IMPLEMENTATION OF A GPS/INS/ODOMETER NAVIGATION SYSTEM

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Abstract. *The complementary properties of the GPS and the INS have motivated several works dealing with their fusion by means of a Kalman filter. However, if the GPS signal is unavailable this fusion is actually equivalent to an unassisted INS. This occurs, for instance, when the vehicle enters a tunnel. An efficient and simple solution in these cases is to implement also an odometer/INS integration system. This multi-sensor based navigation system is implemented in this paper, and the key issues, namely data synchronization, multirate operation and GPS antenna lever arm compensation, are properly dealt with. The basic error modeling in NED is described and the integration Kalman filter is discussed. Experimental results show the effectiveness of the GPS/INS/odometer integrated system. As far as the authors are aware, this is the first reported experimental result of its kind in Brazil.*

Keywords: *GPS, INS, Odometer, Integrated Navigation System, Kalman Filter.*

1. INTRODUCTION

The use of GPS (Global Positioning System) for assisting inertial navigation is a well established approach for implementing navigation systems, due to its good characteristics: global coverage, fast acquisition, good accuracy and low price. These characteristics nicely complement those exhibited by INS: inexistence of signal transmission, thence no possibility of jamming or signal loss, and availability at high frequency. For general details on the GPS principles, see Farrell and Barth (1999). Experimental results for the INS/GPS fusion, by means of the Kalman filter, can be found in Ohlmeyer *et al*. (1999); Faruqi (2000); Salychev (2000) and Walchko (2003). See also Hemerly and Schad (2004) for simulation results, and Hemerly and Schad (2005) for experimental ones.

In some applications, however, the GPS signal can be lost, as for instance when a vehicle enters a tunnel, and the navigation solely based on INS can produce large errors in position and attitude. One possible solution is to employ another sensor for assisting the INS navigation. In the applications envisaged in this work, the best option is to employ an odometer: it has low cost and is accurate.

The use of odometer is particularly recommended when a low cost and precise vehicle localization system has to be implemented and there is the risk of GPS coverage failure, which is prone to happen when the vehicle enters a tunnel or cross deep valleys. In Abuhadrous *et al.* (2003) a multi-sensor data fusion system for land vehicle localization is implemented. The 3 main sensors used are IMU, GPS and odometer. A 15 state Kalman Filter is employed, but there is no odometer calibration, what is a too optimistic approach since in practice odometers are expected to exhibit errors, mainly in their scale factors. In Ernest *et al.* (2004) a train locator using inertial sensors and odometer is proposed. However, the error dynamics for use in the Kalman Filter is a crude cinematic model, which is bound to display error if the vehicle undergoes fast dynamic. Moreover, no odometer calibration is performed in real time. A much more efficient procedure for performing GPS/INS/Odometer integration is proposed by Seo *et al.* (2006): it includes lever arm compensation for GPS antenna and odometer scale factor estimation in real time. The Kalman Filter output equation is modified properly in order to account for the lever arm and one additional state, representing the odometer scale factor, is included in the state equation used by the filter.

A GPS/INS/Odometer system for navigation is implemented and tested with real data in present work. It differs from Seo *et al.* (2006) in the sense that the lever arm correction is performed by changing the output signal which drives the filter, and not the output matrix, since this is a simpler approach. Moreover, the odometer bias is also estimated in real time, so as to cope with eventual time variation in this bias. In the experimental results, the GPS is sampled at 10Hz and the IMU and odometer are sampled at 100 Hz. During the experiment the vehicle enters a tunnel, and the GPS signal is thereby lost.

This paper is organized as follows: in section 2 the dynamic equation for the error propagation, necessary for the Kalman Filter implementation in the NED frame, is established. Details concerning the Kalman filter for implementing the GPS/INS/Odometer fusion via the tight approach are also presented in section 2. Experimental results are presented in section 3, which also includes a discussion of the main results obtained. The conclusions are then presented in section 4.

2. ERROR MODEL FOR THE GPS/INS/ODOMETER FUSION

The error dynamics to be used by the Kalman Filter is composed by 17 states, which can be separated in 3 different blocks: a) 9 variables are associated with the body trajectory, in position (latitude, longitude and height), velocity (north, east and down) and attitude (roll, pitch and yaw); b) 6 concern the IMU (gyrometer drift and accelerometer bias), and c) 2 associated with the odometer (bias and scale factor). Thence, the state vector is defined by

$$x = \begin{bmatrix} \delta\phi \\ \delta v \\ \delta LLH \\ \delta w \\ \delta f \\ \delta b_o \\ \delta S_o \end{bmatrix} = \begin{bmatrix} \textit{Attitude Error} \\ \textit{Velocity Error in NED coordinates} \\ \textit{LLH Error} \\ \textit{Gyrometer drift error} \\ \textit{Accelerometer bias error} \\ \textit{Odometer bias error} \\ \textit{Odometer scale factor error} \end{bmatrix} \tag{1}$$

where $\delta\phi, \delta v, \delta LLH, \delta w, \delta f$ are vector in $\Re^3$, and δb_o and δS_o are scalars.

Once defined the state vector (1), we must specify the associated dynamic equation, i.e., the state and output equations in the form

$$\begin{aligned} \dot{x}(t) &= A(t)x(t) \;\; (\textit{continuous time}) \\ y(k) &= Cx(k) \;\;\; (\textit{discrete time}) \end{aligned} \tag{2}$$

Except for the last 2 states in (1), matrix A in (2) can be obtained in any reference dealing with the INS for NED mechanization. See for instance Titterton and Weston (2004) and Farrell and Barth (1999). Since these equations have considerable large size, they will be omitted here.

The last 2 error states associated with the odometer can be considered a first order Markov process, with a given correlation time.

The previous remark is also valid for the output matrix C in (2), and then we present here only the part which depends on the odometer parameters. We start by noting that the odometer readings are performed in the body frame, and then have to be converted to the navigation frame via

$$y_{odo} = C_{nb} \begin{bmatrix} (1+S_o)\sqrt{v_N^2 + v_E^2 + v_D^2} + b_o \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

where C_{nb} is the matrix representing the body attitude. Since (3) is nonlinear with respect to the speed, the present application requires the Extended Kalman Filter. Hence, by differentiating (3) with respect to speed, odometers scale factor and odometer bias we obtain the part of C in (2) which is associated with the odometer. The remainder of C can be found in classical references for inertial navigation assisted by GPS, such as Farrell and Barth (1999), hence it is omitted here.

The basic flowchart for estimating the state (1) via the Extended Kalman Filter, given (2), (3) and the stochastic characterizations for the GPS, IMU and odometer sensors, is shown in Fig. 1.

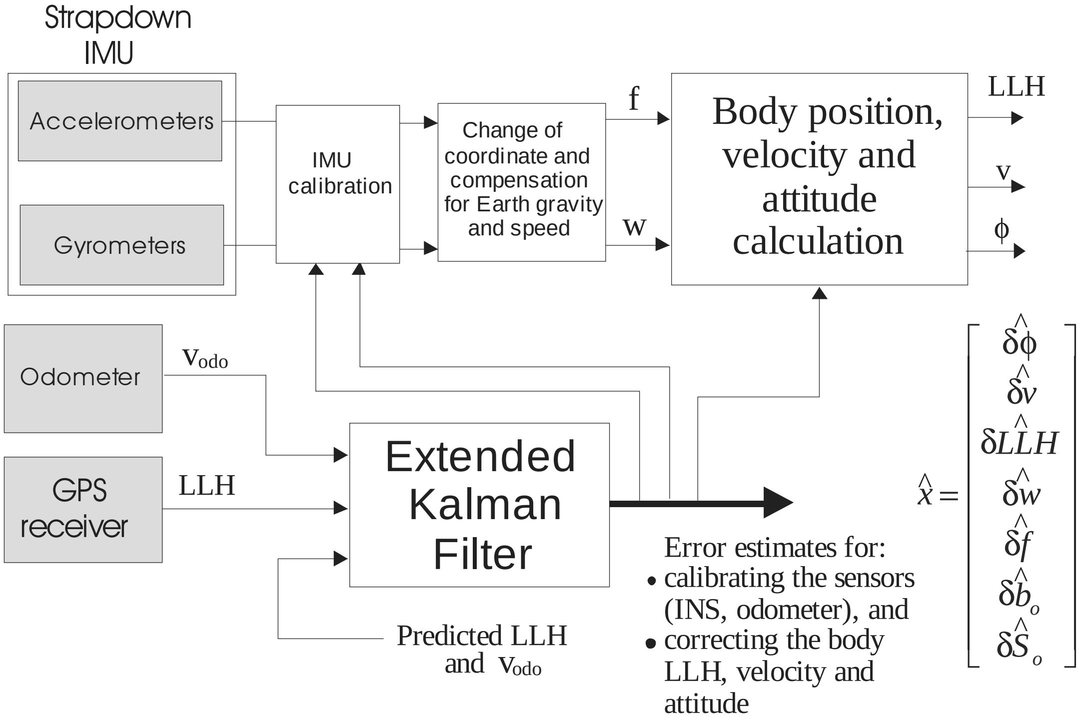

Figure 1. Basic flowchart for GPS/INS/Odometer integration via Extended Kalman Filter

A particularly relevant point in the GPS/INS/Odometer fusion scheme shown in Fig. 1 concerns the arm lever corrections, since the GPS receiver antenna is not located at the same place where the IMU lies. Hence, the LLH measurements performed by the GPS receiver must be transferred to the IMU by using

$$LLL_{IMU} = LLH_{GPS} - M.C_{nb}.r_B \tag{3}$$

where

$M = \begin{bmatrix} 1/(R_N + h) & 0 & 0 \\ 0 & sec(L)/(R_E - h) & 0 \\ 0 & 0 & -1 \end{bmatrix}$, where L is the latitude, h is the altitude and R_N and R_E are defined as function of the Earth semi-major and semi-minor axes. See Farrell and Barth (1999) for details. The vector r_B in (3) stands for the antenna arm coordinates in the body frame, and C_{nb} is the body attitude matrix.

The navigation system shown in Fig. 1 is supposed to work as follows: while the GPS signal is available, the Kalman Filter is used to calibrate the IMU and the odometer. When there is GPS signal failure, the Kalman Filter is disabled and pure inertial navigation assisted by odometer is performed till the GPS signal is once again available.

3. EXPERIMENTAL RESULTS

For the experiments, the following prototype system was used:

- An inertial measurement unit based on fiber optic gyros of the 1 deg/h drift class and force rebalance accelerometers of the 1mg bias class. The measurements are digitalized with high precision voltage-to-frequency converters;
- A L1/L2 GPS system;
- A Pentium class microprocessor running a real-time operating system;
- An odometer implemented with a bicycle wheel with appropriate mechanical adaptations, running a decoder, giving a 1 mm linear displacement resolution (actual implementation may use existing hardware, like in an ABS braking system).

The system was installed in a van, and photographs of the experimental setup are shown in Fig. 2.

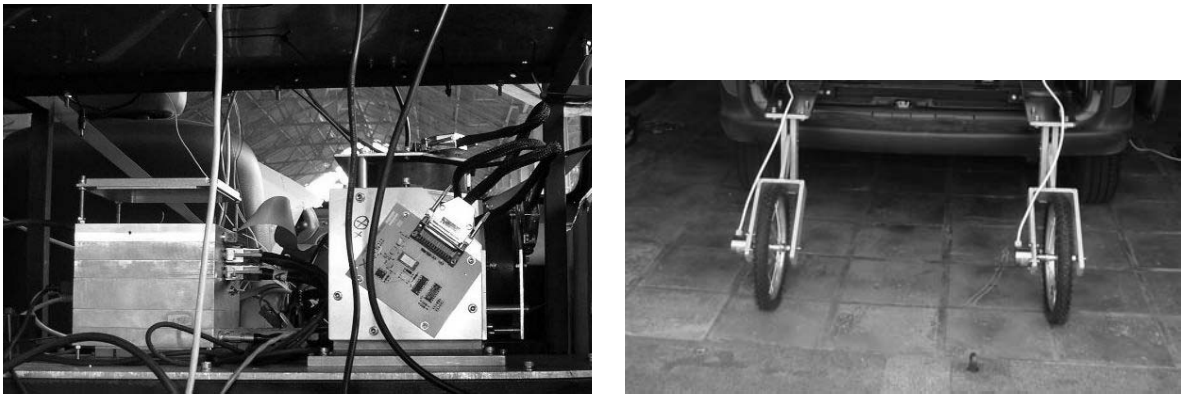

Figure 2. Hardware for testing the GPS/INS/Odometer navigation system: at left, the processor system and inertial measurement unit; at right, the odometer system

Two experimental results are now reported. The first one is performed under favorable conditions, so that the GPS signal is never lost. This enables a detailed performance analysis, since the true trajectory (that obtained by GPS) is always available for performance comparison: GPS failure is simulated and the INS/Odometer trajectory is compared to the GPS trajectory. The second experiment concerns a real scenario. The GPS signal is lost twice: when the vehicle enters a tunnel, and later due to a curve in the trajectory. In these 2 occasions, all there is available is the INS/Odometer trajectory, and it is expected that it represents well the actual vehicle trajectory, since both the IMU and the odometer should have been well calibrated by the Kalman Filter when the GPS signal was available. It should be highlighted that the GPS/INS/Odometer fusion is useful even when there is no GPS failure, since the use of IMU allows the obtainment of a trajectory smoother than that provided by GPS alone, and at a faster rate (in this work the GPS runs at 10Hz, whereas the IMU integration is performed at 100 Hz).

3.1. Trajectory with sharp turns and simulated GPS failure

A long experiment lasting 42 minutes was performed. The resulting longitude x latitude GPS trajectory is shown in Fig. 3.

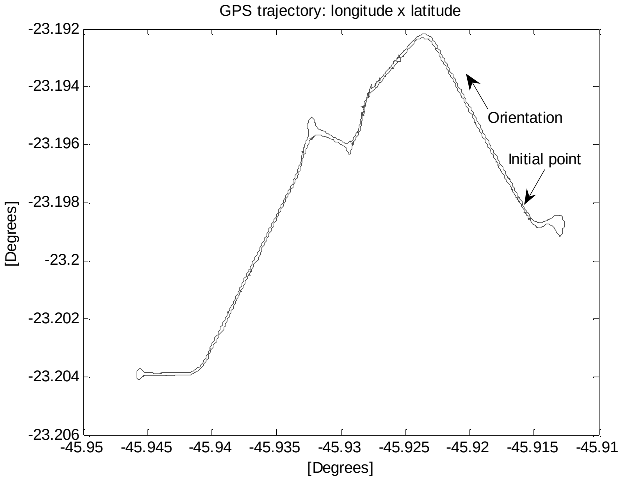

Figure 3. True trajectory for the first experiment

A GPS failure is then simulated, and lasts from t=1200 s till t=2200 s, hence the total failure time is approximately 16 minutes and half. The GPS trajectory and that obtained with the INS/Odometer are shown in Fig. 4.

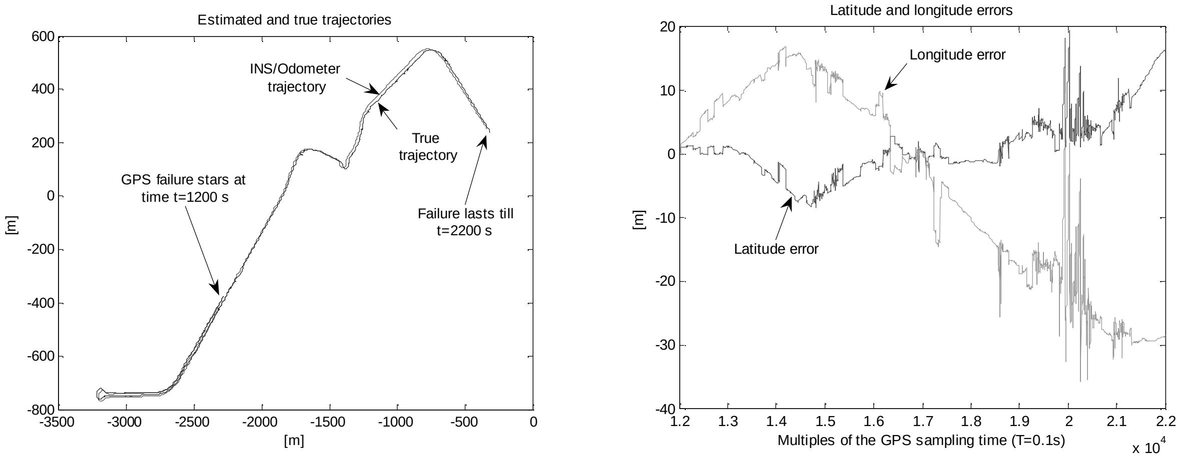

Figure 4. True (GPS) and estimated trajectories, with their associated errors. GPS failure is simulated as starting at time t=1200 s and lasting till t=2200 s

From the second graphic in Fig. 4 we conclude that the accumulated error for latitude is around 16 m, and 29 meters for longitude. The only known work where similar data is provided is Abuhadrous et al. (2003), where accumulated errors of magnitude 15 m are reported, for a GPS failure lasting 11 minutes and using DGPS. Here the failure lasts approximately 16 minutes and half, and GPS instead of DGPS is employed. Hence the errors shown in Fig. 4 are considered to be small.

3.2. Vehicle entering a tunnel with actual GPS failure

An application with actual GPS failure is now considered: the vehicle enters a tunnel and the GPS receiver is then unable to provide the navigation solution. Hence, the Kalman Filter has no LLH measurements to rely upon, and the solution proposed in this paper must be employed: navigation based solely on the IMU and the odometer readings.

The trajectory latitude and longitude are shown in Fig. 5.

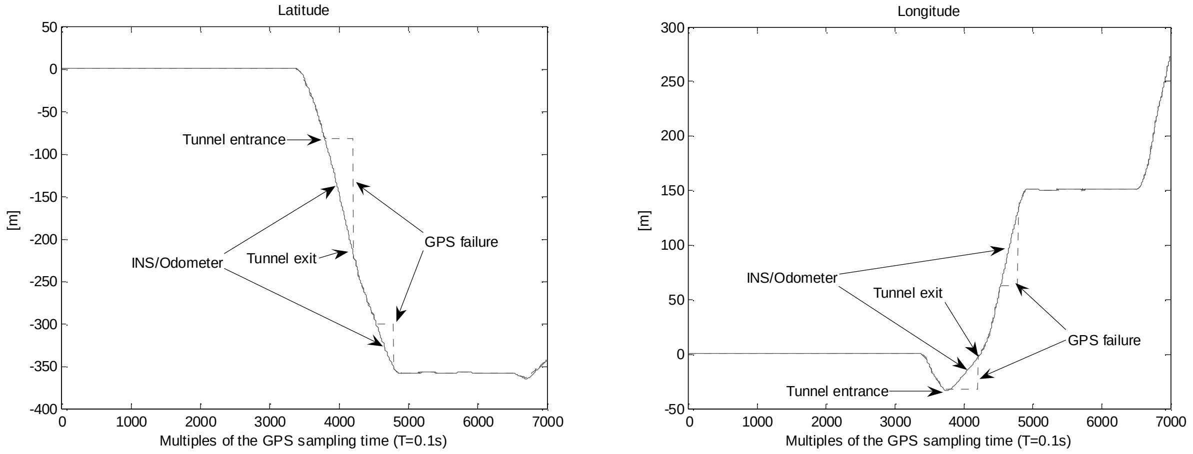

Figure 5. Trajectory latitude and longitude: there are 2 GPS failures, the first one caused by tunnel and the second due to a curve

A detailed analysis of Fig. 5 is now presented: the vehicle starts at the origin of the local coordinate frame. The vehicle starts to move and the Kalman Filter is activated, as in Fig. 1. This means the initial trajectory must be understood as being that obtained by the GPS/INS/Odometer fusion. Then at time t=380 s (which corresponds to time step 3800 in Fig. 5) the vehicle enters a tunnel and the GPS signal is lost. The navigation is then performed by INS and odometer readings only, till the GPS signal returns, at time t=420 s, when the vehicle reaches the tunnel exit. There is a particularly relevant point in Fig. 5: it could be argued that the GPS failure could be treated by a simple interpolation. This is completely false, as can be seen in the longitude graphics: any predictor based on GPS signals only would indicate that the trajectory would continue to decrease, which is actually not the case, since the tunnel is located just after a curve. The second GPS failure is due to a curvilinear trajectory, and the previous remarks are also applicable.

4. CONCLUSIONS

A navigation system based on GPS/INS/Odometer fusion by means of an Extended Kalman Filter was implemented and tested experimentally. While the GPS LLH readings are available, calibration of the IMU and odometer is performed. When the GPS signal is lost, the navigation proceeds by using the IMU/Odometer integration. With this approach it is possible to obtain small errors in situations where the GPS signal can be lost, such as when the vehicle enters a tunnel, hillside, deep valley or area with dense vegetation. Experimental results obtained with the GPS/INS/Odometer navigation system were reported, exhibiting what is expected: IMU and odometer calibration in real time and small latitude and longitude errors during the GPS outage. As an improvement, it can be mentioned the use of GPS velocity readings to detect eventual odometer failure.

5. ACKNOWLEDGEMENTS

The authors would like to thank CNPq and FAPESP for the financial support.

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