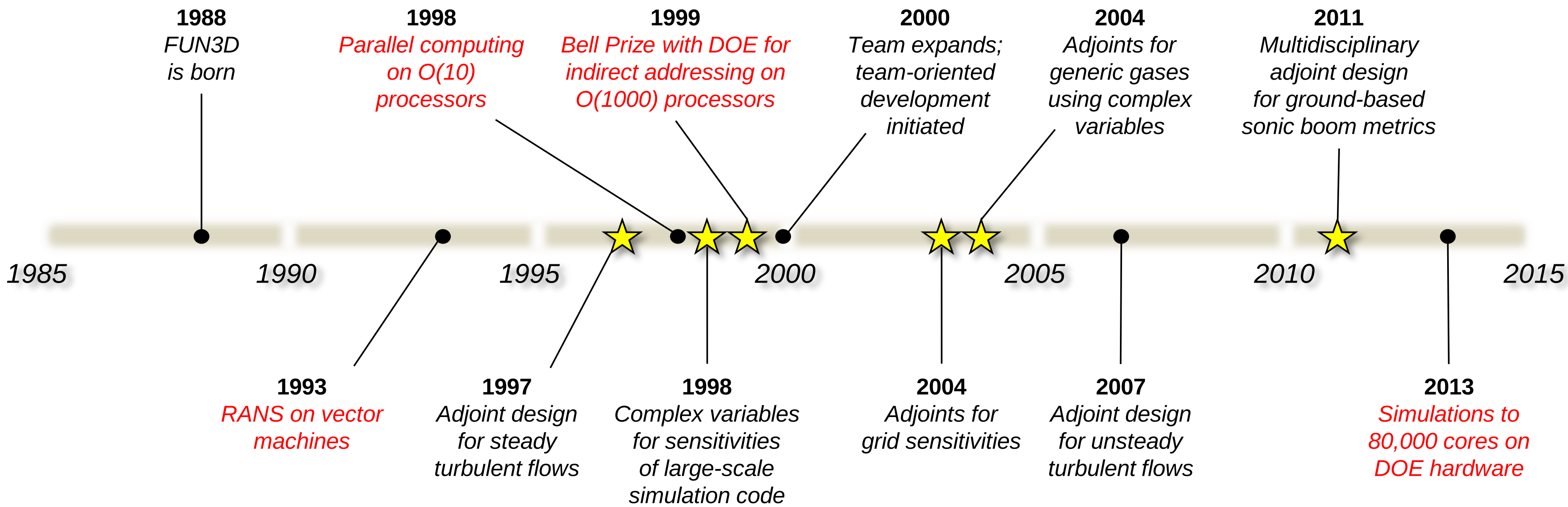
FUN3D and the Road to ModSim-Based Design

Eric Nielsen
and the
FUN3D Development Team

Research Engineer
Research Directorate/Computational AeroSciences Branch

Towards Physics-Based Design

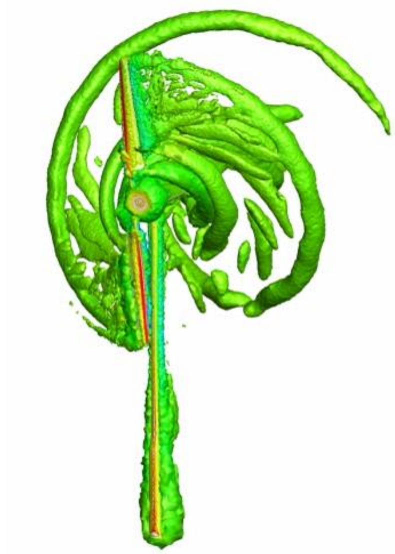
- Many variables & expensive simulations suggest a gradient-based approach
- Conventional sensitivity analysis intractable
- Adjoint method efficiently provides unlimited sensitivities



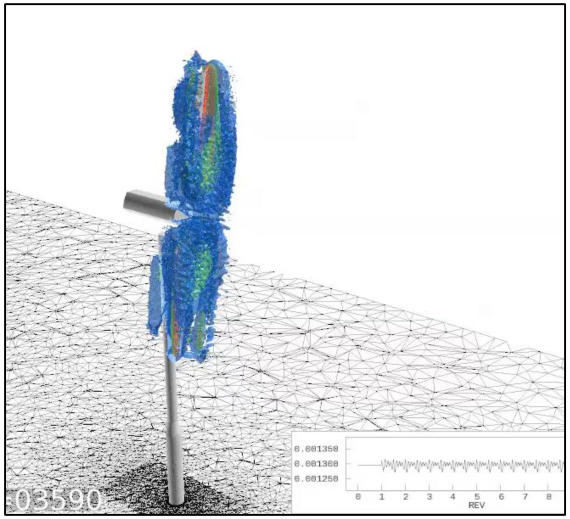
HPC-related milestones in red   ☆ *Internationally-unique capability*

The Adjoint Approach

- The Navier-Stokes equations are solved forward in time to give information about the flow field (lift, drag)
- For design, we need to know how the flow field is sensitive to a change in design parameters (chord, sweep)
- Perturbing each parameter, computing the flow field, and differencing the output to obtain sensitivity is intractable for multiple variables



- An auxiliary set of adjoint equations are obtained by differentiating the governing equations
- Adjoint equations are solved backward in time to determine which parameters impact a given output and how
- This provides efficient sensitivity analysis for all inputs simultaneously



Langley Research Center

The Adjoint Equations

- The time-dependent adjoint equations are considerably more complex than the Navier-Stokes equations
- Total FUN3D implementation consists of nearly 1 million lines of code
- Tremendous amount of software infrastructure required

$$\mathbf{C}_s^n \circ \left[a\frac{\mathbf{Q}_s^n - \mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t} \circ \mathbf{V}_s^n + c\frac{\mathbf{I}_s^n\mathbf{Q}^{n-2} - \mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t} \circ \mathbf{I}_s^n\mathbf{V}^{n-2} + d\frac{\mathbf{I}_s^n\mathbf{Q}^{n-3} - \mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t} \circ \mathbf{I}_s^n\mathbf{V}^{n-3} \right] + \mathbf{R}^n + ((\mathbf{I}_s^n\mathbf{Q}^{n-1}) \circ \mathbf{C}_s^n + \beta\bar{\mathbf{C}}_s^n) \circ \mathbf{R}_{\mathrm{GCL}}^n = 0 \quad \text{(A1)}$$

Proceeding as before, the Lagrangian can be written as

$$\begin{aligned} L(\mathbf{D},\mathbf{Q},\mathbf{X},\mathbf{\Lambda},\mathbf{\Lambda}_g) &= f\Delta t + \sum_{n=1}^{N}[\mathbf{\Lambda}_g^n]^T\mathbf{G}^n\Delta t \\ &+ \sum_{n=1}^{N}\Big\{[\mathbf{C}_s^n \circ \mathbf{\Lambda}_s^n]^T\Big[a\frac{\mathbf{Q}_s^n - \mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t} \circ \mathbf{V}_s^n \\ &+ c\frac{\mathbf{I}_s^n\mathbf{Q}^{n-2} - \mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t} \circ (\mathbf{I}_s^n\mathbf{V}^{n-2}) \\ &+ d\frac{\mathbf{I}_s^n\mathbf{Q}^{n-3} - \mathbf{I}_s^n\mathbf{Q}^{n-1}}{\Delta t} \circ (\mathbf{I}_s^n\mathbf{V}^{n-3})\Big] \\ &+ [\mathbf{\Lambda}_s^n]^T[\mathbf{R}^n + ((\mathbf{I}_s^n\mathbf{Q}^{n-1})\circ\mathbf{C}_s^n + \beta\bar{\mathbf{C}}_s^n)\circ\mathbf{R}_{\mathrm{GCL}}^n] \\ &+ [\mathbf{\Lambda}_f^n]^T[\mathbf{A}^n\mathbf{Q}^n] + [\mathbf{\Lambda}_h^n]^T[\mathbf{P}^n\mathbf{Q}^n]\Big\}\Delta t \\ &+ (f^0 + [\mathbf{\Lambda}_g^0]^T\mathbf{G}^0 + [\mathbf{\Lambda}^0]^T\mathbf{R}^{\mathrm{in}})\Delta t \end{aligned} \quad \text{(A2)}$$

On time levels 1 and 2, the time derivatives are assumed to be discretized with the BDF1 and BDF2 schemes, respectively. Taking into account the dependencies on data at time levels $n-2$ and $n-3$, the adjoint equations are obtained as follows:

S:

$$\begin{aligned} &\frac{a}{\Delta t}\mathbf{V}_s^n \circ \mathbf{C}_s^n \circ \mathbf{\Lambda}_s^n + \left[\frac{\partial \mathbf{R}^n}{\partial \mathbf{Q}_s^n}\right]^T\mathbf{\Lambda}_s^n + [\mathbf{A}_s^n]^T\mathbf{\Lambda}_f^n + [\mathbf{P}_s^n]^T\mathbf{\Lambda}_h^n = -\left[\frac{\partial f}{\partial \mathbf{Q}_s^n}\right]^T \\ &-\mathbf{I}_s^n\Big\{[\mathbf{I}_s^{n+1}]^T\Big[\Big(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1} - \frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1} - \frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2} \\ &+ \mathbf{R}_{\mathrm{GCL}}^{n+1}\Big) \circ \mathbf{C}_s^{n+1} \circ \mathbf{\Lambda}_s^{n+1}\Big] + [\mathbf{I}_s^{n+2}]^T\Big[\Big(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+2} \circ \mathbf{\Lambda}_s^{n+2}\Big] \\ &+ [\mathbf{I}_s^{n+3}]^T\Big[\Big(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+3} \circ \mathbf{\Lambda}_s^{n+3}\Big]\Big\} \end{aligned}$$

F:

$$\begin{aligned} &\left[\frac{\partial \mathbf{R}^n}{\partial \mathbf{Q}_f^n}\right]^T\mathbf{\Lambda}_s^n + [\mathbf{A}_f^n]^T\mathbf{\Lambda}_f^n + [\mathbf{P}_f^n]^T\mathbf{\Lambda}_h^n = -\left[\frac{\partial f}{\partial \mathbf{Q}_f^n}\right]^T \\ &-\mathbf{I}_f^n\Big\{[\mathbf{I}_s^{n+1}]^T\Big[\Big(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1} - \frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1} - \frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2} \\ &+ \mathbf{R}_{\mathrm{GCL}}^{n+1}\Big) \circ \mathbf{C}_s^{n+1} \circ \mathbf{\Lambda}_s^{n+1}\Big] + [\mathbf{I}_s^{n+2}]^T\Big[\Big(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+2} \circ \mathbf{\Lambda}_s^{n+2}\Big] \\ &+ [\mathbf{I}_s^{n+3}]^T\Big[\Big(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+3} \circ \mathbf{\Lambda}_s^{n+3}\Big]\Big\} \end{aligned}$$

H:

$$\begin{aligned} &\left[\frac{\partial \mathbf{R}^n}{\partial \mathbf{Q}_h^n}\right]^T\mathbf{\Lambda}_s^n + [\mathbf{A}_h^n]^T\mathbf{\Lambda}_f^n + [\mathbf{P}_h^n]^T\mathbf{\Lambda}_h^n = -\left[\frac{\partial f}{\partial \mathbf{Q}_h^n}\right]^T \\ &-\mathbf{I}_h^n\Big\{[\mathbf{I}_s^{n+1}]^T\Big[\Big(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1} - \frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1} - \frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2} \\ &+ \mathbf{R}_{\mathrm{GCL}}^{n+1}\Big) \circ \mathbf{C}_s^{n+1} \circ \mathbf{\Lambda}_s^{n+1}\Big] + [\mathbf{I}_s^{n+2}]^T\Big[\Big(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+2} \circ \mathbf{\Lambda}_s^{n+2}\Big] \\ &+ [\mathbf{I}_s^{n+3}]^T\Big[\Big(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+3} \circ \mathbf{\Lambda}_s^{n+3}\Big]\Big\} \end{aligned}$$

for $3 \leq n \leq N$ (A3)

S:

$$\begin{aligned} &\frac{3}{2\Delta t}\mathbf{V}_s^n \circ \mathbf{C}_s^n \circ \mathbf{\Lambda}_s^n + \left[\frac{\partial \mathbf{R}^n}{\partial \mathbf{Q}_s^n}\right]^T\mathbf{\Lambda}_s^n + [\mathbf{A}_s^n]^T\mathbf{\Lambda}_f^n + [\mathbf{P}_s^n]^T\mathbf{\Lambda}_h^n = \\ &-\left[\frac{\partial f}{\partial \mathbf{Q}_s^n}\right]^T - \mathbf{I}_s^n\Big\{[\mathbf{I}_s^{n+1}]^T\Big[\Big(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1} - \frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1} \\ &-\frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2} + \mathbf{R}_{\mathrm{GCL}}^{n+1}\Big) \circ \mathbf{C}_s^{n+1} \circ \mathbf{\Lambda}_s^{n+1}\Big] \\ &+ [\mathbf{I}_s^{n+2}]^T\Big[\Big(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+2} \circ \mathbf{\Lambda}_s^{n+2}\Big] \\ &+ [\mathbf{I}_s^{n+3}]^T\Big[\Big(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+3} \circ \mathbf{\Lambda}_s^{n+3}\Big]\Big\} \end{aligned}$$

F:

$$\begin{aligned} &\left[\frac{\partial \mathbf{R}^n}{\partial \mathbf{Q}_f^n}\right]^T\mathbf{\Lambda}_s^n + [\mathbf{A}_f^n]^T\mathbf{\Lambda}_f^n + [\mathbf{P}_f^n]^T\mathbf{\Lambda}_h^n = -\left[\frac{\partial f}{\partial \mathbf{Q}_f^n}\right]^T \\ &-\mathbf{I}_f^n\Big\{[\mathbf{I}_s^{n+1}]^T\Big[\Big(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1} - \frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1} - \frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2} \\ &+ \mathbf{R}_{\mathrm{GCL}}^{n+1}\Big) \circ \mathbf{C}_s^{n+1} \circ \mathbf{\Lambda}_s^{n+1}\Big] + [\mathbf{I}_s^{n+2}]^T\Big[\Big(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+2} \circ \mathbf{\Lambda}_s^{n+2}\Big] \\ &+ [\mathbf{I}_s^{n+3}]^T\Big[\Big(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+3} \circ \mathbf{\Lambda}_s^{n+3}\Big]\Big\} \end{aligned}$$

H:

$$\begin{aligned} &\left[\frac{\partial \mathbf{R}^n}{\partial \mathbf{Q}_h^n}\right]^T\mathbf{\Lambda}_s^n + [\mathbf{A}_h^n]^T\mathbf{\Lambda}_f^n + [\mathbf{P}_h^n]^T\mathbf{\Lambda}_h^n = -\left[\frac{\partial f}{\partial \mathbf{Q}_h^n}\right]^T \\ &-\mathbf{I}_h^n\Big\{[\mathbf{I}_s^{n+1}]^T\Big[\Big(-\frac{a}{\Delta t}\mathbf{V}_s^{n+1} - \frac{c}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1} - \frac{d}{\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-2} \\ &+ \mathbf{R}_{\mathrm{GCL}}^{n+1}\Big) \circ \mathbf{C}_s^{n+1} \circ \mathbf{\Lambda}_s^{n+1}\Big] + [\mathbf{I}_s^{n+2}]^T\Big[\Big(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+2} \circ \mathbf{\Lambda}_s^{n+2}\Big] \\ &+ [\mathbf{I}_s^{n+3}]^T\Big[\Big(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+3} \circ \mathbf{\Lambda}_s^{n+3}\Big]\Big\} \end{aligned}$$

for $n=2$ (A4)

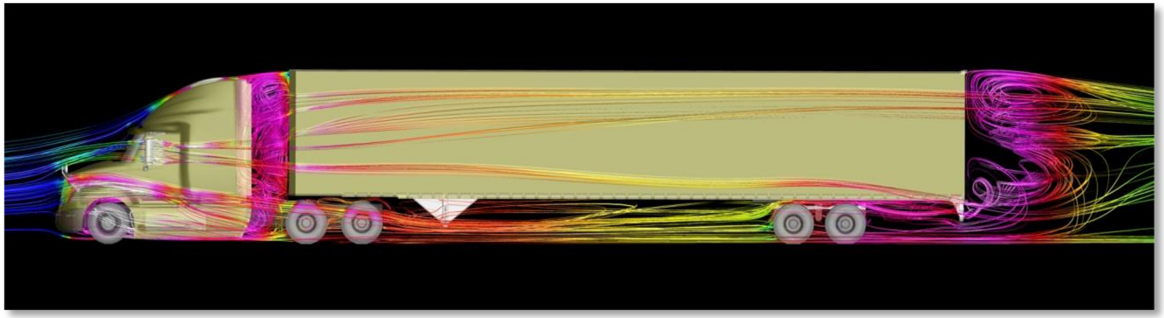
$$\begin{aligned} S:\ &\frac{1}{\Delta t}\mathbf{V}_s^n \circ \mathbf{C}_s^n \circ \mathbf{\Lambda}_s^n + \left[\frac{\partial \mathbf{R}^n}{\partial \mathbf{Q}_s^n}\right]^T\mathbf{\Lambda}_s^n + [\mathbf{A}_s^n]^T\mathbf{\Lambda}_f^n + [\mathbf{P}_s^n]^T\mathbf{\Lambda}_h^n \\ &= -\left[\frac{\partial f}{\partial \mathbf{Q}_s^n}\right]^T - \mathbf{I}_s^n\Big\{[\mathbf{I}_s^{n+1}]^T\Big[\Big(-\frac{3}{2\Delta t}\mathbf{V}_s^{n+1} \\ &-\frac{1}{2\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1} + \mathbf{R}_{\mathrm{GCL}}^{n+1}\Big) \circ \\ &+ [\mathbf{I}_s^{n+2}]^T\Big[\Big(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\Big) \circ \\ &+ [\mathbf{I}_s^{n+3}]^T\Big[\Big(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\Big) \circ \\ F:\ &\left[\frac{\partial \mathbf{R}^n}{\partial \mathbf{Q}_f^n}\right]^T\mathbf{\Lambda}_s^n + [\mathbf{A}_f^n]^T\mathbf{\Lambda}_f^n + \\ &= -\left[\frac{\partial f}{\partial \mathbf{Q}_f^n}\right]^T - \mathbf{I}_f^n\Big\{[\mathbf{I}_s^{n+1}]^T \\ &-\frac{1}{2\Delta t}\mathbf{I}_s^{n+1}\mathbf{V}^{n-1} + \mathbf{R}_{\mathrm{GCL}}^{n+1}\Big) \circ \\ &+ [\mathbf{I}_s^{n+2}]^T\Big[\Big(\frac{c}{\Delta t}\mathbf{I}_s^{n+2}\mathbf{V}^n\Big) \circ \\ &+ [\mathbf{I}_s^{n+3}]^T\Big[\Big(\frac{d}{\Delta t}\mathbf{I}_s^{n+3}\mathbf{V}^n\Big) \circ \mathbf{C}_s^{n+3} \circ \mathbf{\Lambda}_s^{n+3}\Big]\Big\} \end{aligned}$$

Page 1 of 4 of the adjoint equations derived and implemented in:

Nielsen, E.J., and Diskin, B., "Discrete Adjoint-Based Design for Unsteady Turbulent Flows on Dynamic Overset Unstructured Grids," AIAA Journal, Vol. 51, No. 6, June 2013.

Long-Term Research Effort

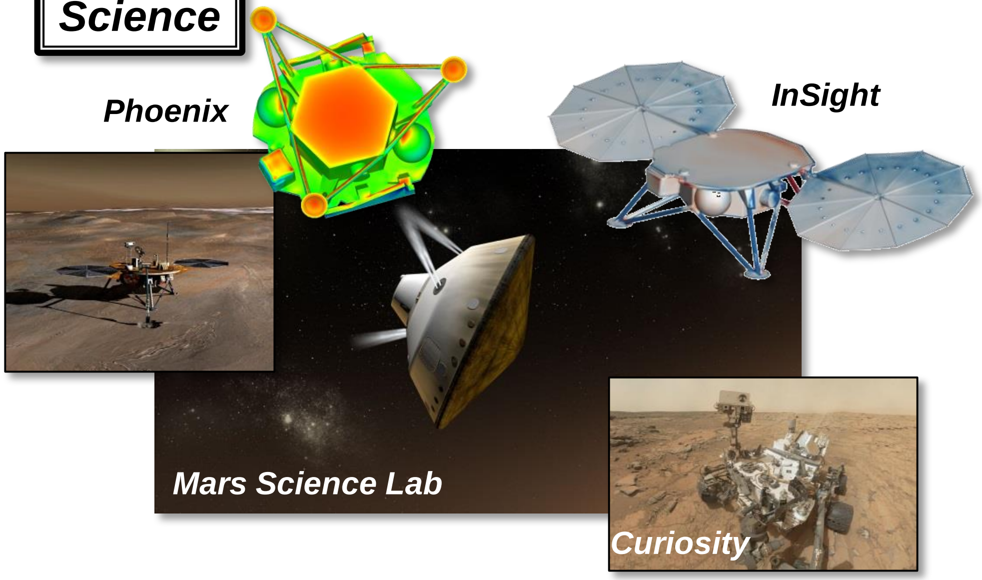
- FUN3D development has involved more than 25 years of dedicated work
  - Weathered numerous programmatic/organizational restructurings
  - Has attracted participation from numerous researchers
  - High-risk / high-payoff in line with NASA's mission
- Robust analysis capability is foundational to physics-based design
- A sizeable user base has grown up with FUN3D development
  - Support for numerous NASA missions
  - FUN3D has been integrated into validated industry processes
  - The increase in capability is quickly adopted by existing users
  - User base continues to grow
- Broad application has helped to harden the analysis capability



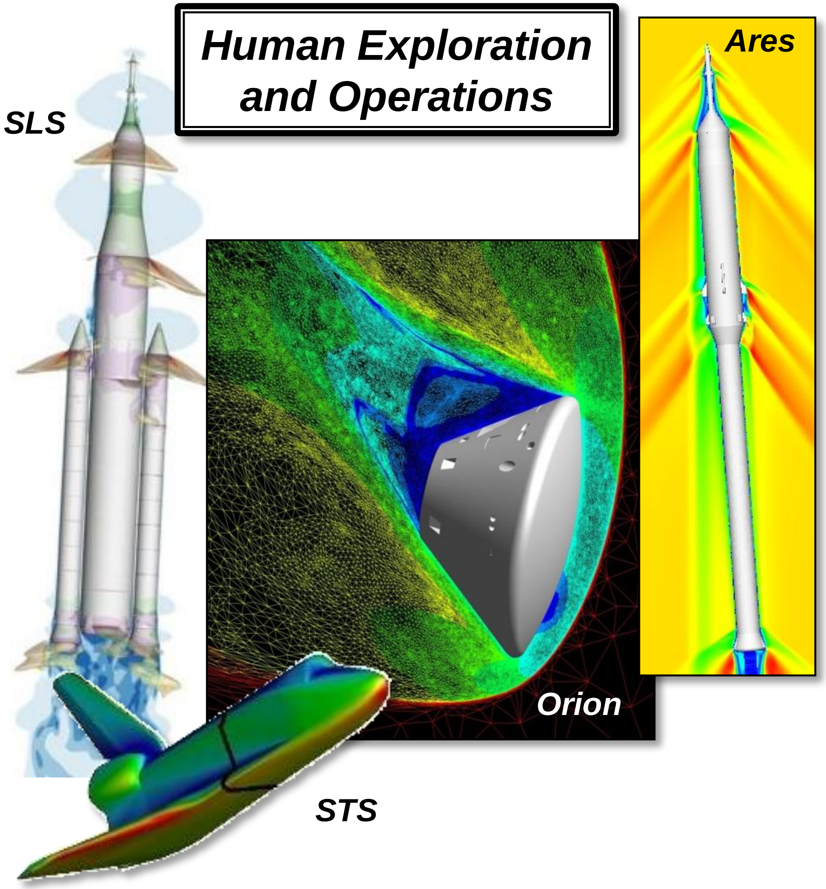
Across NASA Missions

FUN3D supplies critical physics-based aerodynamics for a broad range of applications across all Mission Directorates

Science



Human Exploration and Operations



"The FUN3D team has developed a capability that continues to find new and unique applications of significant importance to the agency."

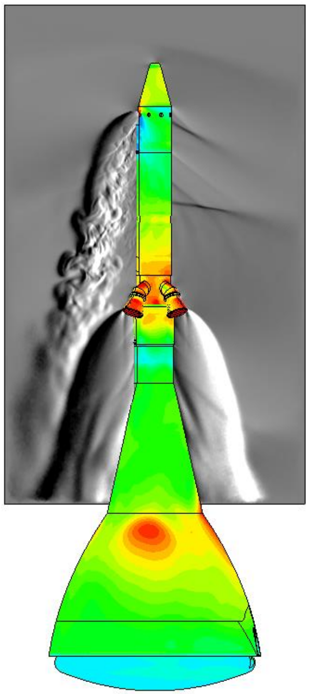
- Dave Schuster
NASA Technical Fellow for Aerosciences
NASA Engineering and Safety Center

Langley Research Center

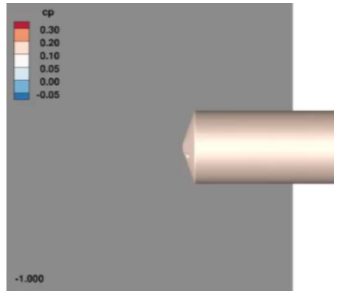
Across NASA Missions

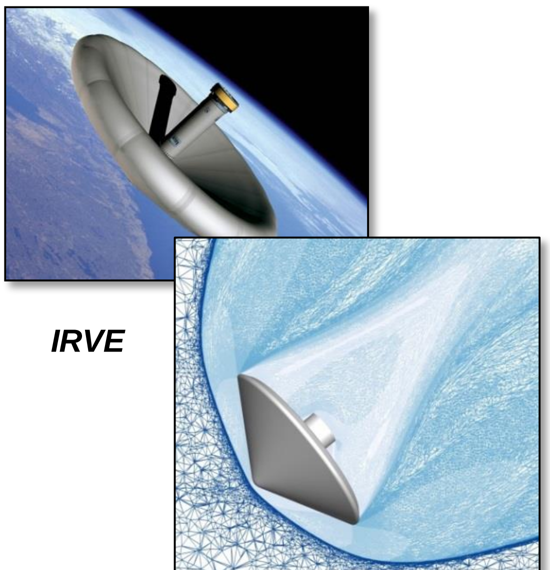
Space Technology

Launch Abort



Supersonic Retropropulsion

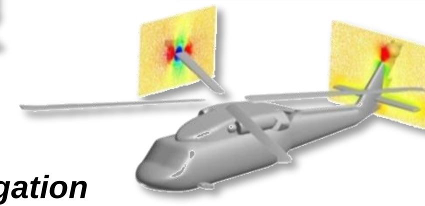




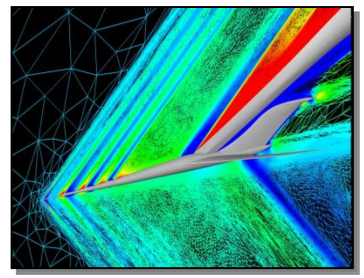
IRVE

Aeronautics Research

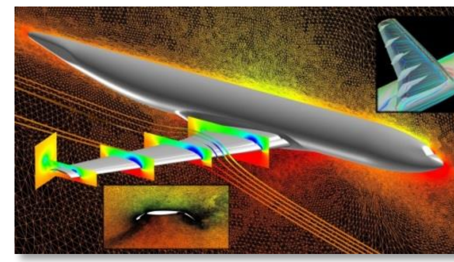
Rotorcraft

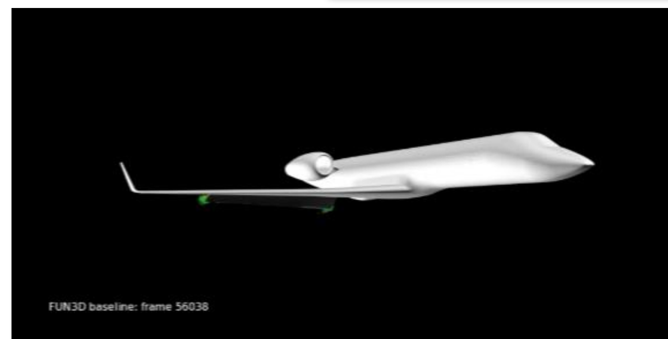


Sonic Boom Mitigation



Airframe Noise





Due to increased demand from NASA scientists and engineers, FUN3D simulations now account for the single largest block of supercomputing cycles at the Agency: 12% of NAS, or approximately 200 million hours per year

Across the Aerospace Industry

SPACEX

First private company to achieve orbit
and dock with the International Space Station

Primary aerodynamics tool: FUN3D

- FUN3D used for extensive analysis of Falcon 1 and Falcon 9 rockets, Dragon spacecraft
- Team consults frequently and provides new features and capabilities as requested

"The FUN3D software suite and development team have enabled SpaceX to rapidly design, build, and successfully fly a new generation of rockets and spacecraft."

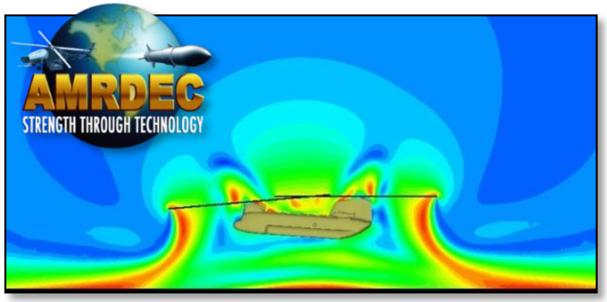
- Justin Richeson
Manager, SpaceX Aerodynamics

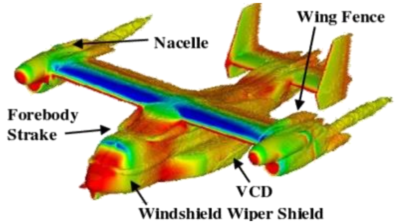
At the Department of Defense


CH-47

AMRDEC at Redstone Arsenal

- **Troop safety:** airworthiness qualification
- **Dramatic cost savings:** fewer tunnel & flight tests
- Intense demand for timely results on massive computing systems
- Decade of use in direct support of the US warfighter





V-22

Air Force Research Labs

- Funded on-site training workshop (20 students)

NAVAIR at Patuxent River

- Hosted on-site training workshop
- Hired two recent Georgia Tech PhD grads
  - FUN3D development for theses

Other Government Agencies

Argonne NATIONAL LABORATORY

LAWRENCE LIVERMORE NATIONAL LABORATORY

- Gordon Bell Prize awarded to FUN3D / ANL / LLNL team
  - Most prestigious award in High Performance Computing community

OAK RIDGE National Laboratory

BMI Corporation

- Joint collaboration improving fuel efficiency for 18-wheeler trucks
- Covered by print and TV news
- Simulations performed on Jaguar
  - The world's most powerful supercomputer at the time

NSF

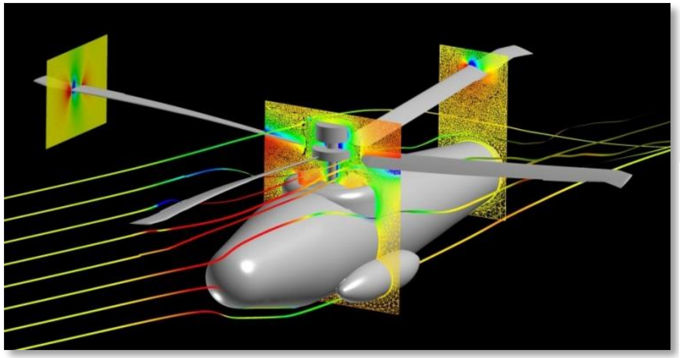
NCSA

GT

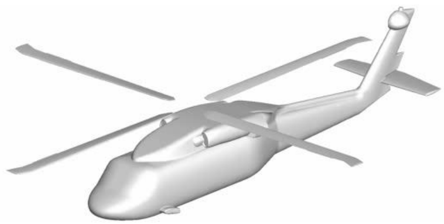
- Reduced wind turbine noise while maintaining performance

Across Academia

- Over 50 students have interned with the team or conducted thesis work using FUN3D: 20 MS and PhD theses generated
- Graduates with hands-on FUN3D experience are highly sought after

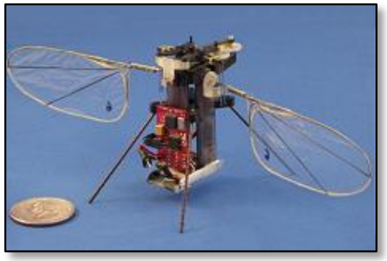


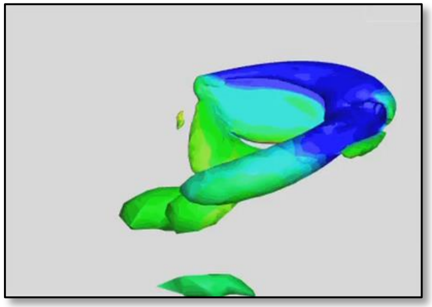
Georgia Tech has played a significant role in modeling vehicles with moving parts, such as helicopters



"FUN3D is a vital national resource…the investment that NASA has made has generated at least a hundredfold in return on investment…"

- Dr. Marilyn Smith, Georgia Tech





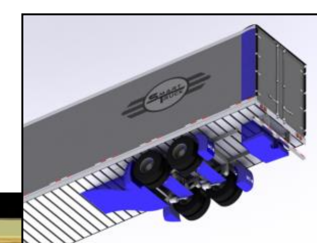
North Carolina A&T has used FUN3D to optimize biologically-inspired micro-air vehicles for the US Army

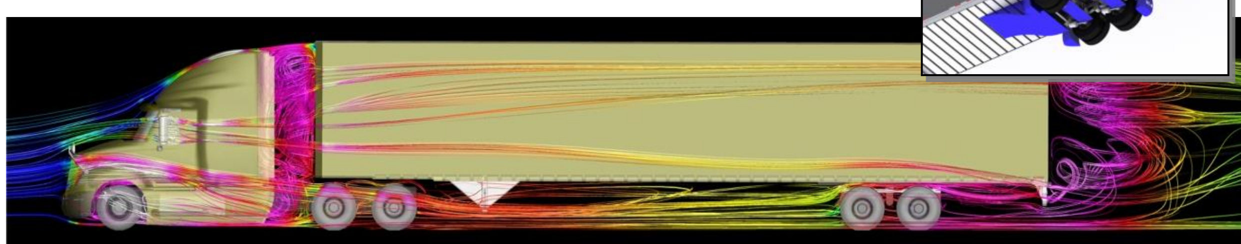
Outside Aerospace

BMI Corporation

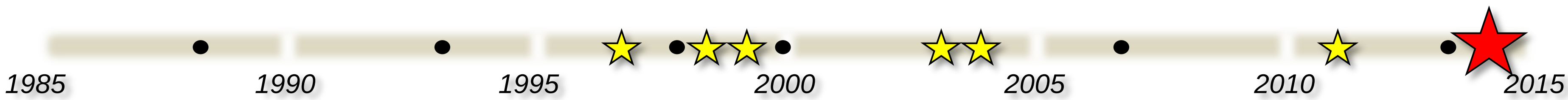
- Used FUN3D on world's largest supercomputer to perform the most advanced truck simulations ever attempted
- Developed add-on kits that improve fuel mileage by as much as 11%
- Spin-off company has sold over 40,000 units

"FUN3D is a national asset."
- Mike Henderson,
BMI Founder





Long Term R & D Pays Off



2014: Efficient Sensitivity Analysis for Unsteady Flows and General Kinematics

- FUN3D provides sensitivities for thousands of design parameters at the cost of a single simulation using the adjoint approach
- Culminating publication was recently awarded the H.J.E. Reid Award

What Has Made It Possible

- Extensive research in algorithms and turbulence modeling
- Collaborative software development and automated testing
- End-to-end high-performance computing strategies
- Continued reliance on experimental validation

What is the Impact

- Design with thousands of variables and high-end CFD simulations now tractable
- A number of innovations considered seminal in the field of adjoint methods
- Numerous organizations around the world cite FUN3D as a model for their own efforts
- Starting to formally address MDO through collaboration with other disciplines

Team-Oriented Development

Team-oriented strategy is critical

- Broad expertise necessary for broad success
- High *truck* number

Pair programming boosts *truck* number, improves code quality

Weekly scrums

- Very quick summary of “Did, Do, In-the-Way”
- Scrum master notes impediments
- No “Death by PowerPoint”
- Management may attend but cannot talk

Automated testing of repository commits

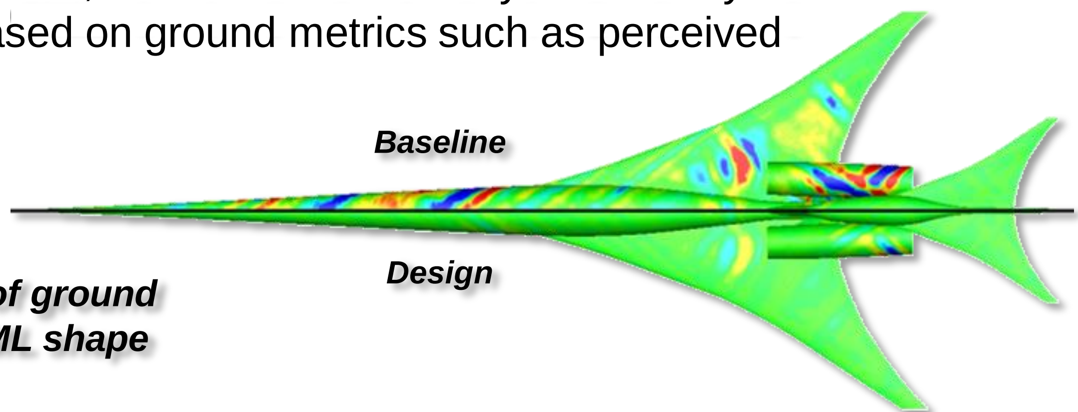
- Every commit screened for adherence to coding standard
- Each commit triggers a series of regression tests
- Successful gauntlet means FUN3D is safe to ship

Jennifer Abras
Natalia Alexandrov
Kyle Anderson
Bala Balakumar
Bob Bartels
Karen Bibb
Bob Biedron
Alejandro Campos
Jan-Renee Carlson
Mark Carpenter
Joe Derlaga
Boris Diskin
Austen Duffy
Peter Gnoffo
Dana Hammond
Clara Helm
Bill Jones
Bil Kleb
Beth Lee-Rausch
Eric Lynch
Steve Massey
Eric Nielsen
Hiro Nishikawa
Dave O’Brien
Mike Park
Sriram Rallabhandi
Shatra Reehal
Chris Rumsey
Rajiv Shenoy
Marilyn Smith
Jim Thomas
Veer Vatsa
David Venditti
Jeff White
Bill Wood
Kan Yang

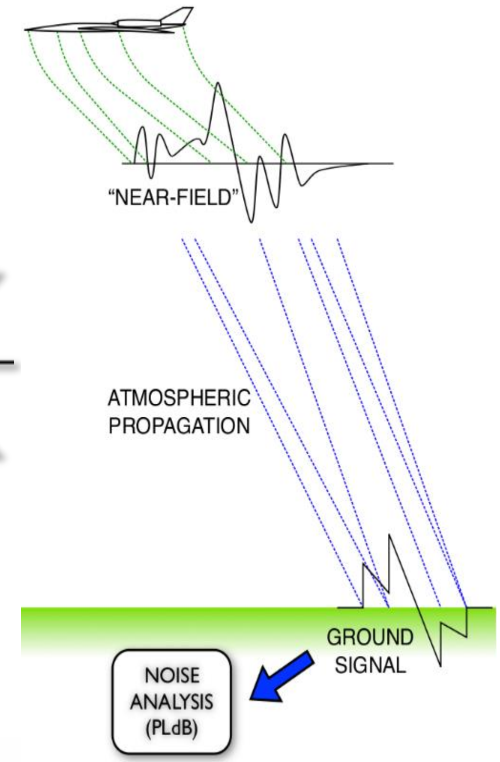
Design with High-End CFD

Multidisciplinary Optimization Using Ground-Based Sonic Boom Metrics

- Adjoint across three coupled disciplines provides sensitivities of ground metrics with respect to aircraft OML
- For the first time, aircraft can now be systematically designed based on ground metrics such as perceived loudness

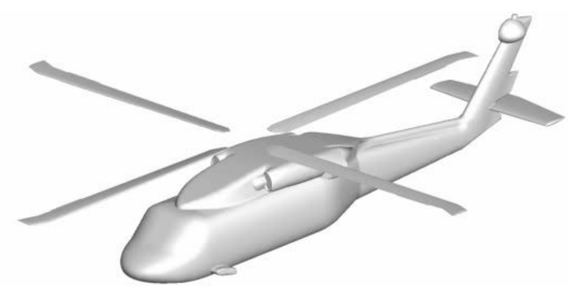


Sensitivity of ground noise to OML shape



Aero Optimization of UH-60 Black Hawk

- Time-dependent RANS, overset grids with complex kinematics
- Determine optimal shape, pilot collective/cyclics
- Maximize performance while trimming via nonlinear constraints



So What Have We Learned?

Great progress has been made, but much remains to be done towards achieving the ultimate goal of ModSim

CFD
- Cannot accurately predict turbulent separated flows
- Human intuition for meshing is often misleading
- Anisotropic mesh adaptation difficult
- Primal solver must be bulletproof
- Need high-order methods
- Sensitivity analysis for chaotic flows

High-Performance Computing
- Limited computing resources and expertise

Multidisciplinary Design
- Formulating design problem not always straightforward
- Need for global optimization techniques
- Discipline coupling is not straightforward
- Many disciplinary tools not scalable, lack sensitivities
- Geometry parameterization tools lacking

Summary

Long-term Investment Is Paying Off Substantially…

- FUN3D is an award-winning tool with broad impact and recognized as a national asset
- Platform for educating the next generation of scientists and engineers
- An innovation leader in the field of adjoint methods

…But Significant Challenges Remain

- HPC
  - Completely lacking this core competency
  - Readily available hardware is orders of magnitude behind SOA
- MDO must be a fundamental thread woven into everyone's thought processes and tool development
- Availability of validation data remains critical to building confidence in ModSim