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PERFORMANCE ANALYSIS OF INTEGRATED NAVIGATION SYSTEMS

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ABSTRACT

A generalized Covariance Error Analysis Simulator (CEASIM) has been developed for GPS/INS integrated navigation systems. Equations for the propagation in time of the attitude, position, velocity and sensor errors are implemented with a 64-state system model. Alignment equations for a typical fourth-order INS alignment/calibration loop are incorporated for covariance initialization. CEASIM can be used to study various Kalman filter and sensor configurations as part of proposal or preliminary design efforts. The simulator is capable of analysing GPS/INS system performance over a variety of mission profiles, including aircraft, ships and land vehicles.

I. INTRODUCTION

The marketing, design and production of GPS/INS (Global Positioning System/Inertial Navigation System) integrated navigation systems necessitates the development of detailed computer simulations to compare and validate design concepts and predict performance. Each phase of system development, from marketing to production, imposes a unique set of simulation requirements. CAST has developed a family of products which satisfy these needs, and range in capability from covariance and Monte Carlo designs to special purpose simulators for evaluation of detailed design issues. The initial development was part of a successful marketing effort conducted with Interstate Electronics Corporation (IEC) for the GPS Range Application Program (GPS-RAP). In order to predict the performance of the system being proposed, CAST developed a covariance error analysis simulation CEASIM for stand alone, and inertially aided (strapdown) GPS systems operating on a wide range of vehicles (aircraft, ships, jeeps, etc.). CEASIM is designed to support proposal, feasibility, and preliminary design studies, and is the topic of this paper. The remaining products developed to support detailed design and flight test evaluation will be the subject of future papers.

II. OVERVIEW

CEASIM is a general purpose error covariance simulator for GPS/INS integrated navigation systems. The input/output and control is shown in Figure 1. It is designed to provide a high degree of flexibility with minimal demands placed upon the user. All input and control parameters are clearly defined in the input data files.

The system design parameters which can be optimized and/or evaluated by the simulations on CEASIM include the following:

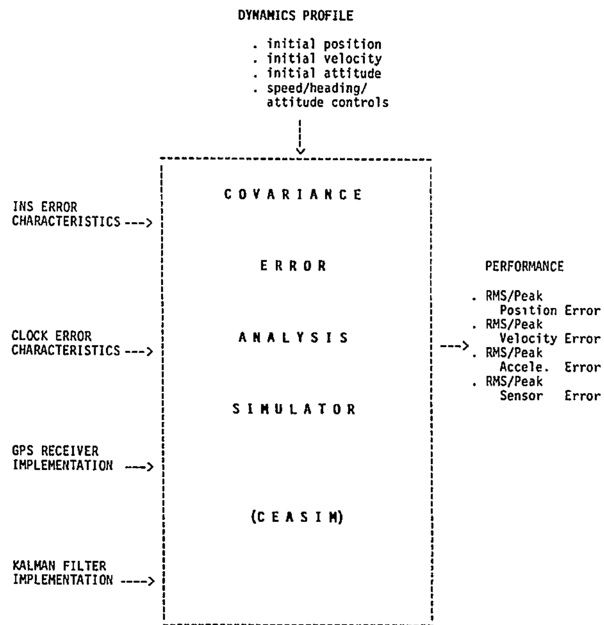

Figure 1: CEASIM INPUT/OUTPUT STRUCTURE

INS
. Gyro Characteristics
. Accelerometer Characteristics
. Gyro/Accelerometer Configuration

GPS Receiver
. Clock Characteristics
. Number of Channels
. Channel Dwell Time
. Delta-range Interval
. Satellite Tracking Strategy

Filter
. Filter States
. Adaptive Process Noise
. Tuning Parameters

Antenna
. Antenna Shadowing
. Antenna Selection

CEASIM also has the capability of simulating a variety of practical real-world conditions. This capability has been designed into the simulator in the form of operator controlled inputs that allow a variety of signal environments and vehicle dynamics:

Signal environment
. User/Satellite geometry
. Signal shading/outage

Vehicle dynamics
. Acceleration/deceleration
. Constant velocity cruise
. Turn/pitch/roll
. Climb/descend

The CEASIM Block diagram is shown in Figure 2 and consists of the following modules:

1. EXEC : Main Executive
2. UMG : User Motion Generator
3. SMG : Satellite Motion Generator
4. ALIGN : INS Alignment/Calibration
5. COVPRO : Real-World Covariance Propagation
6. COVUPT : Real-World Covariance Update
7. FILTER : Kalman Filter
8. LOS : Line-of-Sight Computation
9. SHADE : Antenna Shadowing
10. COORD : Coordinate Transformations
11. SATSEL : Satellite Selection
12. GDOP : GDOP Computation
13. RCVR : Receiver Controller
14. UTILITY : Utility Routines

For specified initial conditions and a set of motion profile inputs involving speed, heading and attitude changes, the User Motion Generator (UMG) numerically integrates the host vehicle's equations of motion. Outputs from UMG at specified time intervals, including vehicle position, velocity, acceleration, jerk, attitude and attitude rates, expressed in reference, body, and sensor frames, are used to drive the Real-World Error Covariance Propagation (COVPRO) routine and Kalman Filter (FILTER).

The Covariance Propagation routine (COVPRO) simulates a complete model of INS and GPS sensors and propagates the associated error covariance matrix. The Line-of-Sight (LOS) routine computes the line-of-sight vector to each satellite, using the vehicle states from UMG and the satellite states from the Satellite Motion Generator (SMG). The GDOP computation routine (GDOP) computes the GDOP (geometric dilution of precision) value for all possible combinations of four or five visible satellites. Outputs from GDOP are used by the Satellite Selection routine (SATSEL) to select the optimal and backup satellite constellations. The Antenna Shadowing routine (SHADE) computes the azimuth and elevation angles to each satellite and determines the satellite visibility. Outputs from SATSEL and SHADE are used by the Receiver Controller routine (RCVR) to assign optimal or alternate satellites for measurement processing. The line-of-sight vectors for the selected satellites are provided to the Kalman Filter routine (FILTER) to update the Kalman filter error covariance. The Kalman gain generated by FILTER is then used by the Covariance Update routine (COVPUT) for real-world error covariance measurement update. In addition to the control program execution, the Main Executive (EXEC) routine also computes and outputs the square roots of the real-world and Kalman filter error variances. An off-line program plots these errors and provides statistical data such as peak and RMS errors.

CEASIM generates the following error summary for a specified scenario:
a. Real-World position, velocity, acceleration, tilt, clock bias and frequency errors,
b. Real-World gyro and accelerometer bias errors,
c. Filter estimated position, velocity, acceleration, tilt, clock bias and frequency errors, and
d. Filter estimated gyro and accelerometer bias errors.

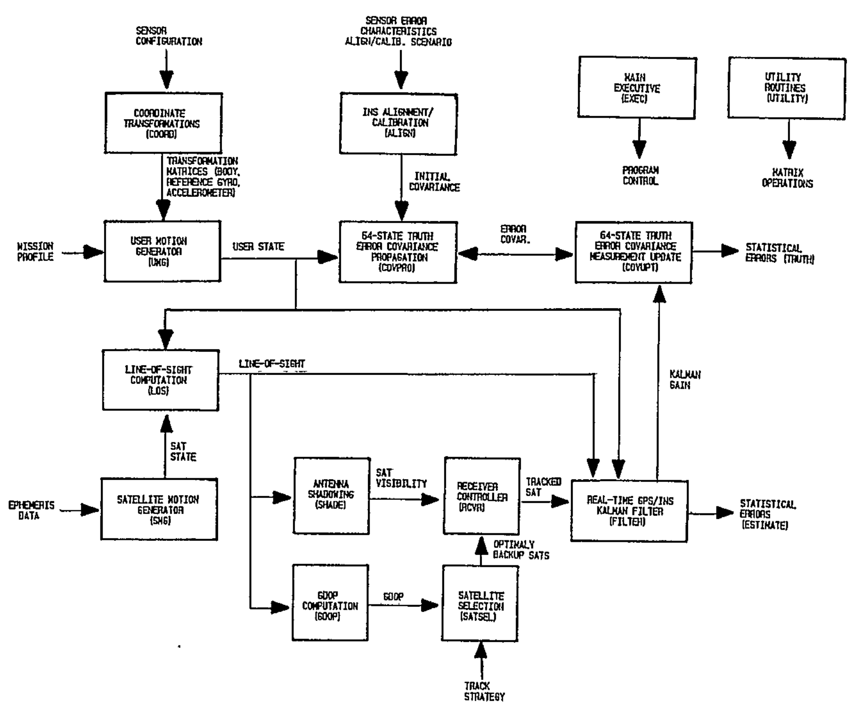

Figure 2: GPS/INS COVARIANCE ERROR ANALYSIS SIMULATOR (CEASIM)

CEASIM performs an essential role in the design and evaluation of GPS/INS integrated navigation systems. The primary uses include:

a. Performance Evaluation,
b. Filter Design Trade-off,
c. Receiver Configuration Trade-off,
d. Error Budget, and
e. Sensitivity analysis.

The benefits derived from the simulation include the following:

a. statistical evaluation of system performance,
b. low cost screening of candidate system design,
c. timely evaluation results,
d. repeatable tests using validated model,
e. insight into system behavior, and
f. optimal selection of sensor error parameters.

III. PROCESSING DESCRIPTION

The main purpose of CEASIM is to evaluate integrated system performance as a function of the Kalman filter design and sensor error characteristics.

The Kalman filter equations provide a simple set of rules for designing optimal linear filters. At first glance, the problem of filter design appears to have been solved. However, when the Kalman filter is applied to practical problems, several difficulties arise. The truly optimal filter must model all error sources in the real-world system, this usually results in an impossible burden on the computational capabilities available, and forces the filter designer to ignore or simplify certain aspects of the design. In addition, the system dynamics and error statistics are usually not known precisely, and results in a suboptimal design. It is imperative to perform a simulation of the proposed system and establish the effects of mismodeling and approximations relative to the real-world system.

CEASIM models the real-world using a 64-state truth model which includes the system performance and sensor error models in a single covariance matrix.

The real-world system model can be completely characterized by the following five system matrices:

P_0 the initial truth model covariance matrix (m x m)

F the truth model dynamics matrix (m x m)

H the truth model measurement matrix (r x m), where r is the number of measurements

Q the truth model process noise matrix (m x m)

R the truth model measurement noise matrix (r x r)

These five system matrices represent a linearized description of the entire physical system.

The alignment equations for a typical fourth-order INS alignment/calibration loop are incorporated as part of the covariance initialization process.

The Kalman filter can be completely characterized by the following five filter matrices:

$\hat{P}_0$ the initial filter covariance matrix (n x n)

$\hat{F}$ the filter dynamics matrix (n x n)

$\hat{H}$ the filter measurement matrix (r x n), where r is the number of measurements

$\hat{Q}$ the filter process noise matrix (n x n)

$\hat{R}$ the filter measurement noise matrix (r x r)

In general, F, H, Q, R, $\hat{F}$, $\hat{H}$, $\hat{Q}$, and $\hat{R}$ are time-varying matrices, whose elements are computed during the course of the problem solution.

The immediate objective in running the program is to produce:

a. A quantitative measure of overall system performance, showing how the n-state filter design performs in the m-state real world,
b. a detailed error budget, showing the contribution of each system state or driving noise (both those that are modeled and those that are unmodeled in the filter) to estimated errors

The results provide insight into the various error mechanisms involved, and lead to improved filter design and sensor selection.

The two sets of covariance equations, involving P and $\hat{P}$, are presented below. Both sets of equations are recursion relations which alternately propagate the covariance between measurements and update the covariance at measurement times. The relationship between these two sets is explained with the aid of the information flow diagram in Figure 3. This relationship is a key element in determining the organization of the covariance analysis computer program.

The filter covariance equations are

a) Time Propagation:

$$\hat{P} = \hat{F}\,\hat{P}\,\hat{F}^T + \hat{Q} \qquad (2\text{-}1)$$

b) Measurement Update:

$$\hat{K} = \hat{P}\,\hat{H}^T\,[\hat{H}\,\hat{P}\,\hat{H}^T + \hat{R}] \qquad (2\text{-}2)$$

$$\hat{P} = (I - \hat{K}\,\hat{H})\,\hat{P} \qquad (2\text{-}3)$$

The truth model covariance equations are

a) Time Propagation:

$$P = F\,P\,F^T + Q \qquad (2\text{-}4)$$

b) Measurement Update:

$$P = (I - K\,H)\,P\,(I - K\,H)^T + K\,R\,K^T \qquad (2\text{-}5)$$

where K is n m x m matrix which is the same as the filter calculated gain matrix $\hat{K}$ (n x n) with additional zero elements in those states which are not estimated by the filter.

As shown in Figure 3, the upper half of the diagram represents the solution of the filter covariance equations. These are solved in order to generate the sequence of filter gains, K, which are used by the lower half of the diagram, representing the solution of the truth model covariance equations.

The propagation of the P and $\hat{P}$ matrices as a function of time represents the major funciton of the simulator and all of the performance and error sensitivity information is contained in these matrices.

The outputs of a simulation run are represented by specific values and time averages of elements of the P matrix.

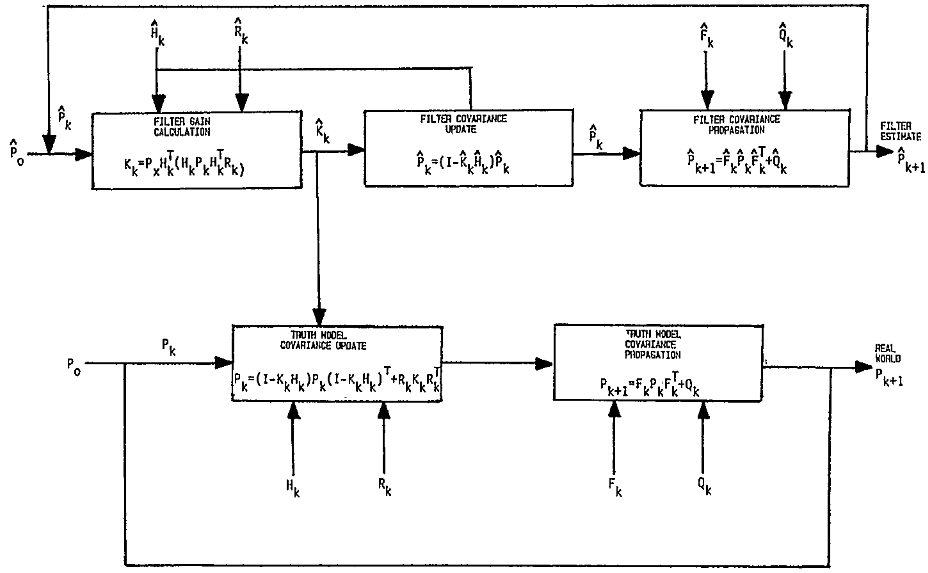

Figure 3: **COVARIANCE ANALYSIS INFORMATION FLOW**

IV. CONCLUSION

The GPS/INS Covariance error analysis Simulator (CEASIM) which has been developed represents a complete system model for an inertial unit and a GPS receiver. These two sensors are integrated using a Kalman filter. CEASIM allows a high degree of flexibility in the selection of various GPS/INS sensor parameters and filter designs.

The purpose of this simulator development has been twofold. One is to evaluate the system performance under specified environments. Simulations may be performed for a variety of specified conditions and the results used for the screening of candidate system configurations. The second purpose is to verify preliminary design and analysis of various GPS/INS implementations. Particular benefits which have been derived are the concept verification of Kalman filter designs.

CEASIM was developed to accommodate a wide range of environmental modifications. The inputs include sensor errors, vehicle maneuver profile, satellite constellation, receiver configuration, antenna shadowing silhouette, and satellite tracking strategy. Its capability to predict system performance under a broad spectrum of simulated conditions has already proven CEASIM to be a highly useful tool for the study/design of GPS/INS integrated navigation systems.

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