An Automated Capsule Mesh Generator For Icarus

Summer Internship Project

August 12, 2022

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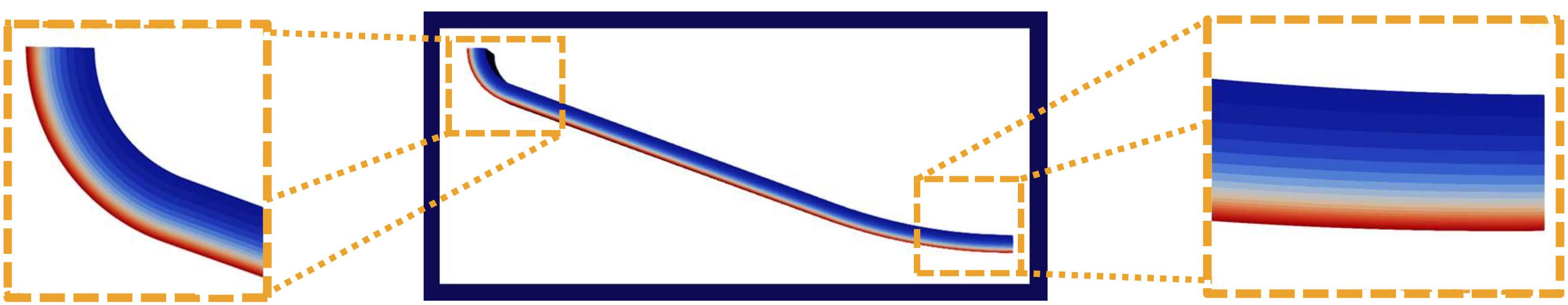
AMA at NASA Ames Research Center

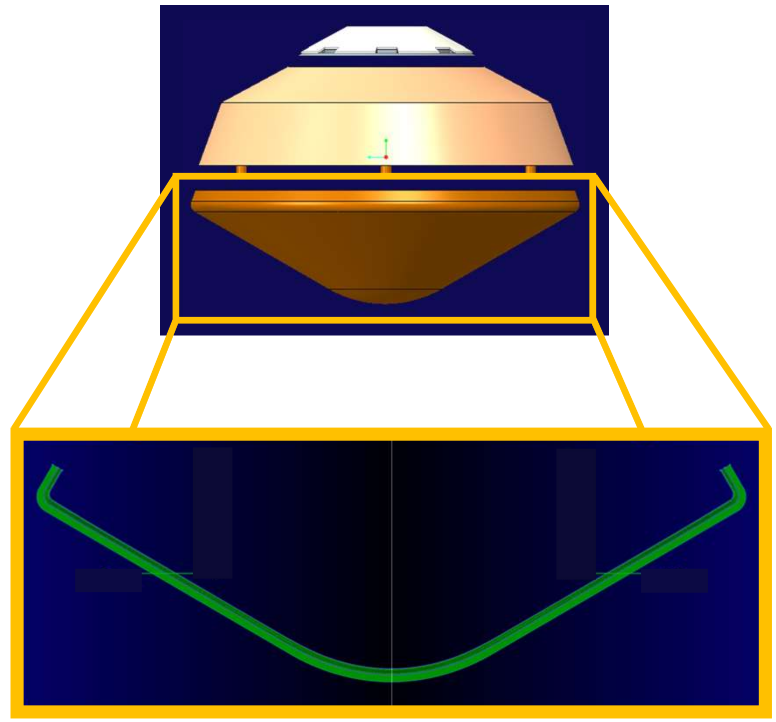
Mentor: Dr. Georgios Bellas Chatzigeorgis



OUTLINE

1) Background & Motivation
2) Capsule Mesh Generator Code Workflow
3) Capsule Mesh Generator Test Cases & Icarus Simulation Results
4) Conclusions & Future Directions

Dragonfly-EDL Capsule



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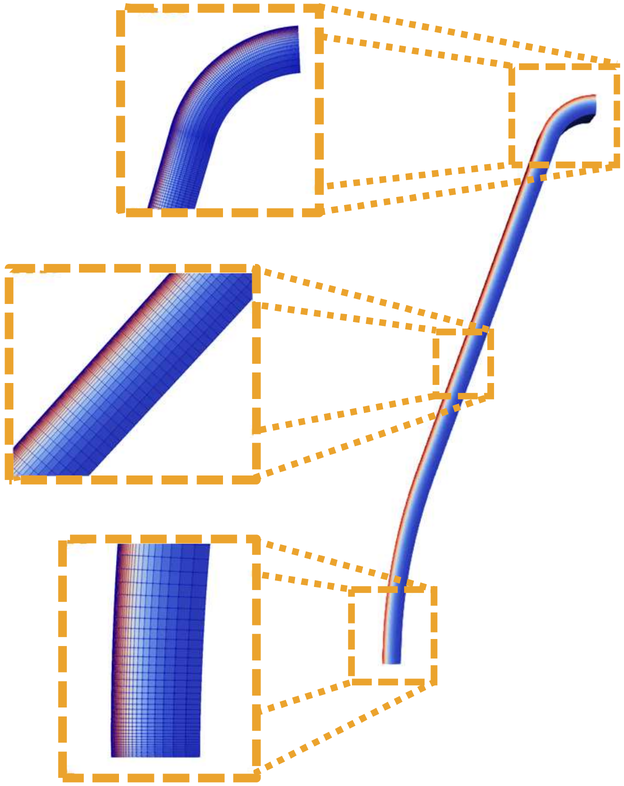
Icarus simulation of the Dragonfly capsule

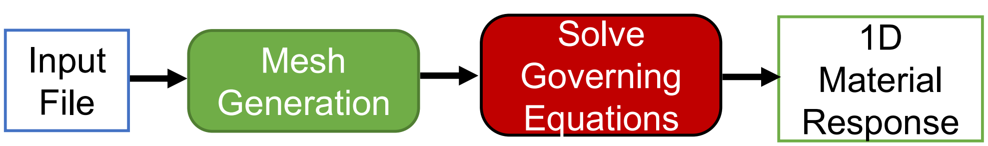


BACKGROUND & MOTIVATION

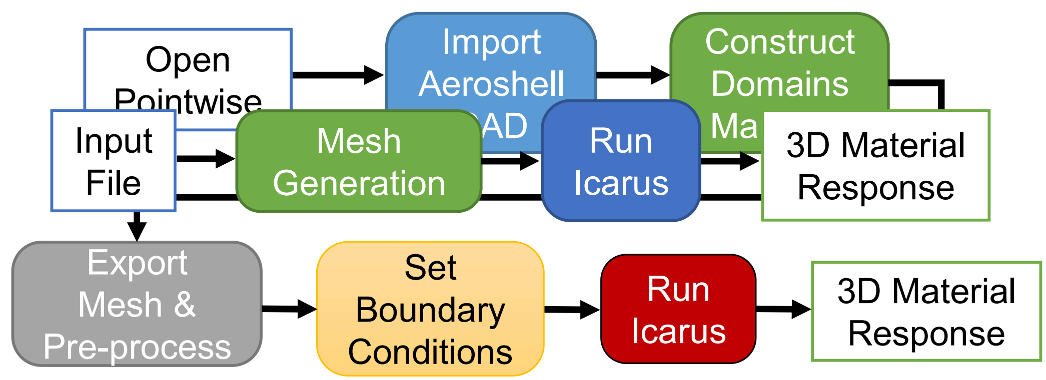
Icarus – A Material Response Design Tool

- Next-generation spacecraft TPS modeling tool under active development in the branch
- Is a 3-D finite volume, unstructured material response code that can model ablating, pyrolyzing, melting, or vaporizing materials
- Computes the in-depth material response of a multi-layer TPS material stack-up
- Is capable of modeling complex geometries and multidimensional physics that are not commonly captured by one-dimensional legacy models (*primary TPS design tools*):
  - Fully Implicit Ablation and Thermal Response Program (FIAT)
- FIAT's input is a 1D multi-layer mesh but with Icarus extending that to 3-D, the mesh generation becomes more complex and time consuming.

FIAT



Icarus



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FIAT

Input File

```
Dragonfly EV TPS
 2  0.   0.   360.   0   0   0
 5   0
 0.106 0.203 0.456 0.7 2.290
 0   0
 1.0 354.0 10.0
 51.378  2  0
 1  PICA                     329.67  1.50000 0.0
 2  HT-424                   329.67  0.02000 0.0
 3  M55Jb-composite          329.67  0.06000 0.0
 4  Al-hc-4.3-2.5in          329.67  2.50000 0.0
-5  M55Jb-composite          329.67  0.06000 0.0
```

Icarus

Input File

```
geometry:
  # Dragonfly OML
  half_cone_angle: 70 # (deg)
  cone_base_radius: 1.52 # (m)
  nose_radius: 0.442 # (m)
  shoulder_radius: 0.034 # (m)
  shoulder_angle: 20.0 # (deg)
  shoulder_length: 0.10 # (m)

layers:
  # thickness
  pica_width: 0.018 # (m)
  al-hc_width: 0.012 # (m)
  ht424_width: 0.001 # (m)
  m55j_width: 0.001 # (m)
  layer_order:
      - "pica"
      - "ht424"
      - "ht424"
      - "al-hc"
      - "m55j"
```

ANALYTICAL MECHANICS ASSOCIATES

BACKGROUND & MOTIVATION

Icarus – Physics & Boundary Conditions

- Pyrolysis results in the decomposition of the virgin material into gaseous and solid products
  - Mass balance - initial virgin material = decomposed solid/liquid and a gas mixture

Mass Conservation Solid

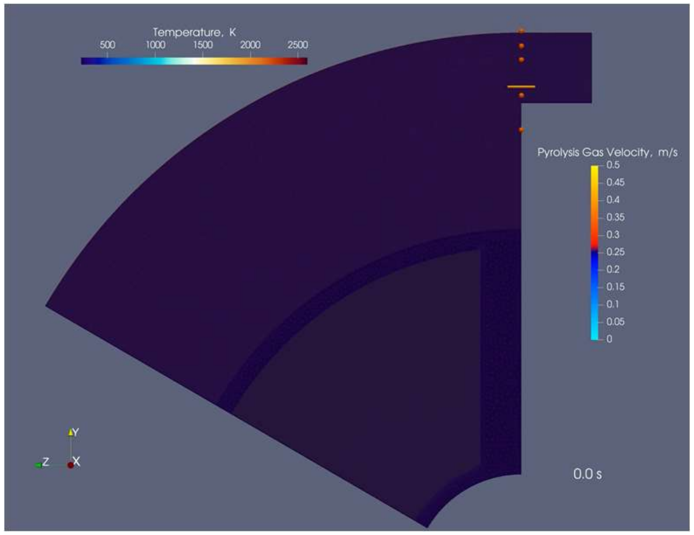
$$\frac{\partial \rho_{s,n}}{\partial t} = -k_n \rho_{v,n} \left(\frac{\rho_k - \rho_{c,n}}{\rho_{v,n}} \right)^{\psi_n} e^{(-T_{a,n}/T)},$$

Mass Conservation Gas Mixture

$$\frac{\partial (\phi \rho_g)}{\partial t} + \frac{\partial}{\partial x_i} \left(\phi \rho_g u_{g,i} \right) = \dot{\omega},$$

Energy Conservation

$$\frac{\partial (\rho e)}{\partial t} + \frac{\partial}{\partial x_i} \left(\phi \rho_g h_g u_{g,i} \right) - \frac{\partial}{\partial x_i} \left(\kappa_{ij} \frac{\partial T}{\partial x_j} \right) = 0.$$



- The boundary conditions (BCs) at the surface is the connection to the fluid equations
- A known heating profile is applied on the solid surface to calculate the material thermal response.
- The governing equations are solved using the finite volume method
  - ***A mesh is needed*** to apply these equations to specific volumes

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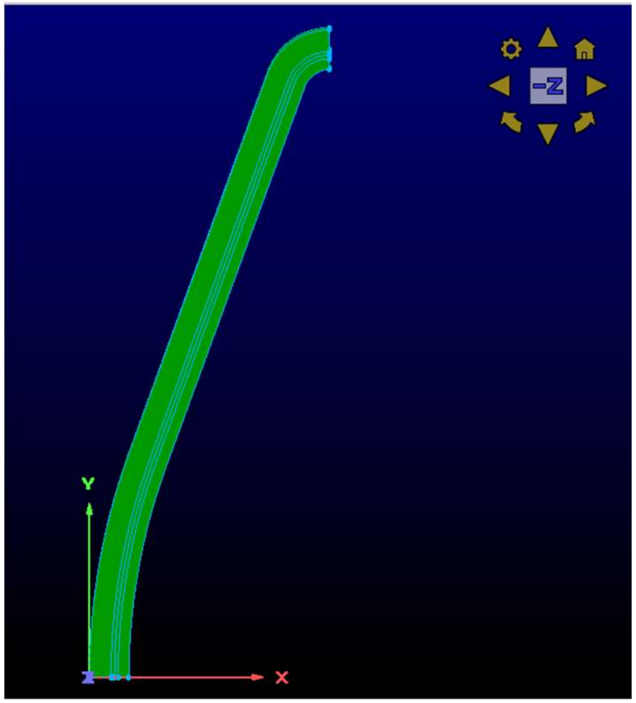
Multi-layer TPS Material Stack-up Mesh



CAPSULE MESH GENERATOR – CODE WORKFLOW

Startup

Input Parsing

2D Axial Profile Coordinates

Glyph Script

Mesh File

Command Terminal Window

```
(base) ARLAL0222020061:Mesh_Generator_Repository malemanc$ python mesh_generator.py

Automated Heat Shield Mesh Generator
Current version: 1.0

python mesh_generator.py -i [INPUT YAML file name] -o [OUTPUT Mesh file name] -m [MESH SPECS TYPE] -s [SHOULDER TYPE]

[INPUT YAML file name]: Include YAML file name without the .yaml extension
[OUTPUT Mesh file name]: Mesh file name without the extension (.pw & .cas files are output)
[MESH SPECS TYPE]: two options -> custom (custom values specified in the YAML file), default
[SHOULDER TYPE] two options -> default (termination at the shoulder apex)
                               extruded (shoulder extends in the backshell direction)

Example command:

python mesh_generator.py -i dragonfly_config -o dragonfly_test -m default -s default
```

CAPSULE MESH GENERATOR – CODE WORKFLOW

Startup

Input Parsing

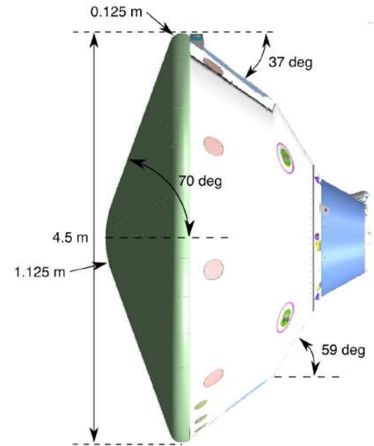
2D Axial Profile Coordinates

Glyph Script

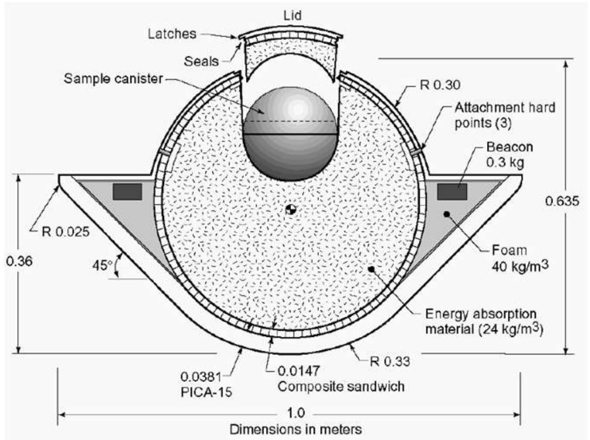
Mesh File

Outer Mold Line (**OML**) **primary dimensions**:

- *Half-cone angle*
- *Base radius*
- *Nose radius*
- *Shoulder radius*
- *Shoulder angle*
- *Shoulder length*



*Edquist K., Dyakonov A., Wright M., and Chung T., "Aerothermodynamic Design of the **MSL Heatshield**." 41st AIAA Thermophysics Conference 2009*



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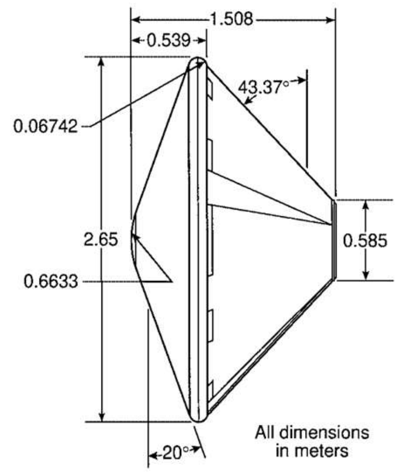
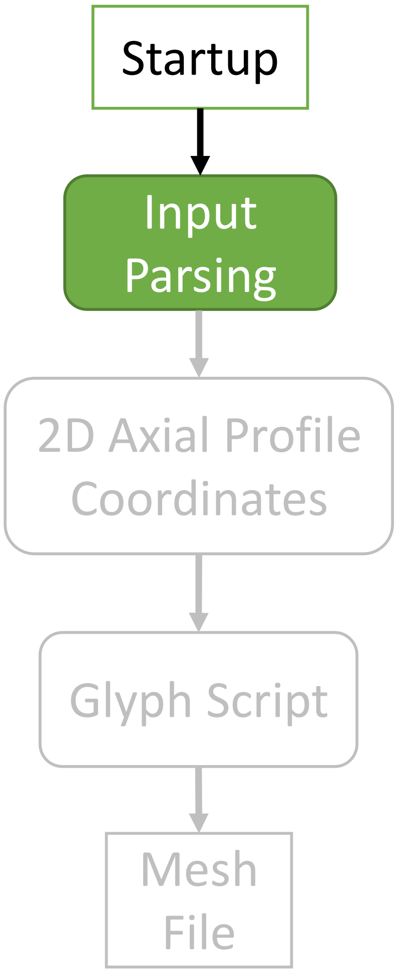


*Spencer, D., Blanchard, R., Braun, R., Kallemeyn, P., & Thurman, S., "**Mars Pathfinder Entry, Descent, and Landing Reconstruction**". Journal of Spacecraft and Rockets. Vol 36, No. 3, 1999.*

CAPSULE MESH GENERATOR – CODE WORKFLOW



Input Files:

- *YAML formatting* is used
  - Human-readable data serialization language
  - Easy to understand
- The files **MUST contain**:
  - OML dimensions
  - Layer dimensions
- All dimensions are in SI units (meters)
- The files can have extra **OPTIONAL inputs**:
  - Mesh specifications

YAML Input File


```yaml
mesh:
  pica:
    nose_points: 100.0 # Dimensionless
    ramp_points: 200.0 # Dimensionless
    shoulder_points: 100.0 # Dimensionless
    width_points: 30.0 # Dimensionless
    wall_spacing: 0.0005 # Dimensionless
  al-hc:
    nose_points: 100.0 # Dimensionless
    ramp_points: 200.0 # Dimensionless
    shoulder_points: 100.0 # Dimensionless
    width_points: 15.0 # Dimensionless
    wall_spacing: 0.0005 # Dimensionless
  ht424:
    nose_points: 100.0 # Dimensionless
    ramp_points: 200.0 # Dimensionless
    shoulder_points: 100.0 # Dimensionless
    width_points: 5.0 # Dimensionless
    wall_spacing: 0.0005 # Dimensionless
  m55j:
    nose_points: 100.0 # Dimensionless
    ramp_points: 200.0 # Dimensionless
    shoulder_points: 100.0 # Dimensionless
    width_points: 5.0 # Dimensionless
    wall_spacing: 0.0005 # Dimensionless
```

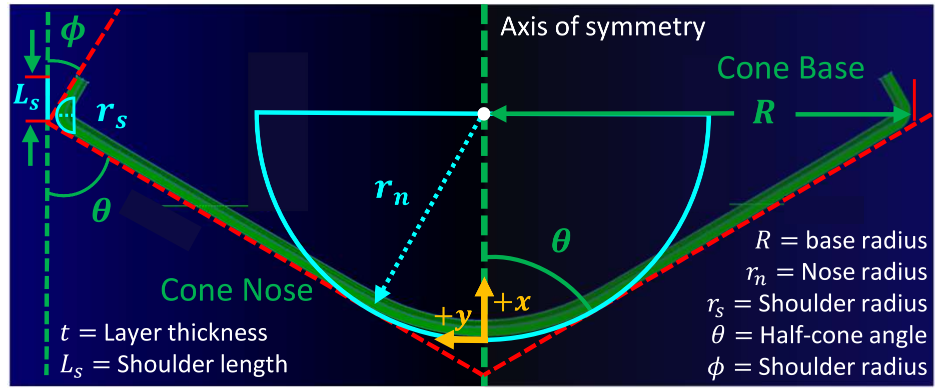
CAPSULE MESH GENERATOR – CODE WORKFLOW

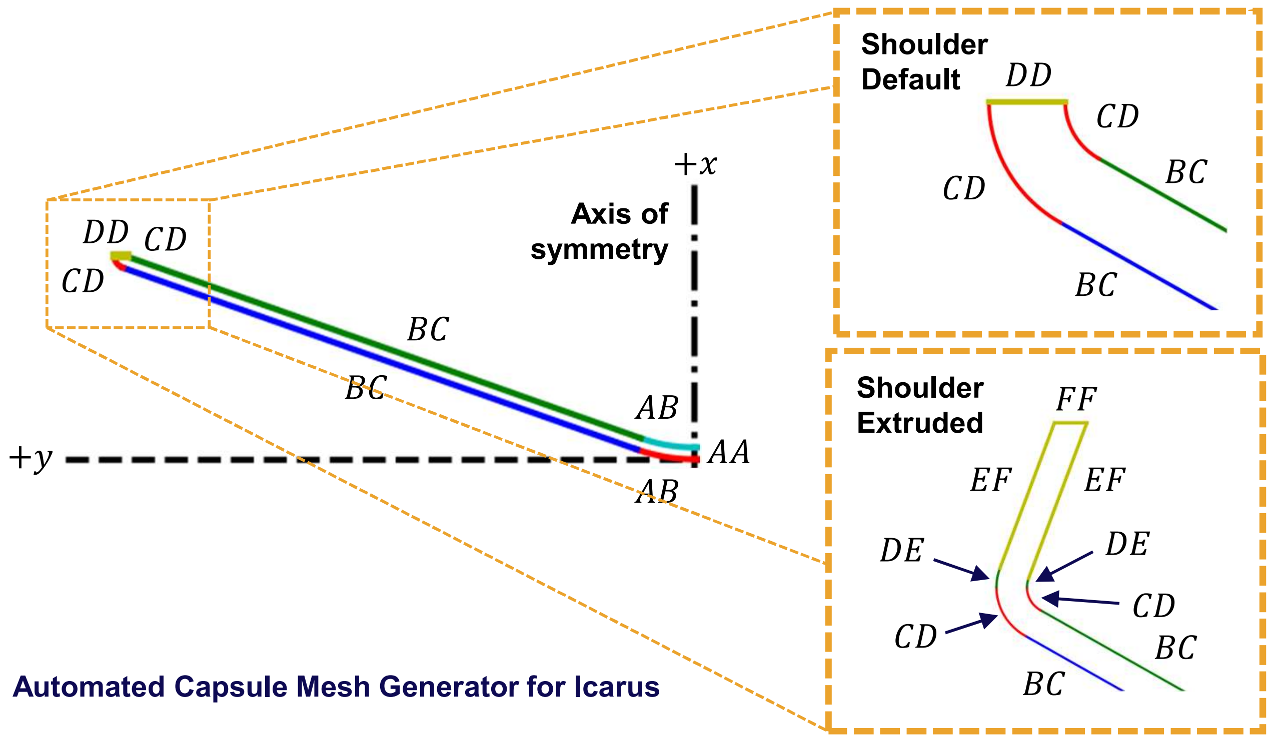
- Startup
- Input Parsing
- 2D Axial Profile Coordinates
- Glyph Script
- Mesh File

Segments (connectors):

- Arc AB
- Line BC
- Arc CD

- Arc AB
- Line BC
- Arc CD
- Arc DE
- Line EF





Nodes	
Outer	Inner
A_o	A_i
B_o	B_i
C_o	C_i
D_o	D_i
E_o	E_i
F_o	F_i

CAPSULE MESH GENERATOR – CODE WORKFLOW

Startup

↓

Input Parsing

↓

2D Axial Profile Coordinates

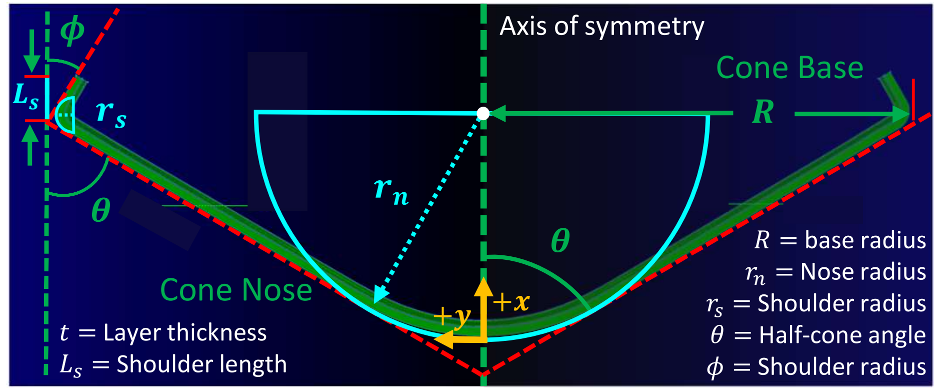
↓

Glyph Script

↓

Mesh File

Nodes			
Outer		Inner	
A_o	D_o	A_i	D_i
B_o	E_o	B_i	E_i
C_o	F_o	C_i	F_i



$$\boldsymbol{A_o} = [A_{o_x}, A_{o_y}] = [0,0]$$

$$\boldsymbol{B_o} = [A_{o_x} - r_n\cos(\theta), r_n - r_n\sin(\theta)]$$

$$\boldsymbol{C_o} = [-R + (r_s - r_s\cos(\theta)), B_{o_y} + (-C_{o_x} + B_{o_x})(\cos(\theta)/\sin(\theta))]$$

$$\boldsymbol{D_o} = [-R, C_{o_y} + r_s\sin(\theta)]$$

$$\boldsymbol{E_o} = [D_{o_x} + (r_s - r_s\cos(\phi)), D_{o_y} + r_s\sin(\phi)]$$

$$\boldsymbol{F_o} = [E_{o_x} + \left(D_{o_y} + L_s - E_{o_y}\right)\tan(\phi), D_{o_y} + L_s]$$

$$\boldsymbol{A_i} = [A_{o_x}, A_{o_y} + t]$$

$$\boldsymbol{B_i} = [B_{o_x} + t\cos(\theta), B_{o_y} + t\sin(\theta)]$$

$$\boldsymbol{C_i} = [C_{o_x} + t\cos(\theta), C_{o_y} + t\sin(\theta)]$$

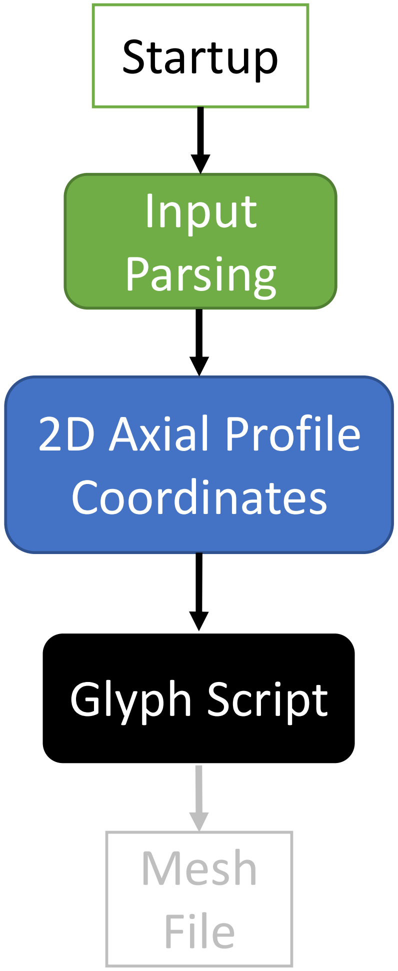
$$\boldsymbol{D_i} = [D_{o_x} + t, D_{o_y}]$$

$$\boldsymbol{E_i} = [E_{o_x} + t\cos(\phi), E_{o_y} - t\sin(\phi)]$$

$$\boldsymbol{F_i} = [F_{o_x} + t/\cos(\phi), F_{o_y}]$$

where $\boldsymbol{t}$ = **layer thickness**

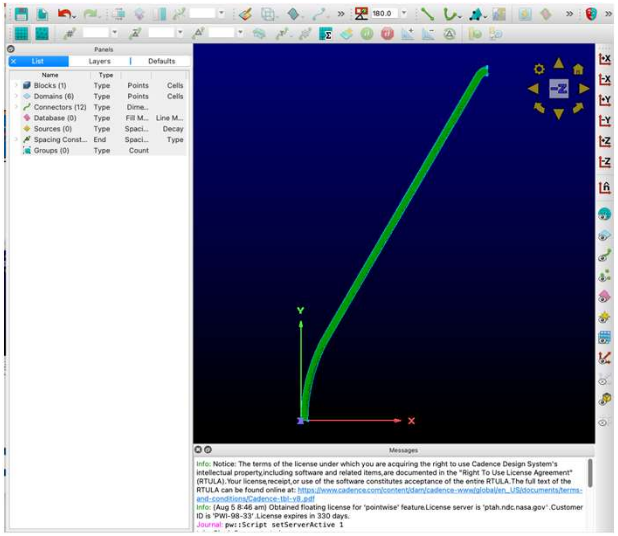
CAPSULE MESH GENERATOR – CODE WORKFLOW



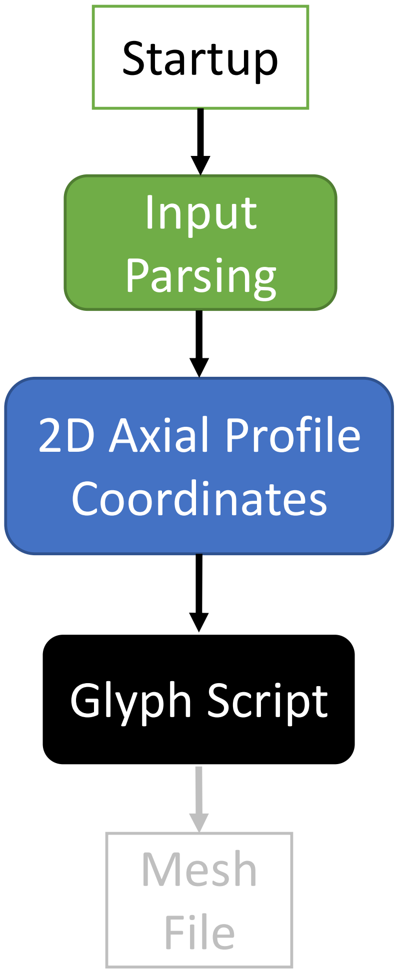
<u>Meshing Software:</u> ***Pointwise***

- *<u>Glyph</u>* is the native scripting language of Pointwise
- Pointwise has a *<u>Glyph Server</u>* that:
  - Allows an external process to connect to a user-specified port
  - Allows interaction with Pointwise to execute Glyph actions
- In Sept. 2018 Pointwise added the *<u>Glyph API for Python</u>* in Python client package
  - Previously python scripting required to build up Glyph command strings that were sent to the server
  - The new API makes glyph scripting in Python look and act like Python

Mesh in Pointwise



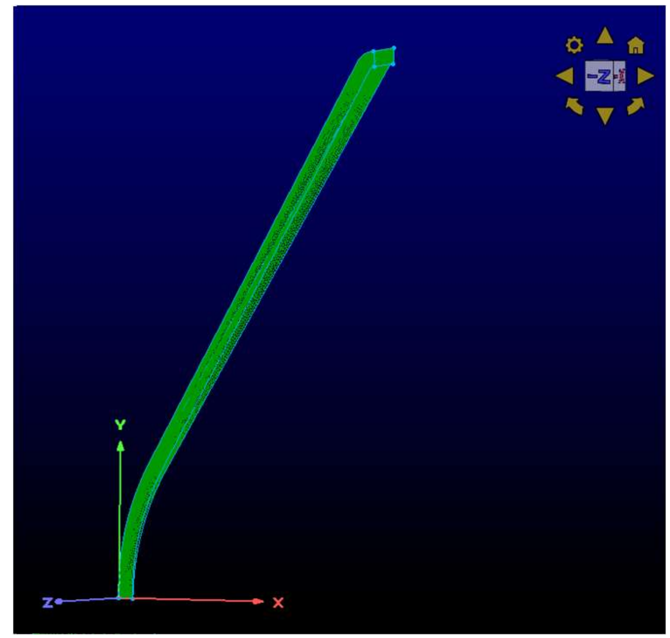
CAPSULE MESH GENERATOR – CODE WORKFLOW



Meshing Software: ***Pointwise***

- Actions required to make TPS mesh:
  1) Draw connectors
  2) Dimension connectors
  3) Adjust distribution spacings
  4) Create 2D structured domains
  5) Run elliptic solver to ensure orthogonality
  6) Rotate extrude (single step)
  7) Assign BCs and volume conditions
- These actions were “translated” from glyph to Python using the Glyph API for Python

Mesh in Pointwise



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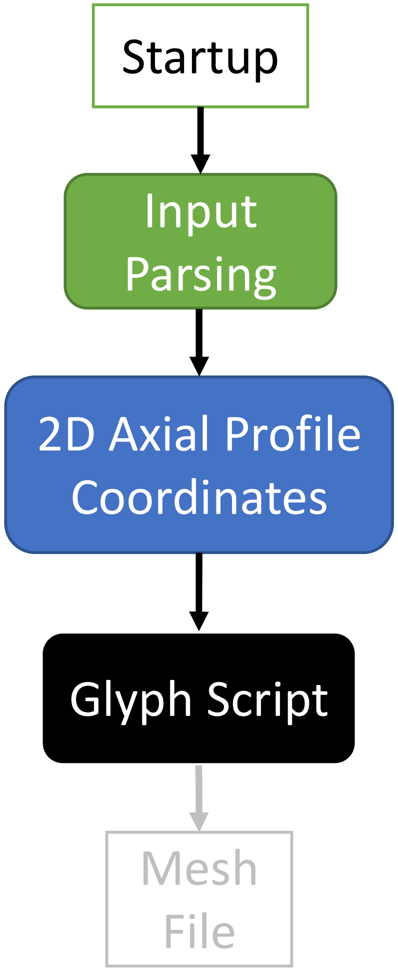

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Example command:

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```

ANALYTICAL MECHANICS ASSOCIATES

CAPSULE MESH GENERATOR – CODE WORKFLOW

Startup
↓
Input Parsing
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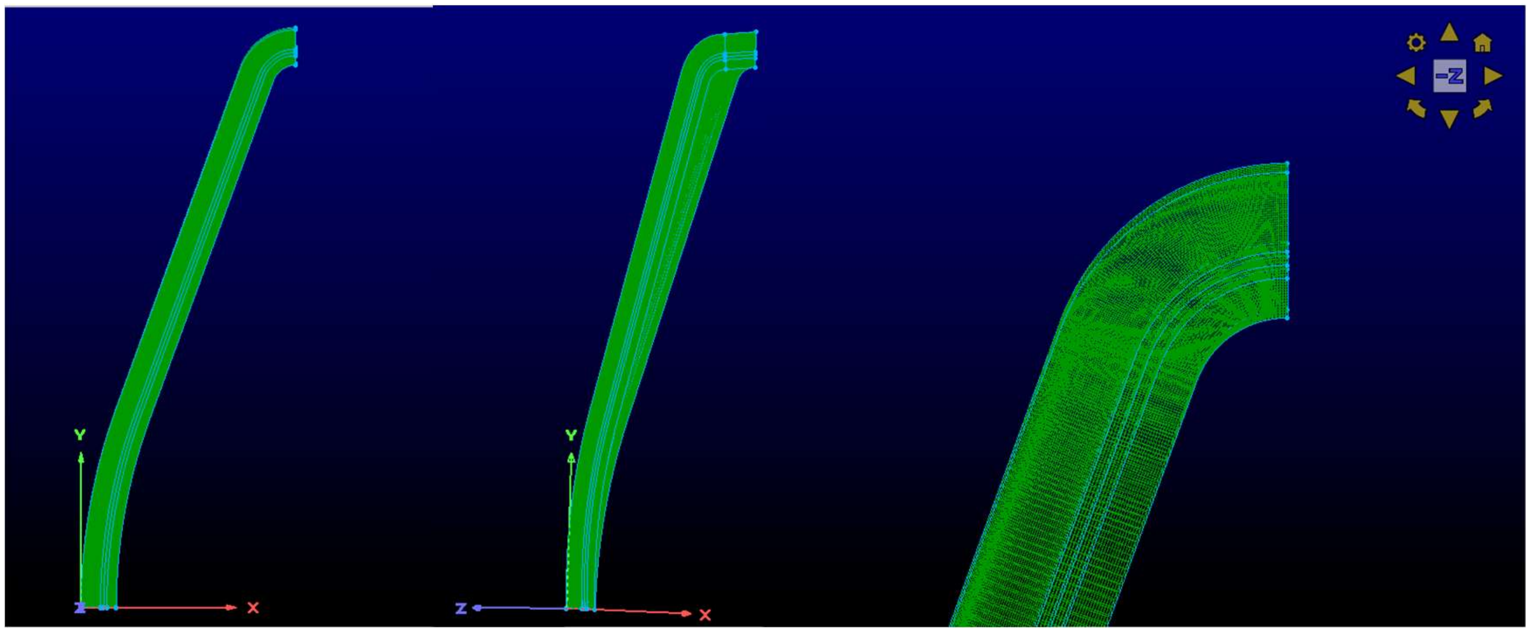
2D Axial Profile Coordinates
↓
Glyph Script
↓
Mesh File

Dragonfly Multi-layer TPS Material Stack-up Mesh



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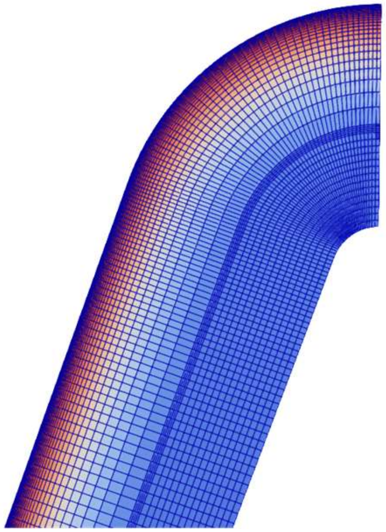
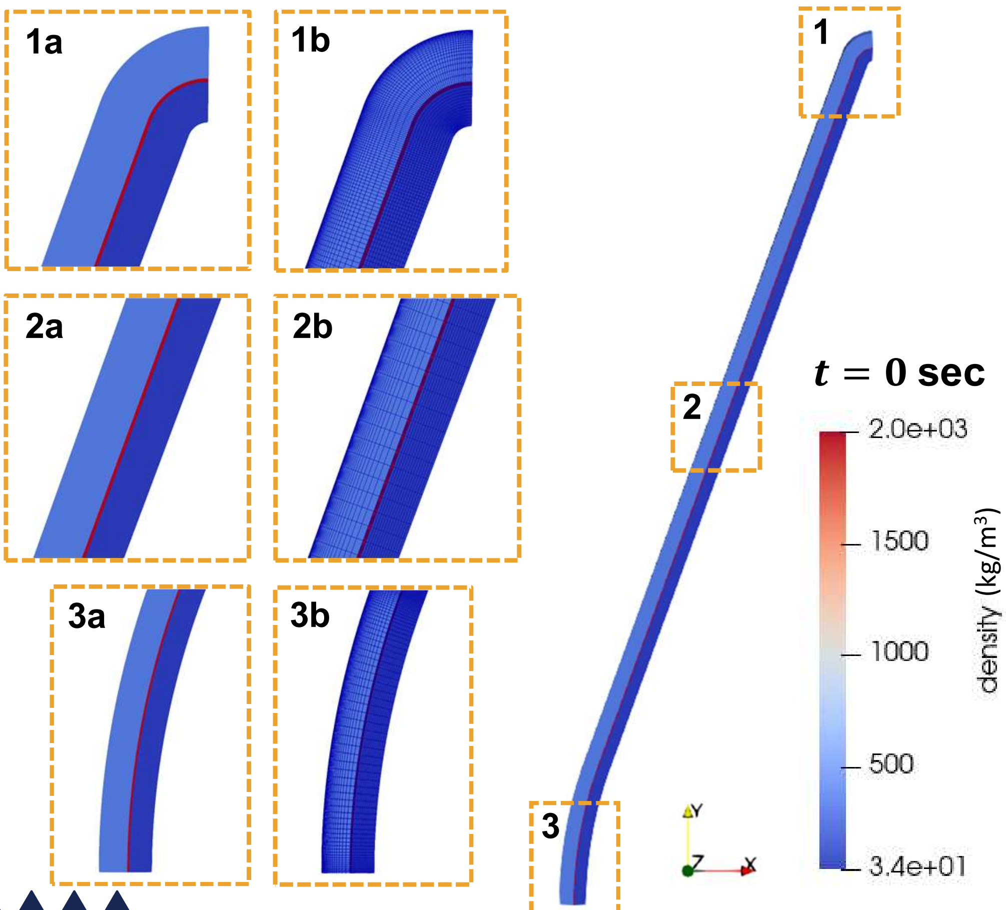
Temperature distribution of capsule shoulder with multi-layer stack of TPS Materials

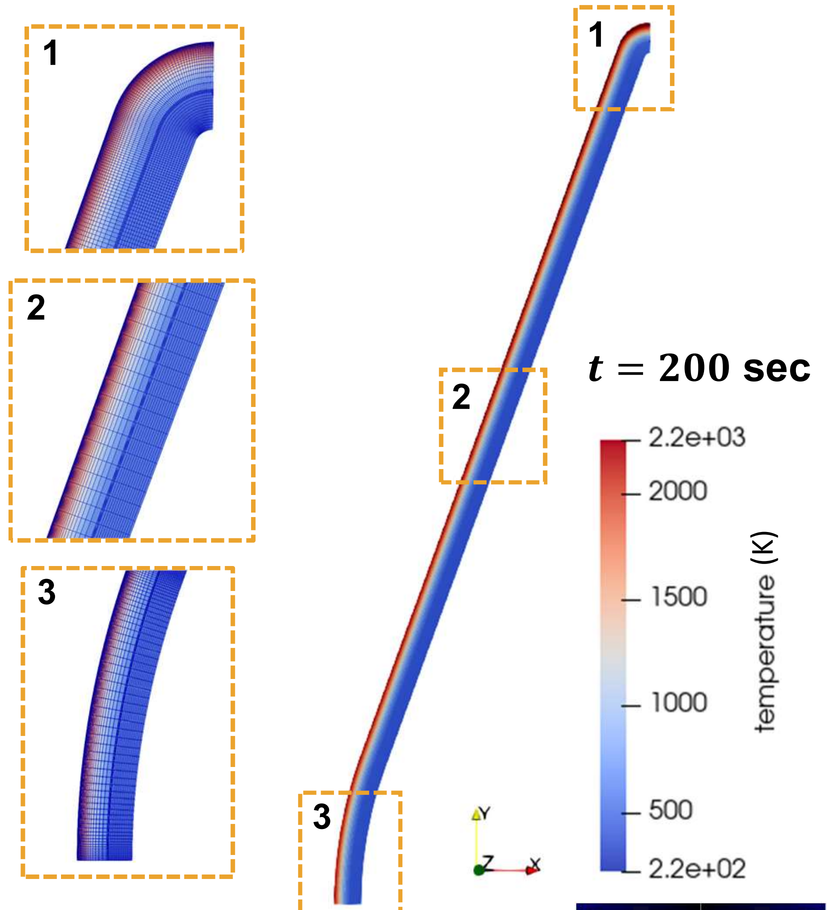


MESH GENERATOR – DRAGONFLY TEST CASE

Icarus Simulation – TPS Materials Density



Icarus Simulation – Temperature Dist.



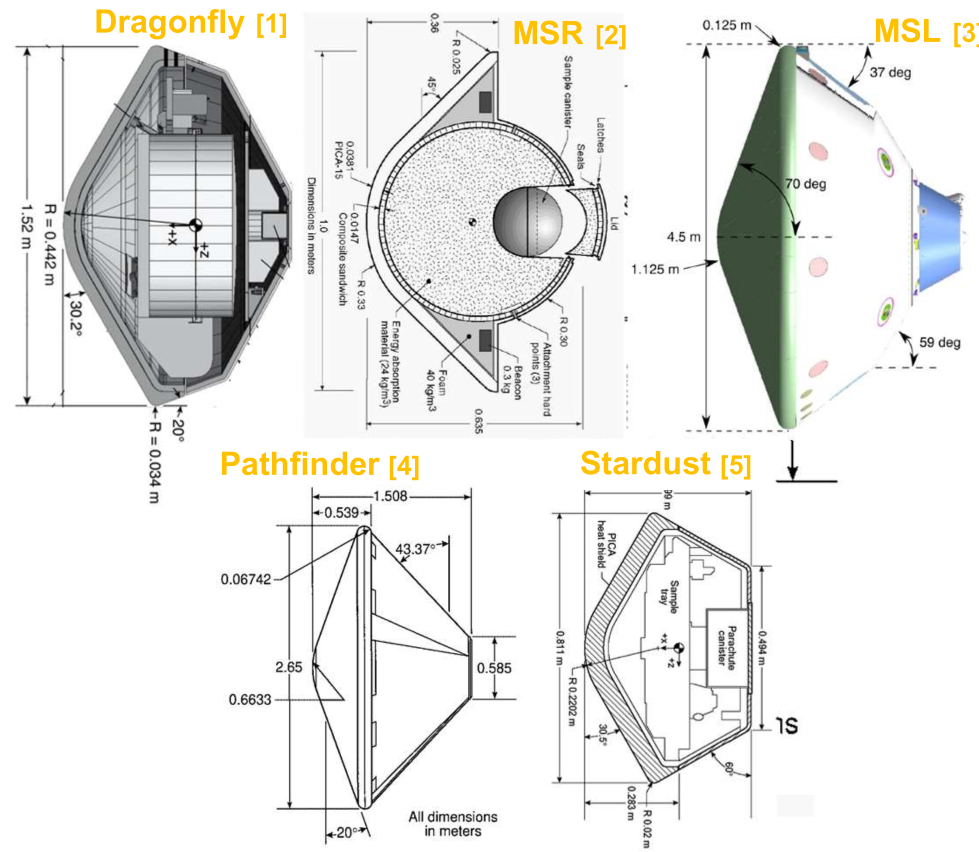
MESH GENERATOR TEST CASES RESULTS

Mesh Generator – Test Cases

	TPS Single Material Stack-up		TPS Multi Material Stack-up	
Mission Name	**Shoulder Default**	**Shoulder Extruded**	**Shoulder Default**	**Shoulder Extruded**
Dragonfly	✓	✓	✓	✓
MSR	✓	NA	✓	NA
MSL	✓	✓	✓	✓
Pathfinder	✓	✓	✓	✓
Stardust	✓	✗	✓	✗

- The ***MSR*** capsule has a default shoulder config. (not extruded towards the backshell)

Capsule Geometry



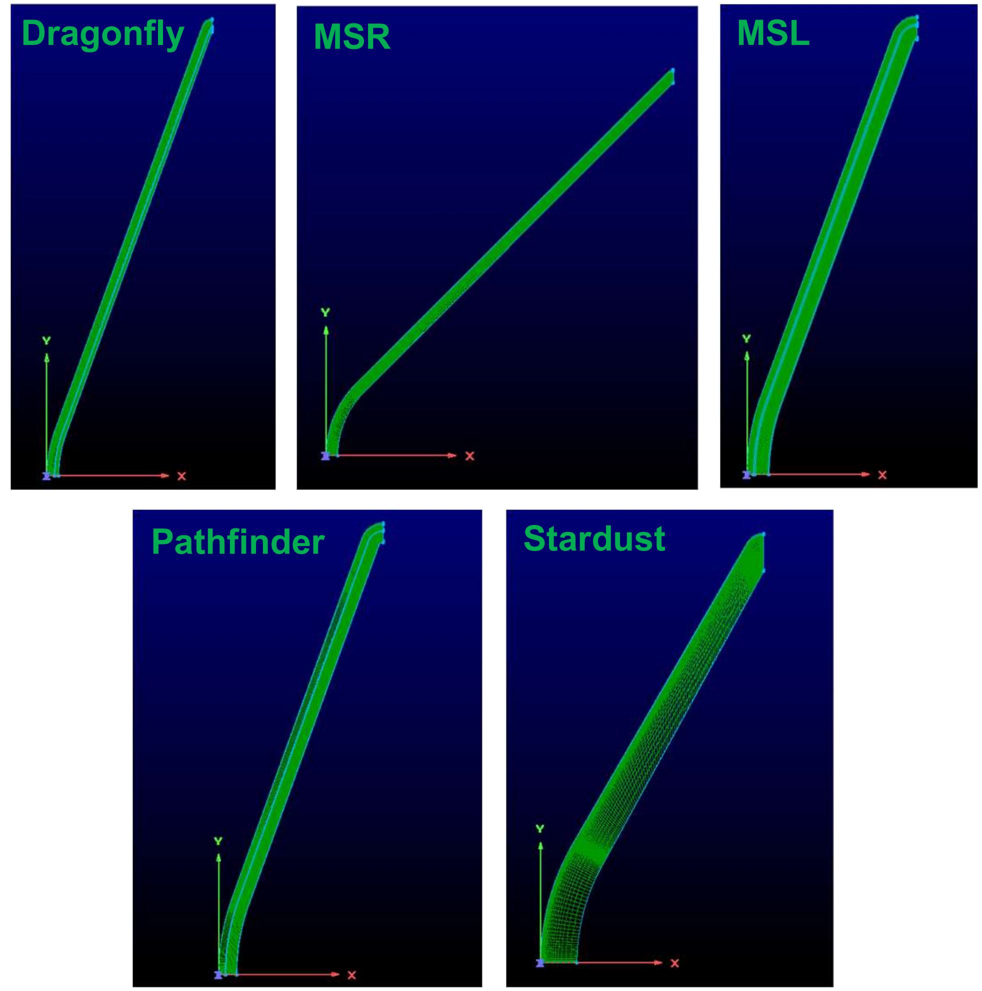
[1] *Dragonfly OML (Icarus Team)*
[2] *Mitcheltree R., Kellas S., Dorsey J., Desai P., & Martin C. "A passive Earth-entry capsule for **Mars sample return**." In 7th AIAA/ASME Joint Thermophysics and Heat Transfer Conference 1998.*
[3] *Edquist K., Dyakonov A., Wright M., & Chung T., "Aerothermodynamic Design of the **MSL Heatshield**." 41st AIAA Thermophysics Conference 2009*
[4] *Spencer, D., Blanchard, R., Braun, R., Kallemeyn, P., & Thurman, S., "**Mars Pathfinder** Entry, Descent, and Landing Reconstruction". Journal of Spacecraft and Rockets. Vol 36, No. 3, 1999.*
[5] *Kontinos, D. A., & Wright, M. J. "Introduction: Atmospheric entry of the **Stardust** sample return capsule". Journal of Spacecraft and Rockets. Vol. 47, No. 5, 2010.*

ANALYTICAL MECHANICS ASSOCIATES

MESH GENERATOR – OVERALL RESULTS

- The mesh generation process takes *less than 5 seconds* vs. *1+ hours* per case
  - Takes ~1 hour for an experienced user, and 2 weeks for a new user

- *This new tool enables*:
  - Sequential adjustment of cell number/spacing
  - Performing automated grid refinement studies
    - Mesh convergence
    - Mesh sensitivity
  - Automation of the rapid design optimization approach that is used with FIAT
  - Performing TPS sizing true optimization



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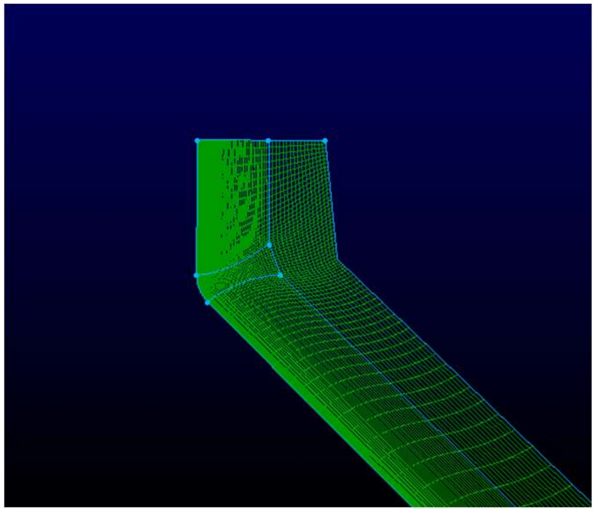
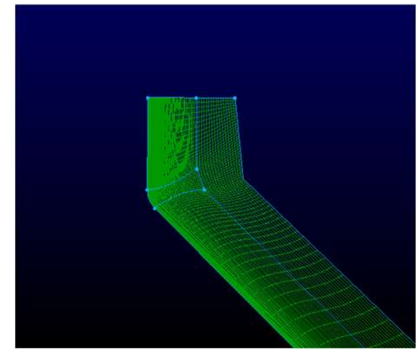
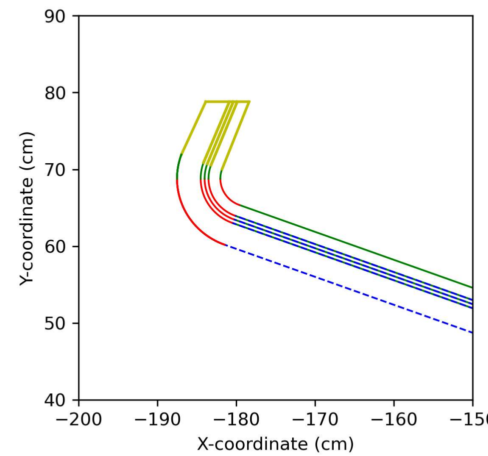
Complex shoulder geometry



CONCLUSIONS & FUTURE DIRECTIONS

- An automated capsule mesh generator for Icarus was developed using Python
- This tool can automatically generate a capsule TPS axisymmetric mesh with:
  - *Single or multiple-layer TPS material stack-up*
  - *Two shoulder configurations*
- The mesh generation process duration is *less than 5 seconds*
- The *main application of this tool is to automate*:
  - *Mesh convergence and sensitivity studies*
  - *Mission design studies and TPS sizing*
- ***This tool is a step forward into completing the Icarus code workflow***
- *Future directions/goals*:
  - Incorporate the ability of having layers with different domain types
  - Generate the mesh for the backshell
  - Automate the material orientation process.





Special thanks to:
Dr. Georgios Bellas Chatzigeorgis
Dr. Eric Carl Stern
Icarus Team

THANK YOU!

Questions?