Eleventh International Conference on Computational Fluid Dynamics (ICCFD11), Maui, Hawaii, USA, July 11-15, 2022

ICCFD11-1802

Progress Toward Realizing the CFD Vision 2030

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Abstract: With less than a decade remaining until its titular deadline, the goals of NASA's CFD Vision 2030 Study remain generally aspirational. That is not to imply that there have not been advances in the study's focus areas of effective utilization of high performance computing resources, accurate turbulence modeling with transition and separation, implementation of autonomous simulation processes, effective knowledge extraction, and use of multi-disciplinary frameworks. Rather, achievement of these goals is either highly localized within the overall community of CFD practitioners, is the result of heroic versus workmanlike effort, and/or is for only one or two foci rather than all of them simultaneously. Progress since the study's publication in 2014 is used to identify work remaining to realize the vision. Also, ongoing efforts to create grand challenge problems that can help quantify progress toward the vision are described.

Keywords: CFD, numerical algorithms, high performance computing, turbulence modeling, fluid dynamics, geometry modeling, mesh generation, knowledge capture, visualization, in-situ processing.

1 Introduction

The CFD Vision 2030 Study [1] (hereinafter, the Study) succinctly stated that by its titular deadline "a single engineer/scientist must be able to conceive, create, 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."

To focus this Vision, the Study identified four grand challenge (GC) problems that NASA, the Study's targeted user community, must be able to solve by the year 2030. These GC problems are a wall-resolved LES simulation of an aircraft throughout its flight envelope, an off-design turbofan engine transient simulation, a multi-disciplinary simulation of an advanced aircraft, and a probabilistic simulation of a powered space access configuration.

The aerospace CFD community's response to the Study has been strong and sustained. In addition to spawning a large number of technical papers and workshops as well as sparking advancements in CFD technology, a committee was formed within the American Institute of Aeronautics and Astronautics' (AIAA) integration and outreach organization (the CFD 2030 Integration Committee, hereinafter the IC) to promote a community of practice dedicated to shaping the future of simulation-based engineering relative to the Study's goals. The author is vice-chair of the IC.

With fewer than eight years remaining until 2030 and in light of the Vision's ambitious goals, a reassessment of the Vision, including an assessment of progress, is warranted. The following sections of this paper provide background on the Study itself, introduce the committee created to foster the Vision, and assess progress toward the Vision through 2021. These sections are followed by a look forward at creating and managing GCs and the overall future of the Vision.

2 Background

The Study was written by a multidisciplinary team of experts in response to a NASA Research Announcement with the goal of documenting a knowledge-based strategy for overcoming CFD's challenges circa 2014 such that NASA's CFD goals could be met by the year 2030. The Study begins by clearly praising CFD's successful evolution over the preceding decades by noting that it has "fundamentally changed the aerospace design process."

This is followed by recognition that several limitations in CFD's then-current capabilities prevent or limit its use on many significant classes of aerospace configurations. The Study classified these limitations into six domains or areas for research on its technology development roadmap (hereinafter Roadmap) as described in the following list.

1. High Performance Computing (HPC) – Dominated by MPI and OpenMP implementations of parallelism, CFD software will likely have to adopt emerging HPC technology such as GPU computing or more exotic platforms like quantum leading to an exascale computing capability.
2. Physical Modeling – CFD is unable to accurately simulate turbulent, separated flows which confines its range of applicability to the core of the flight envelope. Scale-resolving techniques such as Large Eddy Simulation (LES) were deemed immature.
3. Algorithms – CFD flow solvers exhibit inconsistent convergence behavior and lack the ability to control errors or quantify uncertainty.
4. Geometry and Grid Generation – Mesh generation's inability to generate a suitable mesh on a complex geometry on the first attempt has been cited as a primary roadblock to CFD process automation.
5. Knowledge Extraction – Current post-processing software lacks the ability to efficiently process exascale-level simulations, to simultaneously process a large number of simulations, and to merge data from sources beyond CFD.
6. Multidisciplinary Analysis and Optimization – Multidisciplinary simulations including CFD are too difficult to setup properly and rely on ad hoc methods of data exchange between tools related to the individual disciplines.

The Study also included several budgetary and programmatic recommendations to NASA that could address the CFD impediments noted in this section. These recommendations are not relevant to the purpose of this paper and are therefore omitted.

2.1 Similar and Follow-On Work

Publication of the Study did not occur in a vacuum. The Study directly motivated research in many of the Roadmap's domains with publication and demonstration of the results of that research continuing to this day. At a higher level, the Study has co-existed similar work in related fields.

With respect to the latter, NASA subsequently funded research that resulted in a Vision 2040 for materials and systems simulation [2]: "A cyber-physical-social ecosystem that impacts the supply chain to accelerate model-based concurrent design, development, and deployment of materials and systems throughout the product lifecycle for affordable, producible, aerospace applications." This vision for 2040 dovetails with the Study in several areas, including high-performance computing (HPC), uncertainty quantification (UQ), and multi-disciplinary environments. More closely related to the Study's focus on fluid dynamics is the publication by Tyacke and coauthors on the future of turbomachinery flowfield simulation [3]. More recently, Jansson and coauthors [4] describe a framework in which solutions to the Euler equations are said to meet the goals of the Vision.

Broader than just CFD, the ASSESS Initiative [5] (www.assessinitiative.com) has a mission "to lead every aspect of engineering simulation toward a more valuable and accessible future in the medium to long-term, leveraging the expertise and knowledge of top-level figures in industry, government, and academia." The themes around which ASSESS is aligned have considerable overlap with elements of the Study. ASSESS themes include verification, validation, and UQ; broader accessibility (also known as democratization); and integration of simulation tools within a multi-disciplinary and multi-fidelity environment. ASSESS recently became part of NAFEMS.

With respect specifically to the democratization of engineering simulation, Revolution in Simulation (Rev-Sim) is a "collaborative community to help increase the value of engineering simulation (CAE) investments through the Democratization of Simulation" [6]. Stated more directly, the goal of Rev-Sim is to dramatically expand the use of engineering simulation by eliminating barriers to entry such as software complexity and required user expertise. While not using the same language, the Study identifies geometry modeling and mesh generation as barriers to entry with respect to CFD.

While no causation is implied by the confluence of efforts and organizations focused on advancing engineering simulation, it would be fair to say that the Study was published at a fertile time. Further evidence of causal fertility can be found in the CFD community's (especially aerospace CFD) embrace of the Study as a lens, motivation, and rallying point for research.

3 The CFD Vision 2030 Integration Committee

Given the Vision's focus on aerospace CFD, conferences of the American Institute of Aeronautics and Astronautics (AIAA) became the main forums for publication, presentation, and discussion of the Vision. These events became sufficiently popular that the AIAA formed the CFD 2030 Vision Integration Committee (IC) (cfd2030.com) in 2018 for the purpose of fostering the Vision.

AIAA ICs "are focused on the cross-discipline integration, programmatic and societal interface and outreach areas of interest of the Institute," and often span more than one technical discipline in their scope as opposed to technical committees that are narrowly focused on a single discipline. Membership in an IC is not limited to AIAA members.

The mission of the CFD 2030 IC is to encourage and support a community of practice in computational simulation technologies; promote the development, application, and integration of enabling technologies; communicate and engage with the community; and ensure CFD is an integral component of the digital transformation of engineering. The IC organization consists of a leadership team (chair, vice-chair, secretary, emeritus chairs), a steering committee, subcommittees related to the ICs mission (stewardship, roadmap, outreach), subcommittees related to operating the IC (membership, publications, liaisons), and working groups related to specific activities being pursued by the IC (e.g. grand challenges).

The IC's current roster consists of over 60 individuals representing academic, government agencies, industrial end users, and commercial software developers spread across the globe.

4 Progress Toward the Vision: 2015-2021

One key aspect of the IC's mission to foster the Vision is to monitor progress toward its goals. This is a function of the Roadmap Assessment and Update (aka Roadmap) subcommittee. Roadmap draws its name from the now iconic image of the Study's technology development roadmap (Figure 1).

In 2019, the IC hosted at the AIAA Aviation Forum a session of invited presentations that assessed progress toward the Vision during the first five years after the Study's publication [References 7, 8, 9, 10, 11, 12, 13]. (In cases of an oral-only presentation, the presentation slides may be found at cfd2030.com.) In 2020, the Roadmap subcommittee produced its first comprehensive review of progress toward the Vision which included the first annual update (for 2020) as well as a 5-year lookback. The complete report is published at cfd2030.com [14] with condensed versions available via AIAA [15] and IEEE [16]. The most recent annual update for 2021 is complete but not yet published on cfd2030.com.

To keep this paper relatively brief, the following subsections provide only a high-level overview of progress. The reader is directed to the references cited in the preceding paragraph for the details.

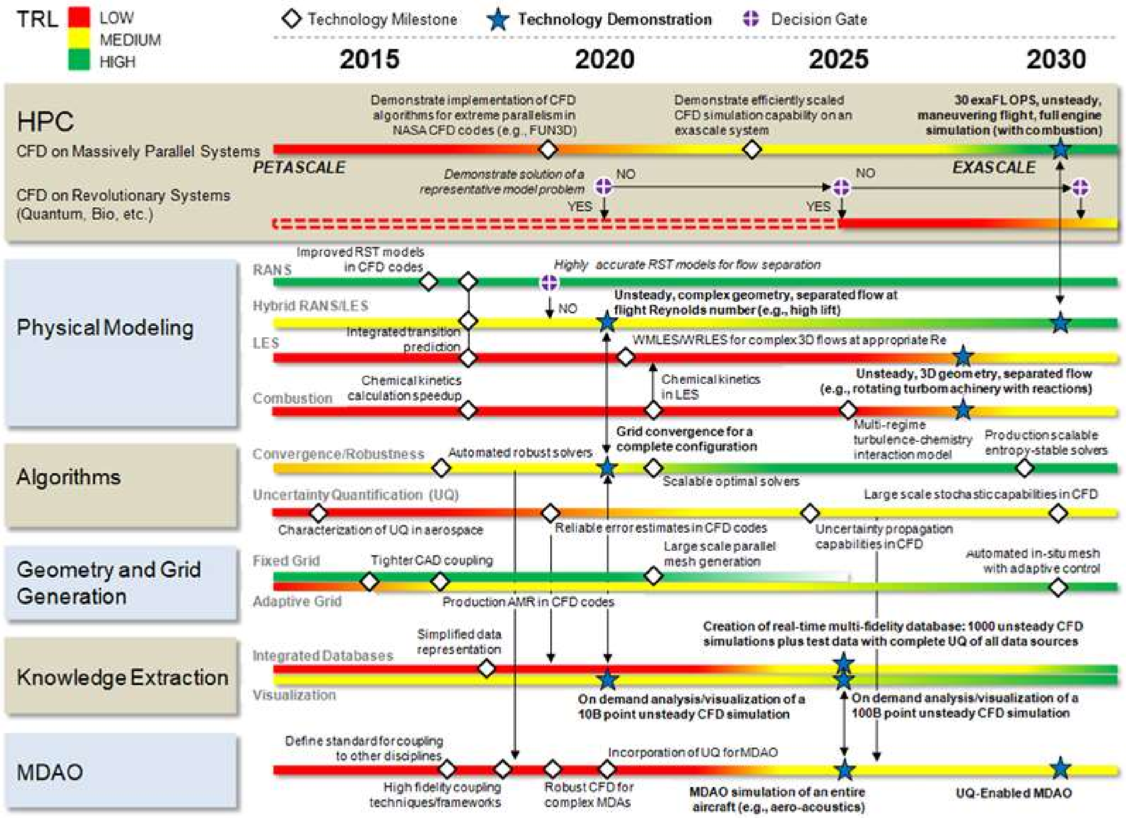

Figure 1: The CFD Vision 2030 Study's technology development roadmap.

4.1 High Performance Computing

As can be seen in Figure 1, HPC is positioned as an enabling technology over all technology domains on the roadmap. HPC is also split into two timelines for massively parallel systems (i.e., fully exploiting contemporary systems and their capabilities) and revolutionary systems (i.e., monitoring progress on and considering the programming implications of quantum and similarly advanced systems).

Historically, programming CFD for performance has been a practical matter of utilizing on the order of hundreds of compute cores via MPI or OpenMP and taking advantage of incremental compiler and platform updates. As presented in the Study, the move to exascale-class computing requires changes in programming paradigms that are much more revolutionary. Consider the case cited in [14] of porting NASA's FUN3D flow solver to the Dept. of Energy's Summit HPC system in which excellent scaling to 1,024 nodes (6,144 GPUs) was obtained, reducing simulation times from "several years to several days." That level of performance came with a considerable price in terms of years of programming effort including partnership with the hardware vendor and implementing drastic reductions in data motion across the system. The implication is that all legacy CFD software will require substantial rewriting (or restarting from scratch) to achieve just a fraction of peak performance. Other challenges faced in achieving massive parallelism are the relatively limited access to top systems (like Summit) and the fact that CFD software developers historically have not had the computer sciences skills to achieve massively parallel performance.

The situation with respect to revolutionary computing systems is similar but amplified with respect to the challenges. As noted in [14], progress on quantum platforms will involve choosing specific computational problems in CFD that are amenable to quantum and partnering with a platform provider to begin the process of porting the software.

4.2 Physical Modeling

The Physical Modeling domain of the 2014 Roadmap involves turbulence, laminar-turbulent transition, and chemical reactions. The scope of Physical Modeling was broadened in 2020 to including other modeling needs such as icing, two-phase flows, and real gas and plasma. Four timelines are included on this element of the Roadmap: RANS, Hybrid RANS/LES, LES, and Combustion. It is recognized that there is overlap between the first three.

When it comes to assessing progress on turbulence and transition, the situation is well delineated. Because RANS simulations are significantly less computationally expensive than scale-resolving simulations, there is significant motivation to improve turbulence models for use with RANS. Progress comes in the form of several detailed, high-quality experimental studies of turbulent separated flows for validation. (Of course, this experimental data can also be used for validation of scale-resolving methods as well.)

Significant effort has been spent on developing and implementing Reynolds Stress Transport (RST) models with mixed results. They have been shown to produce slightly better results for swirl-dominated flows but at higher computational cost. Their inability to show any relative improvement in the prediction of separation will not diminish interest in scale-resolving techniques.

Continued development of RANS models including RST is likely to continue for the foreseeable future, especially given that new technology like machine learning (ML) hadn't been accounted for in the Study. Several major efforts are underway to apply ML to the simulation of turbulent and separated flows such that by 2025 the community should have a better idea of the success (or at least the potential) of this approach.

Because accurate transition modeling is a critical CFD need, development of scale-resolving techniques continues at a rapid pace, yet results continue to be uneven. "Consistently accurate computations near maximum lift conditions remain collectively elusive." As the accuracy of these techniques mature so too must their computational performance to be competitive with RANS.

4.3 Numerical Algorithms

The Numerical Algorithms domain of the Roadmap covers the obvious topic as split into two timelines for convergence and robustness and uncertainty quantification (UQ). It is interesting to note that work on improving numerical algorithms is closely tied to advancements in mesh generation such as adaptive meshes and curved meshes to support high-order algorithms.

NASA's work on the Hierarchical Adaptive Nonlinear Iteration Method (HANIM) is notable for its convergence to machine zero while also being fast, reducing some computations from hours and days to a matter of minutes. Of course, HANIM is not the only advancement in numerics; low dissipation versions of traditional methods are proving to deliver accuracy while remaining low-cost. Adjoint methods continue to proliferate for error estimation. Advances in mesh adaptation are moving that technology toward maturity while at the same time presenting CFD algorithms with highly skewed and distorted cells that require robust handling.

More generally, high-order methods continue to mature and demonstrate a balance of accuracy and cost. These methods either higher accuracy for the same total number of degrees of freedom or similar accuracy at much lower – an order of magnitude in some cases – lower computational cost. An enabling technology for high-order methods is the ability to generate high-order meshes that are curved to match the boundary shape of the geometry model. Because a high-order mesh uses fewer cells than a linear mesh, generating these coarser meshes on complex geometries has proven to be a challenge unto itself. Therefore, these technologies advance in lock step.

A small but active community continues to work on UQ but the number of practical implementations remain few. Because of the complexity of UQ for CFD a lot of work involves surrogate modeling. AIAA's draft standard for CFD uncertainty is now available and includes a distinction between aleatory and epistemic uncertainties.

4.4 Geometry Modeling and Mesh Generation

The 2014 version of the Geometry Modeling and Mesh Generation domain of the Roadmap considered two timelines: fixed meshing and adaptive meshing. In 2020, this domain was updated to include timelines for geometry modeling and HPC meshing.

Fixed (or static) meshing developments are dominated by evolutionary improvements in methods to improve robustness and produce higher quality cells. Methods cover the gamut of techniques from morphing driven by geometry model changes, techniques for generating quad- or hex-dominant meshes, or optimized, mix-cell mesh generation. As a specific class of static mesh generation, high-order curved meshes continue to be a large component of ongoing research and development in order to better support ongoing development of high-order CFD numerics. Unlike the original version of the Roadmap that showed Fixed Meshing fading out by the year 2025, advancements in this technology will likely continue well into the future.

Mesh generation software's use of HPC resources for exascale is driven by both the need for speed and the need to accommodate billions of cells, although the need for the latter is being mitigated by advancements in adaptive meshing. The Study made it very clear that the use of HPC assets by flow solvers could use improvement but for pre- and post-processing the Study stated the situation was much worse. What is needed is the ability to rapidly generate a large number of moderately sized meshes on a regular basis and the ability to generate a few massively-sized meshes as needed. Most of the on-going research and development involves the former need and utilizes a hybrid approach to parallelism: coarse grain at the domain decomposition level and fine grain at the compute node level.

It is worth noting that virtually all reviewed literature on HPC meshing involves unstructured grids. The algorithms used to generate structured quad grids are much more amenable to parallelization and offer a tantalizing opportunity should the other changes associated with structured grids (i.e., domain decomposition) be overcome.

The Study specifically cited the inability to generate a suitable mesh on the first attempt as an impediment to the Vision. For a static mesh, the burden becomes one of generating the best mesh right from the start. Adaptive meshing promises to remove that up-front burden by starting from a minimum viable mesh (which can presumably be generated more reliably and robustly) and modifying that mesh in response to the evolving flow solution. Recently published work has demonstrated this capability in practice. Some adaptive mesh implementations have matured to the point where one of the remaining challenges is surface mesh adaptation in the presence of tolerance-level features in the geometry model.

The suitability of Mechanical CAD (MCAD) geometry models for CFD simulation continues to vex the community. To avoid the challenges typically presented by MCAD geometry models, a trend has been the development of proprietary geometry kernels and modeling systems that focus on the simulation needs of analysts. Not only does this approach avoid most interoperability problems but this newer software can also target HPC platforms better than legacy tools.

4.5 Knowledge Extraction

The Knowledge Extraction domain of the Roadmap considers not just visualization but the ability to store, recall, query and otherwise manipulate exascale-level CFD datasets. As the other domains of the Roadmap drive simulation to larger sizes (for accuracy or for multidisciplinary simulations) strategies are needed for maximizing the engineering knowledge that can be extracted from them both at the time of simulation and throughout the life of the object being simulated.

Extremely large simulations have been interactively visualized recently including a 10 billion element FUN3D computation of NASA's Mars Lander, a 150 TB dataset. Another active line of development involves extracting minimal datasets while the flow solver is running to minimize dataset size and extract only the quantities of interest.

Research into compilation of simulation datasets is active at a number of organizations but suffers from cross-organization or cross-application interoperability.

4.6 Multidisciplinary Analysis and Optimization

The Study anticipates that multidisciplinary simulations will be routine and will couple fluids with thermal, structures, acoustics, and other disciplines. Each discipline will necessarily require advancement in terms of all the other elements of the vision (e.g. algorithms, meshing) in order to be efficient but the entirety will require effective, standardized interoperability frameworks for the sharing of information.

Much of the progress in MDAO has taken the partitioned approach in which each discipline involved utilizes a separate solver. As is often the case, the focus in a partitioned approach is data sharing at the interfaces between disciplines (e.g. fluid and solid regions) such that accuracy is maintained. To date, no widely accepted standard means of managing the interfaces has been developed. Pathfinding efforts have revealed quite clearly that efficient turnaround time dictate that file I/O must be avoided. Instead, they have illustrated the use of direct memory access using a common API. The need for computational efficiency cannot be overstated as the number of design parameters in a multidisciplinary simulation can be on the order of 100,000.

4.7 Updated Roadmap and TRL

The 2020 Roadmap update presented an opportunity beyond assessing progress toward the Vision but also in terms of updating the Roadmap itself. The result is shown in Figure 2.

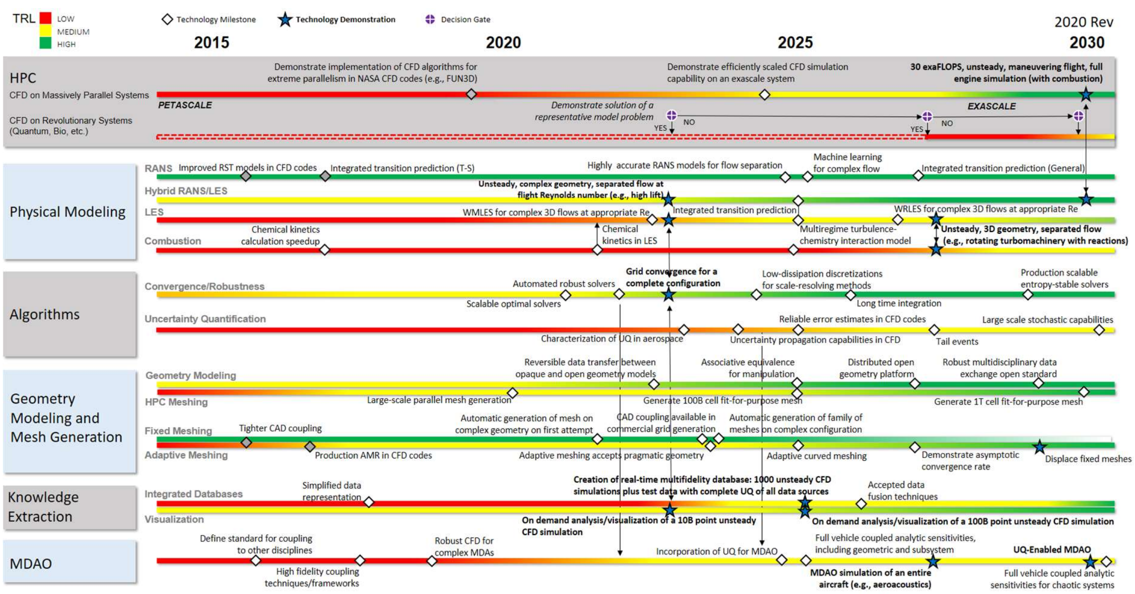

Figure 2: The CFD Vision 2030 Technology Development Roadmap as updated in 2020.

During the 2020 roadmap update, the issue of assessing progress in an objective manner was addressed. Without any such objective measures, it will be difficult to assess progress or achievement of any of the milestones or demonstrations noted along the timelines. The original Study utilized a qualitative low-medium-high (red-yellow-green) scale. The 2020 Roadmap update instituted a quantified 1-9 scale based upon those documented by the U.S. Dept. of Defense in their Defense Acquisition Guidebook. The definitions of the levels were modified to fit the purposes of the Vision and are as follows.

1. Publication of a high-quality conference article in which the concept and underlying principles are described.
2. Publication of a high-quality journal article in which results from a feasibility study are described.
3. Publication of an article or high-quality paper in which the capability of a prototype (perhaps under limited scope) is demonstrated.

4. A basic demo involving successful evaluation and/or implementation of the capability has been performed by a single group.
5. A production-level application involving successful demonstration of the capability has been performed by a single group.
6. Multiple production-level applications involving successful uses of the capability have been completed by a single group.
7. An evaluation/use (beyond demonstration) of the capability has been successfully performed by independent organizations (perhaps in different implementations) based on a significant milestone in terms of efficiency, ease of use/robustness, or accuracy.
8. Application (beyond demonstration) of the capability has been successfully performed by multiple independent organizations based on sufficient robustness and a return of value in excess of the investment.
9. Routine, standard, and successful application of the capability by multiple organizations and acceptance of results by multiple groups.

5 Grand Challenges

In order to better assess the state of CFD relative to the Study's goals, the CFD 2030 IC has reassessed the GC problems included in the Study and commenced the design and implementation of a progression of updated GC problems in the areas of high-lift aerodynamics [19], gas turbine engines [20], and space vehicles [21]. A fourth GC based on hypersonic flows is currently under consideration.

Each GC shares similar needs: experimental datasets for validation, a build-up of sub-challenges, and a framework for demonstration over time of advancement toward achievement of the GC. Executing the GCs will require a community effort. Leveraging existing communities such as those involved with AIAA's ongoing CFD workshops may present a viable path forward. Discussions on this topic were to be held at the AIAA Aviation Forum in June 2022.

5.1 High-Lift Aerodynamics

For aircraft CFD in particular, achievement of the Vision should make aircraft certification by analysis (CbA) possible. The prospects for achieving CbA were assessed in [18]. The GC being considered by the IC is a common maneuver in the regulatory process called a wind-up turn (WUT). The aircraft is operating at a subsonic condition with flaps deployed and a coordinated turn is performed at constant altitude and airspeed while angle of attack and load factor are increased.

Simulating a WUT will stress nearly every aspect of the Vision including unsteady separated flow, complex and deforming geometry, powered engine effects, UQ, and more. As is the case for all the GCs, a series of sub-challenges (SC) will be required to build up capability and confidence as we approach the full GC. The first SC will be the flow physics of an aircraft in high-lift configuration, something already being addressed by the AIAA's High Lift Prediction workshop series which is focused on a standard and open configuration, the NASA Common Research Model (CRM). Other SCs will include diverse topics such as propulsion effects, stability and control, icing, and multidisciplinary coupling.

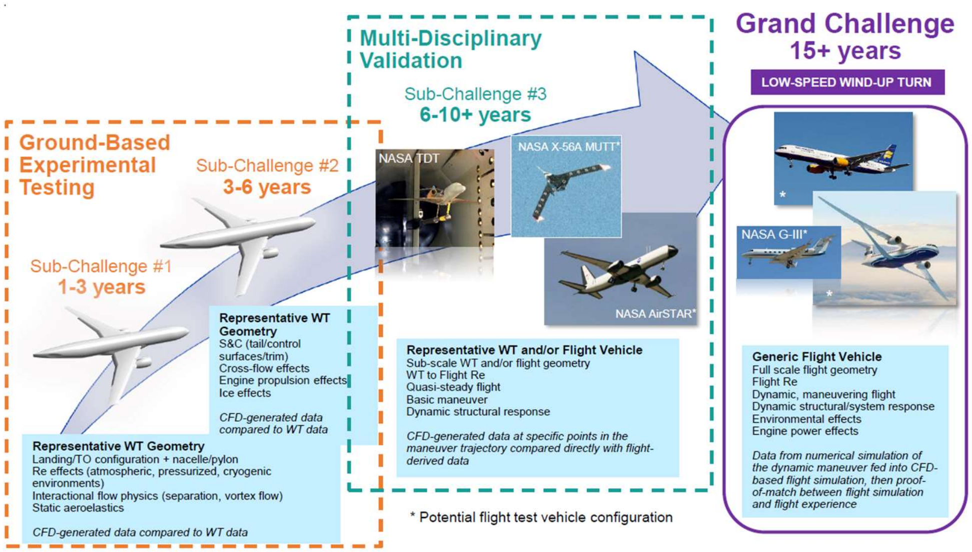

Figure 3: Illustration of a grand challenge for high-lift aerodynamics.

5.2 Gas Turbine Engines

Given that gas turbines will likely be the predominant form of propulsion for transport aircraft for the foreseeable future, a GC centered around transient simulation of a complete gas turbine engine (fan, compressor, combustor, turbine) at an off-design condition is a logical choice.

As is the case for the other GCs, every aspect of the Vision will be touched by this including the need for high fidelity geometry, boundary layer separation and reattachment, high heat loads and the necessary cooling, and coupling multiple solvers. If simulations like this GC could be completed in a week of calendar time, the savings to industry would sum into the billions of dollars.

Unlike the high-lift GC, an additional challenge faced by the gas turbine GC is the lack of a standard and open geometry model like the CRM and associated experimental dataset.

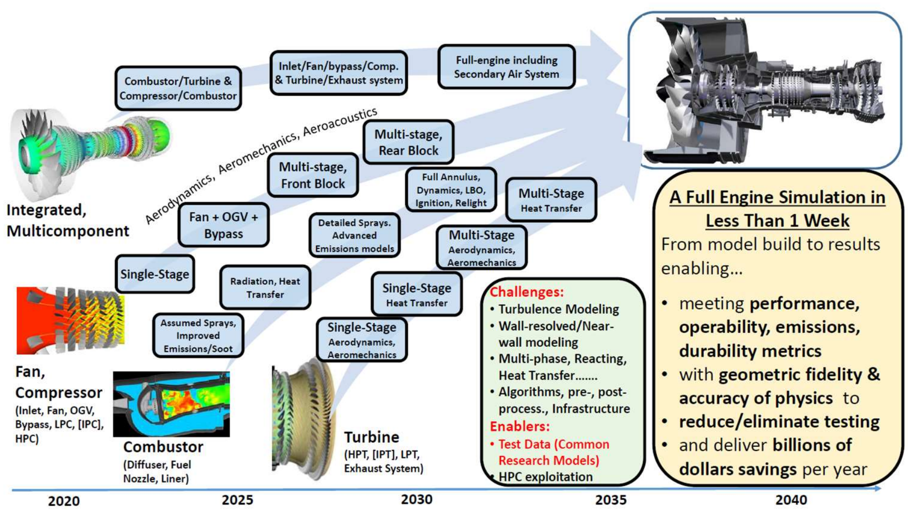

Figure 4: Illustration of a grand challenge for a complete propulsion system.

5.3 Space Vehicles

Simulation of spacecraft, whether during ascent or during entry, descent, and landing (EDL) presents several unique challenges. Unlike other flight vehicles that can be designed to operate within relatively narrow flight regimes, launch vehicles and landers fly across the entire subsonic, supersonic, hypersonic spectrum. Because of the latter (hypersonics), there are often few ground or flight test opportunities to collect relevant data for validation. Flight often occurs at a wide range of vehicle orientations which subject the vehicle to a wide range of boundary layer separation often induced by shock wave interactions. Maneuvering often calls for the use of nozzle gimballing and reaction control jets which necessitate plume interactions. Geometry can be quite complex, especially a launch vehicle, and varying if ablation need be accounted for. For the purposes of a GC, an EDL configuration might be preferred if only for the simpler geometry.

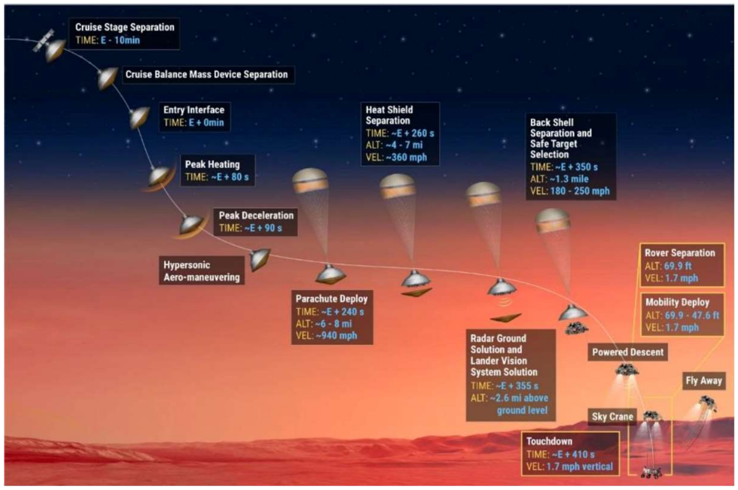

Figure 5: Example of a Mars lander's entry, descent, and landing mission profile as the basis of a space grand challenge.

6 Conclusion and Future Work

The CFD Vision 2030 Study has galvanized and focused CFD development on a shared future that extends beyond aerospace. Whether the year 2030 is a notional target or an achievable milestone is not really relevant; the timelines of proposed grand challenges extend to 2040. Execution of grand challenge problems and their component sub-problems offer the ability to quantify progress and more rigorously assess technology readiness levels. More than that, they provide a motivation for the community to drive CFD forward. Toward that end, the CFD 2030 Integration Committee seeks active volunteers to bring the Vision to fruition. While progress in CFD technology would be made regardless, by rallying around the CFD Vision 2030 the industry has an opportunity to achieve something truly transformational.

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