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The performance evaluation of the INS/GNSS integrated navigation system with Analytic constraints

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Abstract

The integration of Global Navigation Satellite System (GPS) and Inertial Navigation System (INS) using Inertial Measurement Unit (IMU) is now widely used for Mobile Mapping System (MMS) and Navigation applications to seamlessly determine position, velocity and attitude of the mobile platform. With low cost, small size, ligh weight, and low power consumtion, the Micro-Electro-Mechanical System (MEMS) IMU and low cost GPS receivers are now a trend in research and using for many applications. However, the previous researchs indicated that the the performance of the low cost INS/GPS systems is still poor, particularly, in case of GNSS-noise and –denied environment. To overcome this problem, this research uses analytic contraints including Non-holonomic constraint and zero velocity update in the data fusion engine such as Extended Kalman Filter to improve the performance of the system. The benefit of the proposed method will be demonstrated through experiments and data analysis.

Keywords: GNSS; INS; Navigation; Analystic Constrains

1. **Introduction**

For navigation applications and the Mobile Mapping System (MMS), the integration of the Inertial Navigation System (INS) using an Inertial Measurement Unit (IMU) and the Global Positioning System (GPS) is widely applied for determining state vectors, which include the position, velocity, and orientation of the mobile platform. The advantages of INS are autonomous operation, high measurement sampling rate, and short-term accuracy. However, its navigation accuracy degrades rapidly with time if no external aiding source is available. This is particularly true when a low-cost IMU is applied. In contrast, GPS is able to provide long-term position and velocity accurately. However, a low sampling rate, environmental dependence, and the lack in orientation determination with single antenna are the primary limitations for navigation oriented-applications with GPS alone. The integration of INS and GPS is an optimal solution that utilizes the advantages of each system and overcome in limitations (Chiang, et al., 2013).

Although an integrated navigation system can work in GPS-denied environments, problems include the cost of the inertial sensors and the length of time that the GPS signals are unavailable, which affect its applicability. Tactical-grade or better inertial systems can achieve sufficient position accuracy and sustainability during long-duration GPS signal blockages (Titterton and Weston, 2004). For example, the high-end, expensive systems can provide less than 3 m real-time position accuracy with a GPS gap lasting one minute. However, the cost of the

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sophisticated inertial sensors is prohibitive for applications such as the primary navigation module for general land vehicles. For this reason, strap-down Micro-Electro-Mechanical Systems (MEMS) inertial sensors are preferred as the complementary component to GPS for general, seamless vehicle navigation applications. However, the position accuracy of these low-cost inertial sensors degrades rapidly with time when GPS signals are interrupted. The sustainability of an integrated INS/GPS system using currently available commercial MEMS inertial technology in typical GPS-denied environments is thus limited. However, the progress in MEMS inertial sensors has advanced rapidly. Thus, the inclusion of MEMS inertial sensors for general land-vehicle navigation has considerable potential in terms of cost and accuracy (Rogers, 2007).

To improve the performance of low cost INS/GNSS integrated system in the GNSS-hostile environment, this research proposes of analytic constrains to apply in the Extended Kalman Filter in order to bound the error during GNSS outages. Analytics constraint can be understood as the utilizing the physical condition and theory of moving platform to apply in the INS/GPS integrated system without additional physical sensors. Non-holonomic constrain (NHC) is firstly proposed by Dissanayake, et al., (2001) to apply for the low cost, strap-down INS in land vehicle applications. The principle of the NHC is that in the land vehicle, the velocities in the directions that perpendicular to the forward direction is assumed to be zero. Zero Velocity Update (ZUPT) is proposed from the fact that when the vehicle stops, the velocity in all directions is zero.

The next sections of this article will be organized as follows: Section 2 is about fundamental INS/GNSS integration. Section 3 introduces a scheme of INS/GNSS integration with analytic constrains. Section 4 is experiment and discussion. Section 5 is conclusion.

2. Fundamental of INS/GNSS integration

2.1. INS mechanization

The outputs of the IMU are the angular rates and the specific forces in the body frame, the frame that is rigidly attached to and defined within the vehicle carrying the navigation system. The raw measurements of the IMU in the body frame are processed by the INS mechanization to obtain navigation solutions, which are the position, the velocity, and the attitude in the navigation frame. Figure 1 illustrates the INS mechanization in the local level frame. Equation (1) gives the dynamic equations for position, velocity, and attitude:

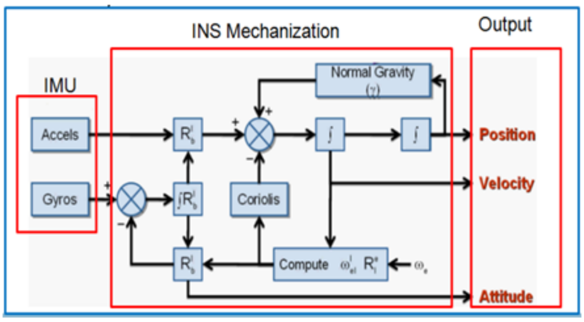


Figure 1. Architecture of INS mechanization

$$\begin{bmatrix}\dot{r}^l\\ \dot{v}^l\\ \dot{R}^l\end{bmatrix} = \begin{bmatrix} D^{-1}v^l \\ R_b^l f^b - \left(2\Omega_{ie}^l + \Omega_{el}^l\right)v^l + g^l \\ R_b^l\left(\Omega_{ib}^b - \Omega_{il}^b\right)\end{bmatrix} \tag{1}$$

where $\dot{r}^l$ is the time derivative of the position in the local level frame; $\dot{v}^l$ is the time derivative of the velocity; $\dot{R}^l$ is the time derivative of the attitude; f^b is the vector of applied forces sensed by accelerometers; Ω_{ib}^b is the angular velocity of the body frame relative to the inertial frame and parameterized in the body frame; R_b^l is the transformation matrix from the body frame to the local level frame; Ω_{ie}^l and Ω_{el}^l are the rotation rate of the earth with respect to the inertial frame and the rotation rate of the navigation frame with respect to the earth, respectively; g^l is the normal gravity in the local level frame; and D^{-1} is defined as follows:

$$D^{-1} = \begin{bmatrix} 0 & \frac{1}{M+h} & 0 \\ \frac{1}{(N+h)\cos\phi} & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where N is the radius of curvature in the prime vertical, M is the meridian radius of the curvature, h is the ellipsoid height, and ϕ is the latitude at the current location.

An INS mechanization algorithm by itself seldom has good performance because of inertial sensor biases and fixed-step integration errors, which cause the navigation parameters to diverge quickly. The navigation software must have some approach to account for these error sources to correct the estimated parameters. The dynamic error model used in the KF for the navigation parameters (position, velocity, and attitude) can be determined through the linearization of the INS mechanization equations and by neglecting insignificant terms in the resulted linear model.

2.2. INS/GNSS integration

Commonly, a Loosely Coupled (LC) is applied due to it simpility for data processing. In the original LC INS/GNSS integration scheme, the GNSS processing engine calculates position fixes and velocities in the local level frame and then sends the solutions as measurement updates to the main EKF. By comparing the navigation solutions provided by the INS mechanization with those provided by the GNSS processing engine, the navigation states can be optimally estimated (Figure 2). The primary advantage of the LC architecture is the simplicity of its implementation in the way that no advanced knowledge of processing GPS measurements is required. The disadvantage of this implementation is that the measurement update of the integrated navigation system is possible only when four or more satellites are in view (Wendel and Trommer, 2004).

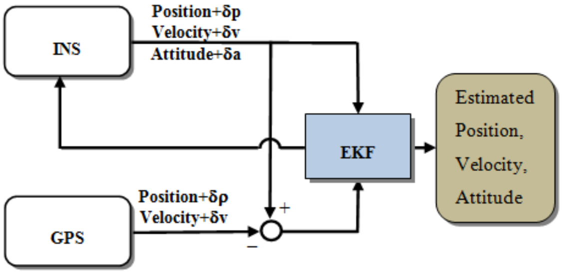


Figure 2. Loosely coupled INS/GPS scheme

2.3. Estimation algorithms

The Estimation is necessary in integration of INS and GNSS to derive the optimal navigation solutions. The widely used method for such integration is the EKF with simple mechanization equations in the local level frame. To apply EKF, first, mathematical models are formed.

The system model is built based on INS error model:

$$x_k = \Phi_{k-1;k} x_{k-1} + w_k \tag{3}$$

Where $x = [\delta R\ \delta V\ \delta\psi\ b_a\ b_g\ s_a\ s_g]^T_{21\times 1}$ is state vector, its components include position, velocity, attitude errors, biases and scale factor of accelerometers and gyroscopes; $\Phi_{k-1;k}$ is the state transition matrix from epoch $k-1$ to k, wk is system noise.

The measurement model is built based on GPS measurement:

$$z_k = H_k x_k + n_k \tag{4}$$

Where zk is measurement vector, Hk is mapping matrix, and nk is measurement noises at time k, respectively.

Based on the system model expressed in Equation (3), the states and corresponding covariance at time k are predicted based on the state and covariance at time k-1.

$$\hat{x}_k^- = \Phi_{k-1;k} \hat{x}_{k-1} \tag{5}$$

$$P_k^- = \Phi_{k-1;k} P_{k-1} \Phi_{k-1;k}^T + Q_k \tag{6}$$

Whenever aiding measurements are available, the states and covariance are updated based on following equations:

$$K_k = P_k^- H_k^T \left[H_k P_k^- H_k^T + R_k \right]^{-1} \tag{7}$$

$$\hat{x}_k = \hat{x}_k^- + K_k \left(z_k - H \hat{x}_k^- \right) \tag{8}$$

$$P_k = P_k^- - K_k H_k P_k^- \tag{9}$$

Where: $\hat{x}_k^-, P_k^-$ are the predicted states and covariance at time k, $\hat{x}_{k-1}, P_{k-1}$ are the estimated states and covariance at time k−1, and $\hat{x}_k, P_k$ are the estimated states and covariance at time k.

3. INS/GNSS integration with analytic constraint

3.1. Non-holonomic constraint

Dissanayake, et al. (2001) explained that if the vehicle does not jump off the ground or slide sideways under normal conditions in a land vehicle platform, the velocities of the vehicle in the plane perpendicular to the forward direction are approximately zero. This assumption becomes a constraint condition for land-based navigation applications. In terms of implementation, the velocity components in the y and z directions in the body frame will be zero, as expressed in Equation (10) and shown in Figure 3.

$$\begin{cases} v_y^b = 0 \\ v_z^b = 0 \end{cases} \tag{10}$$

where the superscript (b) denotes the body frame.

For the EKF, the velocity vector estimated by INS is transformed into the body frame:

$$v^b = C_n^b v^n \tag{11}$$

The measurement equation for EKF can be constructed as follows:

$$\delta z = \begin{bmatrix} v_y^b - 0 \\ v_z^b - 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} C_n^b \delta v^n + \begin{bmatrix} \varepsilon_{vy} \\ \varepsilon_{vz} \end{bmatrix} \tag{12}$$

Where ε_{vy} and ε_{vz} are velocity noise in the y and z directions, respectively.

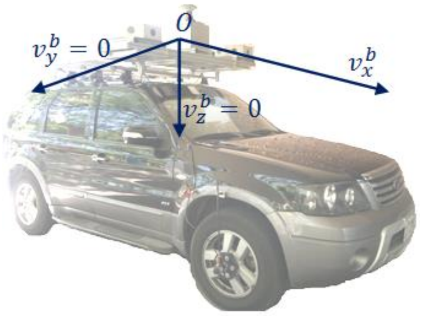


Figure 3. Non-holonomic contraints (NHC)

The NHC is an analytic correction; no additional sensor is required; therefore, it can be applied to any land-based integrated navigation system to improve the navigation accuracy. However, if the assumption of the vehicle behavior is violated, the NHC may cause more noise to the system. Normally, under an open sky, the GNSS is more reliable than the NHC. Therefore, in the proposed system, the NHC is activated only when GNSS signal outages take place. In addition, the update interval of the NHC is subject to change depending on the quality of the IMU: the higher the IMU quality, the longer the update interval of the NHC should be.

3.2. Zero Velocity Update

Zero velocity updates (ZUPT) means the occasional stop of the system for short duration to estimate system errors and allows bounding the inertial sensor errors growth. If the vehicle stops, the velocity outputs in any directions should be zero. Taking this constraint into consideration, the measurement update equation of ZUPT mode is shown as

$$\delta z = \begin{bmatrix} \hat{v}_N^l & -0 \\ \hat{v}_E^l & -0 \\ \hat{v}_D^l & -0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \delta v^l + \begin{bmatrix} n_{vx} \\ n_{vy} \\ n_{vz} \end{bmatrix} \tag{13}$$

Where: $\hat{v}_N^l$, $\hat{v}_E^l$, $\hat{v}_D^l$ are North, East, and Down components of estimated velocity vector of the INS in the navigation frame, n_{vi} is the velocity noise in the direction i.

3.3. Integration architecture

In the new integration architecture, NHC and ZUPT with velocity constraints are considered as measurement updates in the EKF as shown in the Figure 4. NHC is update with given interval set by user. ZUPT is automatically detected and activated based on the velocity of the forward direction. If the velocity of the forward direction is smaller than a given threshold, ZUPT is activated.

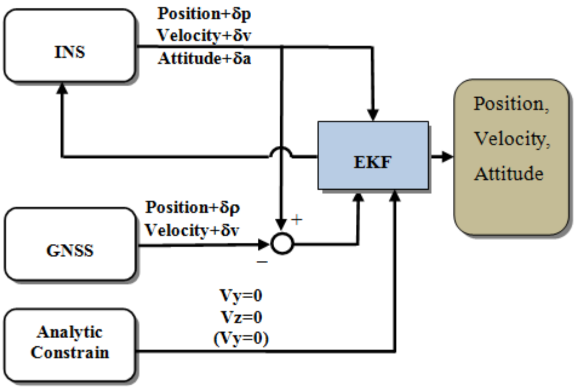


Figure 4. INS/GNSS integration with analytic constrain

4. Experiment and discussion

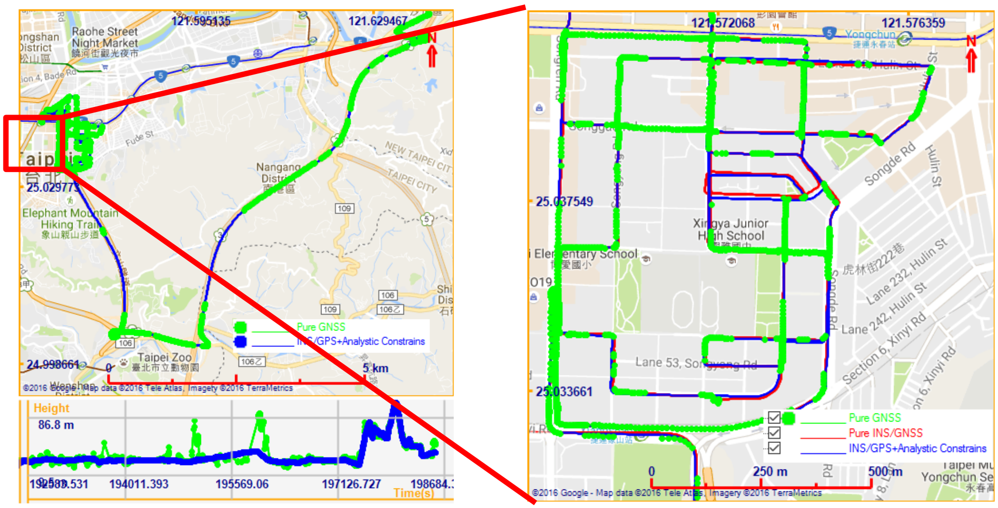
For the test, two INS/GNSS integrated navigation systems were set up to conduct a field test. The reference system comprised a high-end tactical-grade IMU, SPAN-LCI (NovAtel). A dual-frequency geodetic-grade GNSS receiver, ProPak V3 (NovAtel). A distance measurement instrument (DMI). The testing system comprised a MEMS IMU, STIM300 (Sensonor). The specifications of the testing system are shown in Table 1. Both systems were mounted on a mobile mapping van for data collection to validate the performance of the proposed algorithms.

Table 1. Testing system specifications.

Physical characteristics	**IMU performance**	
	Gyro bias instability (deg/h)	0.5
	Angular random walk (deg/√h)	0.15
	Accelerometer bias instability (mg)	0.05
	Velocity random walk (m/s/√h)	0.07

The testing data sets were collected under various environment scenarios in urban and suburban areas in Taipei, Taiwan. The testing trajectory is shown in Figure 5(a). The reference trajectory was generated with the reference system with its IMU raw measurements and raw GPS carrier phase measurements processed in differential mode with commercial software, Inertial Explorer (NovAtel), performing sensor fusion in TC smoothing mode with aid from DMI. In general, the kinematic positioning accuracy of the applied reference system was less than 10 centimeters, which is considered sufficient.

For the testing, two scenarios including INS/GNSS and INS/GNSS with Analytic constrains were implemented. Figure 5(a) shows the whole trajectory of the test. For performance analysis, an interested area is extracted as shown in the Figure 5(b). The analyzed results including position and orientation, were compared to the reference data. Figure 6, 7 and Table 2 illustrates the performance of the two integration strategies in terms of position and attitude Root mean square error (RMSE).



(a) (b)

Figure 5. (a) Test trajectory; (b) Trajectory of extracted area. Green dot is GNSS only and Blue line is INS/GNSS trajectory.

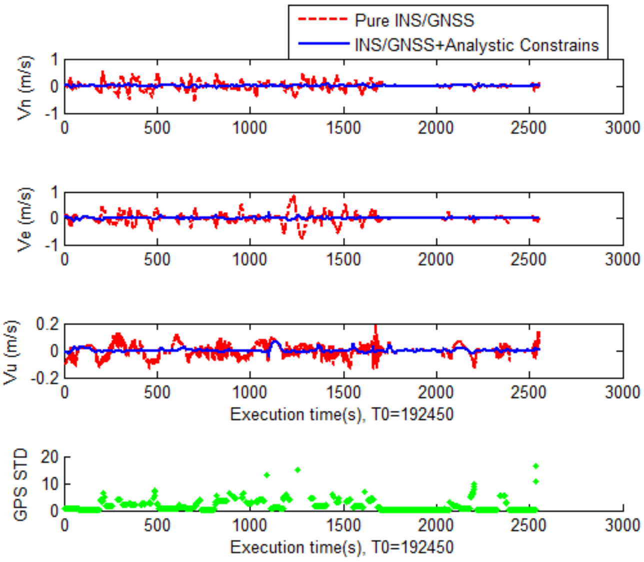


Figure 6. Positional error

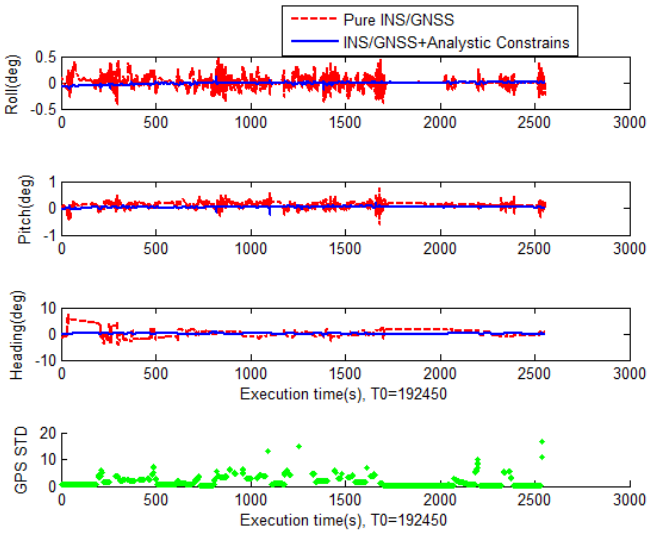


Figure 7. Attitude error

Table 2. RMSE of two integration strategies

RMSE	**INS/GNSS**	**INS/GNSS + Analytic Constraints**
East (m)	2.4935	0.6834
North (m)	2.9559	0.6681
Up (m)	1.6486	0.6296
3D (m)	4.2039	1.1445
Roll (^{o})	0.1358	0.023
Pitch (^{o})	0.1772	0.0273
Heading (^{o})	0.0408	0.0128

The analysis indicates in general, the integration of INS/GNSS can overcome the issue of GNSS in GNSS-hostile environment such as in the urban area or through the tunnels where GNSS signal is noisy or blocked. On the other hand, with the support of the Analytic Constraints such as NHC and ZUPT, the performance of the system improved significantly comparing to the pure INS/GNSS, in terms of both position and attitude as shown in the Figure 6,7 and Table 2.

5. Conclusions

This paper analyzes and evaluates the performance of the INS/GNSS integrated navigation system with analytic constraints including non-holonomic constraint and zero-velocity update.

The test results show that the performance of the proposed system improved significantly comparing with the pure INS/GNSS in terms of position and attitude. The result also demonstrates the benefit of the analytic constraints that can help to improve the performance of the system without additional sensors.

For future work, error model of analytic constraints will be more investigated. Stop status detection strategies will be considered for automatic ZUPT activation.

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