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Multi-constrained suboptimal powered descent guidance for lunar pinpoint soft landing

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ABSTRACT

A multi-constrained suboptimal guidance method based on an improved zero-effort-miss/zero-effort-velocity (ZEM/ZEV) algorithm and the recently developed model predictive static programming (MPSP) is presented in this paper for lunar pinpoint soft landing. Firstly, the ZEM/ZEV algorithm is improved so that the trajectories generated by the algorithm are always above the surface of the Moon without thrust magnitude and look-angle constraints violated. A concept of virtual control is introduced for the continuity of the guidance commands and the enforcement of the thrust vector constraint at the terminal point. Taking the trajectory generated by the improved ZEM/ZEV algorithm as the initial guess history of the MPSP method, and the virtual control history as its control history, we develop a multi-constrained fuel suboptimal powered descent guidance law with the help of the high computational efficiency of the MPSP technique. Extensive simulations are conducted to verify the design features of the algorithm. The testing results demonstrate that the proposed algorithm is accurate and robust, and has a good capability of retargeting.

1. Introduction

In recent years, more than 50 years after humans first time reached the Moon, the interest of lunar exploration has been renewed. The Moon is the outpost for space exploration, and a well-planned program of human exploration of the Moon would produce an experience base necessary to successfully and safely conduct human exploration of Mars or other planets [1]. In the near future, long-term research bases will be established on the Moon, and pinpoint soft landing will be essential to send humans and equipment to the Moon accurately, which cannot be done by the guidance technique in the Apollo era because of the poor precision and lesser autonomy [2]. For example, in the absence of human vision based navigation, the predicted landing ellipse for Apollo 12 measured 13.3 km by 4.8 km [3].

A typical lunar descent trajectory from a parking orbit is divided into transfer orbit phase and powered descent phase [2,4–6], and obviously the guidance of the powered descent phase directly determines the final landing precision. To improve upon the landing precision and autonomy, a number of agencies and individuals have investigated new guidance techniques intensively. As early as in 1997, D'Souza [7] proposed an explicit guidance method which minimized control effort. The method introduced time-to-go into the cost function to solve the time-to-go analytically and avoid the error caused by estimating the time-to-go numerically. However, path constraints were not considered by D'Souza. Ueno and Yamaguchi [8] developed a suboptimal guidance law for the SELENE mission, which could just satisfy the terminal conditions specified by three-dimensional velocities and height at the terminal point and naturally could not be applied to pinpoint landing. The methods in Refs. [7,8] are all optimal control theory based closed-loop guidance schemes; on the contrary, the gravity turn guidance law is an open-loop one [3,9]. The original gravity turn steering is only theoretical and cannot be used as a guidance algorithm, because it can only meet final state constraints by adjusting the initial state [10]. McInnes [11] extended the domain of validity of the classical gravity turn solution from low-velocity terminal descent to complete descent from a low parking orbit. In order to correct for the deficiencies of the gravity turn method, Chomel et al. [12,13] developed an analytical algorithm that generated reference trajectories online and then obtained the guidance commands by tracking the reference trajectories. Again, the limitation of the guidance scheme is that it can only generate two-dimensional trajectories and path constraints are not considered. Uchiyama [14] employed a barrier function to obtain a guidance law with an input constraint and an analytical solution was achieved which could generate a reference trajectory in real time. Based on the reference trajectory, a state feedback controller was developed. Issues with

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this approach include a lack of fuel optimality and applicability to three-dimensional flight. Acikmese and Ploen [15] presented a convex programming algorithm for the powered descent guidance problem, which led to a fuel-optimal and fully constrained guidance law. Although this approach holds much potential, it has the disadvantage of using a numerical solver that the outer iteration to find the best time is computationally expensive and it would be difficult to verify convergence for all possible scenarios [5]. Cognizant of the existing problems, enhancements on the guidance algorithm were presented in Ref. [16]. With the assumption of constant gravity and constant thrust acceleration magnitude, Rea et al. [5,17] derived a fuel-optimal powered descent steering law which could be analytically reduced to a one-dimensional bounded root-finding problem. While the problem can be solved quickly and reliably and the result is fuel optimal, the approach does not take into account the no-subsurface and look-angle constraints, and it is hard to add path constraints to the algorithm even with modification. By using the perturbation technique, Afshari et al. [18] got a closed-loop time-optimal control strategy for the lunar landing mission, but it was still discussed in a plane. Desiderio and Lovera [19] applied the differential flatness theory to the guidance and control problems of the two-dimensional powered descent phase. Azimov [20] proposed a closed-form analytical guidance algorithm for the powered lunar descent and landing trajectory as an enhancement of Apollo ground-based targeting solution. Zhou and Xia [21] modified the ZEM/ZEV optimal feedback algorithm so that the landing vehicle always flew above the surface of planets, while some parameters have to be tuned carefully and the optimality of the ZEM/ZEV algorithm is greatly degraded.

Though the research on powered descent guidance has been conducted intensively, both the numerical methods and the analytical methods have various limitation, such as relying on the assumption of constant thrust magnitude, lacking applicability to three-dimensional descent and considering no path constraints. In practice, constraints are of especial importance for successful soft landing because any violation of constraints may degrade the exploration, even result in a disaster. For instance, violating the no-subsurface constraint means that landing vehicles will hit the moon or planets. Though the violation of some constraints like the look-angle constraint and the final thrust vector constraint do not damage landing vehicles, the landing precision may be ruined. To improve upon these, a three-dimensional multi-constrained suboptimal closed-loop guidance law is presented in this paper, based on an improved ZEM/ZEV algorithm and the MPSP technique.

Similar to the well-known zero-effort-miss (ZEM) distance, the zero-effort-velocity (ZEV) error is the velocity error at the final time if no further control acceleration is imparted. The concept of ZEV was firstly introduced and employed to the derivation of a robust optimal sliding mode guidance law for an interceptor by Ebrahimi et al. [22]. Since then, the ZEM/ZEV algorithm has been used as optimal feedback controllers for problems of planetary landing, intercept, asteroid close-proximity, orbit transfer, etc. [21,23–26]. In practice, since gravity is a function of position, the solution obtained by the ZEM/ZEV algorithm is not optimal, but suboptimal (or near-optimal) [26]. Especially, the ZEM/ZEV algorithm not taking path constraints into account, when it is applied to a powered descent problem, the resulting guidance commands may lead to the trajectory to fly blow the surface of the planet [21]. Cognizant of the deficiency, the ZEM/ZEV algorithm is improved such that all the path constraints are met in the powered descent problem in this paper.

Model predictive static programming (MPSP) technique is a computationally efficient algorithm that has been proposed recently to solve a class of finite horizon optimal control problems with terminal constraints, and the advantages are as follows: 1) it demands only a static state vector for the control history update; 2) the costate vector has an analytic solution; 3) the sensitivity matrices for obtaining the solution can be computed recursively. These characteristics make the MPSP algorithm very efficient and suitable for online guidance [27–30]. Essentially, MPSP is an approximation of the optimal control problem in the neighborhood of the initial guess history. Of course, the guess history is crucial to the optimality of the solution. Though the theory of the MPSP technique is being developed, it has been used in the design of guidance laws and got some rather promising results [27,29,30].

In this paper, the improved ZEM/ZEV algorithm is employed to the generation of a three-dimensional trajectory with relaxed terminal position and velocity constraints, which, however, satisfies constraints on height, thrust magnitude and look-angle stringently. To enforce the constraint that the thrust points exactly upwards at the terminal point and ensure the continuity of the commanded acceleration, we introduce a concept of virtual control, from which real control can be derived. Taking the trajectory generated by the improved ZEM/ZEV algorithm as the initial guess history of the MPSP technique, and the virtual control history as its control history, we develop a closed-loop three-dimensional pinpoint landing guidance law with multiple constraints, which owes to the excellent capability of enforcing terminal constraints and high computational efficiency of the MPSP technique. Finally, extensive simulations are conducted to verify the correctness, effectiveness and robustness of the algorithm.

The rest of this paper is structured as follows. In Section 2, a lunar powered descent problem is formulated. Then, the improved ZEM/ZEV algorithm is presented in Section 3. Next, a summary of the MPSP theory is given in Section 4. In Section 4.2, the guidance scheme is derived by combining the improved ZEM/ZEV algorithm and the MPSP technique tightly. And then, numerical simulations are conducted to verify the design feature. Finally, some conclusions are drawn in Section 6.

2. Problem formulation

2.1. Equations of motion

For the problem formulation, an inertial reference frame O-XYZ is defined, which is Moon-centered with the XOY plane coinciding with the Moon equatorial plane, the X-axis pointing from the origin to the arc of zero degree longitude when powered descent begins and the Z-axis pointing to the north pole of the Moon. In the lunar descent flight, the height and horizontal distance to fly is both small, and naturally, the flight time is rather short. Hence, the rotation of the Moon can be ignored. A ground-fixed reference frame is defined which has its origin attached to the nominal landing site. As illustrated in Fig. 1, the x-axis points to local east, the y-axis points to local north, and the z-axis points along the radial position vector. The equations of motion can be formulated in the ground-fixed reference frame o-xyz as [31]

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

$$\dot{\mathbf{v}} = \mathbf{a} + \mathbf{g} \tag{2}$$

$$\mathbf{a} = \mathbf{T}/m \tag{3}$$

$$\dot{m} = \|\mathbf{T}\|/(I_{sp} g_e) \tag{4}$$

where, $\mathbf{r} = [x, y, z]^T$ is the position vector; $\mathbf{v} = [u, v, w]^T$ is the relative velocity vector; $\mathbf{a} = [a_x, a_y, a_z]^T$ is the acceleration vector; $\mathbf{g}$ is the gravity vector of the Moon; $\mathbf{T} = [T_x, T_y, T_z]^T$ is the thrust vector; m is the mass of the vehicle; I_{sp} is the specific impulse of the engine; g_e is the gravity of the Earth at sea level; $\dot{\mathbf{r}}$, $\dot{\mathbf{v}}$ and $\dot{m}$ are the derivatives of $\mathbf{r}$, $\mathbf{v}$ and m with respect to time respectively.