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Multidisciplinary Design and Optimization of Suborbital Transatmospheric Vehicles

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Abstract. Suborbital vehicles, which have the potential to drastically reduce the flight time of medium- and long-range missions to durations below one hour, are attracting increasing attention from the scientific community. The iConDeS (Integrated Conceptual Design Tools for Suborbital Vehicles) research project aims to develop advanced methodologies for the conceptual design and optimization of this class of vehicles. In this context, the present work investigates the influence of thrust-to-weight ratios on the design characteristics of a fully reusable two-stage launcher, with the objective of minimizing its liftoff mass.

Introduction

This work presents a multidisciplinary framework for the conceptual design and optimization of suborbital transatmospheric vehicles intended for space tourism and rapid global transportation of people and goods. The possibility of covering distances comparable to half of Earth's circumference in exceptionally short flight times would be a dramatic improvement for human society, and significant attention and investments have been drawn to this application. In recent years, private companies have developed suborbital vehicles for commercial use, notably in space tourism. Examples include Blue Origin's vertically launched New Shepard, Virgin Galactic's air-launched SpaceShipOne and SpaceShipTwo, and XCOR's Lynx, a rocket plane with conventional takeoff and landing. In parallel, major aerospace firms and research centers have focused on technology demonstrators for suborbital and hypersonic missions, such as Boeing X-37, Dream Chaser, CIRA's USV, and ESA's IXV. Research into fully reusable hypersonic aircraft continues, with key projects including SKYLON [1], LAPCAT A2, ZEHST, SpaceLiner [2], and HYPLANE [3]. The EU-funded STRATOFLY project further explores high-speed stratospheric flight [4]. Despite progress, integrated tools for efficient and safe suborbital vehicle design remain an active research need. This paper is based on the outcomes of the research program iConDeS (Integrated Conceptual Design Tools for Suborbital Vehicles) funded by the European Union through Next Generation EU (Project Identification Number P202272HBN). In this frame, a suborbital vehicle with a mission profile divided into four phases is considered: (i) an acceleration that brings the vehicle out of the atmosphere; (ii) a ballistic transfer covering most of the travel distance; (iii) an atmospheric re-entry close to the destination; (iv) a glide to the landing site. The methodology integrates sizing, aerodynamics, and trajectory analysis to design a minimum mass, fully reusable, two-stage vehicle tailored to specific mission scenarios. As a result, a multi-disciplinary technique

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is obtained that integrates all analysis tools [5, 6]. Building upon previous results, this study investigates the influence of the thrust-to weight ratios of both stages of the vehicle on its design characteristics at launch and on the overall mission profile, with the ultimate goal of analyzing and characterizing the design space to simplify and enhance the efficiency of the launcher's optimization process, which represents the final objective of the research project. The theoretical framework is complemented by numerical analysis to support the findings and ensure their validity.

Methodology

The conceptual design process, as shown in Fig. 1, follows a structured, iterative sequence of disciplinary modules. The design process begins with the definition of the Top-Level Requirements (TLR), which specify a fully reusable two-stage vehicle capable of transporting 50 passengers to the desired destination using liquid oxygen (LOX) and liquid methane (LCH4) as propellants. During the mission, the maximum acceleration must not exceed 4.5 g in either the ascent or descent of the flight, as higher values are considered hazardous for humans [5]. Initial data is generated using a statistical database and heuristic strategies (to estimate design velocity). The Weight and Sizing module, comprising HASA [7] for hypersonic orbiter and MARYLAND [8] for booster, iterates until mass convergence is reached. An embedded optimization minimizes fuel split while meeting acceleration limits. The design is then simulated in the Trajectory module, allowing the sizing of the Thermal Protection System (TPS), whose feedback refines velocity and mass. After convergence, the mass balance, the inertial properties, and the visual output are finalized. A detailed description of each disciplinary module and their integration within the design framework can be found in Ref. [6], where both stages were assumed to operate with fixed thrust-to-weight ratios, and the gross liftoff mass together with the optimal propellant distribution was determined to meet the mission objectives. In the present work, building on the results of previous studies, a design of experiments on the thrust-to-weight ratios for both stages is addressed. The goal is to identify the configuration that minimizes the total liftoff mass for a given mission, while fully complying with the Top-Level Requirements and the associated operational constraints.

Results

A design matrix was set up to assess the effects of varying the thrust-to-weight ratios of the booster ($(T/W)_1$) and the aircraft ($(T/W)_2$), ranging from 1.15 to 1.6 and from 0.9 to 1.2, respectively. The ranges of variation of the two ratios were selected to enable a comprehensive analysis of the strong relationships between these parameters and the characteristics of the vehicle at launch (gross mass, length, TPS ratio), as well as the trajectory flown to reach the target destination (acceleration, deceleration, heat flux profiles). Although no feasibility assessment of propulsion technologies was performed, the selected ranges still represent realistic scenarios for possible vehicle configurations. As a further remark, based on practical and technological considerations, the analysis was limited to configurations where the thrust-to-weight ratio of the first stag$(T/W)_1$) is always greater or, at most, equal to that of the second stage ($(T/W)_2$).

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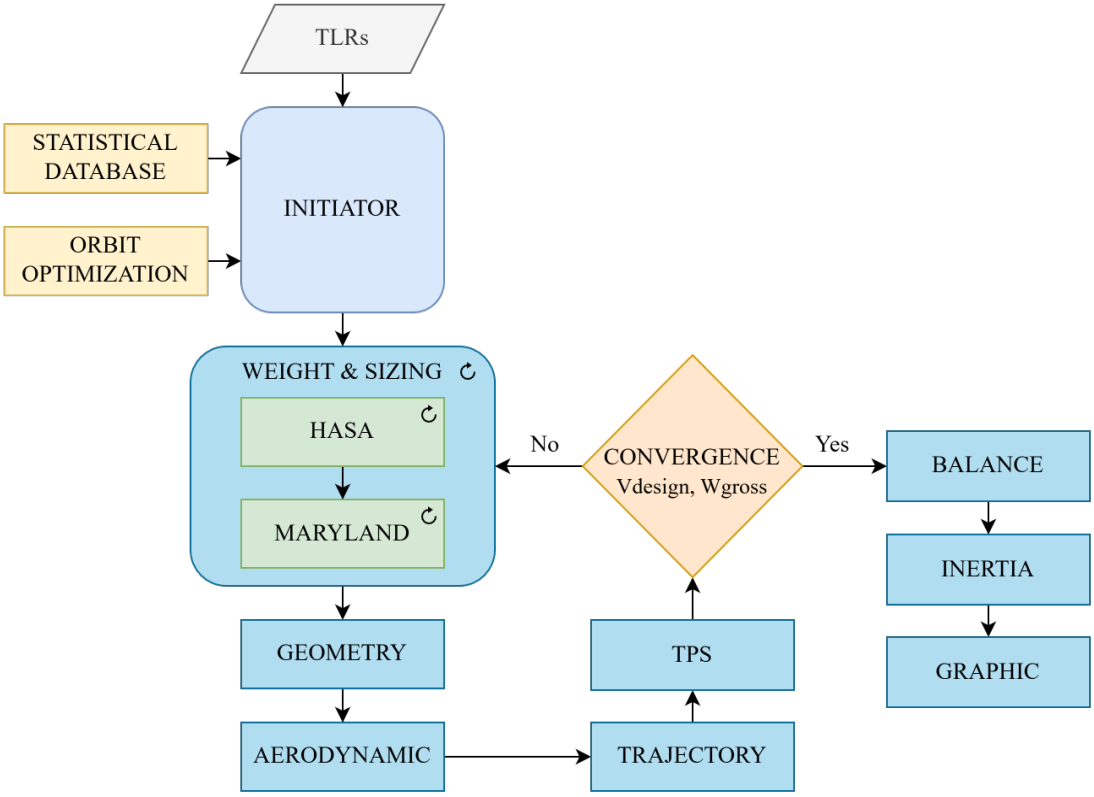


Figure 1: Workflow of the vehicle design methodology.

Fig. 2 shows a scatter plot of the results in terms of the gross mass of the entire vehicle at liftoff. Note that the graph includes some points that marginally exceed the maximum acceleration constraint (by less than 5%), and these points are marked with crosses. From this plot, it immediately emerges that the acceleration constraint poses an upper limit to the thrust-to-weight ratios, as excessive values of these parameters would bring the identified configuration to the bottom right corner of this plot, where all the crosses are distributed. The results shown in Figure 2 clearly indicate that the behavior of the gross mass at liftoff as a function of the two ratios is non-trivial, as it presents several local minima within the analyzed region. The global minimum can be identified at $(T/W)_1 = (T/W)_2 = 1.155$, corresponding to a total mass of 827.1 t. This point lies on the boundary delimiting the region of acceptable configurations and, importantly, the gradient of the gross mass is very steep in the vicinity of this minimum: a variation of only 4% in either parameter results in a change of approximately 10% in the gross mass.

Another region of interest can be observed around $(T/W)_1 = 1.25$ and $(T/W)_2 = 1.10$, corresponding to a total mass of 840.1 t. Unlike the previous case, the mass gradient in this region is milder with more gradual variations of the mass for the same variation in either parameter. Considering this region instead of that near the global minimum could therefore yield a more robust and less sensitive design solution.

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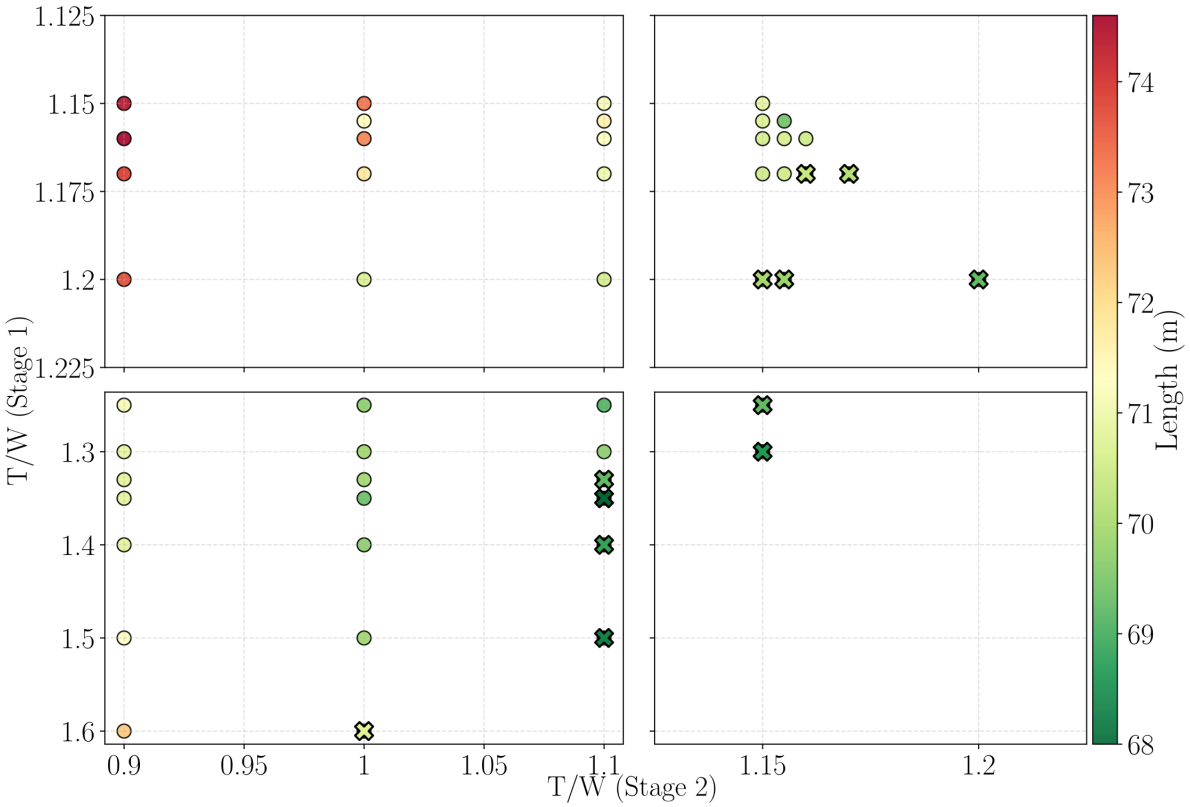


Figure 2: Scatter plot of considered points colored by gross mass. Circles represent configurations that comply with the maximum acceleration constraint, while crosses those that marginally exceed it. Axes are split and rescaled for clarity.

It is worth noting that, when including the solutions slightly violating the acceleration constraint, the global minimum corresponds to the configuration with $(T/W)_1$ = 1.35 and $(T/W)_2$ = 1.10, yielding a total mass of 812.5 t. This case achieves the mission with nearly 20 t less propellant compared to the configuration at $(T/W)_1 = (T/W)_2$ = 1.155, thus representing a significant design improvement while exceeding the acceleration limit by less than 1%. This small acceleration difference could be absorbed by considering control techniques of thrust and angle of attack in the launch and reentry phases, respectively, making this configuration fully acceptable.

Fig. 3 shows a scatter plot similar to that in Fig. 2 but with the points colored according to the total length of the vehicle instead of the gross mass. This quantity appears to qualitatively follow the same trend as the gross mass described previously. However, its variation with respect to the ratios is smaller, with a peak deviation of about 5% at $(T/W)_1$ = 1.15 and $(T/W)_2$ = 0.9 relative to the mean value across all configurations. This result indicates that variations in the thrust-to-weight ratios of the two stages have only a minor influence on the vehicle geometry, whose configuration at the acceptable global minimum is shown in Fig. 4 - 5.

Summary

A preliminary design of a suborbital vehicle capable of transporting 50 passengers from Naples to Port Moresby has been developed while satisfying, among other requirements, the acceleration constraints on the payload. The design optimization was conducted through a systematic design of experiments, varying the thrust-to-weight ratios of the two stages. The analysis revealed a nonlinear dependence of the vehicle gross mass on these parameters, with several local minima identified. Interestingly, the vehicle length remains nearly constant across all these minima, indicating a robust geometric configuration and suggesting that operational performance could be further optimized even after the vehicle's construction.

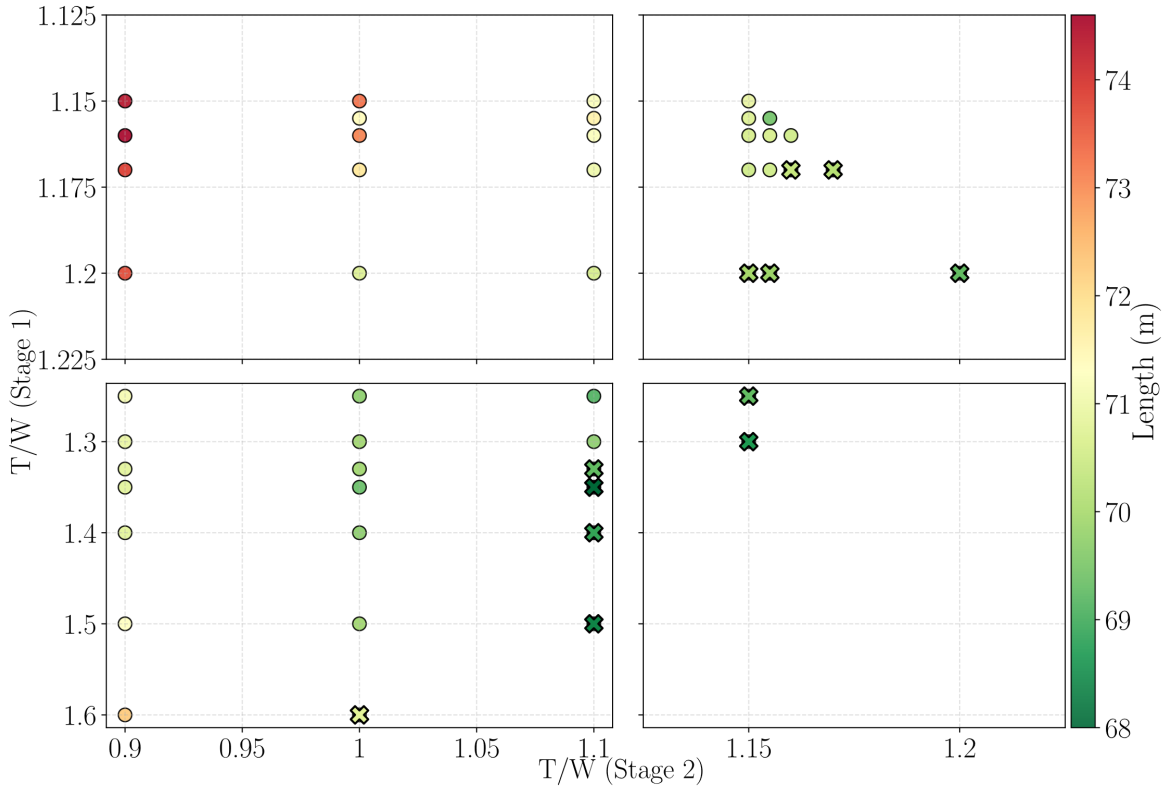


Figure 3:. Scatter plot of considered points colored by the total length of the vehicle. Circles represent configurations that comply with the maximum acceleration constraint, while crosses those that marginally exceed it. Axes are split and rescaled for clarity.

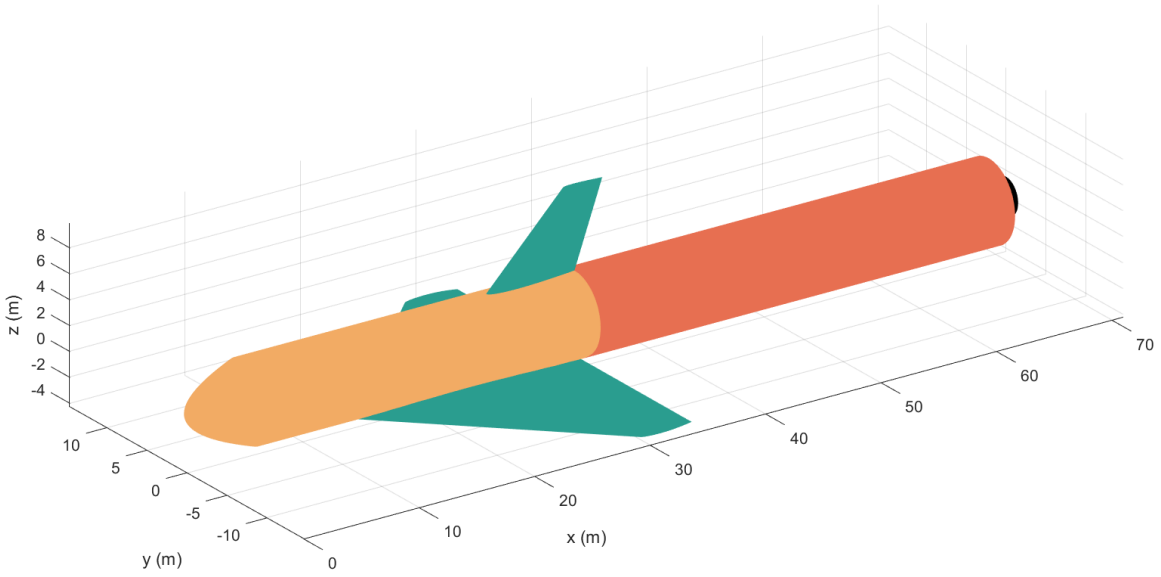


Figure 4: Three-dimensional view of the vehicle design.

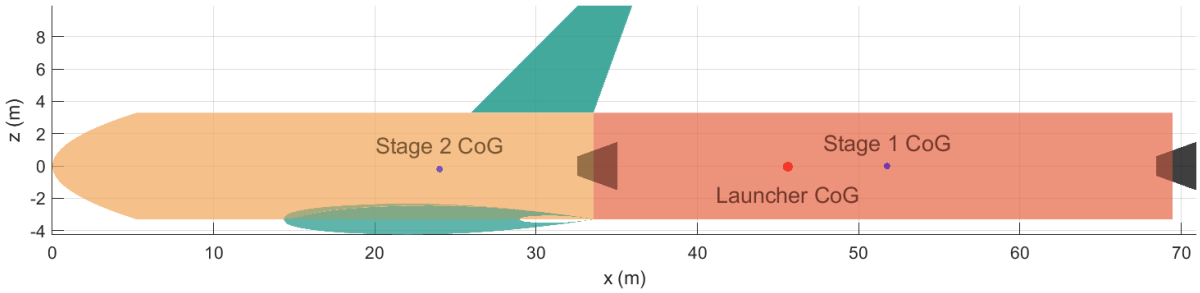


Figure 5: Lateral view of the vehicle design showing the center-of-mass positions at liftoff.

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