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Optimal nonlinear feedback guidance algorithm for Mars powered descent

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ABSTRACT

In this paper, an optimal nonlinear feedback guidance algorithm with complex state and control constraints is developed for Mars powered decent. The analysis of the optimal control problem for Mars powered descent is undertaken firstly. Then based on the real-time sampling optimal feedback control theory, the Mars powered descent guidance (PDG) algorithm is designed and analysed. A practical method is also proposed to solve the problem of the initialization of the PDG algorithm. Numerical simulations are performed to evaluate the effectiveness of the proposed PDG algorithm. The effects of the sampling period and the prediction errors on landing errors are studied in the numerical simulations. The fuel consumption performances of the proposed PDG algorithm and the Apollo guidance algorithm are also studied and compared. The simulation results show that the less fuel consumption is obtained with the proposed PDG algorithm. Monte Carlo simulation verifies the high landing precision of the proposed PDG algorithm.

1. Introduction

The process of delivering a Mars lander from the planetary orbit to a stationary position on the Mars surface, which presents a unique set of challenges, may generally be split into three phases: entry, descent, and landing (EDL) for MSL-class landers [1,2]. The future Mars missions, such as the sample return, may target scientifically interesting features that lie in areas far more hazardous. To avoid hazards and land safely and precisely, during the powered decent phase, future landers must have the ability to detect hazards in the landing zone and manoeuvre to a selected safe landing site, which requires autonomous, onboard trajectory planning and execution, with hazard detection sensors in the control loop [3].

A substantial number of papers that examine the trajectory optimization and guidance algorithm design for Mars powered descend have been published. Wong presents a Mars powered decent guidance (PDG) algorithm similar to that used for the Apollo lunar module, using polynomials of time to describe the desired position, velocity, and acceleration profiles [3]. This guidance algorithm is autonomous in nature and satisfies the request of real-time guidance. This guidance algorithm is not an optimal guidance law in that it does not minimize fuel or any other cost functional. Also, the state and control constraints are neglected by Wong in his paper. Topcu derives a solution with maximum–minimum–maximum structure for the minimum-fuel powered descent guidance [4]. However, the state constraints are not considered in [4]. Taking state and control constraints into account, Acikmese [5] presents a convex optimization approach for the fuel-optimal Mars powered descent. Blackmore [6] further develops this method for the case where no feasible pinpoint landing trajectories exist. Guo investigates an optimization approach to generate waypoints in the context of employing the zero-effort-miss/zero-effort-velocity feedback guidance algorithm for the Mars landing problem [7], in which two cases with power-limited and thrust-limited engine are considered respectively. The approaches [4–6] require precise mathematical model of the lander dynamics and are not robust against uncertainties, e.g., the aerodynamic drag and wind, due to the open-loop strategy. This may lead to great errors at the final time. It is shown in [4–6] that the optimal solutions can be efficiently computed numerically using the interior point methods or indirect methods. But the uses of interior point methods and indirect methods in a real-time terminal descent scenario are still an open research issue [8]. Although a closed-loop feedback is adopted to improve the robustness in [7], the complex constraints, e.g., thrust pointing constraints introduced by [5], cannot be handled sufficiently. Using the desensitized optimal control methodology, Shen [9] develops a Mars powered decent guidance law, which aims at reducing the sensitivity of the minimum-fuel powered descent trajectory in the presence of uncertainties and perturbations.

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Sostaric uses a Legendre pseudospectral method to develop a numerical solution to the Mars powered descent [10]. However, numerical optimization algorithms adopted to find approximate optimal solutions in [7,9,10] remain a challenge to approximate the optimal solution precisely with computations as less as possible, which may make these approaches inapplicable for autonomous onboard implementation, especially the real-time guidance. Therefore, to develop real-time and robust Mars PDG algorithms, in which the state and control constraints are sufficiently considered, much more work is needed.

In this paper, we investigate a novel nonlinear closed-loop guidance algorithm applicable to the suboptimal-fuel guidance for Mars powered decent. The proposed PDG algorithm uses a sampling optimal feedback approach and is applicable for the autonomous onboard implementation. In addition, the proposed PDG algorithm is robust against uncertainties and unmodeled dynamics. The PDG algorithm is developed with the consideration of the state and control constraints and has its roots in the real-time sampling optimal feedback control theory [11–14].

This paper is organized as follows. In Section 2, we formulate the powered descent guidance problem for Mars pinpoint landing with complex state and control constraints. In Section 3, the analysis of the optimal control problem for Mars powered descent is undertaken firstly. The development of the proposed PDG algorithm goes after the analysis of the optimal control problem. The analysis of the performance of the proposed PDG algorithm is also presented in this section. In Section 4, several numerical simulations are performed to evaluate the effectiveness of the proposed PDG algorithm. The simulation results are discussed and analysed in this section. Finally, a 200-run Monte Carlo simulation is performed considering several uncertainties and navigation errors.

2. Powered decent control problem formulation

The powered descent control problem formulation includes the lander translational motion dynamics and several constraints on the states and controls of the lander. The lander translational motion equations are presented firstly. To this end, we assume that n identical thrusters with equal thrust vector $\boldsymbol{T}$ at each time is mounted such that it is canted at an angle ϕ from the net thrust direction [5,6,8]. The translational motion equations of the lander in this document use a Mars surface-fixed Cartesian coordinate system with x and y axis located in the horizontal plane, z axis pointing upward and completing the right-hand coordinate system. The equations of motion neglect the Coriolis accelerations due to the Mars rotation because the accelerations are too small compared to the thrust acceleration. The equations of the translational motion for the lander are as follows:

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

$$\dot{\boldsymbol{v}} = \boldsymbol{g}(\boldsymbol{r}) + \left(\boldsymbol{T}_{\text{net}} + \boldsymbol{F}_{\text{per}}\right)/m \tag{2}$$

$$\dot{m} = -\left\|\boldsymbol{T}_{\text{net}}\right\|/I_{\text{sp}} g_e \cos\phi \tag{3}$$

where $\boldsymbol{r} = [x, y, z]^{\text{T}}$ and $\boldsymbol{v} = [v_x, v_y, v_z]^{\text{T}}$ are the position and Mars-relative velocity vectors respectively; $\boldsymbol{g} = [0, 0, g_m]^{\text{T}}$ denotes the gravitational acceleration vector on the surface of Mars, where $g_m = 3.76\ \text{m/s}^2$ is the average gravitational acceleration on the surface of Mars; $\boldsymbol{T}_{\text{net}} = n\boldsymbol{T}\cos\phi$ is the net thrust vector; $\boldsymbol{F}_{\text{per}}$ is the total perturbing force, accounting for unmodeled or unknown forces, such as the perturbations from the wind and aerodynamic forces; m is the lander mass. I_{sp} is the specific impulse, $g_e = 9.807\ \text{m/s}^2$ is the Earth's gravitational constant.

The complex constraints on the lander motion include inequality and equality constraints. In detail, they are the constraints on the thrust magnitude, boundary conditions, lander mass, path, and net thrust vector direction respectively. The complex constraints are introduced briefly here. For more details about the derivation process of the constraints above, readers may refer to [5,6]. These constraints are summarized in Table 1 for the formulation of the powered descent control problem in this paper. In Table 1, $T_{\min}$ and $T_{\max}$ are the minimum and maximum value of the thrust magnitude; t_0 and t_f are the initial and final time of the power descent; $\boldsymbol{r}_0$, $\boldsymbol{v}_0$, and m_0 are the initial value of the position, velocity, and lander mass; $\boldsymbol{r}_f$ and $\boldsymbol{v}_f$ are the final value of the position and velocity, which are determined by the landing requirement; m_{dry} is the mass of the lander without the propellant. The mass constraint is used to avoid the lander running out of the fuel during the powered decent for a safely landing. The path constraint is constructed to prevent the subsurface fight, where $\tilde{\theta}_{\text{alt}} \in [0, \pi/2]$ is a constant angle and $\boldsymbol{c} = [0, 0, 1]^{\text{T}}$ is a unit vector. The thrust vector direction constraint considers a vision-based lander powered decent landing scenario. The lander is equipped with a camera which is required to be directed to the ground during the control process. Consequently, the downward pointing camera imposes a constraint on the lander attitude motion. For a lander with a single net thrust vector, the translational motion is controlled through the attitude manoeuvre of the lander and changing the direction of the net thrust force. To ensure the camera working normally with high imaging qualities, the value of the angle θ_{cam} between the net thrust vector and the horizontal plane should have a right scope. In reality, a small θ_{cam} can result in a failing imaging. In Table 1, $\tilde{\theta}_{\text{cam}} \in [0, \pi/2]$ is a design parameter related to the camera.

Table 1
Complex constraints on the lander motion.

Constraints	Representations
Thrust magnitude constraint	$T_{\min} \le \left\|\boldsymbol{T}_{\text{net}}\right\|/n\cos\phi \le T_{\max}$
Boundary conditions constraint	$\boldsymbol{r}(t_0) = \boldsymbol{r}_0,\ \boldsymbol{v}(t_0) = \boldsymbol{v}_0$ $\boldsymbol{r}(t_f) = \boldsymbol{r}_f,\ \boldsymbol{v}(t_f) = \boldsymbol{v}_f$
Mass constraint	$m(t_0) = m_0,\ m(t_f) \ge m_{\text{dry}}$
Path constraint	$0 \le \sin\tilde{\theta}_{\text{alt}} \le \sin\theta_{\text{alt}} = \boldsymbol{c}^{\text{T}}\boldsymbol{r}/\left\|\boldsymbol{r}\right\| \le 1$
Net thrust vector direction constraint	$0 \le \sin\tilde{\theta}_{\text{cam}} \le \sin\theta_{\text{cam}} = \boldsymbol{c}^{\text{T}}\boldsymbol{T}_{\text{net}}/\left\|\boldsymbol{T}_{\text{net}}\right\| \le 1$

The translational motion model described by Eqs. (1)–(3) is employed to simulate the power descent of the lander. In the development of the PDG algorithm, the total perturbing force Eq. (2) is neglected. The purpose of the PDG algorithm is to find a command $\boldsymbol{T}_{\text{net}}$ in each guidance cycle for delivering the lander to the specified landing point, while simultaneously satisfying the constraints listed in Table 1 above and consuming the fuel as less as possible.

3. Optimal feedback guidance design and analysis

3.1. Analysis of the optimal PDG

The analysis of the optimal PDG problem neglects the effects of the total perturbing force and expresses the net thrust vector by

$$\boldsymbol{T}_{\text{net}} = T_{\text{net, max}} u \boldsymbol{\alpha} \tag{4}$$

where $T_{\text{net,max}}$ is the maximum net thrust magnitude, $u \in [0, 1]$ is the net thrust ratio, and

$$\boldsymbol{\alpha} = [\cos\beta\cos\theta, \cos\beta\sin\theta, \sin\beta]^{\text{T}} \tag{5}$$

is the unit vector of the net thrust direction with the direction angle β and θ defined as in Fig. 1.

Thus, we have the equations of the translational motion for the analysis and design of the PDG:

$$\dot{\boldsymbol{r}} = \boldsymbol{v} \tag{6}$$

$$\dot{\boldsymbol{v}} = \boldsymbol{g}(\boldsymbol{r}) + T_{\text{net, max}} u \boldsymbol{\alpha}/m \tag{7}$$