Aerospace Science and Technology 76 (2018) 37–48

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Computational guidance for planetary powered descent using collaborative optimization

Xiuqiang Jiang [a], Shuang Li [a,*], Ting Tao [b]

[a] College of Astronautics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, People's Republic of China
[b] Hong Feng Control Co. Ltd. of Sanjiang Aerospace Corp, Xiaogan, Hubei 432000, People's Republic of China

ARTICLE INFO

Article history:
Received 2 June 2017
Received in revised form 26 October 2017
Accepted 4 February 2018
Available online 7 February 2018

Keywords:
Planetary powered descent
Computational guidance
Multi-discipline optimization
Collaborative optimization

ABSTRACT

An innovative computational guidance framework is proposed for planetary powered descent using collaborative optimization approach. First, the dynamical model and constraints for planetary powered descent are presented. Then, using collaborative optimization strategy, the computational guidance framework for powered descent is formulated as a multi-discipline optimization problem including trajectory optimization, optimal guidance, and system-level optimization. Finally, the computational guidance approach employs three algorithms for respectively solving the three optimization modules to implement numerical simulations. The optimality and robustness of the computational guidance approach are verified with all constraints satisfied even in the presence of initial state uncertainty.

© 2018 Elsevier Masson SAS. All rights reserved.

1. Introduction

Powered descent is typically the method used to land a spacecraft on a planetary surface. Pinpoint landing missions require the development of more advanced guidance approaches. The guidance algorithms should be able to: a) drive the lander from a given initial state to the desired landing site with approximately zero velocity and a position error of less than 100 m; b) autonomously determine an optimal landing site and retarget to reach it; and c) flexibly coordinate the landing accuracy and fuel consumption to achieve comprehensive optimality under uncertain conditions, un-modeled items, and landing site retargeting [1–3]. Most of the powered descent guidance algorithms developed during the Apollo era are based on linear control theories, which cannot meet the requirements of current and future planetary landing missions [4].

After the 2012 Mars Science Laboratory (MSL) and the 2013 Chang'e-3 (CE-3) lunar lander missions, planetary powered descent guidance technologies have been further improved. More attention has been paid to the fuel optimality, robustness against uncertainty, and autonomous retargeting to avoid hazards [5,6]. An improved Apollo suboptimal-fuel guidance and some supplementary linear guidance laws were piecewise employed during MSL powered descent to ensure safe landing under uncertainty. Furthermore, autonomous hazard avoidance technologies were developed in CE-3 lunar landing mission, where proportion-integration-differentiation (PID) guidance is designed to adapt landing site retargeting for hazard avoidance. Different from those segmented guidance laws, Wibben and Furfaro proposed a guidance law for lunar landing and retargeting using a hybrid control strategy. Though it has good flexibility for retargeting during landing, the fuel-consumption optimality is not taken into account [7]. The zero-effort-miss/zero-effort-velocity (ZEM/ZEV) algorithm usually focuses on minimizing the terminal state errors, which has excellent adaptability and robustness against retargeting maneuvers and uncertainties. However, the optimal fuel-consumption is also not taken into account in the ZEM/ZEV guidance [8]. The main concern of the optimal feedback guidance algorithms is always the guidance performance optimization under uncertain perturbations, but this kind of approaches usually doesn't consider retargeting [9]. To combine hazard avoidance with fuel sub-optimality, Zhang proposed a hybrid guidance algorithm for Mars powered descent using ZEM/ZEV and optimal feedback [10]. In summary, these existing methods for planetary powered descent still have design limitations when combining fuel optimality with retargeting flexibility and robustness against uncertainty.

As a promising solution to provide more optimality and flexibility, the Computational Guidance and Control (CG&C) concept has recently emerged [11]. The distinguishing features of the CG&C concept are summarized as follows [11]: a) guidance laws and controllers of fixed structures are replaced by numerical algorithms; b) the process of determining guidance and control commands may be model-based or data-based and does not require significant pre-mission planning, gain tuning, or extensive offline design of nominal references; c) the generation of guidance and

* Corresponding author.
E-mail addresses: jiangxq@nuaa.edu.cn (X. Jiang), lishuang@nuaa.edu.cn (S. Li).

https://doi.org/10.1016/j.ast.2018.02.009
1270-9638/© 2018 Elsevier Masson SAS. All rights reserved.

control commands relies extensively on online computation, often involving iterations; d) the output of the CG&C algorithm is typically the optimal solution based on the current actual state and the control effect; and e) the performance of the CG&C algorithm depends upon the optimization problem formulation and corresponding optimization algorithms. For online computational guidance, Lu [12] developed an entry guidance method combining a fully numerical predictor–corrector algorithm for trajectory planning with a linear quadratic regulator (LQR) for tracking control. However, the LQR gains must be designed offline. Pinson [13] applied the convex optimization method to design an optimal propellant powered descent trajectory that can be quickly computed onboard. This algorithm can run autonomously once the dynamical model coefficients are determined. Dueri and Açıkmeşe proposed a new onboard-implementable, real-time convex optimization-based powered descent guidance algorithm for planetary pinpoint landing [14]. These studies show that the capability to generate optimal powered descent guidance trajectories onboard can significantly enhance the landing accuracy of a vehicle. At the same time, the robustness and flexibility are not good enough due to the lack of onboard collaborative optimal control.

The multi-disciplinary optimization (MDO) provides the benefits of combining multiple optimization algorithms to solve multi-module, multi-objective and multi-constraint optimization problems [15]. D'Souza [16] proposed a multi-disciplinary design, analysis, and optimization (MDAO) approach that can be used to generate the trajectory and guidance for planetary atmospheric entry. Bonetti [17] conceptually introduced the MDO strategy in the Mars entry descent and landing (EDL) guidance system design. As an effective approach of MDO, collaborative optimization (CO) is a decomposition algorithm which uses projection to transform the MDO problem into a bi-level programming problem consisting of a master problem (i.e. system-level problem) and multiple sub-problems (i.e. subsystem-level problems or disciplines) [15]. Since each of the design disciplines is enclosed into one of the independent sub-problems, CO allows a high-level of modularity in the solution process.

To date, there are still no related reports that using MDO approaches to design a computational guidance for planetary powered descent comprehensively considering fuel optimality, retargeting flexibility, and robustness against uncertainty [16,17]. In this work, we introduce a novel CO-based computational guidance approach for planetary powered descent. To enhance the flexibility, optimality and accuracy, the CO approach is used for the powered descent guidance problem. The proposed computational guidance framework has the inherent capability to incorporate multiple optimization algorithms under a hierarchical mechanism. Thus, the guidance command autonomously generates and flexibly coordinates the trajectory planning and tracking control to adapt to the real state and minimize the state errors caused by uncertainties, un-modeled items, and landing site retargeting. The comprehensive performance of the guidance system is optimized accordingly.

2. Planetary powered descent dynamics model and constraints

In formulating the lander guidance problem for planetary powered descent, we model the lander dynamics near the planetary surface using the following three-degree-of-freedom dynamic equations with respect to a coordinate system with the origin on the surface of the planet. This study only considers spherical central planet that excluding the asteroid cases with non-central gravitational field [18]. The major forces acting on the lander are the gravitational force from the planet and the thrust forces generated by the propulsion system of the lander, while other forces (e.g., aerodynamic disturbances, gravitational perturbation, and un-modeled items) acting on the lander are typically minimal or absent. Under these conditions, the dynamical equations for a planetary lander can be expressed as follows [7,19,20]:

$$\dot{\boldsymbol{r}} = \boldsymbol{v} \tag{1}$$

$$\dot{\boldsymbol{v}} = -\frac{\mu}{\|\boldsymbol{R}+\boldsymbol{r}\|^3}(\boldsymbol{R}+\boldsymbol{r}) + \frac{\boldsymbol{T}}{m} + \boldsymbol{p} \tag{2}$$

$$\dot{m} = -\frac{\|\boldsymbol{T}\|}{I_{sp} g_0} \tag{3}$$

where $\boldsymbol{r}$ and $\boldsymbol{v}$ are the position vector and velocity vector of the lander, respectively, $\boldsymbol{T}$ denotes the commanded thrust vector with the thrust magnitude $\|\boldsymbol{T}\| = \sqrt{T_x^2 + T_y^2 + T_z^2}$, $\boldsymbol{R}$ represents the radius of the planet, m is the mass of the lander, μ denotes the gravitational constant of the planet, I_{sp} is the specific impulse of the retrorocket, $g_0 = 9.80665$ m/s^2 is the Earth's sea-level gravitational acceleration, and $\boldsymbol{p}$ represents any perturbing or un-modeled accelerations. This model is employed to simulate the real lander descent dynamics driven by the commanded thrust (i.e., guidance command).

Considering the limit of the retrorocket engine, the magnitude of the thrust should satisfy the constraint

$$\Gamma_{\min} \le \|\boldsymbol{T}\| \le \Gamma_{\max} \tag{4}$$

To plan a trajectory for a planetary pinpoint soft landing, the terminal position should be at the selected landing site $\boldsymbol{r}_f$, and the terminal velocity should be zero. Thus, the state constraints at the terminal time t_f are

$$\boldsymbol{r}(t_f) = \boldsymbol{r}_f, \qquad \boldsymbol{v}(t_f) = [0,\ 0,\ 0]^T \tag{5}$$

The initial states of the lander are assumed to be known before the trajectory planning and tracking control at the initial time t_0 are

$$\boldsymbol{r}(t_0) = \boldsymbol{r}_0, \qquad \boldsymbol{v}(t_0) = \boldsymbol{v}_0, \qquad m(t_0) = m_0 \tag{6}$$

Without loss of generality, two important assumptions are made:

Assumption 1. The available onboard fuel should be sufficient for the entire powered descent and landing process and satisfies

$$m_0 \ge m(t) \ge m_{dry} \tag{7}$$

where m_{dry} denotes the dry mass of the lander.

Assumption 2. The maximum magnitude of the thrust is significantly larger than the magnitude of the resultant force of gravity and any perturbative or un-modeled forces. That is,

$$\frac{\Gamma_{\max}}{m} > \left\| -\frac{\mu}{\|\boldsymbol{R}+\boldsymbol{r}\|^3}(\boldsymbol{R}+\boldsymbol{r}) + \boldsymbol{p} \right\| \tag{8}$$

during the entire flight. It is to indicate that the total system is under control with the thrust.

3. Guidance strategy design

The planetary powered descent guidance problem can be generally formulated as follows: given the current state of the lander, determine a real-time acceleration command program that brings the lander to the target landing site on the planetary surface with zero velocity [7,19,20]. We further consider the optimality and flexibility of the guidance so that the lander can safely and precisely arrive at the specified landing site with minimal fuel cost in the cases of retargeting, perturbing or un-modeled accelerations, and uncertain initial errors and thrust deviation.

Download English Version:

https://daneshyari.com/en/article/8057797

Download Persian Version:

https://daneshyari.com/article/8057797

Daneshyari.com