Engineering Notes

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Linear Optimal Guidance for an AIM-9L Missile

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Introduction

IN 1977, a study was conducted to develop a guidance law via optimal control theory for an AIM-9 type short-range air-to-air missile (AAM). The guidance law yielded small performance improvements over proportional navigation (pro-nav) in situations where heading errors are relatively small and the target maintains a high maneuver level.[1] The guidance law was developed from linear quadratic Gaussian theory

$$A_{M_C} = 3(S_R/t_{go}^2 + V_R/t_{go}) \tag{1}$$

where A_{M_C} is the three-component missile-commanded acceleration vector, S_R is the three-component relative position vector, V_R is the three-component relative velocity vector, and t_{go} is time-to-go, given by

$$t_{go} = -R/\dot{R} \tag{2}$$

where R is the missile-to-target range, and $\dot{R}$ is the range rate.

This presented two questions: 1) Was the lack of performance improvements due to the poor response of the missile? or 2) was there a problem with the derivation of the guidance law? Several studies were conducted thereafter using a highly responsive bank-to-turn missile model using Eqs. (1) and (2). Not much performance improvement over pro-nav was realized. In addition, no discrepancies were found in Eq. (1). Therefore, it was determined that t_{go} was a critical variable in the guidance law. Equation (2) is based on the assumption that range rate $\dot{R}$ is constant over the entire engagement.[2,3] This is very inaccurate for highly dynamic air-to-air engagements. Further, it has been demonstrated that the only difference between Eq. (1) using the time-to-go of Eq. (2) and pro-nav is that pro-nav assumes the missile is launched on a near-collision course such that the line-of-sight angles remain small over the entire engagement. Equation (1) does not make this assumption.[4] Studies have indicated that the small-angle assumption does not significantly alter the performance of the guidance law, thus accounting for the results in Ref. 1.

Much has been done to improve the estimate of t_{go}.[2,3] The time-to-go algorithm selected for this study is

$$t_{go} = \frac{2S_{RX}}{-V_{RX} + \sqrt{V_{RX}^2 + 4A_{MX}S_{RX}/3}} \tag{3}$$

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where S_{RX} is the X component of relative position, V_{RX} is the X component of relative velocity, and A_{MX} is the X component of achieved missile acceleration. Can significant performance improvements over pro-nav be realized for current short-range air-to-air missiles? This paper presents an analysis, to this end, using a high-fidelity AIM-9L six-degree-of-freedom missile simulation.

Note that the implementation of Eqs. (1) and (3) requires active information. Much work has been accomplished investigating several estimation techniques to acquire the required information from passive seekers.[3,5]

Guidance Law Implementation

The AIM-9L does not have an autopilot. The line-of-sight rate $\dot{\sigma}$ is processed by a first-order lag to obtain the differential piston coil currents, ΔI. This is shown by

$$\Delta I = [K_m/(\tau_m S + 1)]\dot{\sigma} \tag{4}$$

The differential piston coil currents produce a commanded differential pressure across the pistons which results in a commanded servotorque. The details of this are presented in Ref. 6. The proportional navigation guidance law is imbedded in the $K_m\dot{\sigma}$ term, where K_m is the gain of the servo-amplifier, $\dot{\sigma}$ is in deg/s, and ΔI is in mA; therefore, K_m is in mA-s/deg.

To mechanize Eq. (1), which is in ft/s², a relationship between $\dot{\sigma}$ and A_{M_C} is needed. This can be easily obtained from the pro-nav equation:

$$A_{M_C} = 3\dot{R}\dot{\sigma}/57.3 \tag{5}$$

where A_{M_C} is in ft/s², and $\dot{\sigma}$ is in deg/s. Therefore, the relationship between $\dot{\sigma}$ and A_{M_C} is

$$\dot{\sigma}/M_{M_C} = 57.3/3\dot{R} \tag{6}$$

The combination of Eqs. (4) and (6) provides a mechanization of the guidance law (1) with the missile model.

Performance Evaluation

Equations (1) and (3) were mechanized in a six-degree-of-freedom digital simulation of an AIM-9L missile. For the modern guidance law and pro-nav, an inner launch boundary was generated through numerous simulated flyouts. The inner launch boundary defines the minimum range from which the missile can be launched and achieve a hit. (A hit is scored any time the point of closest approach is within 10 ft of the target's center of gravity.) In order to limit the evaluation process, a set of initial launch conditions is selected to provide a good sampling of the weapon's performance under all expected initial conditions.

1) Missile and target are at the same speed and flying straight and level at launch (0.9 Mach).

2) Missile and target are at the same altitude at launch (10,000 ft).

3) The initial aspect angle is varied from 0 to 180 deg.

4) The initial off-boresight angle is either 0 or 30 deg lagging.

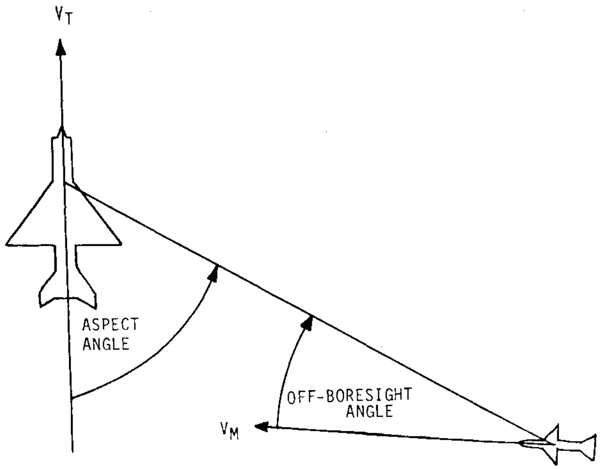

Fig. 1 Initial engagement geometry.

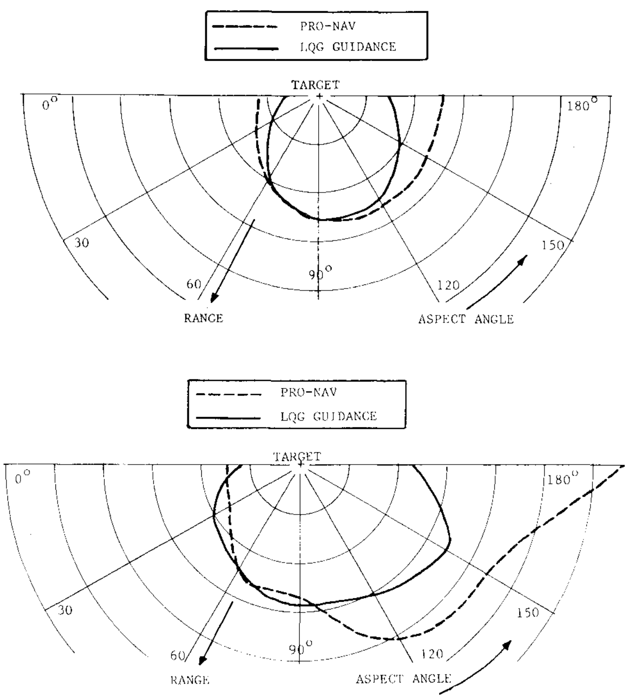

Fig. 2 Inner launch boundaries: a) 0-deg off-obresight angle, b) 30-deg off-boresight angle.

The first two conditions (speed and altitude) were selected to be representative of dogfight conditions. The aspect angle can, in reality, vary from 0 to 360 deg; however, it was limited at 180 deg because these angles represent a worst case due to the nature of the target maneuver. The two off-boresight angles were selected to evaluate the missile under a favorable off-boresight condition (0 deg) and at a difficult off-boresight condition (30 deg lagging). The initial engagement geometry is depicted in Fig. 1.

The target travels straight and level until range R is less than 6000 ft, then the target pulls a 9-g maneuver away from the missile. The results are illustrated in Fig. 2.

Results and Conclusions

The results in Fig. 2 show that modern guidance laws can provide an overall performance improvement over pro-nav, particularly in the forward-hemisphere shots. The small areas in Fig. 2b where pro-nav performed better are due to the nature of modern guidance law, which commands higher accelerations at the beginning of the engagement, then tapers off. Pro-nav, on the other hand, provides lower commands in the beginning and is forced to command high accelerations at the end. In the areas where the modern guidance law did not do as well as pro-nav, the high-acceleration commands caused the missile to act unstably. The overall performance improvements are significant. Better performances could probably be achieved if the sluggishness of the missile could be modeled into the guidance or if the missile's autopilot is modified for improved responsiveness.

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