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Reliability-based trajectory optimization using nonintrusive polynomial chaos for Mars entry mission

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Abstract

This paper presents the reliability-based sequential optimization (RBSO) method to settle the trajectory optimization problem with parametric uncertainties in entry dynamics for Mars entry mission. First, the deterministic entry trajectory optimization model is reviewed, and then the reliability-based optimization model is formulated. In addition, the modified sequential optimization method, in which the nonintrusive polynomial chaos expansion (PCE) method and the most probable point (MPP) searching method are employed, is proposed to solve the reliability-based optimization problem efficiently. The nonintrusive PCE method contributes to the transformation between the stochastic optimization (SO) and the deterministic optimization (DO) and to the approximation of trajectory solution efficiently. The MPP method, which is used for assessing the reliability of constraints satisfaction only up to the necessary level, is employed to further improve the computational efficiency. The cycle including SO, reliability assessment and constraints update is repeated in the RBSO until the reliability requirements of constraints satisfaction are satisfied. Finally, the RBSO is compared with the traditional DO and the traditional sequential optimization based on Monte Carlo (MC) simulation in a specific Mars entry mission to demonstrate the effectiveness and the efficiency of the proposed method.

Keywords: Entry trajectory; Reliability-based optimization; Nonintrusive polynomial chaos; Parametric uncertainty

1. Introduction

Mars entry mission is essential to the surface exploration, which offers an opportunity for the human to gain in-depth knowledge of this red planet, e.g. the potential history of life. However, the lack of knowledge of Mars environment imposes a great challenge to the entry mission (Braun and Manning, 2007). Although there have been satellites observing the Mars atmosphere, it is still a difficult task to predict the atmospheric change precisely before the entry mission is implemented. Besides, because the atmospheric density has a great effect on the entry trajectory, the uncertainty in atmospheric density makes the entry mission challenging. Another challenge related to the atmosphere is the aerodynamic performance of the vehicle flying in the Mars atmosphere. Because the trajectory control of existing entry vehicles generally depends on the lift force, the aerodynamic performance directly affects the trajectory generation and the parachute deployment accuracy. Another significant challenge for Mars entry mission comes from the navigation error due to the limited measure techniques. The uncertainties in initial entry state not only degrade the deployment accuracy, but also may aggravate the burden of guidance and control system.

The traditional trajectory design for entry mission tends to obtain the optimal trajectory under nominal conditions rapidly and readily. The means of ensuring the reliability of entry trajectory fall into two categories, i.e. means of

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implementing online trajectory planning and means of improving the tracking ability for the reference trajectory (Li and Jiang, 2014). The methods of online trajectory planning, in which the trajectory is reformulated according to the current state and the predicted deviation from the required targeting point, improve the reliability via real-time trajectory design. There have been a lot of efforts on improving the computational efficiency and the optimal performance of online trajectory in existing literature. The typical online trajectory planning methods use nonlinear optimal control techniques, i.e. indirect and direct optimization theories. The methods based on indirect optimization usually meet difficulties in general application (Lu and Xue, 2010; Llama, 2011; Heydari and Balakrishnan, 2013; Putnam and Braun, 2015; Zheng et al., 2017). Compared with indirect optimization methods, direct optimization methods show stronger generality (Li and Peng, 2011; Liu and Shen, 2015; Franco and Rivas, 2015; Jiang and Li, 2016). However, the challenge of implementing the online direct optimization lies in the computational cost. Another special method in the family of online trajectory planning methods is the predictor-corrector method (Bairstow and Barton, 2007; Halbe, Raja, and Padhi, 2013; Lu, 2014), which has notable ability to adapt to uncertainties. Nevertheless, because the predictor-corrector method depends on lots of iterations of entry flight problem, this method will also aggravate the burden of onboard computer. Moreover, the anti-uncertainty performance of predictor-corrector method depends on the knowledge of uncertainties, thus makes this method less applicable for entry scenarios with unknown uncertainties, e.g. Mars entry mission (Kluever, 2008). In the philosophy of trajectory tracking methods, the deviation from the optimal nominal trajectory is eliminated by the tracking controller (Benito and Mease, 2008; Furfaro and Wibben, 2012; Shen and Li, 2016). Therefore, the trajectory reliability using tracking methods depends on the tolerance to uncertainties of the tracking controller, while the anti-uncertainty capability of nominal trajectory remains underexplored. An economic and reasonable way to ensure the reliability of practical trajectory is to design a reference trajectory with consideration of the uncertainties in entry dynamics.

The optimal trajectory obtained by the DO under nominal entry conditions, which is traditionally employed as the reference trajectory, will fluctuate around the limitation of constraints with consideration of the uncertainties in entry dynamics. Thus the DO usually cannot meet the requirement of path constraints in the practical applications existing uncertainties. Of course, the probability of constraints satisfaction depends on the sensitivity of entry trajectory on uncertainties and the required limitation values of constraints. However, the knowledge of trajectory sensitivity on uncertainties and of uncertainty effects on constraint requirement is usually difficult to be obtained. A way to solve the reliability problem of entry trajectory with existence of uncertainties is to perform the reliability-based trajectory optimization, in which the uncertainties are considered. The reliability-based optimization (RBO) is initially introduced in determining structural configuration, in which the reliability of the structural design is satisfied by ensuring the probability of constraints satisfaction at required level (Valdebenito and Schuëller, 2010). The RBO has gained much attention in scientific and engineering community due to its potential in dealing with optimization problems with consideration of the effects of uncertainties, i.e. the SO problems (Du and Sudjianto, 2003; Eldred et al., 2007; Schuëller and Jensen, 2008; Aoues and Chateauneuf, 2010; Yao et al., 2011). The idea of RBO was also recently introduced in the trajectory optimization by Ren and Shan (2015), in which the uncertainty of gravitational field of irregular shape asteroid was considered in the soft landing trajectory optimization.

In this study, the RBO is introduced in solving the entry trajectory SO problem considering uncertainties in entry dynamics. The main contribution of this paper lies in the formulation of reliability-based entry trajectory optimization problem and the proposed RBSO method for solving the problem. The traditional deterministic optimization model for generating a reference trajectory is updated by the reliability-based optimization model including the stochastic entry dynamics, the robust optimization objective function, the reliability-based inequality constraints and the robust equality constraints. Then the typical sequential optimization method proposed by Du and Chen (2004) is modified to adapt to the entry flight dynamics including the boundary conditions and the constraints. However, the repeated evaluation of the optimization model and the following reliability assessment in the typical method result in high numerical cost, thus pose great challenges to applying the method in entry problem. The PCE method, which can effectively quantify the effects of uncertainties (Prabhakar, Fisher and Bhattacharya, 2010; Fisher and Bhattacharya, 2011; Jones, Doostan and Born, 2013), is integrated into the sequential optimization procedure to improve the computational efficiency of the typical reliability-based optimization method. Furthermore, the MPP searching method, which can assess the constraint reliability only up to the necessary level, is also employed to further improve the computational efficiency.

This paper is organized as follows: The traditional DO model for entry trajectory is first reviewed, and then the reliability-based entry trajectory optimization model is formulated in Section 2. The detailed description of the proposed RBSO method and its procedure are presented in Section 3. The numerical demonstration of the RBSO and the comparisons with the DO and the traditional sequential optimization based on MC are shown in Section 4. Finally, the conclusions are given in Section 5.

2. Problem formulation of reliability-based trajectory optimization

This section provides an approach to formulate the reliability-based trajectory optimization model. The deter-