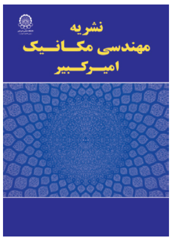

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Cut-off Insensitive Implicit Guidance via Flight Path Angle Correction

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ABSTRACT: The complexity of solid fuel engines cut-off demands a comprehensive method for guiding these missiles. This paper presents an implicit cut-off insensitive guidance scheme for ballistic missiles. The main idea behind this scheme is to correct the nominal flight path angle, without dependency to cut-off, at an arbitrary time with respect to the value of disturbances and uncertainties such as wind, thrust misalignment, thrust value, aerodynamic coefficients, to satisfy the nominal burnout time conditions. This flight path angle correction is related to an explicit function. Compared with the preset scheme, the proposed scheme is more robust to motor performance uncertainty. The circular error probability of the proposed method is calculated 1.242 km which is 61% less than the preset method's circular error probability. It is also simpler and has a lighter calculation load, although it needs a high pre-launch calculation. It is shown that the algorithm has good performance through the computer simulation.

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1- Introduction

Many different techniques have been developed for the design of the ballistic missiles guidance algorithm that can be divided into two categories: those are depended on thrust termination facilities and those that independent to them. The absence of the cut-off system due to its complexity and cost, in vehicles propelled with solid motors, made some challenges in the guidance algorithms.

The closed-loop guidance of solid propellant vehicles can be divided into two groups [1]; namely implicit guidance and explicit guidance. In the case of explicit guidance, the deviation of velocity from the required velocity is minimized at each instant of flight. For computation of required velocity, the Lambert problem [2] must be solved. Several guidance schemes, such as the General Energy Management (GEM) [2], Iterative Lambert Guidance (ILG) [3], cross product guidance [4], optimal control based guidance [5, 6], Cut-off Insensitive Guidance (CIG) with variable flight time [7] can be categorized as explicit methods. Notably, these algorithms use the Velocity Capability (ΔV_{cap}) of the rocket motor. Generally, it is not easy to exactly estimate the velocity capability on the basis of the propellant remaining in the flight because of motor performance uncertainty. Therefore, the GEMS and ILG produce a large target miss in the presence of this uncertainty. De Swarte [8] proposed an optimal method for computation of ΔV_{cap}. Amini and Qhaffari [9] suggested an empirical relation for ΔV_{cap}. Then Alizadeh and Massoumnia [10] derived an optimal ΔV_{cap} for minimum thrust angle deviation. These methods rely on the prediction of ΔV_{cap} which due to uncertainties, cannot be accurate enough. The CIG method wastes some uncertain parts of ΔV_{cap} toward the range insensitive direction and thereby reduces target miss. However, it tries to identify the range-insensitive direction with the parameters obtained through simulation, and it may not be able to determine this accurately. Further, because of the iterative calls of the Lambert routine [11], the process of finding a solution satisfying $\Delta V_{cap} = V_g$, where Vg is the required velocity (or velocity to go) has a rather heavy calculation load and the scheme is complicated. Additionally, the target miss increases as the motor uncertainty increases, because the parameters tuned in the simulation are fixed. Roshanian and Esrafilian [12] proposed a method with no prediction of ΔV_{cap}, but it requires iterative calls of the Lambert routine. Kim and Um [13] proposed a Flight-Path Angle Control (FPAC) scheme to eliminate the search algorithm that complicates the routine. Because the FPAC method manipulates the flight-path angle to follow the required flight-path angle corresponding to the current velocity, no search algorithm is necessary. Thus, not only is the scheme simple but the calculation load is also light. Further, it is robust to motor performance uncertainty because the FPAC does not use the uncertain velocity estimate ΔV_{cap}, which is the main source of target miss. Nevertheless, this method depends on the flight time.

In case of explicit guidance methods such as delta guidance [14], Instantaneous Impact Point (IIP) [15], functional [16], S function [17], and preset the deviation of the actual trajectory from a reference trajectory is minimized at each instant of flight. The main advantages of this technique are simplified guidance logic and the use of onboard computers with lesser speed.

In this paper, an implicit cut-off insensitive guidance scheme

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that presented in earlier authors work [18] is developed. The main idea behind this scheme is to correct the nominal flight path angle, without dependency to cut-off, at an arbitrary time with respect to the value of disturbances and uncertainties such as wind, thrust misalignment, thrust value, aerodynamic coefficients, to satisfy the nominal burnout time conditions.

2- Governing Equations

Using the following definitions:

$$\begin{aligned} \delta J(t) &= \bar{R}_r . \delta \bar{r}(t) + R_V . \delta V(t) + R_\gamma . \delta \gamma(t) \\ \delta \dot{J}(t) &= \bar{R}_r . \delta \bar{V}(t) + R_V . \delta \dot{V}(t) + R_\gamma . \delta \dot{\gamma}(t) \end{aligned} \tag{1}$$

where:

$$\begin{aligned} &\bar{R}_r = \frac{\partial R}{\partial \bar{r}} = R_x e_x + R_y e_y + R_z e_z \\ &R_x = \frac{\partial R}{\partial x}, \quad R_y = \frac{\partial R}{\partial y}, \quad R_z = \frac{\partial R}{\partial z} \\ &\bar{R}_V = \frac{\partial R}{\partial \bar{V}} = R_{V_x} e_x + R_{V_y} e_y + R_{V_z} e_z \end{aligned} \tag{2}$$

The Flight-Path Corrected Implicit Guidance (FCIG) algorithm can be derived as:

$$\begin{aligned} &\delta \gamma_c = -\begin{cases} \dfrac{\delta J(t)}{R_\gamma} & \| \delta \gamma_c \| \le \delta \gamma_m \\ \delta \gamma_m & \| \delta \gamma_c \| \ge \delta \gamma_m \end{cases} \\ &\gamma_{com}(t) = \gamma^*(t) + \delta \gamma_c \end{aligned} \tag{3}$$

where $\delta\gamma_c$ is the flight path angle correction in pitch program, $\delta\gamma_m$ is the maximum correction, γ_{com} is the commanded flight path angle and $\gamma^*(t)$ is nominal flight path angle.

A three-degree-of-freedom is conducted to evaluate the effectiveness of the proposed scheme in the value of disturbances and uncertainties presence such as wind, thrust misalignment, thrust value, aerodynamic coefficients. The behavior of the proposed algorithm is compared with preset guidance. The overall trajectory is shown in Fig. 1. The correction flight path angle as well as pitch rates, and angle of attacks can be seen in Figs. 2 to 4 in the upper and lower uncertainties presence.

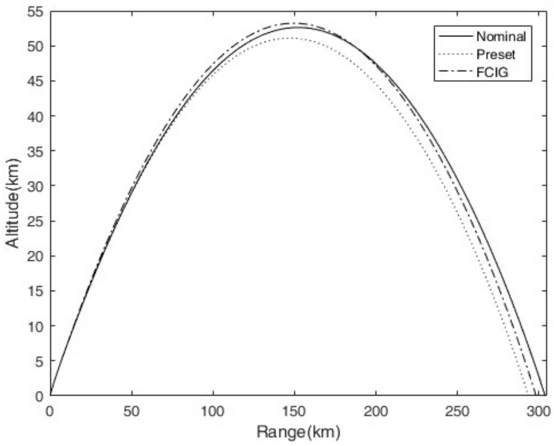

Figure 1. Trajectory comparison.

3- Conclusion

This paper presents Flight-path Corrected Implicit Guidance (FCIG) scheme for guiding a missile that lacks thrust termination systems. This method is based on the correction of the nominal flight path angle, without

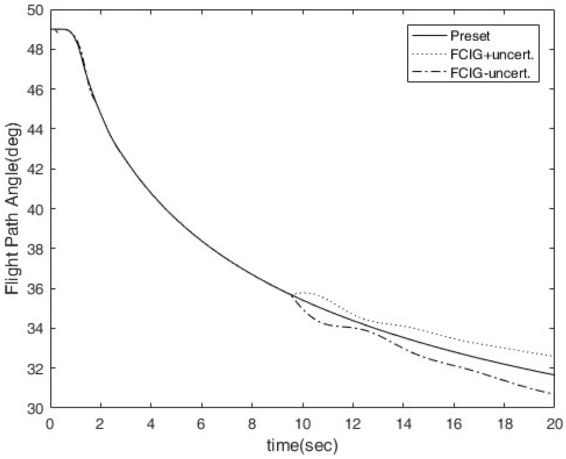

Figure 2. Flight path angle variations.

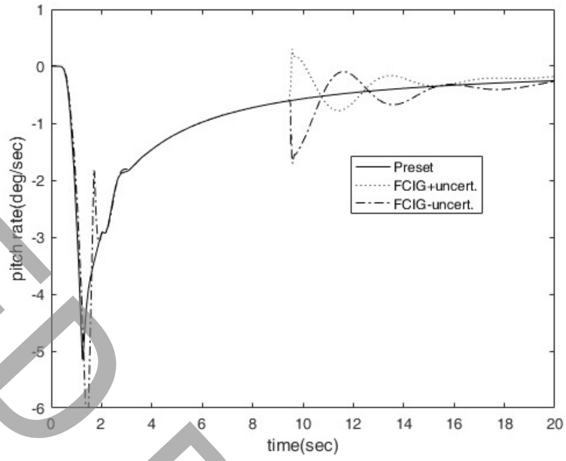

Figure 3. Flight path angle rate variations.

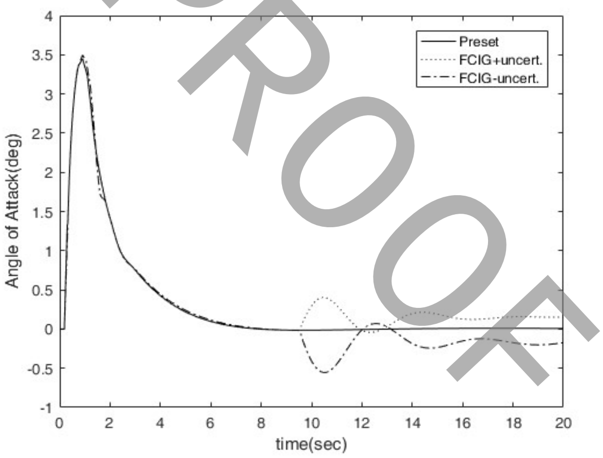

Figure 4. The angle of attack variations.

dependency to cut-off, at an arbitrary time with respect to the value of disturbances and uncertainties such as wind, thrust misalignment, thrust value, aerodynamic coefficients, to satisfy the nominal burnout time conditions. The algorithm used in this scheme is simpler, has a lighter calculation load, and is more robust to motor performance uncertainty than those used in existing schemes, which use the estimate of the velocity capability on the basis of the propellant remaining in the flight. The robustness of the algorithm in the face of worst-case uncertainties was examined by Monte Carlo simulation.

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