DOI: 10.13009/EUCASS2022-6118
9TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Landing a Propulsive Stage with Bézier Curves

P. Vernis, A. Passeron

ARIANE Group Les Mureaux, France
e-mail: philippe.vernis@ariane.group

ABSTRACT

From a GNC standpoint, recovering the propulsive stages of a launcher is a challenging way for reducing the cost of a launch. Up to now and since the APOLLO program many guidance schemes have been designed to perform an accurate soft-landing after a powered descent phase for any kind of spacecraft such as an interplanetary probe, a demonstrator or, more recently as achieved by Space-X or Blue Origin, a propulsive stage of a launcher.

Because the terminal descent path describes a very smooth trajectory, the driving idea developed in this paper is to rely on a Bézier curves modelling of the descent path and to use the properties of the Bézier curves to design a guidance scheme able to cope with propulsive constraints such as min and max thrust level and thrust modulation rate. Main mission constraints are then to limit the miss-range and the vertical and horizontal velocities at touch down as well as to avoid too large tiltings of the vehicle.

The performance of this new guidance scheme is illustrated considering a 100 tons class booster, the aerodynamic flight phase between the braking and landing burns being achieved thanks to a dedicated guidance scheme relying either on a classic proportional navigation or on a Bézier-curves based guidance originally developed to perform a full aerodynamic atmospheric entry.

1. INTRODUCTION

Since Space-X's first successive landings on the ground or off-shore, recovery has become almost a routine for Falcon 9 and Falcon Heavy launchers, even if Blue Origin has been the first company to re-use a flown booster. In comparison to a classical atmospheric entry of a spacecraft (a capsule, a lifting body or a winged body), the recovery of a booster with limited ranging capabilities for reach a limited-size landing pad may be more challenging. In addition, recovering the booster in the vicinity of the launch pad may increase the complexity of the return mission, a flip over maneuver having to be achieved.

As already performed by Space-X, there are two generic missions to recover a booster: on ground near the launch pad (Return To Launch Site scenario, or RTLS) or at sea on a droneship, or any site on ground but far away from the launch site (DownRange Landing scenario, or DRL), see Fig. 1. The RTLS scenario limits the recovery operations but this is done at the expense of a reduced payload and more stressing safety issues. At the opposite, the DRL scenario enables a heavier payload, reduces the safety issues for a recovery at sea but yields different operating constraints: a too rough sea may be not compliant with a droneship landing and if not well fixed on the droneship after landing, the booster may be lost at sea during the back cruise. Nevertheless a DRL scenario considering a landing on a droneship rather than on a fixed ground site offers clearly more flexibility at Mission Analysis level.

DOI: 10.13009/EUCASS2022-6118

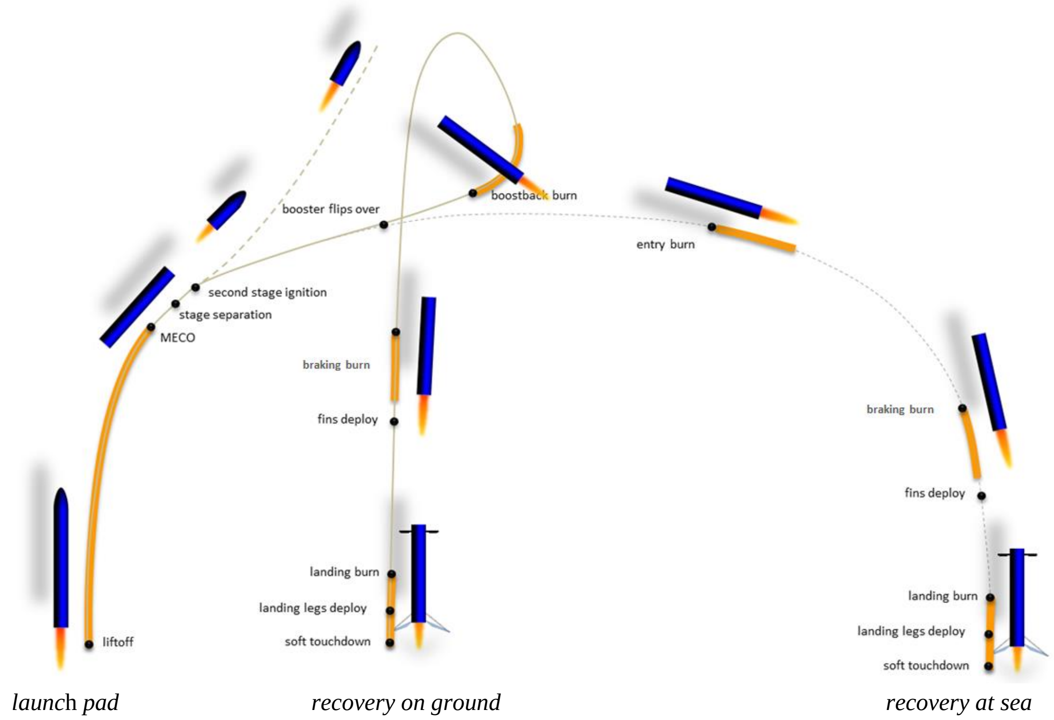


Figure 1. VTVL recovery missions scenarii

Once the landing gate conditions are reached, the final landing burn may be fired. The objectives of the terminal guidance are then to cancel out the lateral position and velocity offsets observed at landing gate's crossing and to enable an accurate and safe soft-landing. Mission requirements for the Guidance function are defined wrt the final miss-range to the centre of the landing pad, the descent rate at touch-down as well as the horizontal velocity in order to avoid any lateral drift that could yield a tilt over of the booster after touch-down.

Landing guidance schemes have been widely investigated since the Surveyor and APOLLO programs in the 60's: Gravity Turn [1] or APOLLO guidance [2,3] have demonstrated their ability to safely land on the Moon for automatic or manned missions. Following US Mars missions considered similar landing principles for full powered terminal descent phases, even if the required accuracy at landing point was not so stressing. Landing guidance analyses have been continued mainly to cope with interplanetary missions that became more and more demanding towards final accuracy objectives. Within the frame of ESA activities but also internal R&D studies, Ariane Group designed different guidance solutions. Among them were a 2nd degree APOLLO guidance [4] that was derived from the original APOLLO guidance, or an Artificial Neural Networks (ANN) landing guidance [5] that demonstrated a high fulfilment rate of the landing requirements defined for an interplanetary liquid- or solid-fueled lander enabling an in-flight retargeting induced by Hazard Detection and Avoidance operations when nearing the ground.

With the increase of the on-board computers performance, envisaging more complex guidance algorithms became possible. For instance convex optimization is more and more considered within guidance schemes [6]. Ground facilities having also more and more powerful computation means, implementing ANN guidance that requires preliminary extensive learning phases could also be considered, but the adaptation to various missions yielding different nominal conditions at landing gate does not appear compliant with some missionisation objectives. Recent developments on the use of Bézier curves for defining an entry trajectory [7] were a starting point for Ariane Group to investigate new entry guidance methods. The designed Bézier-Curves-Based Guidance [8] produced interesting results enabling to perform a large range of entry missions. Because the

terminal landing path is a very smooth trajectory almost vertical, applying a similar guidance principle to perform the landing phase became obvious.
The objective of this paper is to present the design of a new soft-landing guidance algorithm relying on Bézier curves, and to provide a preliminary performance assessment considering a 100-ton class VTVL booster. In a first part, the use of the Bézier curves to design the landing guidance scheme is described. This paper being Guidance-oriented, the performance assessment relies on 3-DOF Monte-Carlo simulations taking into account the propulsive model of the booster and state-of-the art off-nominal flight conditions wrt kinematics, aerodynamics, environment, and propulsion. Those simulations are performed from the end of the braking boost down to the touch-down, the aerodynamic guidance relying either on a classical Proportional Navigation law [9,10] or on the Bézier-Curves Based Guidance [8], or BCBG, developed to perform an atmospheric entry.

2. GUIDANCE DESIGN

Bézier curves are not new. They have been invented in the 50's by Pierre Bézier, a French automotive engineer to ease the design of industrial parts, and became later the basis of computer-aided design processes such as CATIA. But their application is not limited to computer-aided design, and for instance, they may be considered for defining reference trajectories for UAV.

Bézier curves are just polynomial parametric curves allowing easily matching a given shape using control points. Limiting the number of control points to only two in order to ease the implementation of the guidance scheme, the 3rd-order Bézier curve may be simply defined as Eq.1

$$P(\omega) = \sum_{i=0}^{3} P_i B_i^n(\omega) \tag{1}$$

where ω is the dimensionless Bézier parameter ($0 \leq \omega \leq 1$), P_i are waypoints or control points used to define the curvature of the trajectory and $B_i^n(\omega)$ the Bernstein polynom, see Eq.2

$$B_i^n(\omega) = \frac{n!}{i!(n-i)!}\omega^i(1-\omega)^{n-i} \tag{2}$$

Defining the P_i points by their geocentric coordinates (radius r_i, longitude λ_i and latitude φ_i), it is then possible to express any point of the trajectory by the expression of Eq.3:

$$\begin{pmatrix} r(\omega) \\ \lambda(\omega) \\ \varphi(\omega) \end{pmatrix} = P(\omega) = \sum_{i=0}^{n} B_i^n(\omega) P_i = \sum_{i=0}^{n} B_i^n(\omega) \begin{pmatrix} r_i \\ \lambda_i \\ \varphi_i \end{pmatrix} \tag{3}$$

The driving idea in using Bézier curves to define a guidance scheme is to use the kinematics properties of the curve in order to get the acceleration that is required to track the curve but also achievable by the vehicle. For an unpowered flight phase, the guidance command is defined by the lift acceleration, or a set of bank angle and angle-of-attack. For a powered flight phase, the guidance command is given by the propulsive acceleration (mass-flow rate q_{pro}, thrust pitch θ_{pro} and yaw angles Ψ_{pro}), assuming at guidance level that the propulsive acceleration is delivered along the vehicle's roll axis. This process requires differentiating twice with respect to the Bézier parameter ω the equations of motion that are expressed wrt time t, see Eq.4:

DOI: 10.13009/EUCASS2022-6118

$$\begin{pmatrix} r(\omega) \\ \lambda(\omega) \\ \varphi(\omega) \end{pmatrix} = P(\omega) \qquad \begin{pmatrix} r'(\omega) \\ \lambda'(\omega) \\ \varphi'(\omega) \end{pmatrix} = \frac{dP}{d\omega}(\omega) \qquad \begin{pmatrix} r''(\omega) \\ \lambda''(\omega) \\ \varphi''(\omega) \end{pmatrix} = \frac{d^2P}{d\omega^2}(\omega) \tag{4}$$

Unlike what can be considered for an atmospheric entry[8], there is no real need in modelling the landing path by a succession of elementary cubic Bézier curves. The landing trajectory is thus fully defined by the landing gate's crossing P_0, the landing pad centre P_3 and two control points P_1 and P_2 that can be defined wrt initial (P_0) and final (P_3) conditions as presented at Eq.5 and Eq.6:

$$P_1 = P_0 + k_0 \frac{V_0}{3} \begin{bmatrix} \sin\gamma_0 & \dfrac{\cos\gamma_0 \sin\chi_0}{r_0 \cos\varphi_0} & \dfrac{\cos\gamma_0 \cos\chi_0}{r_0} \end{bmatrix}^t \tag{5}$$

$$P_2 = P_3 - k_f \frac{V_f}{3} \begin{bmatrix} \sin\gamma_f & \dfrac{\cos\gamma_f \sin\chi_f}{r_f \cos\varphi_f} & \dfrac{\cos\gamma_f \cos\chi_f}{r_f} \end{bmatrix}^t \tag{6}$$

where k_0 and k_f are adaptation coefficients given by $k_0 = t'(0)$ and $k_f = t'(1)\dfrac{V_f}{V_0}$, t'(0) and t'(1) corresponding here to the derivatives of the time wrt the Bézier parameter ω in P_0 ($\omega = 0$) and P_3 ($\omega = 1$), and γ and χ respectively the flight path angle and the heading angle.

The classic approach to use Bézier curves in a guidance scheme is to write first the equations of motion that will be inverted to get the needed acceleration to track the curve. Even if the Earth rotation could be neglected with respect to the duration of the final landing burn, the equations of motion are expressed considering Earth rotation as well as J2 terms. But instead of writing the equations of motion in a geocentric frame using spherical coordinates as for a classic atmospheric entry [8], we consider a trihedron attached to the landing pad, with x_g and y_g axes on the local horizontal plan and the z_g axis on the vertical to the landing pad, and Cartesian coordinates. This preliminary step yields a relation between the Cartesian coordinates of the total acceleration of the vehicle on the landing path, and the position components, via the geocentric coordinates (r, λ, φ), the velocity components in a local geocentric frame (V, γ, ψ), and the geocentric coordinates of the landing pad (r_T, λ_T, φ_T), see Fig. 2.

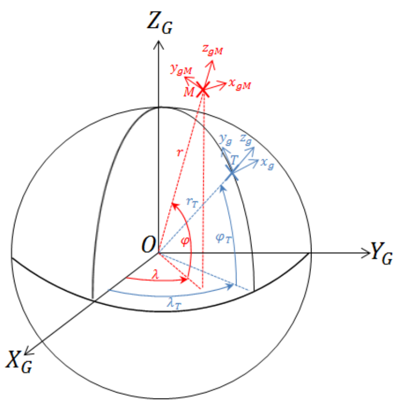


Figure 2. Trihedra definition

Then, instead of solving the guidance problem, i.e. finding straightforwardly the acceleration from the kinematics on the Bézier curve, as done for the atmospheric entry [8], we introduce some simplifications.

DOI: 10.13009/EUCASS2022-6118

We first use the knowledge of the current altitude to establish a link with the Bézier parameter ω accordingly to the altitudes z_i of the P_i points, Eq.7:

$$z(t) = z_{BC}(\omega) = (1-\omega)^3 z_0 + 3(1-\omega)^2 \omega z_1 + 3(1-\omega)\omega^2 z_2 + \omega^3 z_3 \quad (7)$$

Then, relying on the Navigation data, the desired total acceleration $\begin{bmatrix}\ddot{x}_d & \ddot{y}_d & \ddot{z}_d\end{bmatrix}^t$ is supposed being defined:

- by the horizontal acceleration needed to cancel the current horizontal position offsets to the Bézier curve;
- and by the vertical acceleration needed to track a predefined descent rate profile $V_{zp}(t)$.

The last step of the guidance process is to compute the commanded propulsive acceleration $\vec{T}$ from the equations of motion accordingly to Eq.8

$$\begin{aligned}
T_x &= \ddot{x}_d - f(\dot{x}_{BC}, \omega_{Earth}, V, r, \lambda, \varphi, V, \gamma, \chi, D, L_x, g_x, g_y, g_z) \\
T_y &= \ddot{y}_d - f(\dot{y}_{BC}, \omega_{Earth}, V, r, \lambda, \varphi, V, \gamma, \chi, D, L_y, g_x, g_y, g_z) \\
T_y &= \ddot{z}_d - f(\dot{z}_{BC}, \omega_{Earth}, V, r, \lambda, \varphi, V, \gamma, \chi, D, L_z, g_x, g_y, g_z)
\end{aligned} \quad (8)$$

drag D and lift L acceleration being deduced from the desired acceleration and the velocity vector, $\begin{bmatrix}\dot{x}_{BC} & \dot{y}_{BC} & \dot{z}_{BC}\end{bmatrix}^t$ representing the velocity on the Bézier curve.

The commanded acceleration is then transformed in terms of mass flow rate q_{com} Eq.9, pitch θ_{com} Eq.10, and yaw ψ_{com} Eq.11:

$$q_{com} = \frac{m\sqrt{T^2{}_x + T^2{}_y + T^2{}_z}}{g_0.Isp(t)} \text{ with } q_{com} \in \begin{bmatrix} q_{min} & q_{max}\end{bmatrix} \text{ and } \dot{q}_{com} \le \dot{q}_{max} \quad (9)$$

$$\psi_{com} = a\tan\frac{T_y}{T_x} \text{ with } \psi_{com} \in \begin{bmatrix}-\pi & \pi\end{bmatrix} \quad (10)$$

$$\theta_{com} = a\sin\frac{T_z}{\sqrt{T^2{}_x + T^2{}_y + T^2{}_z}} \text{ with } \theta_{com} \in \begin{bmatrix}\theta_{min} & \frac{\pi}{2}\end{bmatrix} \quad (11)$$

A main contributor to the success of the soft-landing mission is the value of the braking thrust commanded by the guidance. If too large discrepancies have to be considered, some failure cases such as hard-landing (descent rate at impact beyond -3 m/s) or hopping (guidance is disabled when the altitude increases yielding a ballistic final flight), may occur as illustrated on Fig. 3.

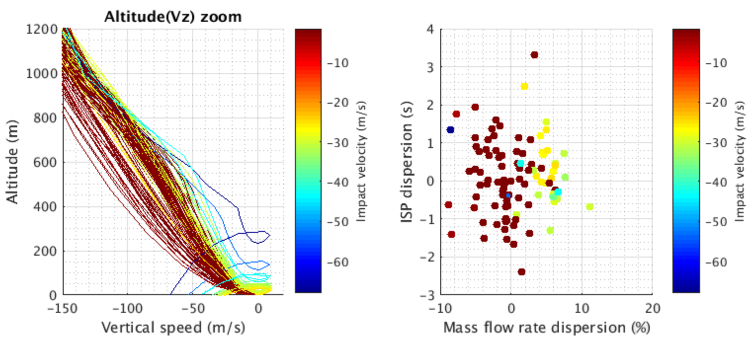


Figure 3. Potential landing failure cases

DOI: 10.13009/EUCASS2022-6118

To prevent those cases, we implement an additional safety logic by introducing a terminal corridor whose main action will be to increase or decrease the commanded mass-flow rate accordingly to the current state of the vehicle wrt to upper (thrust is decreased) and lower (thrust is increased) boundaries of this corridor. With such terminal corridor, the soft landing is performed in all simulated cases and the flight profiles, displayed in terms of altitude vs descent rate, are well narrowed below 200 m AGL as illustrated on Fig. 4.

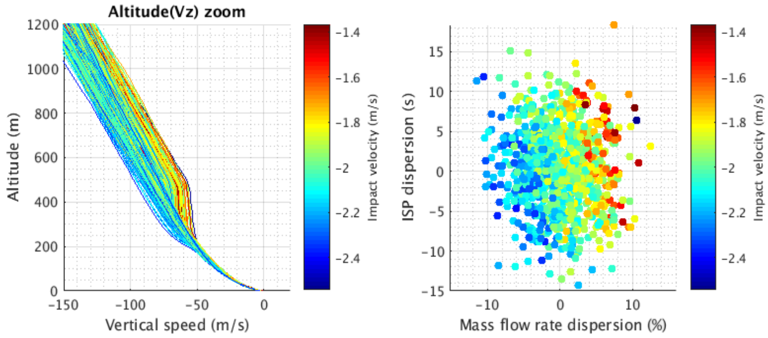


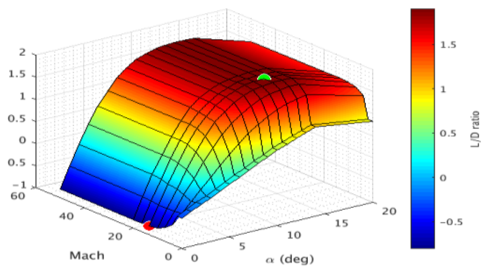
Figure 4. Impact of the terminal landing corridor

Eventually, when nearing the ground, a MPS shutdown predictor is implemented to avoid too large velocity at impact or unexpected hopping at touchdown.

3. GUIDANCE PERFORMANCE

Before assessing this new Bézier-curves based landing guidance, or BCLG, all the guidance parameters needs to be properly set. Because we assess the performance of the guidance from the end of the braking burn, we realize a global optimisation of the internal data of both guidance schemes retaining either the BCBG guidance [8], or a more classic PN law [9,10] for the glided phase. This preliminary setting phase is performed using genetic algorithms with the guidance in the optimisation loop order to get a robust setting over the whole set of expected uncertainties and discrepancies. The landing gate is considered being defined only in terms of altitude.

Table 1. VTVL booster main features

Propulsion		**Aerodynamic model**
propellant	4000 kg	
min thrust	200 kN	
max thrust	700 kN	
max MFR rate	40 %/s	

The previous table summarizes the main features of the booster for simulation starting at the end of the braking burn. Monte-Carlo simulations are performed using a dedicated guidance-oriented 3-DOF simulation platform considering a point mass problem and a rotating Earth, the WGS84 model with J2 terms. Navigation and Control functions are supposed ideal.

DOI: 10.13009/EUCASS2022-6118

Figures 5 to 8 display 1000 runs simulation results when considering the aerodynamic glided phase controlled with the PN or the BCBG guidance, the landing gate being set, after genetic algorithms optimisation, at 1600 m AGL for both baseline, the red curve corresponding in each case to the nominal guided trajectory.

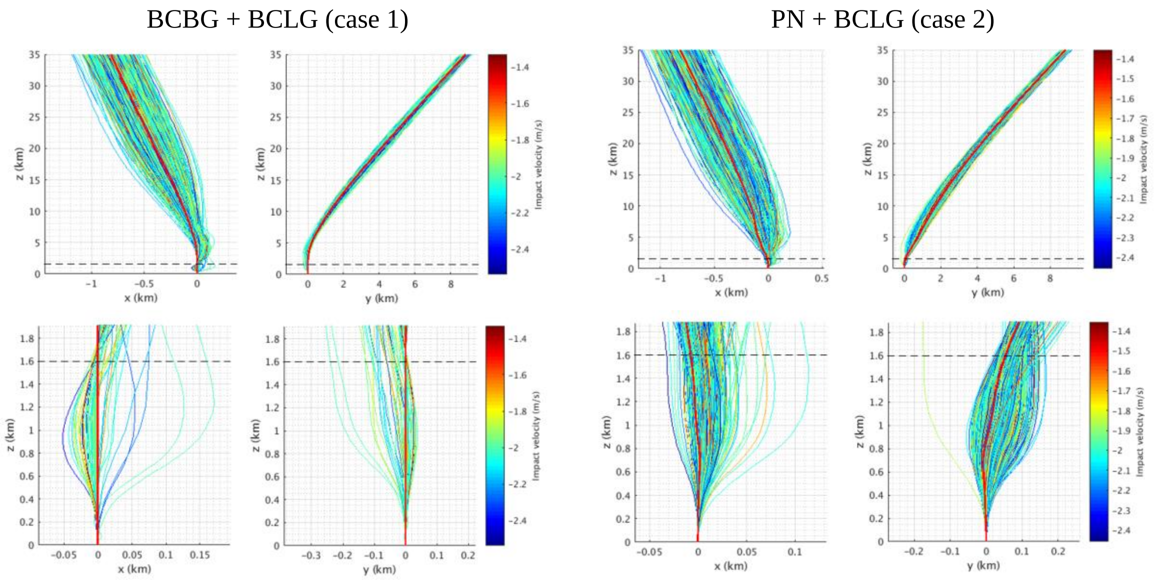


Figure 5. Monte-Carlo trajectory profiles

Before analysing the kinematic conditions at touch-down, the first point to notice is that the PN aerodynamic guidance law yields larger trajectory profiles, see Fig. 5, and consequently larger kinematic dispersions at landing gate's crossing, see Fig. 6 (conditions at landing gate's crossing are plotted with black dots for the PN aerodynamic guidance).

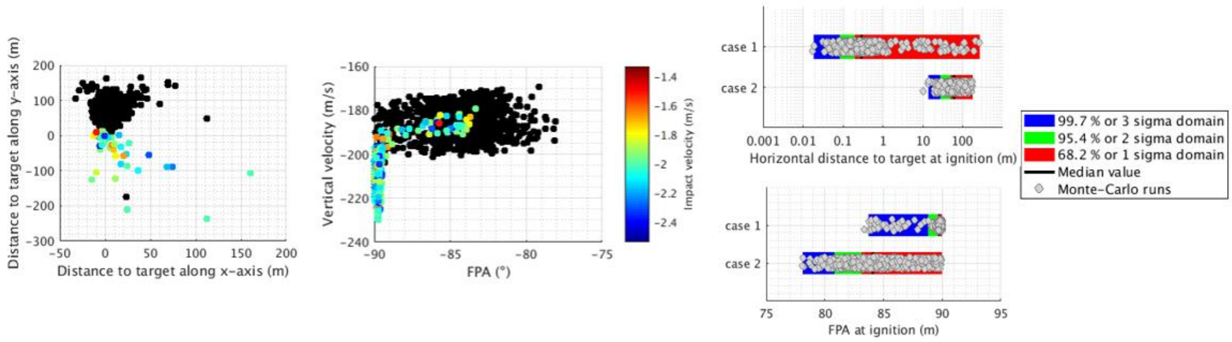


Figure 6. Monte-Carlo conditions at landing burn firing

Because of a higher descent rate at landing burn ignition, the risk of final hopping is reduced. Without the terminal speed corridor more than the half of the simulation cases for the PN+BCLG baseline would yield a hopping what is not the case for the full Bézier guidance baseline even if rather large propulsive dispersions have been considered. For both baseline, the final vertical velocity remains below, in absolute value, the -2.5 m/s requirement, see Fig. 7, descent rate being higher for under-propulsive configurations.

DOI: 10.13009/EUCASS2022-6118

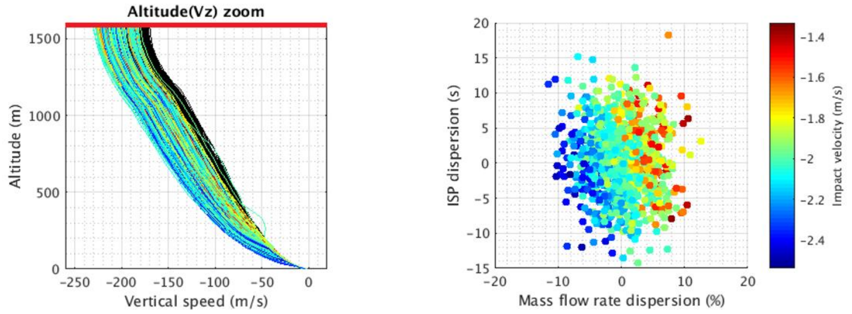


Figure 7. Monte-Carlo landing profiles and final conditions wrt propulsive dispersions

The success criteria for the landing are to land less than 5 m away from the centre of the landing pad and to limit the vertical velocity at touchdown below -3 m/s, and the horizontal one below 1 m/s.
For both guidance baseline, the success criteria are all met in a similar way with important margins left, as illustrated on Fig. 8 for miss-range and horizontal velocity at touchdown, resp. less than 0.5 m and 0.1 m/s (MTCL results for baseline 1 and 2 have been superimposed).

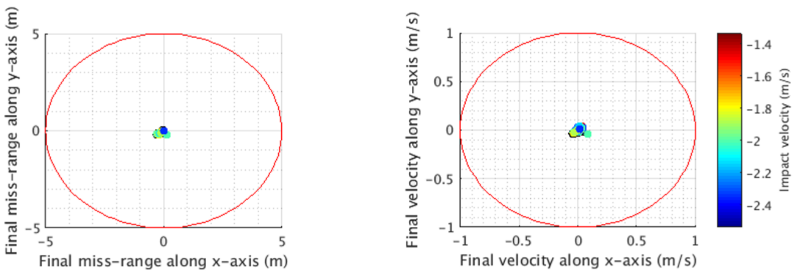


Figure 8. Monte-Carlo final conditions wrt mission requirements

The Bézier-curves based landing guidance is thus able to reach a high precision at touchdown meeting all mission requirements. In addition, the PN guidance for the glided phase yielding a degradation of the kinematic conditions at landing gate's crossing, it shows some robustness to degraded initial conditions.

4. CONCLUSION

After a first use of Bézier curves to design a new guidance scheme able to manage the atmospheric entry with closed-loop control of the angle-of-attack and/or the bank angle it was decided to apply the Bézier curves to the design of a new landing guidance scheme for a VTVL booster.

Firstly, the implementation of a Bézier curves based guidance for the landing phase is eased by the fact that the landing path is much more smooth and straight than for an atmospheric entry having to perform a skip or large cross-range deviations. Then via the introduction of some simplifications, solving the guidance problem can be done in a different manner by decoupling vertical and horizontal command logics. Adding some safety logics to avoid too large descent rate at touchdown or even hopping, this new landing guidance scheme yields an interesting performance level even if the preceding aerodynamic flight phase is guided considering a classic guidance scheme as the PN law. Additionnal investigations would have to be envisioned to assess the performance of the coupled Guidance and Control functions considering more realistic booster definition as well as mission scenarii including real winds, only sustained winds with a constant heading having been considered.

DOI: 10.13009/EUCASS2022-6118

REFERENCES

[1] R.K. Cheng, “Surveyor Terminal Guidance’

[2] A. Klumpp, “APOLLO Lunar Descent Guidance”, Draper Laboratory, June 1971

[3] D.M. Azimov, “Enhanced Apollo-Class Real-Time Targeting and Guidance for Powered Descent and Precision Landing”, AIAA Guidance, Navigation and Control conference, Boston 2013

[4] S. Cabrol, P. Vernis, A. Martinez Barrio “Enhanced Apollo Guidance for ESA High Precision Landing Mission on Mars”, 5th International ARA Days, Arcachon 2015

[5] G. Gelly, P. Vernis, “Neural Networks as a Guidance Solution for Soft-Landing and Aerocapture”, AIAA Guidance, Navigation and Control conference, Chicago 2009

[6] Michael Szmuk, Behcet Acikmese, “Successive Convexification for 6-DoF Mars Rocket Powered Landing with Free-Final-Time”, 2018 AIAA Guidance, Navigation and Control Conference,

[7] Trajectory Optimization of Common Aero Vehicle through Genetic Algorithm aided with Rational Bézier Curve F. Usman, Z. Ke, A. Mir Soban EUCASS, 7th European Conference for Aeronautics and Space Sciences, Milano 2017

[8] P. Vernis, J.B. Carroy, “Hypersonic Entry Guidance and Bézier Curves”, 8th European Conference for Aeronautics and Space Sciences, Madrid 2019

[9] P. Lu, “Intercept of Non-moving Targets at Arbitrary Time-varying Velocity”, AIAA 1997

[10] P. Lu, D.B. Doman,J.D. Schierman, “Adaptive Terminal Guidance for Hypervelocity Impact in Specified Direction”, AIAA GNC 2005, San Francisco

NOTATIONS AND ABREVIATIONS

AGL	Above Ground Level
ANN	Artificial Neural Network
BC	Bézier Curve
BCBG	Bézier-Curves Based Guidance
BCLG	Bézier-Curves Landing Guidance
DOF	Degree Of Freedom
DRL	DownRange Landing
MPS	Main Propulsion System
MTCL	MonTe-CarLo
PN	Proportional Navigation
VTVL	Vertical Take-off Vertical Landing
B	Bersntein polynom
D	drag acceleration
$g_{x,y,z}$	components of the gravitational acceleration
$k_{0,f}$	control points adjustment ratio
$L_{x,y,z}$	components of the lift acceleration
n	order of the Bézier curve
Pi	waypoints or control points
q_{com}	commanded mass flow arte
r	Distance to Earth centre
t	time
$T_{x,y,z}$	components of the thrust acceleration
$V_{0,f}$	relative velocity (initial, final)
V_{ZP}	descent rate profile
Δx	miss-range to the Bézier curve along X axis
Δy	miss-range to the Bézier curve along Y axis
$\gamma_{0,f}$	Flight path angle (initial, final)
θ_{com}	commanded pitch
ψ_{com}	commanded yaw
$\chi_{0,f}$	heading angle (initial, final)
$\varphi_{0,f}$	latitude (initial, final)
ω	Bézier parameter