AIAA 82-4125

Optimal Control and Estimation for Strapdown Seeker Guidance of Tactical Missiles

Paul L. Vergez* and James R. McClendon†
U.S. Air Force Armament Laboratory, Eglin Air Force Base, Fla.

Abstract

MOST contemporary tactical guided weapons utilize proportional navigation as the terminal guidance law and an inertially stabilized gimballed seeker to provide guidance information. The proportional guidance law is most often used because it can be easily implemented. It has been shown that proportional navigation is most effective under restrictive engagement conditions, i.e., small off-boresight angle launches, intercepting low-maneuverability targets; however, when employed in engagements that deviate from these conditions, proportional navigation's performance is degraded. Inertially stabilized gimballed seekers, which track the target, have been used in the past because of field-of-view limitations, physical implementation requirements to maintain seeker lock-on, and the practical consideration that this method provides the most direct means of obtaining the required inertial line-of-sight rates necessary for proportional navigation.

Contents

The air-to-air engagement (fighter vs fighter) is analytically and operationally the most demanding and complex scenario in the guided weapons arena from the point of view of the kinematics of the engagement. Further, trends in operational requirements indicate that future air-to-air missiles will require a high probability of kill under total sphere launch engagement conditions and a launch and leave capability when employed against a wide variety of highly maneuverable, intelligent targets. These requirements, when applied to conventional guided weapons, demand the use of expensive gimbals which can function under high dynamic conditions. However, this does not guarantee good missile performance. Recent advancements in seeker technology have resulted in seeker designs with much larger fields-of-view and seeker tracking characteristics which do not require the seeker centerline to point in the general vicinity of the target. Examples of such seekers include optical and radar correlators, holographic lens used with laser detectors, and phased array antennas.

The potential advantages of such seekers are numerous and result basically from the fact that the seeker can now be rigidly fixed to the weapon body. These body-fixed seekers (also referred to as strapdown seekers) have the potential of eliminating the tracking rate limits and structural limitations of inertially stabilized gimballed seekers while simultaneously reducing the mechanical complexity of implementation and calibration. The elimination of mechanical moving parts would in turn eliminate frictional cross-coupling between pitch and yaw tracking channels and accuracy degradation due to missile acceleration, and would create the potential for an increase in reliability of electronic components over mechanical ones. Finally, there are potentially significant cost savings associated with eliminating the gimbals.

Despite all these advantages, there are potential hazards associated with integrating strapdown seekers into the overall guidance system. These strapdown seekers introduce large measurement errors caused by their optics and electronics. Conventional guidance techniques do not work well with strapdown seeker measurements for two reasons. First, the measurement errors introduced by strapdown seekers are much more severe than measurement errors from a gimballed seeker, making conventional filtering techniques inadequate for filtering the noise from the measurements. Second, conventional guidance requires inertial referenced measurements but strapdown seekers only provide body-fixed measurements.

In a strapdown system the major error sources are the seeker measurements themselves, with the major contributors being scale factor error, radome errors, glint noise, and inherent angle alignment errors. For the purposes of this paper the error sources used are scale factor error and thermal noise. The approach is to develop an extended Kalman filter that explicitly accounts for these error sources and to estimate the state information required by an advanced guidance law. This approach along with some digital simulation results are presented in this paper.

Many control and estimation theories applicable to tactical missile guidance have been investigated. The guidance law selected for this study has been found to be good in terms of performance vs complexity with the performance assessed by maximizing inner and outer launch boundaries for a specified maximum miss distance, and complexity measured in terms of digital implementation in state-of-the-art weapon systems. The guidance law selected is derived from Linear Quadratic Gaussian theory. The only assumption made in the derivation of the guidance law is that the missile has instantaneous response and complete control over its acceleration. The guidance law is expressed in the following equation:

$$A_{M_C} = 3(S_R/\text{tgo}^2 + V_R/\text{tgo} + K_T A_T) \tag{1}$$

where A_{M_C} is the missile acceleration command referenced to the missile body (ft/s^2); S_R is the relative position referenced to the missile body (ft); V_R is the relative velocity referenced to the missile body (ft/s); A_T is the target acceleration referenced to the missile body (ft/s^2); and K_T is the target acceleration gain.

$$K_T = (e^{-\lambda \text{tgo}} - \lambda \text{tgo} + 1)/\lambda^2 \text{tgo}^2 \tag{2}$$

where λ is the target acceleration response time coefficient and tgo stands for time-to-go (s).

$$\text{tgo} = \frac{2S_{R_X}}{-V_{R_X} + \sqrt{V_{R_X}^2 + 4S_{R_X}A_{XX}/3}} \tag{3}$$

Received Feb. 13, 1981; synoptic received Oct. 8, 1981. This paper is declared work of the U.S. Government and therefore is in the public domain. Full paper available from the National Technical Information Service (NTIS), Springfield, Va. 22151, at the standard price (available upon request).

*Program Director, 6.1 Basic Reseach Program, Guided Weapons Division.

†Program Engineer, 6.1 Basic Research Program, Guided Weapons Division.

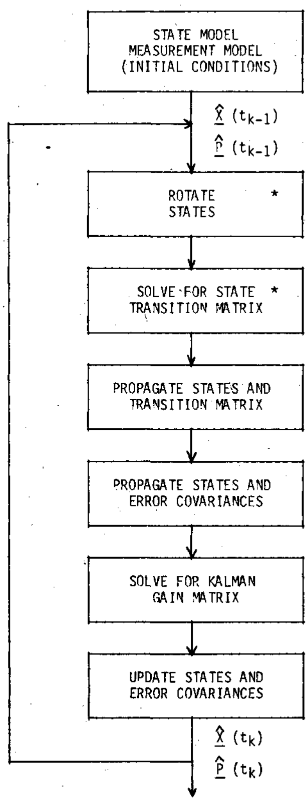

Fig. 1 Modified EKF flow diagram.

where A_{XX} is the difference between missile acceleration command and $K_T{}'X$ target acceleration in the axial direction (ft/s²).

$$A_{XX} = A_{M_X} - K_T{}' A_{T_X} \tag{4}$$

where $K_T{}'$ is K_T evaluated at the previous time interval

$$K_T{}' = K_T|_{(t-\Delta t)} \tag{5}$$

The active filter/estimator selected for this study is an extended Kalman filter (EKF). This type of filter was selected because the measurements could be modeled using nonlinear equations. The filter is needed to process the noise from a strapdown seeker and to estimate the information needed by the guidance law referenced to the missile's body-fixed coordinate system. The time invariant standard EKF will only work in an inertial fixed coordinate system and will only process Gaussian white noise (thermal noise). The filter must be modified to estimate information referenced to the body-fixed coordinate system and to process noises other than Gaussian white noise. A flow diagram of the modified EKF designed for the study is illustrated in Fig. 1, with the modifications noted with an asterisk. $\hat{X}$ and $\hat{P}$ are the estimates of the filter's state and error covariances, respectively. The remaining steps in the diagram are accomplished in the same manner as a time invariant standard EKF.

To mechanize the EKF with its state model and measurement model referenced in the missile's body-fixed coordinate system and to process both thermal noise and scale factor error requires special modifications. An 11-state EKF was used where the states are composed of the three components of relative position (S_R), relative velocity (V_R), target acceleration (A_T), and the longitudinal and lateral components of scale factor error (E_S), where

$$\dot{S}_R = V_R \qquad \dot{V}_R = A_T - A_M + W_M$$
$$\dot{A}_T = -\lambda A_T + W_T \qquad \dot{E}_S = 0 + W_S \tag{6}$$

where W_M, W_T, and W_S are the process noises for missile acceleration, target acceleration, and scale factor error, respectively.

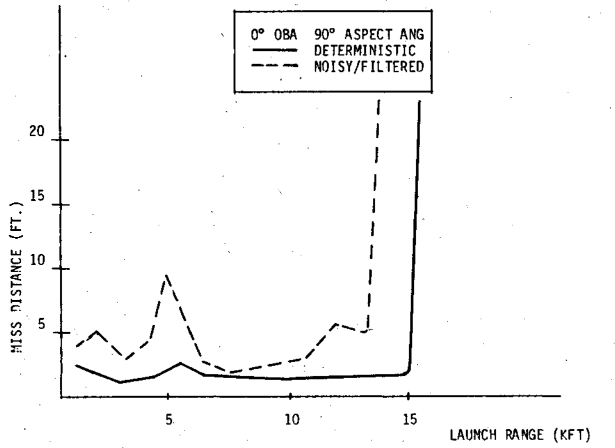

Fig. 2 Performance evaluations.

To rotate the filter's states (X) it is necessary to have a good measure of the angular displacement of the missile over a given Δt, where

$$\Delta t = t_k - t_{k-1} \tag{7}$$

The angular rates (p, q, and r) are known for any given point in time and can be used to obtain the angles necessary to rotate the filter states. If the assumption is made that the angular accelerations are constant over Δt, the angular displacement (ϕ, σ, and ψ) can be derived in the following manner:

$$\phi(\Delta t) = \Delta t \frac{p(t_k) + p(t_{k-1})}{2}$$
$$\sigma(t) = \Delta t \frac{q(t_k) + q(t_{k-1})}{2} \tag{8}$$
$$\psi(t) = \Delta t \frac{r(t_k) + r(t_{k-1})}{2}$$

To rotate the filter states from time t_{k-1} to t_k, the following operation is needed.

$$\hat{X}' t_k = T'(\phi, \sigma, \psi) \hat{X}(t_{k-1}) \tag{9}$$

$\hat{X}' t_k$ are the states which are to be propagated and T' is a roll, pitch, yaw ordered rotational matrix.

To evaluate the guidance and estimation algorithms developed for this study a detailed six-degree-of-freedom (6DOF) simulation of a generic bank-to-turn short range air-to-air missile was used. The target used in the simulation incorporated a "smart" target algorithm incorporating a $9g$ out-of-plane evasive maneuver. To evaluate the algorithms, a plot of miss distance vs launch range was generated. Figure 2 shows the results of this evaluation. The solid line represents the results if all the information required by the guidance law was available without any noise corruption (this represents the deterministic results). The dashed line represents the results using the guidance and estimation algorithms and realistic noise models. Because the noise models represent random processes, numerous Monte Carlo analyses had to be performed. A mean miss distance of 10 ft or less was considered a hit, and anything greater than 10 ft was considered a miss.

The results of this effort have demonstrated the feasibility of using optimal control and estimation theory for deriving advanced tactical missile strapdown seeker guidance concepts to yield high performance guidance algorithms.

To pursue the full potential of this high payoff technology, a more detailed study geared toward the derivation of guidance and estimation algorithms using theories (such as dual control theory) that are more applicable to the strapdown seeker guidance problem should be considered. The consideration of all typical noise sources from a strapdown seeker should also be included in this study.