions for hyperbolic meshes
- Overlapping grid points must exhibit similar trajectories to maintain overlap
- Enforced via float-along boundaries
- Convergence: displacement of boundary between iterations falls below specified tolerance



Overlapping initial curves
(distance exaggerated)

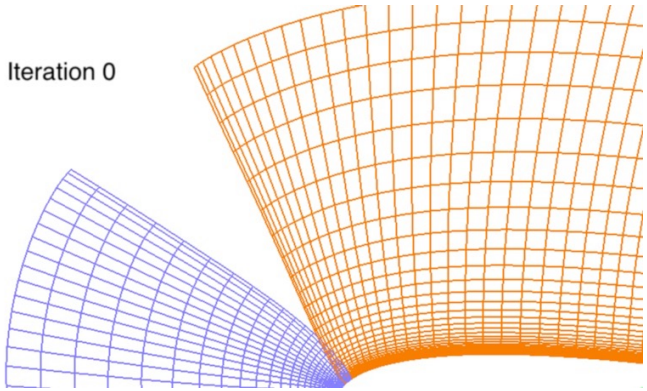
New boundary curve (magenta)
extracted for blue mesh

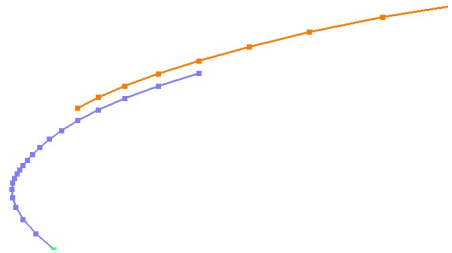




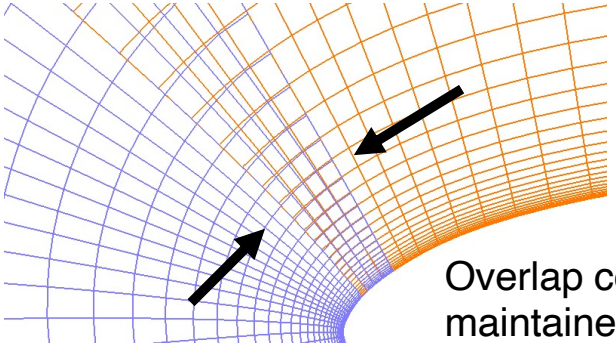
New boundary curve (green)
extracted for orange mesh

LOOSELY COUPLED BOUNDARY CONDITIONS (2)

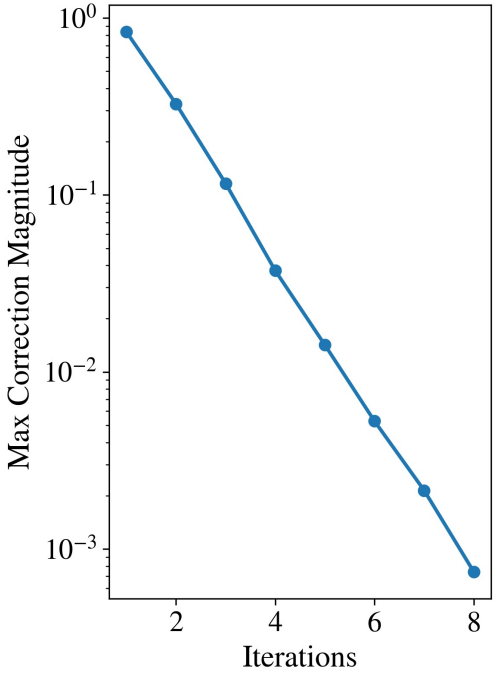




Overlapping initial curves
(distance exaggerated)



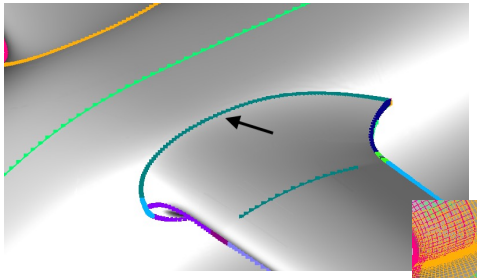
Overlap consistently
maintained across
marching direction



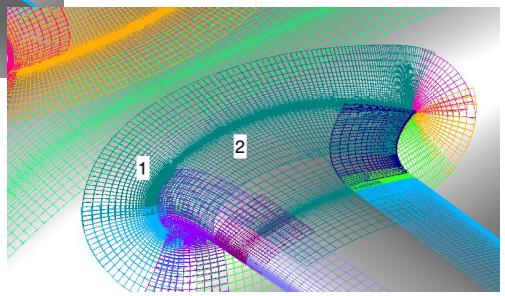
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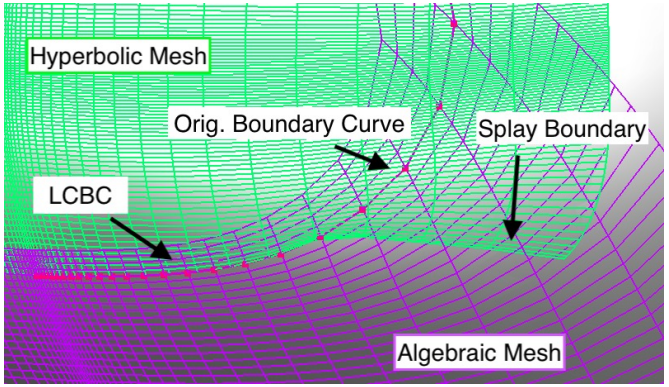
LCBC FOR SURFACE MESH GENERATION

- Setup connectivity between node and edge meshes
- Coupling can occur between hyperbolic and algebraic edge meshes
- Boundary enforcement similar to field meshes
- Revert to splay for potential difficult boundaries from algebraic grids



Surface meshes generated from overlapping set of node & edge curves



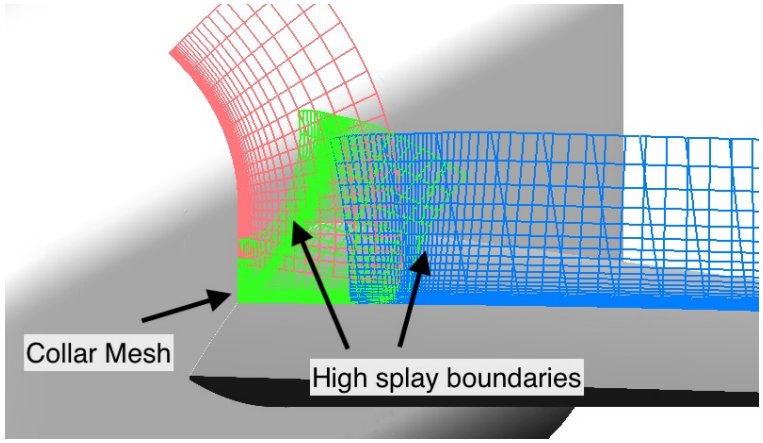


Transition to splay for coupled hyperbolic and algebraic grids

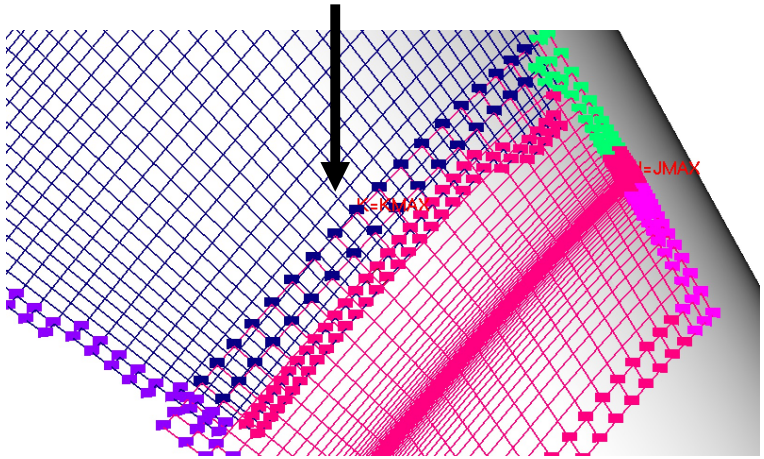
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LCBC FOR VOLUME MESH GENERATION

- Surface domain connectivity:
  - Face mesh retraction
  - Fringe point donor stencil search
- Collar meshes are excluded from LCBC



Coupling of initial surface meshes through surface domain connectivity

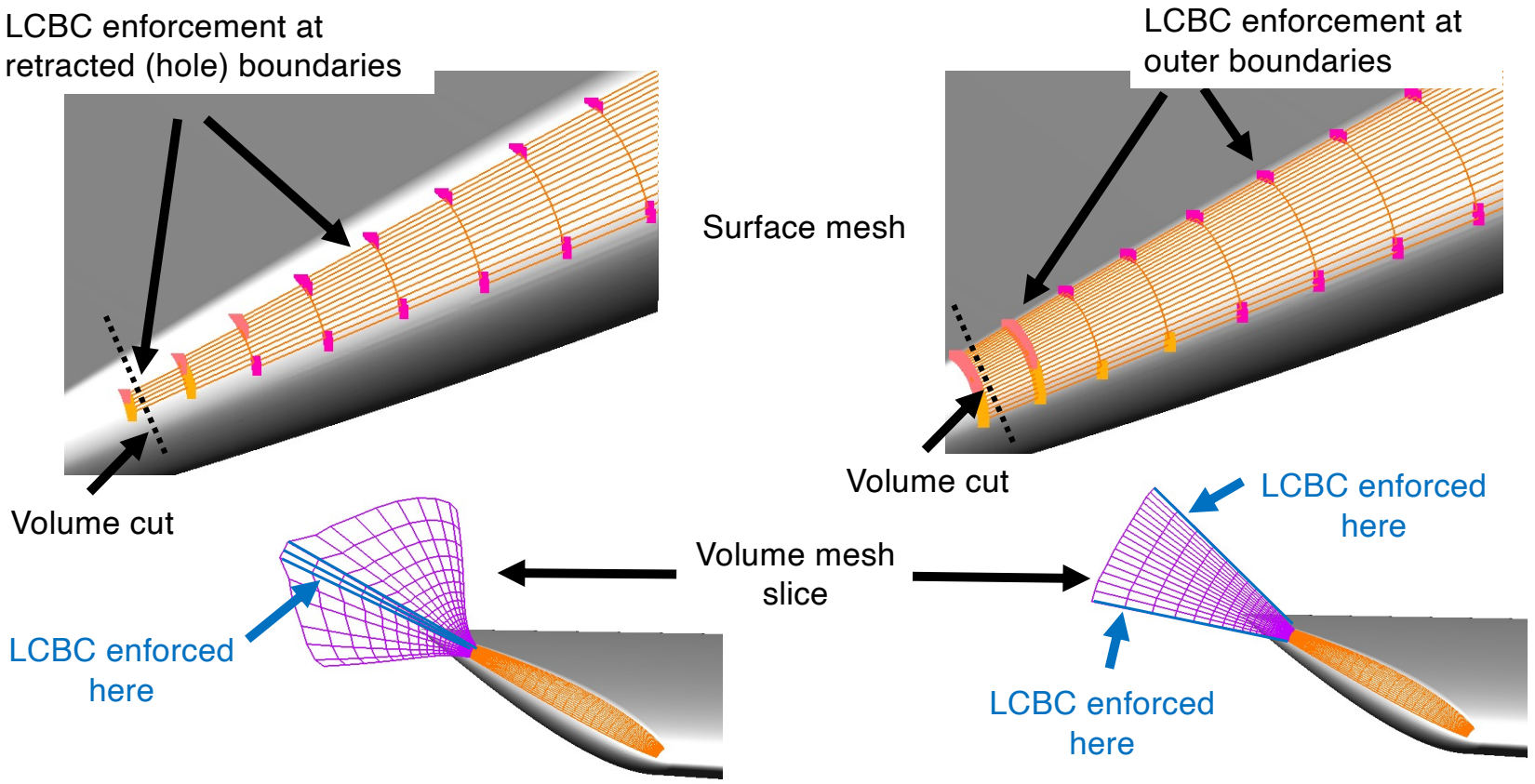


Chan, W. M., Pandya, S. A., and Haimes, R., "Automation of Overset Structured Surface Mesh Generation on Complex Geometries," AIAA Paper 2019-3671, June 2019. https://doi.org/10.2514/6.2019-3671.

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LCBC ENFORCEMENT FOR FACE (VOLUME) MESHES

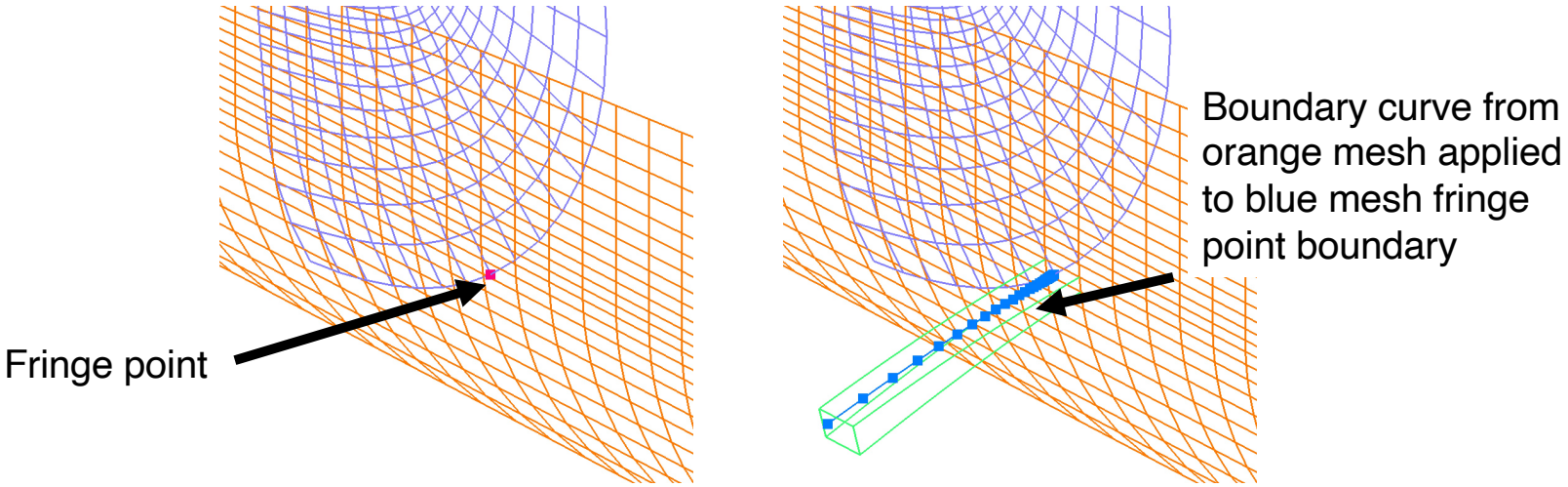
(work in progress)



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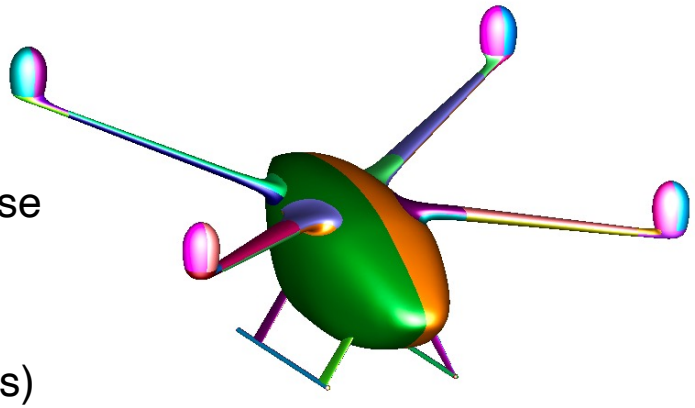
BOUNDARY ENFORCEMENT FOR VOLUME MESHES

- Coupling is done by floating-curve enforcement for each fringe point
- Boundaries at J=1,J=JMAX,K=1,K=KMAX indices left as splay if not fringe point



6-PAX QUADROTOR

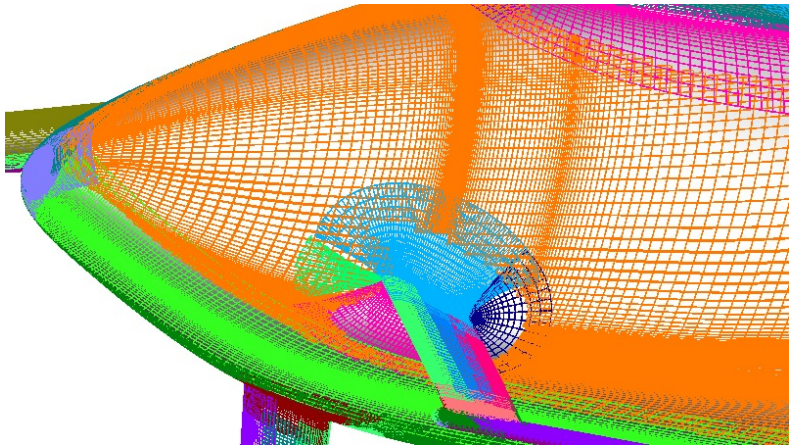
- 56 Face Meshes, 168 Edge and Node Meshes (224 meshes total)
- Surface Mesh with LCBC
  - Applied to all node and edge meshes
  - 17 iterations
  - Total wall time: 61 seconds (4 second increase from without LCBC)
- Volume Mesh with LCBC
  - Applied to skid meshes (19 meshes, 1.3M pts)
  - 60 iterations
  - Total wall time: 4.5 minutes



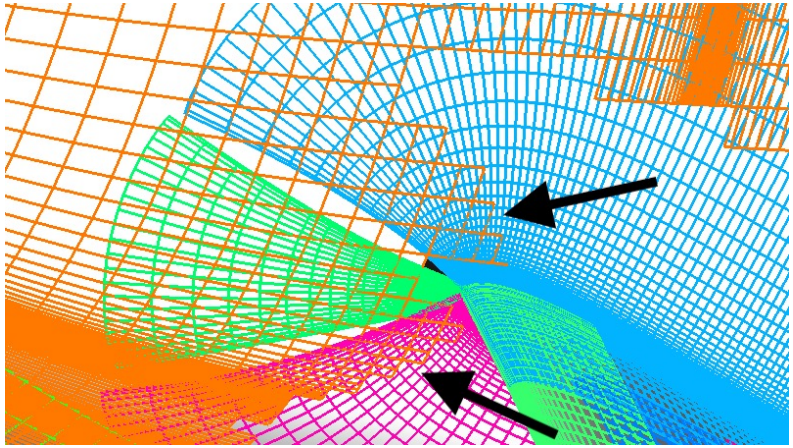
Quadrotor Geometry

Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," AIAA Paper 2018-3847, June 2018. https://doi.org/10.2514/6.2018-3847.

6-PAX QUAD SURFACE MESH – WITHOUT LCBC

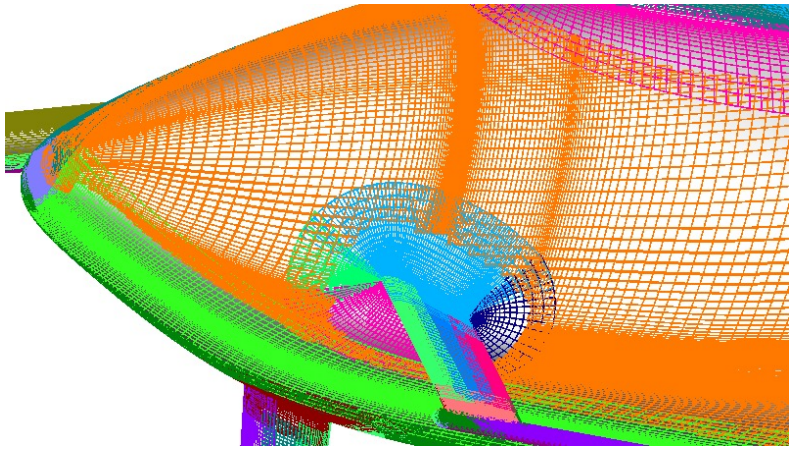


Hyperbolic meshes generated around strut-body junction

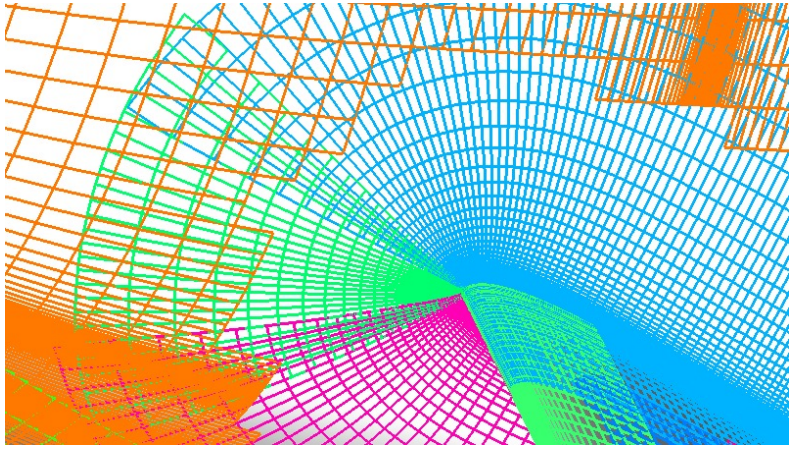


Face meshes forced into gap between hyperbolic meshes

6-PAX QUAD SURFACE MESH – WITH LCBC



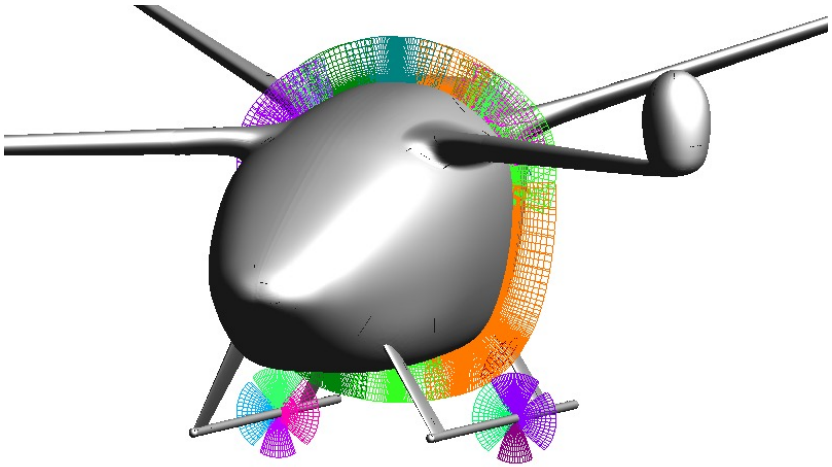
Hyperbolic meshes generated around strut-body junction



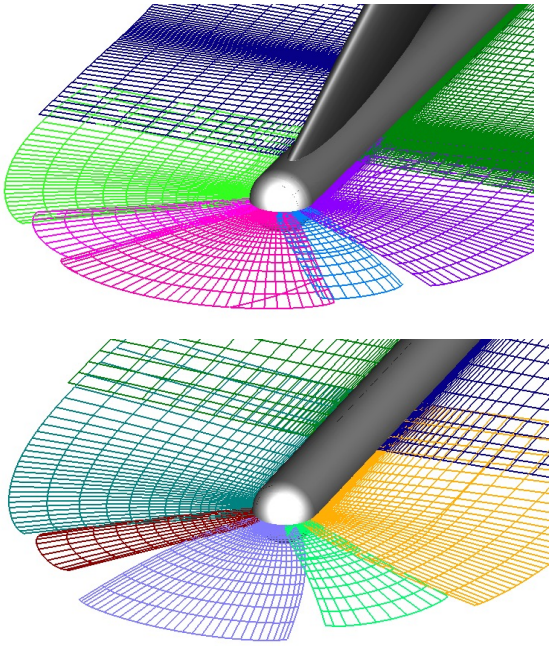
Face meshes removed from overlap between meshes

6-PAX QUAD VOLUME MESH – WITHOUT LCBC

Applied to Skid meshes



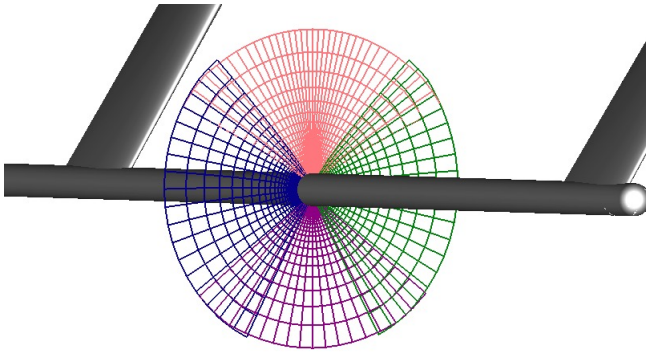
Cross-sec cut of volume meshes at X=0



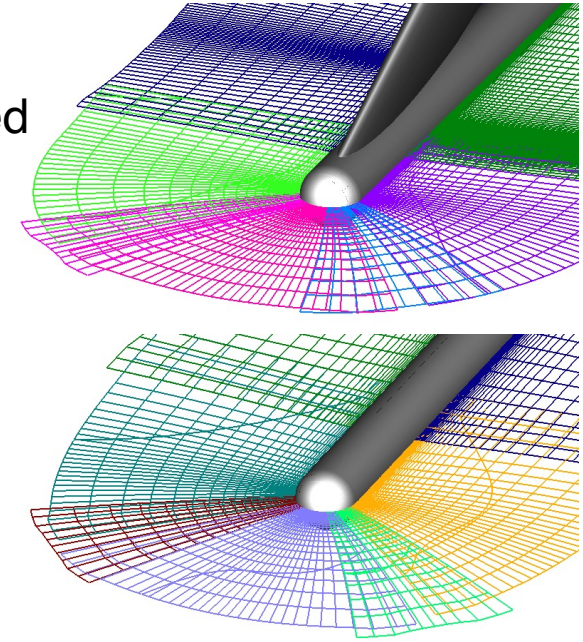
Center Z-plane cut of front (top) and rear (bottom) skid tips

6-PAX QUAD VOLUME MESH – WITH LCBC

- Volume mesh boundaries retain consistent overlap – gaps in overlapping regions removed



X=0 plane cut of skid volume meshes

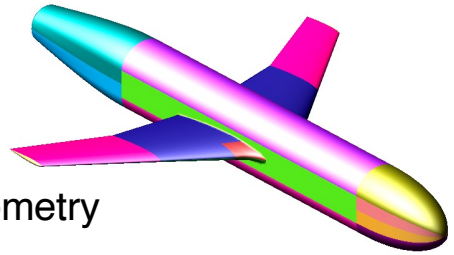


Center Z-plane cut of front (top) and rear (bottom) skid tips

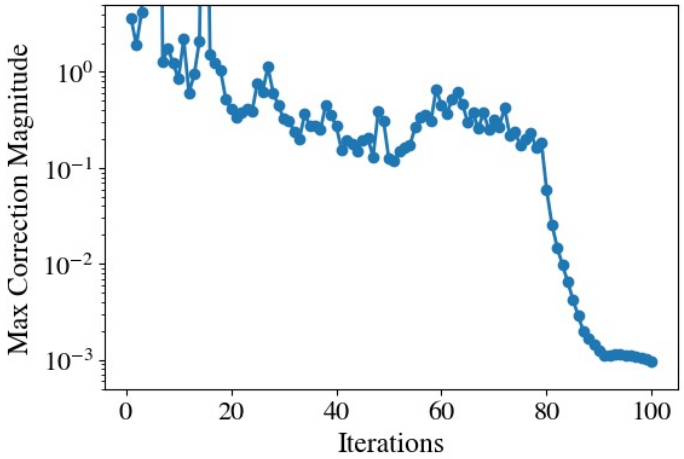
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JUNCTURE FLOW EXPERIMENTAL MODEL 0015 WING

- 37 Face meshes, 109 Edge and Node meshes (146 meshes total)
- Surface mesh with LCBC
- Near-body volume mesh with LCBC
  - Applied to full geometry (13.3M pts)
  - 100 iterations, total wall time: 56 min.
  - Fringe-pt. count with donor stencil quality ≥0.9
    - Without LCBC: 96.6%
    - With LCBC: 99.3%



JFM Geometry



Convergence of max boundary displacement

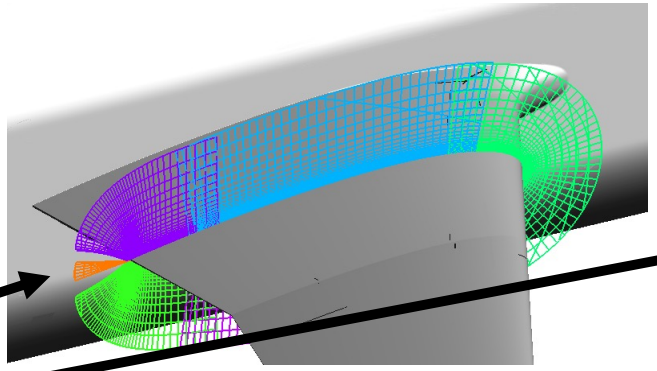
Kegerise, M. A., and Neuhart, D. H., "Wind Tunnel Test of a Risk-Reduction Wing/Fuselage Model to Examine Juncture-Flow Phenomena," Tech. Rep. NASA/TM-2016-219348, NASA Langley, November 2016.

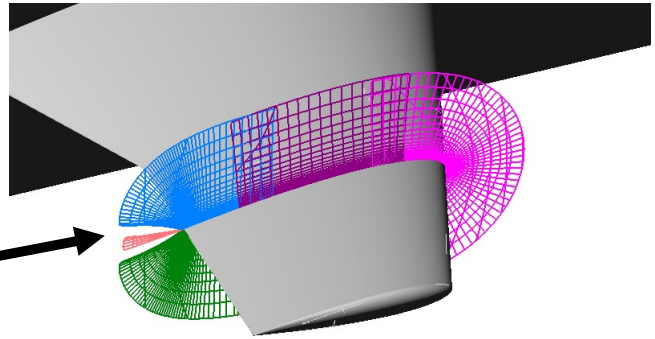
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JUNCTURE FLOW MODEL – WITHOUT LCBC

Y = 550

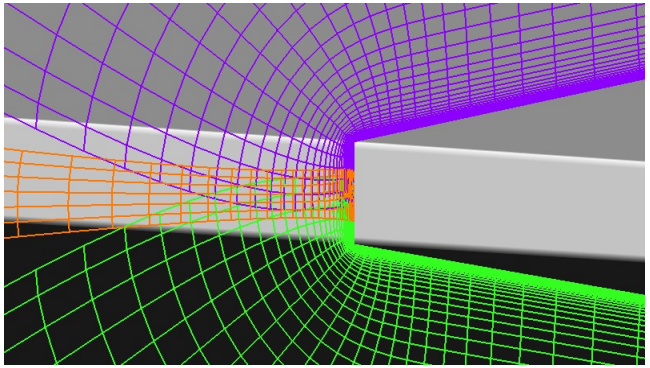
Y = 1150

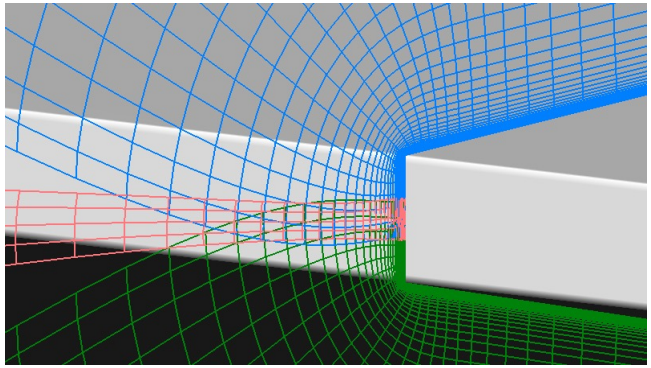




Large gaps develop in trailing edge wake

Mesh divergence occurs near-wall in wake



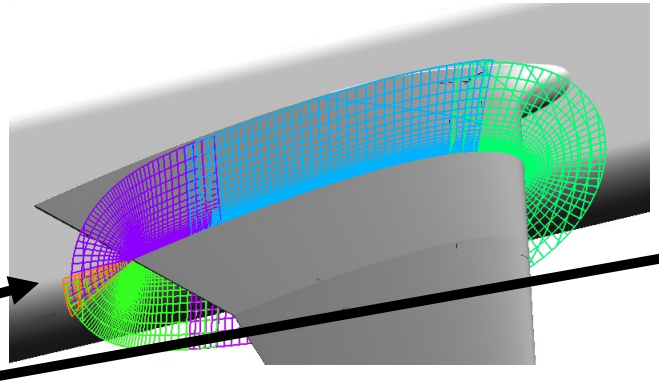


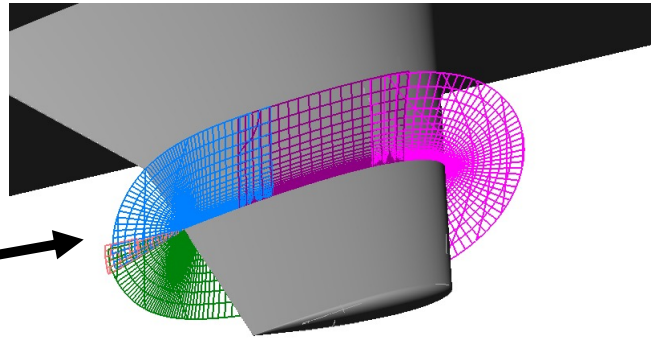
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JUNCTURE FLOW MODEL – WITH LCBC

Y = 550

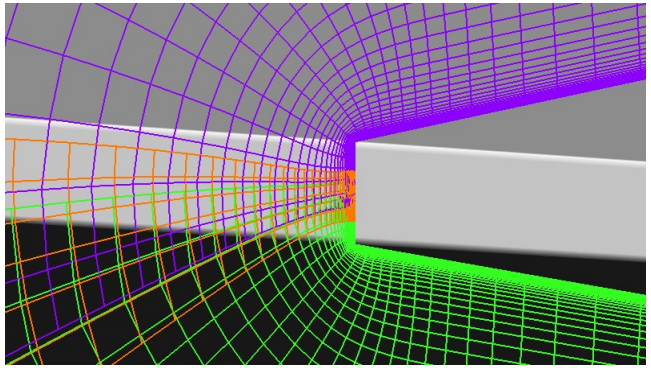
Y = 1150

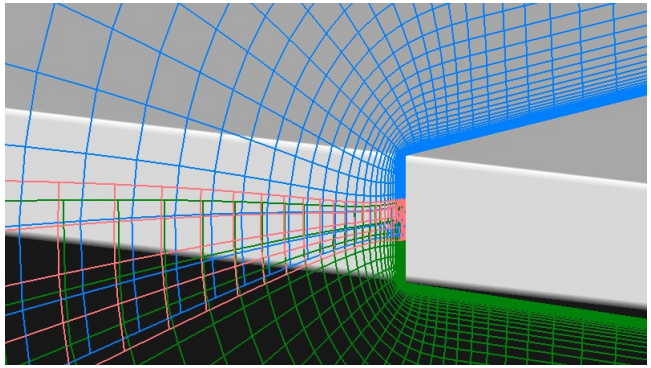




Trailing edge gaps are closed

Overlap consistent with initial surface maintained across marching direction



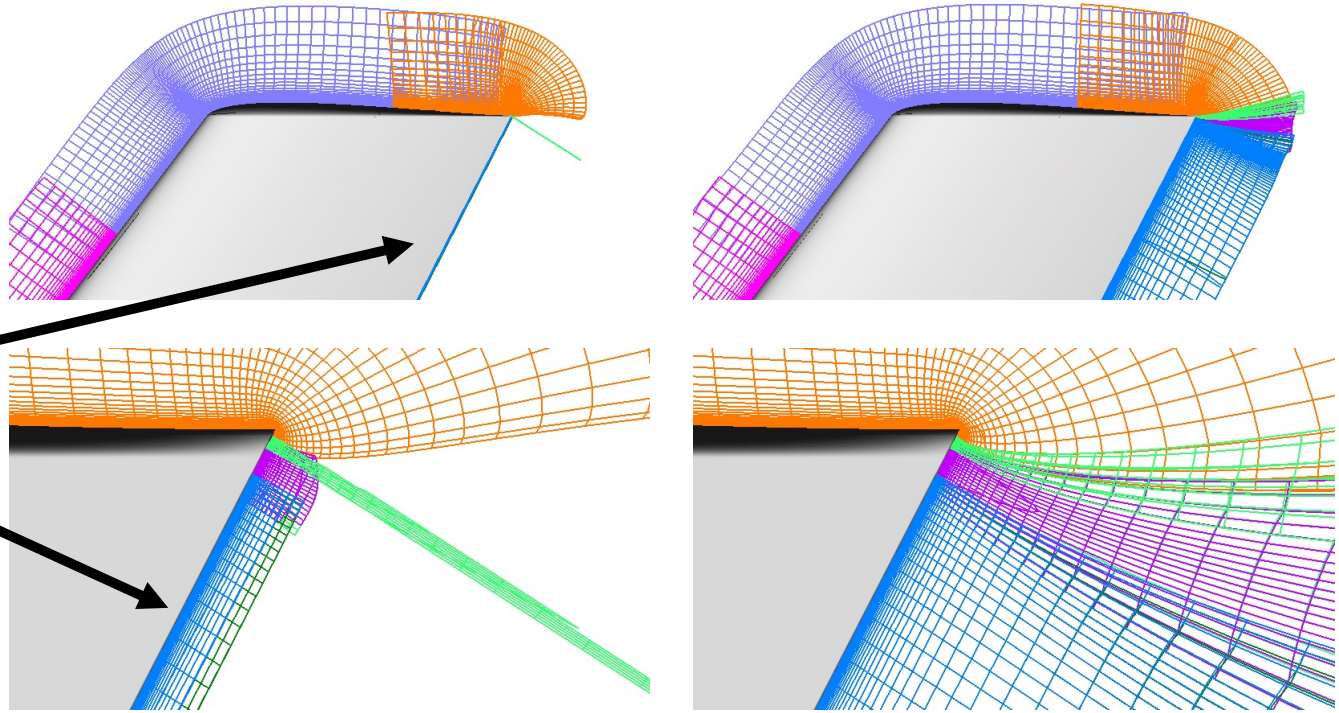


WINGTIP TRAILING EDGE ($Z = 0$)

Without LCBC

With LCBC

Meshes bend away from trailing edge due to splay boundary



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VOLUME MESH STENCIL QUALITY

	Initial		Final	
Quality	Count	% Total	Count	% Total
$Q = 0.0$	18212	8.73	0	0.00
$0.1 \leq Q < 0.2$	1183	0.567	0	0.00
$0.2 \leq Q < 0.3$	1061	0.509	0	0.00
$0.3 \leq Q < 0.4$	1192	0.571	0	0.00
$0.4 \leq Q < 0.5$	919	0.441	0	0.00
$0.5 \leq Q < 0.6$	1367	0.655	0	0.00
$0.6 \leq Q < 0.7$	1581	0.758	0	0.00
$0.7 \leq Q < 0.8$	1514	0.726	0	0.00
$0.8 \leq Q < 0.9$	2602	1.25	861	0.413
$0.9 \leq Q < 1.0$	3787	1.82	2406	1.15
$Q = 1.0$	175141	84.0	205326	98.4

6-Pax Quadrotor (Skid)

	Initial		Final	
Quality	Count	% Total	Count	% Total
$Q = 0.0$	58377	2.63	3547	0.16
$0.1 \leq Q < 0.2$	801	0.362E-1	0	0.00
$0.2 \leq Q < 0.3$	790	0.357E-1	0	0.00
$0.3 \leq Q < 0.4$	801	0.362E-1	2	0.903E-4
$0.4 \leq Q < 0.5$	758	0.342E-1	8	0.361E-3
$0.5 \leq Q < 0.6$	926	0.418E-1	28	0.126E-2
$0.6 \leq Q < 0.7$	1050	0.474E-1	329	0.149E-1
$0.7 \leq Q < 0.8$	1166	0.526E-1	226	0.102E-1
$0.8 \leq Q < 0.9$	10948	0.494	10550	0.476
$0.9 \leq Q < 1.0$	29521	1.33	29749	1.34
$Q = 1.0$	2110521	95.3	2171220	98.0

Juncture Flow Model

LCBC RECAP

- Presented an automatic approach to maintain sufficient overlap between hyperbolic meshes in auto-generated surface and volume grid systems
- Prevented face/off-body meshes from filling in gaps in overlap region (avoids mismatch in grid spacing)
- Reduced manual effort needed to maintain overlap (hours to minutes)
- Demonstrated applications of LCBC in both surface and volume meshing on two aeronautical vehicles

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SOFTWARE MODULES (1)

EGADS2SRF

- Interface to geometry file using Engineering Sketch Pad (ESP) from MIT

- Input
  - Boundary Representation (BRep) solid in a STEP or IGES file
  - Global parameters: max grid spacing, max turning angle, max stretching ratio, min number of points on an edge
  - Optional geometric components specification file
  - Options (face removal for open boundary cases, single component meshing)

- Output
  - Surface triangulation (CART3D format)
  - Discretized Faces (PLOT3D surfaces)
  - Discretized Edges (PLOT3D curves)
  - Edge/face topological relationship (text)
  - Input parameters file for POGS (text)

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SOFTWARE MODULES (2)

POGS (Pre-processor for Overset Grid Simulations)

- Generate edge and node surface meshes and compute surface connectivity
- Generate near-body and off-body volume meshes
- Perform volume mesh domain connectivity * Work in progress
- Write input files for flow solvers and component aero-loads computation

Input

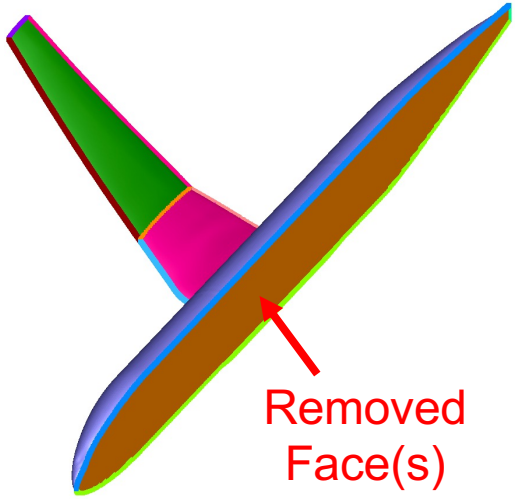
- Output files from EGADS2SRF (or files with equivalent data)
- Optional geometric components specification file

Output

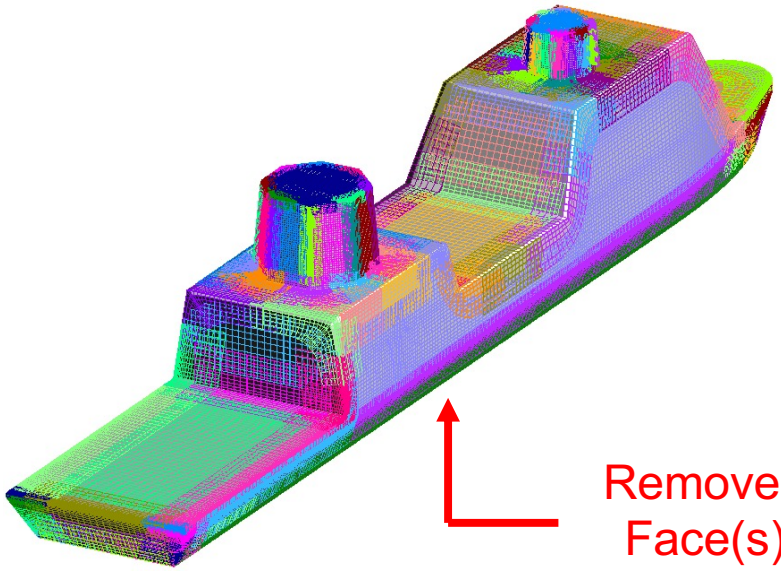
- Surface grids with iblanks (PLOT3D surface grids)
- Surface grid donor stencils data file (SINTOUT)
- Near-body + Cartesian off-body volume grids with iblanks (PLOT3D volume grids)
- Volume grid donor stencils data file (INTOUT) * Work in progress
- Input file for component aero-loads computation (FOMOCO)
- Input file for flow solver (OVERFLOW & LAVA)

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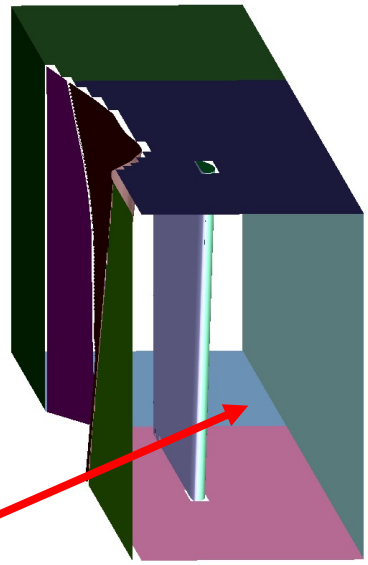
GEOMETRIES WITH OPEN BOUNDARIES



Half-Body



Truncated-Body



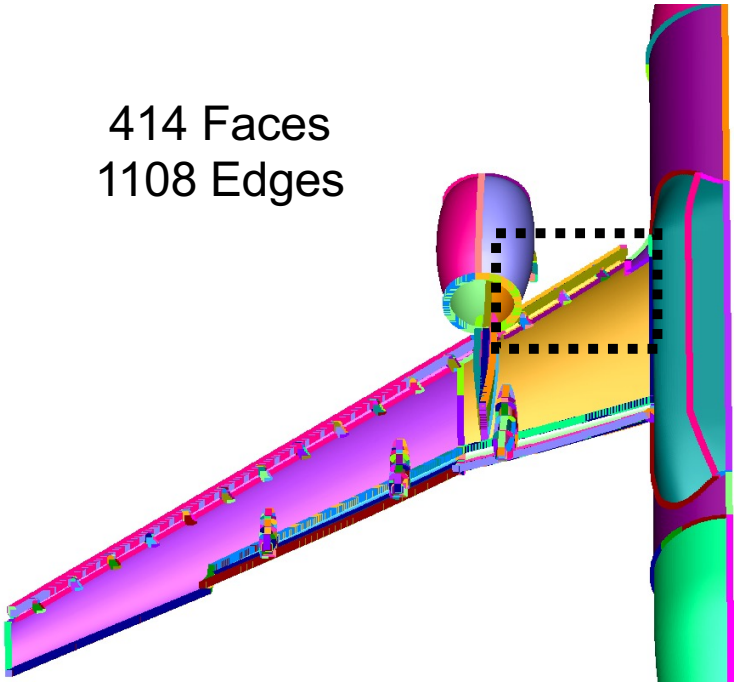
Internal Flow with
Entrance and Exit

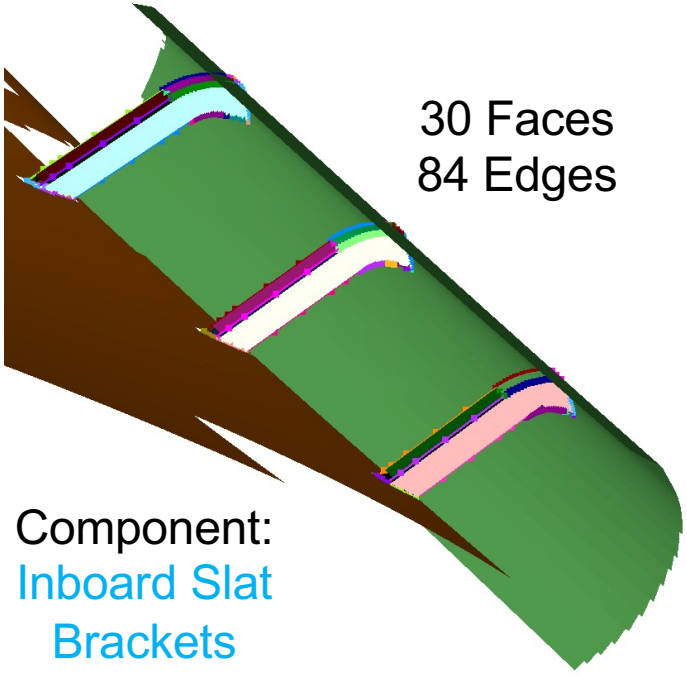
- Option to specify list of BRep faces to be removed before meshing
- Auto Edge/Face relationship update
- Allow for open boundaries in Edge/Node mesh construction

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SINGLE COMPONENT MESHING OPTION

414 Faces
1108 Edges





30 Faces
84 Edges

Component:
Inboard Slat
Brackets

- Option to specify a subset of BRep Faces as the meshing domain via geometric component specification
- All neighboring Faces that touch component are also meshed (includes associated collar grids)

TEST CASES

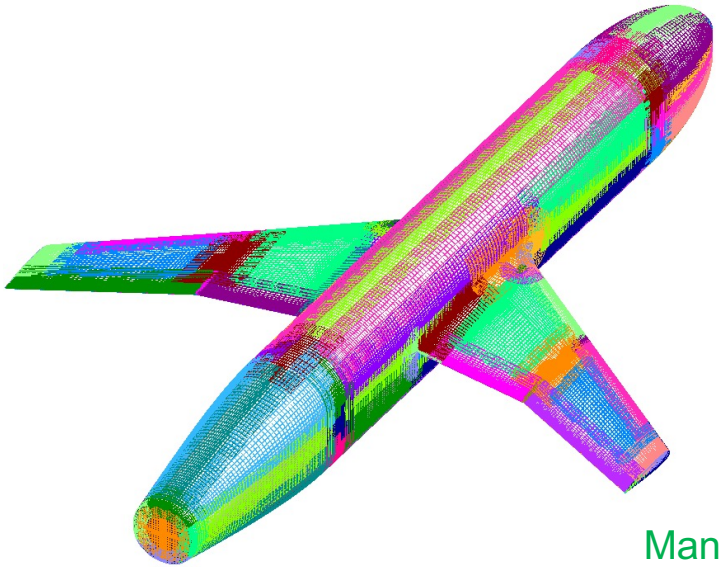
- All cases ran on 2018 Mac laptop, 2.9 GHz Intel Core i9, 16GB memory
- Surface meshes – mostly single processor
- Volume meshes – OpenMP on 6 threads

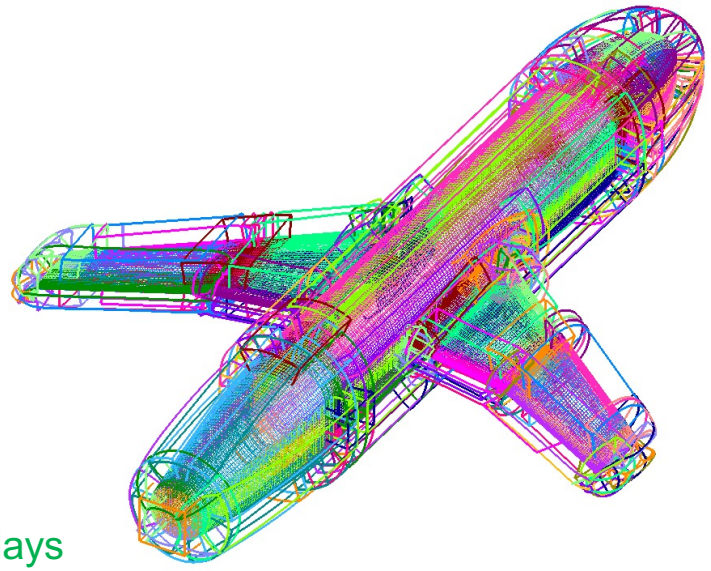
- Percent acceptable
- Percent of surface meshes with no negative cell areas
- Percent of volume meshes with no negative Jacobians

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JUNCTURE FLOW EXPERIMENT
NACA 0015 WING-BODY

Geometry: 41 Faces, 100 Edges, 51 Nodes
Surface meshes: # meshes = 146, 100% acceptable
Volume meshes: # points = 13.4 M, 96% acceptable
Wall clock time for surface + volume meshes = 57 sec.





Manual meshing time ~ days

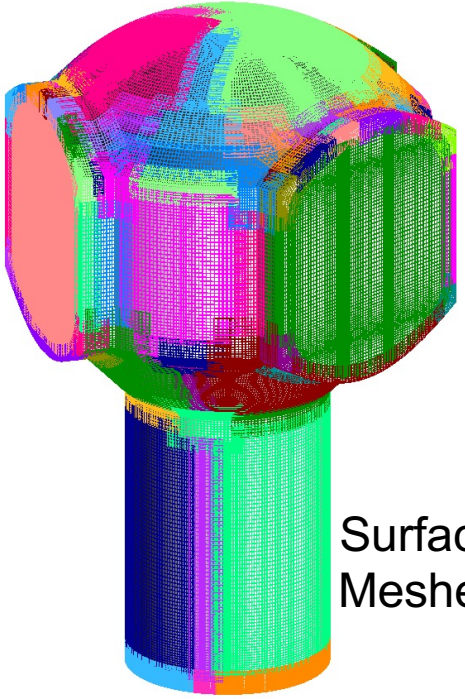
ROTOR HUB

Geometry: 34 Faces, 79 Edges, 45 Nodes

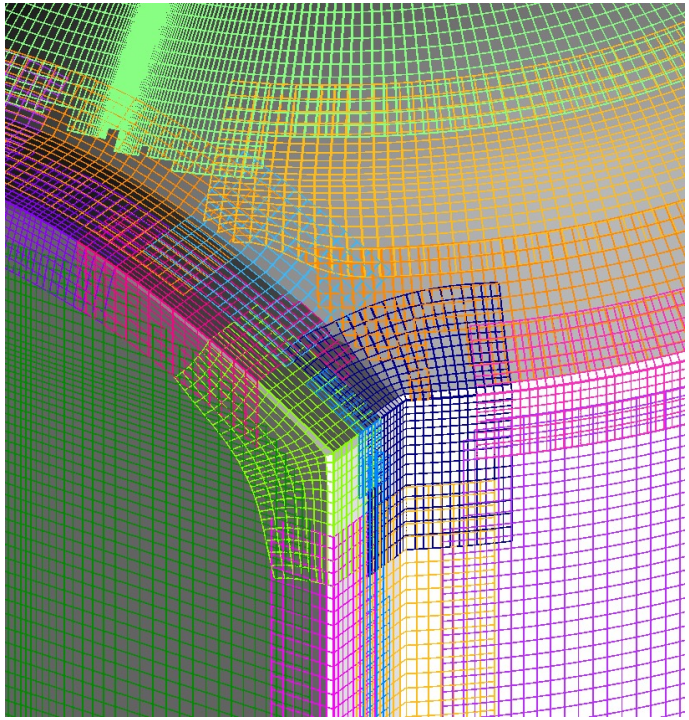
Surface meshes: # meshes = 142, 99% acceptable

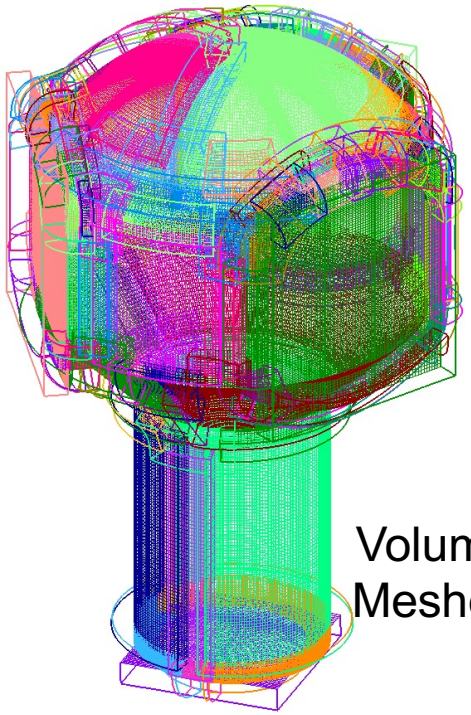
Volume meshes: # points = 4.9 M, 99% acceptable

Wall clock time for surface + volume meshes = 35 sec.



Surface Meshes



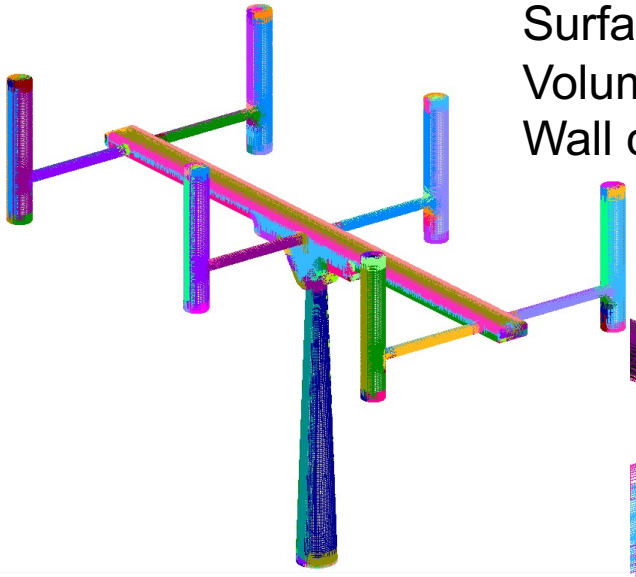


Volume Meshes

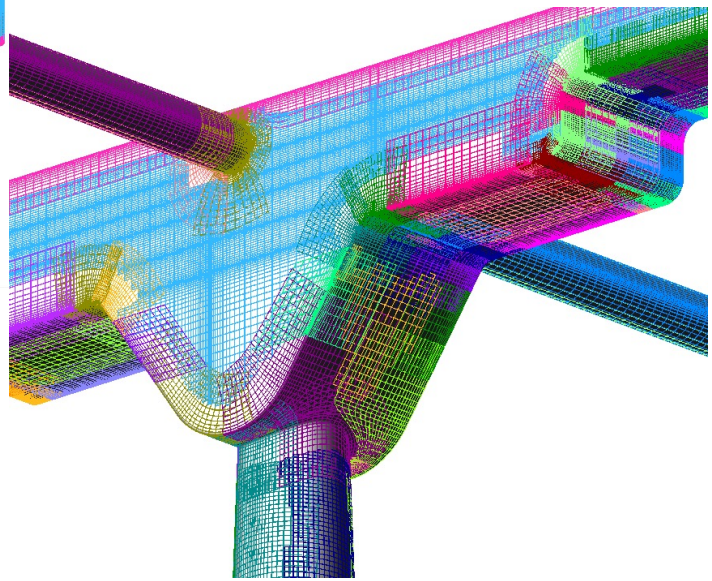
Ames Research Center

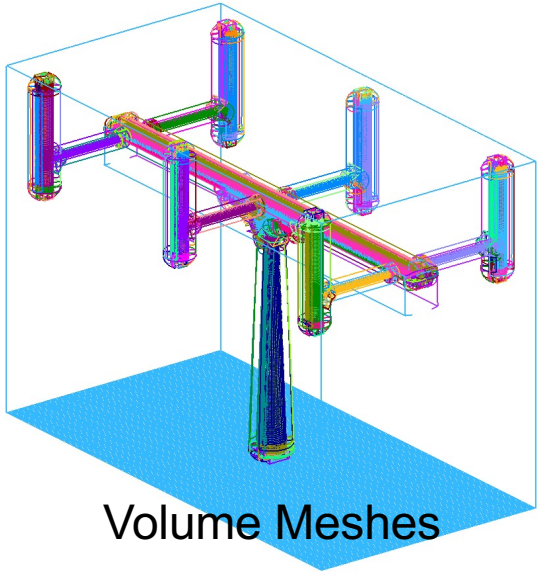
MULTI-ROTOR TEST BED

Geometry: 65 Faces, 166 Edges, 110 Nodes
Surface meshes: # meshes = 258, 100% acceptable
Volume meshes: # points = 35.6 M, 100% acceptable
Wall clock time for surface + volume meshes = 1 min. 35 sec.



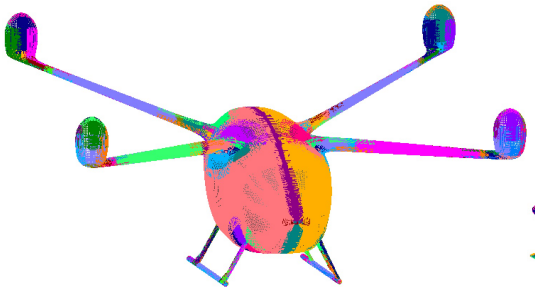
Surface Meshes



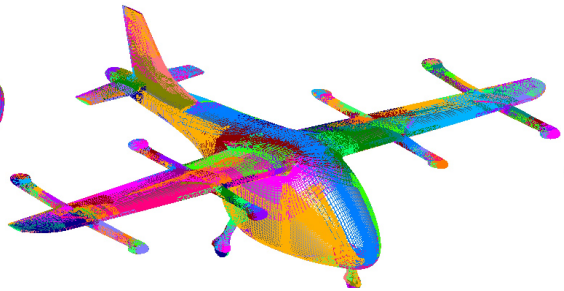


Volume Meshes

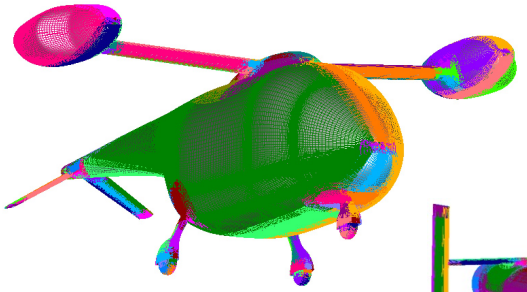
ROTORCRAFT CONCEPT VEHICLES



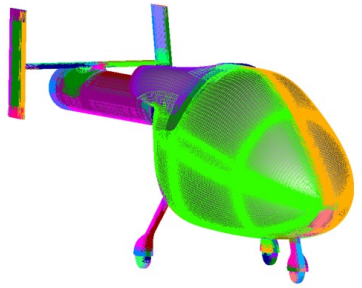
6-Pax Quadrotor



Lift+Cruise

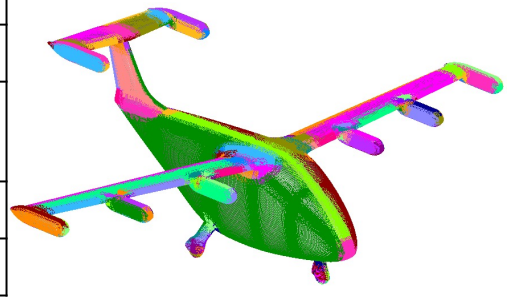


Side-By-Side Hybrid



Quiet Single Main Rotor

Concept Vehicle	# Meshes	# Volume mesh pts	% Acceptable meshes Surface	Volume	Wall clock time surface+volume
6-Pax Quadrotor	224	22.5 M	100%	79%	4 min 15 sec
Lift+Cruise	351	23.4 M	97%	91%	4 min 32 sec
Quiet Single Main Rotor	179	17.3 M	97%	84%	3 min 32 sec
Side-By-Side	160	16.9 M	99%	86%	4 min 22 sec
Tiltwing Cruise	287	52.1 M	95 %	87%	7 min 44 sec



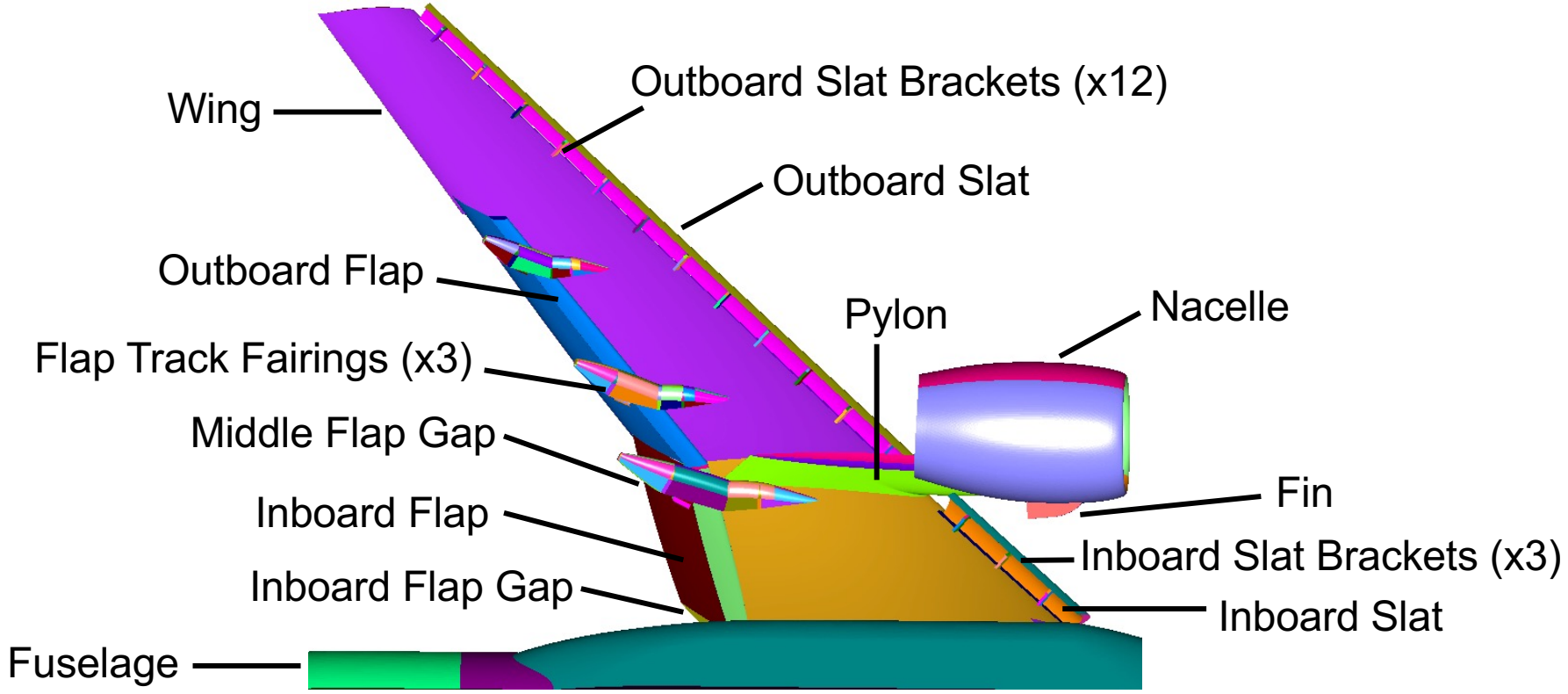
Tiltwing Cruise Mode

Manual meshing time ~ weeks per vehicle

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HIGH-LIFT COMMON RESEARCH MODEL (HLCRM)
High-Lift Prediction Workshop 4

Half-body geometry: 414 Faces, 1108 Edges, 698 Nodes



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HLCRM AUTO SURFACE MESH STATISTICS

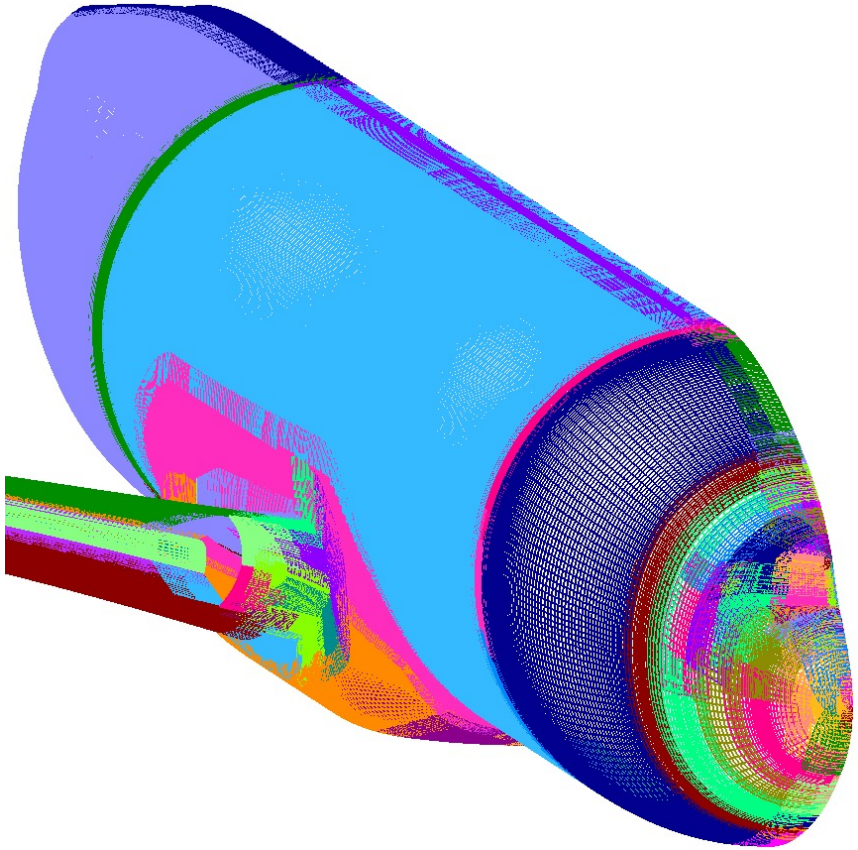
Single Component Runs

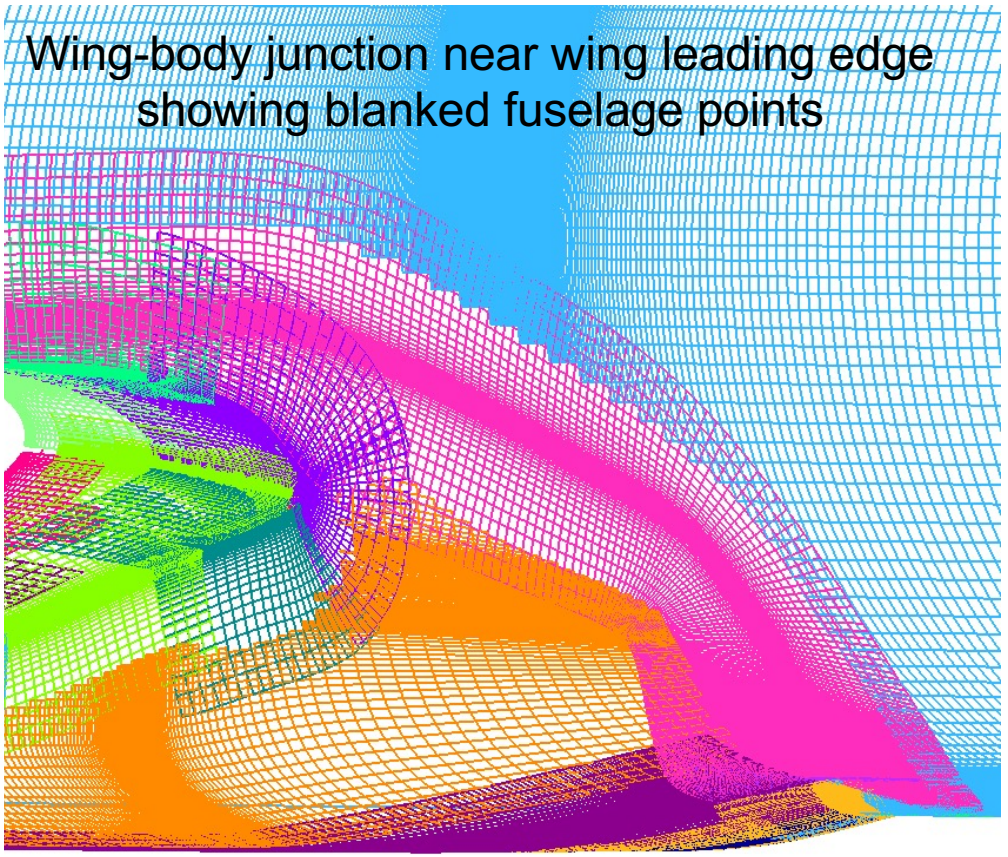
Component	# Meshes	# Mesh pts (x 10^6)	% Acceptable meshes	Wall clock time
Fuselage	123	0.63	99%	25 min 29 sec
Inboard Slat	59	0.18	85%	10 min 13 sec
Outboard Slat	147	0.91	87%	18 min 5 sec
Flaps + gaps	99	0.30	75%	12 min 14 sec
Pylon+Nacelle+Fin	74	0.61	89%	17 min 43 sec
Inboard Slat Bracs (x3)	95	0.17	85%	10 min 49 sec
Outboard Slat Bracs (x12)	426	0.51	84%	16 min 13 sec
Inboard Flap Track Fair.	176	0.25	94%	12 min 35 sec
Middle Flap Track Fair.	182	0.30	93%	12 min 44 sec
Outboard Flap Track Fair.	183	0.33	92%	14 min 26 sec
FTF Connectors (x3)	124	0.30	75%	10 min 6 sec
Wing	451	1.70	85%	59 min 20 sec
Complete HLCRM	413 (f)	2.70 (f)	100% (f)	44 min 16 sec (f)

(f) Face meshes only. Edge + node meshes in progress Manual meshing time ~ 1.5 – 4 months

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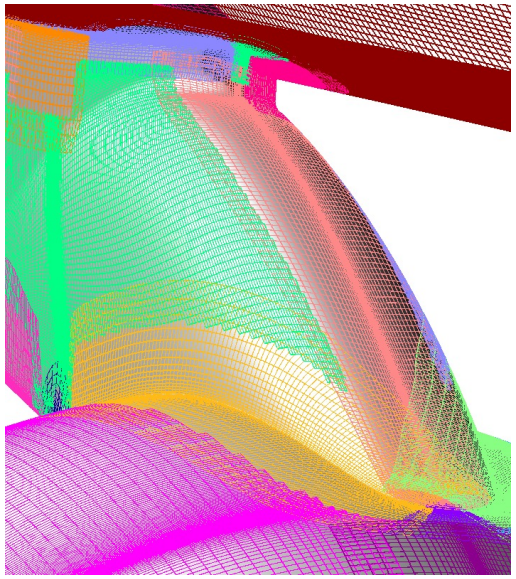
HLCRM: FUSELAGE



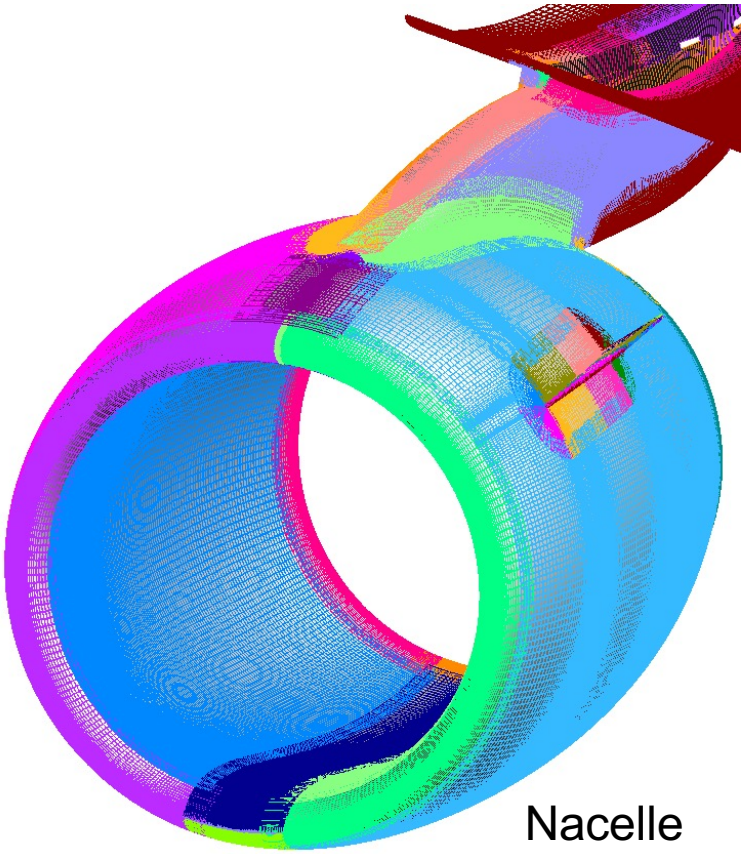


Ames Research Center

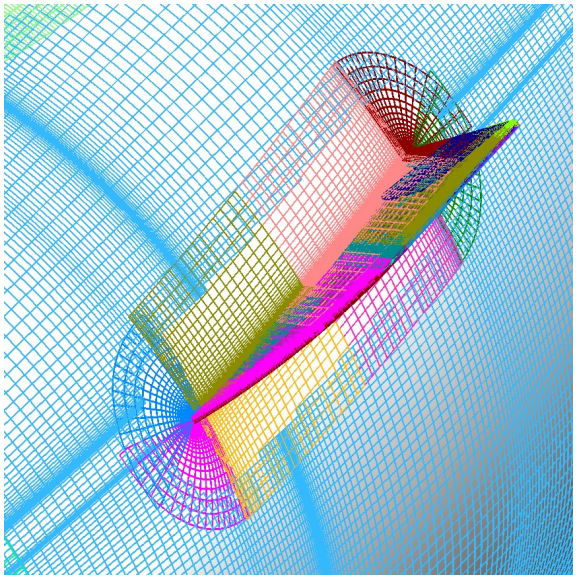
HLCRM: PYLON/NACELLE/FIN



Pylon



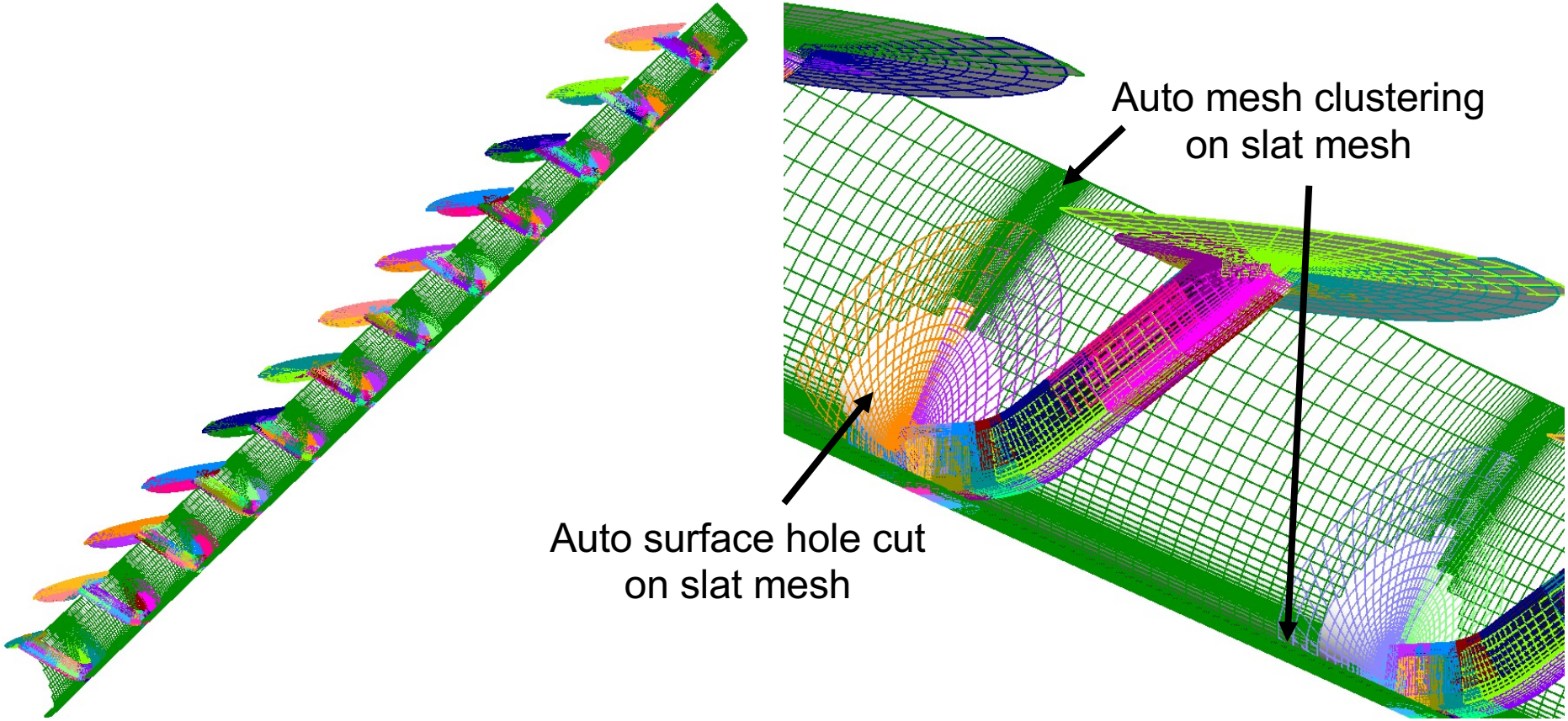
Nacelle



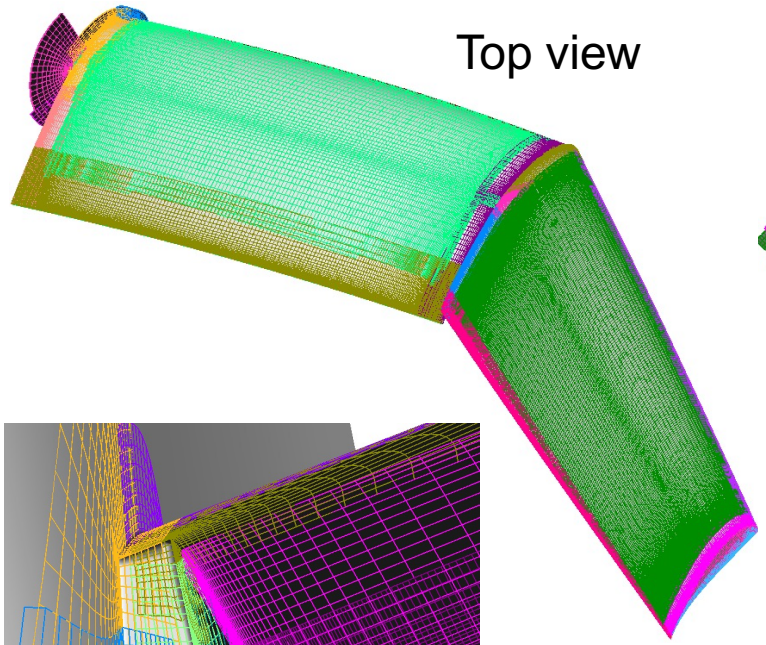
Fin

Ames Research Center

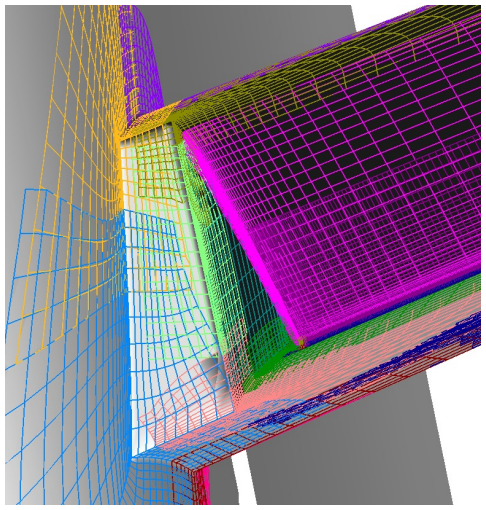
HLCRM: OUTBOARD SLAT BRACKETS



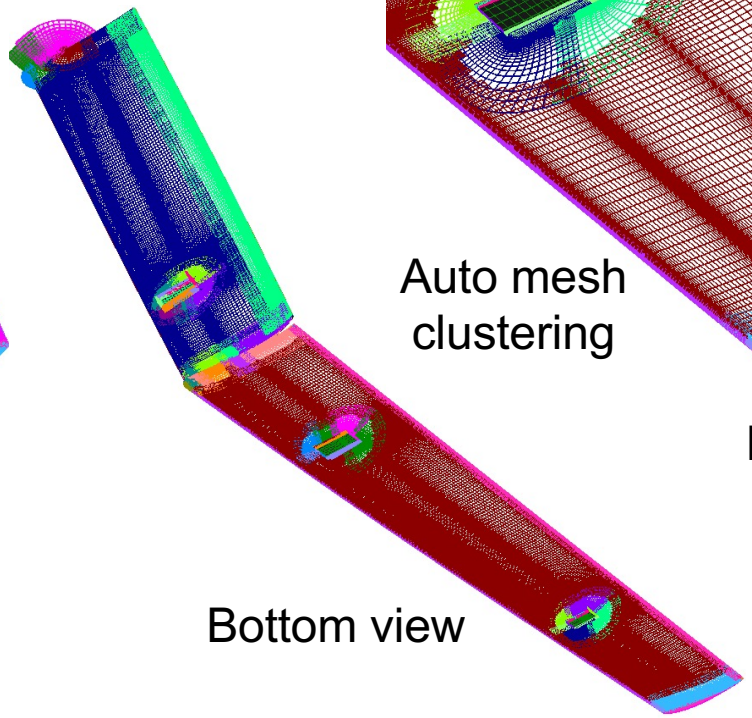
HLCRM: FLAPS



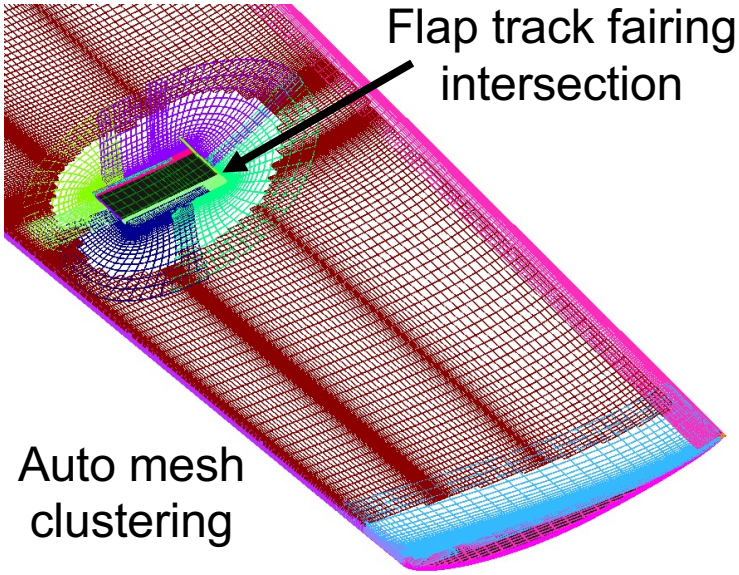
Top view



Inboard flap gap



Bottom view



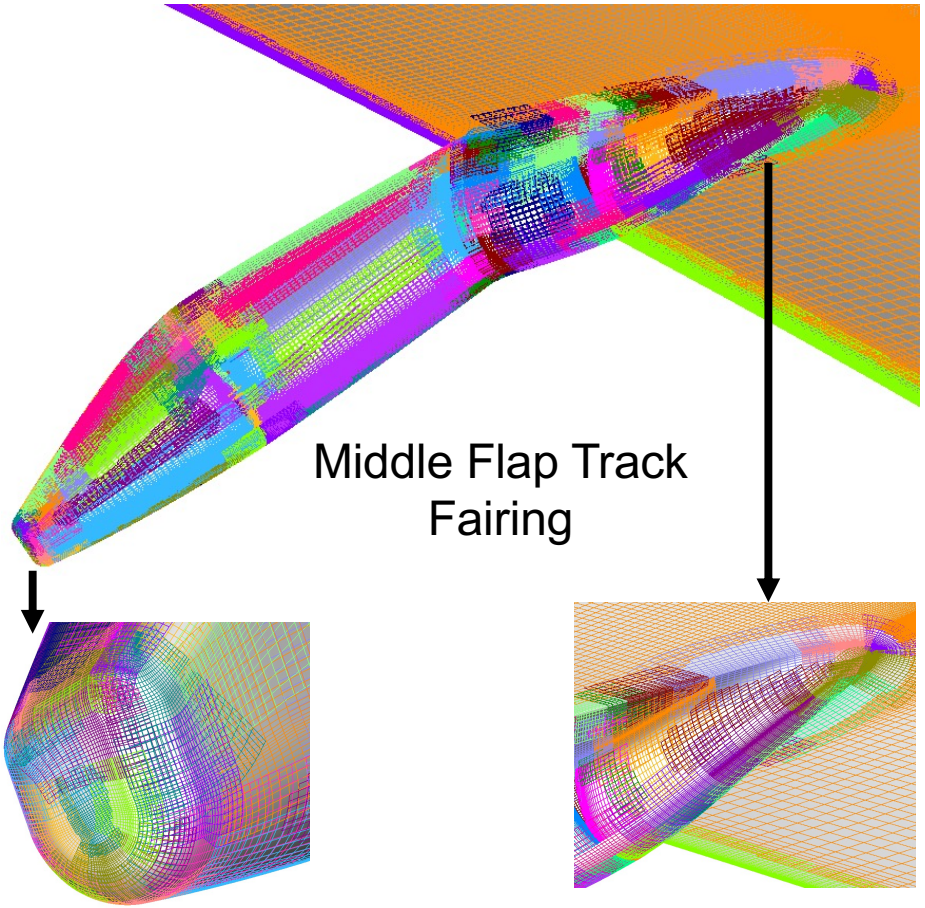
Flap track fairing intersection

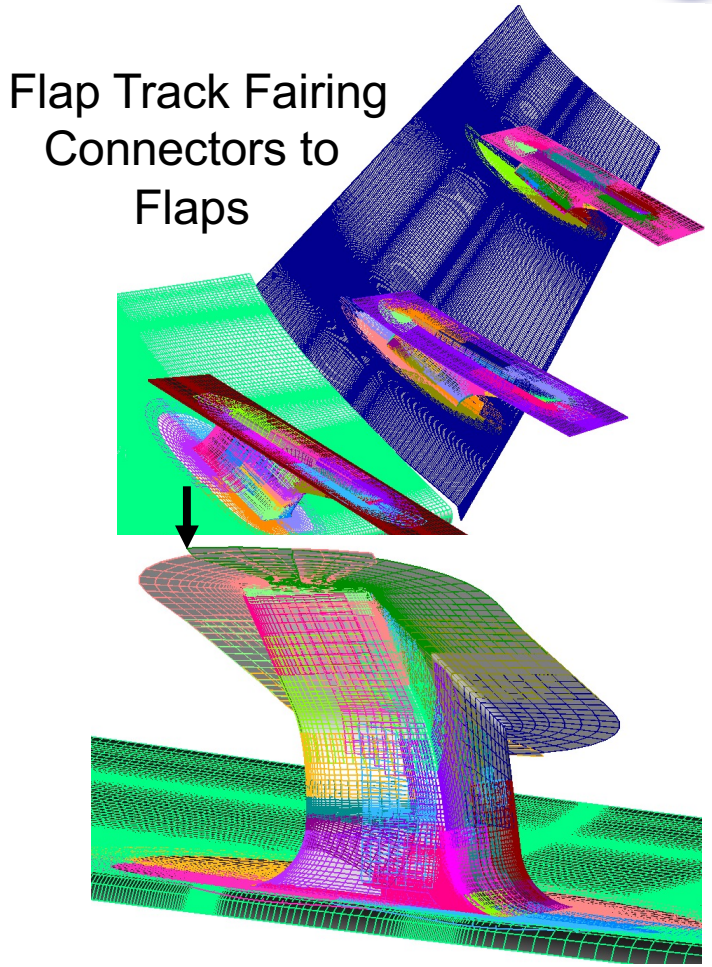
Auto mesh clustering

Bottom view near outboard tip

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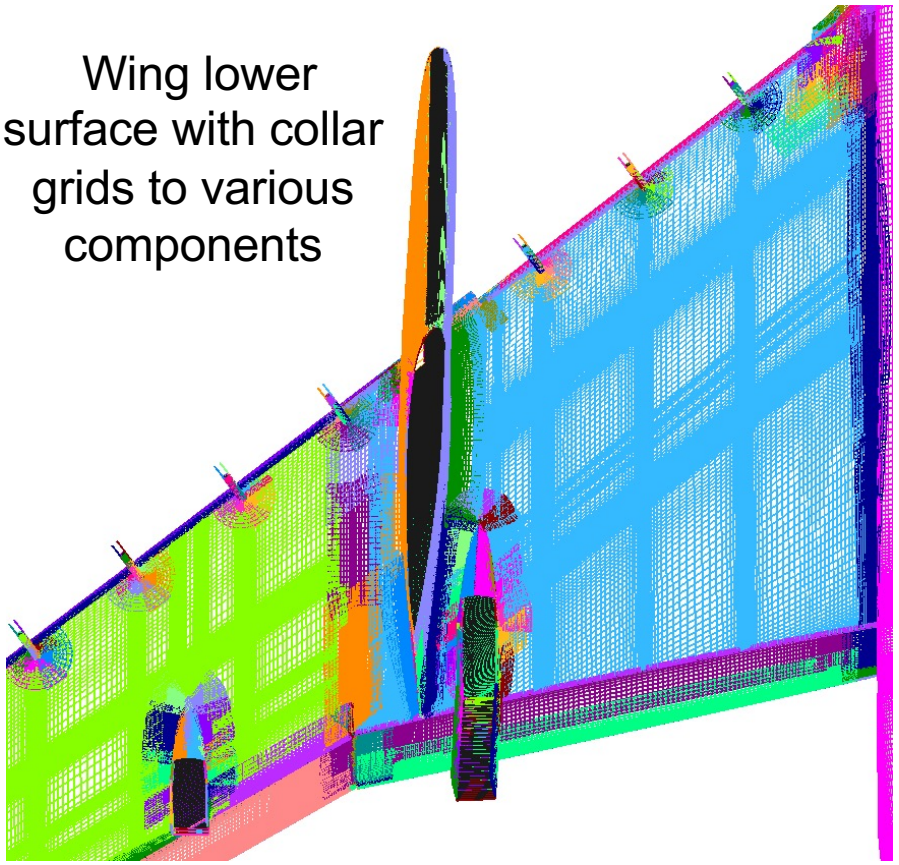
HLCRM: FLAP TRACK FAIRIINGS





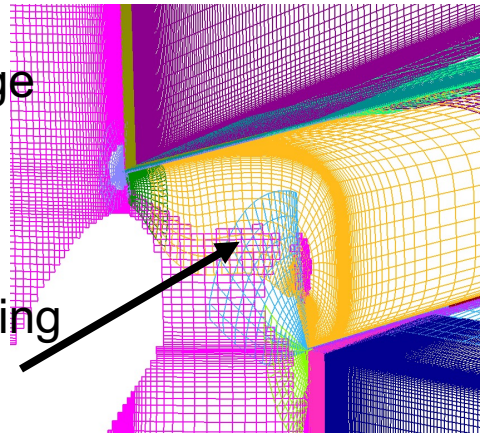
HLCRM: WING

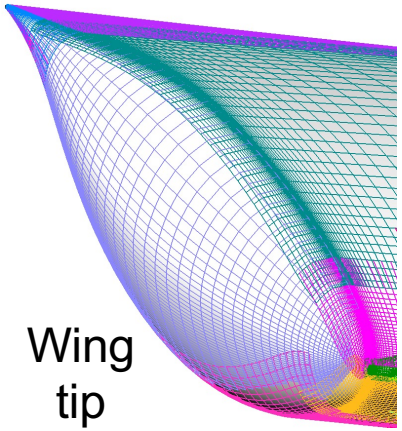
Wing lower surface with collar grids to various components



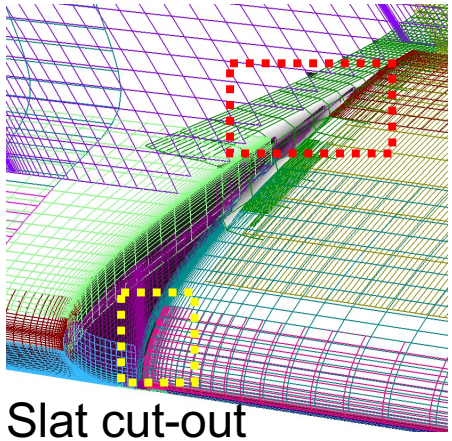
Fuselage

Wing root trailing edge cove





Wing tip



Slat cut-out

WORK IN PROGRESS AND CONCERNS

Work in progress

- About 95+% of unacceptable meshes - concave regions of hyperbolic meshes (challenge #5)
- Remaining unacceptable meshes - choice of Node mesh initial curve at saddle points or marching scheme selection
- Automatic surface mesh local refinement based on orphan point locations
- Volume mesh domain connectivity automation

Geometry Input Concerns

- BRep solid geometry not always available
- Poor choice of BRep topology from geometry construction
- Face parameter space not lined up with surface curvature
- Unnecessarily excessive number of Edges and Faces on smooth geometry

CONCLUDING REMARKS

- Automation scheme
  - Surface domain decomposition into face, edge, node meshes
  - Grid point distribution
  - Hyperbolic / algebraic meshes
  - Domain connectivity (surface and volume)
  - Flow solver and post-processing input file generation
- Recent features: open boundary geometries, component specification
- Two software modules: egads2srf, pogs (internal testing only)
- Successful application to a variety of aeronautical vehicles
- Percentage of acceptable auto-generated meshes (75% - 100%)
- Significant reduction in manual effort and time: hybrid auto and manual meshes (weeks/months -> days, days -> hours)

ACKNOWLEDGEMENTS

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NASA Revolutionary Vertical Lift Technology (RVLT) Project

Computational Resources

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