

Democratizing Mesh Adaptation for Computational Fluid Dynamics

Michael Park

NASA Langley Research Center

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Motivation

Technology roadmap of the CFD Vision 2030 Study¹

“Mesh generation and adaptivity continue to be significant bottlenecks in the CFD [Computational Fluid Dynamics] workflow, and very little government investment has been targeted in these areas.”

“Ultimately the mesh generation process should be invisible to the CFD user or engineer.”

¹Slotnick et al. NASA CR-2014-218178

Motivation

Supporting Certification by Analysis

- ▶ Demands the accurate simulation of steady and time-dependent separated flows for complex configurations (e.g., maximum lift of transport aircraft)
- ▶ Requires improved automation and robustness for complex geometry models and database creation (outside center of flight envelope where CFD typically applied)
- ▶ Includes verification and validation exercises for the entire adaptive mesh toolchain

Motivation

“In industry, CFD has no value of its own. The only way CFD can deliver value is for it to affect the product. To affect the product, it must become an integral part of the engineering process for the design, manufacture, and support of the product.”²

²Johnson, Tinoco, and Yu, Thirty Years of Development and Application of CFD at Boeing Commercial Airplanes, Seattle, Computers and Fluids, 2005

Encourage Use and Development of Adaptive Mesh Technology in Response to CFD 2030 Vision Findings

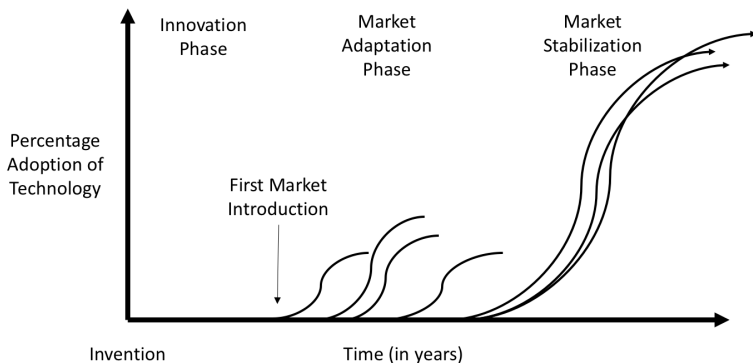
AIAA Paper 2016-3323

Unstructured Grid Adaptation: Status, Potential Impacts, and Recommended Investments Toward CFD Vision 2030

- ▶ What is the best strategy to defuse technology?

Mesh Adaptation Technology Diffusion Strategy

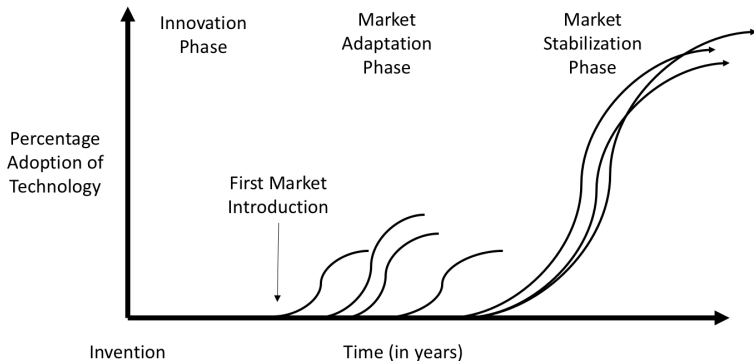
Phases in the technology diffusion process³



³Ortt and Schoormans, The Pattern of Development and Diffusion of Breakthrough Communication Technologies, European Journal of Innovation Management, 2004

Mesh Adaptation Technology Diffusion Strategy

It is important to establish the position of the technology in the pattern of development and diffusion and that strategies should be tailored to this position.⁴



⁴Ortt and Schoormans, The Pattern of Development and Diffusion of Breakthrough Communication Technologies, European Journal of Innovation Management, 2004

Mesh Adaptation Technology Diffusion Strategy

Take-off is caused by outward shifting supply and demand curves.⁵

[Number of mesh adaptation implementations is a more important factor than the efficiency of a particular implementation to trigger rapid adoption.]

Democratization drives adoption!

The choice being made is not a choice between adopting and not adopting but a choice between adopting now or deferring the decision until later. . . . Adoption should not take place the instant that benefits equal costs, but should be delayed until benefits are somewhat above costs.⁶

⁵Agarwal and Bayus, The Market Evolution and Sales Takeoff of Product Innovations, Management Science, 2002

⁶Hall and Khan, Adoption of New Technology, National Bureau of Economic Research, Working Paper 9730, 2003

Mesh Adaptation Toward CFD Vision 2030

AIAA Paper 2016-3323

Unstructured Grid Adaptation: Status, Potential Impacts, and Recommended Investments Toward CFD Vision 2030

- ▶ Literature survey
- ▶ **Unstructured mesh adaptation status and 15 year forecast**
- ▶ **Recommendations for investment** and potential impacts

Unstructured Grid Adaptation Working Group (UGAWG)

- ▶ Informal group with monthly virtual meetings focused on publication
- ▶ Test cases available for analysis or developing new methods
<https://UGAWG.GitHub.io>
- ▶ Diffuse verified adaptive mesh technology to displace fixed meshes where appropriate

In Five Years: 2020

Forecast

- ▶ Error estimation and metric construction mature for CFD
- ▶ Orthogonality of adaptive mesh elements improves
- ▶ Research includes 2D and 3D methods

Recommendations

- ▶ Improve solver automation to impact all disciplines
- ▶ Evaluate mesh and geometry databases (e.g., MOAB, PUMI), which include linkages to CAD and CAD surrogates
- ▶ Improve error estimation for CFD
- ▶ Improve anisotropic initial mesh generation and adaptation
- ▶ Sequential algorithms become parallel

In Ten Years: 2025

Forecast

- ▶ Reliable error estimation extensions will include other disciplines, coupling terms, and turbulent eddy resolving methods
- ▶ Design optimization and uncertainty quantification based on adapted mesh solutions with comparable or superior efficiency to fixed meshes
- ▶ Accurate Common Research Model (DPW) solution with reliable error estimate verified by asymptotic convergence rate demonstration
- ▶ Customers will require the option of adaptive methods and error estimates from vendors easing the initial mesh generation task

Recommendations

- ▶ Robustness also be incorporated into higher levels of the system
- ▶ Shift in emphasis from pre-deployment testing to monitoring the application in production due to high complexity and throughput
- ▶ All research in parallel, application includes heterogeneous hardware

In Fifteen Years: 2030

Forecast

- ▶ Adaptive mesh computations displace fixed meshes as the default
- ▶ Practitioner will rarely visualize the mesh directly
- ▶ Verification databases provide high confidence in discrete solutions
- ▶ Modeling, coupling, and manufacturing errors will be quantified, controlled, and balanced to increase design robustness
- ▶ Error estimation and adaptation is a clear competitive advantage

In Fifteen Years: 2030

Recommendations

- ▶ Embrace adaptive execution and fault tolerance on heterogeneous and throttling architectures
- ▶ Define standards for analysis certification and certification by analysis

Forecast Realization

How much progress has been made toward the first five year prediction?

- ▶ Not meant to be exhaustive
- ▶ Focusing on work that relates to stated recommendations from UGAWG and NASA
- ▶ **My apologies in advance for omitting your work!**

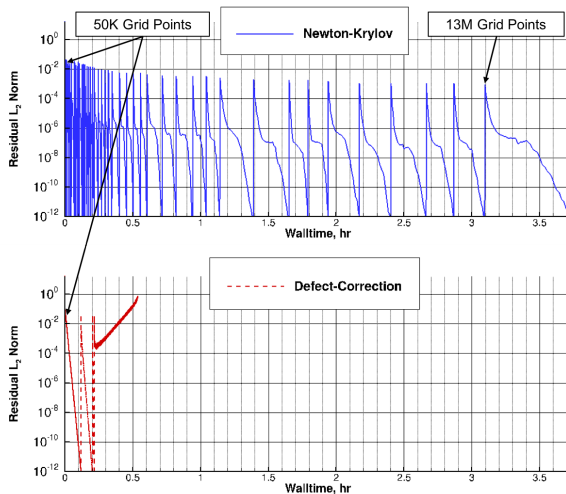
Solver Automation Progress

AIAA working groups and special sessions

- ▶ AIAA High-Fidelity CFD Workshop in planning
- ▶ AIAA Solver Technology special sessions
- ▶ Newton-Krylov (Jacobian Free)
 - ▶ Wolf (INRIA)
 - ▶ GGNS (Boeing, General Geometry Navier Stokes)
 - ▶ FUN3D-SFE (NASA, Fully Unstructured 3D Stabilized Finite-Element)
 - ▶ SANS (MIT, Solution Adaptive Numerical Simulator)
 - ▶ Enigma (NASA)

Solver Automation Progress

Thompson and O'Connell, Streamlined Convergence Acceleration for CFD Codes, AIAA 2019-3709



Mesh and Geometry Databases Progress

Mesh Database

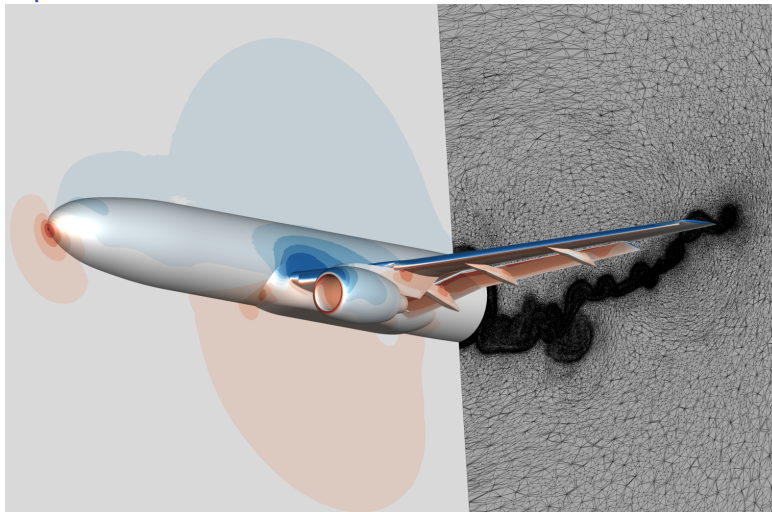
- ▶ Typically native mesh database
- ▶ PUMI (Parallel Unstructured Mesh Infrastructure) used by Omega_h

Geometry Database

- ▶ Mesh association with geometry topology and parameters persistence
- ▶ Native geometry evaluation
- ▶ High-order discrete surrogate geometry
- ▶ EGADS (OpenCASCADE based) and EGADSLite (MIT, Engineering Sketch Pad)
- ▶ MeshLink and Geode (Pointwise)

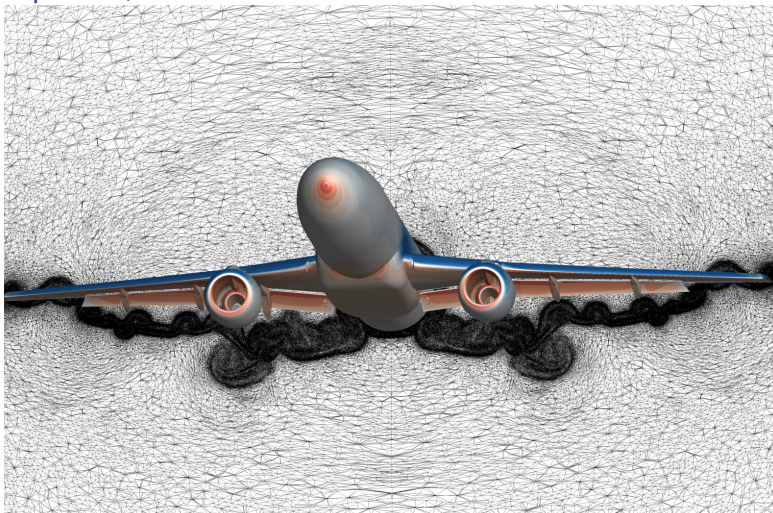
Integration with Geometry Databases

Park et al., Geometry Modeling for Unstructured Mesh
Adaptation, AIAA 2019-2946



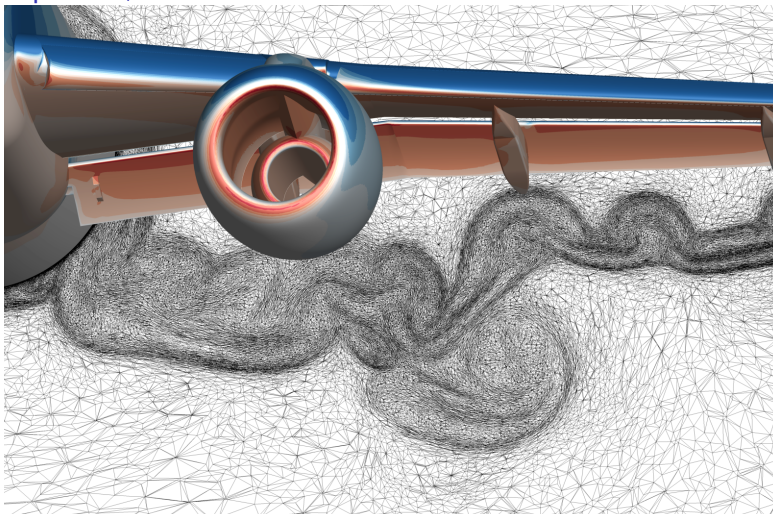
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Anisotropic Metric Construction Progress

Interpolation Error Control

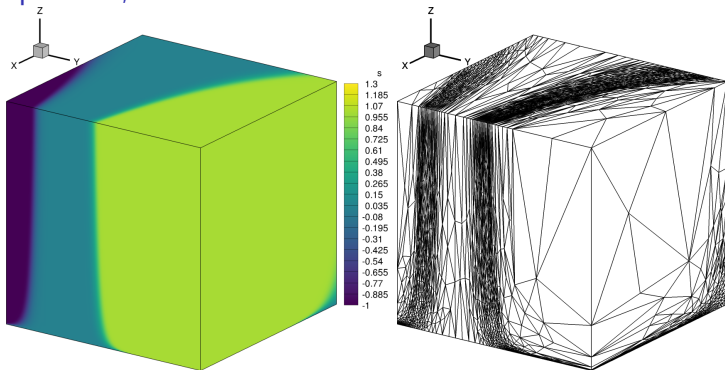
- ▶ UGAWG multiscale metric verification

Output or Goal Error Control

- ▶ Mesh adaptation to target a simulation engineering output
- ▶ INRIA and Boeing in AIAA-2018-0920 and AIAA-2019-2947
- ▶ MOESS (MIT, Mesh Optimization via Error Sampling and Synthesis)

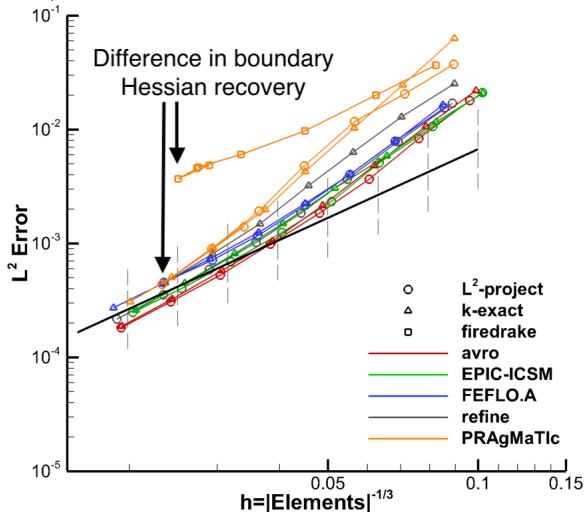
Anisotropic Metric Construction Progress

Park et al., Verification of Unstructured Grid Adaptation Components, AIAA 2019-1723



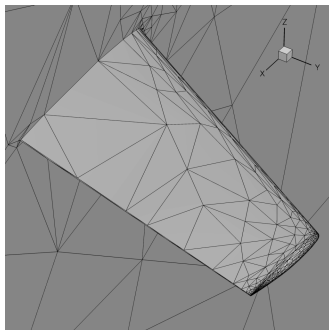
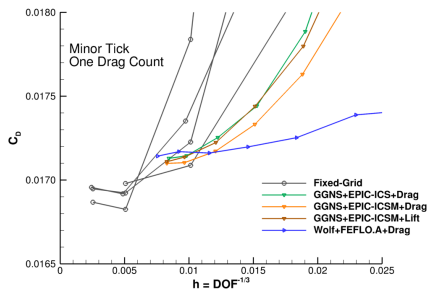
Anisotropic Metric Construction Progress

Park et al., Verification of Unstructured Grid Adaptation Components, AIAA 2019-1723



Anisotropic Metric Construction Progress

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Anisotropic Initial and Adapted Meshes Progress

Initial

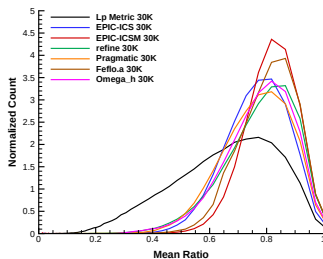
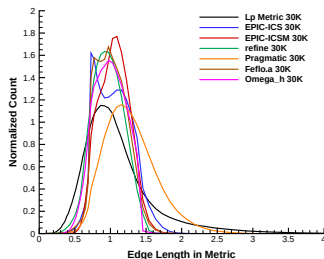
- ▶ Marcum and Alauzet, Metric-Orthogonal Anisotropic Mesh Generation, IMR, 2017
- ▶ Pardue and Chernikov, Three-Dimensional Prism-Dominant Mesh Generation for Viscous Flows Around Surface Slope Discontinuities, AIAA-2018-3722
- ▶ Park et al., Geometry Modeling for Unstructured Mesh Adaptation, AIAA 2019-2946

Adaptive Mesh Metric Conformity

- ▶ Park et al., Unstructured Grid Adaptation and Solver Technology for Turbulent Flows, AIAA 2018-1103

Anisotropic Metric Conformity Progress

Park et al., Unstructured Grid Adaptation and Solver Technology for Turbulent Flows, AIAA 2018-1103



Wall-Clock Time and Parallel Execution

Status

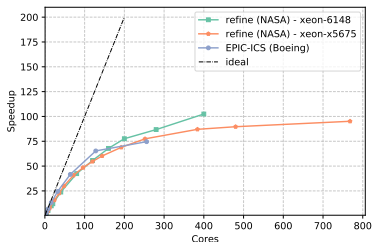
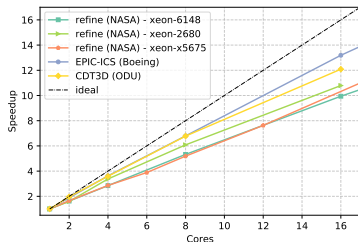
- ▶ Tsolakakis et al., Parallel Anisotropic Unstructured Grid Adaptation, AIAA-2019-1995

Near future

- ▶ Graphic Processor Units (GPUs) available on leadership-class HPC clusters and coming to a machine near you
- ▶ Where are challenges and synergies with adaptive mesh mechanics?
- ▶ Will adaptive mesh mechanics remain a small contribution to wall-clock time on these new machines with improving CFD solver technology?

Parallel Execution Scaling

Tsolakis et al., Parallel Anisotropic Unstructured Grid Adaptation, AIAA-2019-1995



Summary

- ▶ CFD 2030 Vision Study identifies mesh generation and adaptivity as CFD bottlenecks
- ▶ Technology diffusion research indicates that multiple entrants are required to trigger a rapid technology adoption phase
- ▶ Collaboration is required to encourage these multiple entrants and improve the quality of each entrant
- ▶ The informal UGAWG fosters this collaboration

Summary

- ▶ 5, 10 and 15 year predictions and recommended investments are included in AIAA Paper 2016-3323
- ▶ Significant progress has been made to address these recommendations
- ▶ Continued collaboration will set the stage for addressing the remaining recommendations and identifying new requirements toward the CFD 2030 Vision
- ▶ Mesh adaptation can be brought under automated process control to enable Certification by Analysis
- ▶ Adaptive mesh techniques replace fixed-mesh approaches making the grid invisible to the CFD user or engineer

Outreach and Acknowledgment

Unstructured Grid Adaptation Working Group (UGAWG)

- ▶ Informal group with monthly virtual meetings
- ▶ <https://UGAWG.GitHub.io> test cases for analysis or developing new methods
- ▶ UGAWG@Mail.EmailHorse.com or Mike.Park@NASA.gov
- ▶ Diffuse verified adaptive mesh technology to displace fixed meshes where appropriate

Acknowledgment

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