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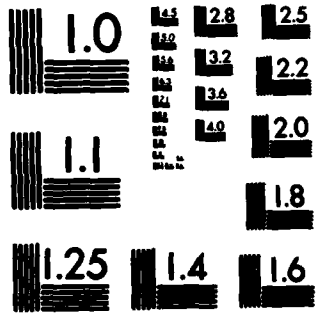

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Annual Technical Report
for
AFOSR-84-0371

Advanced Guidance Algorithms for Homing Missiles With Bearing-Only Measurements

by

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Summary

The research of this grant is directed toward the development of an advanced guidance system (navigation filter and guidance law) for a short-range air-to-air missile having a passive seeker (angle-only measurements). During this year, four subjects have been investigated. First, additional experience has been gained with the modified-gain extended Kalman filter; it is becoming apparent that it works the same as or better than the extended Kalman filter for the homing missile problem. Second, a new target-acceleration model has been developed to replace the first-order Gauss-Markov process normally used; this model allows target acceleration vector to rotate and keeps its magnitude within bounds. Third, because the homing missile problem with angle-only measurements is nonlinear, the guidance law affects the performance of the filter; a new guidance law based on maximizing a measure of the size of the information matrix has been developed and has been shown to improve filter performance. Fourth, a study of the use of new theory on fault detection has been initiated; the intent is to use this theory to detect target maneuvers (the target maneuver appears as a fault) so that the filter can be restarted.

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19. ABSTRACT (Cont.)

The research of this grant is directed toward the development of an advanced guidance system (navigation filter and guidance law) for a short-range air-to-air missile having a passive seeker (angle-only measurements). During this year, four subjects have been investigated. First, additional experience has been gained with the modified-gain extended Kalman filter; it is becoming apparent that it works the same as or better than the extended Kalman filter for the homing missile problem. Second, a new target-acceleration model has been developed to replace the first-order Gauss-Markov process normally used; this model allows target acceleration vector to rotate and keeps its magnitude within bounds. Third, because the homing missile problem with angle-only measurements is nonlinear, the guidance law affects the performance of the filter; a new guidance law based on maximizing a measure of the size of the information matrix has been developed and has been shown to improve filter performance. Fourth, a study of the use of new theory on fault detection has been initiated; the intent is to use this theory to detect target maneuvers (the target maneuver appears as a fault) so that the filter can be restarted.

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Research Objectives and Status

A special class of stochastic control systems (compensators) is being developed for the guidance law of a homing missile by exploiting the special nonlinear structure of the missile-target engagement (plant). The system block diagram is given in Viewgraph 1. The current guidance law, proportional navigation, although generally effective, degrades under initial intercept geometries that produce large nonlinearities about the homing triangle, or due to active target motion which can also induce large nonlinearities.

Our guidance law investigations have emphasized measurements from passive sensors for which only bearing information is available although many results can be extended to the active sensors where range and range rate information is available. However, the bearings-only guidance problem is the most challenging because the stochastic controller has a dual role (Fel'dbaum's dual control) which is to enhance the filter performance so as to achieve minimal expected terminal miss. Nevertheless, given the classical information pattern inherent in current missile guidance formulations, the separation theorem of Witsenhausen states that the filter structure is independent of the controller structure although the guidance system structure is highly dependent on the predicted filter performance. These notions are expressed in Viewgraph 2 along with two additional difficulties inherent in the plant that must eventually be included in the guidance formulation.

Motivated by the separation theorem, high-performance estimators have been developed first; they are tailored to the special nonlinearities of the missile-target engagement. By investigating the properties of these nonlinearities, it has been noticed that they belong to a special class which has a universal linearization with respect to the nonlinear measurement function. This means that the estimation error equations is Gauss-Markov conditioned on the measurement function and the current state estimate. Therefore, a Kalman filter formulation is reasonable where the Kalman gain reflects this universal linearization. This new filter is called the modified-gain extended Kalman filter (MGEKF) and is the subject of Viewgraph 3. Two important engineering problems fall into this special class; systems with linear dynamics in a cartesian frame but linear measurements in a spherical frame (the missile problem and state and parameter estimation in linear systems. Although we consider the MGEKF a breakthrough in guidance filter development, the coordinate-transformation-based filter [3] has shown considerable promise. The results of [2] have been applied to the problem of estimating the state and stability derivatives of the F-111 [4]. Based upon the quality of these results, we are currently reformulating the F-111 adaptive flight control system to include this estimator.

Simultaneously with this nonlinear filtering development, filter enhancement by trajectory modulation is being investigated so as to eventually design dual control guidance laws. Our initial approach (see Viewgraph 4) has been to use some measure of the Fisher information matrix as a performance index. The trace of the information matrix is most convenient since it commutes with the integration operator. Initial results show that along an information optimized path, filter performance is dramatically improved over that of a homing path using proportional navigation [5,6]. In these initial studies, the Fisher information matrix has been constructed by using the extended Kalman filter algorithm. Although much insight has been gained, the results are

performance indices are too complex to reduce to simple guidance laws. However, if guidance system analysis is simplified by assuming a deterministic structure where the filter is replaced by an observer, the dual control requirement is retained. Note that most current deterministic guidance studies assume perfect information, and, therefore, ignore delays and state estimation errors introduced by the nonlinear observer. If the information measure (or observability measure in this deterministic formulation) is based on the pseudomeasurement observer, which produces biased estimates in the presence of noise [1], then the performance index reduces to a quadratic function in the states. Combining this with the current linear-quadratic guidance problem produces a linear-quadratic cost which is not convex but seems to capture the essence of the dual control problem. The properties of this new guidance formulation are being investigated with the hope that it will have significant impact on homing guidance design.

The remainder of Viewgraph 4 describes additional difficulties that must be overcome in designing practical guidance laws. First, the measurement noise statistics are not known apriori. An algorithm for determining these statistics on-line is given in [7]. Finally, but very important, target-motion models, which reflect the missile-target engagement and are easily included in filter algorithms, are being developed [8].

References

1. T. L. Song and J. L. Speyer, "A Stochastic Analysis of a Modified Gain Extended Kalman Filter with Applications to Estimation with Bearings Only Measurements," Proceedings of the IEEE Decision and Control Conference, December, 1983, and to be published in the IEEE Trans. on Auto. Control, October, 1985.

2. T. L. Song and J. L. Speyer, "The Modified Gain Extended Kalman Filter and Parameter Identification in Linear Systems," Proceedings of the American Controls Conference, June, 1984, and to be published in Automatica, January, 1986.

3. S. Balakrishnan and J. L. Speyer, "A Coordinate-Transformation Based Filter for Improved Target Tracking," Proceedings of the IEEE Decision and Control Conference, December, 1984.

4. J. L. Speyer and E. Z. Crues, "On-Line State Estimation and Identification of Aircraft Stability Derivatives Using the Modified Gain Extended Kalman Filter," Proceedings of the AIAA Atmospheric Flight Mechanics Conference, August, 1985.

5. J. L. Speyer, D. G. Hull, C. Y. Tseng and S. W. Larson, "Estimation Enhancement by Trajectory Modulation for Homing Missiles," AIAA Journal of Guidance, Control, and Dynamics, Vol. 7, No. 2, March-April, 1984.

6. D. G. Hull, J. L. Speyer and C. Y. Tseng, "Maximum Information Guidance for Homing Missiles," AIAA Journal of Guidance, Control and Dynamics, Vol. 8, No. 4, July-August, 1985.

7. D. G. Hull, J. L. Speyer, and W. M. Greenwell, "Adaptive Noise Estimation

for Homing Missiles," AIAA Journal of Guidance, Control and Dynamics, Vol. 7, No. 3, May-June, 1984.

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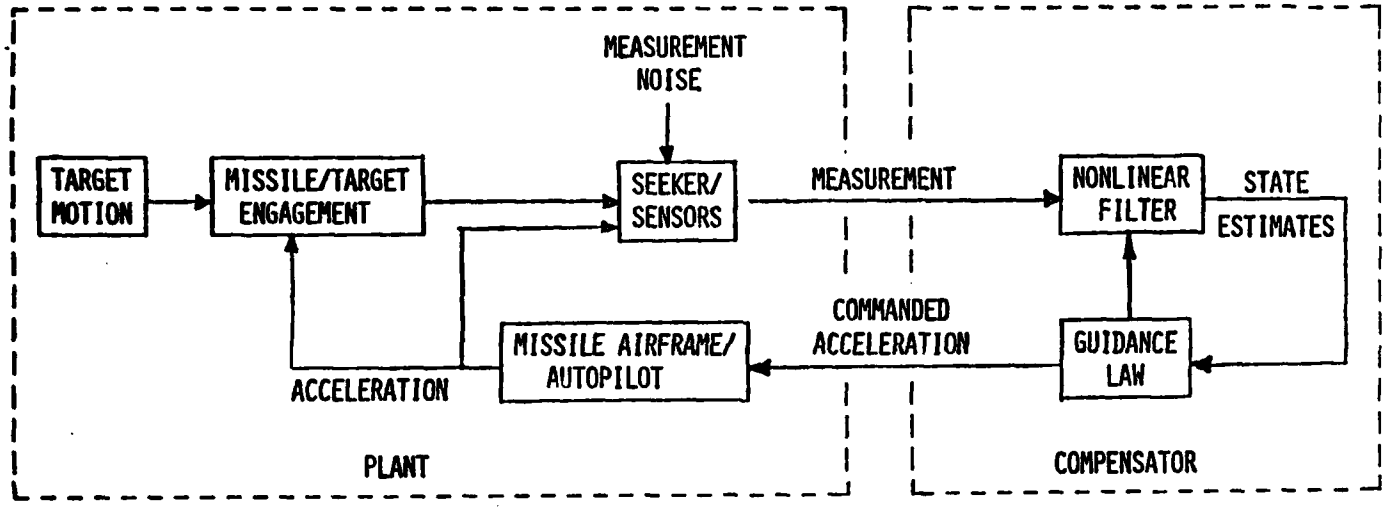
GUIDANCE SYSTEM



PLANT MODEL FOR CONTROL AND ESTIMATION

VIEWGRAPH 1

ESSENTIAL DIFFICULTIES IN GUIDANCE/FILTER DEVELOPMENT

- PLANT DESCRIBED BY A STOCHASTIC NONLINEAR SYSTEM.
  - ⇒ FILTER IS NONLINEAR BUT INDEPENDENT OF GUIDANCE LAW.
  - ⇒ GUIDANCE SYSTEM DEPENDENT ON FILTER PERFORMANCE.
    - FILTER OBSERVABILITY SHOULD BE ENHANCED BY GUIDANCE SYSTEM.
- MEASUREMENT NOISE NOT KNOWN APRIORI.
- STOCHASTIC TARGET MODEL CRITICAL.

TECHNICAL APPROACH: EXPLOIT STRUCTURE OF ENGAGEMENT MODEL

VIEWGRAPH 2

MODIFIED GAIN EXTENDED KALMAN FILTER

- SPECIAL CLASS OF NONLINEARITIES WHICH INCLUDES:
  - BEARINGS-ONLY MEASUREMENTS (ALSO RANGE AND RANGE-RATE).
    - # FORMULATED FOR THE "STRAPDOWN SEEKER ADVANCED GUIDANCE" PROJECT.
  - STATE AND PARAMETER ESTIMATION.
- CHARACTERIZED AS A GLOBALLY STABLE OBSERVER AND AN EXPONENTIALLY BOUNDED FILTER UNDER MILD CONDITIONS.
  - PROPERTIES NOT AVAILABLE FOR THE EKF.

INFORMATION ENHANCEMENT

- TRAJECTORY MODULATION FOR ENHANCED OBSERVABILITY.
  - DEVELOPED INFORMATION MEASURES.
  - DEMONSTRATED DRAMATIC IMPROVEMENT IN EKF PERFORMANCE.
  - WITH SIMPLIFIED MISSILE ENGAGEMENT MODEL DETERMINED INFORMATION ENHANCED TRAJECTORIES WITH WEIGHTED SUM OF STANDARD QUADRATIC INDEX AND INFORMATION MEASURE.
    - # OBJECTIVE IS TO DEVELOP ON-LINE GUIDANCE/FILTER SYSTEM.
- ON-LINE ESTIMATION OF MEAUREMENT NOISE STATISTICS.
  - IMPROVED MISS PERFORMANCE ESTIMATING MEASUREMENT VARIANCE ON-LINE.
  - PROCESS NOISE ESTIMATION NOT SUCCESSFUL.
- NEW TARGET MODELS FOR ESTIMATION ALGORITHM.
  - TARGET MODEL ALLOWS ROTATION OF THE ACCELERATION VECTOR AND ACCELERATION MAGNITUDE WITH BOUNDS.
    - # NEW MODEL IS IN SPHERICAL COORDINATES.
    - # OLD MODEL IS GAUSS-MARKOV.

VIEWGRAPH 4

Personnel

The personnel associated with this grant during the 1984-85 period were the following:

Dr. Jason L. Speyer
Harry H. Power Professor in Engineering

Dr. David G. Hull
M. J. Thompson Regents Professor

William P. H. Bernard
Graduate Research Assistant, M.S. student

David B. Burris
Graduate Research Assistant, M.S. student

James J. Tursa
Graduate Research Assistant, Ph.D. student

No graduate degrees based on this research were awarded during this time.

Publications

a. T. L. Song and J. L. Speyer, "A Stochastic Analysis of a Modified Gain Extended Kalman Filter with Applications to Estimation with Bearings Only Measurements," IEEE Trans. on Auto. Control, October, 1985.

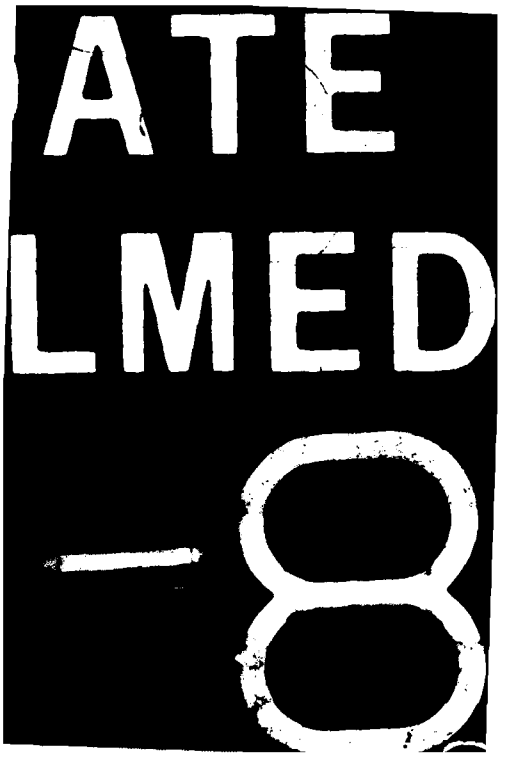
b. T. L. Song and J. L. Speyer, "The Modified Gain Extended Kalman Filter and Parameter Identification in Linear Systems," Automatica, January, 1986.

c. D. G. Hull, J. L. Speyer and C. Y. Tseng, "Maximum Information Guidance for Homing Missiles," AIAA Journal of Guidance, Control and Dynamics, Vol. 8, No. 4, July-August, 1985.

Presentations

a. S. Balakrishnan and J. L. Speyer,"A Coordinate-Transformation Based Filter for Improved Target Tracking," Proceedings of the IEEE Decision and Control Conference, December, 1984.

b. J. L. Speyer and E. Z. Crues, "On-Line State Estimation and Identification of Aircraft Stability Derivatives Using the Modified Gain Extended Kalman Filter," Proceedings of the AIAA Atmospheric Flight Mechanics Conference, August, 1985.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