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Multi-objective optimization for re-entry spacecraft conceptual design using a free-form shape generator

Antonio Viviani, Luigi Iuspa, Andrea Aprovitola *

Universitá degli Studi della Campania "Luigi Vanvitelli", Dipartimento di Ingegneria Industriale e dell'Informazione, Via Roma 29, 81031 Aversa (CE), Italy

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ABSTRACT

In this paper we developed a multi-disciplinary, multi-objective optimization procedure for the shape generation of re-entry spacecrafts performing conventional landing from a Low Earth Orbit return mission. A special free-form parametric model, able to define complex vehicle shapes with no explicit support surfaces, was defined and used for this purpose. Model capabilities have been preliminary validated by emulating the HOPE-X vehicle prototype and computing the aerodynamic coefficients at Mach number 2 and 10. Multi-objective optimization has been performed by considering a multidisciplinary approach comprising aerodynamic analysis, trajectory estimation, and heating analysis starting by fixed waypoints along the descent path. A Pareto front based on mass and cross range objective functions was generated, highlighting the existence of several design scenarios: minimum mass, maximum winglet, maximum cross range. The existing trade-offs between the objective functions were related mainly to bank angle values and vehicle length, featuring main design trends.

1. Introduction

Objectives of future space missions and a growing demand also for space tourism have pushed the way to search for a different spacecraft design. Currently, ballistic re-entry vehicles are the only viable option either for sub-orbital spaceflight or crew-rescue after the Space Shuttle dismission. Nonetheless, both private and public investors are developing prototypes of Winged Re-entry Vehicles (RV-W) designed also as a single-stage-to-orbit configuration to improve operability allowing at same time lower flight costs compared to existing expendable multi-stage rockets [1,2]. Multi-objective shape optimization is often adopted in a conceptual phase of the RV-W design to gain an assessment of the vehicle performances over the search space of design parameters [3–8]. Optimization is also a powerful tool to improve the design and to reduce the experimental test campaign. High order fidelity tools, like Computational Fluid Dynamics, have been applied mainly to local shape optimization problems. However, the number and the range of variation of parameters required to properly set up an optimization procedure for a typical re-entry mission drives to a computational overhead that makes the CFD methods not applicable to the conceptual design phase [6,9,10]. Therefore, a preliminary appraisal of vehicle performances is commonly obtained using a suitable parameterization of vehicle geometry that gives a support to a multidisciplinary analysis based on more efficient low-order fidelity methods [2,5]. Several studies that uses a multidisciplinary analysis to perform a preliminary design of RV-W are already present in literature. Tava et al. [6] proposed a multi-objective shape optimization to maximize the cross range and minimize the total heat absorbed. Geometry parameterization was obtained by a rotation of a parametric curve defining the longitudinal outline of the shape. Dirkx et al. [5] used different Hermite spline surfaces (properly merged), to parameterize a winged vehicle with elevon and winglets. Lobbia [7] developed a wave-rider geometry with analytic and spline-based parameterizations integrated in a design tool, performing a multiobjective optimization with respect to the mass, lift-to-drag ratio, and downrange. Non-uniform Rational B-splines (NURBS) and NURBS surfaces are a *de facto* standard in Computer Aided Design softwares (CAD). NURBS-based parameterization allows a simple control over geometric curvatures [11], and therefore it has been extensively applied to multi-objective optimization procedures of re-entry vehicles [5–8]. Despite the high flexibility of the NURBS surfaces, commercial CAD tools are often not suitable for deriving a vehicle parameterization applicable to the conceptual design of RV-W [12,13]. Indeed, the application of knowledge-based systems to parameterize specific portions of a vehicle geometry, e.g. wing or fuselage, may limit the search space excluding some of the feasible configurations that might have higher performance [14]. In addition, a re-entry vehicle is commonly shaped as a blended-wing-body to maximize

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* Corresponding author.
E-mail address: andrea.aprovitola@unicampania.it (A. Aprovitola).

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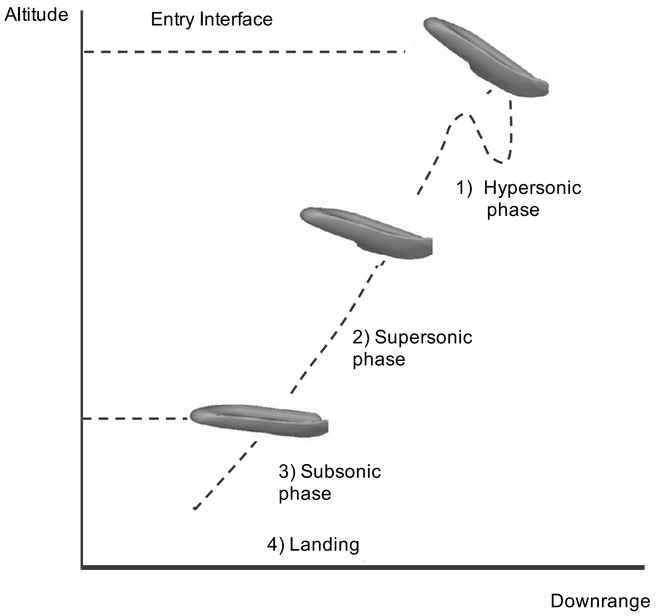

Fig. 1. Mission profile of RV-W: 1) Hypersonic phase; 2) Supersonic phase; 3) Subsonic phase; 4) Landing.

the lift force and to reduce the weight. However, the derivation of a unique parameterization to describe the overall changes of geometry resulting from a shape optimization is not always possible or comfortable while using a commercial CAD tool. Therefore, several NURBS surfaces are used to parameterize different parts of the geometry of the vehicle, and the mutual intersections among them are managed usually outside a CAD environment [5]. In this work a multi-objective shape optimization procedure for an RV-W vehicle, designed for a re-entry mission from LEO orbit and performing a conventional landing is presented. A main contribution in this work is the development of a shape modeling procedure for a winged re-entry vehicle featuring winglet surfaces, that maps the changes of shape into discretized geometries only based on a parametric wireframe. As far as the shape of the vehicle is neither obtained by using NURBS surfaces nor with a feature based modeling approach, the procedure has a reduced computational overhead. Furthermore, being the procedure based on a free-form modeling, the search for unconventional configurations is promoted. The parametric model is used in a multi-objective shape optimization supported by a multidisciplinary analysis comprising aerodynamics, heating analysis, trajectory estimation, and mass estimation, by considering cross-range and mass as objective functions. A set of constraints which establishes thermal and structural feasibility for a conventional air-vehicle landing, has been added.

2. Rationale

The RV-W shape is optimized for the mission shown in Fig. 1 aimed at the return of six crew members from a LEO orbit to Earth surface based on the following stages: 1) Hypersonic phase; 2) Supersonic phase; 3) Subsonic phase; 4) Landing. The RV-W should exhibit a cross-range capability by assigning an initial bank angle μ_a also allowing an Earth landing, like an airplane on a runway. In a previous paper by Viviani et al. [15], a modeling procedure for re-entry shapes was developed. A vehicle surface discretization was created only managing points properly sampled on a wireframe, shown in Fig. 2(a) and Fig. 2(b). Starting from this procedure, a different shape model is introduced here, developing a parametric wireframe that allows a wide degree of freedom for the wing-planform design. The model is now capable of creating a parametrically-defined dihedral wing-planform. A reshaping procedure, consisting of a set of bi-linear affine transformations added to the model, automatically preserves the outline between the cabin and the wing, thus avoiding potentially inconsistent shapes.

3. Wireframe modeling

The parameterization of RV-W is derived according to a procedural approach. A simple wireframe, shown in Fig. 3, is created as geometric support for the computational surface grid. The wireframe always encloses a box-shaped volume, with fixed dimensions, namely $V_{cabin} = (l\times h\times 2b) = (4.95\times 1.5\times 1.76)\ \mathrm{m}^3$, roughly conformed as a living space and/or a cargo bay transportation. Cubic rational B-splines are adopted to model the outline of the wireframe in the symmetry plane shown in Fig. 4(a). This choice adds an high flexibility in modeling nose bluntness, allowing precise shape variations which may heavily affect the aero-thermal performances. Piecewise linear interpolators are used to keep the overall design of cross-sections first finding, for every interval point of the current poly-line frame, the maximum allowable fillet radii between internal points P_{1i} as shown in Fig. 4(b) (an additional zero-length condition for the shortest edge is considered here to make the multi-fillet problem well posed [16]), and then applying an unique fractional amount for all the normalized design parameters. The roundness of the fillets is set by the parameter r_{fi}. Six leading cross sections are assigned to define vehicle fuselage outline. This number of leading cross-sections, has been chosen by considering that re-entry shapes typically do not require too many steep changes of cross sections. Excluding nose and tail regions, cross sections basically remain similar, being just stretched to fit symmetry and planform profiles. A similar procedure has been adopted to create the outline of the wing shown in Fig. 4(c). Wireframe parameters (are assumed as design variables) and reported in Table 1, and are assumed as design variables. Parameters ad_{rnose} and H_1 control the nose radius which is defined to avoid inconsistent concavities using the following relation:

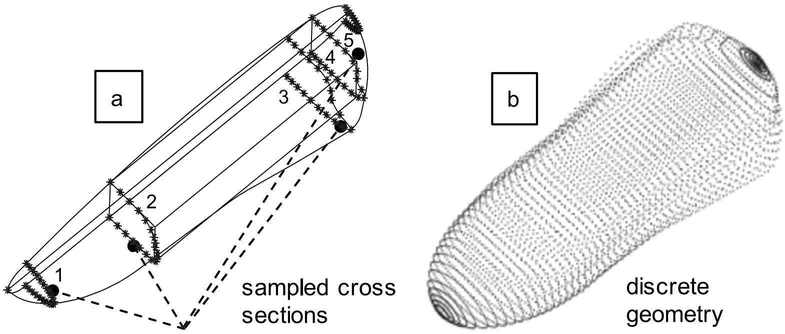

Fig. 2. Lattice wireframe of re-entry vehicle (a); discrete grid obtained by linear interpolation (b).