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Multi-constrained ascent guidance for solid propellant launch vehicles

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ABSTRACT

Solid rocket motors expect to remove the thrust termination mechanism to increase the strength of structure and reduce the cost, which induce new difficulties and challenges to ascent guidance. This paper presents an ascent guidance algorithm for small solid launch vehicles (SSLVs) which shut off by fuel exhaustion. A pointing algorithm is tailored for the baseline guidance algorithm of SSLVs with constraints of the velocity vectors and the position vectors. Subsequently, an energy management technique is developed for dissipating the extra energy that the solid rockets have when shutting off by fuel exhaustion. The energy management technique primarily allocates the energy to different sub-stages, while an attitude control energy management method is applied to the dissipation of the excess energy at one stage. Finally, the proposed guidance algorithm is verified by Monte Carlo simulations in which the dispersions of vehicle mass, operation temperature of motors and aerodynamic coefficient as well as random wind shear are considered. The testing results demonstrate the capability, strong robustness and excellent performance of the proposed guidance algorithm.

1. Introduction

The development of solid propellant launch vehicles has drawn significant interest due to short preparation cycle, quick launch ability and storage stability. Small solid launch vehicles can be launched rapidly with high maneuverability and agility, fulfilling the longed-for requirement of fast entry into outer space [1]. Recent interests in responsive launch have highlighted the need for rapid and fully automated ascent guidance planning and guidance parameter generation for launch vehicles [2]. For solid rocket motors, removing the thrust termination mechanism can not only increase the strength of structure but also reduce the cost, which is the inevitable trend of development. With respect to launch missions, SSLVs are required to adapt different payloads, orbital shape and altitude. These have posed new difficulties and challenges on the ascent guidance in vacuum, which indicate that SSLVs must depend on the autonomous guidance to satisfy the terminal constraints and shut off by fuel exhaustion [3,4]. A four stages solid rocket is investigated in this paper and the typical launch process is shown in Fig. 1.

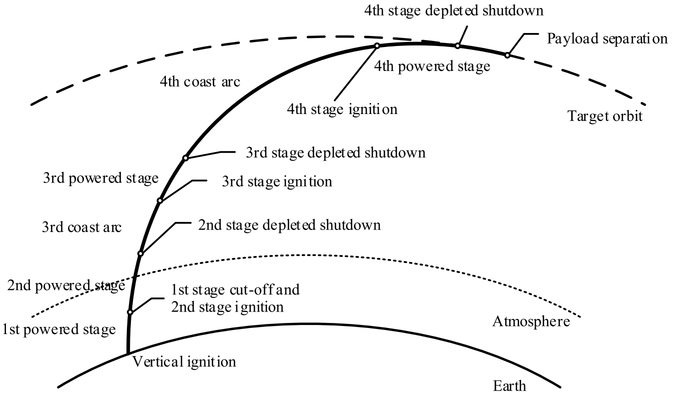

Fig. 1. Typical launch process of a four stages rocket.

Over the past few decades, numerous efforts have been devoted to the ascent guidance of launch vehicles. The existing autonomous guidance methods are mainly applied to liquid rocket-powered launch vehicles with the ability to shut down. The examples of classical exo-atmospheric optimal ascent guidance algorithms include the Iterative Guidance Mode (IGM) guidance employed for the Saturn V rockets and the Powered Explicit Guidance (PEG) for the Space Shuttle. Recently, researchers have made important contributions to solve the optimal ascent problem on-board. Dukeman [5] developed a closed-loop ascent guidance algorithm, which adopts a multiple-shooting method to solve a two-point boundary-value problem and to obtain the optimal ascent thrust direction. Lu [6] used the finite difference method to deal with endo-atmospheric optimal guidance and presented a connection

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Nomenclature

A, N	the aerodynamic axial and normal forces magnitude
C_A	the coefficient of axial force
C_N	the coefficient of normal force
q	the dynamic pressure
$m(t)$	the vehicle mass vs. time
S	the aerodynamic reference area
s_m	the rocket nozzle reference area
I_{sp}	the specific impulse
$P(h)$	the atmospheric pressure vs. altitude
T_s	the rated operating time of the booster
P_{imp}	the intersection point between the suborbital and target trajectory
R_{imp}	the distance between the center of the Earth and the intersection point P_{imp}
W_M	the velocity capability by consuming the whole fuel
R_M	the route capability by consuming the whole fuel
T_c	the centroid time of thrust acceleration profile
W_{PA}	the velocity capability obtained by the pointing algorithm
$W_{M.3}$	the velocity capability by consuming the whole fuel at the third stage
$W_{M.4}$	the velocity capability by consuming the whole fuel at the fourth stage
T_{go}	the remaining work time of the booster
$\Delta\mathbf{v}_G$	the velocity introduced by gravity
$\Delta\mathbf{r}_G$	the position introduced by gravity
$\boldsymbol{\Gamma}$	the thrust direction
t_{ig}	the ignition time
$\mathbf{V}_{sub.f}$	the terminal velocity vector of sliding orbit
$\mathbf{R}_{sub.f}$	the terminal position vector of sliding orbit
$\mathbf{V}_{orb.f}$	the terminal velocity vector of target orbit
$\mathbf{R}_{orb.f}$	the terminal position vector of target orbit
$\mathbf{f}_{sub.imp}$	the true anomaly of sliding orbit at the intersection point P_{imp}
$\mathbf{f}_{orb.imp}$	the true anomaly of target orbit at the intersection point P_{imp}
$R_{a.sub}$	the distance between the center of the Earth and the apogee of the coasting orbit
$\mathbf{v}_{sub.r}$	the vertical velocity of sliding orbit at the impulsive ignition time
$\mathbf{v}_{sub.f}$	the horizontal velocity of sliding orbit at the impulsive ignition time
$\mathbf{v}_{orb.r}$	the vertical velocity of target orbit at the impulsive ignition time
$\mathbf{v}_{orb.f}$	the horizontal velocity of target orbit at the impulsive ignition time
W_g	the required velocity for energy management
φ_{AEM}	the additional attitude angle of energy management

mode for the two algorithms of endoatmospheric and exoatmosphere. Outside the dense atmosphere where the aerodynamic forces can be safely ignored in the guidance solution, an analytical approach [7] was used to obtain the optimal exo-atmospheric ascent trajectory for the upper stage(s) of the vehicle. A large number of research achievements provide a valuable and important reference for the autonomous guidance of SSLVs.

Modern optimization algorithms are core issues such as large computing amount and inability to ensure convergence the overall process. A genetic algorithm is employed to acquire the optimum entire trajectory (ascending, on-orbit, deorbit, and reentry segments) with a maximum target coverage time [8]. Traditional linear programming algorithms have explicit physical parameters and stable solutions benefited from avoiding solving nonlinear equations and numerical integration operations on a large scale, whose advantages are valuable for guidance online as compared to other modern optimization algorithms. A closed-loop guidance method for ballistic missiles [9,10] is based on the required velocity vector algorithm constrained by the ground cross range and down range. If choosing the classical six elements of orbit as constraints, the closed-loop guidance method cannot completely satisfy the constraints of orbital elements, because the required velocity vector algorithm neglects the displacement vector constraints. In [11–15] the guidance method proposed is similar to impulsive orbit transfer, which considered the energy at the last stage as an impulse. Then, based on orbital element equations and the necessary conditions to generate a circular orbit, the impulsive ignition time of the last stage and its necessary attitude on the flight plane are obtained. Patha and McGehee [16] developed an alternate attitude control energy management method, which is an open-loop guidance method and is only suitable for vacuum environment. Zarchan [17] proposed a general energy management method which is a closed-loop guidance method and the vacuum flight assumption has minimal effect on guidance precision. These research achievements support the multi-constrained baseline guidance algorithm and present several energy management methods to dissipate excess energy.

In order to achieve a better performance, autonomous and robustness, such an ascent guidance would potentially provide the rational steering angles to meet the velocity vector and fixed point constraints when solid rocket motors shut off by fuel exhaustion. This study improves a multi-constrained guidance method called the pointing algorithm in Ref. [11] and represents an energy management technique to address the energy management issue of the "burn-coast-burn" ignition mode. The main contributions of this paper are briefly outlined as follows:

i. In terms of the "Hohmann transfer" principle, the theory of a pointing algorithm is deduced in depth so that the closed-loop ascent guidance satisfies the terminal constraints, including velocity vector constraint and position vector constraint (or six orbital element constraints).
ii. Due to remove the thrust termination mechanism, the fuel of SSLVs must be completely consumed. An energy management issue of the "burn-coast-burn" ignition mode is discussed, which includes the consumption of the excess fuel within one stage and the allocation of the energy between different stages.
iii. According to a series of carefully and reasonably designed simulations, the capability and robustness of the multi-constrained ascent guidance are demonstrated.

2. Pointing algorithm

2.1. Dynamics model

The equations of motion of a thrusting rocket through the atmosphere can be expressed in an inertial frame as

$$\begin{cases} \dot{\mathbf{r}} = \mathbf{v} \\ \dot{\mathbf{v}} = \mathbf{g}(\mathbf{r}) + \big[(T - A)\mathbf{x_b} + N\mathbf{y_b}\big]/m(t) \end{cases} \tag{1}$$

The thrust magnitude T, and the axial and normal forces A and N are given by: