Trajectory Engineering with Modular Patched Conics for Entry Systems and TPS (TEMPEST)

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Brief Presenter Biography (<u>35 word limit</u>): Bohdan Wesely is an Aerospace Engineer in the Entry Systems and Technology Division at Ames. He has worked on a variety of projects for NASA including integrated TPS (thermal protection system) flight hardware deliveries and testing services for commercial partners.

Introduction: TEMPEST is a new trajectory analysis framework that is designed to fill the gap between dedicated flight mechanics tools and aerothermal and TPS sizing tools. The project started as an SJSU master's thesis and has since evolved into a general conceptual design tool capable of studying a wide variety of entry problems. Development is ongoing in the Entry Systems and Technology Division at NASA ARC.

Why TEMPEST: Space missions involving entry into a planetary atmosphere involve a series of unique requirements across multiple disciplines. Whether it is traditional entry descent and landing (EDL), or aerocapture, the vehicle must navigate to its target landing location or orbit state, and the TPS must protect the payload during entry. The design process typically involves iterative handoffs between various flight mechanics, flow solver, and material response level tools. During the early conceptual phase, a wide variety of feasible trajectories are simulated in a Monte Carlo scenario which broadly satisfy the mission or landing requirements. Next, computational fluid dynamics (CFD), direct simulation Monte Carlo (DSMC), and other flow solver analyses are performed at various key trajectory points to generate an aero-database, heating and TPS design requirements also emerge at this stage. At this point, with updated aerodynamics from the various flow solvers, trajectories can be re-run, this in turn can change the required freestream conditions for the CFD tools, and as a project progresses, these analyses converge, and uncertainty is reduced. However, there is always a "hand-off" occurring between two inherently coupled phenomena.

Analysis Description: One of the goals with TEMPEST is to use a variety of first principles estimation methods coupled with an atmosphere model to predict vehicle aerothermodynamics across the entire flight regime while propagating a 3 or 6 degree of freedom (DoF) trajectory. Aerodynamics methods include modified Newtonian, Maxwell and Cercignani-Lampis-Lord (CLL) for continuum, transitional, and free molecular flow regimes. Aerothermodynamics include boundary layer and reference enthalpy methods, and Mutation++ for non-equilibrium chemistry modeling. TEMPEST is also capable of stitching multiple trajectory segments together to study mission scenarios like multi-pass aerocapture and aero-gravity assists. Most of the program is implemented in MATLAB using modern system objects, it relies on several C++ shared libraries for supporting tools like Gmsh, the Global Reference Atmospheric Model (GRAM), and Mutation++. The various first principles aerothermal estimation methods are discretized across either a structured axisymmetric panel mesh or an unstructured tri-mesh generated from an open-source tool such as Gmsh, this allows solutions on the same mesh to be compared across tools such as CB-Aero.

CFD Coupling. A physics-aware, gaussian process CFD anchoring scheme is proposed to adjust the various first principles methods as a CFD database is populated. One goal for this anchoring module is to inform the project where CFD should be run. Full knowledge of the entire trajectory, atmosphere, and aerothermodynamics allows for easier identification of high sensitivity areas and uncertainty quantification. While the first principles effects are well known and proven accurate in existing tools such as CB-Aero and Cart3D, a physics aware CFD anchoring scheme increases tool credibility across a project lifecycle.

Material Response Modeling. Correct TPS sizing is critical for optimizing mass for science payloads and ensuring mission success. The process typically involves a thermal analysis along the trajectory with surface heating environments as a boundary condition. Several design constraints are maximum bondline temperature and maximum recession with various margining techniques. The material response tool FIAT, developed out of NASA Ames, is currently being integrated into the TEMPEST environment. TPS recession, shape change, mass loss, and mass property alteration are all factors that can perturb an entry trajectory. For missions like Mars 2020, recession was minimal and was safely handled separately as a post process. For missions such as Jupiter Galileo with a high TPS mass fraction or asteroid entries, recession plays a major role. The proposed fully coupled scheme is to use an epoch-based approach where the trajectory integration is halted after a recession threshold, the energy balance and FIAT are solved at each panel, the mesh, aerodynamics, and mass properties are updated, and the trajectory continues. Several computational tradeoffs have been made during the development of TEMPEST to limit the cost of a single trajectory and preserve its utility as a conceptual, rapid iteration tool.

Conclusion: Development of TEMPEST is ongoing and the project is still in its infancy. This talk aims to showcase its unique capabilities to support future NASA entry systems missions.

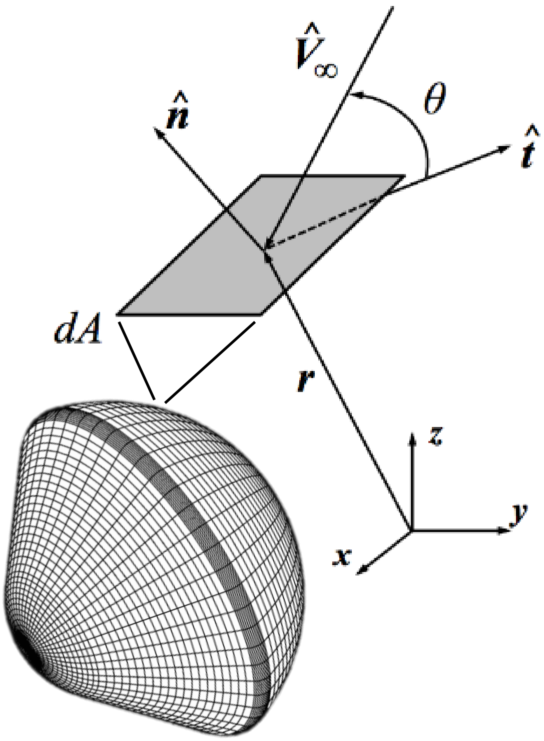

Figure 2. TEMPEST Solves Aerodynamics, Energy Balance, and Material Response at each Panel [1]

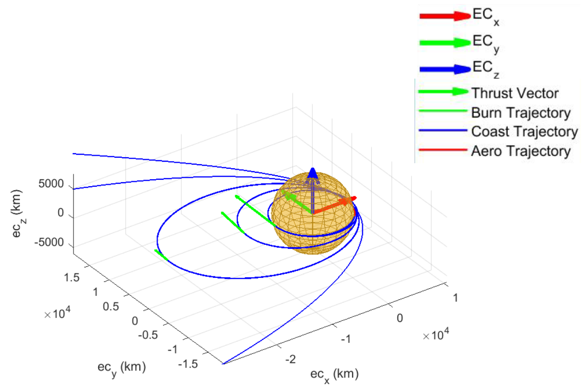

Figure 1 Muti-Pass Aerocapture Mission Scenario Simulated with TEMPEST

References:

[1] K. A. Hart, S. Dutta, K. Simonis, B. A. Steinfeldt and R. D. Braun. (2014) *Analytically derived Aerodynamic Force and Moment Coefficients of Resident Space Objects in Free-Molecular Flow.*

[2] D. Kinney. (2004-31) *Aero-Thermodynamics for Conceptual Design,* 42nd AIAA Aerospace Sciences Meeting and Exhibit.