IMPLEMENTATION OF A POSITIONING SYSTEM BASED ON INS/GPS INTEGRATION

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Abstract. *The implementation of a positioning system is carried out in this paper, based on the global positioning system (GPS)/inertial navigation system (INS) integration, aiming at providing a cost-effective and accurate navigation system. The focus is directed to aeronautics applications and tight implementation is considered, which employs raw measurements from the GPS receiver, thereby increasing the navigation system flexibility, with potential uses in mobile robotics, ships, precision agriculture and land vehicles. In this implementation the low INS precision is compensated by fusion with GPS data via a 17 state Kalman filter.*

Keywords*: Global Positioning System (GPS),Inertial Navigation System (INS), Kalman filter*

1. Introduction

Many recent navigation systems are based on Global Navigation Satellite Systems (GNSS), of which the Global Positioning System (GPS) is the most widely used. Currently the GPS system constitutes primary reference of absolute position. The application of differential techniques makes it possible to obtain errors from the order of 3-5 meters.

However, sometimes the GPS information may not be totally available or with the necessary precision, due to very low signal power levels from the satellites. Moreover it is vulnerable to interfering electromagnetic signals, as occurs periodically during the cycles of maximum solar activity. Additionally, the GPS rate measurement is typically from order of 1 second, which can be very low in applications with fast dynamic vehicles, such as aircrafts.

Increased robustness can be achieved by integrating GPS data with another navigation system. The better solution to keep precision of positioning from order of meters or less and a fast rate of availability of the data, consists in the integration with inertial systems. The additional advantage in such INS/GPS integration concerns the noise reduction in the position and velocity information, which can simplify the implementation of a control system for the vehicle.

The inertial systems can have bandwidth of hundreds of Hz, what allows the following of very fast movements with precision. An INS is a so-called self contained system: the position is calculated using measurements of accelerations and rotations in three dimensions, which are all quantities that can be measured on the vehicle without external aiding or data. The advantage of having a self-contained system, the INS, is that a very robust navigation is possible, in the sense that it is practically impossible to disturb the IMU sensors except by physically destroying them. Additionally, high frequency noise is attenuated in the integration, which works as a low-pass process.

Since the navigation in the INS is based on integration, small measurement errors are accumulated, and then the calculated position “drifts away” from the true position. In particular, the INS is sensitive to biases in the accelerometer and drifts in the gyrometer sensors, which causes exponentially increasing position errors.

The drift is one of the major drawbacks with inertial based navigation systems. There are high-precision IMU sensors with very small biases and noise, but nevertheless, pure inertial systems are not appropriate to keep precisions of the order of meters for long periods, since unaided INS has an unbounded long-term error. This motivates the integration with system GPS data, in order to bound the navigation errors. For further details on the INS/GPS fusion benefits, see (Titterton and Weston, 1997), (Farrel and Barth, 1999) and (Grewal et alli, 2001). More particular cases of integration, with great practical utility, can be found in (Ohlmeyer, 1999) and (Faruqi, 2000).

This papers follows the procedure adopted by (Faruqi, 2000), where the tight INS/GPS fusion is implemented in the NED reference frame. As the main contribution here we can quote: 1) a careful analysis of the impact that the Kalman filter design parameters (initial estimation error covariance matrix, state and output noise covariance matrices) have on the navigation system performance, and b) analysis of the impact that the loss of GPS signal has on the navigation system, since this is a very realistic scenario with which the navigation system may have to face in any practical application.

This paper is organized as follows: in section 2 and 3 the dynamic equations for the error propagation is established. The results and analyses are presented in section 4 and the conclusions follow in section 5.

2. Error Model

The equations composing the navigation error model and Kalman filter can be found in (Faruqi, 2000). The Kalman filter must generate estimates for the errors of the vehicle's full states (position, velocity and attitude), and also of the IMU errors (accelerometer bias, gyro-drifts, GPS clock bias, and GPS frequency bias). There are then a total of 17 states to be estimated by the Kalman filter. The state vector is defined by

$$x = \begin{bmatrix} \delta R \\ \delta V \\ \delta\phi \\ \delta A \\ \delta\omega \\ \delta B \\ \delta F \end{bmatrix} = \begin{bmatrix} \textit{Position Error with respect to NED coordinates} \\ \textit{Velocity Error with respect to NED coordinates} \\ \textit{Attitude Error} \\ \textit{Accelerometer bias error} \\ \textit{Gyrometer drift error} \\ \textit{GPS receiver clock bias error} \\ \textit{GPS receiver clock frequency error} \end{bmatrix} \tag{1}$$

where δR, δV, $\delta\phi$, δA, $\delta\omega$ are vectors in $\Re^3$, and δB and δF are scalars.

The first step to apply the Kalman filter consist in obtaining the dynamic for the state vector x(t) in (1) and the corresponding output equation with respect to NED coordinates. For the cases in which the ECEF coordinates are used in the implementation, see (Hemerly and Schad, 2004) and (Hemerly and Schad, 2005). These equations are

$$\dot{x}(t) = Ax(t) \;\; \textit{(continuous time)} \tag{2}$$
$$\mathrm{y(k) = Cx(k)}$$

where the dinamic matrix is given by

$$A = \begin{bmatrix} 0_{3x3} & I_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0 & 0 \\ 0_{3x3} & 0_{3x3} & A_n^L & C_{Bn}^L & 0_{3x3} & 0 & 0 \\ 0_{3x3} & 0_{3x3} & \Omega_n^L & 0_{3x3} & C_{Bn}^L & 0 & 0 \\ 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0 & 0 \\ 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0_{3x3} & 0 & 0 \\ 0_{1x3} & 0_{1x3} & 0_{1x3} & 0_{1x3} & 0_{1x3} & 0 & 1 \\ 0_{1x3} & 0_{1x3} & 0_{1x3} & 0_{1x3} & 0_{1x3} & 0 & 0 \end{bmatrix} \tag{3}$$

with $A(t) \in \Re^{17x17}$, and the output matrix given by

$$C = \begin{bmatrix} u_1^T & 0^T & 0^T & 0^T & 0^T & 1 & 0 \\ u_2^T & 0^T & 0^T & 0^T & 0^T & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ u_n^T & 0^T & 0^T & 0^T & 0^T & 1 & 0 \\ 0^T & u_1^T & 0^T & 0^T & 0^T & 0 & 1 \\ 0^T & u_2^T & 0^T & 0^T & 0^T & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0^T & u_n^T & 0^T & 0^T & 0^T & 0 & 1 \end{bmatrix} \tag{4}$$

with $C(t) \in \Re^{2nx17}$, where
I_{3x3} : identity matrix,
0_{3x3} : nulle 3x3 matrix,
u : unity vector from the receiver to the satellite, given by

$$u = \frac{1}{\rho_0}\begin{bmatrix} xsat - x \\ ysat - y \\ zsat - z \end{bmatrix} \tag{5}$$

where (xsat, ysat, zsat) is the position of the satellite.

By supposing that n satellites are visible at time t, the output equation (2) is given by

$$y = \begin{bmatrix} \rho_{INS} - \rho_1 \\ \rho_{INS} - \rho_2 \\ \vdots \\ \rho_{INS} - \rho_n \\ \Delta_{INS} - \rho_1 \\ \Delta_{INS} - \rho_2 \\ \vdots \\ \Delta_{INS} - \rho_3 \end{bmatrix} \in \Re^2 \tag{6}$$

where

ρ_{INS} : pseudodistance calculated by using the inertial measurements,

$\Delta\rho_{INS}$: deltadistance calculated by using the inertial measurements,

ρ_n : pseudodistance provided by the receiver for the *n-th* visible satellite.

3. Integration INS/GPS

The integration of raw IMU sensor signals and GPS sensor is performed by means of a complementary Kalman filter. The filter structure used here is depicted in Fig. 1.

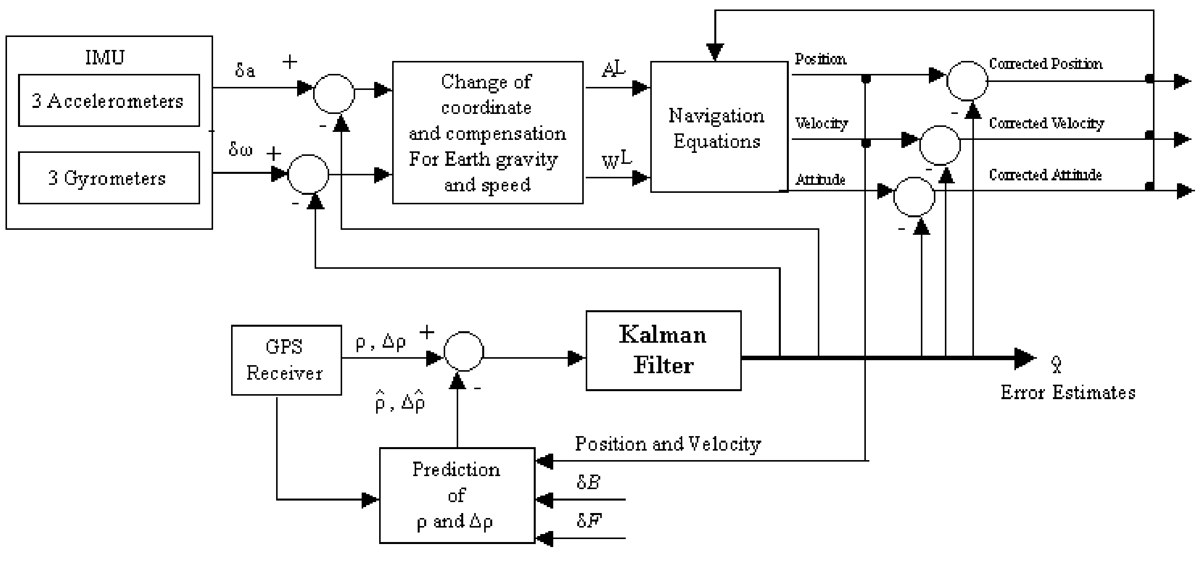


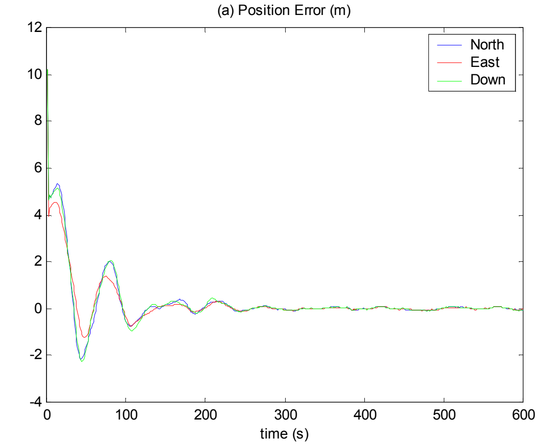
Figure 1. Tight INS/GPS via Kalman filter.

In this paper, GPS readings are measured with the rate of 1 Hz and the INS sensors with 100 Hz. As shown in Fig. 1, the Kalman filter estimates corrections for the gyrometer drift and accelerometer bias, thereby calibrating the IMU sensors in real time. The GPS clock bias and clock frequency error terms are also estimated to calibrate the GPS and the error estimates for position, velocity and attitude are used to correct the final body trajectory and orientation.

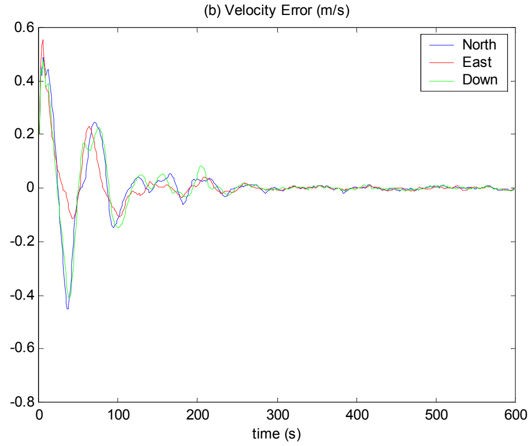
4. Simulations Results

The navigation system shown in Fig. 1 was implemented in MATLAB and tested under several conditions, by varying the magnitude of the sensors bias, the trajectory initial conditions and the design parameters used by the Kalman filter. Due to space limitation, only a typical realization will be presented. The behavior of the difference between the real state and the estimated are shown in figure 2(a)-(f).

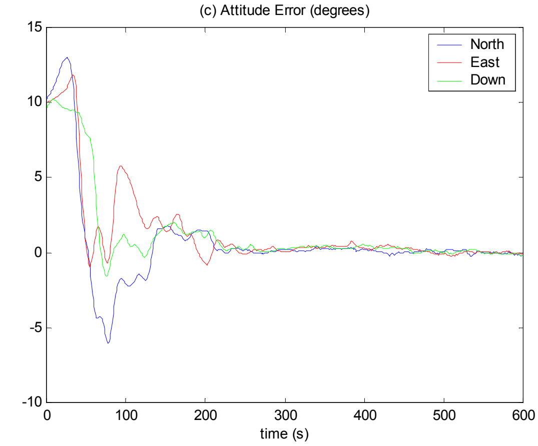
(a) Position Error (m)



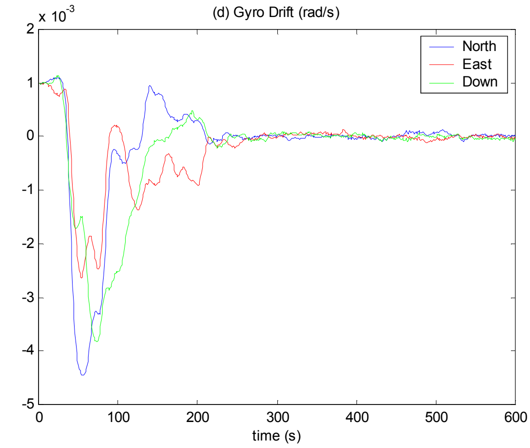
(b) Velocity Error (m/s)



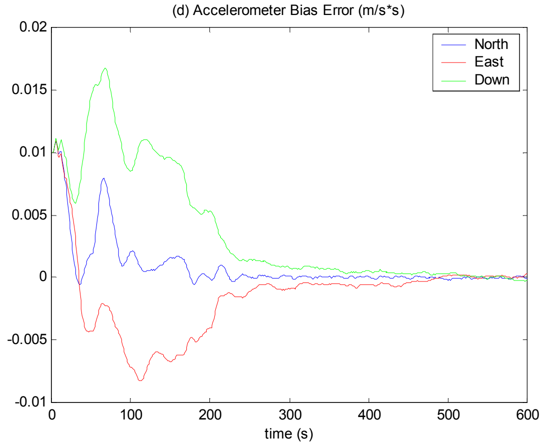
(c) Attitude Error (degrees)



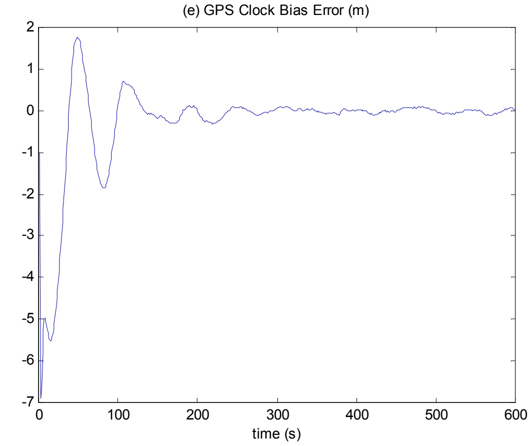
(d) Gyro Drift (rad/s)



(d) Accelerometer Bias Error (m/s*s)



(e) GPS Clock Bias Error (m)



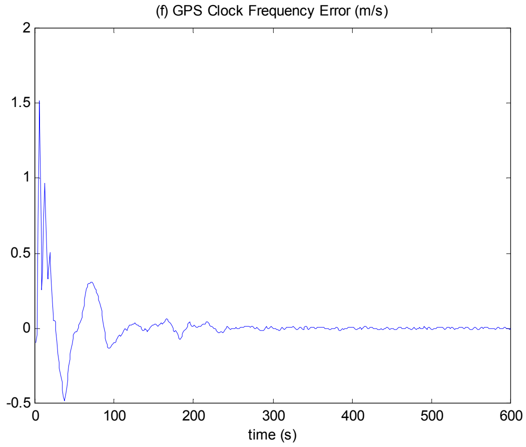


Figure 2(a)-(f). Results for state estimation errors in a typical realization.

From Fig. 2 it follows that convergence in all 17 states is achieved before 300 seconds. Only the accelerometer bias needed more than 300 seconds, this is probably due to the fact that the choice of initial error covariance matrix P(0). In Fig. 2(a) the position errors converge to within 5 meters in less than 10 seconds and converge to their steady state values after 210 seconds. The states relative to vehicles's velocity in Fig. 2(b) converge rapidly, since the initial condition was wrong just by 20% of the nominal value. The plots of the vehicle attitude Fig. 2(c) show a good and fast convergence to their steady state values. The drift gyrometer states, Fig 2(d), also converge after 210 seconds. The Figs. 2(e) and 2(f), regarding the GPS parameters, converge rapidly to their steady state values as well.

This simulation was done considering the use of six satellites. Tests were also done using four and five satellites, but the corresponding precision were worse, as expected.

With the same parameters as before, the accelerometer bias was changed from 0.01 m/s^2 to 0.1 m/s^2 and convergence was also obtained by the Kalman filter, but with faster convergence for the accelerometer bias. For accelerometer bias of 0.1 m/s^2 and gyro drift of 0.01 rad/s, which are considerably high values, convergence of all 17 was achieved, which allows the use sensors of low price and then low quality IMU sensors.

Finally, Fig. 3 exhibits an unfavorable but quite realistic scenario: GPS signal is lost for 40 seconds, time during which the navigation is performed solely by the INS. More precisely, the GPS signal was lost at time 300 s, when the accelerometers and gyrometers were very well calibrated by the Kalman filter, and the GPS signal was recovered at time 340 s. During this interval the navigator keeps calculating the body trajectory and attitude using only the inertial measurements. There was a displacement more significant in the East coordinate of approximately 1 meter, and of almost 0.5 meter in the Down coordinate. Since the inertial sensors were well calibrated, the navigation accuracy was not too spoiled till the GPS signal was restored, as expected.

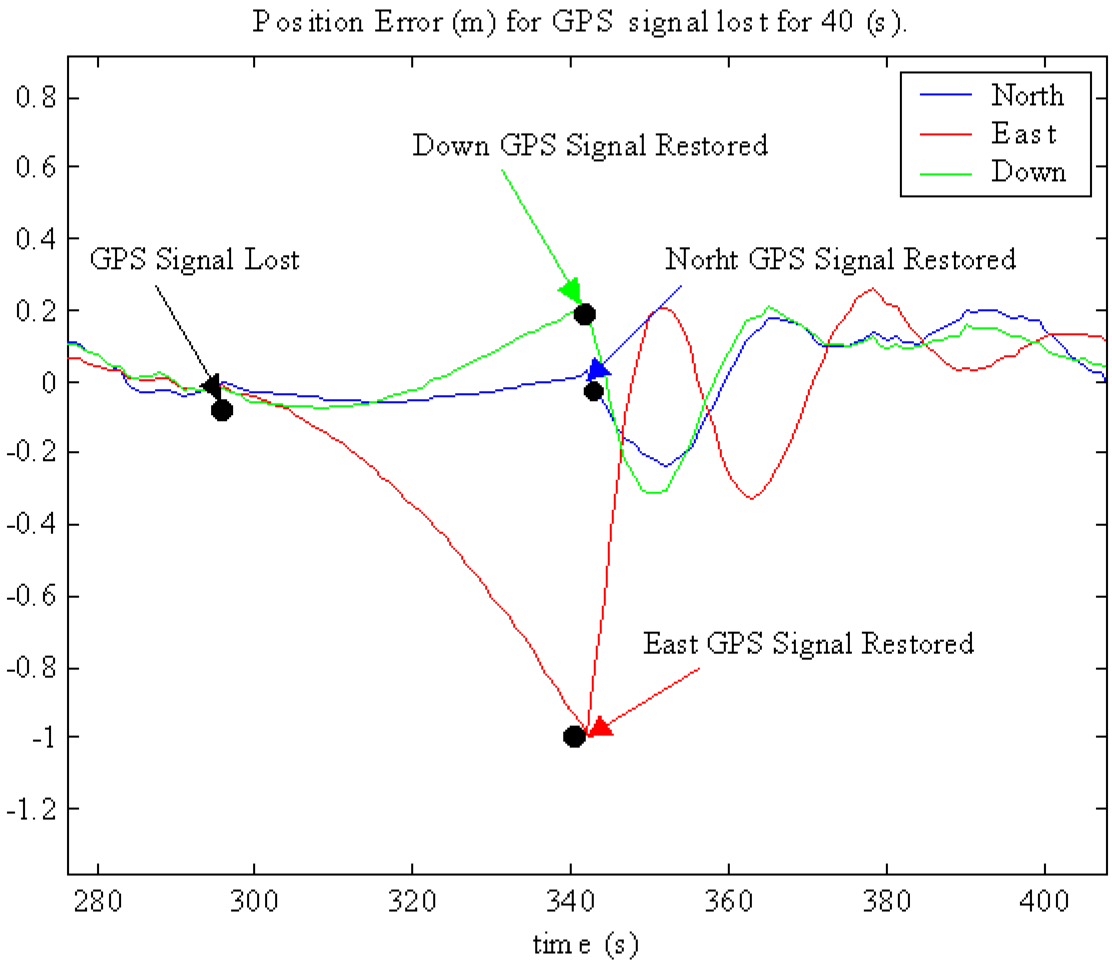


Figure 3. Simulation showing the effect of temporary loss of GPS signal for 40 seconds.

5. Conclusions

An implementation of a positioning system is described in this paper, based on the tight INS/GPS integration by means of a Kalman filter. The impact that the Kalman filter design parameters have on the system performance was investigated, and typical simulation results were presented. Since IMU sensor bias are corrected in real time, this allows the use of low cost IMU. The capability of operation in the realistic scenario with loss of GPS signal was also simulated, and it was concluded that this signal can be absent for approximately 40 seconds, without spoiling too much the trajectory accuracy. The next step concerns in adding attitude readings obtained by multiple GPS antennas, thereby a high precision attitude estimation system, and this work will be reported elsewhere.

6. Ackno

6. References

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