

Article

Model Predictive Control for Gliding Descent on Mars

Jhonathan Murcia-Piñeros ¹, Antônio F. B. A. Prado ² and Ignazio Dimino ^{3,*}

¹ Department of Pure and Applied Mathematics, Institute of Science and Technology (ICT/UNIFESP), São José dos Campos 12247-004, Brazil; jhonathan.pineros@unifesp.br

² Division of Graduate Studies (DIPGR), National Institute for Space Research (INPE), São José dos Campos 12227-010, Brazil; antonio.prado@inpe.br

³ The Italian Aerospace Research Centre (CIRA), 81043 Capua, Italy

* Correspondence: i.dimino@cira.it; Tel.: +39-0823-623308

Featured Application

This is the first time that the implementation of model predictive control for trajectory tracking of a robotic spaceplane descending on Mars is suggested.

Abstract

This paper proposes a closed-loop nonlinear model predictive control for the first time for the trajectory tracking of a spaceplane descending and gliding on Mars. Previous studies presented the optimization of descending trajectory solving optimal control problems to reach a specific region (longitude, latitude, and altitude) by the end of the atmospheric flight. Following those approaches, in this work, an optimal trajectory was selected for a semi-optimal controller, specifically the nonlinear model predictive control. This controller and its robustness were validated through Monte Carlo simulations, demonstrating that it is robust enough to direct the spaceplane along the reference path, even when the atmospheric density changes by 15% of the standard deviation.

Keywords: aeromaneuvers; astrodynamics; closed-loop; guidance; model predictive control; planetary entry; spaceplane



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1. Introduction

Over the last few decades, scientific interest in Mars has grown. Several missions, including rovers, have been deployed, increasing the knowledge of the planet and its atmosphere. New players, including private companies, are investing in and developing spacecraft aimed at future Mars missions. An example of this is NASA's Mars Exploration Program, which spans 2024–2044.

Travel to Mars highly depends on the interplanetary heliocentric trajectory from Earth to Mars, which could take several months. When the mission requires the transportation of either scientific instruments or payloads to the surface of the planet, the spacecraft must survive the atmospheric entry. This is a critical phase of the mission, as most of the spacecraft's kinetic energy is dissipated through friction with the atmosphere, thereby increasing the thermal and structural loads on the spacecraft's surface, as presented in [1,2].

After high-speed or hypersonic entry, the spacecraft is surrounded by a dense enough atmosphere to deploy aerodynamic actuators, such as parachutes, to increase drag, a technology that has been successfully applied in several missions. More details about the aerodynamics of space missions are discussed in depth in [1,2]. On the other hand, another possible system to be used during the Entry, Descent, and Landing (EDL) phase is gliding

spacecrafts, similar to Space Shuttles and the robotic X-37B, also known as spaceplanes. The large surface and aerodynamic shape of the spaceplanes allow them to increase the lift force, which could result in a gliding flight if the lift is controlled. A characteristic of this technology is the ability to control descent with greater precision than a parachute, thereby increasing the flight range. It is essential to note that this technology is beneficial for transporting larger payloads and demonstrates its suitability for reusing spaceplanes for future missions, a concept proposed in [3–11]. The optimization of re-entry involves the use of lift to optimize the trajectory. This is a problem that has been discussed for many years, adapting new solutions from the state-of-the-art technology available at each epoch. One of the earliest studies describing lift control during gliding re-entry is presented in [7]. With the evolution of space technology, new ideas are required that are more complex computationally and adapt to the most advanced systems. For instance, a second-order convex optimization was analyzed for high lift to drag hypersonic gliding vehicles on Earth, solving optimal control problems in less time than traditional nonlinear programming [3]; another approach of a hypersonic gliding flight above the Earth tracking the velocity to control the angle of attack and avoiding specific zones was presented in [4]. An analytical guidance approach was proposed in [5] to reduce the computational cost of hypersonic re-entry above the Earth. The final deceleration and increase in weight of the control angle of attack were proposed in [6] as a short-range guidance strategy for re-entry of a vehicle on Earth. For the case of Mars, deployable devices are designed as an alternative as a decelerator for atmospheric entry on future missions [8–10]. As presented before, to date, most applications of gliding hypersonic technology have been analyzed for missions above Earth. In the case of Spaceplanes, such as the Space Shuttle and X-37, they were validated through multiple missions in Low Earth Orbit (LEO), which makes spaceplane technology a good candidate for missions above atmospheric planets; this is the reason it was selected for analysis in the present paper.

Multiple missions and scientific papers show that a spacecraft designed to leverage the atmosphere of the planet (like the spaceplane) reduces the cost of the mission because it uses the aerodynamic forces to control its trajectory, compensating for the use of chemical propulsion [12–25]. Unlike drag, the manipulation of lift enables us to control the direction of the spacecraft during atmospheric flight, including range and cross-range, and also reduces vertical speed. In the case of hypersonic maneuvers above the planet, the spaceplane performs an aeromaneuver known as an aerogravity assist maneuver (AGAM), which has been widely explored by various authors over the last 30 years [12,14–25]. Hypothetical high-lift-to-drag spaceplanes, like waveriders, could perform AGAM to increase the performance of the fly-by, as described in [12,14–23]. For instance, the control of lift in AGAM increases the curvature angle of the swing-by, which is equivalent to a significant gravitational effect from the planet. Additionally, it is possible to direct part of the lift outside the plane of the trajectory, resulting in a change of the orbital plane (i.e., a change in inclination) [13,24,25]. The AGAMs are a good example of the possible uses of spaceplane technology in aeromaneuvers, but, as it is outside the scope of this paper, we invite you to obtain more information from the references cited earlier.

One of the challenges of aeromaneuvers is the uncertainty of atmospheric conditions, such as density. This stochastic system is influenced by several factors, including solar activity, the spacecraft's attitude and position, date and time, atmospheric dynamics, and weather conditions, among others. Therefore, planning aeromaneuvers depends on the dynamics of the system, constraints, and boundary conditions, which are standard features of an optimal control problem (OCP). As a result, most approaches to determining spacecraft trajectories in the atmosphere are solved via OCP, with promising results [12,15–26]. In 2024, the OCP was explored for a gliding descent of a spaceplane on Mars, aiming to

increase the flight range to reach specific coordinates at the final time [27]. This research demonstrated the successful application of the OCP for multiple trajectories, taking into account variations in the atmosphere and initial conditions. However, the paper analyzed open-loop trajectories without control to correct the course in real time, due to multiple perturbations along the flight path. Therefore, this study investigates the application of a closed-loop system for the same problem described in [27], proposing a new approach for an embedded (real-time) controller during a gliding descent on Mars.

MPC is proposed as the real-time controller for the spaceplane during descent due to its ability to solve an OCP at each time step, applying the initial solution to the system and recalculating the control action for the subsequent state [28–43]. Unlike Linear Quadratic Regulators (LQRs) or other kinds of controllers, MPC has the same constraints, dynamic model, cost, and boundary conditions as an OCP, which is interesting for solving complex trajectories in the field of astrodynamics. At the same time, the advance in computation makes this technique feasible for on-board computers of spacecrafts [28–32]. On the other hand, new research has shown that it is possible to implement MPC in complex maneuvers [32]—for instance, in cases such as decay [33], atmospheric descent [34,35], rendezvous [37], and re-entry [36,38].

In the specific case of re-entry using MPC, new methods employing nonlinear MPC for hypersonic re-entries have recently emerged [44]. The use of flaps and LQR was examined for blunt bodies in [45]. Additionally, a reachability analysis for designing MPC controllers for re-entries was presented in [46], demonstrating feasible results. A robust approach, employing a different method explored in this paper, analyzes the robustness of hypersonic re-entry while avoiding specific points to solve a trajectory tracking problem [47]. However, the literature review shows that there are no applications of a spaceplane using closed-loop MPC for trajectory tracking on gliding descent above Mars, which is the novelty of this paper. This paper is proposed as a proof of this concept to determine the feasibility of the closed-loop maneuver via MPC.

The manuscript is arranged as follows: Section 2 presents the mathematical model. Section 3 presents the simulation results, followed by a discussion in Section 4.

2. Materials and Methods

In Section 2, the equations that describe the dynamics of the spaceplane above Mars are presented; the assumption and formulation of the aerodynamic model, as well as the cost function to minimize the trajectory tracking problem, are discussed, which represent the main components of the MPC.

2.1. Equations of Motion

Mathematically, the spaceplane is modeled as a point of mass, where the forces of weight (product of the mass by the gravity mg), lift (l), and drag (d) are acting. This point is the origin of the inertial velocity vector (V). The distance from this point to the center of the planet represents the magnitude of the position vector (R). The angle between the local horizon and the velocity vector is the flight path angle (FPA, γ), and the projection of the velocity on the horizon, in clockwise direction from the north, is the azimuth (A). Completing the spherical coordinates are the angles of longitude (θ) and latitude (φ). The banking angle (β) represents the angular distance between the lift and the local vertical or unit vector of R .

A spaceplane without variation in mass (gliding, without propulsion), flying on an isothermal static atmosphere above the spherical planet, with a uniform distribution of mass, is assumed. The planet is assumed to be static, without rotation. Those assumptions regarding the atmosphere and the gravitational model are selected due to the lack of

information on a more recent and comprehensive model available to the international scientific community. The six differential equations, also known as state equations (first-order dynamic constraints of the OCP), on the local rotational reference frame are as follows [12,14–17,22–25,27]:

$$\dot{R} = V \sin \gamma, \quad (1)$$

$$\dot{\theta} = \frac{V}{R} \cos \gamma \left(\frac{\sin A}{\cos \varphi} \right), \quad (2)$$

$$\dot{\varphi} = \frac{V}{R} \cos \gamma \cos A, \quad (3)$$

$$\dot{V} = \frac{d}{m} - g \sin \gamma, \quad (4)$$

$$\dot{\gamma} = \left[\left(\frac{l}{m} \frac{\cos \beta}{V \cos \gamma} - \frac{g}{V} \right) + \frac{V}{R} \right] \cos \gamma, \quad (5)$$

$$\dot{A} = \frac{l}{m} \frac{\sin \beta}{V \cos \gamma} - \frac{V}{R} \cos \gamma \tan \varphi \sin A. \quad (6)$$

2.2. Aerodynamic Model of the Spaceplane

The total aerodynamic force is composed of a perpendicular component to the velocity relative to the flow—in this case, lift, and the opposite force to the movement, which is drag. Both forces are a function of their specific coefficients, c_l and c_d , which are determined by the shape and material of the spacecraft. Those coefficients are a function of the properties of the continuum flow, and, in this particular case, are a function of the angle of attack (AOA- α). The AOA is the angular distance between the velocity vector and the axial axis of the spaceplane [1–3]. An ideal spaceplane was selected, with the ideal aerodynamic configuration similar to X-34 due to the availability of the experimental data to calculate its aerodynamic coefficients as a function of the AOA [11,24,27]. This is also the spaceplane with better aerodynamic performance due to its large lift-to-drag ratio. This angle is one of the control variables to be adjusted by the MPC along the flight path. The other control variable is the banking angle, described in Equations (5) and (6). The functions of the aerodynamic coefficients are presented in Figure 1. The aerodynamic model could be affected by flow and atmospheric variations; for this reason, and to model the uncertainties, it is proposed that a Monte Carlo analysis be used in Section 2.3. A detailed aerodynamic analysis is outside the scope of this research.

The model of the aerodynamic force depends on the density (ρ) of the flow. For this analysis, the atmosphere was assumed to be hydrostatic and isothermal, with density varying as a function of altitude (h). The model is considered in this way due to the lack of information about a more comprehensive model of Mars' atmosphere available to the scientific community. The exponential model of the atmosphere is

$$\rho = \rho_0 \exp(-h/H) \quad (7)$$

In Equation (7), H is the scale height, and the value used here is 11.1 km. The density at the surface (ρ_0) is 0.02 kg/m³ [48]. Then, it is possible to model the aerodynamic forces as follows [12–19,27]:

$$l = C_l \frac{A}{2} \rho V^2, \quad (8)$$

$$d = C_d \frac{A}{2} \rho V^2. \quad (9)$$

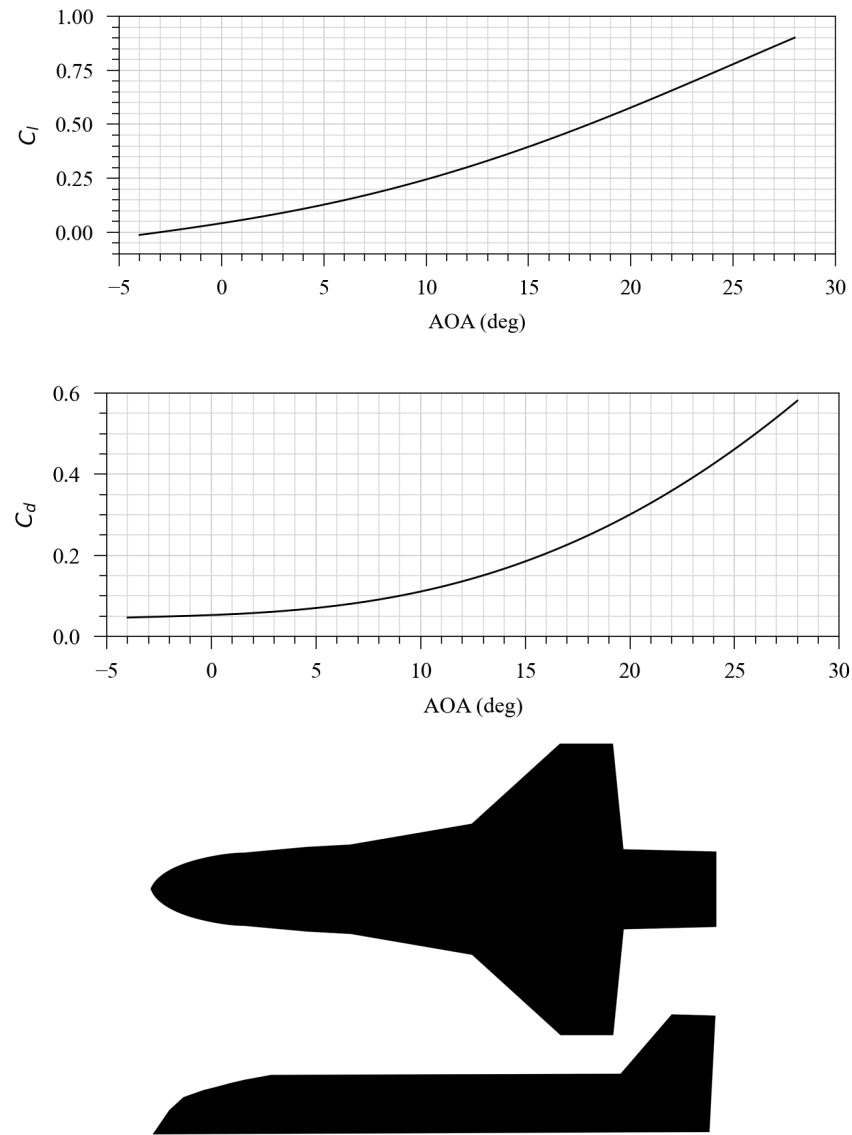


Figure 1. Aerodynamic configuration selected for the spaceplane: lift coefficient as a function of the angle of attack (**top**); drag coefficient as a function of the angle of attack (**middle**); top and lateral view of the shape of the spaceplane, adapted from [11] (**bottom**).

2.3. Constraints

The trajectory tracking problem described here follows a reference trajectory calculated from [27], which aims to direct the spaceplane to minimize the distance between two final coordinates of longitude and latitude. The path constraints within which the changes of the controller on the trajectory, from an initial time (t_0) to a final time (t_f), were selected from [27]. The range of motion of the variables to find a solution via MPC is the same as that of the OCP. In the case of the control variables, or the aerodynamic angles, the boundary conditions are restricted to the functions presented in Figure 1.

The boundary conditions of latitude and longitude describe the full range of the sphere of the planet, just as the azimuth. In the case of the FPA, it is selected to have its main component on the horizontal line, like a gliding horizontal flight, without abruptly increasing the AOA. As mentioned before, the initial altitude and velocity are selected

according to [27], allowing solutions to reach the planet's surface and reduce the velocity. The aerodynamic angles are a function of the model presented in Section 2.2.

$$\left. \begin{array}{l} t_0 < t \leq t_f \\ R_{planet} \leq R(t) < R_{planet} + 92 \text{ km} \\ 0.0 \text{ m/s} \leq V(t) \\ -180 \text{ deg} \leq \theta(t) \leq 180 \text{ deg} \\ -90 \text{ deg} \leq \varphi(t) \leq 90 \text{ deg} \\ -20 \text{ deg} \leq \gamma(t) \leq 20 \text{ deg} \\ 0 \text{ deg} \leq A(t) \leq 359.9 \text{ deg} \end{array} \right\} \quad (10)$$

$$\left. \begin{array}{l} -4 \text{ deg} \leq \alpha(t) \leq 28 \text{ deg} \\ -180 \text{ deg} \leq \beta(t) \leq 180 \text{ deg} \end{array} \right\} \quad (11)$$

2.4. Objective Function

Similar to the OCP, a cost function is required for the MPC because it is continuously solving an OCP at each step. In Equations (5) and (6), it is possible to observe that the FPA and the azimuth are functions of all of the variables of the dynamics, aerodynamics, and control. For this reason, the cost function is selected to minimize the error between the real flight and the reference values of the FPA ($\gamma_{Ref}(t)$) and azimuth ($A_{Ref}(t)$) as a function of time calculated previously from the OCP. Then, the objective function (J) for the MPC is to minimize the quadratic difference of the two angles as a function of time between the initial (t_0) and final time (t_f) of flight, subject to the dynamic constraints given by Equations (1)–(9), and the path constraints, Equations (10) and (11).

$$\min_{t_0, t_f} J(x, t) = \int_{t_0}^{t_f} \left[\left(\gamma(t) - \gamma_{Ref}(t) \right)^2 + \left(A(t) - A_{Ref}(t) \right)^2 \right] dt \quad (12)$$

In this case, a single optimization function was selected for a trajectory tracking problem to reduce computational cost, as the change in azimuth and FPA involves changes to all components of the state vector, as presented in Equations (1)–(6), and because it is possible to find solutions on the interval of time of the step, as demonstrated by [49] in the case of an aerogravity-assisted maneuver.

3. Results

A reference trajectory from the solution of the OCP was selected following the methodology presented in [27]. The spaceplane, with a mass of 8200 kg and an area of 332 m² [24], begins its atmospheric descent at an altitude of 92 km, at a longitude and latitude of 0°. The inertial velocity at this point is 6.5 km/s, pointing below the horizon due to the −4 deg of FPA, and directing the flight to the east, with 90 degrees of azimuth, as described in [27].

The software selected to solve the OCP and the NMPC is GEKKO in Python 3.13 [50]. This software was used for dynamic optimization problems, finding optimal trajectories for spaceplanes on gravity-assist maneuvers [25]. For the graphics presented in this paper, the Matplotlib (Version 3.10) library was implemented in Python [51].

The MPC is selected to have the possibility of estimating 4 s at each discretization point (4 s of horizon), requiring two control actions at each second (2 steps). This setup was selected because it is possible to calculate an optimal solution in less than 0.3 s, a time sufficient to execute the actuator and observe the new state. It is assumed that the six variables of the state vector and the two of the controllers are observable along the trajectory. Two modules are created to simulate the trajectory. The first one is the MPC, where the OPC is solved to find the control action to apply to the plant. The second module is a

simulator, where the dynamics of the system are solved at each discretization (0.5 s) using a numerical integrator (RK45), applying the control action calculated by the MPC. Then, the result is sent to the MPC as the initial condition of each step to complete the closed-loop guidance. The mean computational time to follow the complete trajectory is less than 400 s on a PC with a Core i5 (12th) processor and 16 GB of RAM, which is significantly less than the estimated time of flight above 810 s. Figure 2 presents the flowchart of the process.

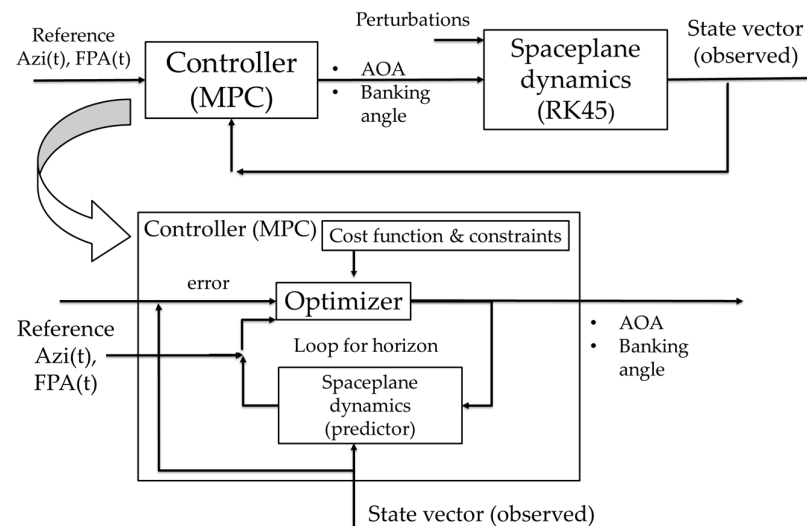


Figure 2. Flowchart used to describe the control process over the maneuver.

To explore the robustness of the NMPC to variations in atmospheric density, 100 trajectories from Monte Carlo simulations were analyzed, where the density was modeled as a normal distribution with a standard deviation of 15%. Results are presented from Figures 3–10. The reference trajectory from the OCP is presented as a dashed black line, and the colored lines represent the results of the simulations for each trajectory. In the figures, it is possible to observe that when the density decreases to values lower than 80% (blue and green lines, which are farther from the reference), this is represented in Figure 10 by the Density Scale, with dark spots indicating density lower than 0.8 or 80%. The drag is not enough to reduce the velocity, so increasing the time of flight makes it impossible for the controller to follow the trajectory.

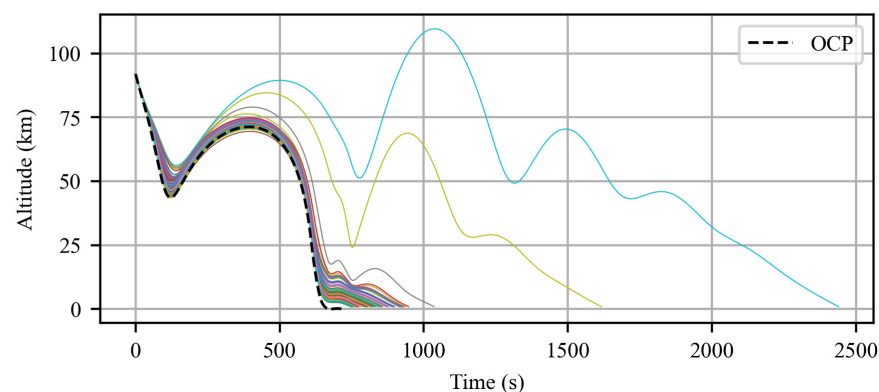


Figure 3. Resulting trajectories from simulations, with altitude as a function of time.

Figure 3 shows how the spaceplane's altitude changes over time during its descent. By analyzing this graph, you can assess the descent rate and determine how well the spaceplane maintains its planned trajectory. Any deviations might indicate atmospheric

variations or control issues. In general, we observe that the spacecraft initiates a descending trajectory until a level near 50 km in altitude, and then it rebounds into the atmosphere, transitioning to an ascending trajectory until near 70 km in altitude, before finally descending rapidly.

Figure 4 illustrates the changes in velocity as the spaceplane descends. It helps to evaluate the effectiveness of the drag and lift forces in controlling descent speed. It shows two decreasing regions separated by an almost flat region, indicating a region of near-zero resultant force in the spacecraft. Deviations from expected velocity could suggest areas for improvement in control strategies.

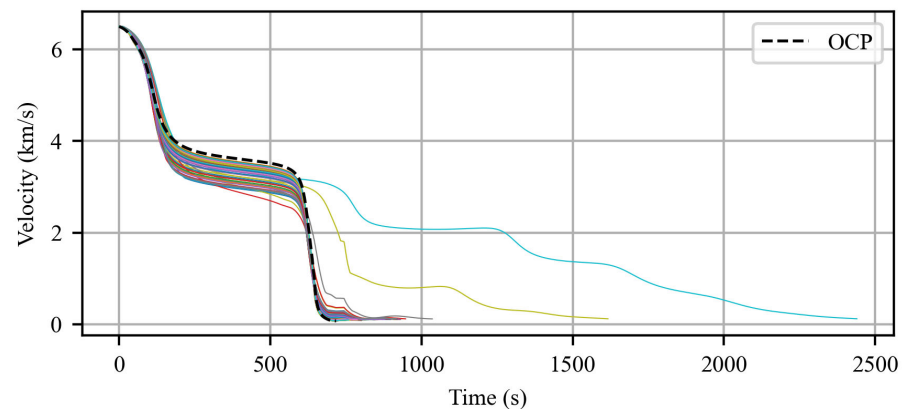


Figure 4. Velocity as a function of time resulting from Monte Carlo simulations.

Figure 5 shows the flight path angle throughout the descent. There are strong oscillations in the final parts of the trajectory, where the drag increases due to the higher values of atmospheric density. It is essential to remember that maintaining the correct FPA is crucial for achieving an accurate trajectory. Significant deviations may indicate control issues that require further investigation and adjustment.

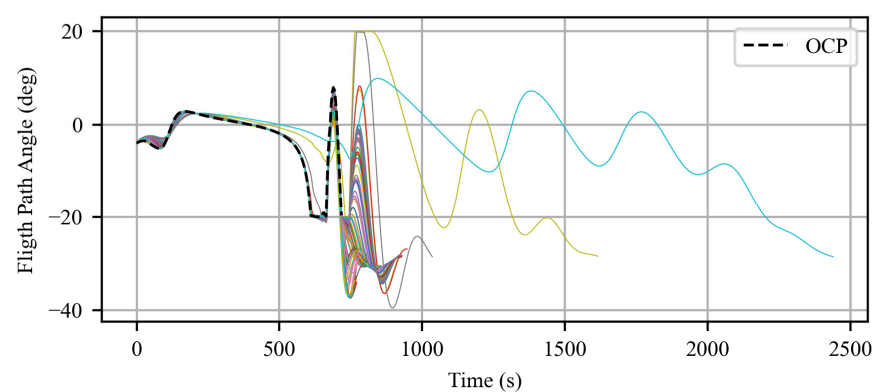


Figure 5. FPA as a function of time resulting from Monte Carlo simulations.

Figure 6 illustrates the changes in the azimuth angle, showing how the direction shifts during descent. The same pattern of strong oscillations in the final parts of the trajectory appears here, as the drag increases due to higher atmospheric density. Precise azimuth control is crucial for hitting the intended landing target. Analyzing this graph helps evaluate how well the spaceplane maintains its intended flight path.

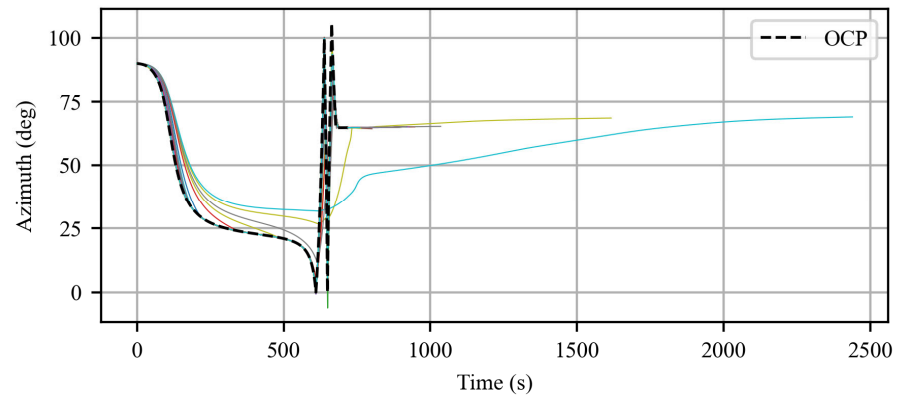


Figure 6. Azimuth as a function of time resulting from Monte Carlo simulations.

Figure 7 represents the spaceplane's trajectory on a horizontal plane, showing its path across the surface of Mars. This figure can help evaluate the overall accuracy of the landing trajectory. Deviations from the planned path might suggest atmospheric or control-related influences.

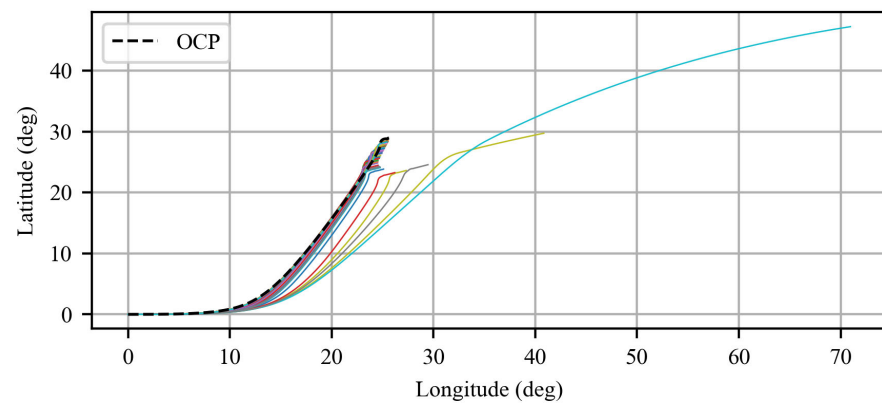


Figure 7. Longitude vs. latitude of the spaceplane resulting from Monte Carlo simulations.

Figure 8 shows how the angle of attack changes during the descent. Monitoring the AOA is crucial for maintaining aerodynamic efficiency. Any significant deviations might require adjustments to the control system.

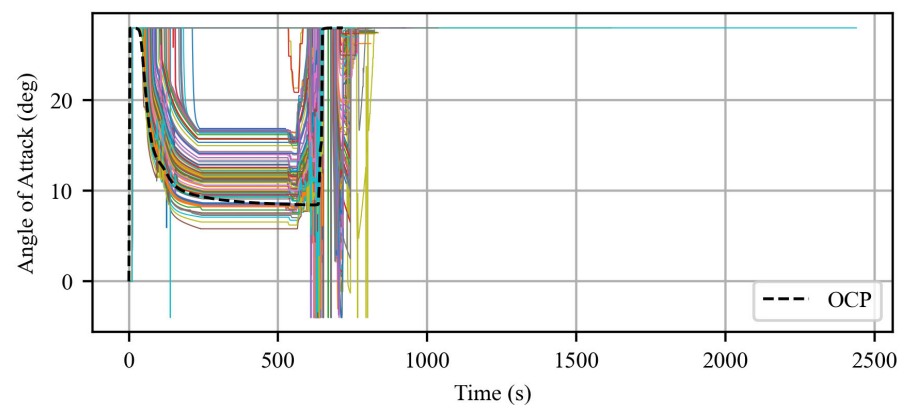


Figure 8. Results of AOA as a function of time for the simulated trajectories.

Figure 9 shows changes in the bank angle, which affects lateral control. Proper bank angle management is essential for steering and stabilizing the spaceplane. Analyzing this figure can help identify areas that need refinement in control strategies.

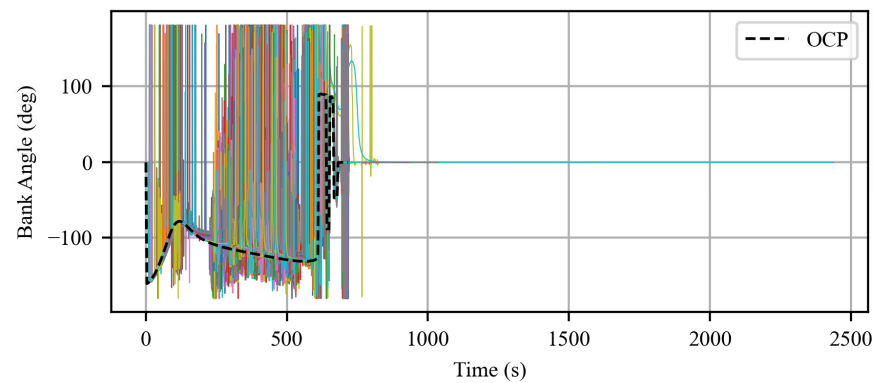


Figure 9. Banking angle as a function of time calculated from MPC during simulations.

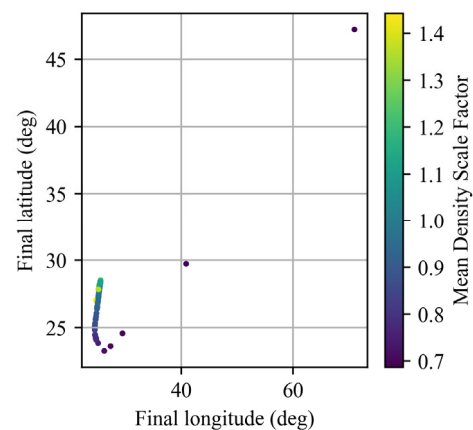


Figure 10. Distribution of longitude and latitude at the end of the simulated trajectories.

4. Discussion

This paper presented a novel approach to using model predictive control (MPC) for the trajectory tracking of a spaceplane during a gliding descent on Mars. It builds upon previous research that focused on optimizing descending trajectories through open-loop optimal control problems. The current study addresses the limitations of open-loop systems by implementing a closed-loop MPC, which is capable of real-time adjustments in response to atmospheric variations.

The results indicated that the MPC is effective in managing trajectory deviations caused by fluctuations in atmospheric density. However, it is noted that when atmospheric density decreases to below 70% of the expected value, the controller struggles to maintain the reference trajectory, highlighting a potential area for further research and improvement.

Therefore, in the context of previous studies, this paper makes a significant contribution by demonstrating the feasibility of real-time control systems for spaceplanes on Mars, a concept not previously applied to gliding descents on the planet. The implications of this research are broad, suggesting potential applications for future Mars missions where precision landing is critical.

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Conflicts of Interest: Author Ignazio Dimino was employed by the company The Italian Aerospace Research Centre (CIRA). The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AGAM	Aerogravity-Assisted Maneuver.
AOA	Angle of Attack.
FPA	Flight Path Angle.
LEO	Low Earth Orbit.
MPC	Model Predictive Control.
NMPC	Nonlinear Model Predictive Control.
OPC	Optimal Control Problem.

References

1. Viviani, A.; Pezzella, G. *Aerodynamic and Aerothermodynamics Analysis of Space Mission Vehicles*; Springer International Publishing: Cham, Switzerland, 2015. [\[CrossRef\]](#)
2. Weiland, C. *Aerodynamic Data of Space Vehicles*; Springer: Berlin/Heidelberg, Germany, 2014. [\[CrossRef\]](#)
3. Liu, X.; Shen, Z. Rapid Smooth Entry Trajectory Planning for High Lift/Drag Hypersonic Glide Vehicles. *J. Optim. Theory Appl.* **2016**, *168*, 917–943. [\[CrossRef\]](#)
4. Guo, J.; Wu, X.; Tang, S. Autonomous gliding entry guidance with geographic constraints. *Chin. J. Aeronaut.* **2015**, *28*, 1343–1354. [\[CrossRef\]](#)
5. Yu, W.; Yang, J.; Chen, W. Entry Guidance Based on Analytical Trajectory Solutions. *IEEE Trans. Aerosp. Electron. Syst.* **2022**, *58*, 2438–2466. [\[CrossRef\]](#)
6. Wang, R.; Tang, S.; Zhang, D. Short-Range Reentry Guidance with Impact Angle and Impact Velocity Constraints for Hypersonic Gliding Reentry Vehicle. *IEEE Access* **2019**, *7*, 47437–47450. [\[CrossRef\]](#)
7. Beiner, L. Optimal re-entry maneuver with bounded lift control. *J. Guid. Control. Dyn.* **1986**, *10*, 321–329. [\[CrossRef\]](#)
8. Cassell, A.; Brivkalns, C.; Bowles, J.; Garcia, J.; Kinney, D.; Wercinski, P.; Cianciolo, A.; Polsgrove, T. Human Mars Mission Design Study Utilizing the Adaptive Deployable Entry and Placement Technology. In Proceedings of the 2017 IEEE Aerospace Conference, Big Sky, MT, USA, 4–11 March 2017. [\[CrossRef\]](#)
9. O'Driscoll, D.; Bruce, P.J.; Santer, M.J. Origami-based TPS Folding Concept for Deployable Mars Entry Vehicles. In *AIAA Scitech 2020 Forum*; AIAA: Orlando, FL, USA, 2020; p. 1897. [\[CrossRef\]](#)
10. Dimino, I.; Vendittozzi, C.; Reis Silva, W.; Ameduri, S.; Concilio, A. A Morphing Deployable Mechanism for Re-Entry Capsule Aeroshell. *Appl. Sci.* **2023**, *13*, 2783. [\[CrossRef\]](#)
11. Brauckmann, G. X-34 Vehicle Aerodynamic Characteristics. *J. Spacecr. Rocket.* **1999**, *36*, 229–239. [\[CrossRef\]](#)

12. Armellin, R.; Lavagna, M.; Ercoli-Finzi, A. Aero-gravity assist maneuvers: Controlled dynamics modeling and optimization. *Celest. Mech. Dyn. Astron.* **2006**, *95*, 391–405. [\[CrossRef\]](#)
13. London, H. Change of satellite orbit plane by aerodynamic maneuvering. *J. Aerosp. Sci.* **1962**, *29*, 323–332. [\[CrossRef\]](#)
14. Anderson, J.D.; Ferguson, F., Jr.; Kothari, A.P. Hypersonic waveriders for planetary atmospheres. *J. Spacecr. Rocket.* **1991**, *28*, 401–410. [\[CrossRef\]](#)
15. Lohar, F.; Mateescu, D.; Misra, K. Optimal atmospheric trajectory for aero-gravity assist. *Acta Astronaut.* **1994**, *32*, 89–96. [\[CrossRef\]](#)
16. Lohar, F.; Misra, K.; Mateescu, D. Optimal Atmospheric Trajectory for Aerogravity Assist with Heat Constraint. *J. Guid. Control Dyn.* **1995**, *18*, 723–730. [\[CrossRef\]](#)
17. Lohar, F.; Misra, K.; Mateescu, D. Optimal aero-gravity assist with heliocentric plane change. *Acta Astronaut.* **1996**, *38*, 445–456. [\[CrossRef\]](#)
18. Johnson, W.R. *Optimization of Atmospheric Fly Through Aero-Gravity Assist Trajectories*; AAE508 Report; Purdue University: West Lafayette, Indiana, 2002.
19. Lavagna, M.; Povolieri, A.; Finzi, A.E. Interplanetary mission design with aero-assisted manoeuvres multi-objective evolutive optimization. *Acta Astronaut.* **2005**, *57*, 498–509. [\[CrossRef\]](#)
20. Lyons, D.; Sklyanskiy, E.; Casoliva, J.; Wolf, A. Parametric optimization and guidance for an aerogravity assisted atmospheric sample return from Mars and Venus. In Proceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Honolulu, HI, USA, 21 August 2008; AIAA 08-7353. pp. 18–21.
21. Henning, G.; Edelman, P.; Longuski, J. Design and Optimization of interplanetary aerogravity-assist tours. *J. Spacecr. Rocket.* **2014**, *51*, 1849–1856. [\[CrossRef\]](#)
22. Edelman, P.J.; Longuski, M.J. Optimal aerogravity-assist trajectories minimizing total heat load. *J. Guid. Control Dyn.* **2017**, *40*, 2699–2703. [\[CrossRef\]](#)
23. Qi, Y.; Ruiter, A. Optimal Powered Aerogravity-Assist Trajectories. *J. Guid. Control Dyn.* **2021**, *44*, 151–162. [\[CrossRef\]](#)
24. Piñeros, J.O.M.; de Moraes, R.V.; de Almeida Prado, A.F.B. Using low Lift-to-Drag spacecraft to perform upper atmospheric Aero-Gravity Assisted Maneuvers. *Adv. Space Res.* **2022**, *70*, 1032–1047. [\[CrossRef\]](#)
25. Murcia-Piñeros, J.O.; Bevilacqua, R.; Prado, A.F.B.A.; de Moraes, V. Optimizing aerogravity-assisted maneuvers at high atmospheric altitude above Venus, Earth, and Mars to control heliocentric orbits. *Acta Astronaut.* **2024**, *215*, 333–347. [\[CrossRef\]](#)
26. Gaglio, E.; Bevilacqua, R. Time optimal drag-based targeted de-orbiting for low Earth orbit. *Acta Astronaut.* **2023**, *207*, 316–330. [\[CrossRef\]](#)
27. Murcia-Piñeros, J.O.; Prado, A.F.B.A.; Dimino, I.; de Moraes, V. Optimal Gliding Trajectories for Descent on Mars. *Appl. Sci.* **2024**, *14*, 7786. [\[CrossRef\]](#)
28. Chai, R.; Tsourdos, A.; Savvaris, A.; Chai, S.; Xia, Y.; Chen, C. Review of advanced guidance and control algorithms for space/aerospace vehicles. *Prog. Aerosp. Sci.* **2021**, *122*, 100696. [\[CrossRef\]](#)
29. Malyuta, D.; Yu, Y.; Elango, P.; Açıkmeşe, B. Advances in trajectory optimization for space vehicle control. *Annu. Rev. Control* **2021**, *52*, 282–315. [\[CrossRef\]](#)
30. Schwenzer, M.; Ay, M.; Bergs, T.; Abel, D. Review on model predictive control: An engineering perspective. *Int. J. Adv. Manuf. Technol.* **2021**, *117*, 1327–1349. [\[CrossRef\]](#)
31. Chai, R.; Savvaris, A.; Tsourdos, A.; Chai, S.; Xia, Y. A review of optimization techniques in spacecraft flight trajectory design. *Prog. Aerosp. Sci.* **2019**, *109*, 100543. [\[CrossRef\]](#)
32. Eren, U.; Prach, A.; Koçer, B.B.; Raković, S.V.; Kayacan, E.; Açıkmeşe, B. Model predictive control in aerospace systems: Current state and opportunities. *J. Guid. Control Dyn.* **2017**, *40*, 1541–1566. [\[CrossRef\]](#)
33. Hayes, A.D.; Caverly, R.J. Model predictive tracking of spacecraft deorbit trajectories using drag modulation. *Acta Astronaut.* **2023**, *202*, 670–685. [\[CrossRef\]](#)
34. Chai, J.; Kayacan, E. Nonlinear Simulation and Performance Characterization of an Adaptive Model Predictive Control Method for Booster Separation and Re-Entry. *Electronics* **2023**, *12*, 1488. [\[CrossRef\]](#)
35. Li, W.; Song, Y.; Cheng, L.; Gong, S. Closed-loop deep neural network optimal control algorithm and error analysis for powered landing under uncertainties. *Astrodynamics* **2023**, *7*, 211–228. [\[CrossRef\]](#)
36. Chai, J.; Medagoda, E.; Kayacan, E. Adaptive and efficient model predictive control for booster reentry. *J. Guid. Control Dyn.* **2020**, *43*, 2372–2382. [\[CrossRef\]](#)
37. Fear, A.; Lightsey, E.G. Autonomous Rendezvous and Docking Implementation for Small Satellites Using Model Predictive Control. *J. Guid. Control Dyn.* **2024**, *47*, 539–547. [\[CrossRef\]](#)
38. Margolis, B.W.; Ayoubi, M.A.; Joshi, S.S. Nonlinear model predictive control of reentry vehicles based on Takagi-Sugeno fuzzy models. *J. Astronaut. Sci.* **2020**, *67*, 113–136. [\[CrossRef\]](#)
39. Allgöwer, F.; Zheng, A. *Nonlinear Model Predictive*; Birkhauser Springer: Berlin/Heidelberg, Germany, 2000.
40. Rakovic, S.V.; Levine, W.S. *Handbook of Model Predictive Control*; Birkhauser Springer Nature: Cham, Switzerland, 2018.

41. Rawlings, J.B.; Mayne, D.Q.; Diehl, M. *Model Predictive Control: Theory, Computation, and Design*, 2nd ed.; Nob Hill Publishing: Madison, WI, USA, 2017.
42. Camacho, E.F.; Bordons, C. *Model Predictive Control*, 2nd ed.; Springer: London, UK, 2007.
43. Reble, M. *Model Predictive Control for Nonlinear Continuous-Time Systems with and Without Time-Delays*; Logos Verlag: Berlin, Germany, 2013.
44. Sun, Q.; Xu, J.; Zhang, H. Guidance for Hypersonic Reentry Using Nonlinear Model Predictive Control and Radau Pseudospectral Method. *Optim. Control Appl. Methods* **2025**. [[CrossRef](#)]
45. Engel, D.; Putnam, Z.; Dutta, S. Assessment of Model Predictive Control for Mars Entry Vehicles with Flaps. *J. Spacecr. Rocket.* **2025**. [[CrossRef](#)]
46. Patel, J.; Subbarao, K. Reachable-Set Constrained Model Predictive Control for Safe Hypersonic Reentry. *J. Guid. Control Dyn.* **2025**, *48*, 1253–1265. [[CrossRef](#)]
47. Ding, H.; Xu, B.; Yang, W.; Zhou, Y.; Wu, X. A Robust Control Method for the Trajectory Tracking of Hypersonic Unmanned Flight Vehicles Based on Model Predictive Control. *Drones* **2025**, *9*, 223. [[CrossRef](#)]
48. Williams, D. Planetary Fact Sheets. 2016. Available online: <https://www.scribd.com/doc/7089255/Planetary-Fact-Sheet-Ratio-to-Earth-Values-NASA> (accessed on 6 April 2025).
49. Murcia-Piñeros, J.O.; Bevilacqua, R.; Gaglio, E.; Prado, A.F.; de Moraes, R.V. Spaceplane Model Predictive Control and guidance for aerogravity assisted maneuvers above Earth. *Acta Astronaut.* **2025**. [[CrossRef](#)]
50. Hedengren, J.D.; Asgharzadeh Shishavan, R.; Powell, K.M.; Edgar, T.F. Nonlinear Modeling, Estimation and Predictive Control in APMonitor. *Comput. Chem. Eng.* **2014**, *70*, 133–148. [[CrossRef](#)]
51. Hunter, J.D. Matplotlib: A 2D graphics environment. *Comput. Sci. Eng.* **2007**, *9*, 90–95. [[CrossRef](#)]

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