Hypersonic Aeroshell Shape Optimization

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Outline

- Motivation
- Objective and Methodology
  - Hypersonic aerodynamics
  - Shape representation
  - Optimization
- Example application
- Summary
- Future work

Motivation

- EDL system performance influenced by two vehicle parameters:

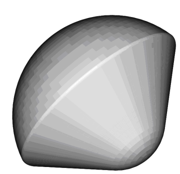
$$\beta = \frac{m}{C_D A} \qquad L/D = \frac{C_L A}{C_D A}$$

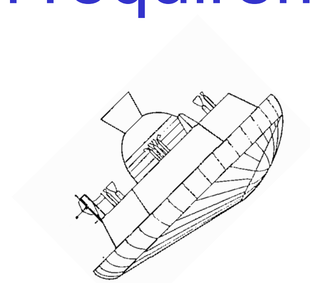
- Ballistic coefficient *(β)* should be as low as possible for heating, deceleration, and timeline
- Lift-to-drag ratio *(L/D)* may be needed to satisfy other mission requirements, like precision landing
- Drag area ($C_D A$) is the common denominator
  - *L/D* should not be attained through large reductions in $C_D A$

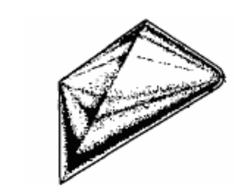
Aeroshell Design

- Aeroshell shape design is a trade-off between drag, stability, heating, packaging, and CG placement

- Shape selection is dependent on specific mission and flight system requirements







Primary driver:	drag	stability	non-equilibrium aerothermodynamics	minimize radiation for high-speed Earth return

Present Investigation

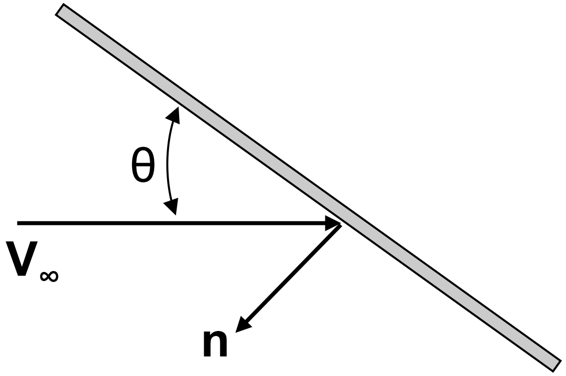
- Objective: Maximize a multi-objective function of drag, stability, and CG placement, subject to constraints on *L/D*, volume, and size
  - Aerothermodynamic constraints not considered yet
  - Shoulder geometry not considered yet

- Formulate as an optimization problem:
  - *Maximize*: $f = w_1 * C_D A - w_2 * C_{m,\alpha} - w_3 * |\text{CG offset}|$
    - *Subject to*: Specified *L/D*, volume, and size constraints
    - *By varying*: Aeroshell shape
    - w_1, w_2, and w_3 are user-defined parameters that provide normalization and weighting
    - For this investigation, drag, stability, and CG offset objectives are normalized to the same order of magnitude

- Approach:
  - Hypersonic aerodynamic analysis
  - Shape representation
  - Shape optimization

Hypersonic Aerodynamics

- Newtonian flow theory
  - Simple, analytic technique
  - Only requires description of aeroshell geometry (impact method)
- Panel methods written in MATLAB



$$C_p = 2\sin^2\theta$$

$$= 2\left(\frac{\mathbf{V}_\infty}{\left|\mathbf{V}_\infty\right|}\cdot\mathbf{n}\right)^2$$

- Aerodynamic forces and moments computed from surface pressure (C_p) distribution

Shape Representation

Approaches considered, increasing in design freedom and complexity:

1) Analytic shapes
   - Parameterized in terms of cone angles, nose radii, etc.

2) Surfaces of revolution
   - Spline profile revolved around centerline

3) Spline surfaces

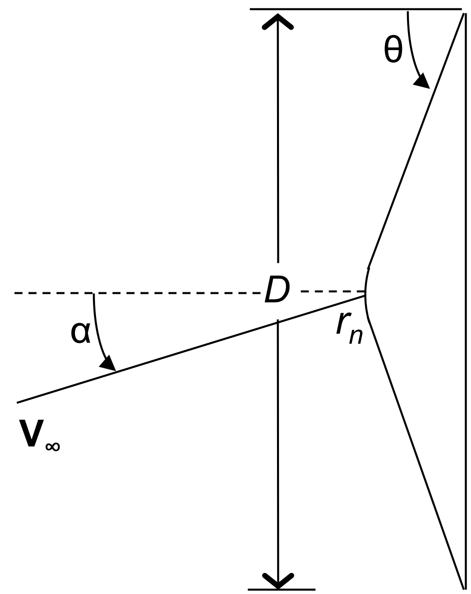
Analytic Shape

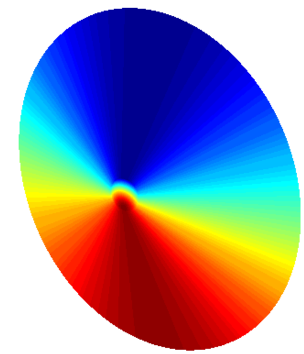
- Sphere-cone aeroshell

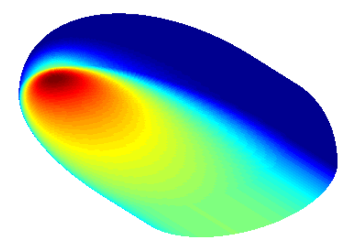
→ 4 parameters/design variables
  - Nose radius
  - Cone angle
  - Maximum diameter
  - Angle of attack

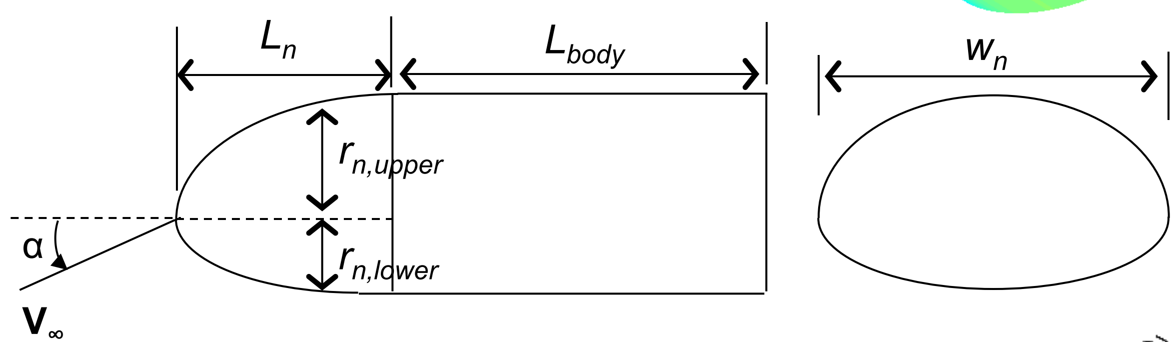
- Ellipsled aeroshell

→ 6 parameters/design variables
  - Top and bottom nose radii
  - Nose width
  - Nose length
  - Body length
  - Angle of attack



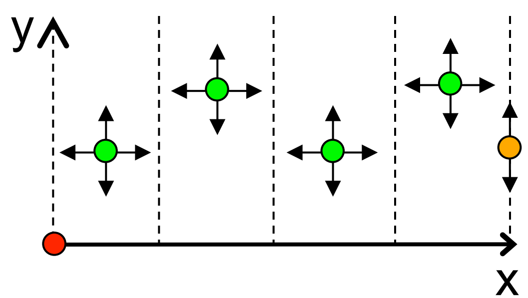




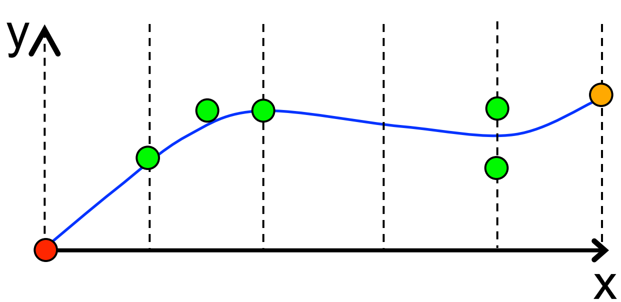


Surfaces of Revolution

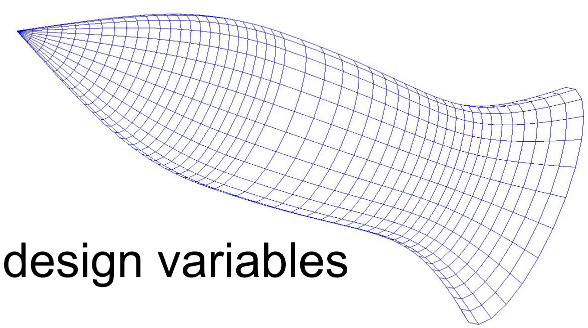
- Position of *control points* defines axial profile
  - 1^{st} control point fixed to generate a closed forebody
  - Last control point constrained to define aeroshell length
  - Remaining control points have 2 degrees of freedom



- Spline generated and revolved around the centerline

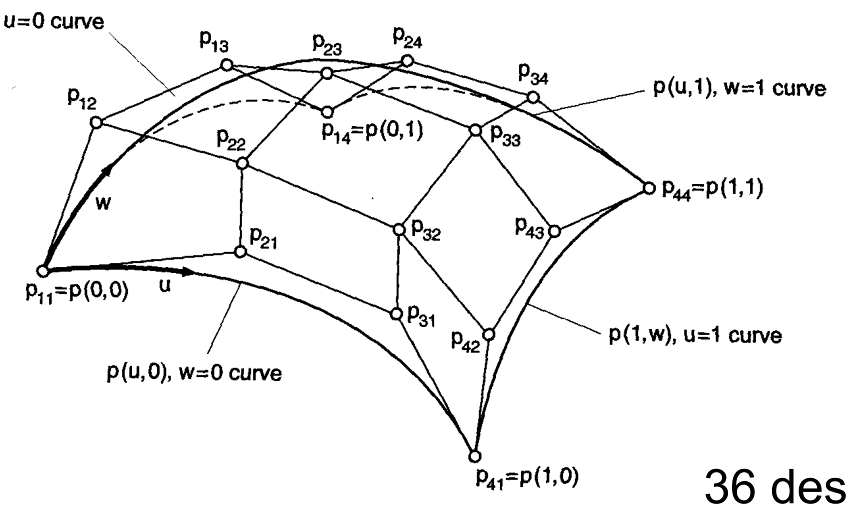


14 design variables

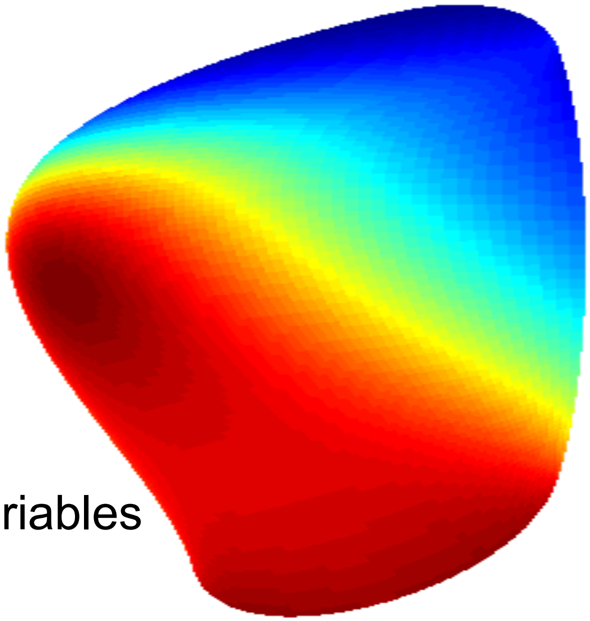


General Spline Surfaces

- Spline surfaces are generated from a net of control points
  - Spline surface theory is a direct extension of spline curve theory



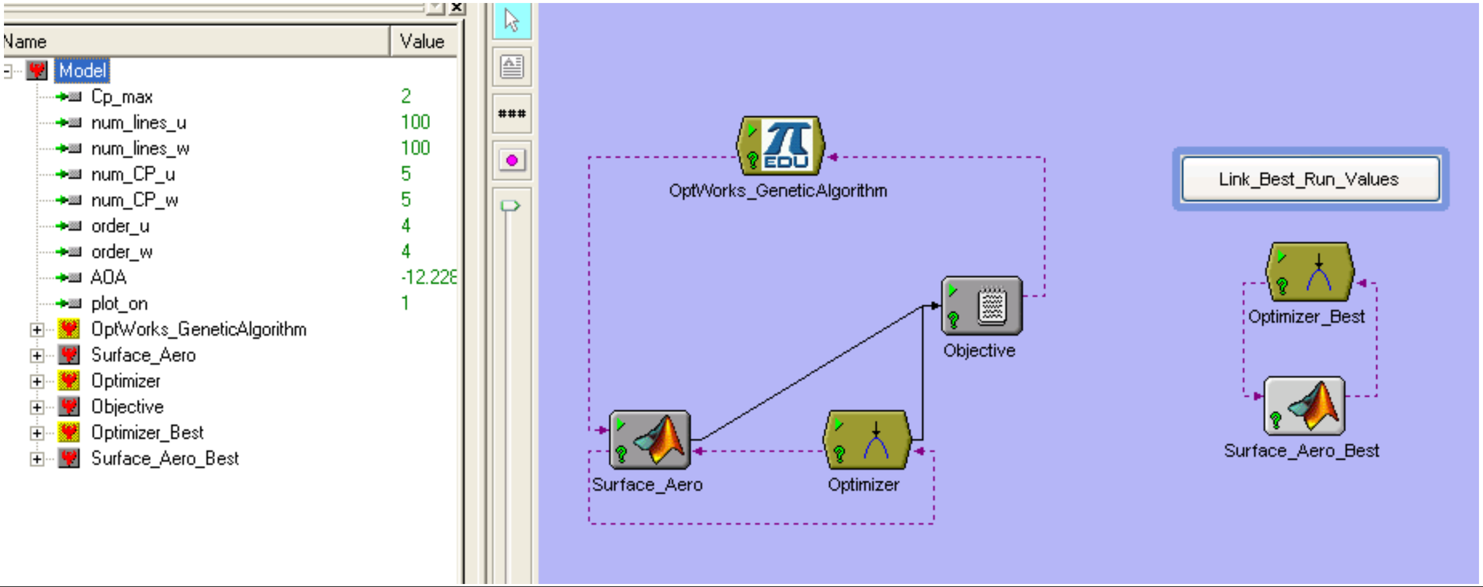
36 design variables



Optimization

- Geometry and aerodynamics analyses input into Phoenix ModelCenter for optimization

- Gradient-based and genetic algorithms used



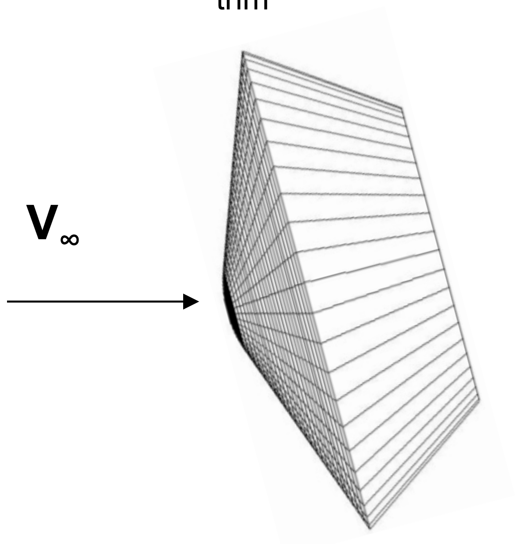
Example Application

- Analytic sphere-cone vs. SOR vs. general surface

- MSL mission used to define constraints
  - L/D = 0.24
  - Volume = 18 m^3
  - Size: Fit within a 4.5 m x 4.5 m x 2.75 m volume

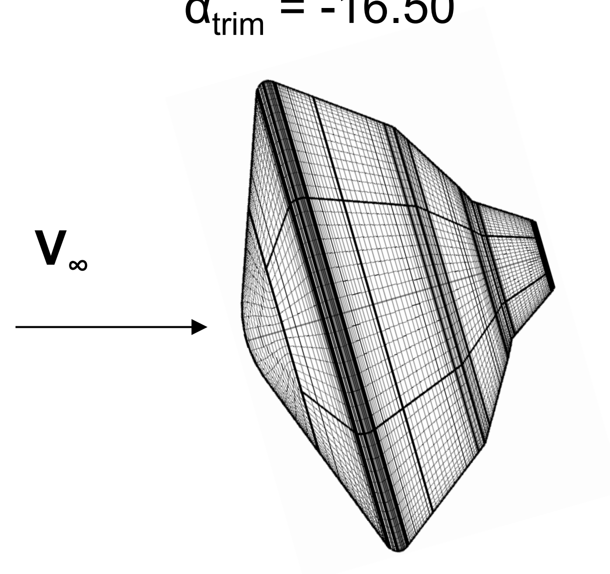
Analytic Reference vs. MSL

α_{trim} = -15.50°



Parameter	Value
C_D	1.6068
$C_{m,\alpha}$	-0.1785
(CG offset)/L_{ref}	0.02812

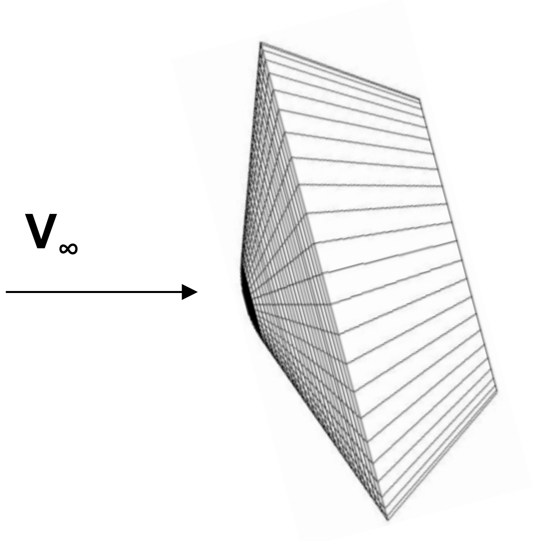
α_{trim} = -16.50°



Parameter	Value
C_D	~1.5
(CG offset)/L_{ref}	0.02150

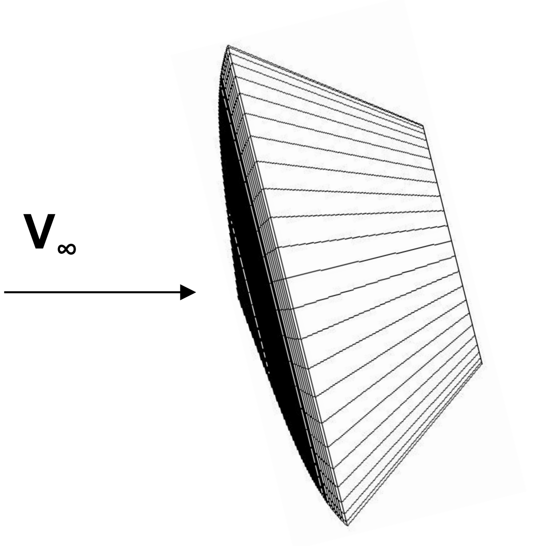
Analytic vs. SOR

$\alpha_{trim} = -15.50^{\circ}$



Parameter	Value
C_D	1.6068
$C_{m,\alpha}$	-0.1785
(CG offset)/L_{ref}	0.02812

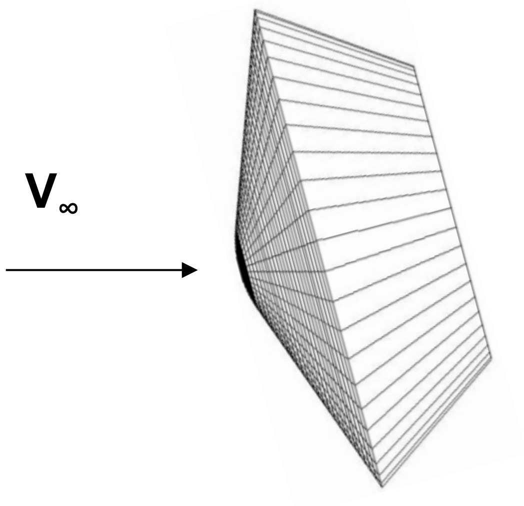
$\alpha_{trim} = -14.76^{\circ}$



Parameter	Value	% Difference
C_D	1.6827	+4.72%
$C_{m,\alpha}$	-0.1552	+13.07%
(CG offset)/L_{ref}	0.02228	-20.77%

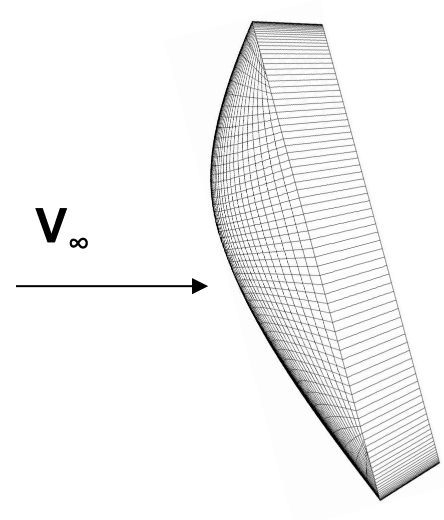
Analytic vs. General Surface

α_{trim} = -15.50°



Parameter	Value
C_D	1.6068
$C_{m\cdot\alpha}$	-0.1785
(CG offset)/L_{ref}	0.02812

α_{trim} = -15.87°



Parameter	Value	% Difference
C_D	1.5140	-5.78%
$C_{m,\alpha}$	-0.2408	-34.91%
(CG offset)/L_{ref}	0.00558	-80.16%

Summary

- Developed capability to trade aeroshell drag, stability, and CG placement in aeroshell shape design
- Increasing levels of design freedom and complexity available
- Compared shapes generated from MSL constraints
  - Results depend on user-defined weightings
  - SOR provides 5% drag improvement for 13% stability penalty, with the CG 21% closer to centerline
  - General surface provides 35% stability benefit for 6% drag decrement, with the CG almost at the centroid

Future Work

- Add aerothermodynamic constraints
  - Nose and shoulder blunting
- Consider other spline techniques
  - Non-uniform rational B-splines (NURBS) to precisely represent analytic shapes like conics and quadric surfaces
  - Convert from cartesian to polar coordinates for the general surface representation to align with physical constraints (launch vehicle)
  - Autonomously enforce convexity
- Explore different optimization algorithms and frameworks