



Gradient-Based MDAO of Scramjet-Powered Hypersonic Vehicle and Trajectory

Amir Mittelman¹, Ingo Jahn², and Rowan Gollan¹

Abstract

Hypersonic scramjet-powered vehicles offer the potential for increasing operational flexibility while reducing launch costs. However, the marginal design space stemming from the extreme hypersonic flight conditions results in a highly coupled and constrained vehicle design space. A gradient-based MDAO framework is suggested to address such cross-coupled design problems and efficiently explore the design space. Prior research demonstrated the successful integration of several Python packages, for geometrical representation, aerodynamics evaluation, and an optimal control solver, into an optimization framework that can perform simultaneous shape and trajectory optimizations for an unpowered hypersonic vehicle (i.e., hypersonic glider). In the current work, a scramjet performance analysis package was developed and successfully integrated with the above-mentioned design tools. The research focuses on developing computationally tractable design and optimization methods for scramjet-powered hypersonic accelerators. Expected results will include demonstrating the feasibility of solving a large-scale (large number of design variables) design optimization problem for such configurations. Additionally, the scope of the optimization problem that needs to be solved will be investigated, i.e., single-point (vehicle) and system-level (vehicle and trajectory) optimizations, and the importance of including trajectory simulation in the optimization sequence will be presented.

Keywords: *MDAO, Vehicle Optimization, Hypersonics*

Nomenclature

$\bar{\theta}_s$	Vehicle design variable vector	EoM	Equations of Motion
$\bar{y}_p$	Physical coupling variable vector	FD	Finite-differences
$\bar{y}_s$	Sizing coupling variable vector	G, H	Constraint functions
$\bar{y}_t$	Trajectory state variable vector	J	Objective function
AD	Automatic Differentiation	MDA	Multi-Disciplinary Analysis
		$MDAO$	Multi-Disciplinary Analysis and Optimization

1. Introduction

The preliminary design of a scramjet-powered hypersonic vehicle presents a significant engineering challenge due to its extreme flight envelope. The vehicle's aerodynamics, thermodynamics, propulsion, and structure are highly interdependent. Therefore, a holistic design approach is needed to capture the complex coupled physical phenomena governing the design. Additionally, the wide range of Mach numbers and altitudes through which a scramjet-powered accelerator operates renders a single-point optimization of limited practical value. Thus, a multi-point or system-level optimization is required to ensure robust performance across the operational envelope. To address these complex interdependencies, Multi-Disciplinary Analysis and Optimization (MDAO) is frequently used [1–5]. Such an approach

¹*School of Mechanical and Mining Engineering, Centre for Hypersonics, The University of Queensland, St. Lucia QLD 4072, Australia*

²*Institute for Advanced Engineering and Space Sciences, Springfield Campus, The University of Southern Queensland, Toowoomba, QLD, 4350, Australia*

allows for the inclusion of all relevant disciplines early on in the design cycle, thus reducing the risk of major design changes later in the design process.

When developing an MDAO framework, one should first define the scope and size of the optimization problem. The scope of the problem will dictate the different disciplines that will be modeled as part of the analysis tools. For example, an unpowered hypersonic glider does not need to include propulsion models [1], which are imperative when designing a scramjet accelerator [3]. The size of the problem is related to the number of design variables involved in the optimization process. System-level multi-disciplinary optimization problems tend to be based on a large number of design variables. However, the computational cost of optimization problems increases exponentially with the increasing number of design variables, especially when relying on high-fidelity computationally costly analysis tools. Gradient-based optimization methods offer a solution for this problem by accelerating the convergence rates of the optimization process. Despite this, gradient-free optimization methods are mostly used in hypersonic vehicle optimization [4, 6, 7] because the task of calculating the design gradients is also one of great difficulty.

This research will build upon current work done at The University of Queensland, and The University of Southern Queensland, in which a gradient-based MDAO framework is being developed. Geometry and aerodynamic analysis tools capable of providing efficient gradient calculations were developed for vehicle optimization and applied to an unpowered glider configuration problem, demonstrating the advantages of gradient-based methods [8]. The glider's system-level (mission) performance optimization was achieved by adding trajectory optimization to a nested co-design framework [1, 9]. To expand the scope of the research to include powered vehicles, a low-fidelity scramjet flow-path model was developed [10], combining finite differences (FD) and analytic calculations for gradient evaluation. Finally, the Adjoint differentiation method was adapted for estimating the derivatives of the vehicle trajectory outcomes, thus providing the system-level objective function gradient [11].

The purpose of the current work is to expand the knowledge and capabilities of the design and optimization of scramjet-powered hypersonic vehicles. The optimization methods and framework will be developed and tested, expanding the current capability to include the scramjet engine component. Efficient gradient calculation techniques, alongside a modular framework approach, will enable the use of gradient-based MDAO methods and preserve computational tractability.

2. Methods

An MDAO framework, including vehicle design tools along with trajectory simulation, is adopted. Thus enabling a system-level objective to be optimized. For computational tractability of the analysis and optimization process, gradient-based optimization methods are used. This requires the calculation of the mission objective and operational constraints functions' values as well as their sensitivities with respect to the design variables of the problem. Flexibility, computational efficiency, and robustness are achieved by breaking down the objective function evaluation, as well as its gradient calculation, into smaller computational tasks, i.e., executing each individual disciplinary analysis tool and superimposing the results as opposed to calculating the full "tip-to-tail" analysis at once. Furthermore, each disciplinary analysis tool provides its respective sensitivities (partial derivatives), which are all combined by applying the chain rule to obtain the overall system gradients [10].

2.1. Optimization Framework

An illustration of the MDAO framework is presented in Fig. 1. The optimization loop controls the vehicle design variables ($\bar{\theta}_s$), such as wing span, and inlet geometry. A sizing Multi-Disciplinary Analysis (MDA) is responsible for generating the vehicle's geometry (sizing coupling variables, $\bar{y}_s$). Next, the physical MDA calculates the aerodynamic and engine characteristics (physical coupling variables, $\bar{y}_p$). Finally, the trajectory simulation MDA ($\bar{y}_t$) is used for calculating the objective (J) and constraint (G, H) functions used to evaluate the performance of the system.

2.2. Geometry

The geometrical representation of the vehicle is produced using the HyperVehicle package [12]. HyperVehicle allows for the computationally efficient rendering of a surface mesh from a parametric input file (Fig. 2).

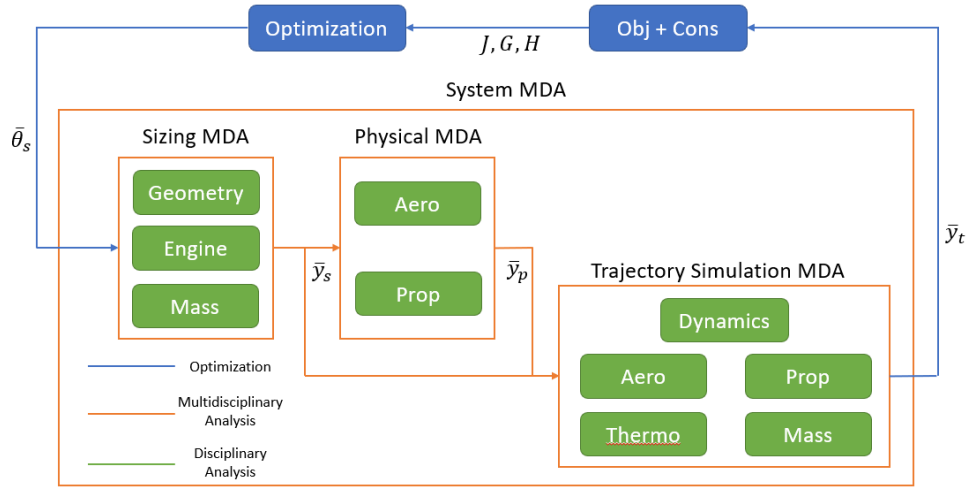


Fig 1. The MDAO framework data flow

Additionally, HyperVehicle provides the sensitivity of the generated mesh with respect to the input variables by employing Dual numbers (Automatic Differentiation - AD) [1].

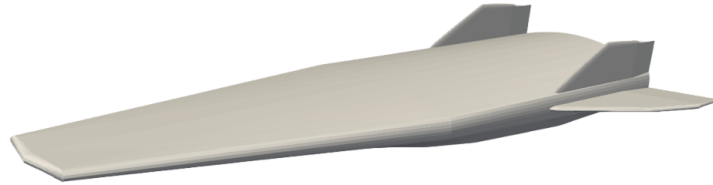


Fig 2. HyperVehicle generated geometry [12]

2.3. Propulsion

The scramjet propulsion system performance is calculated using the HyperPro package [13]. A 2D inlet model, followed by quasi-1D engine duct and combustor models, provides the engine's outflow conditions. The exhaust gases are then expanded over the nozzle section using an extended version of the aerodynamic calculation package, PySAGAS [14]. FD is used for the inlet and combustor gradient calculations, while nozzle performance sensitivity calculation is done analytically. A block diagram of the vehicle design tool is presented in Fig. 3

2.4. Aerodynamics

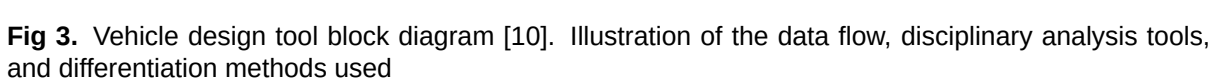
The aerodynamic characteristics of the vehicle are calculated using the PySAGAS package [14]. PySAGAS uses a low-fidelity surface inclination solver for the calculation of the aerodynamic forces. The sensitivities of the aerodynamic characteristics to geometry changes are calculated using an approximate analytical approach [15, 16].

2.5. Trajectory Simulation

A dynamic Equations of Motion (EoM) system is solved to simulate the vehicle's trajectory. The vehicle follows a pre-determined guidance law. The sensitivity of the objective and constraints with respect to the design variables are evaluated using the Adjoint method of differentiation for dynamic systems with termination conditions [11].

3. Expected Results

In previous work, a co-design gradient-based MDAO framework has been developed for an unpowered hypersonic vehicle [1, 9]. This work successfully demonstrates the integration of HyperVehicle, PySAGAS, and trajectory optimization software into a single framework. Furthermore, the calculation of



all partial derivatives needed for the gradient-based optimization method used has been demonstrated. The addition of a scramjet engine to the vehicle design will add not only geometrical degrees of freedom but also expand the flight envelope of the vehicle to include a wide range of Mach numbers and altitudes.

Solving the single-point vehicle optimization problem will be the first step in integrating, testing, and verifying all disciplinary design and analysis tools. Due to the wide flight envelope of the hypersonic accelerator, multiple single-point optimizations will be carried out at various representative flight conditions. The performance of each optimized vehicle will be evaluated and compared with that at its respective "off-design" conditions. The results from this stage can be regarded as the "performance to beat" baseline.

Next, trajectory simulation will effectively integrate the performance over multiple flight conditions, presenting a system-level performance index. A new vehicle design is expected once the trajectory simulation is included in the optimization process, exposing the non-linear (and non-intuitive) relations between all relevant disciplines involved in the design process. The optimized vehicle performance will be compared with that of the single-point optimized design, and the benefits of including the trajectory analysis versus the added complexity will be investigated.

Finally, expanding the MDAO framework while maintaining the ability to solve gradient-based optimization problems will serve as a proof of concept for performing computationally tractable large-scale optimizations. Thus becoming the stepping stone for future full-launch system MDAO framework development.

References

1. Lock, A., Oberman, G., Jahn, I. H., van der Heide, C., Bone, V., Dower, P. M. & Manzie, C. *Hypersonic Glide Vehicle Shape and Trajectory Co-Design*. AIAA SCITECH 2025 Forum. 2025. <https://arc.aiaa.org/doi/10.2514/6.2025-1337>.
2. Coulter, B. G., Huang, D. & Wang, Z. *Geometric Design of Hypersonic Vehicles for Optimal Mission Performance with High-Fidelity Aerodynamic Models*. Journal of Aircraft. 1–13, 2022.
3. Bowcutt, K., Kuruvila, G., Grandine, T. & Cramer, E. *Advancements in Multidisciplinary Design Optimization Applied to Hypersonic Vehicles to Achieve Performance Closure*. 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. 2008. <https://arc.aiaa.org/doi/10.2514/6.2008-2591>.
4. Bowcutt, K. G. *Multidisciplinary optimization of airbreathing hypersonic vehicles*. Journal of Propulsion and Power. 171184–1190, 2001.
5. Lee, K. W., Moase, W., Ooi, A., Manzie, C. & Kerrigan, E. C. *Optimization framework for codesign of controlled aerodynamic systems*. AIAA Journal. 543149–3159, 2016.

6. Preller, D. *Multidisciplinary design and optimisation of a pitch trimmed hypersonic airbreathing accelerating vehicle*. PhD thesis. The University of Queensland, 2018.
7. Jazra, T. *Optimisation of Hypersonic Vehicles for Airbreathing Propulsion*. PhD thesis. The University of Queensland, 2010.
8. Mackle, K. & Jahn, I. *Efficient and Flexible Methodology for the Aerodynamic Shape Optimization of Hypersonic Vehicle Concepts in a High-Dimensional Design Space*. American Institute of Aeronautics and Astronautics (AIAA), 2024.
9. Mackle, K., Lock, A., Jahn, I. & van der Heide, C. *Developing a Co-Design Framework for Hypersonic Vehicle Aerodynamics and Trajectory*. American Institute of Aeronautics and Astronautics (AIAA), 2024.
10. Mittelman, A., Mackle, K., Jahn, I. & Gollan, R. *Sensitivity Derivatives of a Low-Order Integrated Scramjet Propulsion Model for Gradient-Based Co-Design MDAO*. HiSST: 3rd International Conference on High-Speed Vehicle Science Technology. 2024.
11. Mittelman, A., Gollan, R. & Jahn, I. *Adjoint Differentiation Method for Trajectory Simulations with Terminal Conditions*. 63rd Israel Annual Conference on Aerospace Sciences. 2024.
12. Mackle, K. *hypervehicle*. 2024. <https://github.com/kieran-mackle/hypervehicle>.
13. Mittelman, A. *HyperPro*. 2024. <https://github.com/amirmit/HyperPro>.
14. Mackle, K. *PySAGAS*. 2024. <https://github.com/kieran-mackle/pysagas>.
15. Jahn, I. H. *Towards an efficient method for calculating design parameter derivatives in super-and hypersonic flow*. Australasian Fluid Mechanics Conference. 2024.
16. Jahn, I. H. *Approximate Surface Pressures and Heat Load Gradients for the Optimisation of Hypersonic Vehicles*. AIAA SCITECH 2025 Forum. 2025. <https://arc.aiaa.org/doi/10.2514/6.2025-0952>.