An optimization-based procedure for self-generation of Re-entry Vehicles shape

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A B S T R A C T

In the present paper a multidisciplinary optimization procedure for the self-generation of re-entry vehicle shapes has been developed. The procedure relies on a novel parametric model of blended wing-body shapes which is used to create a re-entry configuration around a fixed volume. The flexibility of the model allows us to create lifting body or winged re-entry vehicle from an optimization procedure as monolithic bodies. Multidisciplinary analysis is performed with engineering methods valid in conceptual design. Results of shape optimization for a minimum mass configuration, performed for a Low Earth Orbit Re-entry mission, confirmed the suitability of the procedure by indicating a decrease of vehicle mass configuration that is obtained by reducing the wingspan parameter for a conceptual lifting body configuration.

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1. Introduction

Re-Entry Vehicles (RV) are designed to transfer the crew and payload from a Low Earth Orbit (LEO) to the Earth’s surface [1]. The optimal design of the shape of a RV is a complex problem, because of the different flow regimes and altitudes encountered during the re-entry flight. Atmospheric re-entry is performed by dissipating the high amount of vehicle kinetic energy through blunt shapes having high aerodynamic drag coefficient [2]. Furthermore, at low altitudes in the supersonic and subsonic speed regime, the shape design has to provide efficiency and maneuverability to fulfill the landing requirements. The above reasons show that the optimal design of shape of a RV is a trade-off solution among several disciplines often dealing with conflicting design objectives [3]. Multidisciplinary Design Optimization (MDO) allows to account for the simultaneous variation of design variables on the overall performances of RV [4–6]. MDO splits the vehicle design process into sub-disciplines which address geometry, aerodynamics, flight mechanics and heating [3]. However, due to the coupling among the sub-disciplines, the accurate prediction of the aerothermal and structural environment does not fit with the typical timeline of the conceptual design phase. Therefore, low order fidelity methods whose range of validity is accepted in a conceptual design are adopted to speed up the design process [7]. Within this framework, the shape parameterization has to balance two conflicting requirements i.e. a high degree of freedom in the generation of shape while limiting the number of design parameters [8]. Multidisciplinary optimization for a hypersonic re-entry vehicle has been investigated extensively for a large class of re-entry configuration. While commonly engineering methods were adopted for aerodynamics [9–11], flight mechanics and heating analysis [12], different parameterization of shape were proposed. Analytic shapes obtained by superimposition of geometric primitives like cones, sphere and cylinders segments, provided the shape parameterizations for the Stardust Module, the Genesis Module, and the Apollo command module [1]. Tava et al. [5] developed an MDO procedure for a capsule and a conceptual RV shape, for cross-range and heat objectives. Blunt cone shapes were parameterized using five design variables. Nosratollahi et al. [13] performed a multidisciplinary optimization of a controllable re-entry capsule using drag coefficient, and the total heat absorbed as objectives. A sphere-cone geometry was parameterized with three design variables, Priyadarshi et al. [14] presented a MDO of a semi-ballistic module for the cross-range and total mass objectives. The shape parameterization was obtained with analytic geometries with five design parameters, and two aerodynamic parameters. Dirks et al. [15] performed the shape optimization for a capsule shape using sphere segment, thorax segment and conical frustum. Analytic shapes have the advantage to define the shape parameterization using few design variables. However, they are not suitable to create complex shapes like winged vehicle or particular lifting bodies (HL-X family vehicle) [8, 17], which requires a greater number of design parameters. Non

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uniform rational B-spline surfaces (NURBS) have been introduced in the shape optimization procedure to overcome the drawbacks of analytic shape modeling [8,18]. NURBS are obtained by defining a bi-directional grid of control points, and by considering the parametric surface bounded by the piece-wise rational B-splines through the selected control points [19]. NURBS parameterization allows to describe complex surfaces as it improves the local control of the geometry with respect to other polynomial representation of surfaces, using the same number of design variables. Foster et al. [20] presented an aerodynamic shape optimization of an ogive shaped body, and of lifting bodies. The vehicle parameterization was obtained by grouping a number of discrete cross sections realized with beta-splines along the longitudinal axis. Control points were placed on cross-sections in order to have an axially fixed position; therefore the overall length of the vehicle remained the same. Theisinger et al. [8] have performed a multi-objective optimization for different aeroshell shapes generated with NURBS. Drag area, longitudinal static stability and volumetric efficiency were the optimization objectives. Hypersonic aerodynamics was performed with Newtonian flow theory. Dirkx et al. [15] performed the shape and trajectory optimization for a winged re-entry vehicle. The fuselage and the wing-planform were modeled by two parametric Hermite surfaces and then properly merged. A different approach to an MDO on an unmanned entry capsule was reported in Ridolfi et al. [21]. They used a repository-based approach which exploited the values of the joint probability density function of the previously computed design variables to reduce the computational cost of the optimization. Optimization was related to shape modeling, aerothermodynamics, flight mechanics and thermal analysis. A unified framework based on free-form deformation model based on NURBS was presented by Gagnon et al. [16] to perform aerodynamic optimization of a winged-body shape. Lobbia [17] presented a multidisciplinary optimization procedure for wave-rider crew re-entry vehicle. The wave-rider geometry, was generated by creating a design tool which utilizes analytic and spline surface parameterizations to generate the shape. In this work an MDO procedure for the conceptual design of a hypersonic re-entry vehicle based on the self-generation of the vehicle surface is presented. The novelty of the present approach relies on the shape parameterization which allows us to create the Re-entry shape as a monolithic body. Therefore, the current procedure automatically creates winged or the lifting body configuration without using different parameterizations to model the fuselage, and the wing. The validity of the procedure has been addressed by performing a shape optimization for a minimum mass configuration for a gliding re-entry from a Low Earth Orbit (H = 120 km). Multidisciplinary analysis is performed with engineering methods based on simplified assumptions whose validity is currently accepted in conceptual design [17]; indeed, it is the reduced computational overhead that allows to apply this optimization procedure during the conceptual design phase. Optimization was run using a modified version of an implicit binary coded Genetic Algorithm (GA) [22] and performance of the vehicle was discussed.

2. Shape modeling procedure

A non-deformable box-shaped volume namely the cabin, of overall dimensions of 4950 mm in length, l; 1500 mm in height, h; and 1760 mm in width, b is assigned to accommodate six crew members. A wireframe, in the three dimensions, is created using cubic rational B-splines, enclosing the cabin, as shown in Fig. 1. Rational B-splines curves have the advantage with respect to other cubic interpolators to leverage the local control of the shape, without affecting the entire shape of the curve [19]. Therefore, complex shapes can be created just by using a limited number of control points. Fig. 2 shows the sequence of operations implemented in the procedure to obtain the discretized surface of the RV. A set of primary cross sections, namely A–A, B–B, C–C, D–D, E–E, is uniformly sampled producing several equispaced points (see Fig. 2(a)). These points are linearly interpolated to define discrete approximations of the secondary cross sections reported in Fig. 2(b). The number of the leading cross-sections, was chosen by considering that the shapes adopted in hypersonic regime do not require steep changes of the cross-sections. A higher number of the cross-sections would increase the search space with low sensitivity of the added parameters. Looking at Fig. 2(c) and Fig. 2(d) it appears that excluding the primary cross sections, any of the points created from the interpolations lie on the outline of the wireframe. In order to address this problem, a geometric transformation which translates the points $P_i$ on the corresponding outline of the wireframe given by:

$$P_i = \lambda^s \cdot P'_i \quad (1)$$

is defined. The superscript $s$ denotes the cross-section considered along the longitudinal axis of the vehicle. A schematic representation of the transformation applied to the points which belong to a generic section P–P comprised between the cross section B–B and C–C is shown in Fig. 2(e).

The vector $\lambda^s$ whose components along the directions $y, z$ are given by $\lambda_{s}^y = (P'O_1)/(PO_1)$, measures the displacement of the point $P$. In Fig. 2(f) the discretized vehicle surface is reported. This grid can be rearranged using a rasterized bi-dimensional array with the number of columns equals to the number of cross-sections, and the number of rows equals to the nodes on a cross-section. In the present case, the sampling interval adopted to interpolate the cross sections has been chosen in order to obtain a longitudinal dimension of panels equal to 150 mm, and twenty nodes were adopted to sample half cross section. Such resolution was chosen to provide accuracy of aerodynamic and thermal problem computation, with respect the range of assigned design parameters. Therefore, the total number of nodes used to discretize a cross section is equal to: $N_{tot} = 4 \cdot (N_{nodes} - 1) = 76$. In Fig. 3 several configurations obtained with the described model are reported as example (center view; bottom view), plus a reference sphere (top view) representing the homeomorphic base of transformation of the entire set of parametric models mapped in the search space. However, the sphere itself (and other similarly convex shapes) has been explicitly excluded by the search space because of its uselessness as an aerodynamic shape. In Table 1 the value of the parameters for the configurations depicted in Fig. 3 are also reported.

2.1. Wireframe parameterization

2.1.1. Parametrization of RV in the symmetry plane

The outline of the wireframe in the symmetry plane is shown in Fig. 4. The fore overhang of the vehicle is created by using...
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