Development of a Trajectory-Centric CFD-RBD Framework for Advanced Multidisciplinary/Multiphysics Simulation

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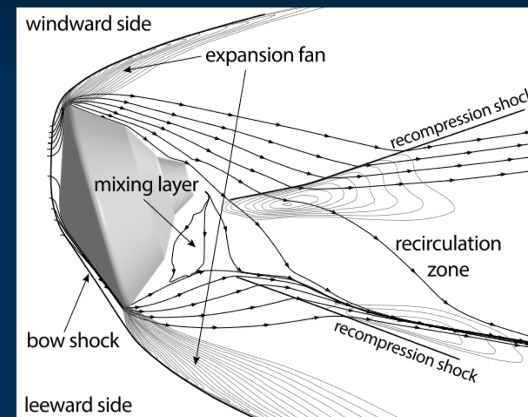
Georgia Tech Aerospace Systems Design Laboratory

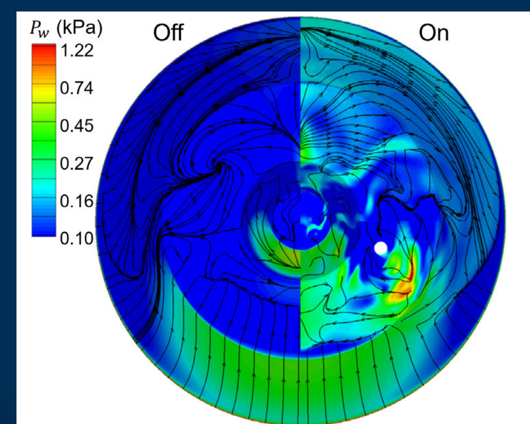
- Introduction
- Framework Construction
- Experimentation and Results
- Conclusion

Unsteady Entry Vehicle Behavior

- Experience a wide range of flight regimes
- Exhibit significant unsteady behavior due to the wake[1]
- Control/propulsion systems disrupt a large volume of flow around the vehicle[1]
- Understanding static & dynamic aerodynamic behavior is critical to control system design, guidance development, trajectory simulation
- Among a class of problems subject to unsteady, coupled behavior:
  - Stage/panel separation
  - Acceleration through transonic regime
  - Flexible vehicles



MSL Hypersonic Flow Regime[2]



MSL RCS Jet Interaction[3]

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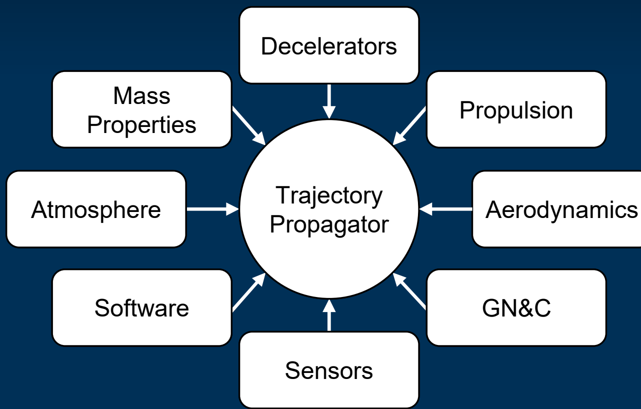
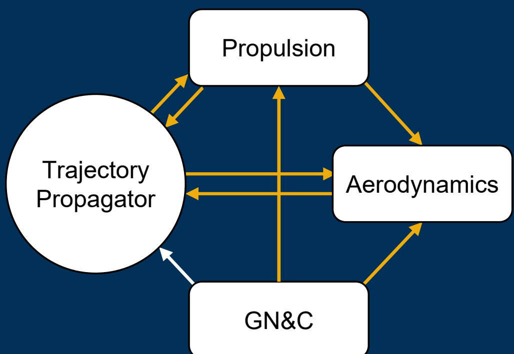
Move to Multiphysics Flight Simulation

- Flight Simulation is used throughout the design process
- Constructed with independent, a priori models such as aerodynamic databases[4]
- Limited modeling of coupling between disciplines
- Interpolation and surrogate model fidelity error

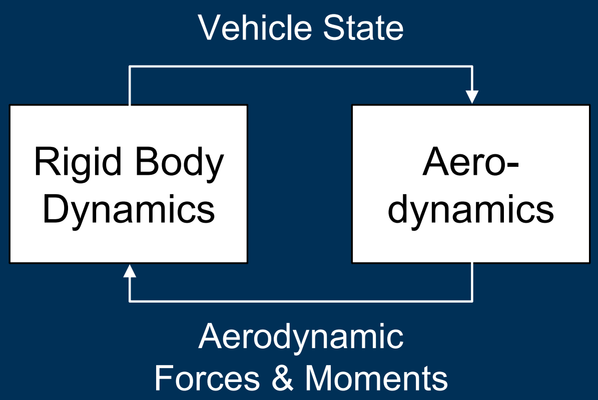




- Desire for coupled, multiphysics simulation[5]
- Coupled disciplines can converge at each time step
- Eliminates interpolation error
- Decreased startup cost for new configurations (updated OML, off-nominal scenarios, etc.)

CFD-RBD Simulation

- Simulates unsteady aerodynamics and rigid-body dynamics simultaneously
  - CFD solves 3-D, time-dependent Navier-Stokes equations
  - 6 DOF rigid-body dynamics (RBD) solved using numerical integration
- Continuous integration of the flow field preserves time history and captures unsteady effects
- History of use in store separation[6] and projectile design[7-9]
- Increasing use for atmospheric entry vehicles[10-13]
- Objective: develop a trajectory-propagator-centric CFD RBD simulation to enable coupling with state-of-the-art guidance, control, and propulsion models



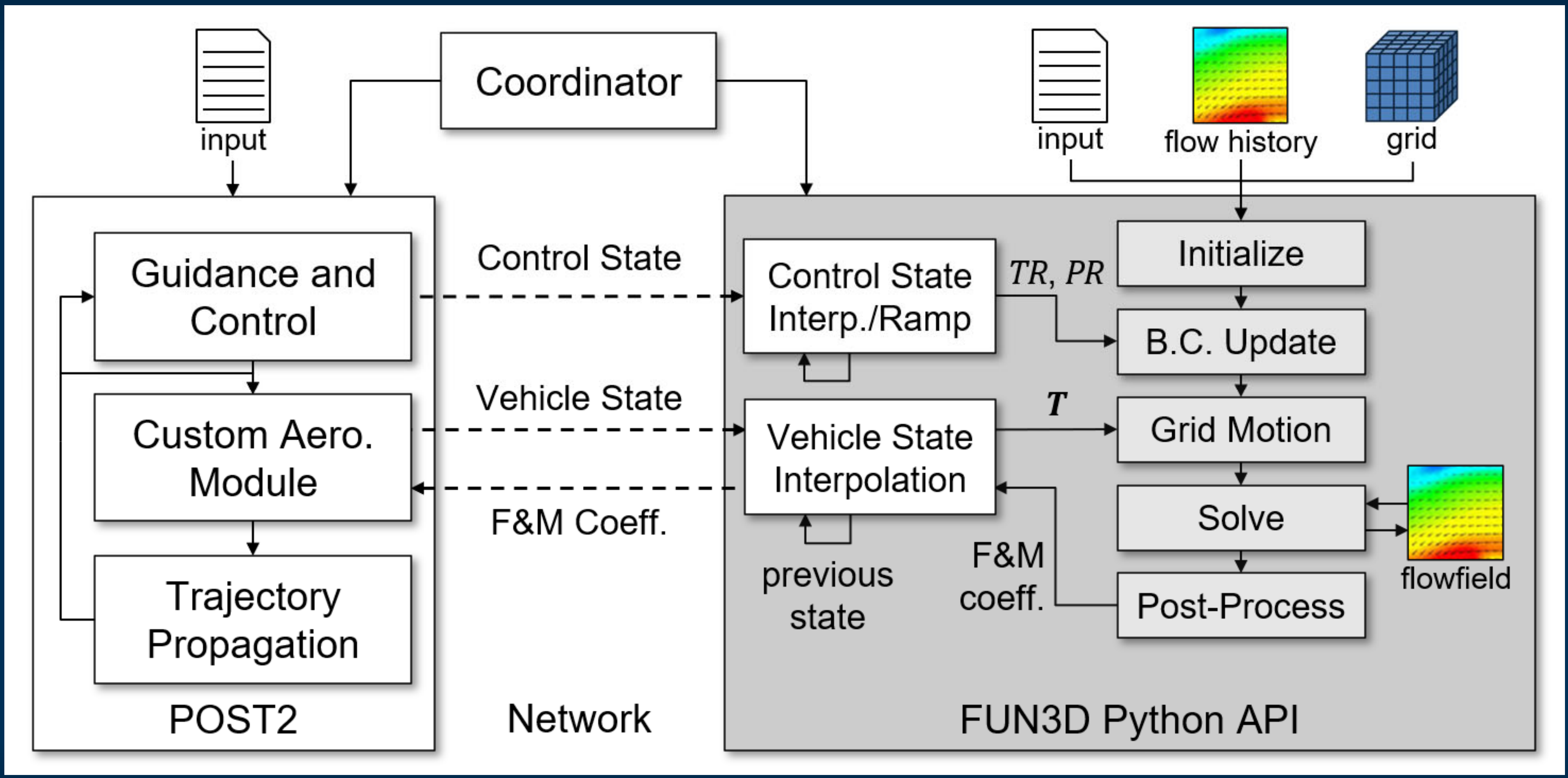
CFD-RBD Flowchart

Framework Construction

Framework Construction

- CFD: Fully Unstructured 3D (FUN3D) flow solver[14]
  - Finite volume, unstructured, mixed element meshes
  - Governing equations include grid motion terms for translation and rotation[15]
  - Previous use for entry vehicle aerodynamic modeling[3, 16]
  - Python API for low-level execution control
- Trajectory Propagator: Program to Optimize Simulated Trajectories II (POST2)[17]
  - 6DoF flight dynamics of vehicle about arbitrary planet
  - MSL and Mars 2020 end-to-end flight simulations built in POST2[4]
  - Designed for flexibility and customization – projects normally write custom code
- Ancillary code: Python 3
  - Open-source programming language
  - Using for constructing wrapper files, post-processing, etc.

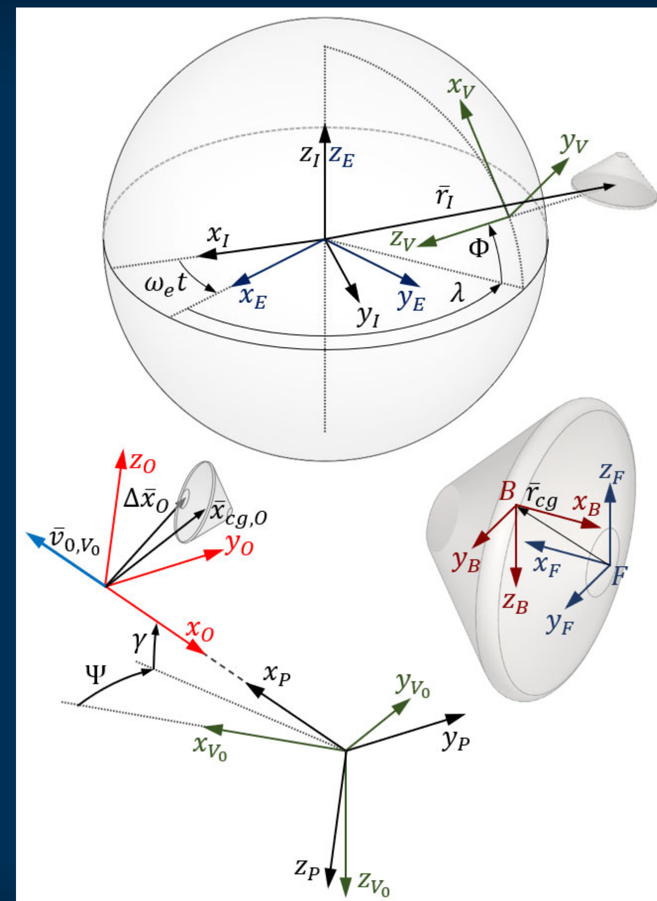
Framework Construction



Framework Architecture

Data Transformation

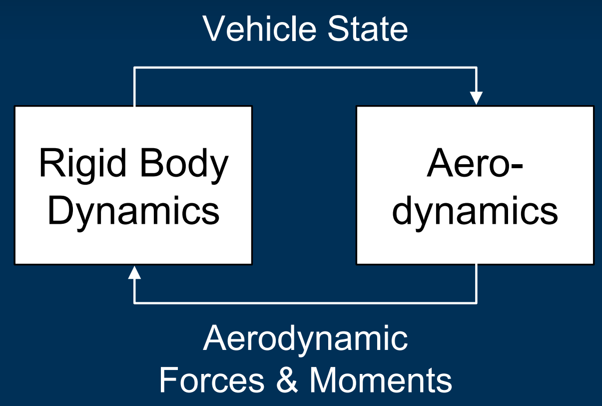
- Transform orientation, c.g. location, and translation from POST2 to FUN3D
  - POST2: Earth-Centered Inertial (I) to Body (B) frames
  - FUN3D: Body Reference (F) to Observer (O) frames
- Account for:
  - Oblate spheroidal planet
  - Nonzero planetary rotation
  - Moving observer frame
- Intermediary frame P for ease of CFD initialization
- Nondimensionalization into grid units
- Transform coefficients from FUN3D to POST2
  - Account for changing dynamic pressure



POST2 and FUN3D Reference Frames

Coupling and Numerical Integration Scheme

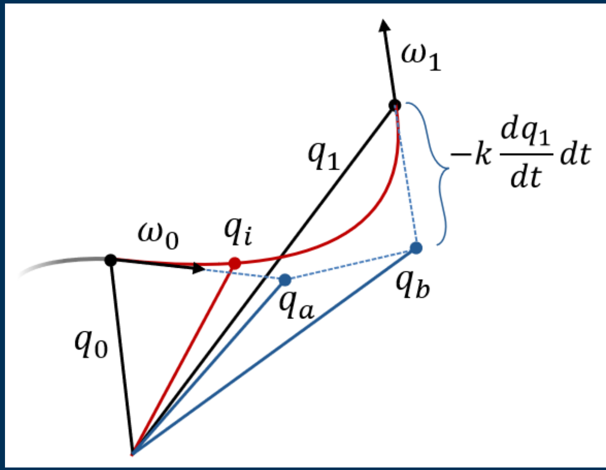
- Coupling using a modified, staggered nonlinear block Gauss-Seidel algorithm[18]
- POST2 integrates equations of motion using RK4 assuming constant forces and moments across the time step
- Preserves monotonic nature of flow history
- Convergence can be assumed for a sufficiently small physical time step
- Compatible with time step interpolation



CFD-RBD Flowchart

Interpolation for Larger POST2 Time Steps

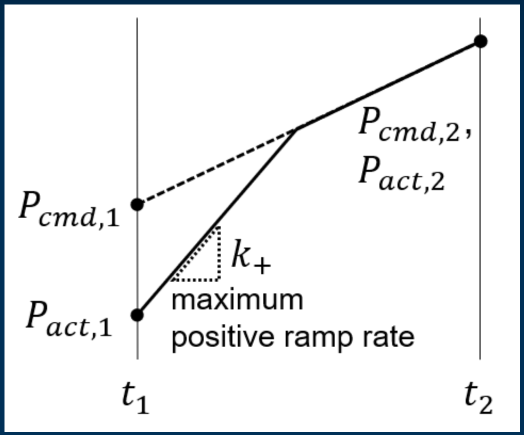
- Inefficient to run POST2 and FUN3D at the same time step
  - Flight dynamics can be resolved at a larger time step
  - Relative cost increases with computational power
- Running POST2 at a larger time step requires interpolation
- Must be C^2-continuous for flow stability
- Translational interpolation: component-wise cubic interpolation
- Angular interpolation: 3rd Order Bézier curves with Bernstein basis[19]
  - Angular components require interpolation in non-Euclidean space



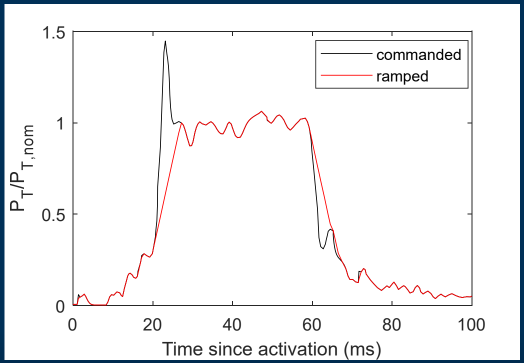
Quaternion Interpolation with 3rd-Order Bézier Curve

Control State Management

- Control state consists of total temperature and pressure T_T, P_T at each nozzle plenum
- POST2 communicates actual control state as determined by propulsion model
- Possibility of convergence problems if plenum conditions change too quickly
- A ramping function is applied to limit the actual P and T change in FUN3D
  - Must also account for interpolation
- P_T and T_T are nondimensionalized into ratios PR and TR relative to the freestream



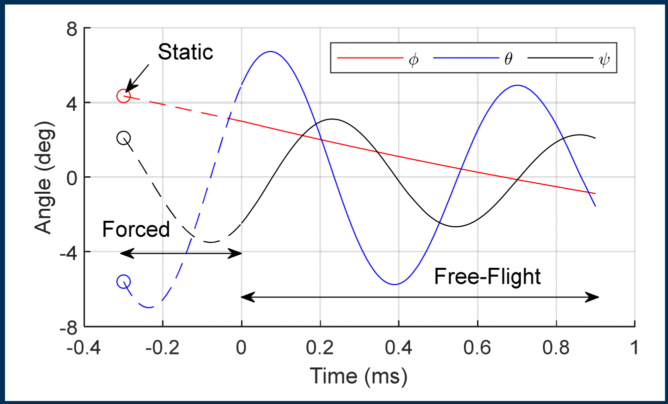
Jet Ramping in Combination with Interpolation



Ramping a Notional Physical Jet

Startup Procedure

- Coefficients must be converged at the start of free flight
- Flow field must be consistent with desired (potentially unsteady) initial conditions: nonzero angular velocity, acceleration, etc.
- Startup Process:
  - Backpropagate trajectory from desired initial conditions (for enough steps to achieve convergence)
  - Generate static solution at new initial conditions
  - Run forced motion simulation to bring vehicle to desired conditions with a consistent flow field
  - “Release” into free-flight simulation

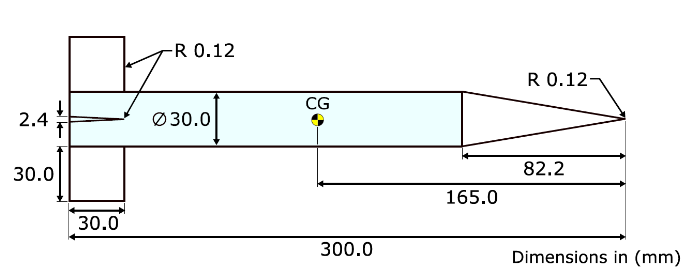


Unsteady Trajectory Initialization Example

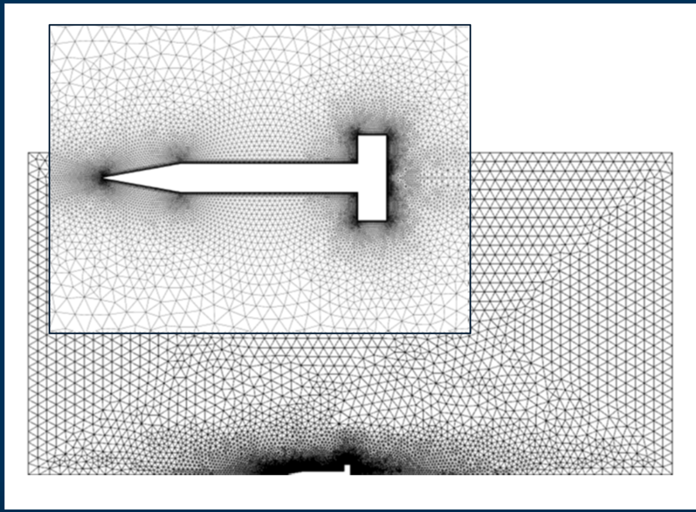
Experimentation and Results

Cross-Code Verification

- Verification against existing FUN3D 6DOF Library[20]
- Simulated ANF projectile in Mach 2 ballistic drop
  - Simple geometry
  - History of use in ballistics research[21,22]
  - Good availability of physical & computational experimental data
- Framework modified to match limitations of 6DOF library
  - Non-rotating planet with $R = 10^9\text{m}$ to approximate uniform gravitational field and inertial frame
  - Constant sea-level atmospheric conditions in POST2



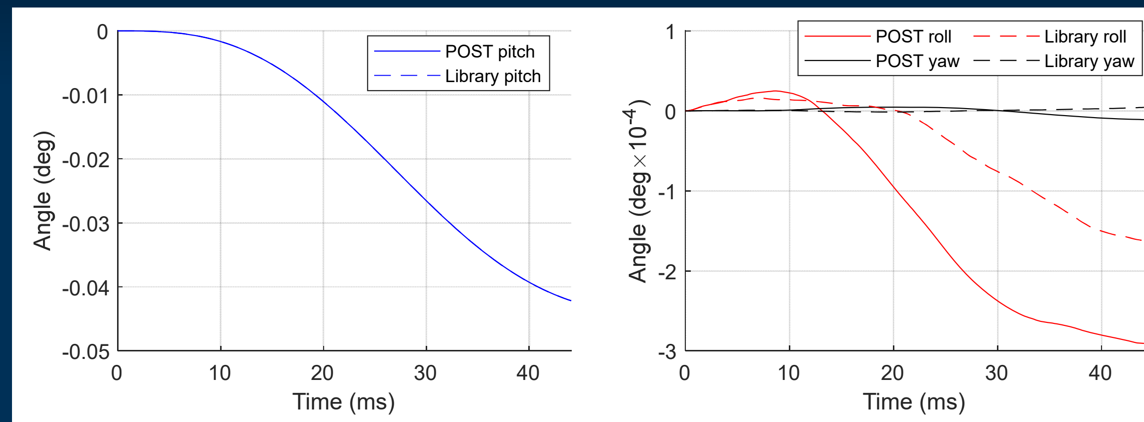
Army-Navy Finner Projectile



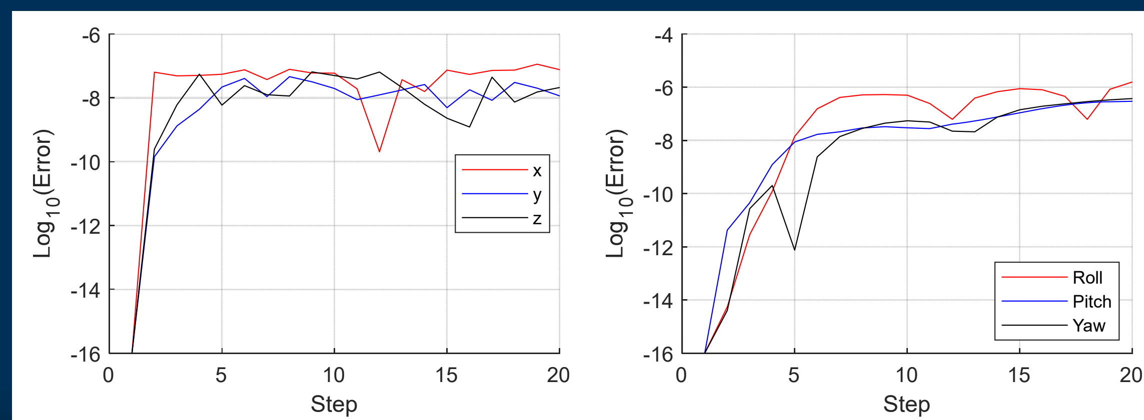
ANF Grid

Cross-Code Verification Results

- Both simulations show expected behavior for ballistic drop
- Pitch behavior matches within 0.01% after 200 steps
- Yaw and roll show expected deviation due to residuals
- Error magnitude growth is bounded
- Cross-code verification judged to be successful



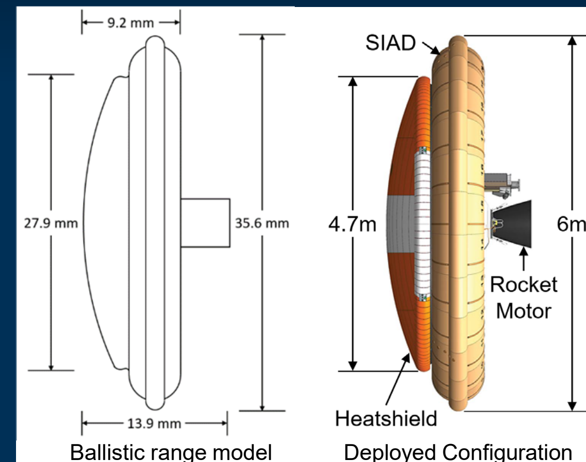
Angular Trajectory Results Comparison



Error Magnitude Growth by Step

Replication of SIAD Ballistic Range Experiments

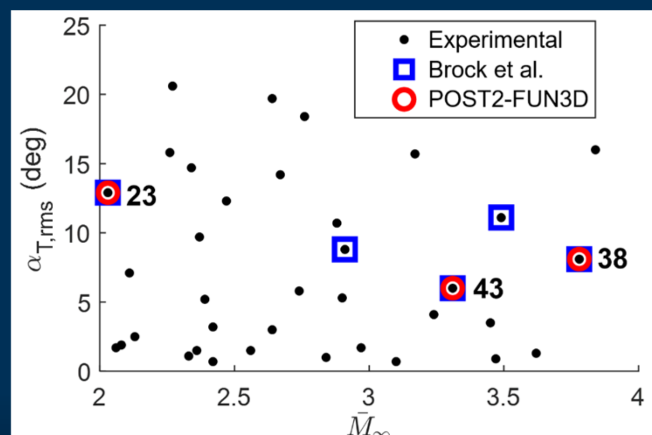
- Supersonic Inflatable Aerodynamic Decelerator (SIAD)
- Validation against Mach 2-4 range experiments performed at NASA Ames HFFAF[23]
- Validation against US3D-based free-flight simulation[13]
- Selected shots that span Mach range and include significant range of initial roll rate



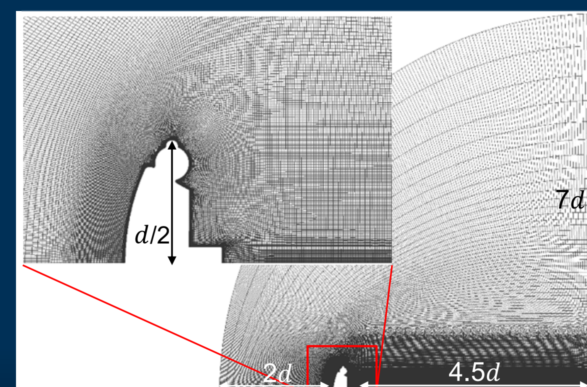
SIAD Test Vehicle Dimensions[23]

Calculated Initial Conditions

Shot	#2623	#2638	#2643
Mach	2.16	3.78	3.46
p^* (deg/s)	-290	-91.3	-1890
q (deg/s)	6640	8150	6100
r (deg/s)	-601	-153	-1030



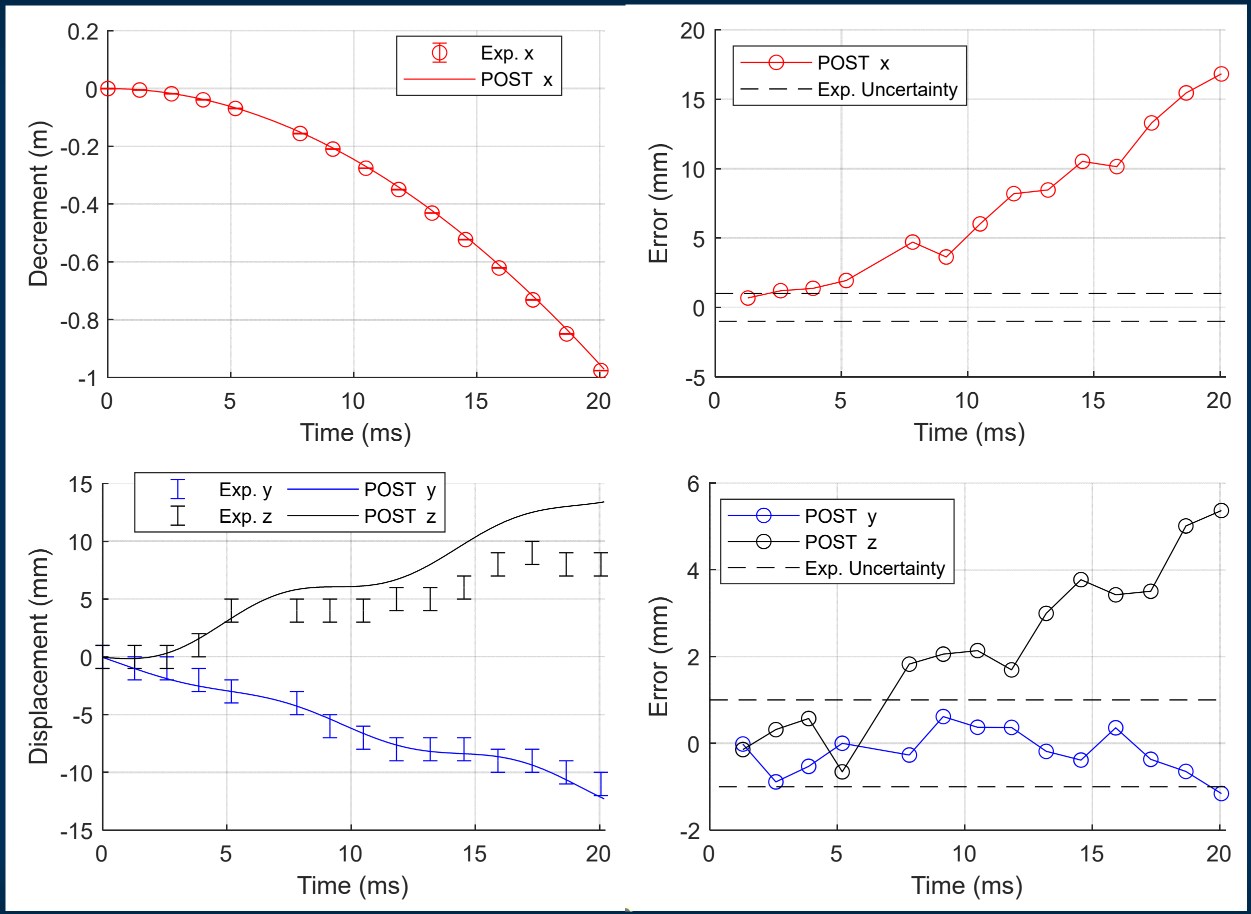
Ballistic Range Shot Conditions[27]



Mesh Quarter Symmetry[27]

Results vs. Physical Experiment: Displacement

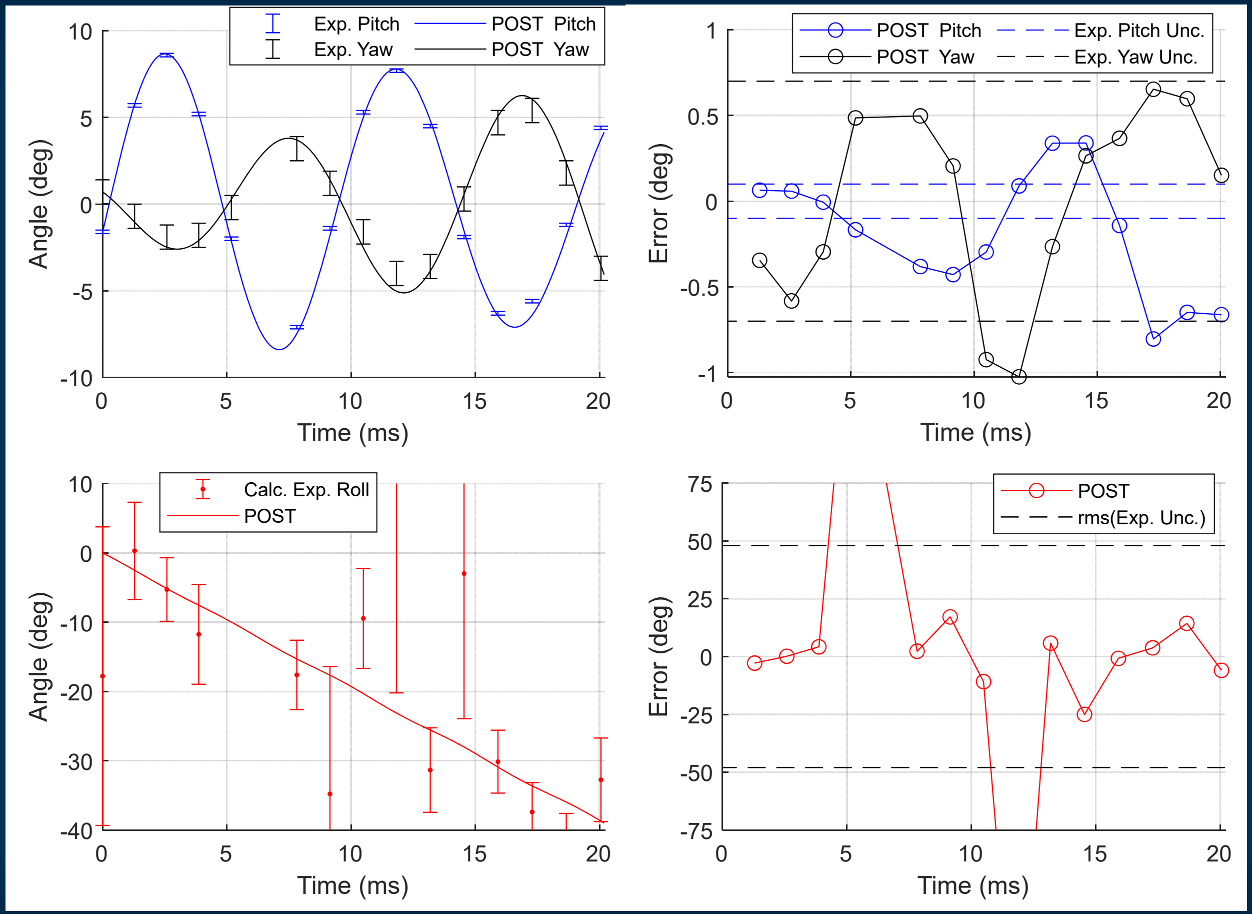
- x-axis displacement within 0.07% of total distance
- Model captures oscillatory behavior in y- and z-axes
- Final error grows to within 1-2 orders of magnitude of experimental uncertainty
- Satisfactory considering displacement is subject to error propagation without restoring forces



Shot 2643 ($M = 3.46$) Recreation, Linear Results

Results vs. Physical Experiment: Orientation

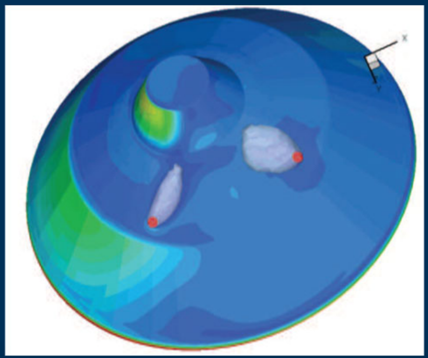
- Pitch and yaw error remains under ~1°
- Significant improvements to pitch and yaw over non-rolling initial conditions
- Supports hypothesis of non-negligible initial roll rate



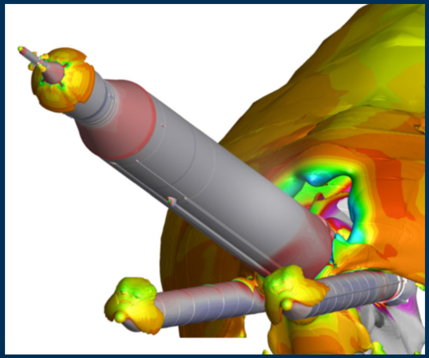
Shot 2643 ($M = 3.46$) Recreation, Angular Results

Conclusion

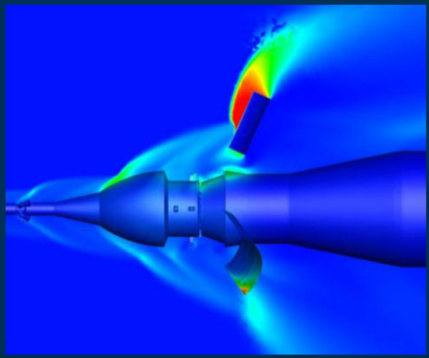
- The POST2-FUN3D framework provides expanded Multiphysics capability
  - Allows for the inclusion of GN&C and propulsion models
- Successful cross-code verification against existing CFD-RBD model
- Successful validation against experimental free-flight trajectory results
- Demonstration underway for free-flight simulation with RCS interaction
- Enhancing capabilities to support research into other Multiphysics problems of interest:



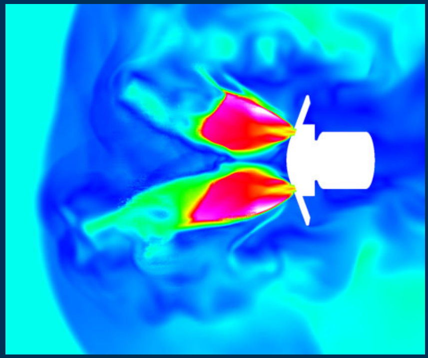
RCS Interaction[3]



Booster Separation[24]



Panel Separation[25]



Supersonic Retropropulsion[26]

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