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On the GPS/IMU sensors' noise estimation for enhanced navigation integrity☆

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Abstract

In this paper, the problem of estimating the measurements' noise statistics of the Global Positioning System (GPS) is addressed. First, a model matching technique is used to estimate the GPS measurements' noise statistics. Then, the formulation of the measurements and process noise estimation using the Autocovariance Least Squares technique will be derived for the time-varying GPS/IMU system. It is assumed that the process noise covariance matrix is known or determined *a priori* through off-line calibration. The Autocovariance Least Squares method improves on the assumptions of the model matching technique by considering the time-correlation in the measurements' residual sequence due to the *a priori* unknown GPS measurements' noise covariance matrix. Both methods make use of statistical sampling theory in the estimation filter. Simulation results for both methods will be presented at the end of the paper. The results are compared and the improvement gained when using the Autocovariance Least Squares method in comparison to the model matching technique will be shown.

Keywords: GPS; IMU; Noise estimation; Statistical estimation

1. Introduction

The use of the augmented Global Positioning System and Inertial Measurement Unit (GPS/IMU) systems for state estimation is increasing [5,6,9,16]. Applications of these systems are finding more horizons in the automotive sector, aerospace industry, and the communication world. Various estimation techniques are used to fuse the GPS measurements and the IMU sensors' measurements. These techniques are mostly centered around the Kalman or extended Kalman filtering algorithms. The knowledge of the statistical distribution of the GPS and IMU measurements is crucial to achieve an acceptable estimation accuracy. Upon choosing an appropriate GPS and IMU error model, there is a need to characterize the dynamics and measurements noise of this error model. Therefore, the dynamics' noise covariance matrix and the measurements' noise covariance matrix need to be estimated. Different estimation methods can be approached to estimate these covariance matrices [1–3,8,10–14,17,18]. From those, covariance matching and the Autocovariance Least Squares techniques are used.

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Currently, GPS users assume nominal operating conditions in setting a fixed measurements' noise covariance matrix or adapt a varying GPS measurements' noise covariance matrix depending on satellites' elevation angles or the satellites' signal to noise ratio, see [4,15,19,20]. In fixing the covariance matrix of the GPS measurements noise, the user completely ignores the possibility of a change in the GPS measurement accuracy due to a change in the GPS receiver's quality or due to the operation in adverse environments. On the other hand, when the GPS measurements' noise covariance matrix is set based on the satellites' elevation angles, other factors such as signal multipath, interference, jamming, or receiver aging are ignored. The problem of using the signal to noise ratio in choosing the measurements' noise covariance matrix is that this signal is not available in common GPS receivers. Even if this signal is available, its physical interpretation is not clear since GPS manufacturers have different techniques in computing this value. Also, the correlation between this value and the value of the measurements' noise covariance matrix is not straight forward. Therefore, using an adaptive technique to estimate the GPS measurements' noise covariance matrix is found very crucial.

Noise-estimation algorithms are used extensively in the field of speech recognition enhancement, Refs. [2,3,17,18]. The algorithms proposed in these methods are based on detecting the speech noise characteristics when no speech signal exists. These methods cannot be adapted for GPS/IMU signals since the GPS receiver and the IMU are always measuring the vehicle ranges to the satellites and the dynamics of the vehicle, respectively. In other words, there is no time when the measurements of the GPS and the IMU are noise-only measurements.

The use of model-based noise statistics estimation is applicable for GPS/IMU measurements' noise estimation [8,10–14]. In this study, the covariance model matching techniques [8,12], and the Autocovariance Least Squares techniques [13,14] will be investigated for GPS measurements' noise statistics estimation. The Autocovariance Least Squares technique was introduced in Refs. [13,14] for time-invariant systems. Because our GPS/IMU system has a time-varying error model, the formulation of the method for time-varying systems will be derived.

In this paper, after the problem of GPS/IMU noise estimation is formulated, the use of the covariance matching techniques [8,12] and the Autocovariance Least Squares technique [13,14] will be compared. The covariance matching noise-estimation technique will be first described. Subsequently, the formulation of the time-varying Autocovariance Least Squares technique will be derived. The GPS measurement noise statistics will be estimated using both methods. The improvement gained when using the Autocovariance Least Squares method over the model matching estimator will be highlighted.

The GPS/IMU estimation filter is initialized with assumed dynamics and measurements' noise covariance matrices. In the covariance matching noise-estimation method, a history of measurements' residuals is continuously stored. The stored measurements' residuals statistical mean and covariance are used to estimate the unknown measurements' noise mean and covariance matrix. This method is a recursive method that estimates the measurements' noise mean and covariance matrix in real-time and updates their values to account for any change in sensors measurements' quality or sensors' environment over time. On the other hand, the Autocovariance Least Squares method is a batch estimation technique. Since the state estimation filter starts with using a possibly inaccurate noise covariance matrices in the filter structure, the measurements' residual sequence will be correlated in time. This correlation is exploited in estimating the unknown covariance matrices.

A GPS/IMU measurements simulation will be utilized in this work to check the performance of the noise estimators. A truth GPS measurements noise will be fed to the simulation. The noise estimation filter will be used to estimate the GPS measurements noise statistics. The estimated measurements' noise statistics will be compared with the simulated one to show the estimation accuracy of the filter. The IMU measurements' noise covariance matrix, which is the system's process noise covariance matrix, will be assumed known. This matrix is usually determined *a priori* through off line calibration techniques.

In the next section, The GPS measurements' equations will be described. The proposed methods can be used for estimating the measurements' noise characteristics of the C/A code, carrier, and range rate measurements. In this paper, the results obtained from applying the two noise-estimation methods to estimate the GPS measurements' noise statistics are presented and compared.

2. GPS measurements

For real-time estimation of a vehicle's position, velocity, and attitude, the GPS C/A pseudo-range and pseudo-range rate measurements are used. To obtain a more accurate vehicle state estimate, the GPS carrier phase measurement is used instead, or with, the C/A GPS measurement [6,16,5].