Hypersonic Aerodynamic Shape Optimisation

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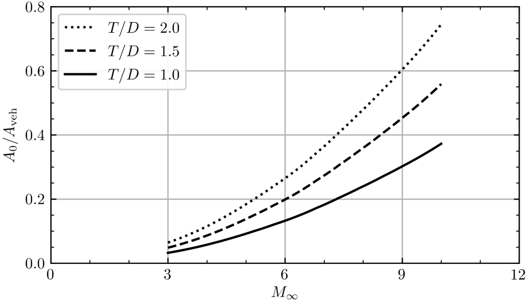
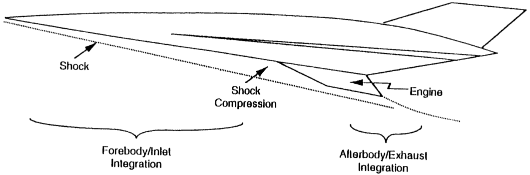
Airframe Integration for Hypersonic Vehicles



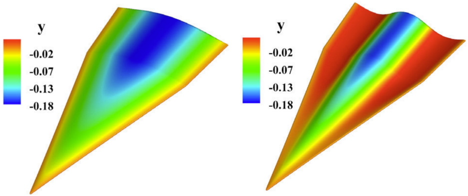
Required capture area vs Mach number (Ward [1]).



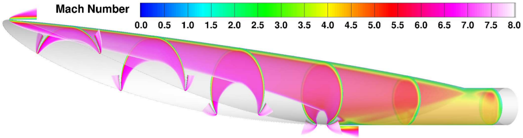
Airframe integration (Schweikart [2]).

- required engine size scales with M_∞
- use airframe to assist with compression & expansion
- components are coupled, geometrically complex, require high-fidelity modelling
    - numerical optimisation

Aerodynamic Shape Optimisation



Optimised hypersonic lifting body (Zhang et al.).



Optimised hypersonic inlet (Drayna).

- two levels of design optimisation: MDO & ASO
- theme in ASO literature: geometric freedom sacrificed for efficiency
- gradient calculation cost for N DVs:
    - finite differences: $N + 1$ flow solutions
    - adjoint method: 1 flow solution + 1 linear system solution
- limited application of adjoint method for 3D hypersonic design

Outline

Thesis aim: *Investigate the applicability of adjoint-based shape optimisation for three-dimensional hypersonic vehicle design.*

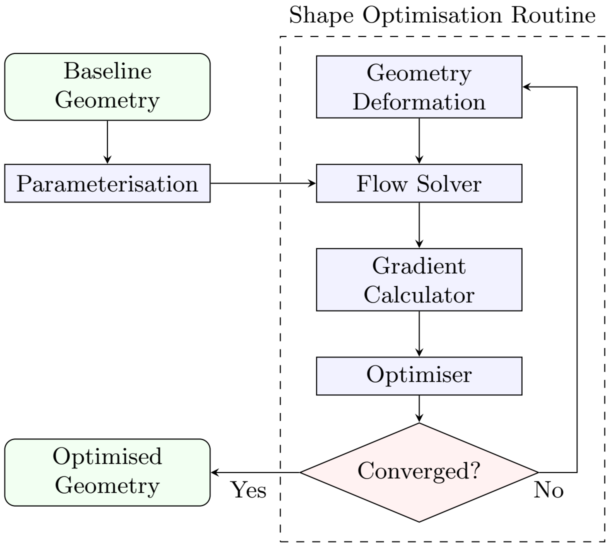
Part 1: Methodology

- geometric manipulation
- gradient calculation

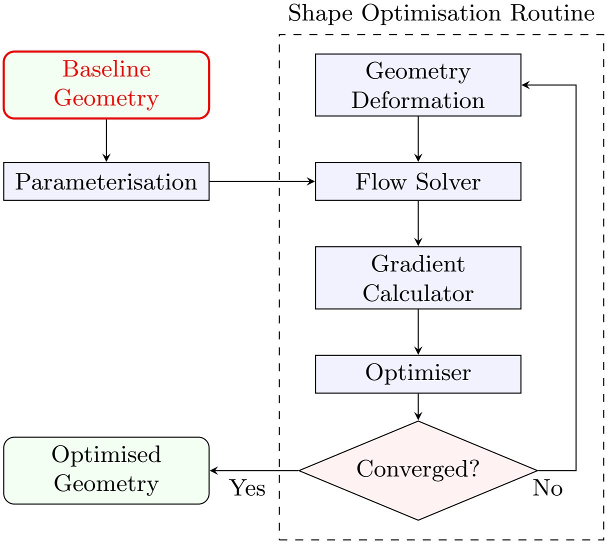
Part 2: Design Applications

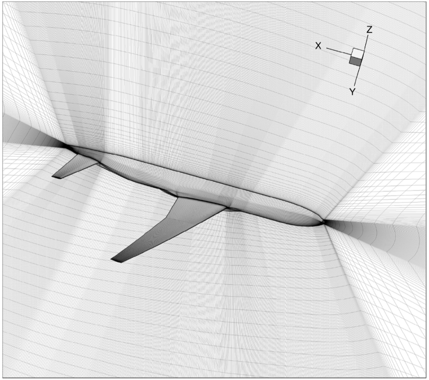
- minimum-drag hypersonic slender body of revolution
- hypersonic lifting body

Aerodynamic Shape Optimisation Routine



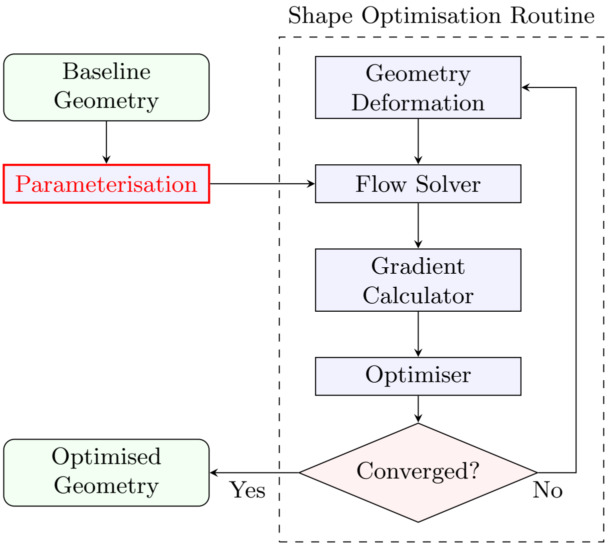
Aerodynamic Shape Optimisation Routine

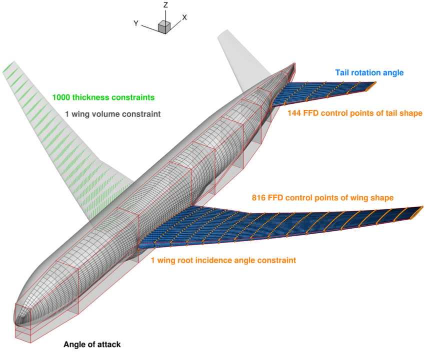




(Chen et al. [5])

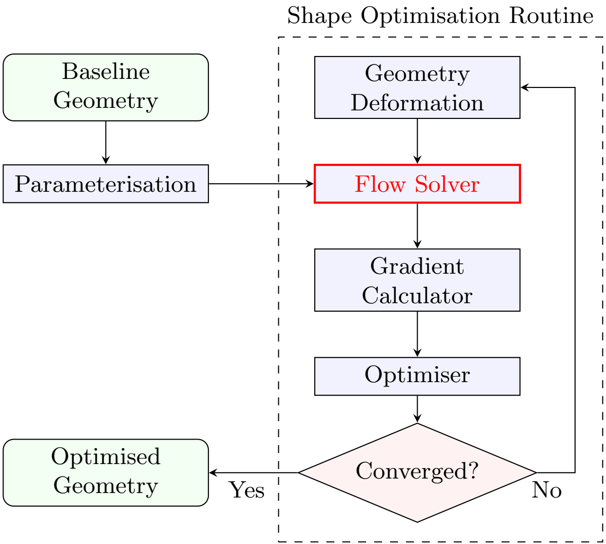
Aerodynamic Shape Optimisation Routine

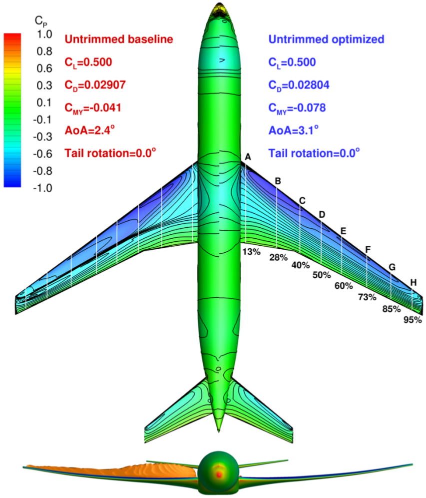




(Chen et al. [5])

Aerodynamic Shape Optimisation Routine





(Chen et al. [5])

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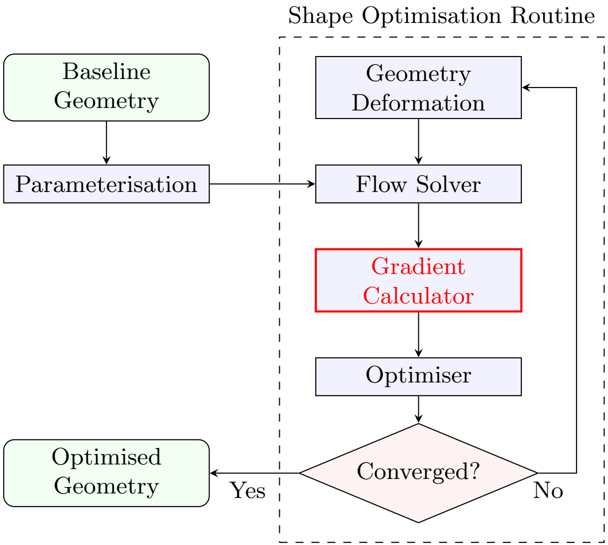

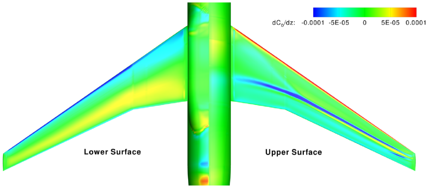

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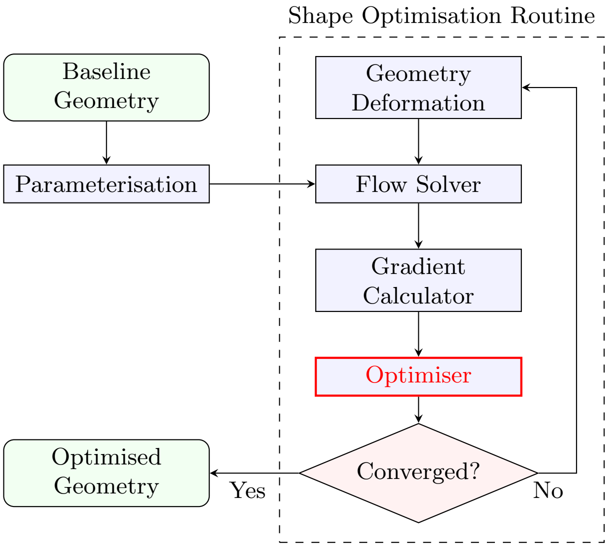

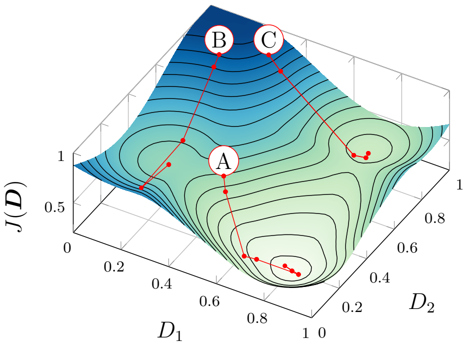

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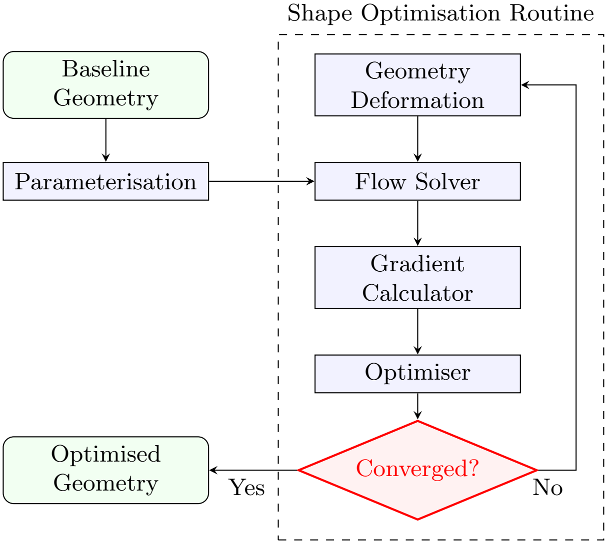

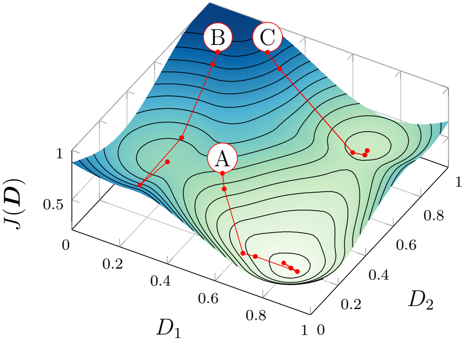

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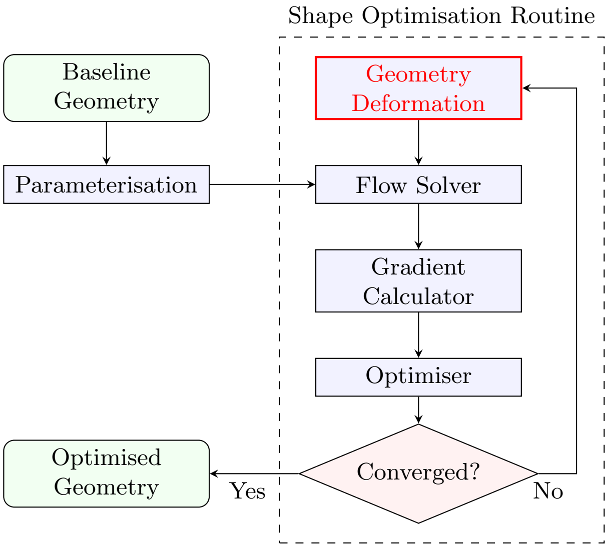
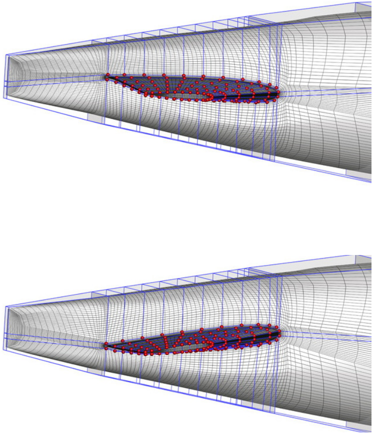
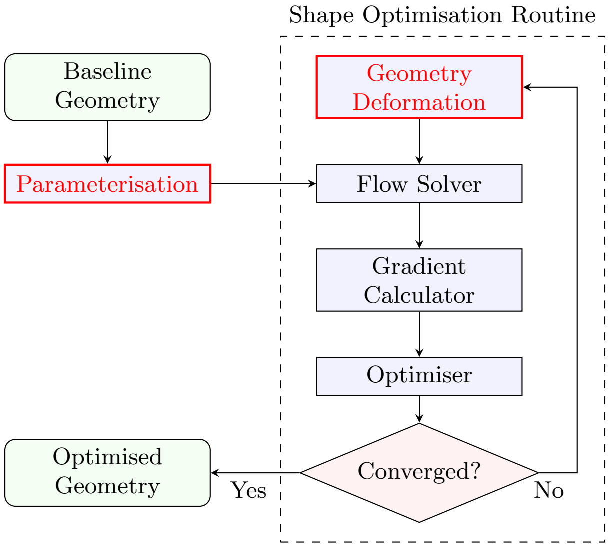


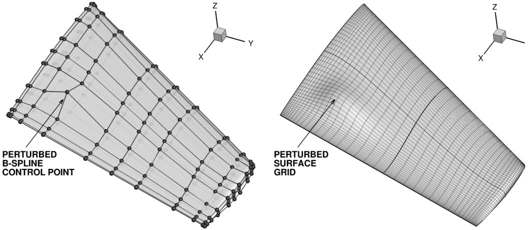


(Chen et al. [5])

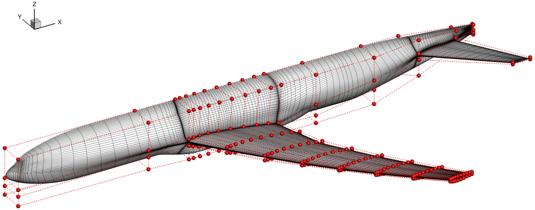
Geometric Parameterisation and Deformation



3D Shape Parameterisation Methods



B-Spline surfaces [6]

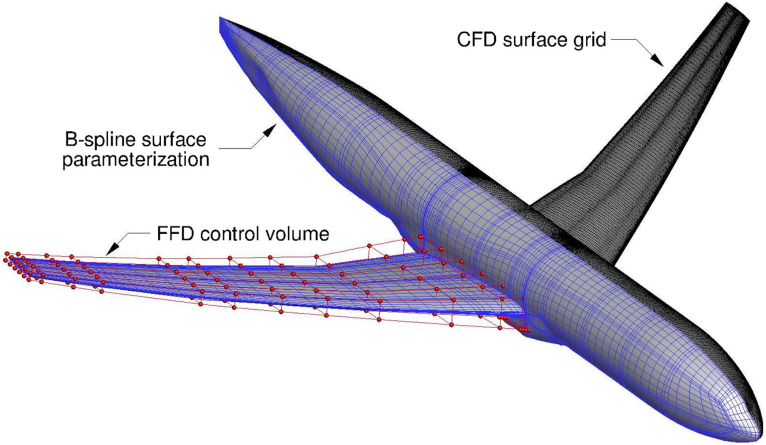


Free-form deformation (FFD) [7]

- high local control, analytical representation, allows integrated mesh movement
- susceptible to overlap, tangency issues

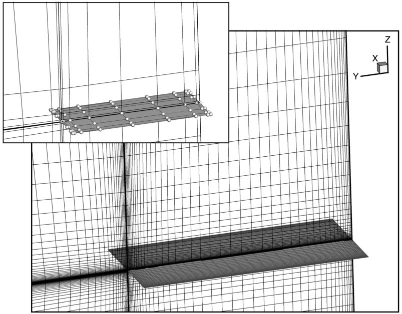
- highly general, robust, DV selection decoupled from surface representation
- discrete representation, separate mesh deformation

Two-level Free-form Deformation



Wing parameterised with two-level FFD (Reist et al. [8]).

Integrated Shape and Grid Deformation



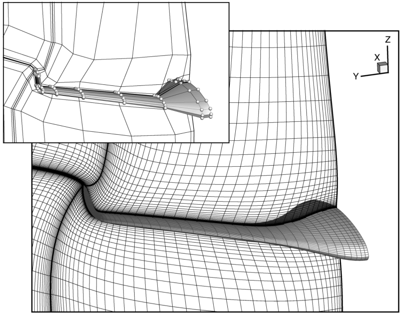
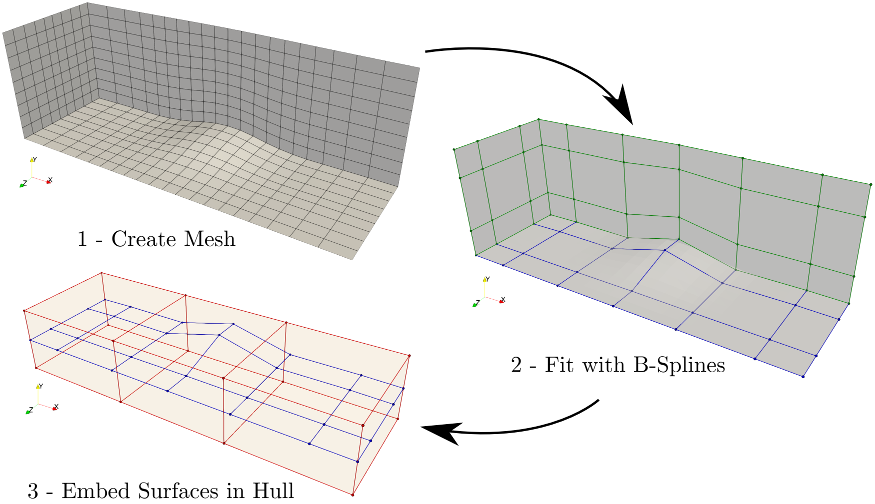


Plate geometry morphed into a blended-wing body (Hicken and Zingg [9]).

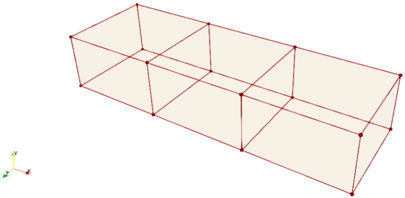
- fit entire mesh with B-Splines
- move mesh control points rather than vertices
- use cheap distance-based routine for control points

Parameterisation Methodology

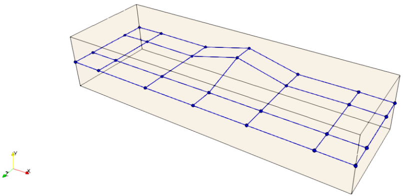


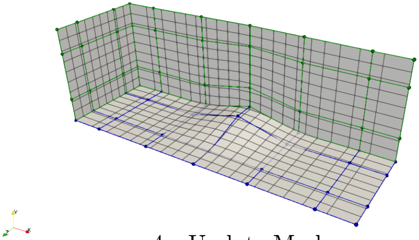
Deformation Methodology

1 - Deform FFD Hull

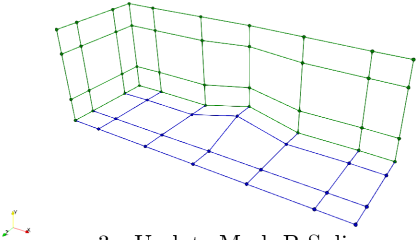


2 - Update Surface B-Splines



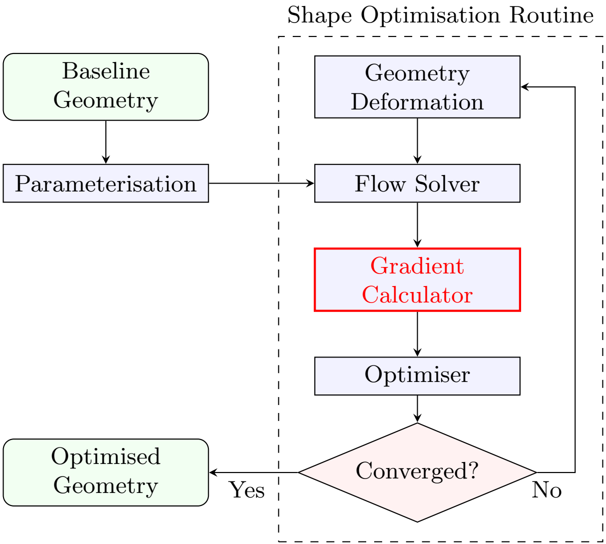


4 - Update Mesh



3 - Update Mesh B-Splines

Gradient Calculation



Shape Sensitivity Calculation

objective function: $J = J(\boldsymbol{D})$, gradients/shape sensitivities: $dJ/d\boldsymbol{D}$

Finite differences

$$\frac{\partial J}{\partial D_j} = \frac{J(D_j + h) - J(D_j)}{h} \quad (1)$$

- for each design variable D_j:
  1. perturb variable: $D_j + h$
  2. update surfaces and grid: $\boldsymbol{X}$
  3. run flow solver: $\boldsymbol{U}$
  4. evaluate function: $J(D_j + h)$
  5. evaluate eqn 1

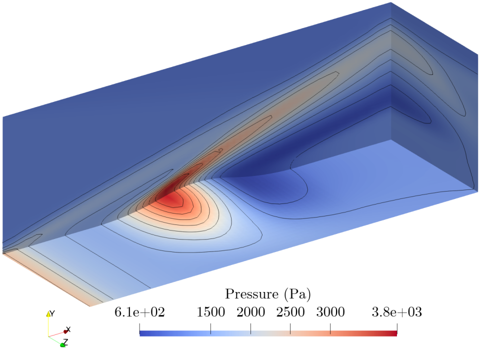
Adjoint method

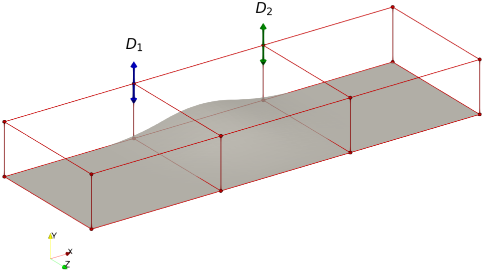
$$\frac{dJ}{d\boldsymbol{D}} = \frac{\partial J}{\partial \boldsymbol{D}} + \boldsymbol{\lambda}^T \frac{\partial \boldsymbol{R}}{\partial \boldsymbol{D}} \quad (2)$$

$$\left[\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{U}}\right]^T \boldsymbol{\lambda} = -\left[\frac{\partial J}{\partial \boldsymbol{U}}\right]^T \quad (3)$$

1. compute partial derivatives
2. solve adjoint equations (equation 3)
   - sparse linear system
3. evaluate equation 2

Shape Sensitivity Verification – Hypersonic Bump



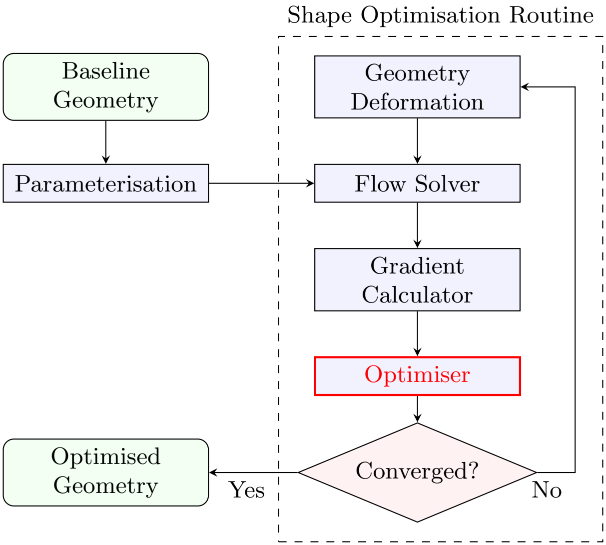


- modelling: Mach 5 flow - Euler, NS & RANS
- objective: $J = F_{D,\text{wave}}$
- design variables: D_1 – vertical translation, D_2 – vertical scaling

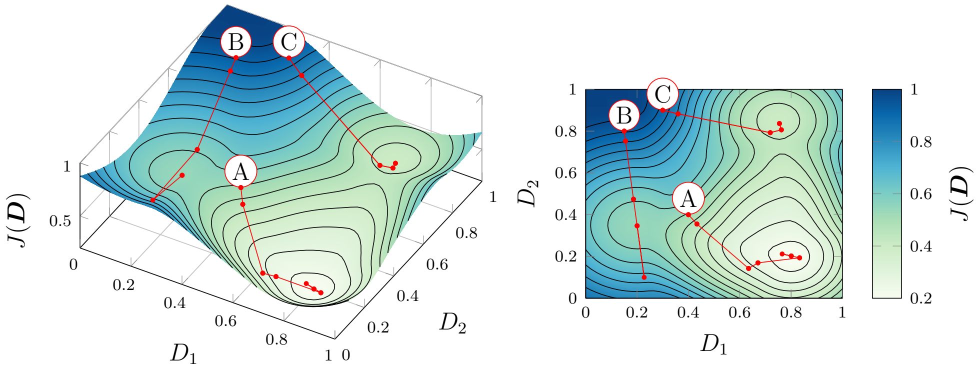
NS Shape Sensitivity Verification

Blocking	Method	$\partial J/\partial D_1$	$\partial J/\partial D_2$
1B	adjoint	7.652439748627**438**e-01	9.8008643528069**10**e-04
	complex-step	7.652439748627**382**e-01	9.8008643528069**64**e-04
2B	adjoint	7.652449114021**621**e-01	9.8008784557861**87**e-04
	complex-step	7.652449114021**596**e-01	9.8008784557861**31**e-04
4B	adjoint	7.6524312915124**93**e-01	9.8008553495246**67**e-04
	complex-step	7.6524312915124**51**e-01	9.8008553495246**28**e-04
8B	adjoint	7.652449084951**116**e-01	9.8008784110591**61**e-04
	complex-step	7.652449084951**075**e-01	9.8008784110591**22**e-04
27B	adjoint	7.6524292886105**84**e-01	9.8008527369557**65**e-04
	complex-step	7.6524292886105**14**e-01	9.8008527369557**54**e-04

Optimisation Algorithm

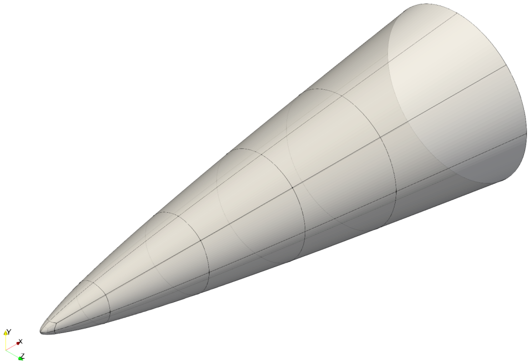


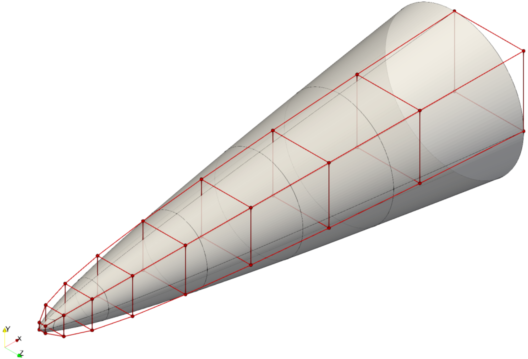
Sparse Nonlinear OPTimizer (SNOPT)



- sequential quadratic programming (SQP) – gradient-based
- constrained non-linear problems
- designed for hundreds to thousands of DVs [10]

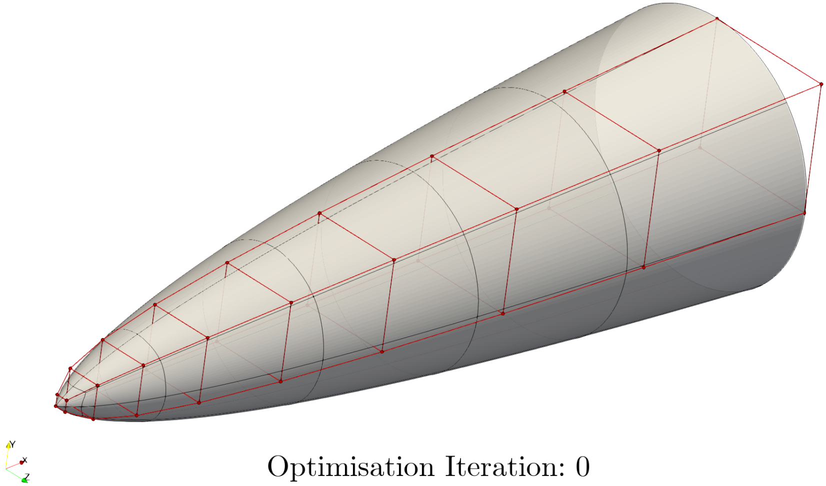
Minimum-drag Hypersonic Slender Bodies of Revolution





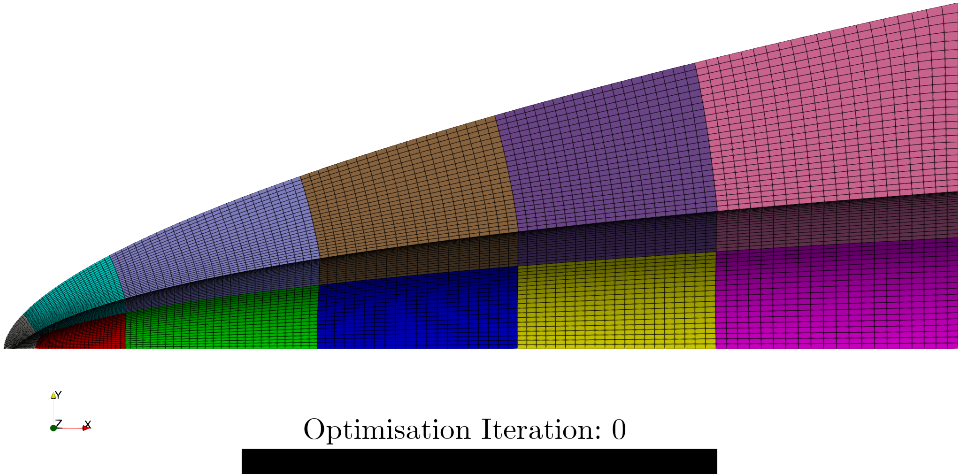
- objective: minimise wave drag
- constraints: fixed length and base diameter ($L/D = 3$)
- parameterisation: 23 DVs – scale and translation of control planes
- modelling: inviscid Mach 6.28 flow

Slender Body Optimisation – Surface Animation

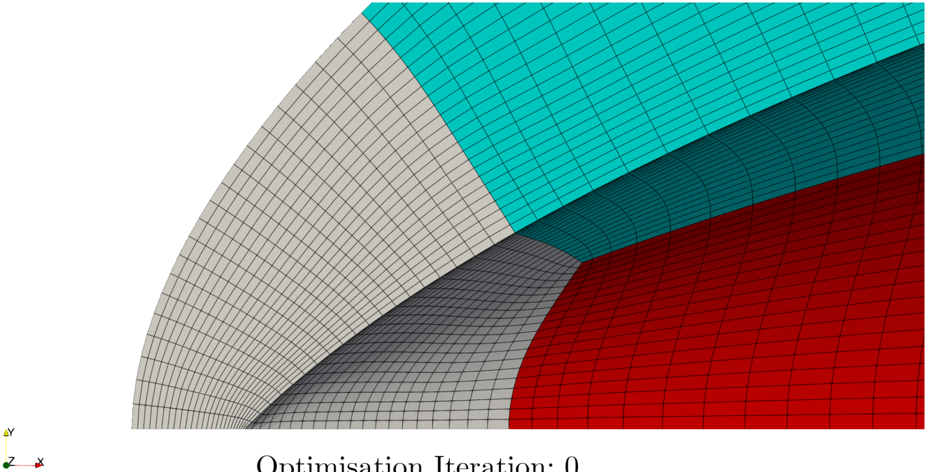


Optimisation Iteration: 0

Slender Body Optimisation – Grid Animation

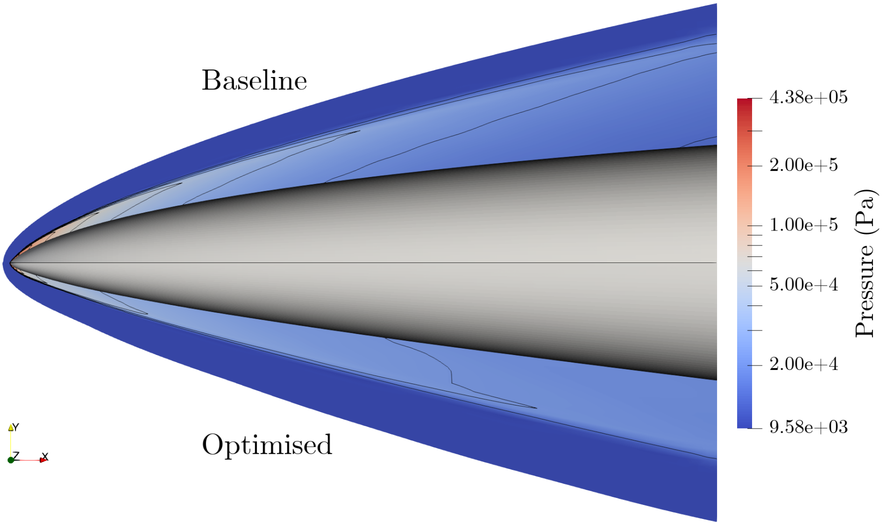


Slender Body Optimisation – Nose Grid Animation

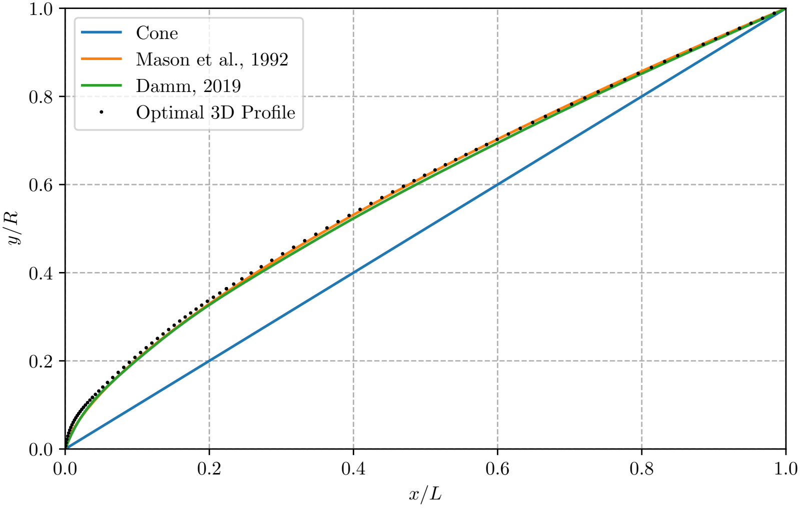


Optimisation Iteration: 0

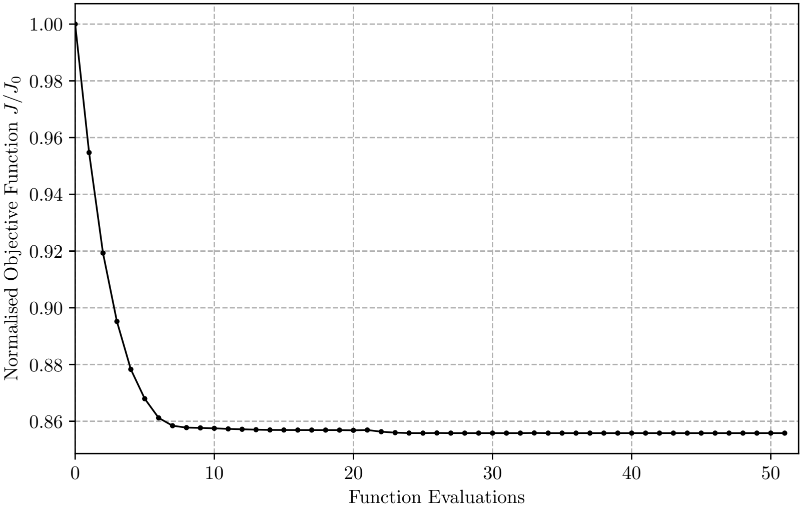
Slender Body Optimisation – Flow Field Comparison



Slender Body Optimisation – Profile Comparison



Slender Body Optimisation – Convergence



Slender Body Optimisation – Breakdown of Costs

Hardware:

- CPU: Intel(R) Xeon(R) Silver 4216 CPU @ 2.10GHz 16 cores
- RAM: 12 $\times$ 16GB (192GB) DDR4 2933MHz

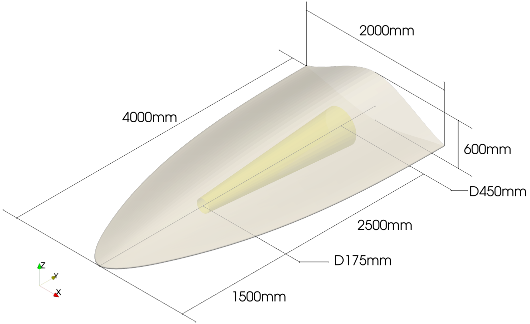
Overall:

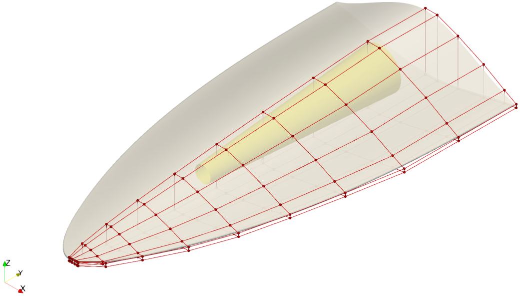
- parameterisation: 15s (serial)
- function & gradient evaluations: 52
- total time: 9hrs 40min

Each design iteration:

- flow solver: 3min 39s (MPI parallel)
- gradient calculation: 7min 34s (shared-memory parallel)
- geometry deformation: 7s (shared-memory parallel)

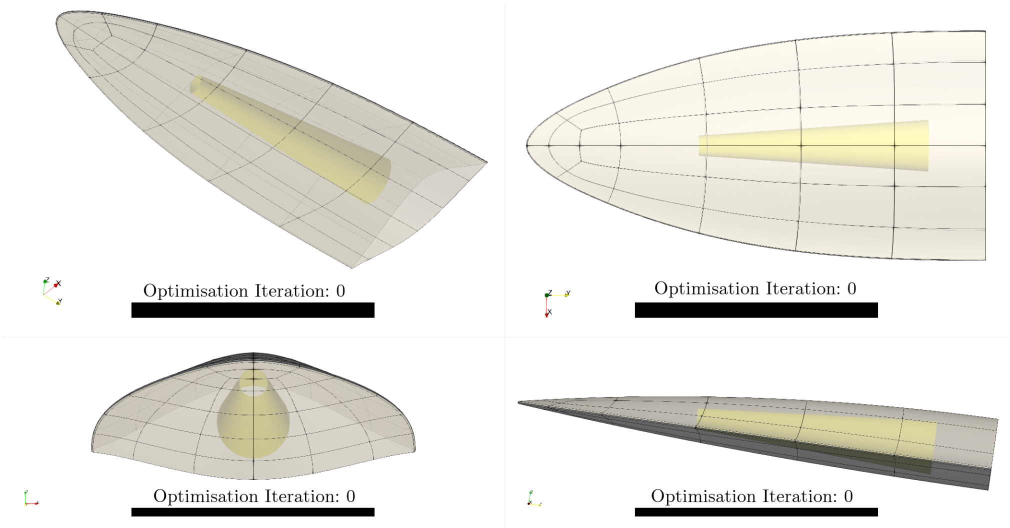
Optimisation of a Hypersonic Lifting Body



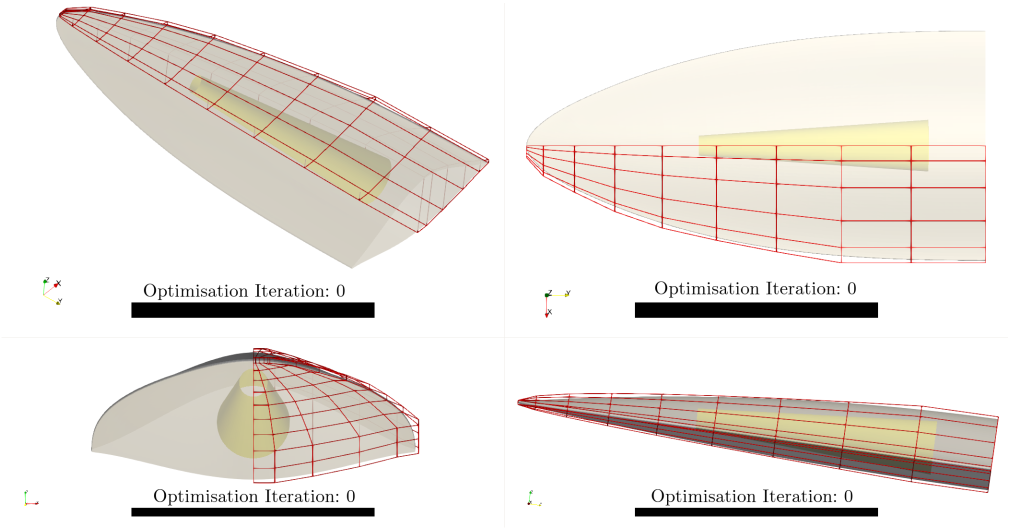


- modelling: $M_\infty = 8$, $\alpha = 8^\circ$, 40km altitude, inviscid, laminar & turbulent
- objective: maximise $J = L/D$
- constraints: fixed length & must contain payload
- parameterisation: 118 FFD DVs & 3 payload DVs

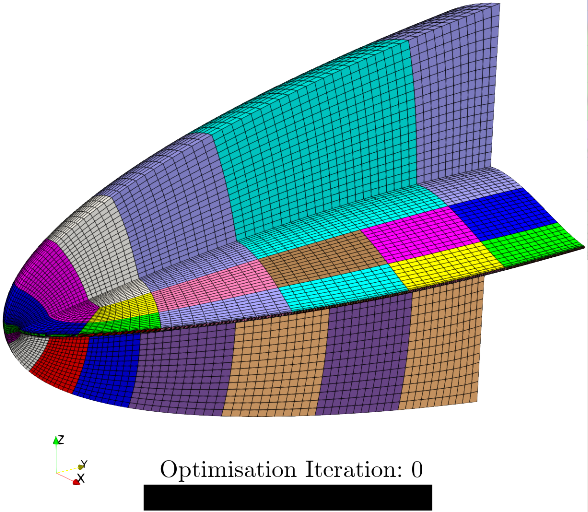
Lifting Body Optimisation – Surface Animation (1/2)

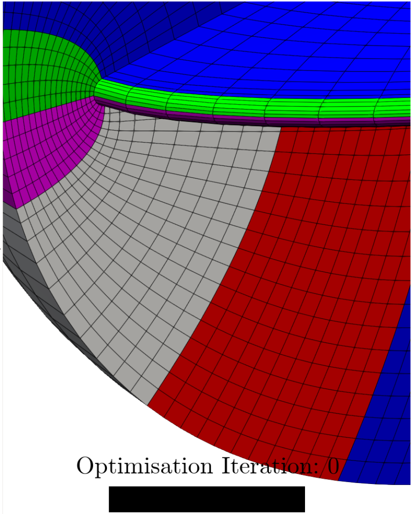


Lifting Body Optimisation – Surface Animation (2/2)



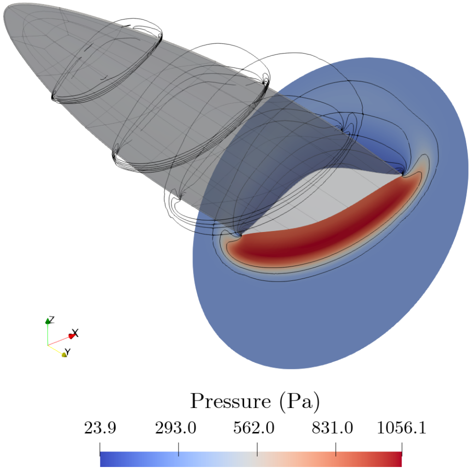
Lifting Body Optimisation – Grid Animation



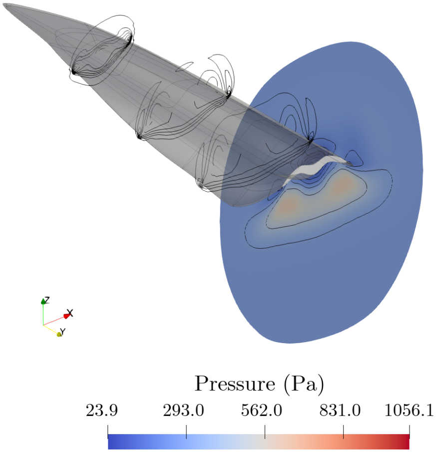


Lifting Body Optimisation – Comparison to Baseline

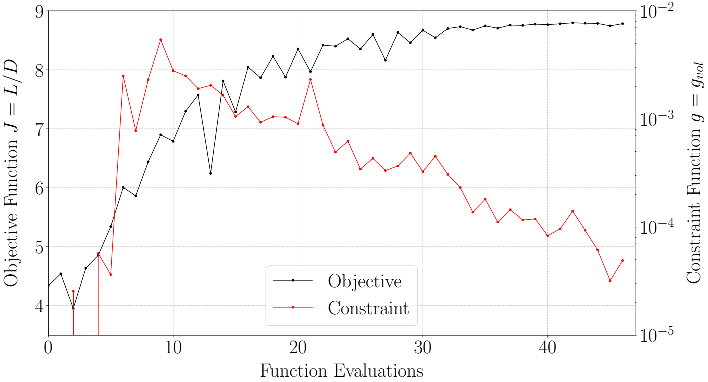
Baseline



Optimised



Lifting Body Optimisation – Convergence



Configuration	Lift L (N)	Drag D (N)	Lift-on-drag L/D
Baseline	9647	2169	4.447
Optimised	2254	258.5	8.719

Lifting Body Optimisation – Breakdown of Costs

Hardware:

- CPU: Intel(R) Xeon(R) Silver 4216 CPU @ 2.10GHz 16 cores
- RAM: 12 × 16GB (192GB) DDR4 2933MHz

Overall:

- parameterisation: 11s (serial)
- function & gradient evaluations: 47
- total time: 2hr 50min

Each design iteration:

- flow solver: 22s (MPI parallel)
- gradient calculation: 2min 47s (shared-memory parallel)
- geometry deformation: 4.4s (shared-memory parallel)

References I

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[2] Larry Schweikart. *The Hypersonic Revolution, Case Studies in the History of Hypersonic Technology: Volume III, the Quest for the Obital Jet: The Natonal Aero-Space Plane Program (1983-1995)*. Createspace Independent Publishing Platform, 1998. ISBN: 9781478146179.

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[6] T. M. Leung and D. W. Zingg. “Aerodynamic Shape Optimization of Wings Using a Parallel Newton-Krylov Approach”. In: *AIAA Journal* 50.3 (2012), pp. 540–550. DOI: 10.2514/1.J051192.

[7] G. K. W. Kenway. “A Scalable, Parallel Approach for Multi-Point, High-Fidelity Aerostructural Optimization of Aircraft Configurations”. PhD thesis. Graduate Department of Aerospace Engineering, University of Toronto, 2013.

References II

[8] T. A. Reist et al. “Cross Validation of Aerodynamic Shape Optimization Methodologies for Aircraft Wing-Body Optimization”. In: *AIAA Journal* 58.6 (2020), pp. 2581–2595. DOI: 10.2514/1.J059091.

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[10] P. E. Gill, W. Murray, and M. A. Saunders. “SNOPT: An SQP Algorithm for Large-Scale Constrained Optimization”. In: *SIAM Review* 47.1 (2005), pp. 99–131. DOI: 10.1137/S0036144504446096.