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Optimized Reentry Trajectories for Winged RLV Stages

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Abstract

Reusable launch vehicles (RLV) are considered to be a potential way towards a more economical and sustainable space transportation. The range of RLV systems currently under investigation goes from partly reusable systems for transport of payload to orbit to fully reusable vehicles for hypersonic intercontinental point to point transport of passengers on earth. A significant portion of these systems contains winged reusable stages. The atmospheric reentry of winged RLV stages is an essential part of the overall RLV mission and its adequate assessment is mandatory from the early design phase on. In this paper an optimal control approach is followed for reentry trajectory analysis of a number of winged RLV stages investigated in DLR. The optimal control problem is solved with TransWORHP, the transcriptor for the nonlinear programming (NLP) solver WORHP. The obtained optimized trajectories are compared with results of alternative methods as e.g. drag acceleration guidance. Conclusions regarding the advantages of optimal control methods for reentry trajectory optimization from a systems analysis point of view are drawn. The impact of optimal control methods application on RLV systems preliminary design is assessed.

Keywords: *Reentry Trajectory Optimization, RLV, WORHP, NLP, SQP*

Nomenclature/Acronyms

ASTRA	Ausgewählte Systeme und Technologien für Raumtransport
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
ESA	European Space Agency
LFBB	Liquid Fly Back Booster
NLP	Nonlinear Programming
OCP	Optimal Control Problem
RLV	Reusable Launch Vehicle
SART	Systemanalyse Raumtransport
SQP	Sequential Quadratic Programming
TransWORHP	WORHP Transcriptor
WORHP	We Optimize Really Huge Problems

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1. Introduction

1.1. Background WORHP/TransWORHP

The basic principle behind the NLP solver WORHP is sequential quadratic programming (SQP). SQP methods are widely used for the solution of optimization problems and known for their robustness and good convergence properties, [1]. In this paper the atmospheric reentry of winged RLV stages is considered as an optimal control problem. The two principal approaches for the solution of optimal control problems are: direct and indirect methods. The latter reformulate the optimal control problem (OCP) into a boundary value problem whereas for the direct methods the discretization of the control and state variables allows an approximation of the infinite dimensional OCP through a finite dimensional NLP problem. In the frame of the present analysis the direct approach is followed. The transcriptor module TransWORHP is used for the transcription of the OCP into a NLP problem that is subsequently solved with the NLP solver WORHP. Both TransWORHP and WORHP are being developed at the University of Bremen's Centre for Industrial Mathematics. WORHP development was supported by the European Space Agency (ESA). Further details on WORHP and TransWORHP can be found in [1] and [2].

1.2. Winged RLV Stages

Analysis of winged RLV stages in DLR goes back to the ASTRA program with one of the most prominent configurations being the ASTRA Liquid Fly Back Booster (LFBB) for application with the Ariane 5 core stages, [3]. SpaceLiner, a conceptual design of a fully reusable hypersonic point to point passenger transport system, is under investigation since 2005, [4].
The following RLV stages are considered in this paper:

- SpaceLiner booster stage, see Fig 1
- SpaceLiner passenger stage, see Fig 1
- Reusable fly back booster type stage, see Fig 2

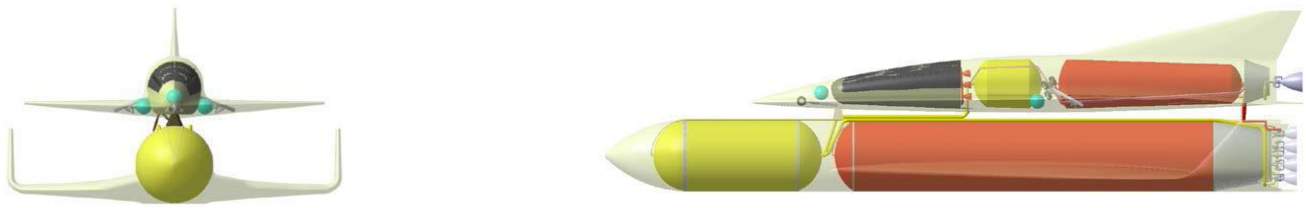

Fig 1. Concept of a fully reusable RLV configuration - SpaceLiner, [4]

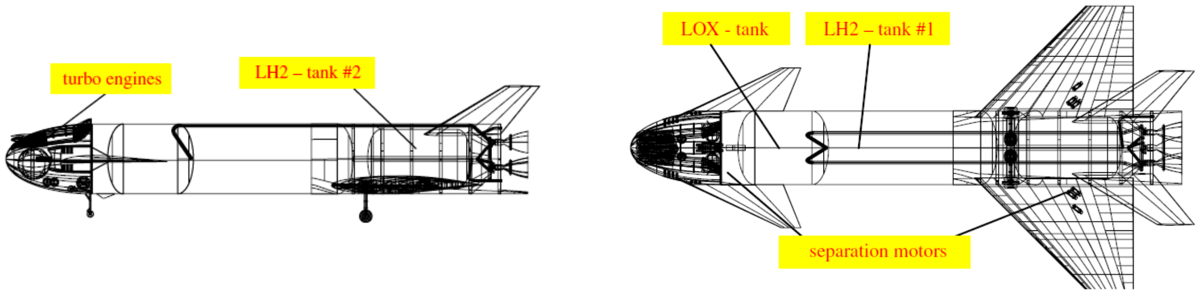

Fig 2. Liquid fly back booster, [3]

2. Optimized Reentry Trajectories

2.1. SpaceLiner Passenger Stage

The SpaceLiner configuration is a fully reusable system. Its Reference Mission consists of connecting Australia and Europe in about 90 minutes of flight time. After mated ascent and booster stage separation the SpaceLiner passenger stage continues on a powered ascent trajectory until engine cut off at about 75 km altitude and a velocity of 7.3 km/s. From this point onwards an unpowered gliding reentry begins and the question of determining controls that are consistent with the overall mission goals and relevant constraints arises. The altitude velocity mappings of two SpaceLiner passenger stage trajectories obtained by a drag acceleration guidance approach and optimization with TransWORHP are shown in Fig 3. The shown trajectories represent the Australia-Europe reference mission of SpaceLiner. The optimization objective for TransWORHP is minimizing integrated stagnation point heat flux. The available control variable is the bank angle while the angle of attack is kept constant at a value that is a compromise between aerodynamic performance and thermal loads.

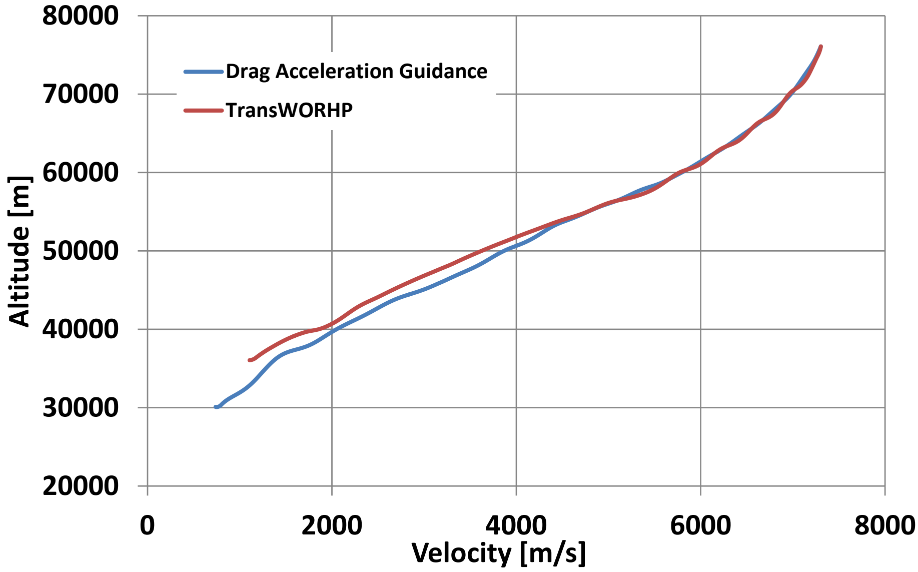

Fig 3. Altitude-Velocity diagram SpaceLiner passenger stage reentry

References

1. D. Wassel, F. Wolff, J. Vogelsang, C. Büskens: The ESA NLP-Solver WORHP – Recent Developments and Applications. In *Modeling and Optimization in Space Engineering*, pp. 85 - 110, Springer, New York, 2013
2. Knauer, M. and Büskens, C.: From WORHP to TransWORHP. In *Proceedings of the 5th International Conference on Astrodynamics Tools and Techniques*, 2012
3. Sippel, M. et al.: Long-term/strategic scenario for reusable booster stages. Acta Astronautica, Volume 58, Issue 4, February 2006, pp 209 – 221.
4. Sippel, M. et al.: SpaceLiner Technical Progress and Mission Definition. 20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 6-9 July 2015, Glasgow, United Kingdom