RECENT DEVELOPMENTS IN BOUNDARY COUPLING FOR HYPERBOLICALLY GENERATED OVERSET GRIDS

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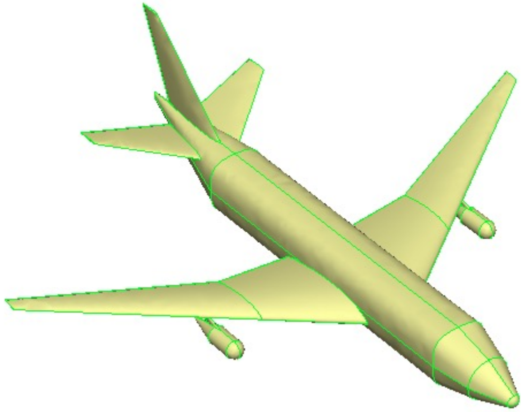
INTRODUCTION

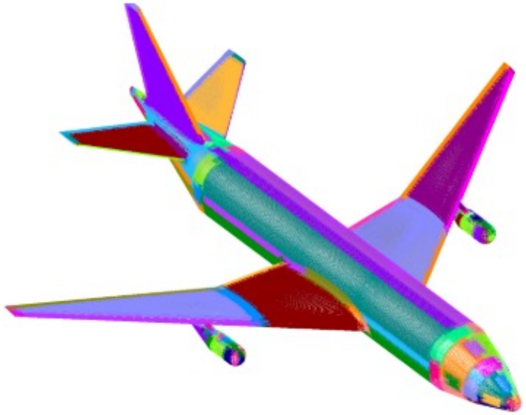
- Overview of Automatic Grid Generation
- Loosely Coupled Boundary Conditions (LCBC)
  - Surface Mesh Coupling
  - Volume Mesh Coupling
  - Face Mesh Reconstruction
- Investigation of Solution Runs with Automatic Meshes
- Concluding Remarks

AUTOMATIC OVERSET MESH GENERATION (1)

- Structured overset mesh generation is an exceedingly tedious task
- Recent advances made in automation [1,2]
- Surface mesh generated for each face, edge, node of Boundary Representation (BRep) solid
- Significant reduction in time and effort (~weeks/days to ~days/hours)



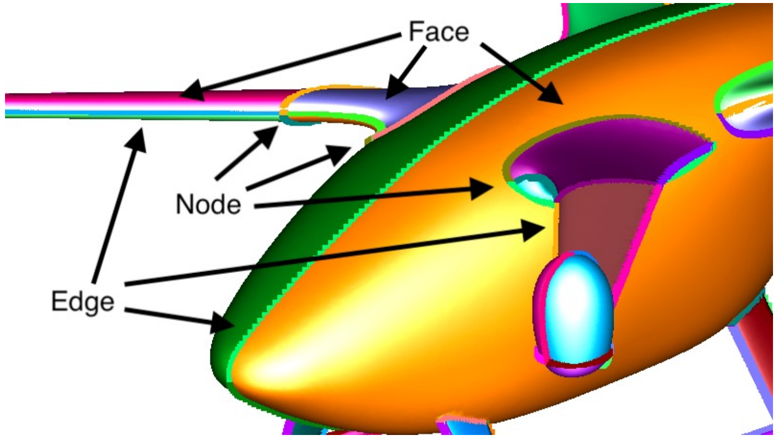
BRep solid of generic airplane



Auto generated surface mesh of airplane

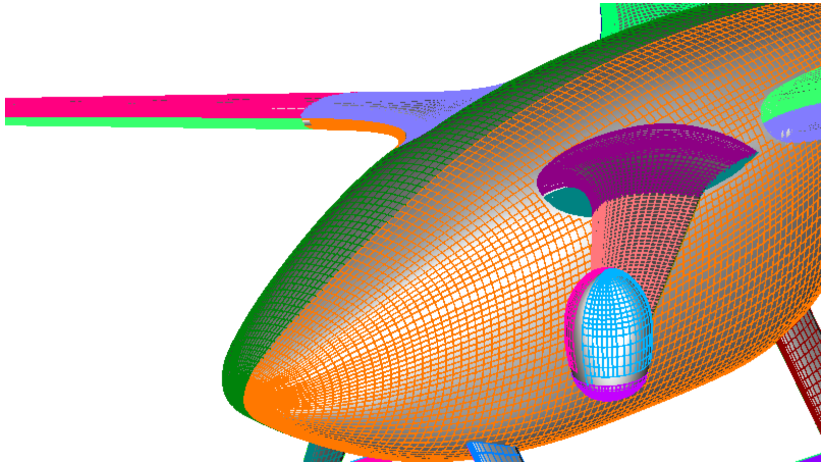
1. **Chan, W. M., Pandya, S. A., and Haimes, R., "Automation of Overset Structured Surface Mesh Generation on Complex Geometries", AIAA Paper 2019-3671, June 2019. https://doi.org/10.2514/6.2019-3671.**
2. **Chan, W. M., Pandya, S. A., & Chuen, A. M, "Automation of Overset Structured Mesh Generation on Boundary Representation Geometries", AIAA Paper 2022-3607, June 2022. https://doi.org/10.2514/6.2022-3607.**

AUTOMATIC OVERSET MESH GENERATION (2)

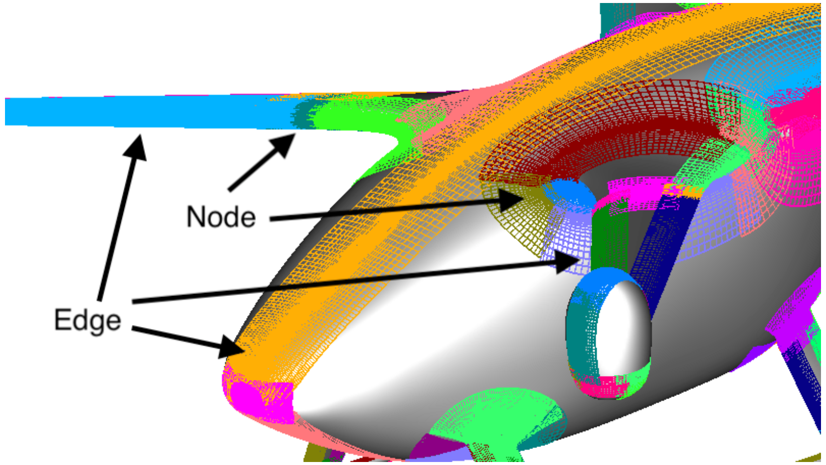


BRep Faces, Edges, Nodes

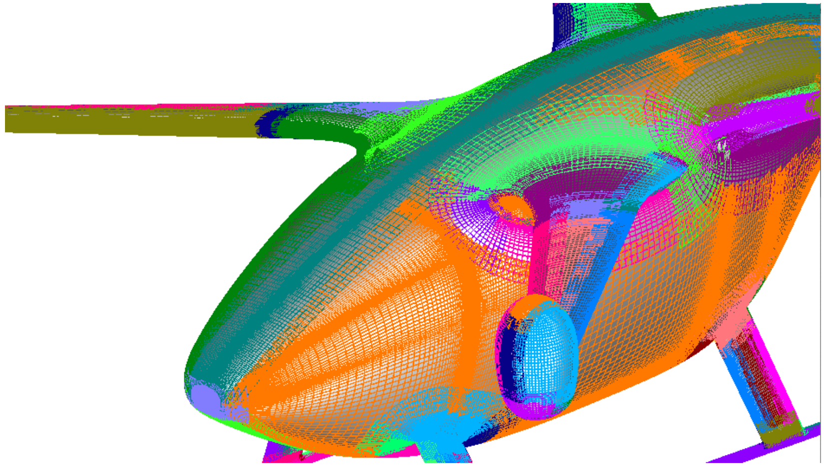
Surface Domain Decomposition → Surface Mesh Generation →



Face Meshes



Edge & Node Meshes



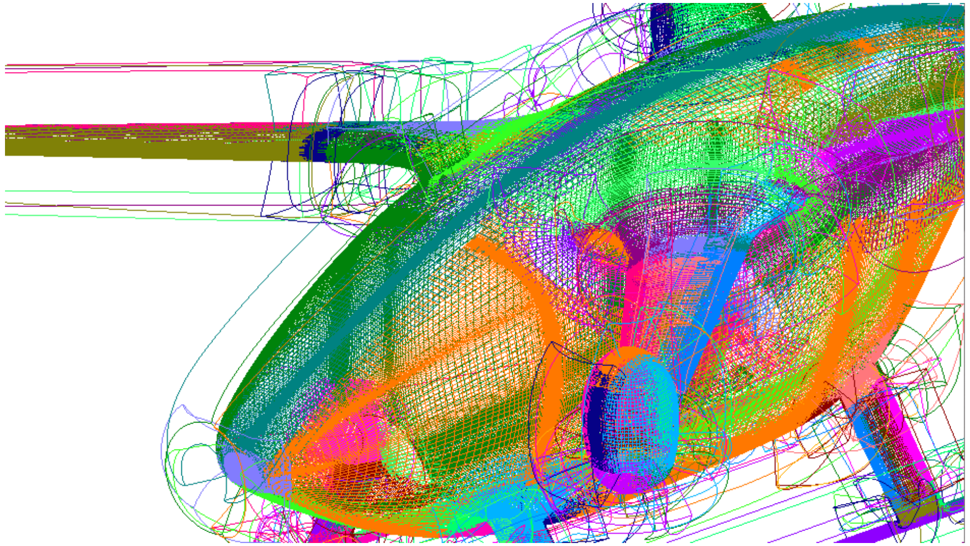
Surface Mesh

AUTOMATIC OVERSET MESH GENERATION (3)

Volume Meshing

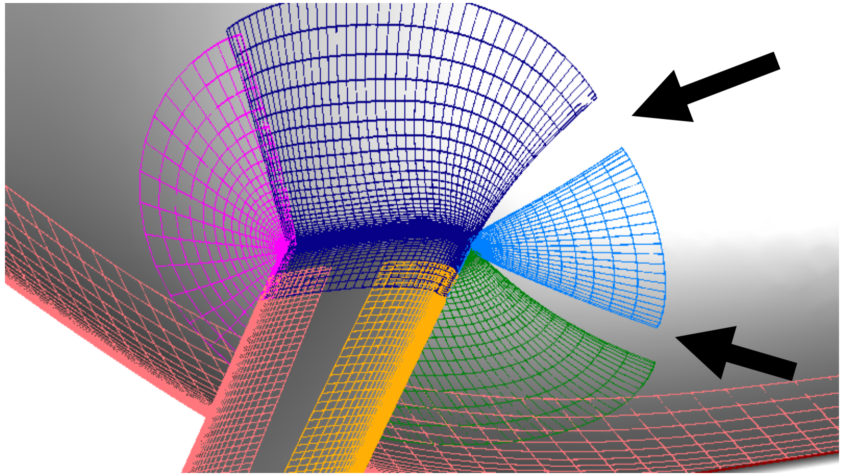
Domain Connectivity

Flow Solver Input Generation

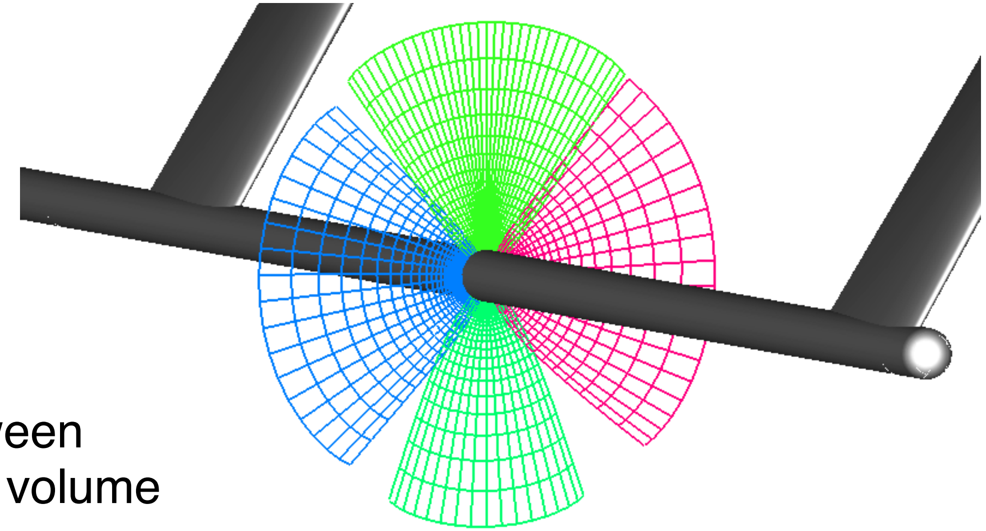


Volume Mesh

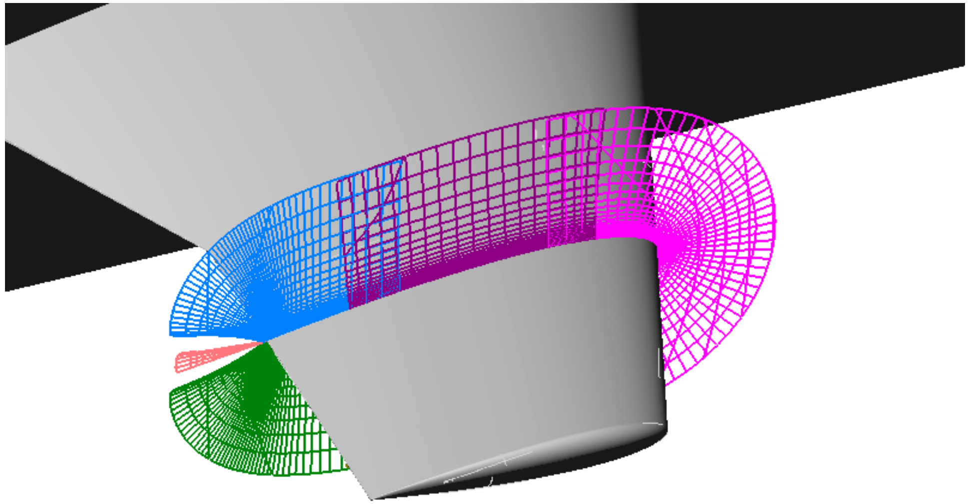
OVERLAP ISSUES IN HYPERBOLIC SURFACE & NEAR-BODY VOLUME MESHES



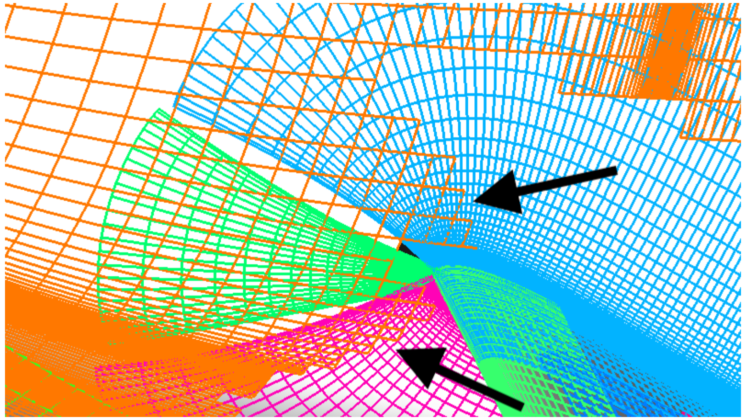
Gaps from splay between hyperbolic collar meshes with overlapping initial curves



Gaps between hyperbolic volume meshes

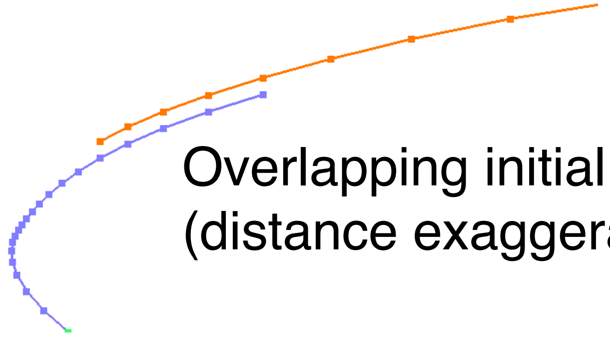


Face mesh (orange) filling in gaps between collar meshes

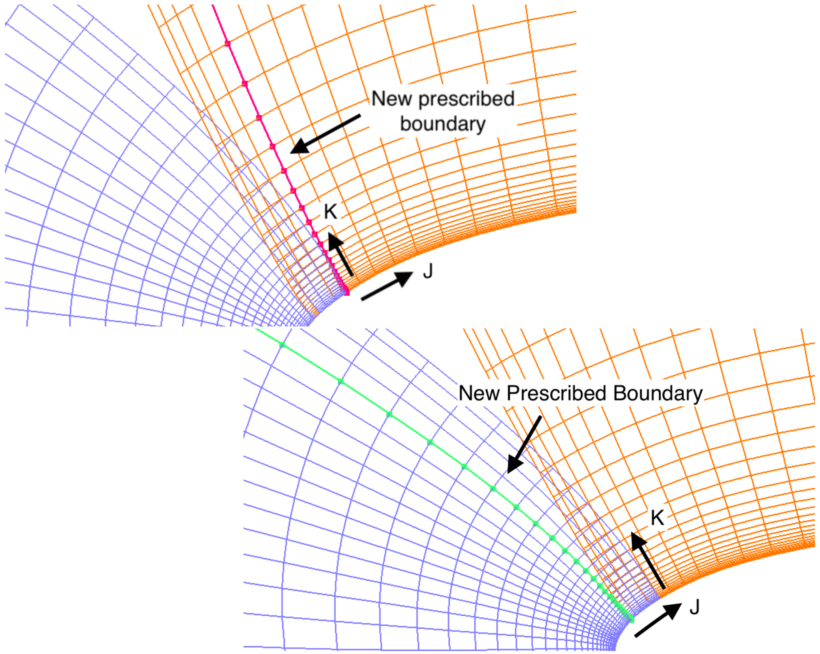


LOOSELY COUPLED BOUNDARY CONDITIONS

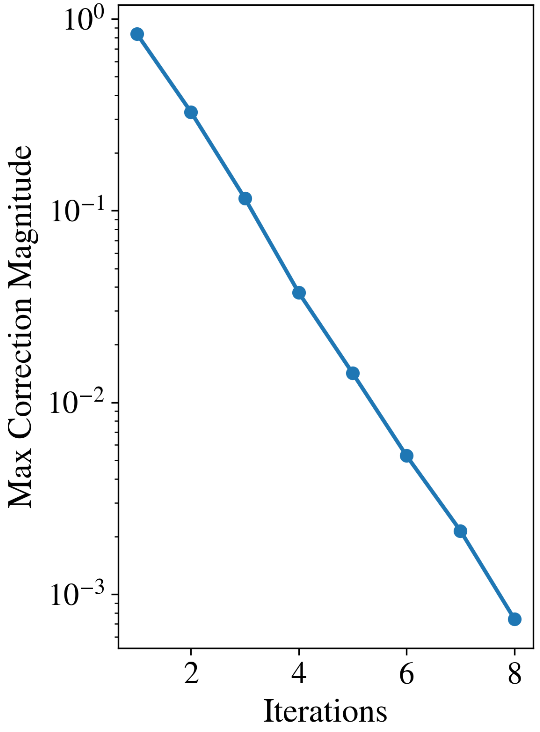
- Hyperbolic grids coupled to neighbors through forced boundaries along marching direction
- Boundaries follow internal grid line of neighbors

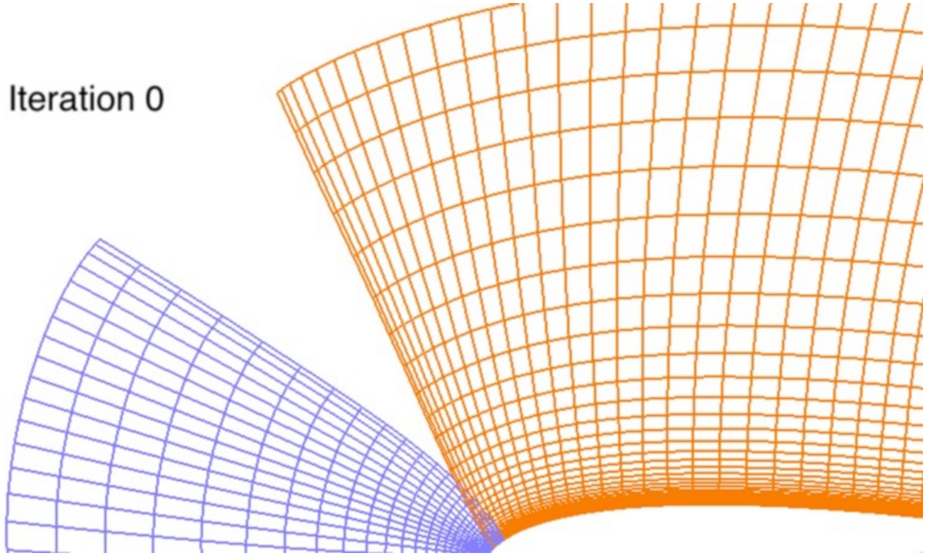


Overlapping initial curves (distance exaggerated)



Magenta/green boundary curve extracted for blue/orange mesh





5 pt overlap maintained across marching direction at final iteration

3. Chuen, A. M., & Chan, W. M., "Overlap Preservation Using Loosely-Coupled Boundary Conditions for Body-Fitted Structured Overset Grids", AIAA 2022-0216, January 2022. https://doi.org/10.2514/6.2022-0216

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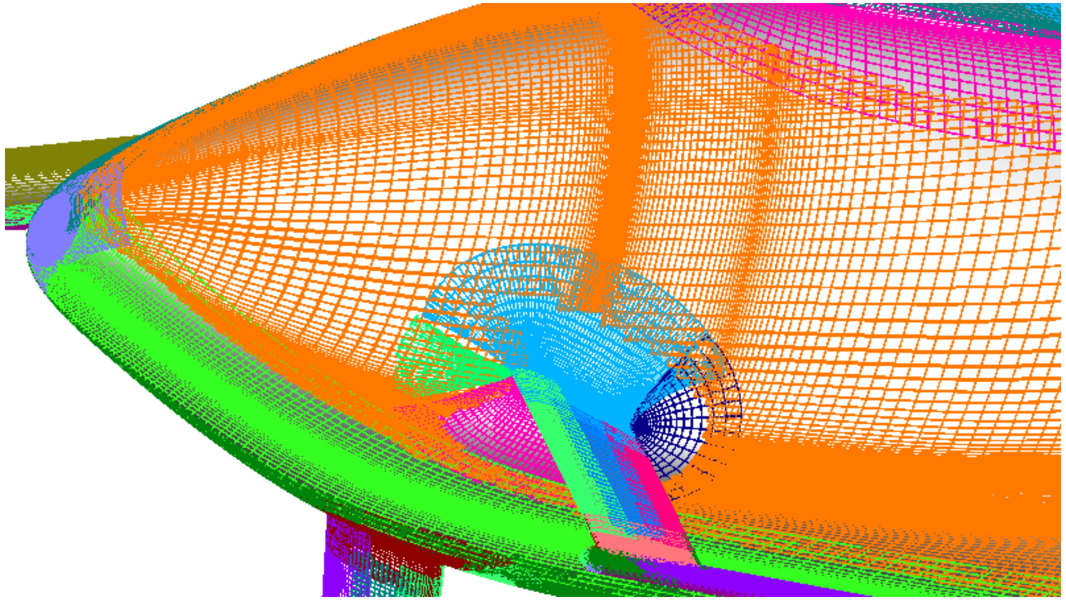
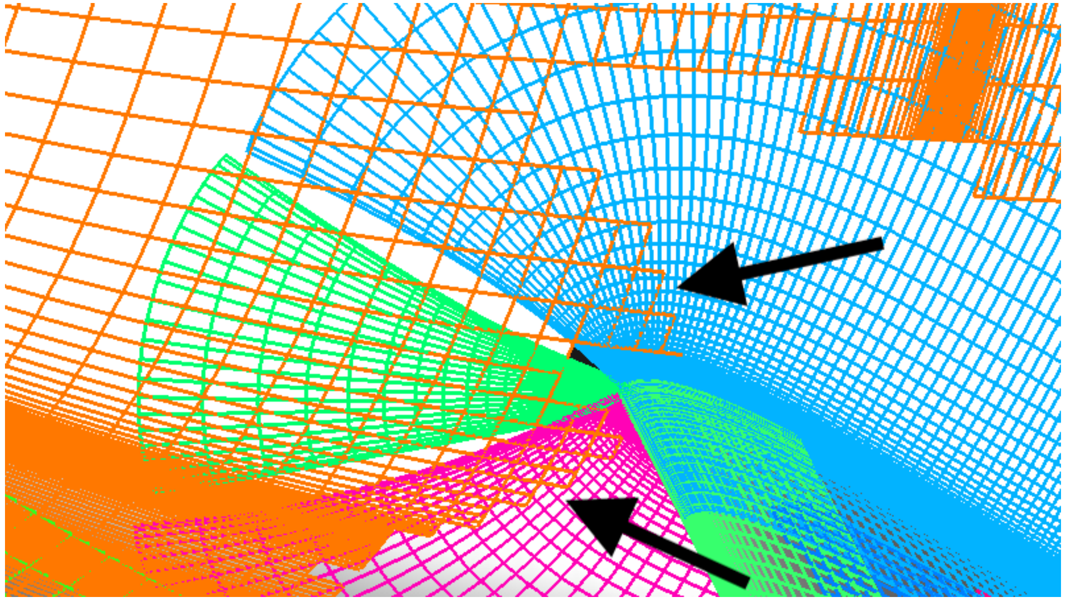
6-PAX QUAD SURFACE MESH – WITHOUT LCBC

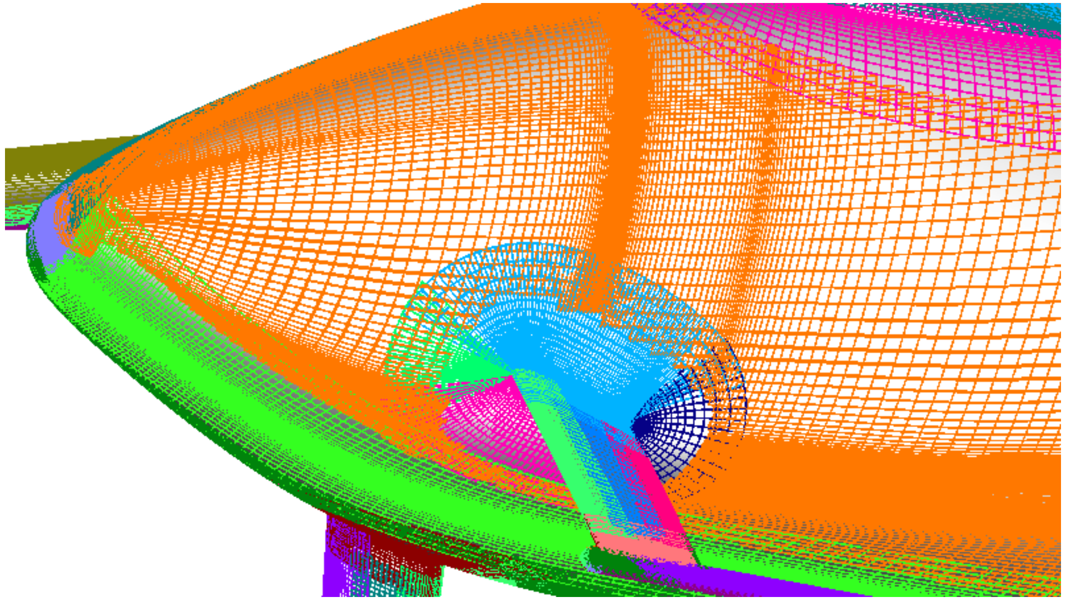


Hyperbolic meshes generated around strut-body junction

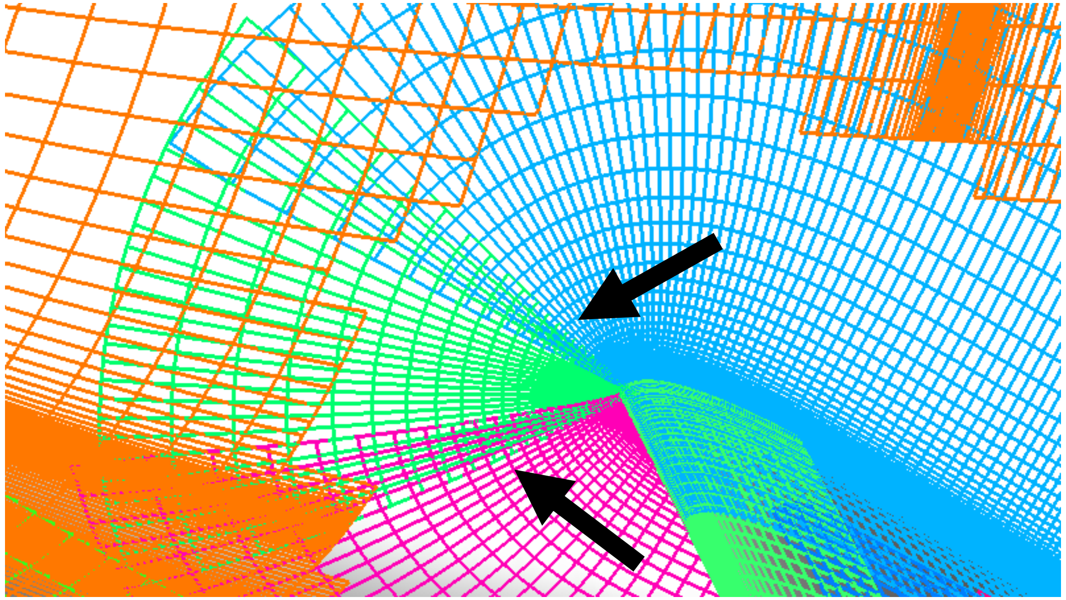


Coarser face meshes forced into gap between hyperbolic meshes

6-PAX QUAD SURFACE MESH – WITH LCBC



Hyperbolic meshes generated around strut-body junction

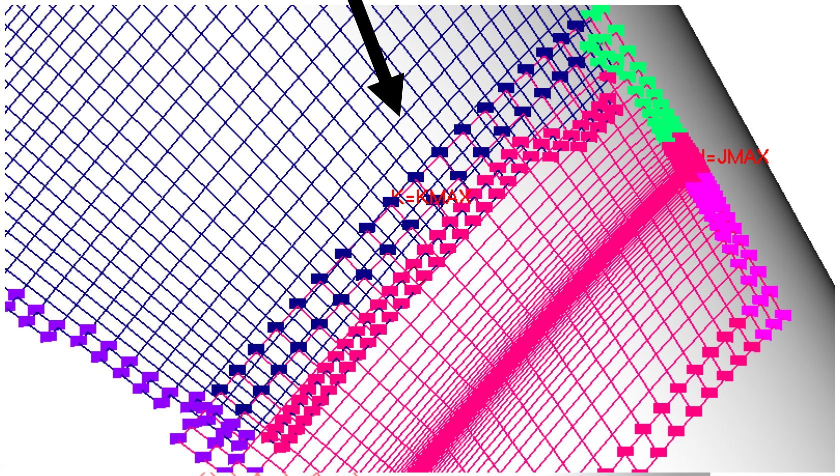


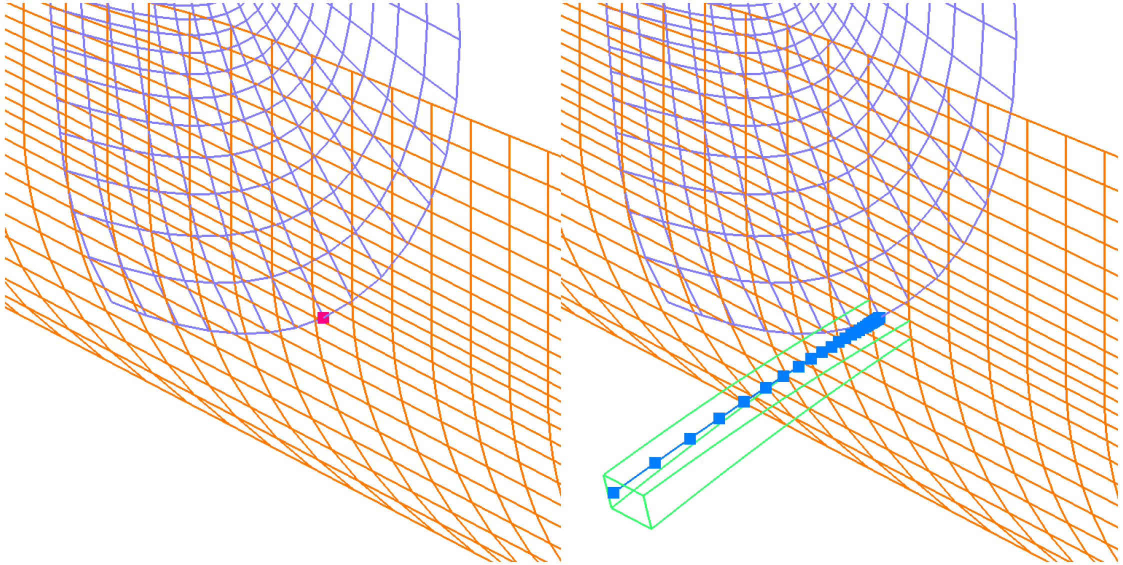
Coarser face meshes can be retracted from overlap region

LCBC FOR VOLUME MESH GENERATION

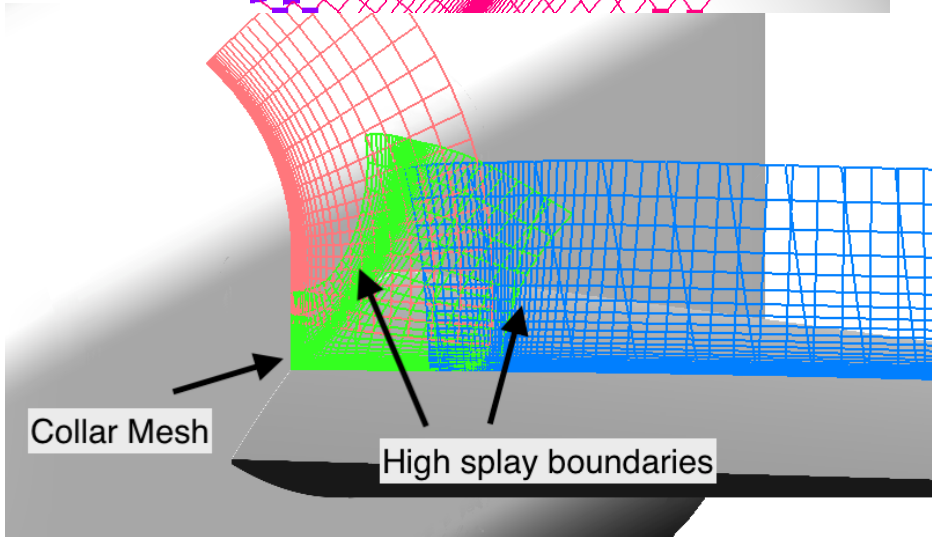
- Increased complexity due to additional deg. of freedom & overlap w/ multiple grids
- Requires surface domain connectivity
- Collar meshes are excluded from LCBC

Coupling occurs at all four boundaries of initial surface



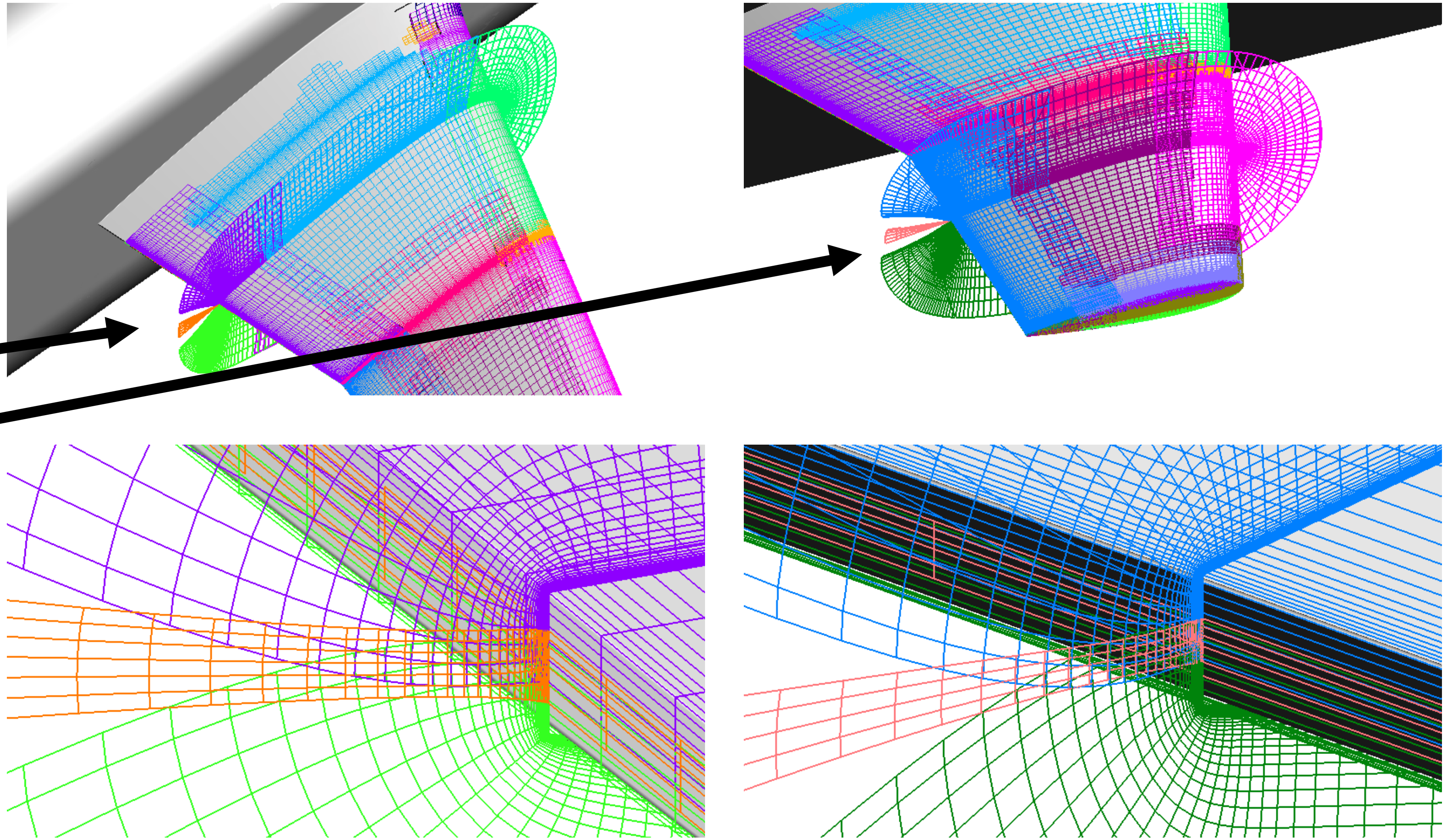


Boundary curve from orange mesh applied to blue mesh fringe-point boundary



JUNCTURE FLOW MODEL WING – WITHOUT LCBC

Y = 550 Y = 1150



Large gaps develop in trailing edge wake

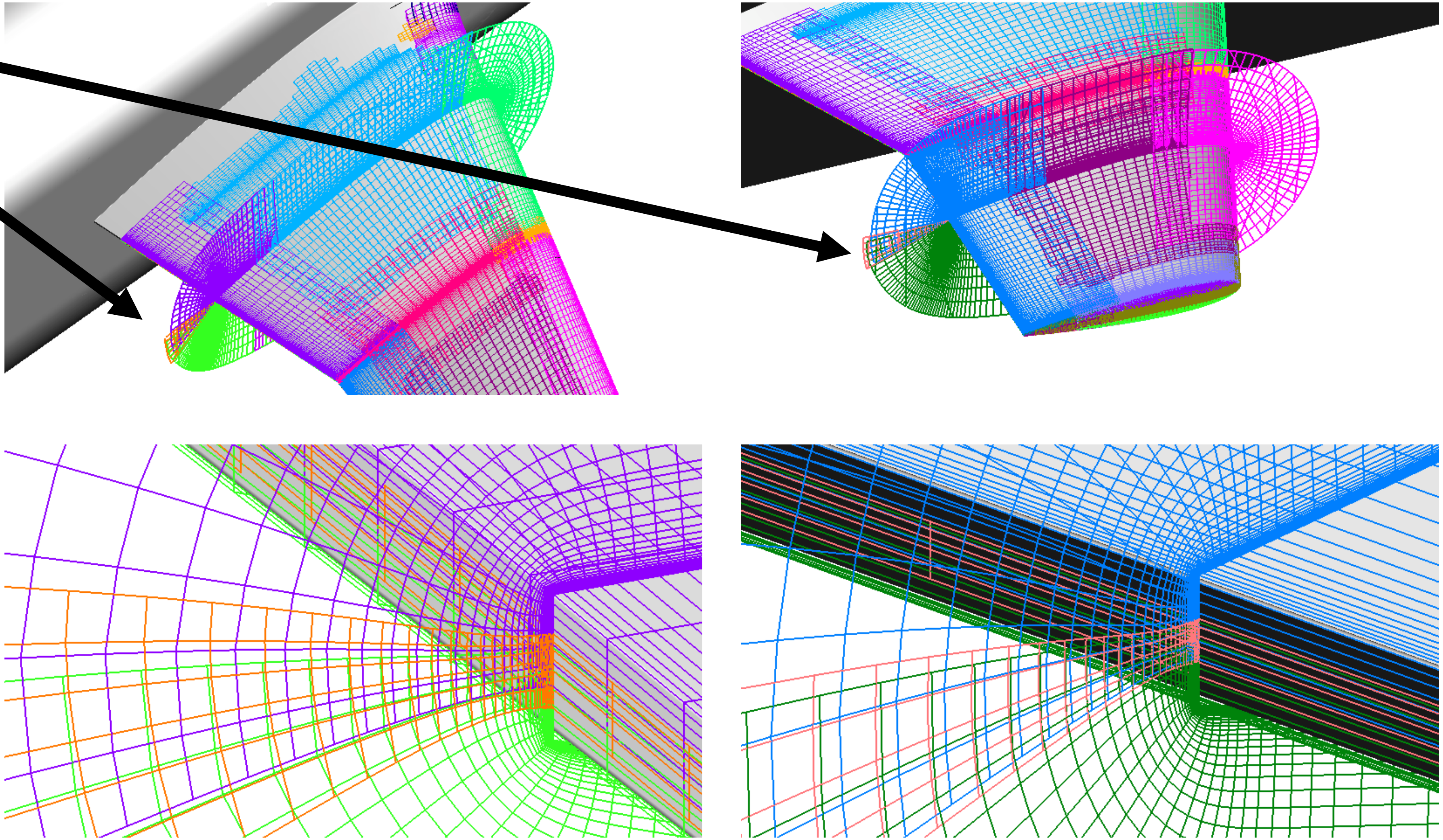
Mesh divergence occurs near-wall in wake

JUNCTURE FLOW MODEL WING – WITH LCBC

Y = 550

Y = 1150

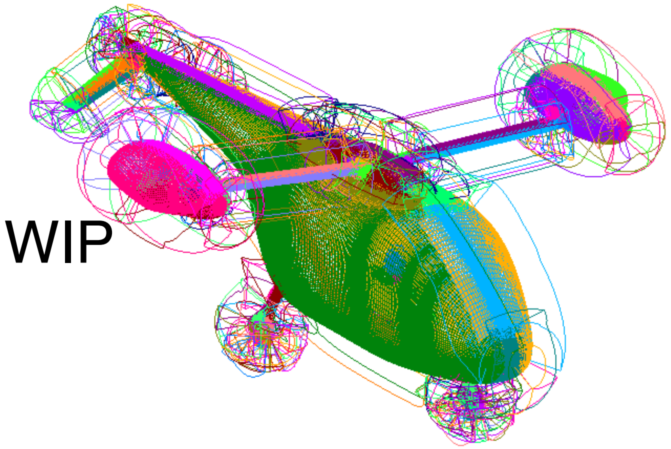
Trailing edge gaps are closed

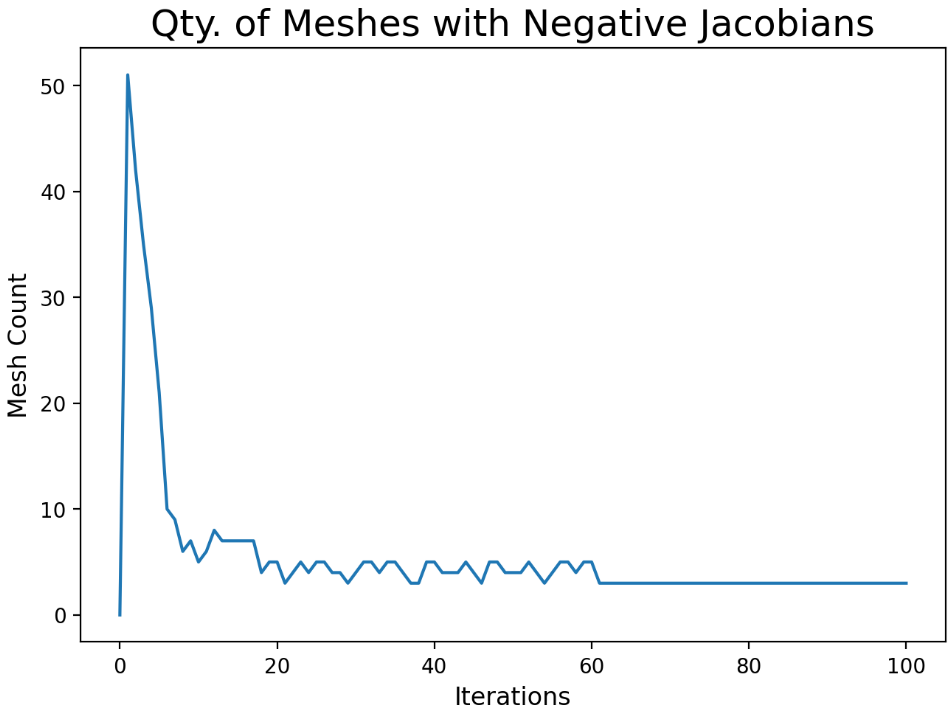


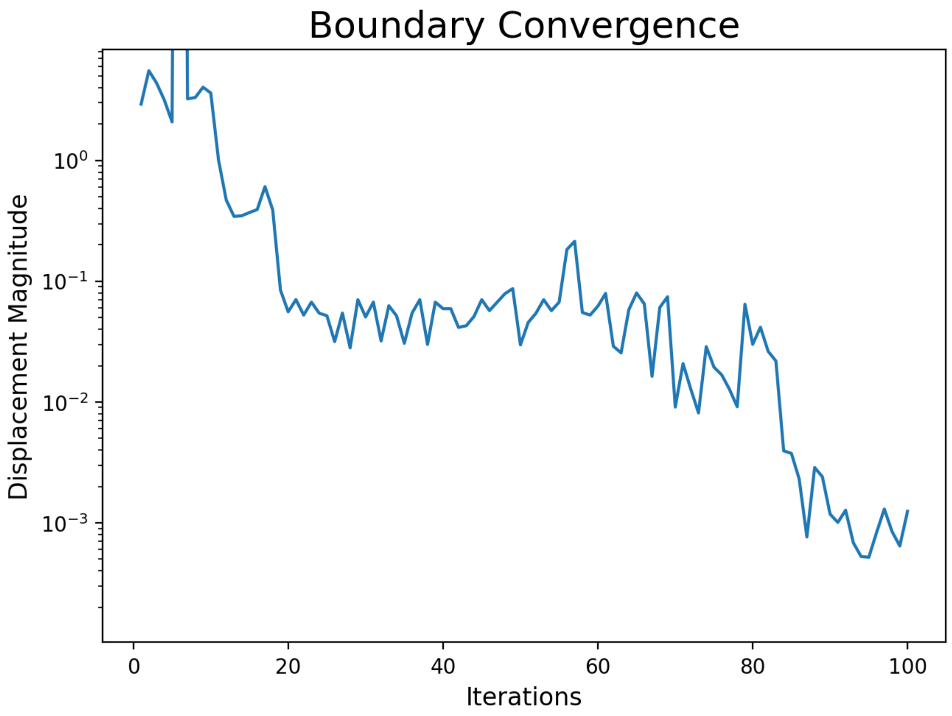
Overlap consistent with initial surface maintained across marching direction

VOLUME MESH LCBC CONVERGENCE BEHAVIOR

- Side-By-Side Hybrid Vehicle
- 100 iterations, 7.8 h wall time (2019 MacBook Pro)
- Algorithmic improvements to reduce wall time/convergence is WIP
- Convergence more difficult due to more deg. of freedom & complex boundaries

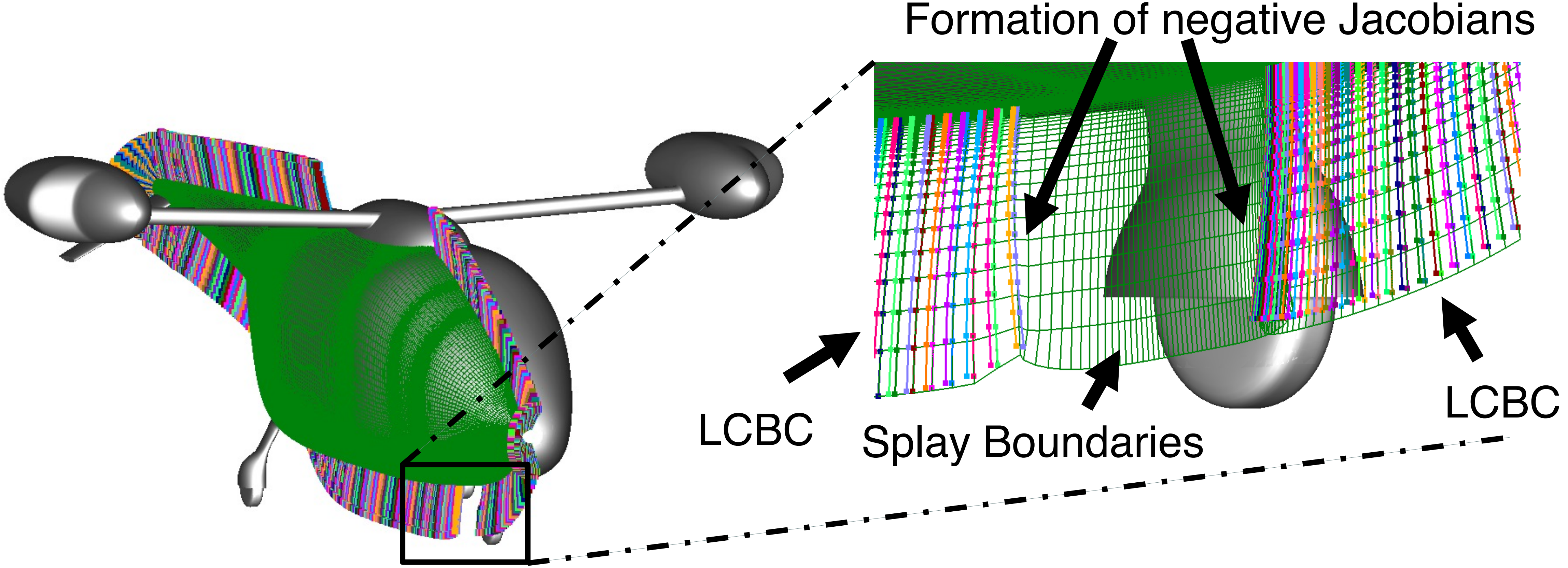






SOURCES OF CONVERGENCE DIFFICULTY

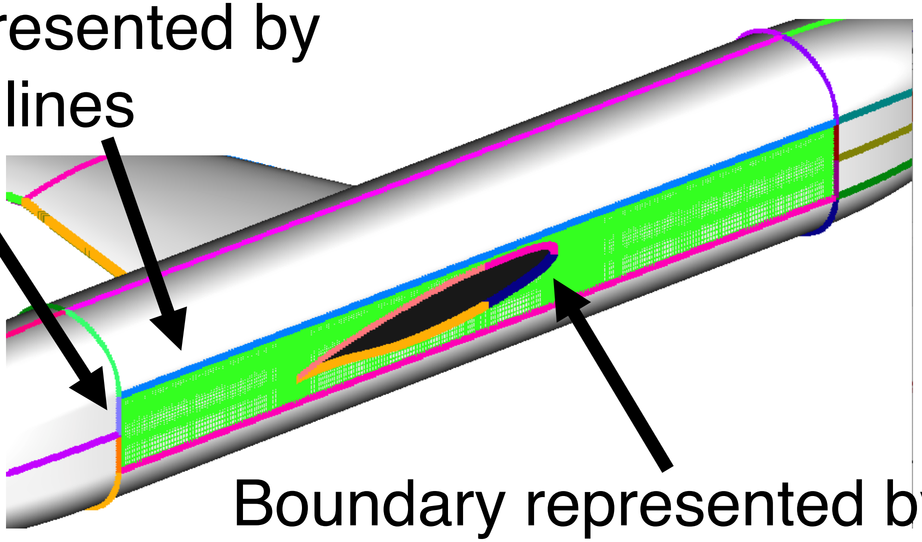
- Mix of LCBC and splay at hole boundaries can affect convergence
- Current investigations ongoing to evaluate best approach to treat hole boundaries



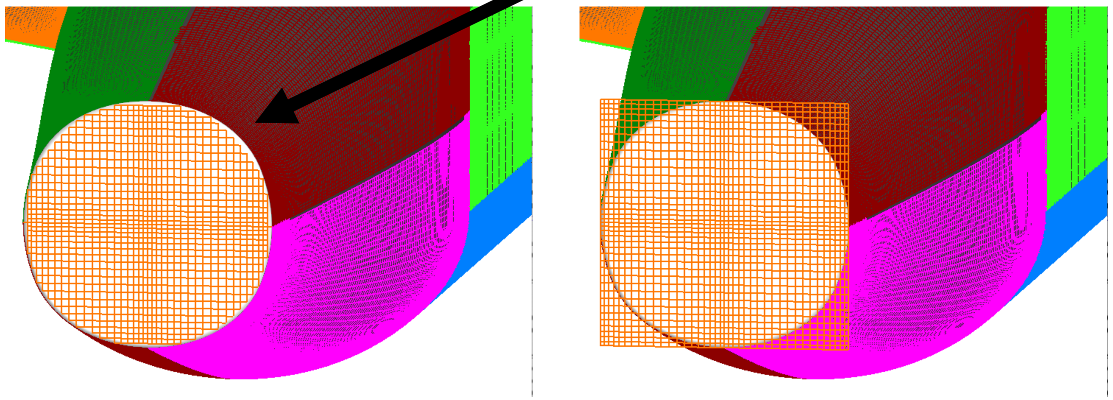
FACE MESH BOUNDARY REPRESENTATION

- Some boundaries on face mesh only represented by IBLANKS (on/off geometry) but not by discrete parametric (grid) lines
    1. **Junction regions** (e.g. wing roots, tail roots, etc.)
    2. **Trimmed faces** (e.g. wing tips, blunt tails, etc.)
- Non-isoparametric boundaries <u>not compatible</u> with LCBC, esp. **trimmed faces**
- Junction regions not an issue due to no coupling at collar meshes

Boundary represented by isoparametric lines



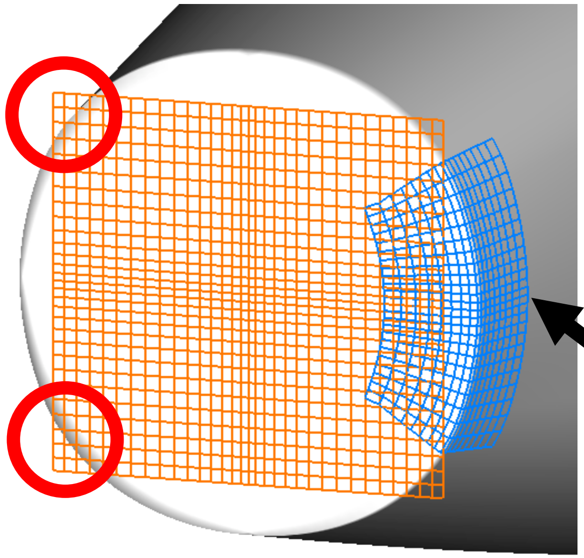
Boundary represented by non-isoparametric lines

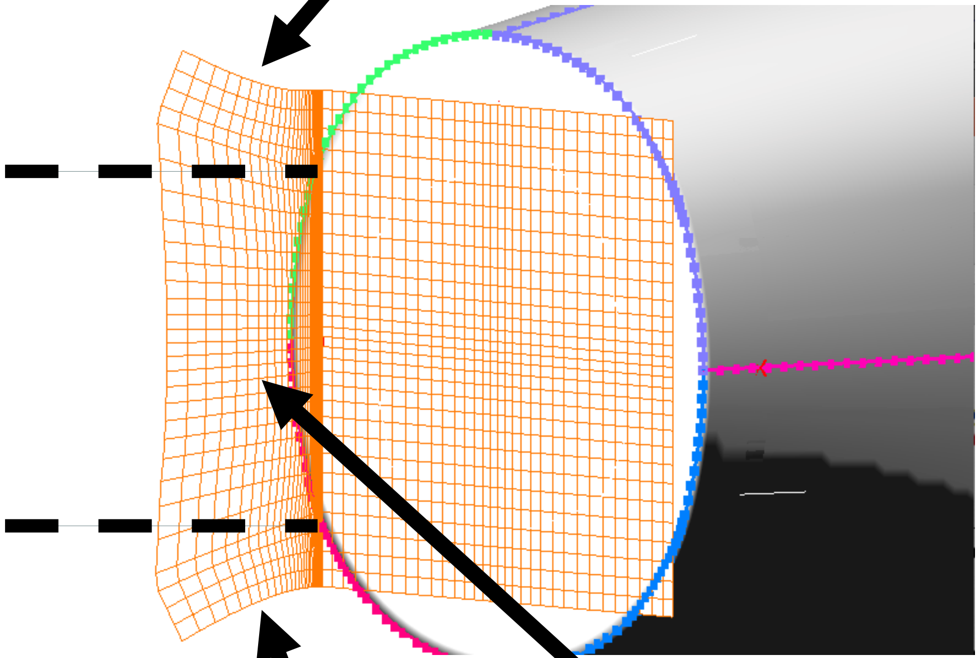


Trimmed face   Untrimmed face

LCBC AND FACE MESH BOUNDARIES

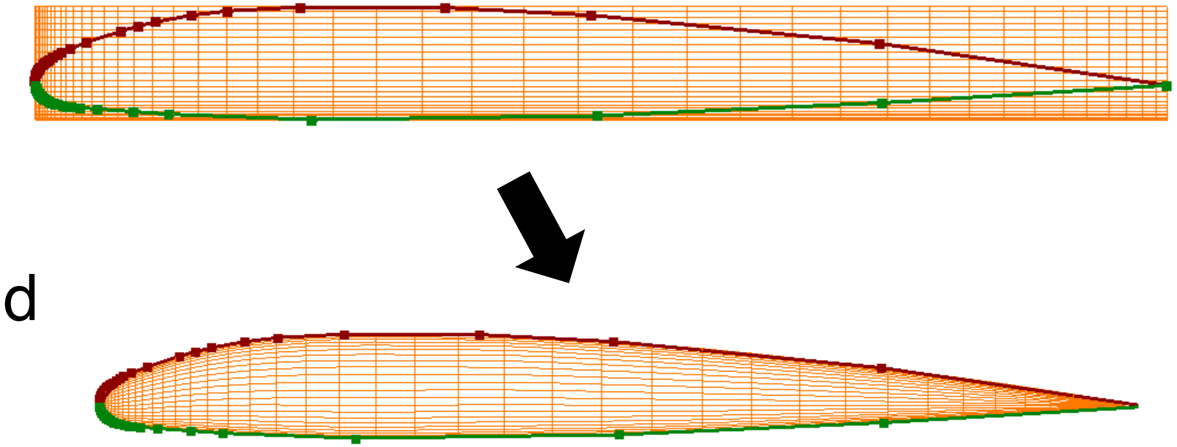
- Hole/trimmed regions do not correspond with real geometry
- If LCBC is applied, negative Jacobians/cell volumes can be introduced into hole/trimmed regions



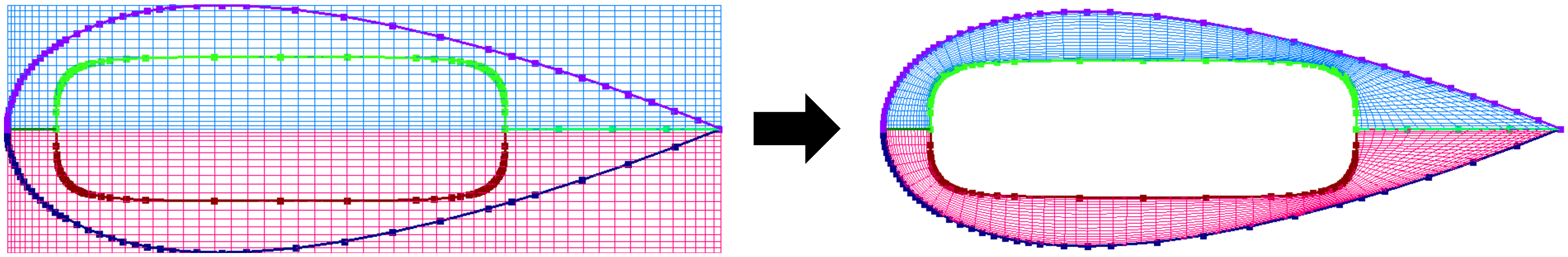


FACE MESH RECONSTRUCTION

- Rebuild face mesh such that external boundaries lie on or within bounding curves
- Along longer dimension, retract normal grid line to within boundary
- Do Transfinite Interpolation (TFI) if face mesh is bounded by 4 non-degenerate edge curves

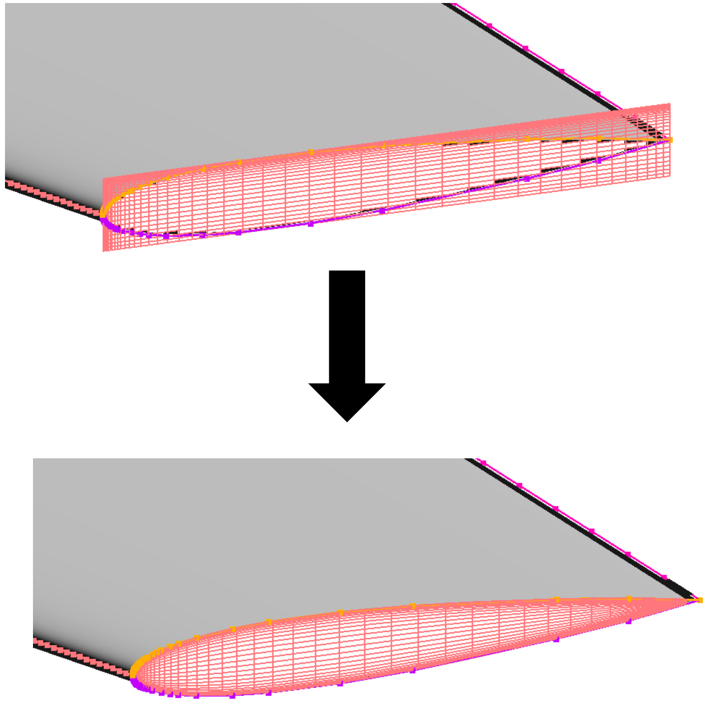


General Reconstruction

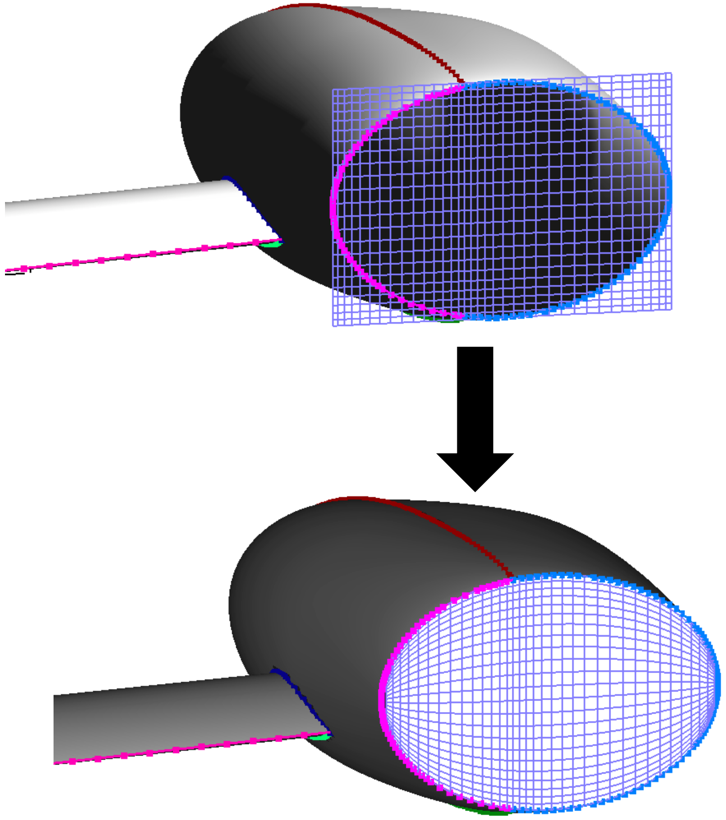


TFI Reconstruction

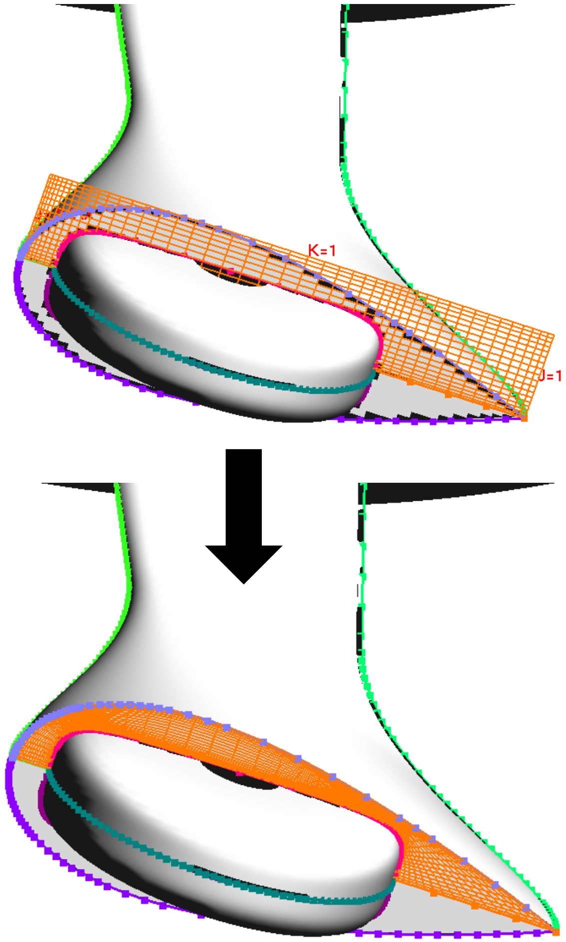
FACE MESH RECONSTRUCTION EXAMPLES



Wing Tip Face



Engine Fairing Tail



Landing Gear

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HYBRID SEMI-AUTOMATIC GRID GENERATION

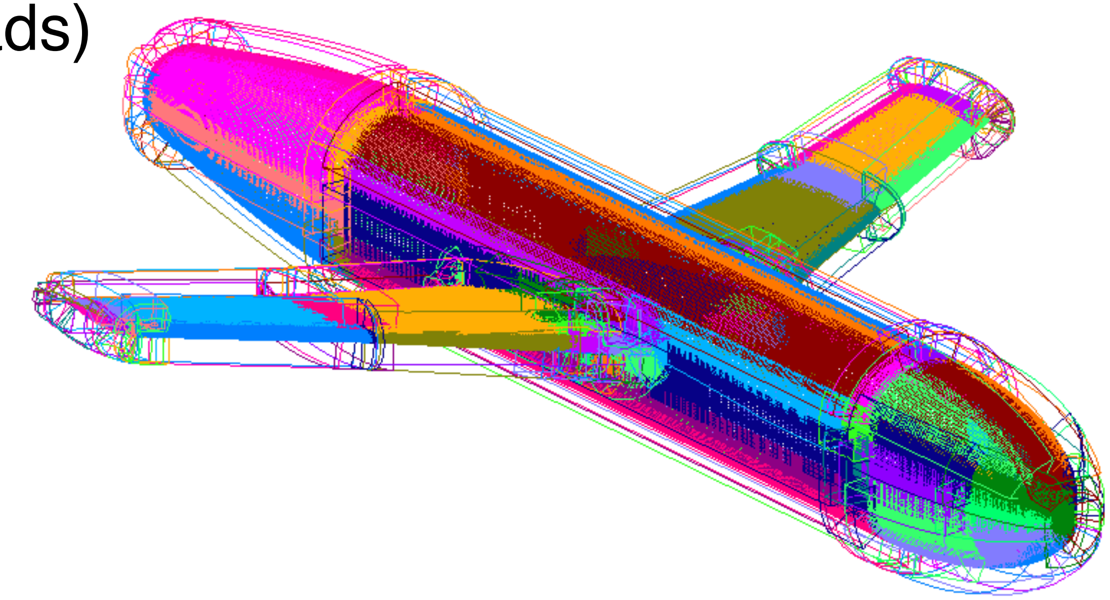
- Hybrid approach uses auto-generated meshes followed by manual repairs on a few defective meshes
- Flow solutions can now be computed on resulting meshes
- How do auto meshes affect accuracy, convergence, efficiency?

Automated Steps	Manual Steps
• Surface Mesh Generation • Volume Mesh Generation • Flow Solver Input File • Aero-loads Computation Input File	• Hole Cutting/Domain Connectivity* • Negative Jacobian volume mesh repair

*Work still underway in automating domain connectivity along with mesh generation

GRID GENERATION – JUNCTURE FLOW MODEL (JFM) F6 WING

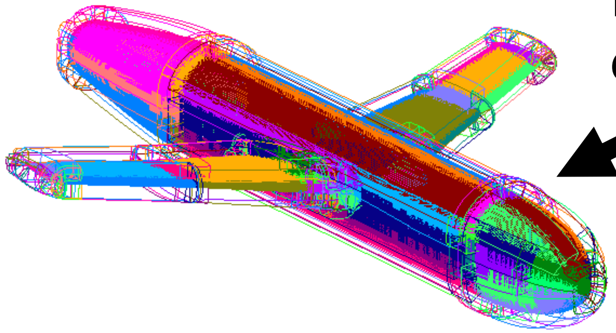
- Auto surface and volume mesh w/ LCBC (2.5 h, 2019 MacBook Pro, 10 OMP threads)
    - Surface Mesh: 4 min 33 s
    - Volume Mesh: 40 s
    - Volume Mesh LCBC: 2.5 h
- Manual steps (~2 hrs):
    - Collar mesh repair (10 meshes)
    - Regenerate coupled meshes for overlap improvement (9 meshes)
    - XRAYS for hole-cutting with DCF



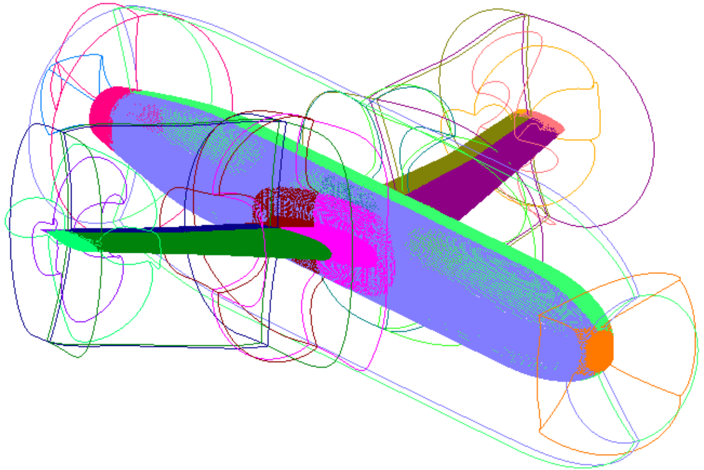
Automatically generated volume mesh

GRID COMPARISONS – JFM F6 (1)

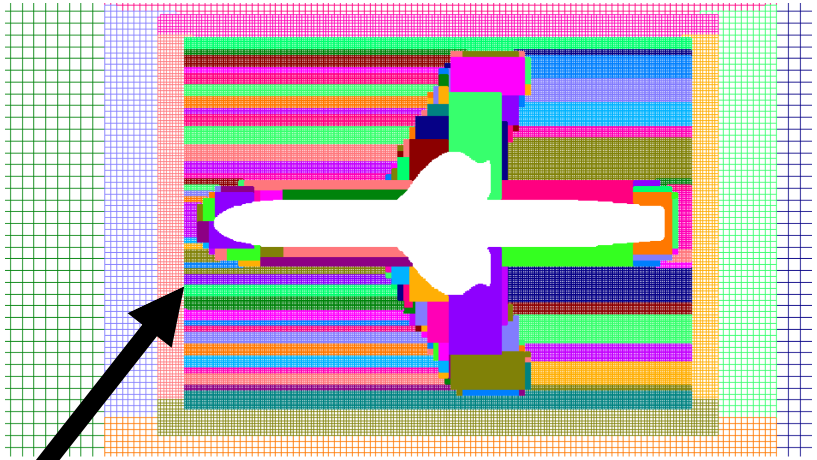
Near-Body

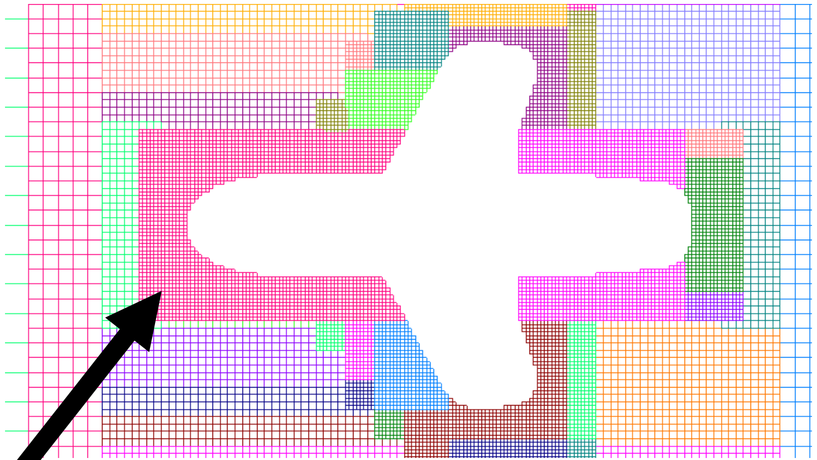


Different vol. marching distances



Off-Body





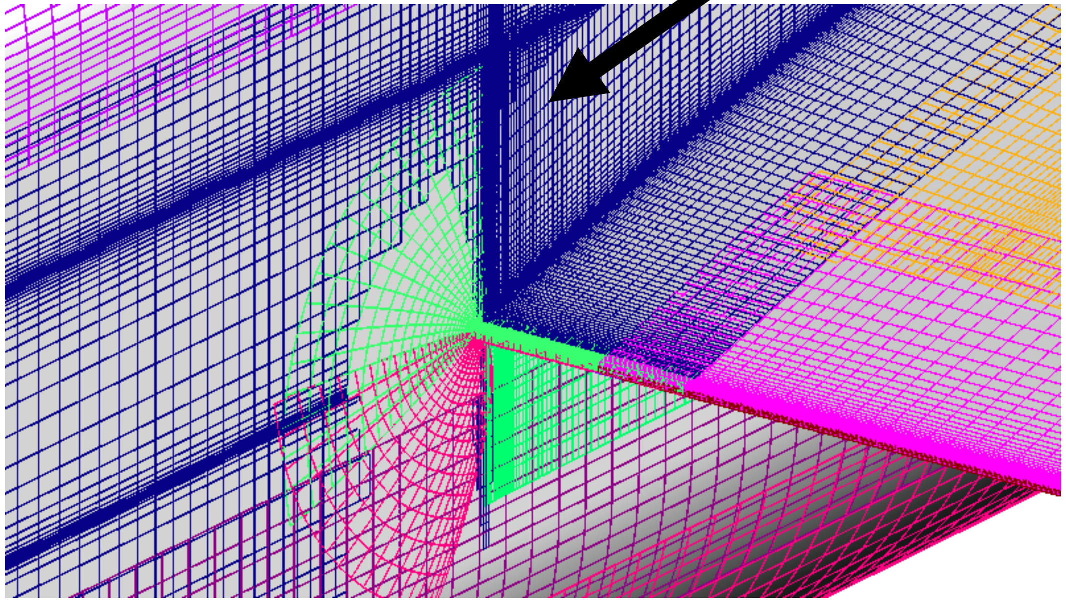
$\Delta s_{min} = 12.5mm$ Automatic

$\Delta s_{min} = 40.0mm$ Manual [4]

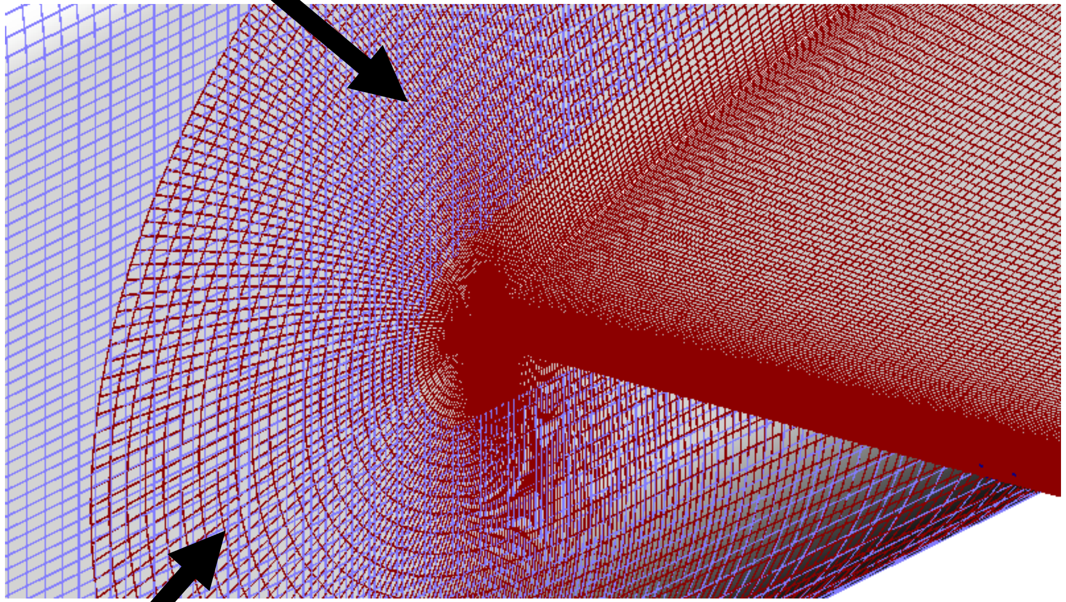
4. Lee, H. C., & Pulliam, T. H., "Overflow Juncture Flow Computations Compared with Experimental Data", AIAA 2019-0080, January 2019. https://doi.org/10.2514/6.2019-0080

GRID COMPARISONS – JFM F6 (2)

Finer mesh resolution in juncture region in manual mesh



Automatic



Manual

Manual meshes contain more overlap in junction regions

GRID COMPOSITION – JFM F6

- Differences can be attributed to…
  - NB volume marching distances/off-body mesh generation (blue)
  - Surface mesh topology

	Automatic			Manual		
	Near-Body	Off-Body	Total	Near-Body	Off-Body	Total
Surface Points	465K	-	-	578K	-	-
Grid Count	180	739	919	17	158	175
Grid Points	29.8M	30.7M	60.5M	48.9M	1.98M	50.9M
Fringe Points	4.85M	10.5M	15.3M	3.28M	829K	4.11M
Blanked Points	4.4M	3.83M	8.23M	524K	145K	669K

COMPUTATIONAL EFFICIENCY – JFM F6

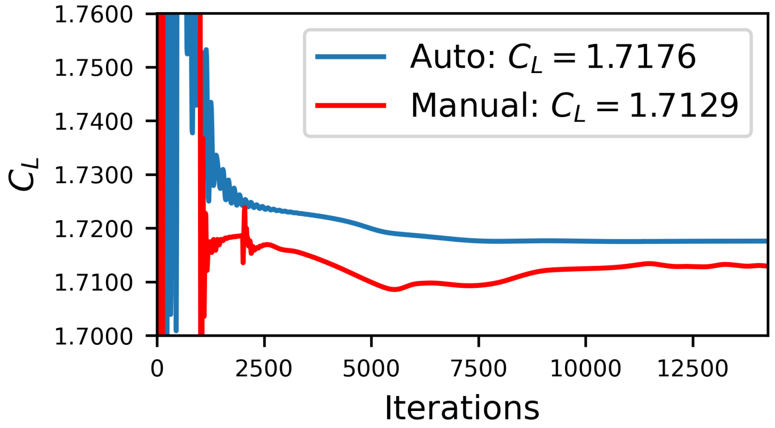
- Medium resolution, 280 Intel Broadwell Cores, 14.3K steps
- Load balancing in OVERFLOW results in roughly similar resource utilization

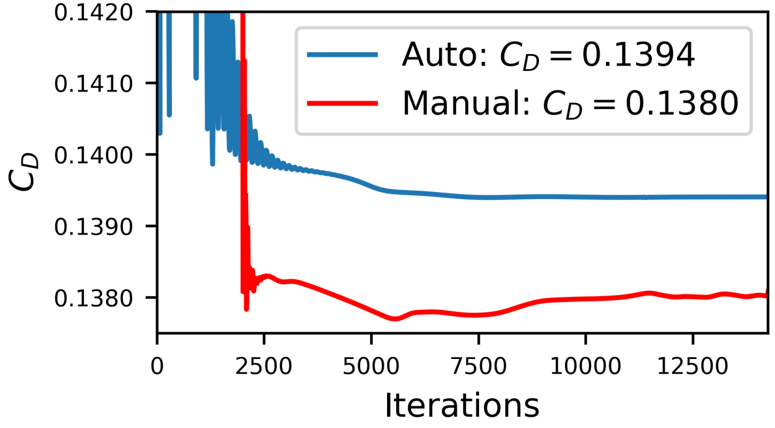
		Automatic	Manual
Before MPI-Splitting	# Grids	919	178
	Total Point Ct.	60.5M	50.9M
After MPI-Splitting	# Grids	1395	949
	Total Point Ct.	66.2M	65.2
	Avg. Pts per Group	298K	294K
	Chimera Boundary Exchange Time/Step	7.86E-02s	3.38E-02s
	Parallel Efficiency	91.4%	93.7%
	Wall Time	7 h 21 min	6 h 50 min

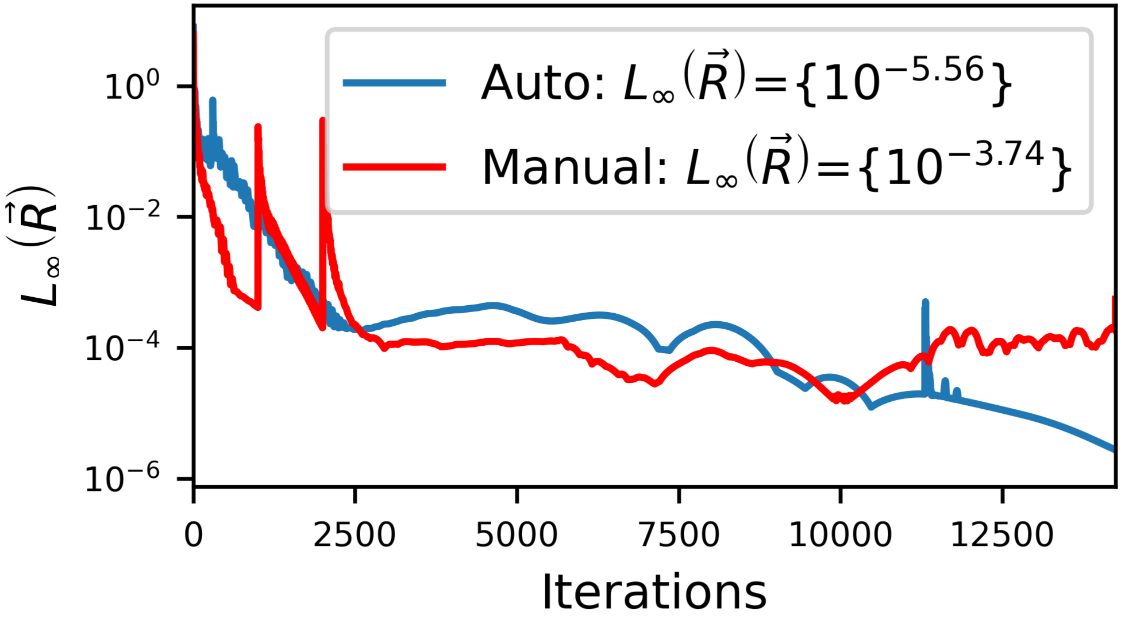
Only 2.3x increase in wall-time vs 3.7x increase in fringe pts

SOLUTION AND CONVERGENCE – JFM F6

- Flow conditions: free air, $M_\infty = 0.189$, $\alpha = 5.0°$, 14.3K steps
- 3rd Order Roe Scheme, ARC3D diagonalized Beam-Warming scalar pentadiagonal scheme, SARC-QCR2013V



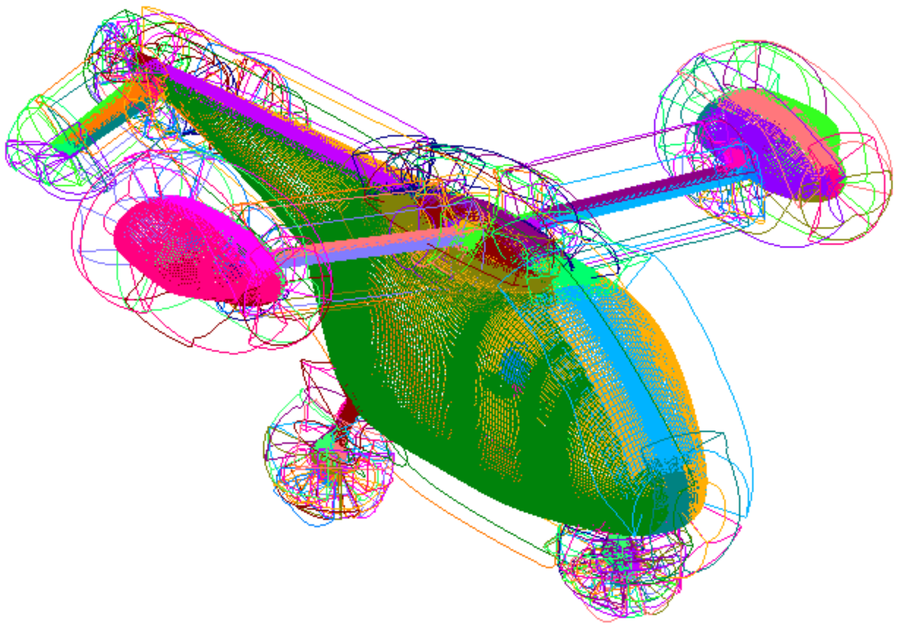




$$\Delta C_L = 0.2\%, \Delta C_D = 1\%$$

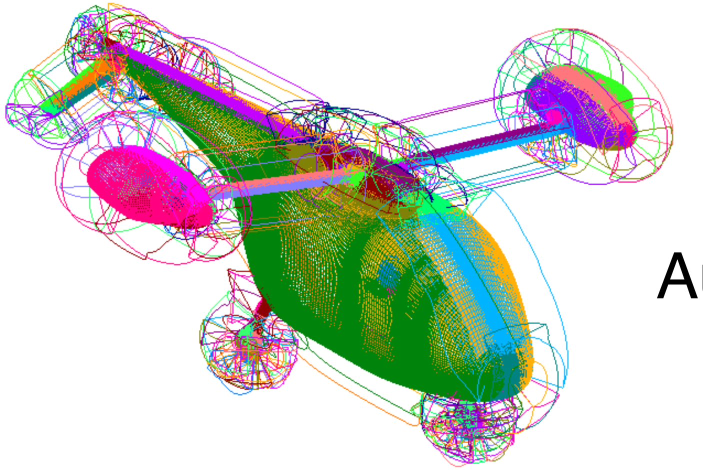
GRID GENERATION – SIDE-BY-SIDE HYBRID (AUTOMATIC)

- Surface & volume mesh generation w/ LCBC (7.8 h, 2019 MacBook Pro, 10 OMP threads):
  - Surface Mesh: 3 min
  - Volume Mesh: 12 s
  - Volume Mesh LCBC: 7.8 h
- Manual steps (~4 hrs):
  - Collar mesh repair (3 meshes)
  - Regenerate various meshes for overlap improvement (36 meshes)
  - XRAYS for hole-cutting with DCF
- Flow Solution Comparison WIP

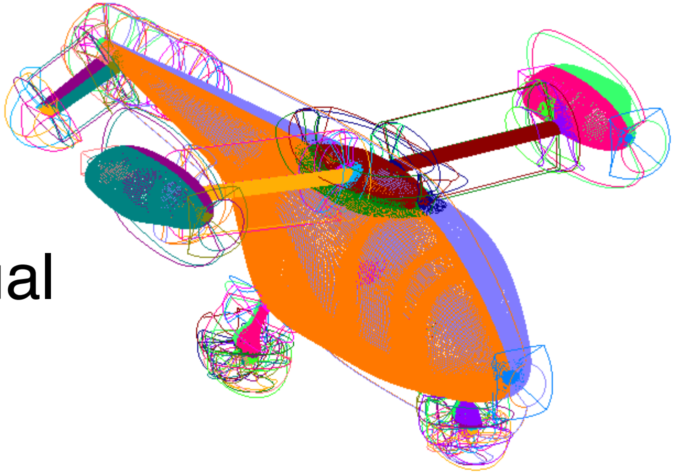


Automatically generated volume mesh

GRID COMPARISONS – SIDE-BY-SIDE HYBRID (1)



Automatic



Manual

Volume meshes generated for Side-By-Side Hybrid

Comparison of Auto vs. Manual mesh generation time (assuming 8 h worked per day)

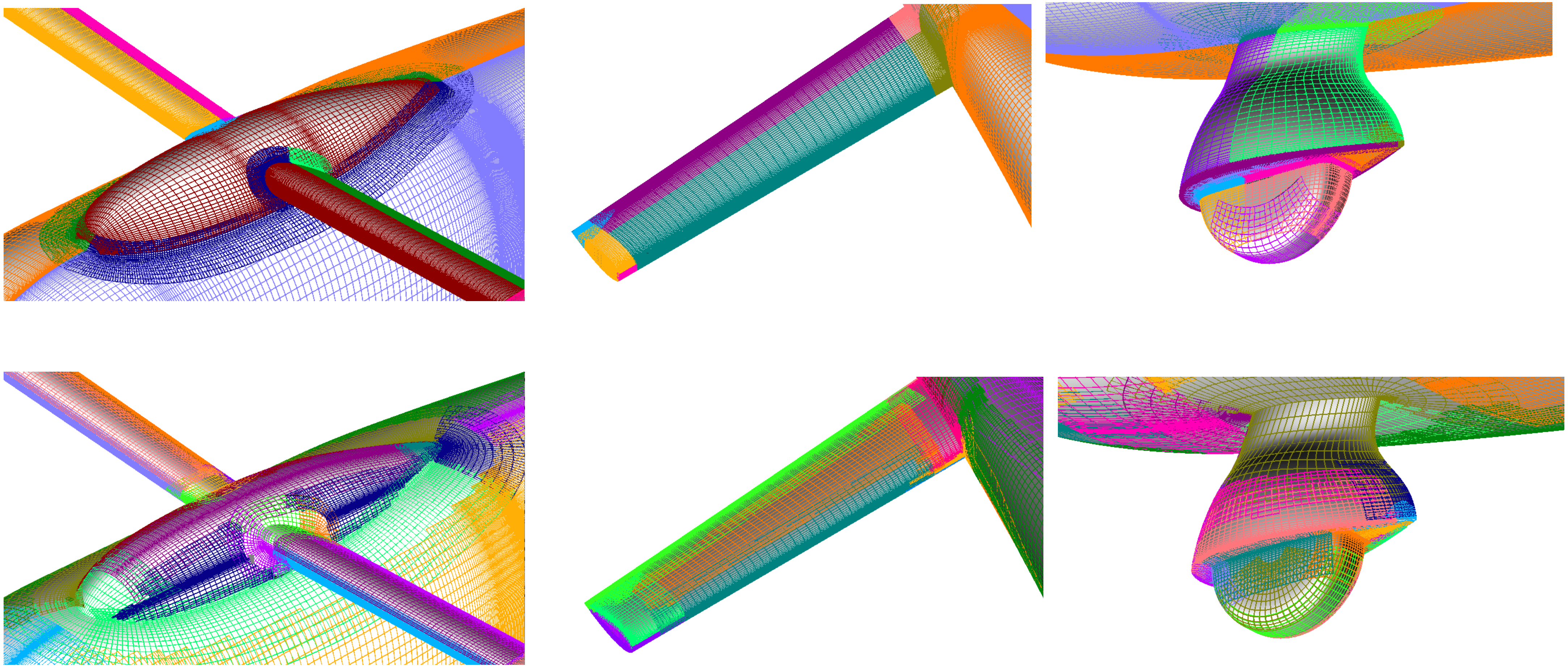
Steps	Automatic	Manual
Surface Meshing	3 min (C)	2-3 wks (M)
Volume Meshing	12 s (C)	1 d (M)
Volume Mesh LCBC	7.8 h (C)	-
Volume Mesh Repair	1-2 h (M)	-
Domain Connectivity	2 h (M)	2 h (M)
Flow Solver Inputs	10 min (M)	30 min (M)
Total Turnaround Time	1-2 d	3 wks

(C): CPU wall-clock time
(M): Manual labor time

GRID COMPARISONS – SIDE-BY-SIDE HYBRID (2)

Manual

Automatic



SBS Center Pod | Right Tail | Front Landing Gear

GRID COMPOSITION – SBS HYBRID

- Used same XRAY cutters & off-body generation inputs
- Differences mainly attributed to surface mesh approach (blue)
  - Refinement of collar meshes
  - Surface topology decomposition

	Automatic			Manual		
	Near-Body	Off-Body	Total	Near-Body	Off-Body	Total
Surface Points	319K	-	-	394K	-	-
Grid Count	162	252	414	86	241	327
Grid Points	20.1M	7.77M	27.9M	24.8M	8.07M	32.9M
Fringe Points	3.40M	2.55M	5.95M	3.21M	2.55M	5.76M
Blanked Points	1.15M	467K	1.62M	1.77M	465K	2.24M

COMPUTATIONAL EFFICIENCY – SIDE-BY-SIDE HYBRID

- 160 Intel Ivy Bridge Cores, 15K steps
- Load balancing in OVERFLOW results in roughly similar resource utilization

		Automatic	Manual
Before MPI-Splitting	# Grids	414	327
	Total Point Ct.	27.9M	32.9M
After MPI-Splitting	# Grids	686	702
	Total Point Ct.	31.9M	38.5M
	Avg. Pts per Group	251K	304K
	Chimera Boundary Exchange Time/Step	3.20E-02s	2.64E-02s
	Parallel Efficiency	94.9%	94.4%
	Wall Time	3 h 50 min	3 h 27 min

CONCLUDING REMARKS

- Presented loosely-coupled boundary conditions (LCBC) for hyperbolic mesh generation (surface and volume)
- Introduced face mesh reconstruction to improve volume LCBC robustness
- Presented preliminary flow solution comparisons between automatically and manually generated grids
- Automatic meshes shows comparable capability in computing flow solutions (convergence, accuracy, efficiency)
- Hybrid auto/manual approach enables significant reductions in turnaround time to perform overset CFD analysis

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