Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 55 (2015) 463–476

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

A comparison of iterative explicit guidance algorithms for space launch vehicles

Eun-Jung Song *, Sangbum Cho, Woong-Rae Roh

Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon 305-806, Republic of Korea

Received 5 February 2014; received in revised form 14 August 2014; accepted 18 September 2014
Available online 30 September 2014

Abstract

This paper analyzes and compares the performance of two prominent explicit guidance algorithms: the iterative guidance mode and the powered explicit guidance. We performed a series of numerical simulations of a space launch vehicle model for both nominal and off-nominal conditions. One of our findings is that if we take into account the originally ignored higher-order terms from the guidance parameters of the iterative guidance mode for a long-range flight, the guidance performance can be enhanced to a level comparable to that of the powered explicit guidance. These higher-order terms can be included by employing an iterative predictor–corrector method like the powered explicit guidance. Also we proposed a remedy of preventing relatively earlier divergence of the guidance commands with the predictor–corrector iteration than that of the linear differential corrector approach by making a better initial guess.

Keywords: Explicit guidance law; Space launch vehicle; Thrust acceleration integrals; Iterative methods; Guidance performance analysis

1. Introduction

Most of the modern multi-staged space launch vehicles adopt closed-loop guidance laws for the exoatmospheric trajectory, although open-loop ascent guidance is effective enough for the first stage maneuver against the atmospheric loads. One of the main virtues of a closed-loop guidance program is that the steering vectors and engine cutoff times can be determined to achieve the target with minimum fuel consumption. For this purpose, various explicit guidance schemes based on linear tangent laws have been developed since the space era of 1960s and their inherent mission flexibility has allowed them to be applied even in today's space launch vehicles (Shrivastava et al., 1986). To handle more complicated mission requirements for future space transportation, guidance algorithms with higher degree of onboard adaptability have been being developed (Hardtla et al., 1987; Jessick and Knobbs, 1992), including those based on onboard trajectory optimization with advances in computer processors (Skalecki and Martin, 1993; Jutty et al., 2000). Other research efforts, also principally indebted to much improved onboard computer capabilities, have been devoted to eliminate simplifying assumptions previously required to derive the closed-form solutions of guidance problems (Delporte and Sauvient, 1992).

It could be said that the iterative guidance mode (IGM) developed for guidance of the Saturn launch vehicles (Chandler and Smith, 1967) and the powered explicit guidance (PEG) algorithm developed during the Space Shuttle Program with various missions (McHenry et al., 1979; Schleich, 1982) are among the most distinguished and flight-proven guidance algorithms ever devised. Although the performance of these algorithms has been demonstrated by hundreds of successful flights, it is rather hard to find open literatures analyzing the effects of the approximations used in their derivation or comparing the

* Corresponding author. Tel.: +82 42 860 2994.
E-mail address: ejsong@kari.re.kr (E.-J. Song).

http://dx.doi.org/10.1016/j.asr.2014.09.025
0273-1177/

performance of these two algorithms. Song et al. (2011) proposed a method to reduce the prediction errors of IGM by taking into account the effect of approximate formula of the angle-to-go prediction to orbit injection accuracy. A higher-order form of PEG was proposed by Sinha and Shrivastava (1990) to consider the high maneuvers of Indian launch vehicles, and they showed that its performance was superior to that of the original form. Vittal and Bhat (1991) and Delporte and Sauvient (1992) formulated the thrust acceleration integrals with constant thrust analytically for the vector form of the linear tangent law, which had been originally approximated by Taylor series values (McHenry et al., 1979; Sinha and Shrivastava, 1990).

This study analyzes and compares the performances of IGM and PEG while seeking methods to improve the performance of these guidance schemes in their original forms. We investigated the effect of higher-order nonlinear terms previously ignored in IGM to derive the approximate linear equations of guidance parameters by employing similar approaches by Sinha and Shrivastava (1990) with PEG algorithm. That is, higher-order terms are shown to be included in almost the same way with PEG algorithm if an iterative predictor–corrector method is adopted. There are some references commenting that PEG can be considered as a kind of a vector form of IGM and the performance of these two algorithms is nearly identical for vacuum flight phase (Jaggers, 1977; Hanson et al., 1995). However, simulation results show that the performance of IGM can be more deteriorated than that of PEG, especially in terms of slower convergence in the time-to-go prediction. It is shown that the performance of IGM can be improved by introducing previously ignored higher-order terms, which again makes the linear angle command assumption of the algorithm more valid.

The guidance parameters of PEG are computed using the iterative predictor–corrector approach starting with an initial guess at every major guidance computation cycle. By comparing with the linear differential correction method using first derivatives to all guidance parameters (Delporte and Sauvient, 1992), it is shown that the initial guess of the predictor–corrector approach is more erroneous as the time-to-go approaches 0, which may lead to more iterations. It is well known that, for iterative algorithms, the first guess close to the answer significantly improves the convergence properties (Luenberger and Ye, 2008). The same applies to the initial guess of the velocity-to-go, the running variable of the iteration process in PEG. In this study, we showed that the convergence of the iteration process in PEG can be enhanced by improving the initial guess of the velocity-to-go.

Although our approaches here may not claim significant performance improvement on these well-developed schemes in their original form, we proved that some deficiencies can be overcome without much more complexities such as onboard optimization methods which are currently one of the major research topics in the space launch vehicle guidance area. Except for this introduction, this paper is organized into four sections. The formulae of higher-order form of IGM are elaborated first and then described is a comparison between the predictor–corrector approach of PEG and the linear differential corrector method. Following the simulation results for the proposed approaches, the conclusions of this work are summarized.

2. Explicit guidance law with higher-order nonlinear terms

Most of the explicit guidance laws have a functional form based on an optimal trajectory minimizing the usage of propellants. Derivation of IGM is also based on the fact that the optimal thrust direction for the flat-earth and uniform gravity model is approximately given by a linear angle form (Chandler and Smith, 1967). The pitch and yaw attitude commands are assumed to be linear relative to the guidance reference system G as follows, with G being defined in the target orbit plane whose origin is located at the center of the Earth.

$$\theta_G = \theta_{G_v} - \left(\theta_{G_P} - \dot{\theta}_G t\right) \quad (1)$$

$$\psi_G = \psi_{G_v} - \left(\psi_{G_P} - \dot{\psi}_G t\right) \quad (2)$$

where current time is set to 0, and t denotes the time varying from 0 to time-to-go, t_{go}, the remaining time before achieving the target injection point. The x-axis of the guidance coordinate system G goes toward the predicted orbit injection point from the origin, the y-axis lies in the normal direction of the target orbit plane, and the z-axis completes the right-handed coordinate system. Among the guidance parameters, $\theta_{G_v}, \theta_{G_p}, \dot{\theta}_G, \psi_{G_v}, \psi_{G_p}$, and $\dot{\psi}_G$ are related to the commanded attitudes (thrust direction) and t_{go} determines the time of the engine shutdown. Finally range-angle-to-go, ξ_{go}, an angle between current position and predicted target injection point, should be computed to define the G frame. These parameters are calculated to satisfy the position and velocity constraints of a target orbit by analytic integration of the following point-mass equations of motion applicable to a typical space launch vehicle in a vacuum.

$$\ddot{x}^G = a \sin\theta_G \cos\psi_G + g_x^G \quad (3)$$

$$\ddot{y}^G = a \sin\psi_G + g_y^G \quad (4)$$

$$\ddot{z}^G = a \cos\theta_G \cos\psi_G + g_z^G \quad (5)$$

where the first terms represent the acceleration by thrust and the second terms by gravity, which are integrated independently.

The derivation procedure of the guidance parameters for IGM in its original (Chandler and Smith, 1967) and a modified form to consider previously ignored higher-order terms, is as follows. First, θ_{G_v} and ψ_{G_v} are derived to satisfy only the terminal velocity constraints under the assumption of invariant thrust direction. Integration of Eqs. (3)–(5) during the remaining burn time leads to