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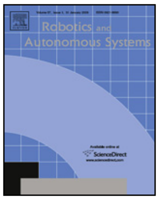

The integration of strap-down INS and GPS based on adaptive error damping

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ABSTRACT

The concept and results of integration of a strap-down inertial navigation system (INS) based on low-accuracy inertial sensors and the global positioning system (GPS) have been presented in this paper. This system is aimed for the purposes of navigation, automatic control, and remote tracking of land vehicles. The integration is made by the implementation of an extended Kalman filter (EKF) scheme for both the initial alignment and navigation phases. Traditional integration schemes (centralized and cascaded) are dominantly based on the usage of high-accuracy inertial sensors. The idea behind the suggested algorithm is to use low-accuracy inertial sensors and the GPS as the main source of navigation information, while the acceptable accuracy of INS is achieved by the proper damping of INS errors. The main advantage of integration consists in the availability of reliable navigation parameters during the intervals of absence of GPS data. The influence of INS error damping coefficients is different depending on the fact whether the moving object is maneuvering or is moving with a constant velocity at that time. It is proposed that INS error damping gain coefficients generally should take higher values always when GPS data are absent, while at the same time their values in the error model (EKF prediction phase) can be additionally adapted according to the actual values of vehicle acceleration. The analysis of integrated navigation system performances is made experimentally. The data are acquired along the real land vehicle's trajectory while the intervals of absence of GPS data are introduced artificially on the parts characterized both by maneuver and by constant velocity.

1. Introduction

The integration of heterogeneous navigation systems is an approach frequently used in order to increase the overall reliability and accuracy of navigation algorithms. One of the most popular examples nowadays consists in the integration of inertial navigation and global positioning systems. The main idea behind this approach is based on the fact that the errors characterizing any one of them separately are not mutually correlated at all. While the GPS errors are due to RF channel disturbances, changes in configuration of observed satellites, occlusions of the receiver antenna, and atmospheric influences, the errors characterizing an INS are of a long periodic nature and are independent on environmental conditions. According to these facts, one can expect that two systems could assist and correct each other, increasing the overall navigation system reliability and accuracy this way. Satellite based positioning system provides more accurate information regarding the moving object's position and linear velocity in comparison to INS, especially if one considers a low-cost strap-down INS suitable for the land vehicle navigation applications. The function of such type of an INS consists in providing navigation parameters on the intervals between consecutive GPS measurements, calculation of an object's angular orientation, and providing the overall set of navigation parameters during the intervals of absence of GPS data. In other words, only the short-term accuracy of an INS is required. While the GPS measurements are available, the estimations of INS errors are calculated and these are used for INS corrections on the intervals when GPS data are absent. Besides this function, GPS data are used during the INS initialization and calibration also.

For the cases of middle- and high-accuracy INS, there are two basic methods/schemes of INS/GPS integration: centralized and cascaded ones [1,2]. In the case of a centralized scheme, there exists a unique INS/GPS navigation algorithm with a generalized navigation parameter error model. In the cascaded integration scheme, corrections of INS output information are done based on GPS measurements, without changes in navigation data processing, neither in the INS nor in the GPS part of the algorithm. Cascaded scheme is the more traditional one, based on the concept that both INS and GPS parts of the system calculate the same set of navigation parameters (position and velocity) independently. The difference of these two sets of data is used as the input of the filter estimating the long-term errors of INS. There are a few general disadvantages of this approach: (1) it generally requires high quality inertial sensors (allowing the small errors of INS—inside the region of linearization) and

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(2) preprocessing inside the GPS part of the system in order to produce position and velocity output causes a loss of information and undesired cross correlation among the output signals. From these points of view, the choice of centralized scheme where the measurements of inertial sensors and measurements of range and range rate are considered as equally relevant inputs while both strap-down INS and GPS mechanizations are implemented together, is advantageous one. On the other hand, wherever the set of independent sources is used, the cascaded integration scheme is preferable (allowing the full freedom of interchanging of GPS receivers and inertial measurement units). If one wants to use the low-cost/low-accuracy INS inside this integration scheme, the problem of system initialization as well as of the on-line error estimation and proper error corrections becomes more meaningful.

The approach used here in integration of INS and GPS is based on theoretical basis presented in [3,1,4,5]. The optimization of an inertial navigation algorithms based on information regarding moving object's dynamics is particularly considered in [6]. The concept of INS error damping is considered in [4,7].

One can recognize the following main items in an attempt to design and implement the integrated INS/GPS navigation system for various applications, including the cases of automatically controlled land vehicles:

1. Overall system configuration (basically it is GPS + "Inertial Measurement Unit", but sometimes without rate gyros, with addition of magnetometer, angular sensors, odometer, etc.);
2. Quality of inertial instruments and their error model parameterization (the type of instrument error models and procedures of actual parameterization);
3. Duration of the initialization/alignment phases (how complex and how long these procedures are and what could be done to make them adaptive in some way in order to reduce their duration);
4. Complexity of an integration algorithm (tight or weak coupling of navigation systems, variability of measurement error model, additional navigation state error damping, how to prepare the system for the intervals of GPS data absence, etc.);
5. System performances during the intervals of absence of GPS data (the existence of vehicle maneuver during these intervals).

While for some applications, [8], it was proposed to use gyro-free "dead-reckoning" configuration, our choice was to use the full strap-down navigation system as the INS part of system, as in [7], because of the fact that moving across a terrain introduces meaningful pitch and roll angles and that the gravity components affect the acceleration measurements in an appreciable extent. The magnetometer and two additional angular sensors have been added for the initial alignment purposes while the usage of an odometer was assumed as the alternative source of velocity data when GPS signals are absent.

There is a general trend to use low-accuracy inertial instruments in these systems (mostly of MEMS type, while in our case these were of electro-mechanical type). The importance of proper error model parameterization was appreciated and this was done in a manner like in [9] where only the strap-down INS was used for a land vehicle navigation purposes.

Some authors, [10–12], have suggested the usage of an adaptive Kalman filter scheme or the banks of Kalman filters in order to reduce the time needed to obtain good estimates of instrument error models during the initial alignment phase. Our approach consisted in use of "regular" extended KF (the same as in navigation mode) because the experiments have shown that the required duration of this process was still acceptable.

Regarding the type of integration scheme, we have chosen the modified cascaded one as the type allowing full separation of navigation systems. The quality of EKF estimation during the integrated navigation phase is generally monitored and in some examples, [13], the adaptive tuning of EKF is suggested. In our case, we have used the simple idea to monitor the values of residuals and to use the predicted values of outputs instead of actual measurements if the last ones are of the "outlier" type. The type of EKF used in our approach was the one with additional control signals, as it was suggested in [4], but the important modification was done by separating INS error damping signals apart from KF control signals.

The very important task of preparing of a system for the prediction phase when GPS data are absent, some authors solve by application of artificial neural networks, [14], in order to make the model of navigation state error as accurate as possible. On the other hand, we have recognized the fact of vehicle maneuvering as the most important one characterizing the dynamic environment at the moment when GPS data are lost and suggested the usage of odometer as the alternate source of velocity data and the adaptation of error damping coefficients according to the measured values of vehicle's accelerations.

The main contribution of this paper consists in a separation of INS error damping and EKF control signals and in acceleration dependent adaptation of velocity error damping coefficients during the intervals of absence of GPS data. Because of these modifications, RMS position errors during the intervals of regular INS/GPS integration mode remained the same, while in intervals of GPS data absence they have been appreciably reduced in comparison to the known results where low-accuracy INS had been used in INS/GPS integration.

The overall INS/GPS integration scheme is explained in Section 2 followed by main aspects of the integration algorithm given in Section 3. The prototype of an integrated INS/GPS system is shortly explained in Section 4. Results and discussion of experimental verification of a system are given in Section 5, followed by the overall conclusions presented in Section 6.

2. INS/GPS integration scheme

The diagram shown on Fig. 1 illustrates the standard INS/GPS integration scheme that is used here. The main working regimes of the integrated navigation system are "INITIAL ALIGNMENT" and "NAVIGATION". Immediately after the system start-up, the initialization procedure starts by transferring GPS data regarding the geographical longitude (φ), latitude (λ), and height (h) as well as of velocity vector ($\mathbf{V}^{\mathrm{GPS}}$). The next step consists in the initializations of Kalman filter matrices, the initialization of the block used for corrections of deterministic errors of inertial instruments (biases, scale factor errors, non-orthogonality, etc.), and in system preparation for the start of "INITIAL ALIGNMENT".

After the initialization is finished, the system automatically starts the first alignment step—"COARSE ALIGNMENT". During this step, the following procedures are made: coarse alignment in azimuth (using the magnetic compass), calibration of gyro drifts, horizontal alignment, initial estimation of angular attitude, determination of quaternion parameters, and calculation of transform matrix (DCM) coefficients. The accelerometers biases are determined using the additional angular sensors. After the "COARSE ALIGNMENT" is finished, the "FINE ALIGNMENT" starts automatically. As a result of this procedure, the following estimates are available: non-stationary components of accelerometers biases and gyro drifts, diagonal elements of covariance matrices in Kalman filter, final estimates of angular attitude, and final data for the correction block. The whole "INITIAL ALIGNMENT" phase is done in stationary conditions and its duration for the ground vehicles is typically of order of 5–10 min. The extended Kalman filter (EKF) is used in "NAVIGATION" mode for the estimation of