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Constrained optimal multi-phase lunar landing trajectory with minimum fuel consumption

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Abstract

A Legendre pseudo spectral philosophy based multi-phase constrained fuel-optimal trajectory design approach is presented in this paper. The objective here is to find an optimal approach to successfully guide a lunar lander from perilune (18 km altitude) of a transfer orbit to a height of 100 m over a specific landing site. After attaining 100 m altitude, there is a mission critical re-targeting phase, which has very different objective (but is not critical for fuel optimization) and hence is not considered in this paper. The proposed approach takes into account various *mission constraints* in different phases from perilune to the landing site. These constraints include phase-1 ('braking with rough navigation') from 18 km altitude to 7 km altitude where navigation accuracy is poor, phase-2 ('attitude hold') to hold the lander attitude for 35 sec for vision camera processing for obtaining navigation error, and phase-3 ('braking with precise navigation') from end of phase-2 to 100 m altitude over the landing site, where navigation accuracy is good (due to vision camera navigation inputs). At the end of phase-1, there are constraints on position and attitude. In Phase-2, the attitude must be held throughout. At the end of phase-3, the constraints include accuracy in position, velocity as well as attitude orientation. The proposed optimal trajectory technique satisfies the mission constraints in each phase and provides an overall fuel-minimizing guidance command history.

Keywords: Lunar soft landing; Constrained optimal control; Pseudo-spectral method

1. Introduction

Because of its proximity to earth, moon is often favored as a base for conducting new demonstrations in space technology. Moreover, exploration of moon has attracted the global attention since it is found to be mineral rich and also can serve as a base for solar power harvesting (Hickman et al., 1990). Further, it can also act as a base for launching ambitious missions to reach halo orbits around a Lagrangian point and to extending human explorations to interplanetary destinations (Dunham et al., 2013). In addition, proof of existence of water on moon confirmed by the impact probe of Chandrayaan-1 (Pieters et al., 2009) has given enormous hope for assistance when an envisaged lunar research base is constructed on the surface of the moon. Hence, there is a renewed interest across the globe for thorough exploration of moon.

Even though human missions have been carried out in the past for technology demonstrations, a more meaningful prolonged and cost-effective exploration of moon can hap-

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pen only when the mission is carried out in autonomous mode with a lander-rover combination. A critical difficulty of such an autonomous mission, however, is the fact that the lander carrying the rover must soft land on the moon surface with the help of on-board sensors, processors and actuators without any human intervention. In order to meet the mission goals and precise landing sequence, the lunar landing trajectory has built-in terminal constraints at various points which must be satisfied. Landing missions on celestial bodies without atmosphere (such as moon) also demand careful planning and execution of engine burns, which minimizes the fuel consumption. If not optimized, this extra fuel must be carried in the spacecraft leading to lesser useful payload mass, and therefore, it is imperative that such a mission must be executed with minimum fuel requirement. This planning makes the overall mission quite cost effective.

Many researchers in the past have attempted to land a probe on the moon and their results have become basis for some of the decisions in descending trajectory design. It is opt to provide their research contributions: An implicit guidance logic for soft lunar landing has been attempted (McInnes and Radice, 1996) in which the lander tries to reach the designated landing point by riding on the line of sight and gradually reducing the approach velocity. However, such an intuitive and simplistic strategy normally does not lead to a proper orientation of the vehicle at the landing site. More importantly, it does not lead to a fuel optimal trajectory. Based on optimal control theory, a generic explicit guidance law has been proposed using linearized dynamics that minimizes the final time as well as the total acceleration in all three directions, thereby leading to a fuel optimal solution (DSouza, 1997). Moreover, the terminal boundary conditions on position and velocity imposed as hard constraints ensure that these constraints are met in an efficient way. Additionally, it leads to a closed form analytic formula for the necessary acceleration in both lateral and axial directions, which leads to ease of onboard implementation. Because of these characteristics, the method has attracted many researchers across the globe to use this approach to address vertical orientation of the lander while touchdown.

The desired lander orientation demands terminal acceleration which has to be enforced as a hard constraint in all three directions. The idea of including the acceleration as one of the state for addressing this constraint has been analyzed by (Uchiyama et al., 2005; Mathavaraj and Padhi, 2017). Even though, the proposed analytical guidance logic ensured vertical orientation of the lander it resulted in dynamic controller. An analytical guidance law is proposed by approximating the cost function using the trigonometric series to address the vertical landing constraint (Afshari et al., 2009). The basic formulation has been subsequently revised to account for the crew visibility and sensor capability (Lee, 2011). This approach resulted in the guidance law in which final orientation angle depends on the initial condition of the lander. So to ensure demanded orientation, a set of initial conditions has to be achieved, which may not be feasible since maneuver error results in trajectory dispersions. A summary of all these developments around the explicit guidance law originally proposed in (DSouza, 1997) can be found in a good review paper (Guo et al., 2011). An augmentation is proposed in the objective function as soft constraint to address the requirement of lander's terminal vertical orientation. Here, the aim is to minimize not only the energy but also the terminal error between the acceleration achieved and acceleration specified by the designer (Ramkiran et al., 2016).

When guidance law derived from linearized dynamics is implemented for the nonlinear system, the trajectory generated results in performance degradation. So researches are interested in finding the non-linear analytic guidance law for addressing moon landing problem. The idea is to approximate the position and velocity trajectory by a polynomial function of time. The coefficients of this polynomial are obtained using the boundary conditions. Using the non-linear dynamics the explicit guidance law is derived, which results in trajectory satisfying position, velocity, attitude boundary conditions (Sachan and Padhi, 2016). Though this technique enforces the boundary conditions, the minimum fuel consumption criterion is not addressed by this approach. Addressing the fuel consumption through the inverse polynomial guidance approach have been proposed that converts the landing problem into static optimization problem (Banerjee and Padhi, 2015). The coefficients of the guidance law are found by solving this problem using non-linear programming approach. However, owing to the usage of simplified linearized dynamics and polynomial approximation of the trajectory in the process of mathematical derivation, the explicit solution and its variants, even though appear to be elegant, do not lead to true optimal solution in general. More importantly, path and hardware constraints (which are typically necessary for a real mission) have not been imposed and hence the solution is not truly elegant.

One way of including this path constraint in optimal control formulation is by using direct trajectory optimization method. Once the guidance history satisfying all the mission constraints are obtained in ground, it is stored on onboard and followed. In literature, lunar landing problem is solved by control parameterization technique and time scaling transform (Zhou et al., 2010), which results in nonlinear guidance law addressing soft landing and terminal attitude constraint. Also, the effect of choosing the de-orbiting altitude on the landing site selection have been reported (Park and Tahk, 2011). Though the proposed method addressed path constraints it is not suited for solving the multi phase lunar landing problem. The idea of splitting the trajectory into de-orbit, braking and vertical descent for addressing terminal landing accuracy and solving this problem using Legendre pseudo-spectral technique (discussed in detail in Appendix A) has been handled earlier (Hawkins et al., 2006). However, mission constraints

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