CFD Vision 2030: Progress and Perspectives

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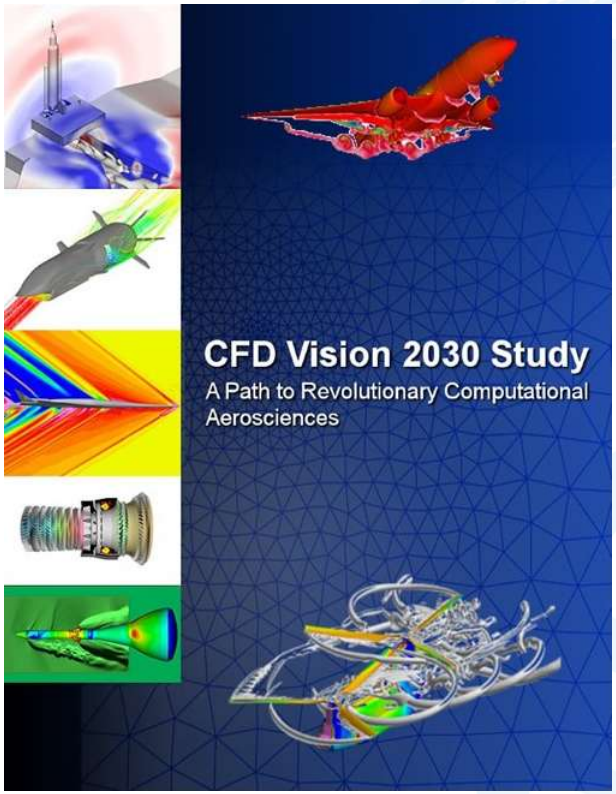
Outline

- Background
- Vision
- Development Roadmap
- Grand Challenges
- Technical Updates
- Looking Towards 2030

Background of Vision 2030 Effort



NASA CR-2014-218178

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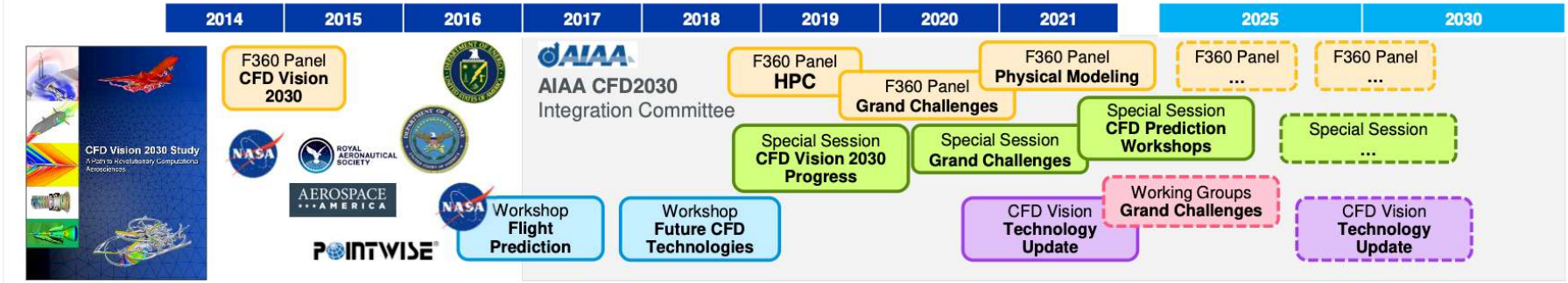
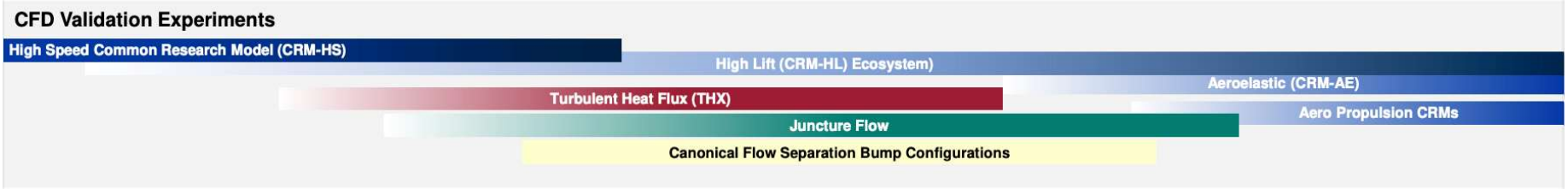
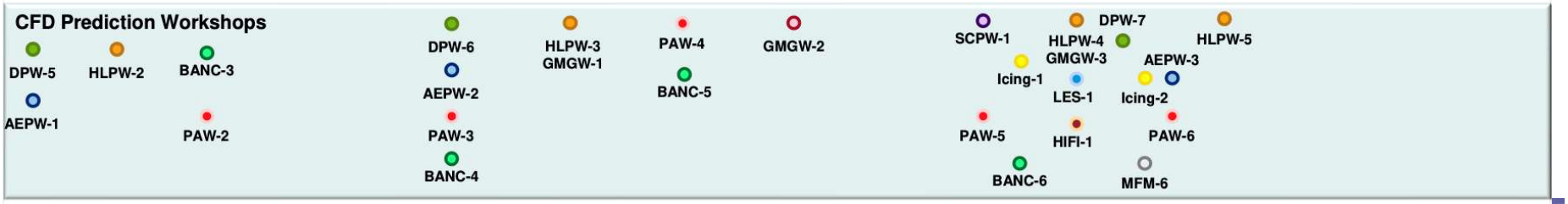
- **One year study → NASA report published 2014**
- **Key Deliverables**
  - Guidelines for NASA CFD development
  - Concept of CFD Grand Challenge Problems
  - Development Roadmap
- **AIAA Integration Committee**
  - Formed in 2018 to provide ongoing awareness and track progress for Vision
  - Roadmap updates
  - Grand Challenge encouragement

Background of Vision 2030 Effort



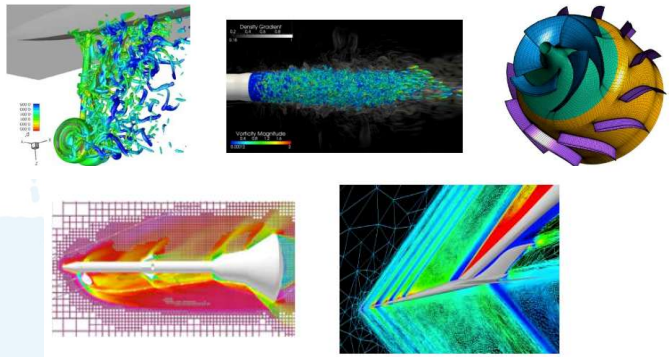




Vision Recommendations and Impact

NASA should

- Develop, fund and sustain a **base research and technology development program** for simulation-based analysis and design technologies
- Develop and maintain an **integrated simulation and software development infrastructure** to enable rapid CFD technology maturation
- **Utilize and optimize HPC systems** for large-scale CFD development and testing
- Lead efforts to develop and execute **integrated experimental testing and computational validation campaigns**
- Develop, foster, and leverage **improved collaborations with key research partners and industrial stakeholders** across disciplines within the broader scientific and engineering communities
- **Attract world-class engineers and scientists**



- Report cited more than 1700+ times
- Proposed to be fully funded in congressional budget
- Spawned creation of Materials Vision 2040 and Certification by Analysis efforts
- Coalesced industry, government and academia around key CFD objectives

Vision Statement

An engineer/scientist must be able to

generate, analyze, and interpret

a large ensemble of related simulations in a

time-critical period (e.g., 24 hours),

without individually managing each simulation, to a

pre-specified level of accuracy and confidence

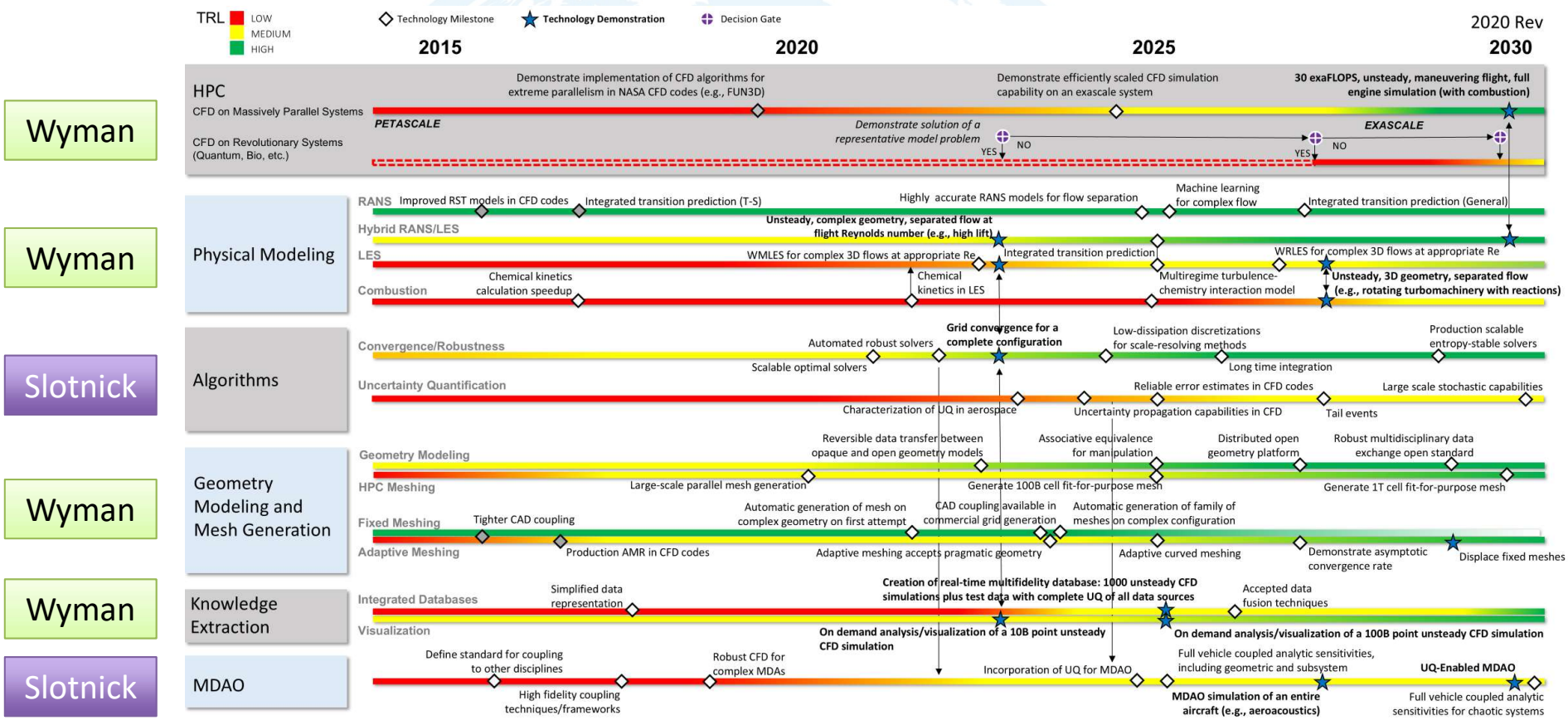
Vision Elements

- **Emphasize physics-based predictive modeling:** Includes turbulence, transitional flow, unsteady/time-accurate, chemically reacting flows, radiation, heat transfer, acoustics, etc.
- **Manage simulation errors and uncertainties:** Quantification of errors and uncertainties arising from physical modeling, mesh and discretization, etc.
- **Develop automation in all steps of the analysis process:** Geometry creation, meshing, large databases of simulation results, extraction and understanding of simulation information, etc.
- **Harness future HPC architectures:** Multiple memory hierarchies, latencies, bandwidths, programming paradigms and runtime environments, etc.
- **Enable Seamless integration with multi-disciplinary analysis and optimizations:** High-fidelity CFD tools, interfaces, coupling approaches, the science of integration, etc.

Examples of Technologies Realized:

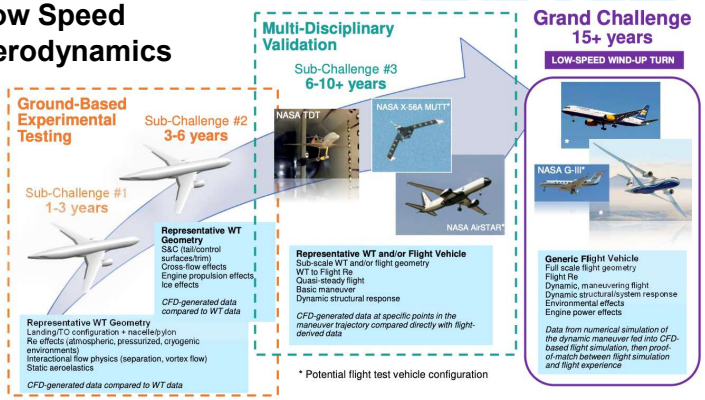
- Scale-resolving simulations
- Multi-fidelity surrogate modeling
- AI-enabled processes, data base automation
- GPU computing
- Integration frameworks, openMDAO

Development Roadmap



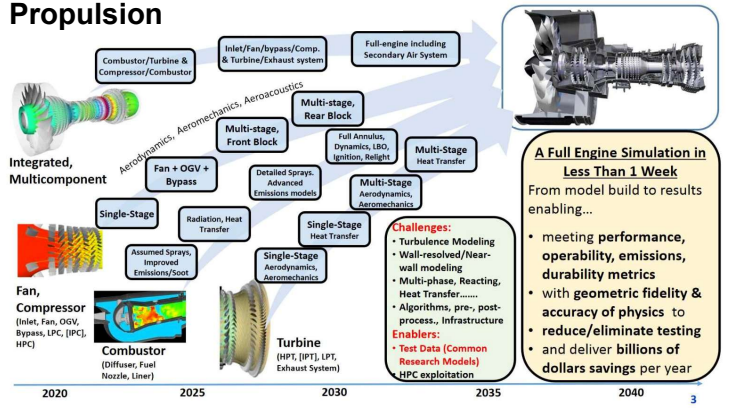
Grand Challenges

Low Speed Aerodynamics

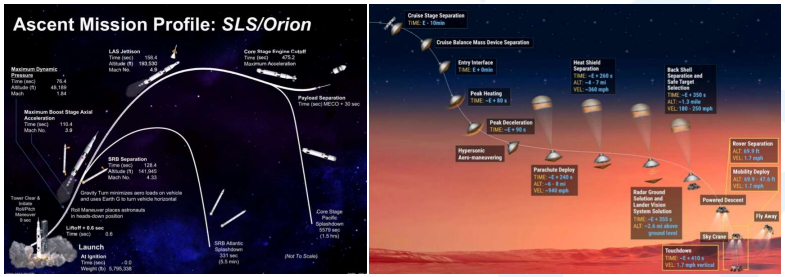


Slotnick, J., and Mavriplis, D. "A Grand Challenge for the Advancement of Numerical Prediction of High Lift Aerodynamics", AIAA 2021-0955, https://doi.org/10.2514/6.2021-0955

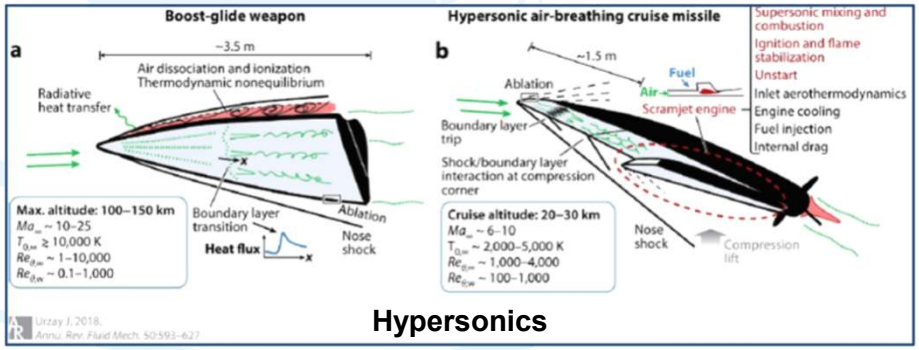
Propulsion



Anand, M. S., et al., "Vision 2030 Aircraft Propulsion Grand Challenge Problem: Full-engine CFD Simulations with High Geometric Fidelity and Physics Accuracy", AIAA 2021-0956, https://doi.org/10.2514/6.2021-0956



CFD-in-the-Loop Monte Carlo Flight Simulation for Space Vehicle Design



Hypersonics

https://cfd2030.com/gc.html

Algorithm Advancements and Needs

		TRL key	0	1	2	3	4	5	6	7	8	9
			2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Algorithms													
Convergence/Robustness													
Automated robust solvers	2022	7	7	7	8	8							
Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)	2023	7	7	7	7	8							
Scalable optimal solvers	2021	6	6	6	6	6							
Improved discretizations for scale-resolving methods (low-dissipation, HO,…)	2024	5	5	5	5	6							
Accurate and robust methods for long time integration	2026	2	2	2	2	2							
Production scalable entropy-stable solvers	2029	3	3	3	3	3							
Uncertainty Quantification (UQ)													
Characterization of UQ in aerospace	2023	4	4	4	4	4							
Reliable error estimates in CFD codes	2025	5	5	5	5	5							
Uncertainty propagation capabilities in CFD	2022	4	4	4	4	4							
Identification of tail events/probabilities from CFD codes	2027	3	3	3	3	3							
Large scale stochastic capabilities in CFD	2030	0	0	0	0	0							

- **Selected Advances**
  - Finite-Element methods for CFD matured with benefits due to compactness, robustness on arbitrary meshes, and strong solvers to eliminate iteration error
  - Decreased numerical dissipation and dispersion increase accuracy for given number of grid points
    - Applied for WMLES and WRLES
    - Enabled GE to run WRLES for new open fan engine architectures on DOE ORNL supercomputers
  - AIAA UQDG Challenge Problems (2024, 2026) demonstrated low-cost consistent results to sample aerodynamic UQ problems with multiple approaches
- **Continued Needs**
  - Low-memory implicit algorithms appropriate for time-accurate (WMLES) simulations on GPUs, particularly with reduced precision
  - Linear/nonlinear solver algorithms that leverage quantum computing strengths
  - Reliable CFD error estimation for industry-relevant problems/solvers

MDAO Advancements and Needs

TRL key		0	1	2	3	4	5	6	7	8	9	
		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
MDAO												
MDAO												
Define standard for coupling to other disciplines	2016	4	4	4	4	4						
High fidelity coupling techniques/frameworks	2017	4	4	4	4	4						
Robust CFD for complex MDAs	2019	4	4	4	4	4						
Incorporation of UQ for MDAO	2025	2	2	2	2	2						
MDAO simulation of an entire aircraft (e.g., aeroacoustics)	2027	3	3	3	3	3						
UQ-enabled MDAO	2030	1	1	1	1	1						
Full vehicle coupled analytic sensitivities, including geometric and subsystems	2025	4	4	4	4	4						
Full Vehicle coupled analytic sensitivites for chaotic systems	2030	0	0	1	1	1						

- **Selected Advances**
  - NASA-led development of openMDAO and Mphys has provided a community and framework for performing gradient-based multi-disciplinary optimization
  - Effective aeroelastic wing optimization using RANS CFD coupled to FEM structural analysis has been demonstrated by the University of Michigan team
  - UC-San Diego and others have demonstrated large-scale distributed multidisciplinary design optimization of the NASA lift-plus-cruise air taxi concept
- **Continued Needs**
  - Standardization and Industry adoption of recent MDO technologies (see AIAA MDO TC working groups in standard analysis interfaces and MDO benchmarks)
  - Design of transient/chaotic multi-disciplinary systems (although progress has been made)

Looking Toward 2030

- **Leverage Grand Challenge Problems to demonstrate advances**
  - Presently surveying status of GC problems to identify progress and current gaps
  - Developing integrated aerodynamic-propulsion-aeroelastic challenge problem

- **Increasing automation as larger databases are being created**
  - Digital engineering / digital thread is pushing CFD size and quantity
  - Provenance tracking and data management for solutions is critical
  - Role of AI/ML advancements/ surrogate modeling needs to be extended

- **Multidisciplinary analysis (and optimization) will continue to grow**

- **Help needed:**
  - Technology gaps have been identified; looking for contributions to solutions
  - Follow activity and provide feedback at www.cfd2030.com (subscribe to email list)

Thank you for your attention!