DATABASE DRIVEN PLANETARY PROBE AUTOMATIC GEOMETRY AND GRID GENERATION TOOL FOR ATMOSPHERIC ENTRY SIMULATIONS

Periklis Papadopoulos[†], Prabhakar Subrahmanyam[††]
Department of Mechanical and Aerospace Engineering,
Center of Excellence for Space Transportation & Exploration
San Jose State University
One Washington Square, San Jose, CA. 95192
ppapado1@email.sjsu.edu, prasub@gmail.com

Abstract

It is desirable when designing new planetary probe architectures or planning for the use of an existing design to rely on computational predictions of vehicle performance, in addition to, wind tunnel and flight data. Essential aspects to assure the accuracy and reliability of these solutions are the selection of the grid topology, grid resolution, and grid quality. This publication presents an integrated planetary probe design framework that automatically generates grids for planetary probes given the geometry of the vehicle and the entry trajectory flight conditions. In addition, the framework links the entry trajectory interface to CFD modeling codes via the automatic grid generation capability. A platform independent GUI-based, relational database-driven tool named *Probe-Mesh* has been developed to generate customized grids required to accurately predict the aerodynamic heating for specified entry trajectories. The heating and deceleration loads experienced by the vehicle during atmospheric entry depend on the trajectory flown, size and shape of the vehicle. The publication presents the operational overview of Probe-Mesh. A comprehensive database of ballistic reentry vehicles has been developed. This includes vehicle dimensions, trajectory data for all the capsules that has been flown and ballistic reentries have been modeled for comparative data analysis. The *Probe-Mesh* GUI provides capabilities to choose from a list of flight vehicle geometric information or entry trajectories. The work presented demonstrates a geometry centered automatic grid generation capability for planetary probes. The design environment is also linked to a trajectory code that calculates pressure, density, temperature, Reynolds number and speed of sound as a function of altitude. The vehicle flight path angle and the free stream flight conditions are used at selected flight conditions along the trajectory to built customized grids tailored to capture the hypersonic reacting flow physical phenomena. A fourth order Runge-Kutta integration is employed for trajectory calculations and engineering correlations are used for stagnation point heating calculations.

Introduction

This publication presents an integrated planetary probe design framework that automatically generates grids for planetary probes given vehicle geometry and entry trajectory flight conditions. It includes access to an extensive database of existing probe designs and provides a mini-CAD capability for construction of new configurations. A relational database-driven tool called *Probe-Mesh* has been developed to generate customized grids required to accurately predict aerodynamic and heating entry environments. The aero-heating environment depends on the trajectory flown, size and shape of the vehicle. Figure 1 shows the overall software architecture.

Figure 2, shows the design options provided through the interface. The user can either choose from the list of available probe designs in the probe database or construct a new configuration using the Geometry Engine. The trajectory is computed at the computational engine. The final step is to automatically generate surface and volume grids. The *TopoGen* utility was developed to construct the topology, internal and external surfaces for preprocessing and set up of the *GridPro* grid generation program.

† *Professor, Department of Mechanical and Aerospace Engineering, SJSU, Senior Member AIAA*
†† *Graduate Researcher & Aerospace Engineer, Mechanical and Aerospace Engineering, Associate Member AIAA*

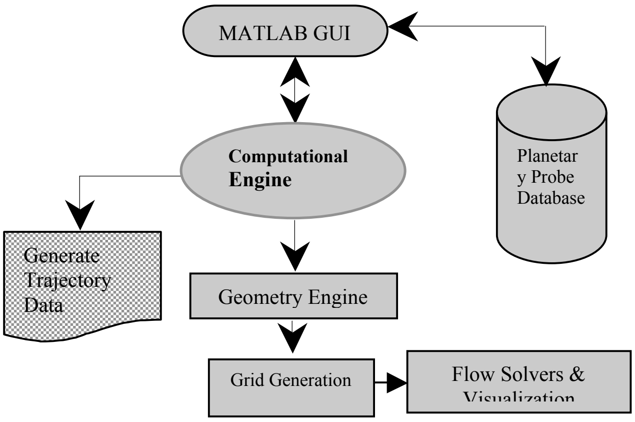


Figure 1. *Probe-Mesh* software architecture.

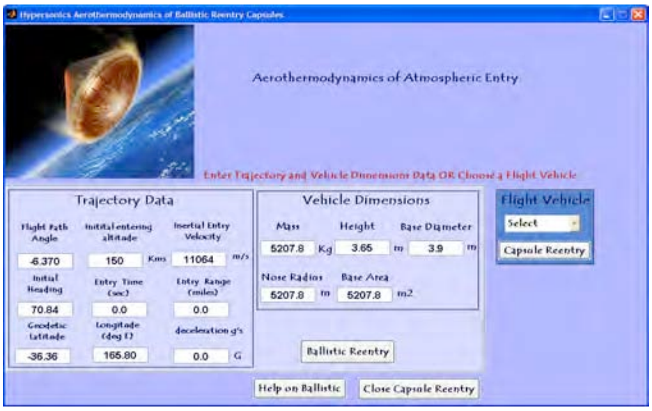


Figure 2. *Probe-Mesh* Graphical interface.

Trajectory Analysis

The Apollo capsules were chosen for demonstration of the trajectory analysis capability. A fourth order Runge-Kutta integration is employed for trajectory calculations. Stagnation Point heating analysis is performed using the Fay-Riddell [1] correlation. User inputs include initial latitude, longitude, inertial velocity, entering altitude and initial flight path angle. The trajectory code generates the vehicle's freestream velocity, flight path angle, range, deceleration, stagnation point heating, Reynolds number and Mach number along the trajectory as a function of altitude. Reentry time and range are calculated as well. Sample trajectory calculations are shown in Figure 3. The Probe-Mesh design environment also links a trajectory code to empirical models of the standard atmospheres of Earth and Mars.

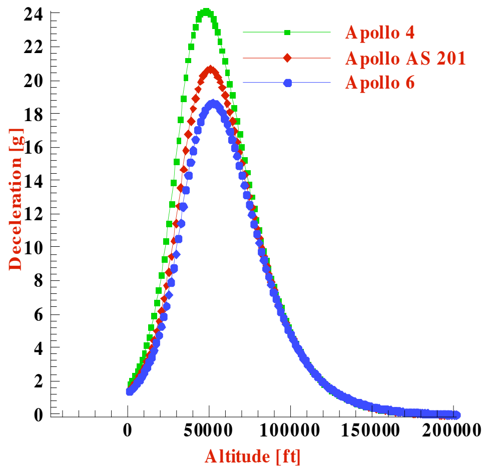


Figure 3. Sample trajectory calculations.

Flight Vehicle Geometry Builder

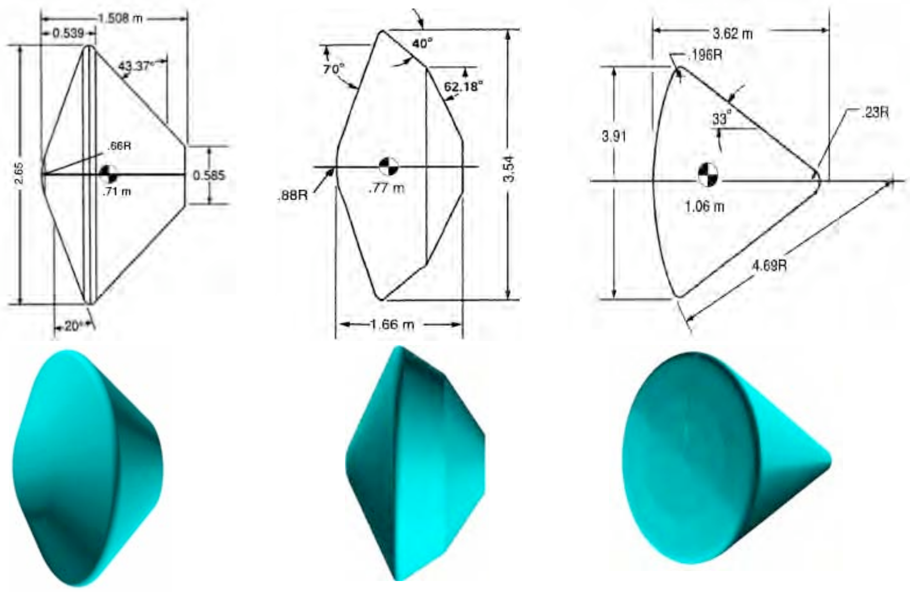
The geometry of the flight vehicle is either constructed from the GUI for user specifications or generated from the database for existing probes [2]. The user specified inputs include forebody vehicle dimensions and any additional base geometry specifications. Other design variables such as the probe mass, reference area and ballistic coefficient are also required to define the vehicle architecture. Through automatic generation of flight vehicle geometry, the necessity to use a CAD tool is eliminated. A comprehensive database of existing planetary probe designs is provided. Trajectory and geometry data are stored for each probe in the database. Figure 4 shows configurations generated from the database for the Pathfinder, Viking and Apollo class vehicles. The user can modify the existing vehicle designs by changing geometric features available in the GUI. A relational database management system has been developed to access the planetary probes database. The databases extend across several tables as shown in Tables 1 and 2, and are linked through common variables. Separate tables for the vehicle geometry, thermal protection system, trajectory and aerodynamic data are included. The database manager allows selective data retrieval through user-entered queries.

Table 1. Vehicle's architecture database with geometric dimensions.

Flight Vehicles	Configuration (Shape)	Nose Radius [m]	Base Area [m^2]	Length [m]	Diameter [m]	Mass [Kg]
Apollo AS-202	Capsule 33 ° Cone	4.69	12.02	3.62	3.91	
Apollo 4	Capsule 33 ° Cone	4.69	12.02	3.62	3.91	5424.9
Viking I	70 ° Sphere Cone	0.88	9.65	1.66	3.54	980
Pathfinder	70 ° Cone	0.66	5.52	1.508	2.65	585.3
Genesis	59.81° Blunt Cone	0.43	12.02	0.93	1.51	201

Table 2. Vehicle's entry conditions database.

Flight Vehicles	Inertial Entry Velocity [km/s]	Relative Entry Velocity [km/s]	Peak heat Velocity[km/s]	Inertial Entry Angle [Degrees]	Control Method
Apollo AS-202		8.29	7.77		Roll Modulation
Apollo 4	11.14	10.73	10.25	-6.92	Roll Modulation
Viking Lander 1	4.61	4.42	4.02	-16.99	3-axis RCS
Pathfinder	7.26	7.48	6.61	-14.06	Ballistic
Genesis	11.00	10.80	9.2	-8.00	Ballistic



Pathfinder **Viking Lander 1 and 2** **Apollo AS-201, AS-202**

Figure 4. Sample probe database architectures and geometry construction.

Grid Generation Process

Once the user specifies the entry trajectory and the probe geometry, the grid generation process is fully automated and transparent to the user. It is organized in three basic steps. First step is to define the computational volume, bounded by the surface of the probe, the outer boundary and the outflow boundary. The outflow boundary is a fixed plane positioned by the user at a specified distance measured in body lengths from the base of the vehicle. An example of the outer boundary shock-fitted surface generated is shown in Figures 5(a) and 5(b). The outer boundary surfaces shown were generated for a Mach 10 flight condition along the trajectory. Figure 5(a) shows an oblique view of the outer boundary along with the overall topology assignments to the outer boundary relative to the planetary probe.

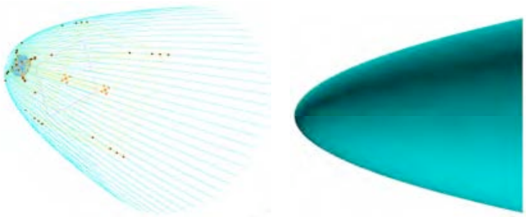


Figure 5. (a) Outer boundary assignment, and (b) shock fitted surface.

Figure 6(a) shows an example of the outflow boundary and Figure 6(b) displays the internal auxiliary surfaces generated automatically for grid refinement at the probe corner and sonic line attachment regions.

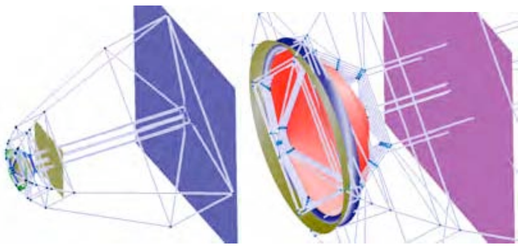


Figure 6. (a) Auxiliary surfaces and (b) topology at corner and sonic line regions.

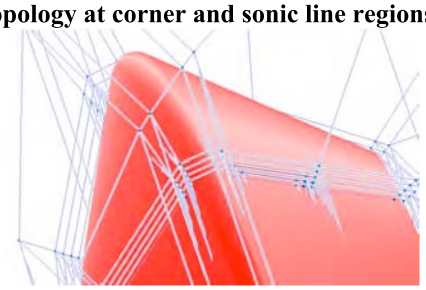


Figure 7. Pathfinder fore-body wrapped and after-body multi-layer nested topology.

The second step in the grid generation process is to construct the overall vehicle topology with local topological refinements in areas specified by the user. The overall topology constructed automatically for the Mars Viking probes is shown in Figure 6(a). Figure 6(b) shows the local compact enrichment and multilayer nesting topology techniques implemented to enhance the grid quality generated in the fore-body sonic line attachment location and the flow expansion at the corner of the vehicle. The GUI allows the user to specify grid refinement at several regions in the flow field.

The refinement regions are defined based on the flow physics in the fore-body, near wake and far wake flow fields. These regions include the probe's corner, expansion layer, base flow, wake, and sonic line attachment. Figure 7 shows an expanded view of the topology constructed for the Mars pathfinder class vehicles. Figure 7 also shows the wrap-around topology around the surface of the probe and highlights the afterbody frustrum topology where the grids are refined to capture the base flow structures. The topology includes multi-layer nesting. The third step in grid generation is the surface assignment of the grid topology. The *Probe-Mesh* module automatically determines the relation between surfaces and topology. Once the surface assignments are made and the topology is completed, the Ggrid solver is ready to compute the volume grid.

Grid Generation Automation

The probe database is also populated with topologies corresponding to the vehicle geometry classes for each probe. These topologies are supplied to the grid generation solver when a class is selected. Based on the flight vehicle geometry and topology specified, grids are automatically generated. *Ggrid* is the *GridPro[3]* grid generation solver and uses topology and surface description as inputs. First the topology is parsed and a multiblock grid is generated. After generating the grid, the any CFD solver can be launched to compute the flow field. The generalized topological structures available in the database are sufficient to cover all currently designed planetary probe geometries. For moderate changes in the surface description the topology does not have to be changed. Through the *ProbeMesh* integrated environment human interaction is entirely removed from the design loop achieving automation of the grid generation process.

Sample Grid Generation Results

The customized grids built for the Pathfinder and Viking class vehicle designs are demonstrated in Figure 8. Figure 8 shows the overall multi-block structure of the generated grids composed of 253 elementary blocks. The outer boundary of the volume grid generated for the case presented is shock fitted for a Mach 10 flight condition along the trajectory. The base region has been extended by ten body lengths to allow computations for the base flow physics as specified by the user to capture shear layer, base flow and the wake viscous core. Figure 9(a) shows an expanded view of the Pathfinder forebody grid generated. Figure

9(b) shows an example of the grid refinement strategy implemented to capture the base recirculation region after the flow expands around the corner of the probe. The grid generated for the specified multi-layered topology in the vehicle's afterbody frustrum is shown in the figure. The nesting topology strategy implemented allows the user to specify local compact enrichment of the computational volume grid with a nesting ratio 1 to 9. The high quality grid generated is shown in Figures 9 (a, b). The figure demonstrates the smoothness and orthogonality of the computed volume grid.

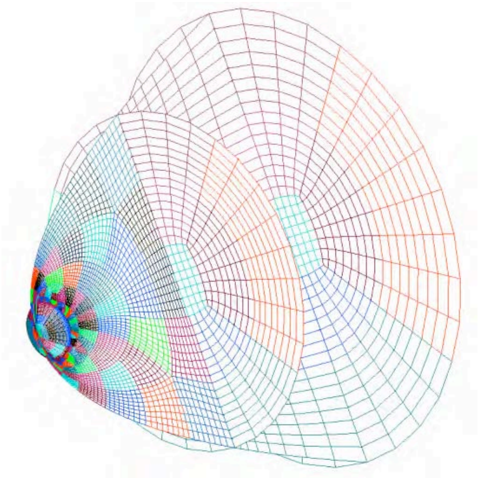


Figure 8(a). Pathfinder class Vehicle's grid.

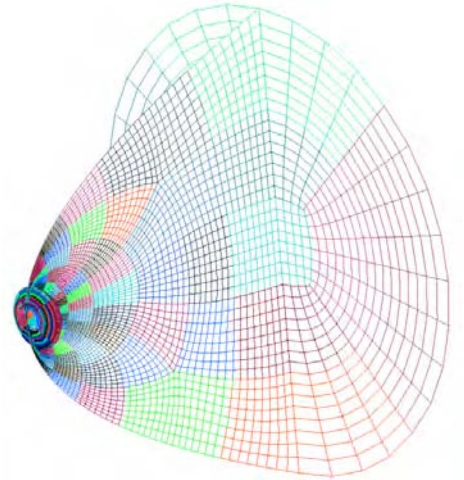


Figure 8(b). Viking class vehicle volume grid.

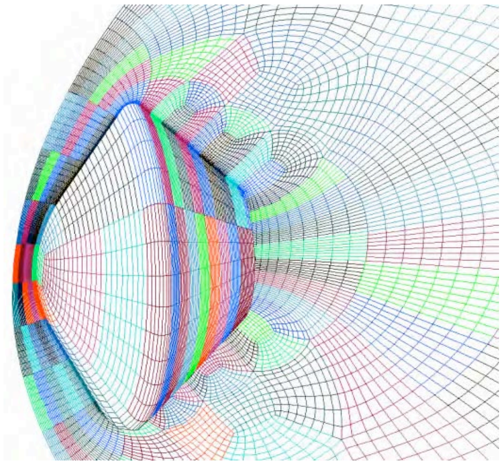


Figure 9(a). Pathfinder fore-body grid.

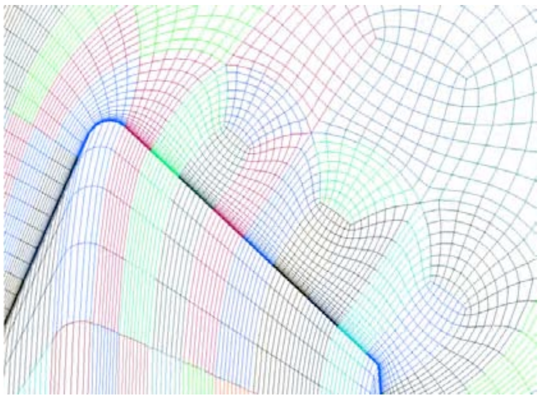


Figure 9(b). Afterbody multilayer nested grid.

Wall Cell Reynolds Number and Grid Spacing

Figure 10 also shows the clustering at the wall for an Apollo class vehicle configuration. The wall spacing is computed from the cell Reynolds number and the stretching ratio. In Figure 9(a) and (b) 32 points were used to capture the viscous layers. The current *Probe-Mesh* module allows for shock grid alignment at the outer boundary and for grid clustering within the boundary layer. Proper cell spacing near the wall is essential for calculating accurate heating rates. The first spacing off the wall in *Probe-Mesh* is calculated from the wall cell Reynolds number requirement at the post shock flow conditions deduced from the trajectory calculation or cell Reynolds numbers specified by the user. The meshes presented here are obtained for a cell Reynolds number of 1.

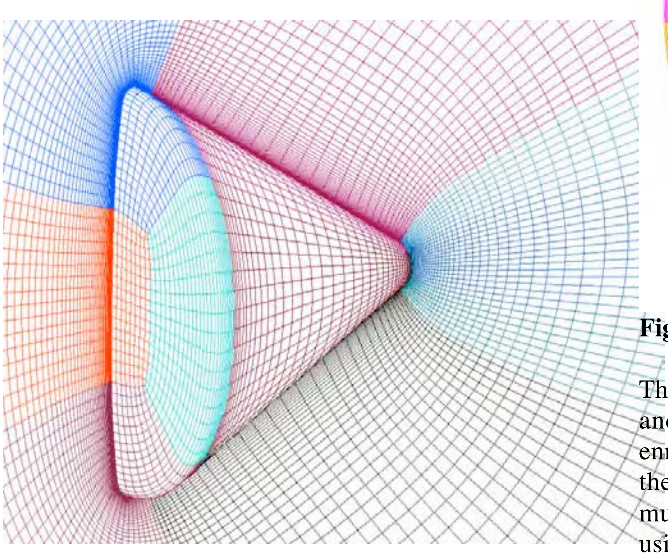


Figure 10. Surface clustering for Apollo class vehicles

Wake and Sonic Line Attachment Grid Nesting

The wake computations are extremely sensitive to the structure of the wake grid. This sensitivity is due to the fact that the wake free shear layer and recirculation vortex are viscous-dominated regions.

Grid resolution in the wake vortex and free shear layer must be of the same order as found in attached wall boundary layers to properly resolve the flow field gradients in these regions. In order to optimize the wake grid structure, the user has control over the base region topology refinement strategy to cluster grid points within the recirculation vortex and to align the stream-wise grid lines with the free shear layer. An example of the multi-block topology built to resolve the base flow in the near wake region for the Mars Pathfinder class vehicles is shown in Figure 11(a).

This topology implemented results in grid refinement to capture the structure of the wake flow field. In addition, the user also controls the grid density and resolution around the nose and corner of the probe where increased heating is expected. Figure 11 (b) shows a multi-layer nesting technique used in the forebody flow field region to study sonic line attachment effects in the overall flow structure.

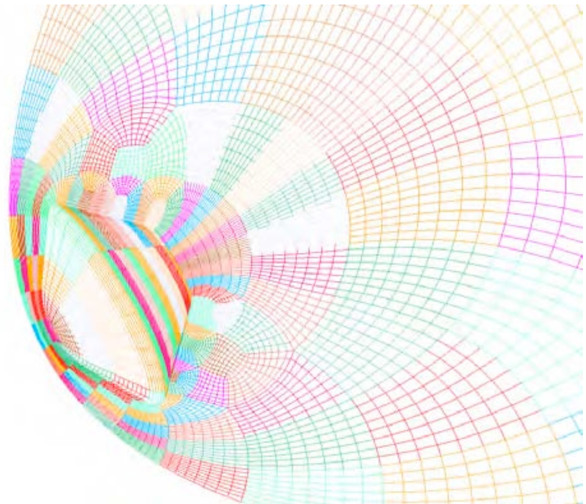


Figure 11 (a). Pathfinder wake block structure.

The user controls the number of nesting layers [4], and the number of grid points for compact enrichment per layer. To ensure the accuracy of the CFD solutions, the generated volume grid must be checked for quality. This is performed using the GridPro utility *qchk* to check for global grid quality. The volume grid is checked for orthogonality and skewness of the cells. Negative volumes are tagged and the user is alerted.

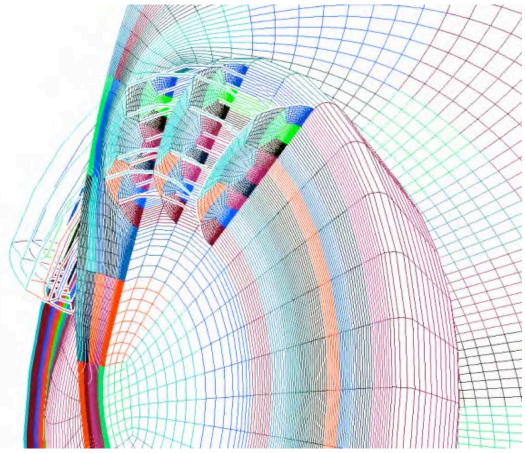


Figure 11(b). Viking forebody nesting.

Summary and Conclusions

A Platform independent standalone Matlab database-driven GUI tool *Probe-Mesh* has been developed. Automatic grid generation capabilities and autonomous CFD capability of predicting the flow field around the flight vehicle and to provide trajectory information for such vehicle has been shown. A wide range of planetary probe geometries has been developed in the database as demonstrated in this paper. The trajectory-based automatic grid generation framework for reentry vehicle architecture was demonstrated. The paper also demonstrates the volume grid quality requirements to capture the flow physics as a function of altitude along entry trajectories.

References

1. J. Fay and F. Riddell, “Theory of Stagnation Point Heat Transfer in Dissociated Air” *Journal of Aeronautical Sciences* 25 (2), Feb 1958.
2. C. Davies, “Planetary Mission Entry Vehicles,” Quick Reference Guide, V.2.1, NASA-ARC, ‘02.
3. Program Development Corp., 300 Hamilton Avenue, Suite 409, White Plains, NY 10601, *GridPro/az3000 User’s Guide and Reference Manual*, 1996.
4. P. Papadopoulos and P. Subrahmanyam, “Trajectory Based Automatic Grid Generation Tool for Atmospheric Entry CFD Modeling”, 9th International Conference on Numerical Grid Generation in Computational Field Simulations. June 2005, San Jose, California.