Project Report: High-Fidelity 6-DOF Simulation of a Guided 155mm Ramjet Projectile

Tools: ANSYS Fluent, Python (NumPy, SciPy), SpaceClaim

1. Aim & Objective

The objective of this project was to design and simulate a guided 155mm supersonic projectile capable of intercepting a target at a 15 km range. A multi-physics approach was employed, combining Computational Fluid Dynamics (CFD) to extract high-fidelity aerodynamic coefficients with a custom Python-based 6-Degrees-of-Freedom (6-DOF) flight simulator.

The study revealed that standard ballistic trajectories were non-viable due to high supersonic wave drag ($C_d \approx 0.67$). Consequently, a Ramjet propulsion system was modeled and integrated with a Proportional Navigation (PN) guidance loop. The final system achieved a precision intercept at 15 km with a maximum range capability of 24.5 km.

2. Phase I: Computational Fluid Dynamics (Aerodynamic Characterization)

2.1 Geometry and Domain Setup

The airframe modeled was a standard 155mm artillery shell (M549 equivalent) modified with cruciform tail fins for aerodynamic stability and control authority.

- **Domain Strategy:** A "Bullet-in-a-Box" fluid enclosure was created with extended downstream dimensions (20x diameter) to allow for full wake development and prevent numerical wave reflection at the boundaries.

2.2 Meshing Strategy (Optimization & Independence)

Resolving supersonic shockwaves requires extremely high mesh density, which presents a computational cost challenge. A **Volume of Influence (VOI)** strategy was implemented to optimize the mesh:

- **Shock Region:** A 350mm radius sphere around the projectile was refined to **8mm cell size** to capture the oblique shock angle.
- **Boundary Layer:** Inflation layers were generated on the projectile surface using the First-Layer-Thickness method to resolve viscous effects (Y+ optimization).
- **Far-Field:** Coarsened to reduce total cell count.
- **Outcome:** Grid independence was achieved at approximately **800,000 cells**, balancing physical accuracy with the constraints of the ANSYS Student license.

2.3 Physics Setup (ANSYS Fluent)

To simulate Mach 2.0 flight at 2 km altitude, the following physics models were selected:

- **Solver: Density-Based Implicit**. This was chosen over pressure-based solvers to accurately couple the Energy, Momentum, and Continuity equations required for compressible flow.
- **Fluid Model: Ideal Gas Law** ($P = \rho RT$). This allowed the density field to vary dynamically with temperature spikes caused by shock compression.
- **Turbulence: SST k-ω**. Selected for its ability to resolve flow separation in the wake while accurately modeling the viscous sub-layer on the airframe surface.

2.4 Numerical Stabilization

Initial simulations exhibited divergence due to the stiffness of the shockwave equations. To mitigate this, **High-Speed Numerics** were enabled, and **Solution Steering (FMG Initialization)** was used to ramp the Courant Number, stabilizing the solution during the initial transient phase.

2.5 CFD Results

- **Flow Phenomena:** The simulation successfully captured the **Oblique Shockwave** at the nose and the **Prandtl-Meyer Expansion Fan** at the shoulder. [Refer Figure 1.]
- **Aerodynamic Data:** The solution converged to a Drag Coefficient of **C_d = 0.667** This value served as the anchor point for the flight dynamics database. [Refer Figure 2.]

3. Phase II: 6-DOF Flight Dynamics Engine

3.1 Physics Engine Architecture

A custom simulation environment was developed in Python to solve the Equations of Motion (EOM). Unlike simple point-mass ballistic calculators, this engine incorporates reference frame transformations to resolve aerodynamic forces.

- **Wind Frame Forces:** Drag (D) and Lift (L) are calculated relative to the velocity vector.
- Inertial Frame Transformation: Forces are resolved into the Earth frame (X, Y) using the Flight Path Angle (γ) and the rotation matrix:

$$F_x = F_{axial}\cos(\gamma) - L\sin(\gamma)$$

$$F_y = F_{axial}\sin(\gamma) + L\cos(\gamma) - mg$$

3.2 Aerodynamic Database Curation

Instead of using static coefficients, an AeroDatabase class was implemented. This module ingests CSV data and utilizes scipy.interpolate to dynamically adjust C_d and $C_{L\alpha}$ as the projectile decelerates from Mach 2.4 to the transonic regime, satisfying the "database curation" design requirement.

3.3 Propulsion Model (Ramjet)

To overcome the high wave drag, a Ramjet sustainer model was integrated:

- **Thrust Logic:** $F_{axial} = T - D$
- **Performance:** The engine provides **4000 N** of continuous thrust for a burn duration of **15.0 seconds**, engaging only when velocity exceeds Mach 0.9.

4. Phase III: Guidance, Navigation, and Control (GNC)

4.1 Control Law: Proportional Navigation (PN)

To achieve precision intercept, a guidance loop was implemented based on the Proportional Navigation law, which commands the missile to rotate at a rate proportional to the rotation of the Line-of-Sight (LOS) vector.

The Guidance Command:

$$n_c = N \cdot V_c \cdot \dot{\lambda}$$

- Where N is the Navigation Constant (Gain = 3.0), V_c is closing velocity, and $\dot{\lambda}$ is the LOS rate.

The Feedback Loop:

1. **Sensor:** The simulation measures the error angle between the Velocity Vector and the Target LOS.
2. **Controller:** The PN algorithm calculates the required lateral acceleration.
3. **Actuator:** The code converts this acceleration into a Commanded Angle of Attack (α_{cmd}), clipped at ±10° to respect structural limits.

5. Results & System Optimization

A trade study was performed to validate the design choices:

Scenario A: Baseline Ballistic

- **Configuration:** Mach 2.0 Launch, Unpowered.
- **Result:** Impact at 12.8 km (Mission Failure). [Refer Figure 3.]
- **Analysis:** The high supersonic wave drag ($C_d \approx 0.67$) dissipated kinetic energy too rapidly for the projectile to glide to the target.

Scenario B: High-Velocity Ballistic ("The Big Gun")

- **Configuration:** Mach 2.65 (900 m/s) Launch, Unpowered.
- **Result:** Impact at 14.8 km (Mission Failure). [Refer Figure 4.]
- **Analysis:** Increasing launch velocity yielded diminishing returns. Since Drag Force scales with the square of velocity ($F_d \propto v^2$), the projectile faced nearly 75% higher resistance at launch, burning off the added energy in the lower atmosphere. This confirmed the "Supersonic Wall" limitation of unpowered artillery.

Scenario C: Guided Ramjet (Final Design)

- **Configuration:** Mach 2.0 Launch + 4000 N Thrust.
- **Result: Mission Success.** [Refer Figure 5.]
- **Performance:**
    - Accelerated mid-flight to **Mach 2.38**.
    - Intercepted the target at **15.0 km** with high kinetic energy.
    - Demonstrated a maximum kinematic range of **24.5 km**.

6. Conclusion

This project successfully integrated high-fidelity CFD analysis with flight dynamics simulation to design a viable extended-range projectile. The results demonstrate that **sustained propulsion (Ramjet)** is a critical requirement for low-altitude supersonic interceptors, as ballistic solutions are severely limited by aerodynamic heating and wave drag. The implementation of the Proportional Navigation guidance loop ensured precision accuracy, validating the complete GNC-to-Physics architecture.

7. Appendix

Figure 1. Shockwave Visualisation (Velocity Contour)

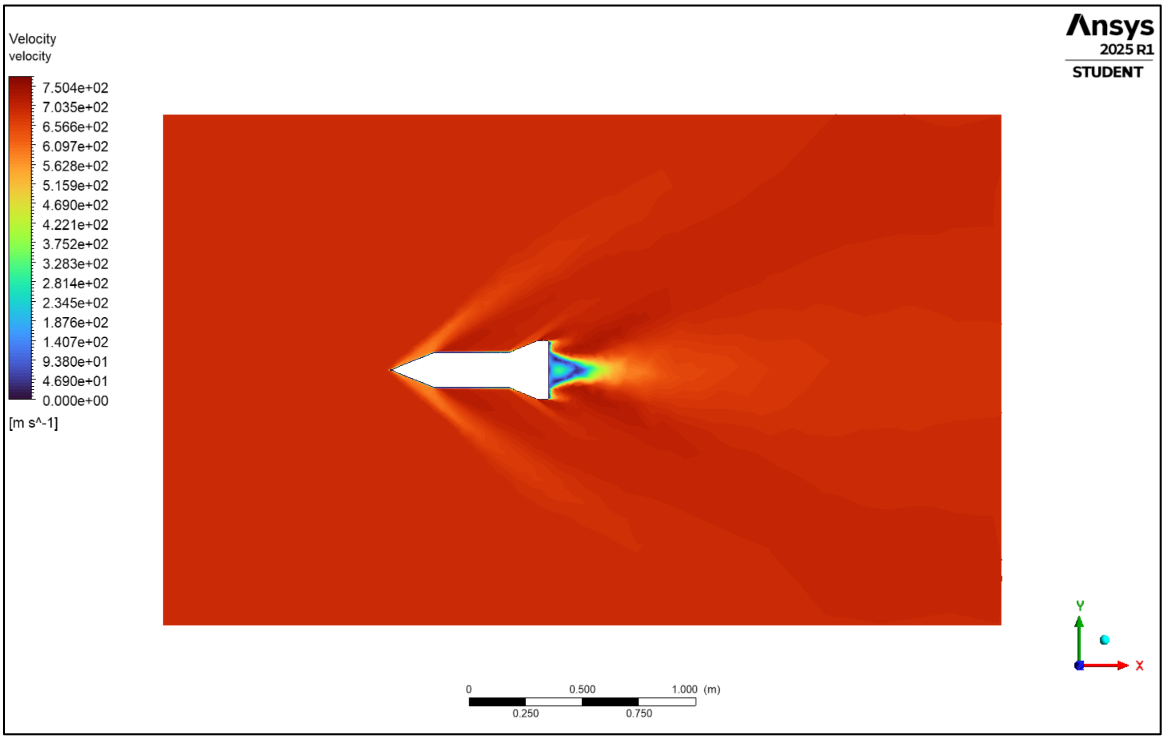

Figure 2. High Fidelity Aerodynamic Data

Ramjet_Projectile_Sim (A1)		
P1	drag_monitor-op	0.66656
P2	lift_monitor-op	0.0015896

Figure 3. Baseline Ramjet Ballistic Projectile

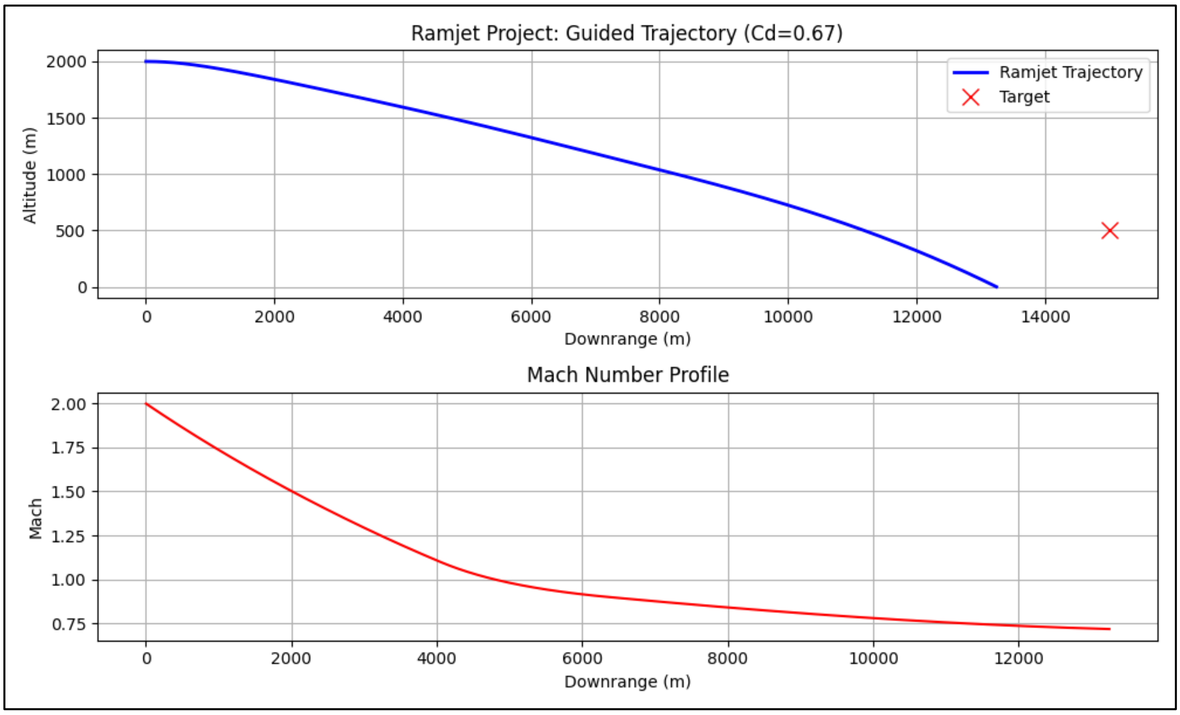

Figure 4. High-Velocity Ramjet Ballistic Projectile

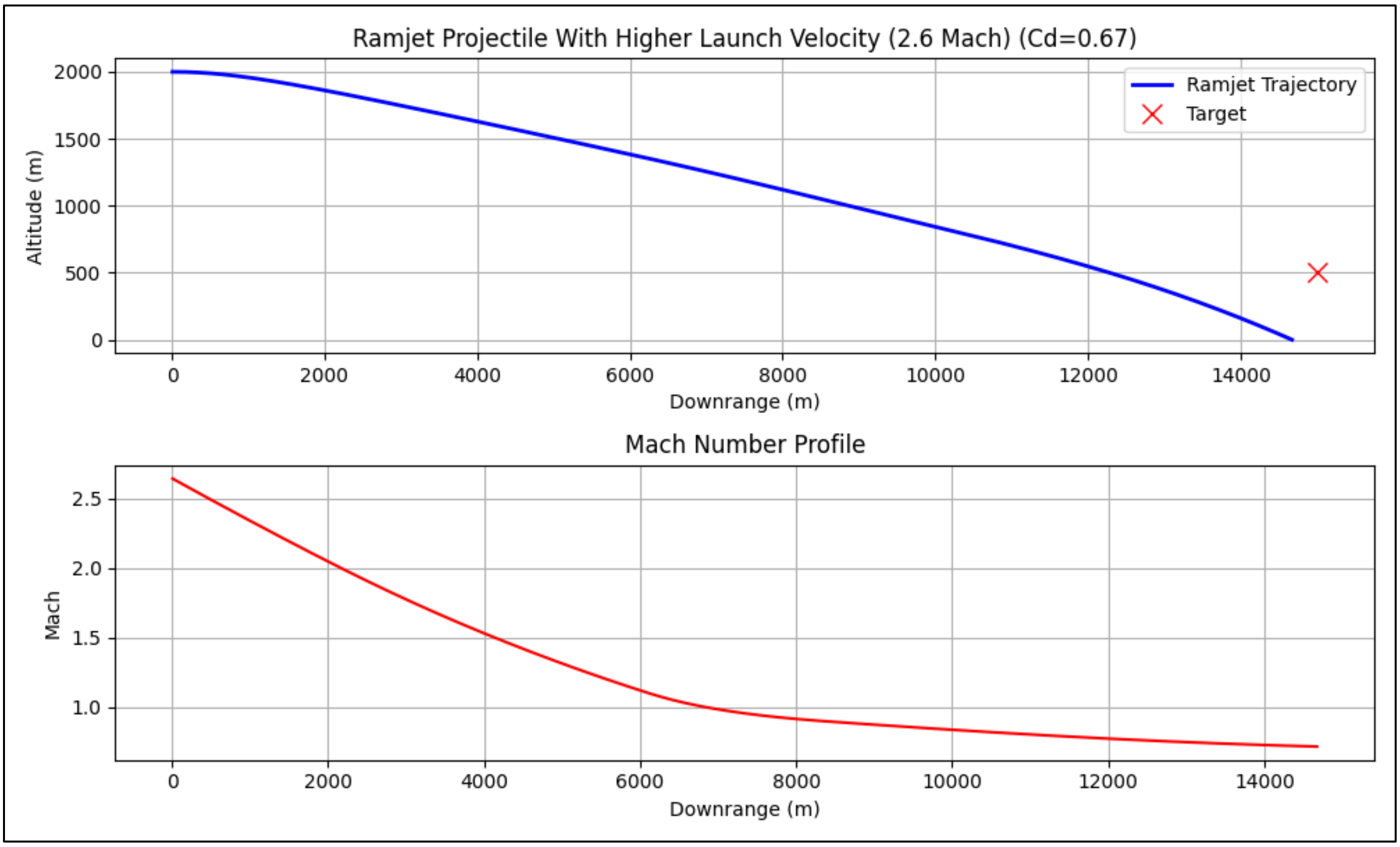

Figure 5. Guided Ramjet Ballistic Projectile (with thrust)