



**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 Raumfahrtssysteme (Institute for Space Systems)
KEP	Kernel Extraction Protocol
LH <sub>2</sub>	Liquid Hydrogen
LOX	Liquid Oxygen
LQR	Linear Quadratic Regulator
LRB	Liquid Rocket Booster
MAAF	Michael Army Air Field
MATLAB <sup>TM</sup>	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	Système 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**

$\alpha$	Angle of attack
$\alpha_k$	Step length
$\beta$	Side slip angle
$\chi$	Azimuth or heading
$\dot{\chi}$	Azimuth rate
$\Delta F$	Change in cost function
$\delta$	Latitude
$\dot{\delta}$	Latitude rate
$\delta_{SB}$	Speed brake setting
$\epsilon$	Total vehicle energy
$\epsilon_{Init}$	Initial vehicle energy
$\epsilon_{Kin}$	Kinetic vehicle energy
$\epsilon_{Norm}$	Normalised vehicle energy
$\epsilon_{Pot}$	Potential vehicle energy
$\dot{\gamma}$	Flight path angle rate
$\gamma$	Flight path angle
$\kappa$	Ratio of specific heats (adiabatic index)
$\dot{\lambda}$	Longitude rate
$\Lambda$	Lagrangian multiplier



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$\lambda$	Longitude
$\mu_E$	Earth gravitational potential
$\dot{v}$	Velocity rate
$v$	Vehicle velocity
$\omega_E$	Earth angular velocity
$\psi$	Introduced parameter
$\rho$	Atmospheric density
$\sigma$	Standard deviation
$\tau$	Time delay
$\vartheta$	Thrust angle
$\xi$	Introduced variable

**Latin Letters**

$\alpha$	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
$C_{d_{\text{Skin Friction}}}$	Drag coefficient with skin friction
$C_{d_{\text{Mach}}}$	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
$F_{Dynamic Pressure}$	Dynamic pressure cost function
$F_{Load}$	Load margin cost function
$F(\vec{p})_{Hopper}$	Hopper cost function
$F(\vec{p})_{X-33}$	X-33 cost function
$\vec{G}$	Gravitation force vector
$\vec{g}$	Gravitation acceleration vector
$G$	Universal gravitational constant
$g$	Gravitational acceleration

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$G_\delta$	Gravitation force with respect to latitude
$g_\delta$	Gravitation acceleration with respect to latitude
$g_i$	Final constraints
$g_j$	In-flight constraints
$\vec{g}_p^k$	Jacobian matrix
$G_\lambda$	Gravitation force with respect to longitude
$g_\lambda$	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**

$\alpha$	Angle of attack
$c$	Commanded steering setting
$\delta SB$	Speed brake setting
$Lim$	Limit
$\mu$	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

**T**HE 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 adaptation 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 non-linear 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

**T**HIS 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.

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James T. A. Chartres

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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)