Landing on Mars: Petascale Unstructured-Grid CFD Simulations on Summit

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FUN3D Overview

- Established as a research code in late 1980s; now supports numerous internal and external efforts across the speed range
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows
- General dynamic mesh capability: any combination of rigid / overset / morphing grids, including 6-DOF effects
- Aeroelastic modeling using mode shapes, full FEM, CC, etc.
- Constrained / multipoint adjoint-based design, mesh adaptation
- Distributed development team using agile/extreme software practices including 24/7 regression, performance testing
- Capabilities fully integrated, online documentation, training videos, tutorials
The Three Pillars of HPC

2018
- Hardening and Deployment

2016
- Technology Demonstration
- Asynchronous, Overlapped Communication
- CUDA-Enabled MPI

2014
- Full App at Scale
- Full App at Node Level
- Language Interoperability
- Matrix Assembly
- CUDA-Enabled MPI
- OpenACC CUDA Fortran
- PTX CUDA C/C++ Kokkos

2012
- Mini-Apps
- Linear Algebra
- Basic Research

2010
- Software
- Workforce Skills
- Hardware

Next-Generation Leadership Class Performance

2010 - 2016
- 2010
- 2012
- 2014
- 2016

NASA / NVIDIA @ SC10

Partnerships & Hackathons

Volta
- GPUDirect RDMA
- Power Efficiency
- Fast Atomics

Pascal
- Hyper-Q
- ECC Memory
- DP Support

Kepler
- Early GPUs
- Linear Algebra
- Basic Research

Software
- Workforce Skills
- Hardware
• Early access during Summit construction enabled early 2018 performance demonstrations shown here
“Enabling Human Exploration of the Red Planet”

- CY19 allocations competitively awarded through Summit Early Science and INCITE programs
  - Total award of 305,000 Summit node-hours
  - Equivalent of ~305,000,000 Xeon Skylake core-hours
- Team includes NASA Langley, NASA Ames, NVIDIA, and Old Dominion University
  - LaRC: Science and computational expertise
  - ARC: Large-scale visualization, network transfers
  - NVIDIA, ODU: Kernel optimizations

Campaign Goals

- **Science**: Advance the understanding of retropropulsion flow physics during Mars EDL of a human-scale lander
- **Computational**: Demonstrate production readiness and efficiency advantages of GPU implementation of the FUN3D CFD code at scale
Human-scale Mars landers require new approaches to all phases of Entry, Descent, and Landing

- Cannot use heritage, low-L/D rigid capsules → deployable hypersonic decelerators or mid-L/D rigid aeroshells
- Cannot use parachutes → retropropulsion, from supersonic conditions to touchdown
- No viable alternative to an extended, retropropulsive phase of flight

### Retropropulsion for Human Mars Exploration

<table>
<thead>
<tr>
<th>Entry Capsule (to scale)</th>
<th>Viking</th>
<th>Pathfinder</th>
<th>MERs</th>
<th>Phoenix</th>
<th>MSL</th>
<th>InSight</th>
<th>M2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (m)</td>
<td>3.505</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
<td>4.52</td>
<td>2.65</td>
<td>4.5</td>
</tr>
<tr>
<td>Entry Mass (t)</td>
<td>0.930</td>
<td>0.584</td>
<td>0.832</td>
<td>0.573</td>
<td>3.153</td>
<td>0.608</td>
<td>3.440</td>
</tr>
<tr>
<td>Parachute Diameter (m)</td>
<td>16.0</td>
<td>12.5</td>
<td>14.0</td>
<td>11.8</td>
<td>19.7</td>
<td>11.8</td>
<td>21.5</td>
</tr>
<tr>
<td>Parachute Deploy (Mach)</td>
<td>1.1</td>
<td>1.57</td>
<td>1.77</td>
<td>1.65</td>
<td>2.2</td>
<td>1.66</td>
<td>1.75</td>
</tr>
<tr>
<td>Landed Mass (t)</td>
<td>0.603</td>
<td>0.360</td>
<td>0.539</td>
<td>0.364</td>
<td>0.899</td>
<td>0.375</td>
<td>1.050</td>
</tr>
<tr>
<td>Landing Altitude (km)</td>
<td>-3.5</td>
<td>-2.5</td>
<td>-1.4</td>
<td>-4.1</td>
<td>-4.4</td>
<td>-2.6</td>
<td>-2.5</td>
</tr>
<tr>
<td>Landing Technology</td>
<td>Retro-propulsion</td>
<td>Airbags</td>
<td>Airbags</td>
<td>Retro-propulsion</td>
<td>Skycrane</td>
<td>Retro-propulsion</td>
<td>Skycrane</td>
</tr>
</tbody>
</table>

### Human-Scale Lander (Projected)

- Diameter: 16 - 19 m
- Entry Mass: 40 - 65 t
- Parachute Diameter: N/A
- Parachute Deploy: N/A
- Landed Mass: 26 - 36 t
- Landing Altitude: +/- 2.0 km

### New EDL Paradigm

Steady progression of “in family” EDL
• Retropropulsion environments impact vehicle performance
• Maturation requires balance between ground testing and computational analysis
• Infeasible to continue with conventional resources, given the computational expense of single solutions (several weeks-to-months each)
• Incremental performance gains in computing will not solve this issue

Examples of solutions with insufficient spatial and temporal resolution

Infeasible to develop models and databases within current conventional computational paradigm
• Rather than pursue small number of “hero” simulations, exploring large ensemble of asymmetric throttle conditions across freestream Mach numbers from 0.8 to 2.4
• Spatial mesh sizes ranging from ~1-10 billion elements
• Long temporal duration (~1.6 sec real time) to capture diverse transients and statistics
• Individual runs can reach 200 TB of output; average ~30 TB / day from ORNL to NASA Ames
• Total of ~2 PB of data generated
All engines at 80% throttle (individual engines are under-expanded)
Vorticity magnitude contours

Vehicle-level design decisions are directly impacted by the ability to characterize and bound aerodynamic-propulsive interference effects.
Game-Changing Performance
Typical Job of 6.5B Elements, 200K Time Steps, 200TB Output

Conventional Computing Approach
• 9 months per run on 5,000 Xeon Skylake cores
  (3 months compute, 6 months queues)
• Multiple runs would take years

Current Summit Campaign
• 4 days per run on 552 V100s
• 6 simultaneous runs on 3,312 V100s
  → 6 jobs done in a workweek
  → Equivalent throughput of
    ~600,000 Xeon Skylake cores