Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

A flexible multi-disciplinary environment for performance, life-cycle cost, and safety evaluation of suborbital vehicles

Christopher P. Frank, Olivia J. Pinon-Fischer, Dimitri N. Mavris

Georgia Institute of Technology, Atlanta, GA 30332-0150, United States

ARTICLE INFO

Article history:
Received 5 May 2016
Accepted 11 March 2018
Available online xxxx

Keywords:
Suborbital vehicles
Conceptual design
Design space exploration
Multi-disciplinary framework

ABSTRACT

Suborbital vehicles are innovative and unconventional aerospace concepts that are characterized by a high level of complexity and a lack of optimized baseline. The present focuses on the development of a flexible multi-objective modeling and simulation environment that provides the capabilities to rapidly evaluate the flying, economic, and safety performance of suborbital vehicles at a conceptual design level. One of the goals of this environment is to enable the exploration of large design spaces and facilitate the mapping between high-level requirements and the identified optimized concept. The environment is broken down into six modules: weight/size, aerodynamics, trajectory, propulsion, economics, and safety. By leveraging empirical models, physics-based approaches, and surrogate modeling techniques, it enables the rapid and parametric assessment and optimization of a multitude of design concepts. It is the first environment of this sort to support informed design space exploration of suborbital vehicles and allow for new trends to be identified and crucial observations to be made.

1. Introduction and motivation

Recent technological developments have resulted in the emergence of new advanced vehicles such as suborbital vehicles, hypersonic commercial aircraft, and manned spacecraft. These innovative vehicles have in turn opened up new markets that are characterized by complex solution spaces driven by multiple competing objectives. The complexity of these vehicles also gives rise to a large combinatorial space of possible configurations for which no baseline has been established and driven by unconventional concepts and new combinations of technologies.

Suborbital vehicles, in particular, benefit from various launch types, landing techniques, airframe configurations, etc. The strong price sensitivity of demand, high customer expectations, and emerging stringent safety regulations also require designers to account for multiple objectives when designing such vehicles. To facilitate an informed design space exploration, a large-scale multi-objective optimization process is needed, which requires a large number of function calls. Hence, a design framework able to rapidly evaluate the performance, life-cycle cost, and safety of all types of suborbital vehicles is needed. This evaluation environment needs to include design variables commonly used at the conceptual level. Detailed information about the vehicle geometry is not available at this point of the process and therefore precise CFD calculations that require a detailed mesh of the vehicle cannot be included within the tool. Indeed, the number of variables would become unmanageable and the execution time too large for a complete design space exploration at this phase of the design. Due to the lack of historical data, the design framework must rely on physics-based models to be able to optimize a given architecture. For example, if a delta wing is chosen, the tool must be able to optimize its shape in terms of sweep angle, taper ratio, root chord, etc. The main design parameters of the rocket engine must also be determined. Similarly, the trajectory must be optimized in terms of flight path angle, speed, etc. Moreover, this environment must have the capability to be integrated within an optimization environment. The integrated environment must also be able to parametrically handle life-cycle costs and safety so each alternative can be evaluated in terms of performance, safety, and life-cycle costs. Finally, the proposed environment must be easy to use. Table 1 compares and evaluate the existing sizing tools for suborbital vehicles against the aforementioned required characteristics. This evaluation shows that there is a lack of readily available sizing and synthesis environment that can evaluate all suborbital concepts against life-cycle costs at a conceptual design level.

In order to bridge this gap, the objective of this research is to develop a flexible Modeling and Simulation (M&S) environment that provides the capabilities to allow designers to efficiently assess the multi-disciplinary performance of unconventional concepts at a conceptual design level.

E-mail address: christopher.frank@gatech.edu (C.P. Frank).

https://doi.org/10.1016/j.ast.2018.03.017
1270-9638/© 2018 Elsevier Masson SAS. All rights reserved.

Please cite this article in press as: C.P. Frank et al., A flexible multi-disciplinary environment for performance, life-cycle cost, and safety evaluation of suborbital vehicles, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.03.017

Table 1
Comparison of the various sizing and synthesis codes.

	Fast	Available	Easy	Design space exploration	Conceptual level	Architecture optimization	Cost modeling	Automation
Sarigul [1]		●	●	●				
Design Sheet [2]	●			●	◖	◖	◖	●
TSSP [3]	●		◖		◖	●		◖
Mattingly [4]	●	●	●		◖			●
FLOPS [5]	●	●	◖		◖	●	●	●
ASTOS [6]	◖	◖		●		◖		◖
RASAC [7]	●	●	◖		●	◖	◖	●
Stanley [8]	●		◖		●	◖		
Olds [9]		◖	◖		◖	●		◖
HAVOC [10]	●		◖		◖	●		●
Braun [11]				◖	◖	●	●	◖

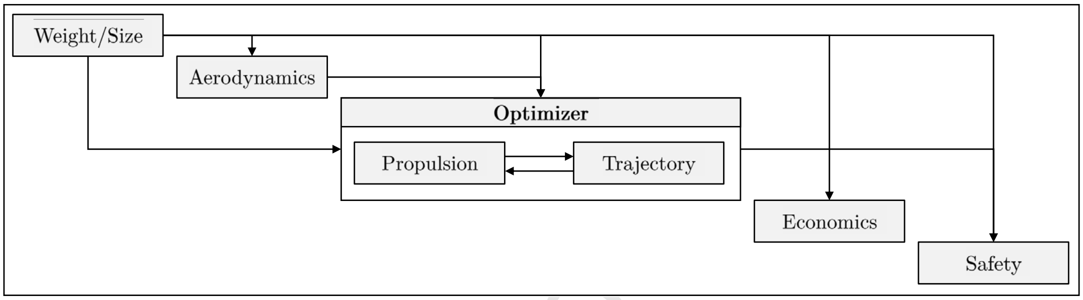

Fig. 1. Structure of the proposed multi-disciplinary design framework.

2. Proposed approach

In order to develop the aforementioned design framework, a structure must first be defined. Since no historical data are available, a physics-based disciplinary structure is selected. Particularly useful at a conceptual design level, a Multi-Disciplinary Feasible (MDF) structure can also decrease the number of function calls by avoiding inconsistent solutions. However, since constraints are handled by the optimizer, solutions are not necessarily feasible before the final convergence. Moreover, there is a need for decreasing the number of design variables in order to increase the efficiency of the algorithm. Local coupling is a commonly used method to reduce both the number of variables and the strength of the coupling in the overall design framework. While the MDF is usually combined with a Fixed-Point Iteration (FPI) algorithm, its well-known convergence issues [12] encourage the development of a local optimizer using gradient-based methods. The implementation of the local optimizer consequently reduces the strength of the coupling and enables the enforcement of the constraints so only feasible solutions are generated. Finally, since the intermediate optimizer is built around continuous variables, it accelerates the overall optimization process. Fig. 1 displays the overall structure and the interactions among the various disciplinary modules, whose development is discussed in the next sections.

3. Modeling and simulation environment

The modules that compose the proposed multi-disciplinary framework are described. One of the unique characteristics of these modules is their use of empirical models to help meet the objective of this research.

3.1. Weight and size module

The presented approach is based on a physical decomposition of the vehicle into 18 subsystems, for which weight/size estimation models are selected.

3.1.1. Weight estimation

Body Brothers [13] developed the empirical model for the body weight W_b presented in Eq. (1), which includes the fuselage, the thrust structure, and the nose. In this equation, S_{fus} is the fuselage area, S_{nose} the surface area of the nosecone, q_{max} the maximum dynamic pressure during the flight, d_{nose} the diameter of the nosecone base, K_t the thrust structure constant, and T_r the maximum vacuum.

$$W_b = 2.167 S_{fus}^{1.075} + S_{nose}\left(2.5\times 10^{-4} q_{max} + 1.7 + \left(3.7 q_{max} 10^{-5} - 3.3\times 10^{-3}\right) d_{nose}\right) + K_t T_r^{1.0687} \quad (1)$$

Lifting surfaces MacConochie [14] proposes empirical models for the wing weight W_{wing} and both the vertical and horizontal tails W_t, as presented in Eqs. (2) and (3), respectively. In these equations, n_u is the ultimate load factor, W_{land} the landing weight, S_b the body planform area, S_{exp} the wing exposed area, t_c the wing thickness-to-chord ratio, b the wing span, d_f the fuselage diameter, and S_t the tail area.

$$W_{wing} = \left(\frac{n_u W_{land}}{1 + \frac{0.2 S_b}{S_{exp}}}\right)^{0.386} \left(\frac{S_{exp}}{t_c}\right)^{0.572} \times \left(0.214 b^{0.572} + 0.05 d_f^{0.572}\right) \quad (2)$$

$$W_t = 1.108 S_t^{1.24} \quad (3)$$

Other subsystems As derived, by Brady [15], the weight of the Thermal Protection System (TPS) is calculated using $W_{tps} = 1.51 S_b$. The landing gear weight W_{lg} can be calculated using Eq. (4) [13,14], where W_{land} is the landing weight.

$$W_{lg} = 0.010784 W_{land}^{1.0861} + 0.0028 W_{land} \quad (4)$$

MacConochie [14] also provides the weight of the hydraulic system defined by $W_{hyd} = 2.1 S_{cs} + 1.68 \times 10^{-4} T_r$, where S_{cs} is the size

Please cite this article in press as: C.P. Frank et al., A flexible multi-disciplinary environment for performance, life-cycle cost, and safety evaluation of suborbital vehicles, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.03.017