Advances in Engineering Software 94 (2016) 32–45

Contents lists available at ScienceDirect

Advances in Engineering Software

journal homepage: www.elsevier.com/locate/advengsoft

A unified trajectory optimization framework for lunar ascent

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ARTICLE INFO

Article history:
Received 14 December 2015
Accepted 10 January 2016
Available online 11 February 2016

Keywords:
Lunar ascent
Trajectory optimization
Fuel-optimal control
Pseudospectral method
Homotopy-based backtracking strategy
Computational guidance and control

ABSTRACT

This paper presents a unified trajectory optimization framework for lunar ascent. Compared with prevailing and emerging studies on lunar ascent trajectory optimization with simplified lunar ascent process and simple constraints, our method formulates in detail the lunar ascent process with complex constraints in a unified manner. The kinematics and dynamics model of lunar ascent with mission-specific constraints explicitly expressed through equalities or inequalities form the fuel-optimal lunar ascent trajectory optimization problem. A proper direct trajectory optimization method is chosen to transcribe the original trajectory optimization problem into a nonlinear programming (NLP) problem solved by a highly efficient NLP solver. The homotopy-based backtracking initial value strategy is designed to enhance convergence of the solving process. First, a two-phase trajectory optimization problem including vertical-rise phase and orbit-insertion phase is solved in the proposed unified framework. Subsequently, to obtain terrain clearance, we directly incorporate terrain description into the lunar ascent problem to obtain the optimal lunar ascent trajectory. Simulation results indicate that the proposed unified trajectory optimization framework has enough adaptability to efficiently handle complex lunar ascent scenarios. The proposed framework may benefit future autonomous lunar ascent missions.

1. Introduction

Recently, given the potential benefits of lunar exploration, some nations have established lunar exploration programs. China has plans to go to the moon. The government is aiming to launch a mission to return lunar samples back to Earth sometime in 2017. Government officials are also working on developing technology that can bring Chinese astronauts to the moon [1]. Russia also has lunar plans. Officials are reportedly planning to launch robotic missions to the moon starting in 2015 [2]. After conducting the Apollo Program from 1961 to 1972, NASA officials have not started any new lunar programs. However, this development does not mean that scientists and engineers at NASA have lost interest in the moon. NASA has recently launched Lunar CATALYST, a program designed to assist and encourage private companies that are interested in lunar exploration [3].

In lunar missions, the efficient and safe design of the lunar ascent trajectory is important. In lunar ascent missions, the Ascent Module (AM) launches from the lunar surface with constant thrust and ascends to insert into a specified orbit [4]. In the Apollo lunar ascent missions, the whole ascent process was mainly divided into two operational phases: vertical rise and orbit insertion. The AM aims to satisfy specified flight requirements in the vertical-rise phase, which is followed by the orbit-insertion phase that was efficiently designed to achieve orbit conditions for subsequent rendezvous [5–7].

Compared with studies on lunar landing, studies on lunar ascent are scarce. Current studies on lunar ascent trajectory optimization simplify the lunar ascent process with simple constraints and are mainly based on optimal control theory. Refs. [5] and [7] described the ascent trajectory of Apollo 11 and Altair in detail, respectively. Only the orbit-insertion phase was optimized by powered explicit guidance. Ref. [6] provided the lunar ascent nominal trajectory of the Apollo missions via the software Simulation and Optimization of Rocket Trajectories. In Ref. [8], the plane change was taken into consideration when the AM is not in the plane of

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http://dx.doi.org/10.1016/j.advengsoft.2016.01.002
0965-9978/

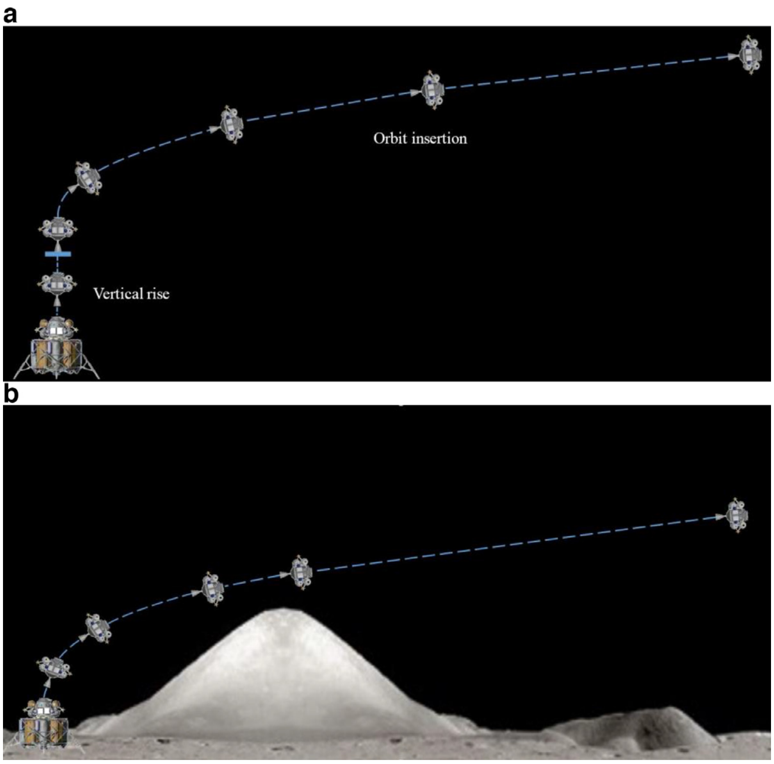

Fig. 1. Lunar ascent trajectory schematic: (a) TPLA mission; (b) TCLA mission.

the target's orbit at liftoff time. Six modes of lunar ascent to rendezvous were investigated on the basis of geometric-based methods. In Ref. [9], the fuel-optimal trajectory of lunar ascent missions with finite thrust was studied. An indirect method, together with the homotopy method, was applied to solve the bang–bang control in this lunar ascent trajectory optimization problem. In Ref. [4], the optimal trajectory for lunar ascent was obtained with the assumption that the ascent was quasiplanar over a spherical moon. Furthermore, the trajectory was assumed to start at the surface of the moon without the vertical-rise phase.

The range of lunar explorations is expected to increase in the future. Approximately 83% of the moon's surface is composed of lunar highlands [10]. The landing sites of the lunar module may be located in lunar areas with complex terrain. Given the rapid improvement of related technology in the past decades, a terrain model of the lunar surface can be accurately derived from preliminary exploration work. Therefore, the terrain clearance process is desirable to be considered explicitly and adaptively in lunar ascent trajectory optimization. Furthermore, the lunar ascent mission is subject to tradeoff between fuel and payload. The lunar ascent trajectory must be optimized for minimum fuel use to conserve fuel for possible contingencies [11]. Hence, the lunar ascent trajectory is expected to be fuel-optimal under safe flight. As far as we know, no previous work has been published with lunar ascent trajectory optimization formulated as a generalized trajectory optimization problem with complete kinematics and dynamics model and complex terrain clearance constraints.

Numerical methods for trajectory optimization fall into two general categories: indirect methods and direct methods [12]. Indirect methods have several disadvantages, including small region of convergence, the need to analytically derive the Hamiltonian boundary-value problem, a non-intuitive initial guess for the costate, and if path constraints are present, a priori knowledge of the constrained and unconstrained arcs [13]. Direct methods do not suffer from the disadvantages of the indirect methods. To solve such a generalized lunar ascent trajectory optimization problem, direct trajectory optimization methods may be more efficient. The direct methods transcribe the continuous-time optimal trajectory problem into an NLP problem, which is then solved by using an efficient NLP solver such as SNOPT [14] and IPOPT [15]. In recent years, a type of state and control parameterization method called pseudospectral method has drawn considerable attention. State and control variables are parameterized by using global polynomials such as Legendre and Chebyshev polynomials and the differential-algebraic equations are approximated by orthogonal collocation. The well-known pseudospectral methods include the Chebyshev pseudospectral method [16], Legendre pseudospectral method [17], Radau pseudospectral method [18], and Gauss pseudospectral method (GPM) [13]. In order to handle the difficulty of rapid trajectory change in certain regions or even discontinuous situation, an hp-adaptive pseudospectral method [19] was recently presented.

To have the capability of dealing with various complex lunar ascent missions in the future, this paper proposes a unified framework for the lunar ascent trajectory optimization problem. First, the basic lunar ascent trajectory optimization problem is established. Two missions for lunar ascent are designed. One is Two-Phase Lunar Ascent (TPLA) mission including vertical-rise phase and orbit-insertion phase, as shown in Fig. 1a. Dynamic optimization problem is formulated with constraints on the vertical-rise phase for checkpoint status (e.g., phase duration, checkpoint height, and checkpoint velocity) and constraints on the orbit-insertion phase for terminal insertion status. The other mission is Terrain-Clearance Lunar Ascent (TCLA) mission, with which terrain description is directly put into the trajectory optimization problem for terrain clearance and only one phase is defined for the whole trajectory, as shown in Fig. 1b. That is to say, terrain clearance requirement and orbit insertion requirement are used to formulate the dynamic optimization problem in a unified way, with no checkpoint explicitly required. The second mission is expected