Uncertainty Analysis of Mars Entry Trajectories Using Stochastic Collocation

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There are many uncertainties in the process of Mars entry, including errors on initial conditions, uncertainties in Mars atmospheric density and vehicle's aerodynamic parameters. These uncertainties pose great challenges to the control system design, especially for the vehicles with low lift-to-drag ratio which have limited control authority. To lower the difficulty in control system design and make entry trajectories more robust to the uncertainties, it is necessary to analyse the nonlinear propagation of entry trajectory uncertainty. In this paper, the propagation of uncertainties due to initial conditions, atmospheric density and aerodynamic parameters in the high- fidelity dynamic model are analysed.

The method of polynomial chaos expansions based on stochastic collocation is proposed to analyse multivariable uncertainties in entry trajectories. The multivariable polynomial chaos expansions in uncertainty parameters are formulated by using tensor products of univariate orthogonal polynomial bases, which are tailored in the Wiener-Askey scheme to achieve excellent convergence. Thus the stochastic solution of the ordinary differential equations describing the high-fidelity entry dynamics can be approximated by multivariable polynomial chaos. To solve the coefficients of the polynomial chaos, the stochastic collocation method which combines the Galerkin projection and pseudospectral collocation is employed. According to the Gauss quadrature rules, nodes of every uncertainty parameter in initial condition, atmospheric density and aerodynamic coefficients are distributed. Then the tensor product grid which consists of the pregenerated nodes is generated and used for the generation of samples which require the evaluation of entry dynamic equations. The stochastic collocation method allows for the usage of existing entry trajectory propagator and does not need to reformulate the stochastic entry dynamic equations every time the uncertainty parameter changes from one to another. The evolution results of stochastic entry dynamics using stochastic collocation are compared with the results using Monte Carlo method. The comparison shows that the stochastic collocation method requires much fewer samples to achieve desired accuracy in approximating the stochastic solution. Characteristics of trajectories under uncertainties due to initial condition, atmospheric density and aerodynamic coefficients are then extensively investigated. A qualitative and quantitative analysis of the effects of parameter uncertainty on entry trajectories is presented. The uncertainty analysis of Mars entry trajectories using stochastic collocation not only further expands the application of stochastic collocation method in high-dimensional nonlinear dynamics, but also provides a basis for the robust design of Mars mission.