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Disturbance observer based model predictive control for accurate atmospheric entry of spacecraft ☆

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Abstract

Facing the complex aerodynamic environment of Mars atmosphere, a composite atmospheric entry trajectory tracking strategy is investigated in this paper. External disturbances, initial states uncertainties and aerodynamic parameters uncertainties are the main problems. The composite strategy is designed to solve these problems and improve the accuracy of Mars atmospheric entry. This strategy includes a model predictive control for optimized trajectory tracking performance, as well as a disturbance observer based feedforward compensation for external disturbances and uncertainties attenuation. 500-run Monte Carlo simulations show that the proposed composite control scheme achieves more precise Mars atmospheric entry (3.8 km parachute deployment point distribution error) than the baseline control scheme (8.4 km) and integral control scheme (5.8 km).

Keywords: Mars atmospheric entry; Trajectory tracking; Model predictive control; Disturbance observer; Monte Carlo simulation

1. Introduction

Mars exploration has drawn great attention due to its scientific significance, such as improving the present knowledge of Mars and even the universe and developing and utilizing space resources and energy (Xia et al., 2015; Zhou and Xia, 2014; Dai and Xia, 2015; Qiao et al., 2012). To date, more than 40 missions to explore Mars have been undertaken. Among these missions, Mars Science Laboratory (MSL) mission is called out as a successful example. The MSL consists of three phases including entry, descent and landing (EDL), from a blend of heritage and innovation (Korzun et al., 2010; Liu et al., 2013; Christian et al., 2008). Future Mars missions focus on exploring the Mars in areas of complex terrain, because these areas usually have more scientific significance (Braun and Manning, 2007; Mourikis et al., 2009). Consequently, it calls for a higher landing accuracy. The whole process of the EDL lasted only 6–10 min, but it is one of the most critical parts of the whole exploration mission. The EDL process begins from entering the Mars atmosphere until landing on the Mars surface (Desai et al., 2008; Prince et al., 2011; Allouis et al., 2006; Spencer and Braun, 1996). During the EDL process, the phase from the atmospheric interface to the parachute deployment is referred to as entry. The entry takes the longest time during the EDL and faces a complex atmosphere environment. After the entry is finished, limited time is left for Mars spacecraft to reduce the landing error. Therefore, the first task of the EDL is to achieve an accurate entry (Mitcheltree

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et al., 1999; Saraf et al., 2004; Spencer et al., 1999). There are two kinds of methods for Mars atmospheric entry: one is the reference-path tracking scheme and the other is the predictor-corrector method. The former method needs a reference path and does not necessarily require significant online computation. The latter method requires significantly more computations. In Kluever (2008), these two methods are compared and the results indicate that the reference-path tracking scheme is more suitable for the Mars atmospheric entry.

The purpose of Mars trajectory tracking is to guide the entry spacecraft to a well-designed parachute deployment point. However, the very complex atmosphere environment during Mars atmospheric entry phase leads to external disturbances and many uncertainties (Yu et al., 2014). First, the influence of Mars wind on Mars spacecraft exists, and it is defined as a kind of external disturbances in this paper. The model of such external disturbances is too complex and often neglected in some publications, such as Li and Peng (2012) and Xia et al. (2014). But it is better if the external disturbances are considered. Second, fast variation of Mars atmospheric density can also be treated as a kind of external disturbances, but the density variation finally leads to uncertainties of aerodynamic parameters (lift coefficient and drag coefficient). Therefore, the influence of Mars atmospheric density variation is treated as uncertainty rather than external disturbance in this paper. Aerodynamic parameters with more significant uncertainties are ballistic coefficient and lift-to-drag ratio (lift coefficient divided by drag coefficient) (Mitcheltree and Gnoffo, 1995; Striepe et al., 2006). Besides, the errors of initial states are also treated as uncertainties in this paper.

Facing these complexities and difficulties, various advanced closed-loop control strategies are proposed to achieve accurate landing for Mars spacecraft in the past few decades. Bharadwaj et al. develop a feedback linearization based method for Mars atmospheric entry trajectory tracking (Bharadwaj et al., 1998). The feedback linearization based method can achieve good tracking performance if the Mars atmospheric entry model is accurate, but the tracking performance is not satisfactory under complex uncertainties. Li et al. propose a direct model reference adaptive control to reduce the adverse effect of parameters uncertainties (Li and Peng, 2012). Xia et al. propose active disturbance rejection control (ADRC) for drag tracking (Xia et al., 2014). The ADRC based method is applied to handle the uncertainties, and the tracking accuracy is improved. Zhao et al. propose a finite-time super-twisting (FTSTW) control law to improve the robustness against uncertainties (Zhao et al., 2015). These approaches gradually improve the tracking accuracy since the disturbances and uncertainties are well handled.

Generally speaking, some unique challenges exist when designing Mars atmospheric entry trajectory tracking method for the spacecraft in the complex atmosphere environment. First, the dynamic model of entry spacecraft is nonlinear and extremely complex. Effective nonlinear method should be employed to handle such nonlinear problem. Second, there are uncertainties not only in the initial states, but also in the aerodynamic parameters. The accuracy of Mars atmospheric entry may not be satisfactory until such uncertainties are well handled. Last, due to the varied atmosphere environment, the external disturbances imposed on the dynamic model may also bring more difficulties. The problems mentioned above should be specially considered when designing the trajectory tracking method to improve the accuracy of Mars atmospheric entry.

Facing these problems, a composite trajectory tracking scheme for Mars atmospheric entry is proposed in this paper. The composite control scheme consists of a model predictive control (MPC), and a disturbance observer (DOB) based feedforward compensator. The MPC is an optimized and advanced control method for nonlinear control problems (Yang et al., 2010; Mayne et al., 2000; Morari and Lee, 1999; Angeli et al., 2000; Cuzzola et al., 2002). The DOB is a convenient and effective method for disturbance estimation and suppression, and it is often combined with advanced feedback controllers to solve complex nonlinear problems. For example, nonlinear MPC and DOB are employed for trajectory tracking of small-scale helicopters (Liu et al., 2012). In Li and Yang (2013), the DOB is combined with the state feedback control method to handle the disturbances and uncertainties in missile autopilot design. In Yang et al. (2014), the DOB is combined with MPC for disturbance rejection of ball mill grinding circuits. Different forms of the DOB and their design rules are introduced in Li et al. (2014) in detail.

The major contributions of this paper include three aspects: (1) The external disturbances, initial states uncertainties and aerodynamic parameters uncertainties of Mars atmospheric entry spacecraft are analyzed in detail. Considering the disturbances and uncertainties as lumped disturbances, a disturbance observer based feedforward compensation is designed to suppress such disturbances. (2) Subsection linearization is a traditional method which is convenient to solve the complex nonlinear problem of Mars atmospheric entry. However, high order nonlinear terms generated in the linearization may affect the control accuracy. In this paper, such nonlinear terms are considered as a component of the lumped disturbance, which is suppressed by the disturbance observer. (3) On the basis of well handling the external disturbances, uncertainties and high order nonlinear terms, a model predictive control is employed for optimized performance of Mars atmospheric entry trajectory tracking. Combining the disturbance observer with model predictive control, a composite trajectory tracking strategy is established, which achieves satisfactory disturbance rejection and accurate trajectory tracking.

Numerical simulations have been conducted to compare the proposed composite control scheme with the baseline and integral control schemes. 500-run Monte Carlo simulations have been performed to evaluate the tracking errors