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Terminal altitude maximization for Mars entry considering uncertainties

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ABSTRACT

Uncertainties present in the Mars atmospheric entry process may cause state deviations from the nominal designed values, which will lead to unexpected performance degradation if the trajectory is designed merely based on the deterministic dynamic model. In this paper, a linear covariance based entry trajectory optimization method is proposed considering the uncertainties presenting in the initial states and parameters. By extending the elements of the state covariance matrix as augmented states, the statistical behavior of the trajectory is captured to reformulate the performance metrics and path constraints. The optimization problem is solved by the GPOPS-II toolbox in MATLAB environment. Monte Carlo simulations are also conducted to demonstrate the capability of the proposed method. Primary trading performances between the nominal deployment altitude and its dispersion can be observed by modulating the weights on the dispersion penalty, and a compromised result referring to maximizing the 3σ lower bound of the terminal altitude is achieved. The resulting path constraints also show better satisfaction in a disturbed environment compared with the nominal situation.

1. Introduction

To date, seven vehicles have landed successfully on Mars [1–3]. All of them have decided to land on the north planet with low elevations (with respect to the Mars orbiter laser altimeter reference ellipsoid) so that denser atmosphere and more space is available for deceleration. However, the ancient highland on the south planet with higher elevation is of more science interest [4]. A higher parachute deployment altitude is needed for landing in these areas for equivalent decelerating space. In addition, the deployment altitude is often a proxy for time-to-ground. A higher parachute deployment altitude could leave more sufficient time and space for the latter landing activities, and allow the lander to handle the unknown landing environment and off-nominal cases with enough flexibility [5]. Therefore, considering the science interest, as well as the landing safety and accuracy, higher deployment altitude is always pursued when designing a Mars atmospheric entry trajectory [6–10].

Previous Mars entry trajectory optimization work is mainly based on the deterministic dynamic system [6–10]. However, for the lack of knowledge of the Martian atmosphere, the variation of the atmospheric density during the entry process is unpredictable [11,12]. In addition, initialization uncertainties at the entry interface as well as the parametric (e.g. the aerodynamic coefficients) uncertainties in the dynamic model will make the entry process more stochastic [13–15]. Such uncertainties cause the deviation of the real trajectory from the nominal trajectory [16,17]. Subsequently, the terminal deployment altitude is distributed around the nominal designed value. In addition, constraints violations may occur even the constraints are satisfied well in the deterministic flight condition [18]. Missions after Viking have relied heavily on the Viking-era space qualification technology [1]. The Viking-like aeroshells are of low lift-to-drag ratios. The maneuverability of the entry vehicle is quite low due to the combination of the low lift-to-drag ratio and the thin Martian atmosphere. Therefore, uncertainties may lead to severe off-nominal cases. It is necessary to include the effect of the possible uncertainties into the Mars entry trajectory design problem.

The desensitized optimal control (DOC) methodology [19] has been successfully employed in many situations [20–22]. By adding a sensitivity related term to the original optimization objective, some performance of the designed trajectory will be less sensitive to the uncertainties and dispersions. References [23–25] have employed the DOC method in the Mars entry trajectory optimization problems. Shen [23] firstly applied DOC to analyze the compromised performance between the control energy and the sensitivity of the final position to the initial state uncertainty. The research [23] concludes that the DOC methodology can help to reduce the final hitting error induced by initial errors, at the expense of more energy consumption. Xu et al. [25] have done a more detailed work based on Shen [23] by further considering the atmospheric

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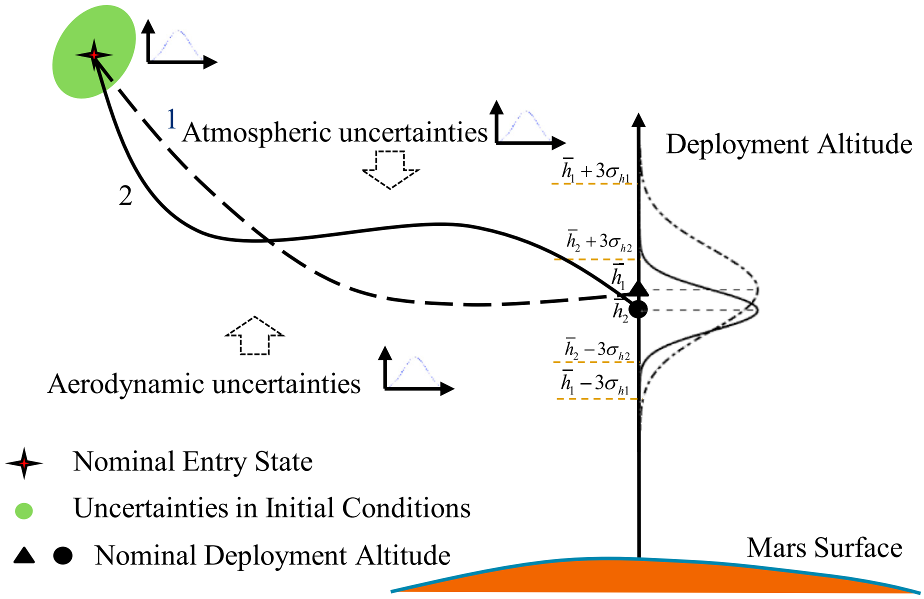
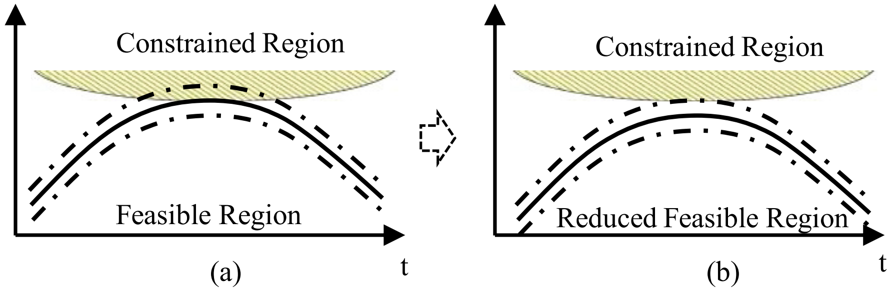


Fig. 1. Illustration of the difference between the two optimization models.



(a) (b)

Fig. 2. Illustration of the difference in path constraint satisfaction.

Table 1
Path and control constraints.

Parameters	Value	Unit
σ_{max}	120	degree
$\overline{q}_{max}$	2.3×10^4	N/m^2
$\overline{Q}_{max}$	86	W/cm^2

Table 2
Boundary conditions of the entry trajectories.

Parameters	Entry point	Parachute deployment point	Unit
Altitude, r	125	Free, to be maximized	km
Velocity, V	5500	450	m/s
FPA, γ	−15.2	Free	degree
Trajectory length, s	0	591	km

and aerodynamic uncertainties. Li et al. [24] analyzed the compromise between the deployment altitude and the sensitivity of the final states to the initial state uncertainty and process dispersion in the longitudinal mode. Li et al. [24] concluded that the final velocity, altitude and downrange errors could be effectively reduced because of the sensitivity decrease, at the expense of deployment altitude loss. However, different from the altitude or energy, the sensitivity matrix is not a physical quantity, which makes it unintuitive to obtain a compromised result between the nominal and dispersion performances by directly modulating the weights on different performance metrics. Furthermore, there is no way to take the sensitivity element into the constraint problem. In contrast, uncertainty propagation methods, which can capture the statistical characteristics of the states and constraints, are more intuitive and convenient for the Mars entry trajectory optimization.

Table 3
Distribution of uncertainties in initial states and parameters.

Parameters	Distribution	Range (3σ)	Unit
Altitude, r_0	Normal	1.5	km
Velocity, V_0	Normal	30	m/s
FPA, γ_0	Normal	0.3	degree
Trajectory length, s_0	Normal	1.5	km
Reference atmospheric density, ρ_0	Normal	2×10^{-5}	kg/m^3
Lift to drag ratio, L/D_0	Normal	1.2×10^{-2}	–
Ballistic coefficient, B_0	Normal	6.85×10^{-4}	m^2/kg

The linear covariance (LC) method and the successfully employed DOC method share the same feature of linearization of the system dynamics, while the LC method can capture the statistical behavior (the mean value and the covariance) of the trajectory. In this paper, LC is employed to calculate the evolution of the statistical characteristics of the trajectory. A weighted sum of the nominal parachute deployment altitude and its standard deviation (STD) is chosen as the performance metrics. By modulating the weighting factors, performance trades can be observed at the terminal point. 3σ lower bound of the deployment altitude is increased. To ensure the path constraint satisfaction in dispersed situations, the model of the path constraints is reformulated. The applicability of the LC method is also demonstrated in the simulation.

The remainder of this paper is constructed as follows: Section 2 introduces the dynamic model of a Mars atmospheric entry vehicle, and