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LEVEL II ①

SLBM FIRE CONTROL COMPUTATIONAL ALGORITHMS

IN SUPPORT OF STELLAR INERTIAL GUIDANCE

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I. Abstract

The addition of stellar guidance to a submarine launched ballistic missile (SLBM) system imposes special computational requirements on the fire control system. In general, the stellar guidance algorithms use the observable misorientations of the guidance inertial platform derived from an inflight star sighting and a statistical representation of the weapon system errors to obtain an estimate of the errors in the guidance computed state vector (i.e., position, velocity, and inertial platform misorientation). In practice, these errors are estimated by the application of a precomputed gain matrix to the sighting information. The computation of this gain is a fire control responsibility. The improvement in weapon system accuracy achievable through incorporation of this stellar inertial guidance scheme is dependent on the orientation of the guidance inertial platform, i.e., the star to be sighted. An additional fire control task, therefore, is the selection of a star (from a catalog of stars) which enhances the observability of system errors and restricts the propagation of non-observable system errors. The implementation of algorithms to perform these tasks in a time constrained environment is the subject of this paper.

II. Introduction

The fire control subsystem associated with a submarine launched ballistic missile (SLBM) system is responsible for the computation and transmission to the missile of all guidance and targeting data. Additional computations are required by the inclusion of a stellar guidance capability. In particular, the selection of the star to be sighted and the computation of the gain to be applied to the sighting information are required. The constituent parts of these computations (e.g., the computation of the apparent places of the candidate stars or the error analysis model used in the gain computation) are reasonably well defined. The implementation of these computations in a time constrained environment and in a manner which is consistent with the interface and accuracy requirements of the total weapon system is the subject of this paper.

The SLBM weapon system is comprised of four major subsystems: navigation, fire control, guidance and the missile. The flow of information between these subsystems is shown in Figure 1. An error flow of this system would be of this same form. Weapon system inaccuracy is the result of errors in the information produced by each subsystem and their propagation through subsequent subsystems. The subsystem errors are produced, in turn, by software inaccuracies and imperfect hardware performance. In a weapon system which uses explicit guidance, all subsystem errors finally manifest themselves as errors in missile position and velocity (as computed in guidance) and often as misorientations of the guidance inertial platform. The basic objective of stellar guidance is the estimation of these guidance state errors using a measurement of the observable misorientation of the guidance platform. The accuracy of this estimate is limited for several reasons: not all system errors produce a misorientation of the guidance platform (e.g., initial velocity errors), only two components of the misorientation of the platform are measured, and the observed misorientations are the result of many individual errors. In particular, the relationship between the position and velocity errors and the observable misorientation is different for each subsystem error. The stellar guidance scheme, under consideration here, obtains an estimate of the guidance state errors through the application of a precomputed gain matrix to the sighting information. This gain, or weighting matrix, is computed by fire control based on a priori subsystem error statistics and mission conditions.

The accuracy of the weapon system may also be shown to be a function of the sighting direction, i.e., the star to be sighted. For example, the observability of significant system errors is enhanced by the proper selection of sighting direction. Since the orientation of the guidance inertial platform is determined by the location of the selected star, the propagation of certain non-observable errors (primarily errors in the guidance inertial elements) may be restricted by the selection of the proper star. The function of the fire control star selection process is, then, to select the star (from a catalog of stars) which

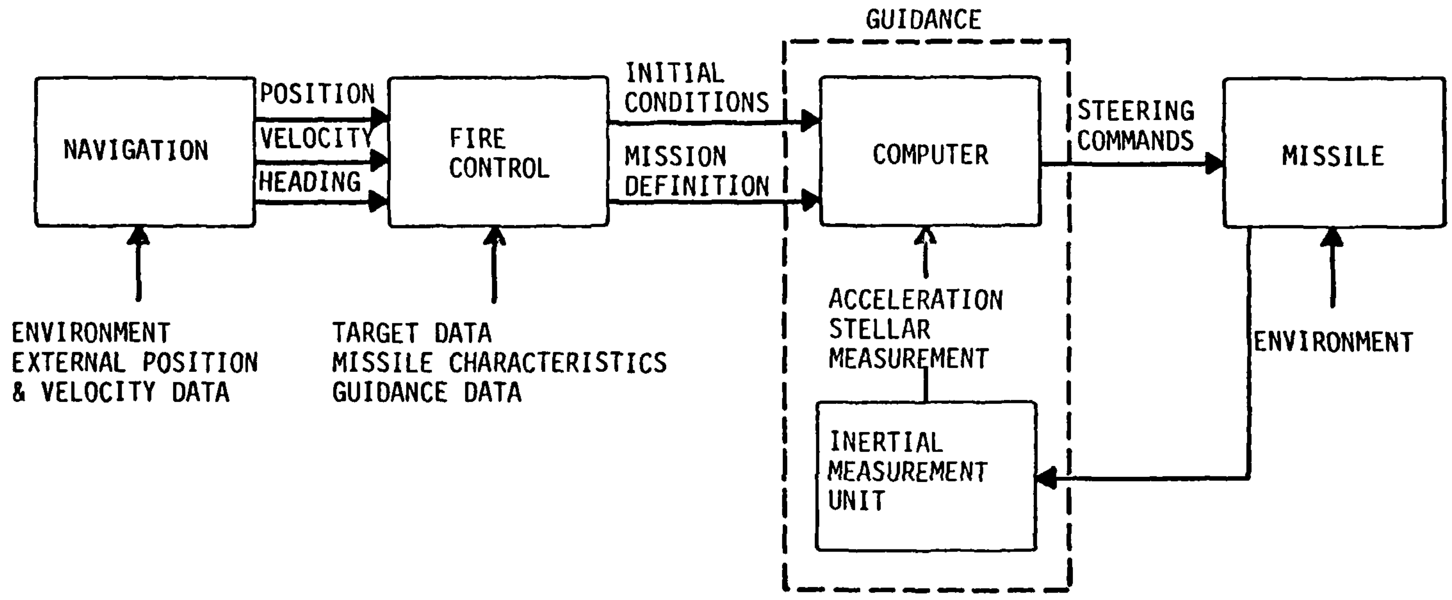

Figure 1. Information Flow

gives the best weapon system accuracy. An estimate of weapon system circular error probable (CEP) is used as a measure of system accuracy in this process. As in the computation of the gain matrix, this determination is based on a priori subsystem error statistics and mission conditions.

The implementation of these computations in fire control is constrained by the capabilities of the fire control computer and by operational conditions. A simplified representation of the operational sequence, from a fire control point of view, is given by Figure 2. After the call to Battle Stations Missile (BSM), the transition of the weapon system to a missile firing state begins. The period between BSM and a missile firing is divided into two phases: TRANSITION and the FIRING INTERVAL. The TRANSITION phase is constrained by the required "readiness time" (i.e., time to launch first missile) while the FIRING INTERVAL is constrained by the desired "firing rate" (i.e., time between successive firings). The operations performed during TRANSITION are directed towards the preparation of the entire weapon system for missile firing. During the FIRING INTERVAL, the operations are directed towards the final preparation of one missile. TRANSITION operations are performed on multiple missiles, tend to require a longer time for completion, and do not require precise knowledge of launch conditions (e.g., time of day or position). For example, positioning of the guidance inertial platform is begun early in TRANSITION. This, in turn, requires that star selection be completed at the beginning of TRANSITION. In theory, star selection requires knowledge of launch conditions. Their non-availability is a driving factor in the star selection implementation discussed in this paper. FIRING INTERVAL operations are very constrained by time and are, therefore, restricted to those which require more exact knowledge of final guidance platform orientation or launch conditions. The computation of the stellar gain matrix falls into this category. Because of the limited computational time available, a simplified and computationally efficient implementation is required. This is also addressed.

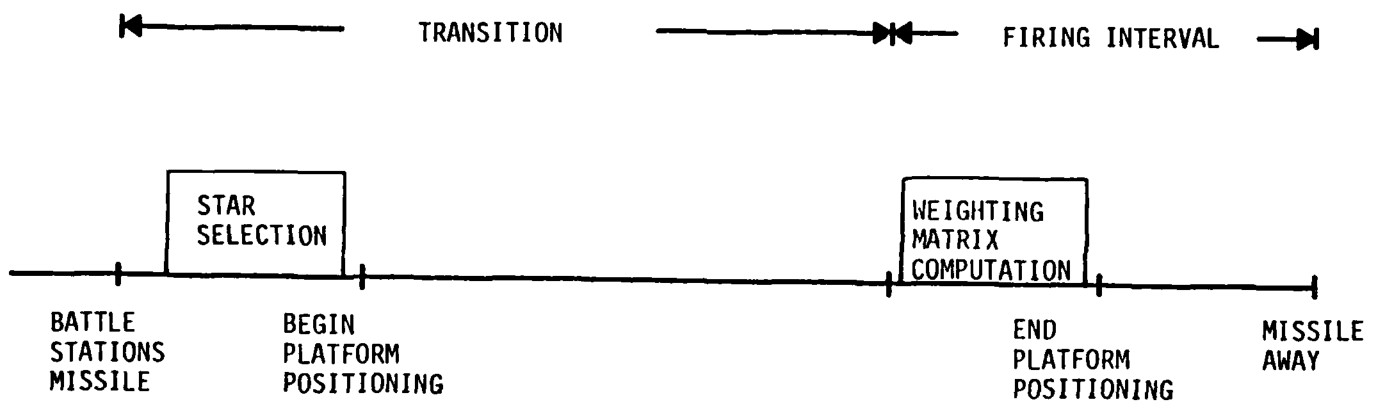

Figure 2. Operational Sequence

III. Weighting Matrix Computation

The weighting matrix is a precomputed (9x2) gain matrix that produces corrections to the guidance indicated position, velocity, and orientation from the stellar observation of two guidance misorientations during the flight. The "optimal" weighting matrix is a linear statistical estimator that minimizes the variance of the errors at sighting and therefore the resulting impact miss. The computation of the weighting matrix requires the system error statistics, error propagation equations, and the trajectory data for the mission.

The weighting matrix computed by fire control is suboptimal because of the approximations that have been made to assure a computationally efficient algorithm. However the approximations were developed so that the suboptimal weighting matrix would not cause a significant degradation of system accuracy.

One approximation is the use of a simplified linear model for the propagation of the errors. The actual system diffential equations are nonlinear, however the error propagation equations are derived by linearizing the nonlinear equations about the nominal missile trajectory as determined by fire control. The equations are also simplified by disregarding the error in the gravity computation due to the position errors. Since the effects of many of the in-flight guidance errors and the prelaunch attitude errors are acceleration dependent, the system errors are propagated using integrals of the nominal missile thrust acceleration.

Another approximation is the reduction of the number of guidance and fire control system errors that are used to compute the weighting matrix. The uncertainties in the guidance errors are assumed to be constant for all guidance systems. These errors are a result of residual errors in the calibration of the instruments and the possible change of the calibration values since the last calibration. From sensitivity studies, it was determined that many of the guidance errors could be eliminated from the computation of the weighting matrix without significantly degrading the accuracy of the estimate. Therefore, the subset of guidance errors that are used in the weighting matrix computation includes only the accelerometer bias and scale factor errors, the gyroscope bias and g-sensitive drifts, and initial misorientation errors.

The fire control implementation also uses approximations to determine the navigation system error covariance matrix. The navigation error covariance matrix changes with various system operating conditions such as latitude, velocity, navigation configuration, and time since the last correction of the navigation system using external measurements. A navigation error covariance matrix that represents the fleetwide navigation system performance can be calculated using a covariance matrix propagation program. The fire control program represents the elements of the navigation covariance matrix as polynomials with latitude and the time since last navigation system correction as independent variables. Many of the correlations between the navigation errors are ignored since they are small.

The degradation of system accuracy resulting from the approximations in the weighting matrix computation was determined by testing the fire control assumptions for many different operating parameters and trajectories. First the weapon system accuracy was determined using an optimal weighting matrix and a complete linear error model which correctly models the system dynamics. Then the suboptimal fire control weighting matrix and the resulting weapon system accuracy were computed for the same conditions. Comparison of the results showed an acceptable accuracy degradation due to the fire control approximations.

IV. Star Selection

The selection of the star to be sighted during flight is also a fire control responsibility. Weapon system accuracy varies with guidance inertial platform orientation (i.e., sighting direction) which, in turn, is a function of guidance system position and time of day. Thus, the selection of the best star, in an accuracy sense, must be performed as a function of launch conditions and predicted trajectory. The program which performs this function has three main elements: (1) computation of apparent positions of stars in star catalog, (2) determination of availability for use of stars in catalog and (3) selection of star which yields best weapon system accuracy.

In addition to the required launch and trajectory conditions, fire control also has available a limited catalog of usable stars, and orbital elements for Mercury, Venus, Earth, Mars, Saturn and Jupiter. The catalog contains a list of stars, and associated position information, which meet certain brightness and separation constraints imposed by the stellar sensor. The position data are for a specified epoch, e.g., 1950.0, and must be updated by the selection program. Thus, constants for use in updating position due to the effects of proper motion, precession, nutation, aberration and heliocentric parallax are also stored. The actual position updates are done in two steps. All stars in the catalog are updated for the effects of precession and proper motion. The positions thus updated are used in all remaining calculations. After a final selection has been made, the position of the selected star is updated to account for the effects of nutation, aberration and heliocentric parallax.

Not all stars in the catalog are usable, or "available", under all combinations of launch and trajectory conditions. To be available for further consideration, a star must not be occluded by any of the planets mentioned above (excluding Earth), the moon or the sun and must satisfy certain directional constraints. The occlusion constraints are implemented in the program by the imposition of minimum angular separations on the celestial sphere between the star and each of the bodies. The positions of the planets, sun and moon are computed, in an earth centered coordinate frame, for the time of star selection in order to compute these angular separations. The occlusion regions include not only the regions of direct occlusion by the body but also the region around the body where the background illumination is incompatible with the requirements of the stellar sensor. Further, the star is constrained to lie within specified elevation limits and within the hemisphere centered about the velocity vector at the time of the star sighting. The lower elevation limit is essentially equivalent to an "earth occlusion" constraint, while the upper elevation limit is imposed by the limitations of the guidance platform. The constraint related to sighting velocity is imposed in order to minimize degradation of missile range capability due to propellant usage for sighting maneuvers. Since the completion of star selection is a prerequisite for the positioning of the guidance platform, this function must be performed early in the launch sequence. Further, the length of time from star selection to the launch of the missile is unknown a priori. Therefore, the directional constraints defined previously must be satisfied both at the time of selection and for a minimum length of time following selection. The occlusion constraints, however, are imposed only at the time of selection. The stars which meet these criteria are candidates for selection and must now be evaluated in terms of weapon system acccuracy.

Weapon system accuracy is dependent on the selected star for two main reasons. First, only two components of the guidance platform misorientation are measured and, thus, the degree to which system errors are observable and, hence, correctable, is a function of the guidance platform orientation. Further, the propagation of certain errors (primarily errors in the guidance inertial elements) is also dependent on guidance orientation. The guidance platform orientation changes not only with choice of star, but also with time, for a given star, since the position of the star relative to an earth fixed reference changes. At the time of star selection, the actual launch time is unknown. Thus, the accuracy potential of each star is evaluated over an "optimization" interval. The "optimization" interval includes the nominal launch time and allows for unexpected delays in the launch sequence. Accuracy potential is measured by average weapon system CEP over the interval which is determined using an error analysis model. The implementation of this process in fire control must consider computational efficiency. This screening limits further consideration to stars near an a priori preferred direction. The acceptability region is defined such that the best catalog star is considered in the accuracy evaluation in nearly all cases. In the accuracy evaluation procedure, the average weapon system CEP over the optimization interval is approximated by the CEP at the middle of the interval, thus, further reducing the number of accuracy evaluations required. Even with these efficiencies, simplification of the error analysis model is required. Thus, a model similar to that developed for the weighting matrix computation is used to compute an approximate CEP. The error propagation through the boost phase of the trajectory is subject to the same approximatons. Error propagation subsequent to the stellar sighting is done using a Kepler transition matrix.