Trajectory Design, Optimisation and Guidance for Reusable Launch Vehicles During the Terminal Area Flight Phase

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Man belongs wherever he wants to go - and he'll do plenty well when he gets there.

Wernher Von Braun (1912 - 1977)

Time magazine, 17th February, 1958

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Nomenclature

Acronyms

3D	Three Dimensional
3DOF	Three Degrees of Freedom
6DOF	Six Degrees of Freedom
AD	Anno Domini
ALIP	Auto and Landing Interface
ALIP3D	Auto Landing I-load Program Three Dimensional
ALIP	Auto Landing I-load Program
AOTV	Aeroassisted Orbital Transfer Vehicle
ARES	Atmospheric Re-entry Experimental Spaceplane
ASTRA	Advanced Systems and Technologies for RLV Application
ATMOS4	Orbital Sciences Corporation Atmospheric Model
BC	Before Christ
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Plastics
COLIBRI	Concept of a Lifting Body for Re-entry Investigations
DFP	Davidon-Fletcher-Powell

DOF	Degrees Of Freedom
EADS	European Aeronautic Defence and Space Company
EADS-ST	European Aeronautic Defence and Space Company, Space Transportation
EAGLE	Evolved Acceleration Guidance Logic for Entry
EELV	Evolved Expendable Launch Vehicle
FESTIP	Future European Space Transportation Investigations Programme
FPGA	Field Programmable Gate Array
GPA	Gradient Projection Algorithm
GPS	Global Positioning System
GTO	Geostationary Transfer Orbit
HAC	Heading Alignment Cylinder/Cone
HWM	Horizontal Wind Model
IMSL	International Mathematics Standards Library
INS	Inertial Navigation System
IRS	Institut für Raumfahrtsysteme (Institute for Space Systems)
KEP	Kernel Extraction Protocol
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
LQR	Linear Quadratic Regulator
LRB	Liquid Rocket Booster
MAAF	Michael Army Air Field
MATLAB™	Matrix Laboratory

MAVERiC	Marshall Aerospace Vehicle Representation in C
MECO	Main Engine Cut Off
MIRKA	Micro Re-Entry Capsule
MOD	Mission Operations Directorate
MSISE	Mass Spectrometer Incoherent Scatter Extended
NASA	National Aeronautics and Space Administration
NEP	Nominal Entry Point
NLP	Non-Linear Programming
NLPQL	Non-Linear Programming Optimiser Sub-routine
OPTG	Optimum-Path-To-Go
PAM	Payload Assist Module
PNN	Polynomial Neural Network
Proto-SNAKE	Prototype Sub-Optimal Nodal Application of the Kernel Extraction
RLV	Reusable Launch Vehicle
SIGI	Space Integrated GPS/ INS
SI	Systéme International
SNAKE	Sub-Optimal Nodal Application of the Kernel Extraction
SQP	Sequential Quadratic Programming
SSO	Sun Synchronous Orbit
SSTO	Single Stage To Orbit
TAEM	Terminal Area Energy Management
TAI	Terminal Area Interface

TEP	TAEM Entry Point
US	United States of America

Greek Letters

α	Angle of attack
α_k	Step length
β	Side slip angle
χ	Azimuth or heading
$\dot{\chi}$	Azimuth rate
ΔF	Change in cost function
δ	Latitude
$\dot{\delta}$	Latitude rate
δSB	Speed brake setting
ϵ	Total vehicle energy
ϵ_{Init}	Initial vehicle energy
ϵ_{Kin}	Kinetic vehicle energy
ϵ_{Norm}	Normalised vehicle energy
ϵ_{Pot}	Potential vehicle energy
$\dot{\gamma}$	Flight path angle rate
γ	Flight path angle
κ	Ratio of specific heats (adiabatic index)
$\dot{\lambda}$	Longitude rate
Λ	Lagrangian multipler

λ	Longitude
μ_E	Earth gravitational potential
$\dot{v}$	Velocity rate
v	Vehicle velocity
ω_E	Earth angular velocity
ψ	Introduced parameter
ρ	Atmospheric density
σ	Standard deviation
τ	Time delay
ϑ	Thrust angle
ξ	Introduced variable

Latin Letters

a	Speed of sound
B_k	Approximate Hessian of the Lagrange function
cos	Cosine function
C_A	Axial coefficient
C_D	Total drag coefficient
C_d	Drag coefficient with Mach number correction
$C_{d_{Skin\,Friction}}$	Drag coefficient with skin friction
$C_{d_{Mach}}$	Drag coefficient correction for Mach number
C_f	Skin friction coefficient
C_L	Total lift coefficient

C_l	Lift coefficient with Mach number correction
$C_{l_{Mach}}$	Lift coefficient correction for Mach number
C_N	Normal coefficient
C_S	Speed brake coefficient
C_{S_D}	Speed brake coefficient for drag
C_{S_L}	Speed brake coefficient for lift
D	Drag force
d_k	k-th solution of the quadratic sub-problem
e	Eccentricity
$\tilde{F}$	Augmented cost function
F	Cost function
f	Function
F_{Aero}	Aerodynamic forces
F_{Control}	Control effort cost function
$F_{\text{Dynamic Pressure}}$	Dynamic pressure cost function
F_{Load}	Load margin cost function
$F(\vec{p})_{\text{Hopper}}$	Hopper cost function
$F(\vec{p})_{\text{X-33}}$	X-33 cost function
$\vec{G}$	Gravitation force vector
$\vec{g}$	Gravitation acceleration vector
G	Universal gravitational constant
g	Gravitational acceleration

G_δ	Gravitation force with respect to latitude
g_δ	Gravitation acceleration with respect to latitude
g_i	Final constraints
g_j	In-flight constraints
$\vec{g}_p^k$	Jacobian matrix
G_λ	Gravitation force with respect to longitude
g_λ	Gravitation acceleration with respect to longitude
G_r	Gravitation force with respect to centre of the earth
g_r	Gravitation acceleration with respect to centre of the earth
$\bar{H}$	Quasi-Newton matrix
h	Altitude
i	Final constraints list
J_i	Jeffery Constants
J_k^*	The set of active constraints
k_B	Boltzman factor
K_k^*	The set of inactive constraints
$\frac{L}{D}$	Lift-to-drag ratio
L	Lift force
$L(x, u)$	Lagrange function
M	Vehicle mass
m	Number of in-flight constraints
Ma	Mach number

Ma_f	Mach number factor
M_E	Mass of the Earth
m_e	Number of final constraints
n	Number of parameters
$\vec{p}$	Set of parameters
$p_{i,l}$	Parameter lower bound
$p_{i,u}$	Parameter upper bound
q	Dynamic pressure
$\dot{r}$	Radius rate
R	Current distance from the Earth's centre
r	Distance from centre of the Earth
R_{Gas}	Gas constant
R_n	Random number
R_E	Radius of the Earth
R_e	Earth equatorial radius
R_{mean}	Mean Earth radius
R_p	Earth polar radius
sin	Sine function
S_{ref}	Aerodynamic reference area
$\vec{s}^k$	Search direction
tan	Tangent function
T	Effective temperature

T	Thrust force
t	Vehicle state variable (normalised energy)
T_{Air}	Temperature
t_{end}	Final flight time
$\vec{u}(t)$	Control history
$\dot{\vec{x}}$	Differential constraints (equations of motion)
$\bar{x}$	Average value
x_i	Current value
x_k	k-th estimate of the optimal solution
$\vec{x}(t_f)$	Final state
$\vec{x}(t_0)$	Initial state

Subscripts

α	Angle of attack
c	Commanded steering setting
δSB	Speed brake setting
Lim	Limit
μ	Bank angle
Max	Maximum
X	X axis
Y	Y axis
Z	Z axis

Abstract

You can't solve a problem with the same kind of thinking that created it.

Albert Einstein (1879-1955)
Theoretical Physicist

THE next generation of reusable launch vehicles (RLVs) require significant improvements in guidance methods in order to reduce cost, increase safety and flexibility, whilst allowing for possible autonomous operation. Research has focused on the ascent and hypersonic re-entry flight phases. This thesis presents a new method for trajectory design, optimisation and guidance of RLVs during the terminal area flight phases. The terminal area flight phase is the transitional phase from hypersonic re-entry to the approach and landing phase.

The trajectory design, optimisation and guidance methods within this thesis are an evolution of previous work conducted on the ascent and re-entry flight phases of RLVs. The methods are modified to incorporate the terminal area flight phase through the adaption of the problem definition and the inclusion of the speed brake setting as a steering parameter.

The methods discussed and developed in this thesis are different to previous methods for the terminal area flight phase as they encompass optimisation, trajectory design and guidance based on the definition of the steering parameters. The NLPQL nonlinear optimiser contained within the International Mathematics Standards Library (IMSL) is utilised for trajectory design and optimisation. Real-time vehicle guidance is achieved using the restoration steps of an accelerated Gradient Projection Algorithm (GPA).

The methods used are evaluated in a three degrees of freedom (3DOF) simulation environment. To properly evaluate the programs and gain a better understanding of the terminal area flight phase, two different vehicles are utilised within this study. These vehicles are the German sub-orbital Hopper concept vehicle, a previously proposed replacement for the Ariane series of launch vehicles and the recently cancelled joint National Aeronautics and Space Administration (NASA) and Lockheed Martin sub-orbital test bed vehicle, X-33. The two vehicles each have a terminal area flight phase, but their mission profiles and vehicle characteristics are significantly different. The Hopper vehicle is a winged re-entry vehicle, whereas the X-33 vehicle is a lifting body.

The trajectory design method takes into account the initial and final conditions, in-flight restrictions such as dynamic pressure and vehicle loads as well as safety margins. The designed trajectories are evaluated to analyse the terminal area flight phase and to assist in the development of the guidance program.

The guidance method is evaluated utilising an program consisting of two parts, a real world simulator with high order models and a representation of the on-board guidance computer, the predictor, which uses low order models for computational efficiency. The guidance method is evaluated against a variety of off-nominal conditions to account for dispersions within the high order real world models and common errors experienced by re-entry vehicles. These off-nominal conditions include atmospheric disturbances, winds, aerodynamic, mass, navigation, steering and initial condition errors.

The results of this study include a detailed analysis of the terminal area flight phase highlighting the major influences for vehicle and trajectory design. The study also confirms the applicability of the non-linear programming method utilising the vehicle steering parameters as a viable option for trajectory design and guidance. A comparison to other available results highlights the strengths and weaknesses of the proposed method.

Statement

THIS work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available in all forms of media, now or hereafter known.

James T. A. Chartres

Date

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Be silent as to services you have rendered, but speak of favours you have received.

Seneca (5 BC - 65 AD)

Roman Dramatist, Philosopher and Politician

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This thesis is dedicated to all those people who have given of themselves in the pursuit of the exploration of space. May their sacrifice be never forgotten or in vain.

If we die, we want people to accept it. We are in a risky business and we hope that if anything happens to us it will not delay the program. The conquest of space is worth the risk of life.

Virgil I. "Gus" Grissom (1926 - 1967)