Journal of Environmental Science and Engineering A 6 (2017) 313-319
doi:10.17265/2162-5298/2017.06.005

The Performance Evaluation of the Integration of Inertial Navigation System and Global Navigation Satellite System with Analytic Constraints

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Abstract: The integration of GNSS (Global Navigation Satellite System) and INS (Inertial Navigation System) using IMU (Inertial Measurement Unit) is now widely used for MMS (Mobile Mapping System) 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 MEMS (Micro-Electro-Mechanical System) IMU and low cost GPS (Global Positioning System) receivers are now the trend in research and using for many applications. However, researchs in the literature indicated that the the performance of the low cost INS/GPS systems is still poor, particularly, in case of GNSS-noise environment. To overcome this problem, this research applies analytic contrains 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.

Key words: GNSS (Global Navigation Satellite System), INS (Inertial Navigation System), navigation, analytic constraints.

1. Introduction

For navigation applications and the MMS (Mobile Mapping System), the integration of the INS (Inertial Navigation System) using an IMU (Inertial Measurement Unit) and the GPS (Global Positioning System) 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 [1].

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 [2]. For example, the high-end, expensive systems can provide less than 3 m real-time position accuracy with a GPS gap lasting one minute [3]. However, the cost of the sophisticated inertial sensors is prohibitive for applications such as the primary navigation module for general land vehicles. For this reason, strap-down MEMS (Micro-Electro-Mechanical

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Systems) 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 [4].

To improve the performance of low cost INS/GNSS integrated system in the GNSS-hostile environment, this research proposes of analytic constraints to apply in the Extended Kalman Filter in order to bound the error during GNSS (Global Navigation Satellite System) 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 such as NHC (Non-Holonomic Constraint) and ZUPT (Zero Velocity Update).

NHC is firstly proposed by Dissanayake, G., et al. [5] to apply for 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. ZUPT is proposed from the fact that when the vehicle stops, the velocity outputs in all directions are zero. The test results indicate that the NHC can improve the performance of the system significantly. The benefits of NHC have been verified by Liu, C. Y. [6] and Chiang, K. W., et al. [1].

The use of a ZUPT and a ZIHR (Zero Integrated Heading Rate) has been mentioned and applied in INS/GPS integration as described by Shin, E. H. [7]. Liu, C. Y. [6] illustrated that the system with ZUPT/ZIHR can significantly improve the accuracy of the navigation solutions during GPS signal blockages. ZUPT is the occasional stopping of the system for a short duration to estimate errors of the system and bound the growth of inertial sensor errors. If the vehicle stops, the velocity outputs in any directions should be zero. The ZIHR utilizes the fact that the heading angle of the vehicle does not change when the vehicle stops. The challenge is how to detect the true stop condition of the vehicle to apply ZUPT/ZIHR. This problem was discussed by Park, S. K. and Suh, Y. S. [8] and Liu, C. Y. [6].

The present study also discusses this problem and applies of analytic constraints including NHC and ZUPT with innovative schemes to improve the robustness and accuracy of the system. A mechanization to automatically detect vehicle status to activate ZUPT and NHC is introduced. In addition, a method for modeling their corresponding error for data fusion such as EKF (Extended Kalman Filter) is proposed in this research.

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

2. Fundamental of INS/GNSS Integration

Commonly, a LC (Loosely Coupled) is applied due to it simplicity 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 (Fig. 1). The primary advantage of the LC architecture is the simplicity of its implementation; no advanced knowledge of processing GPS measurements is necessary. The disadvantage of this implementation is that the measurement update of the integrated navigation system

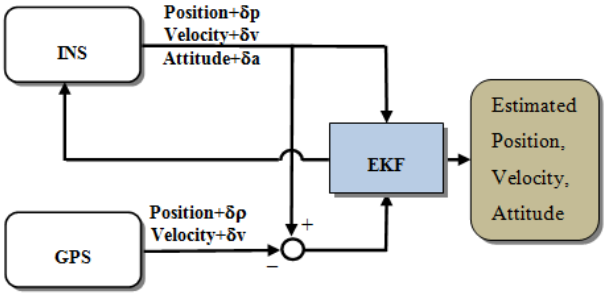

Fig. 1 Loosely coupled INS/GPS scheme.

is possible only when four or more satellites are in view [3].

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:

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

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, w_k is system noise. The details of forming these parameters can be found in Rogers, R. M. [4] and Chiang, K. W., et al. [1].

The measurement model is built based on GPS measurement:

$$z_k = H_k x_k + n_k \tag{2}$$

where z_k is measurement vector, H_k is mapping matrix and n_k is measurement noises at time k, respectively.

Based on the system and measurement models, a process of EKF is applied to determine the optimal estimates of the state vector.

3. INS/GNSS Integration with Analytic Constraint

3.1 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 Fig. 2. NHC is updated with given interval set by user. ZUPT is automatically detected and acctivated based on the velocity of the forward direction. If the velocity of the forward direction is smaller than a given threshold, ZUPT is activated.

3.2 NHC

Dissanayake, G., et al. [5] 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 Eq. (3) and shown in Fig. 3:

$$\begin{cases} v_y^b = 0 \\ v_z^b = 0 \end{cases} \tag{3}$$

where the superscript (b) denotes the body frame.

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

$$v^b = R_l^b v^l \tag{4}$$

The measurement equation for EKF can be constructed as Eq. (5):

$$\delta z = \begin{bmatrix} v_y^b - 0 \\ v_z^b - 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} R_l^b \delta v^l + \begin{bmatrix} \varepsilon_{vy} \\ \varepsilon_{vz} \end{bmatrix} \tag{5}$$

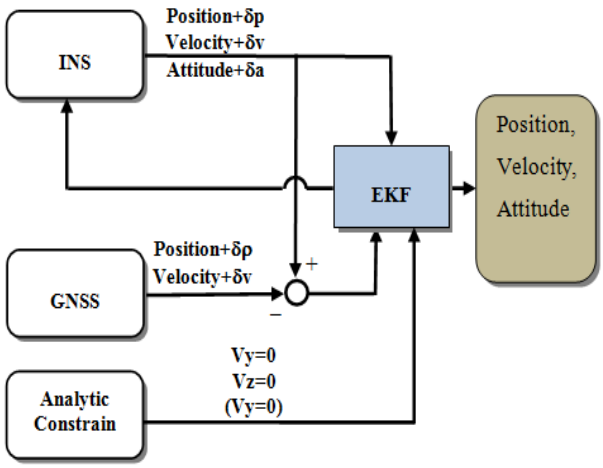

Fig. 2 INS/GNSS integration with analytic constraint.

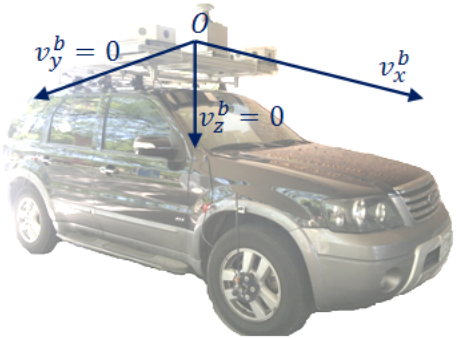

Fig. 3 NHC.

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

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.

3.3 ZUPT

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 in Eq. (6).

$$\delta z = \begin{bmatrix} \hat{v}_N^l & -0 \\ \hat{v}_E^l & -0 \\ \hat{v}_D^l & -0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \delta v^l + \begin{bmatrix} n_{vx} \\ n_{vy} \\ n_{vz} \end{bmatrix} \quad (6)$$

where $\hat{v}_N^l$, $\hat{v}_E^l$ and $\hat{v}_D^l$ are north, east and down components of estimated velocity vector of the INS in the l-frame, n_{vx}, n_{vy} and n_{vz} are the velocity noise in the direction x, y, z, respectively.

In this research, ZUPT is detected and applied automatically. In theory, when the vehicle stops, the velocity in all directions in the navigation frame will be zero. However, because of noise, these values will be bounded by a threshold:

$$\mathrm{norm}(v) = \sqrt{v_n^2 + v_e^2 + v_u^2} < v_{th} \quad (7)$$

In addition, the fact that the noise during vehicle stop is the output velocity of the system:

$$\varepsilon_v = v - 0 = v \quad (8)$$

Therefore, the ZUPT's error model can be modelled during static alignment as Eq. (9):

$$Q_{ZUPT} = E\{\varepsilon_v \varepsilon_v^T\} = E\{vv^T\} \quad (9)$$

Eqs. (8) and (9) are applied for all three axes including x, y and z with ZUPT update and for two axes, y and z with NHC update.

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, a SPAN-LCI (NovAtel) and a dual-frequency, geodetic-grade GNSS receiver, a SPAN-SE (NovAtel). The reference data was generated by the reference system using IMU raw data and differential GNSS measurements. The data was processed by Inertial Explorer software (NovAtel) in tighly coupled with smoothing mode. In general, the accuracy of the reference system was less than 10 centimeters. The testing system comprised a MEMS IMU, STIM300 (Sensonor), with a dual-frequency GPS receiver with Doppler measurement provided, Propak-V3 (Novatel). Both systems were mounted on a mobile mapping van for data collection to validate the performance of the proposed algorithms (Fig. 4).

The testing data sets were collected under various environment scenarios in urban and suburban areas in Taipei, Taiwan. The testing trajectory is shown in Fig. 5.

For the testing, two scenarios including pure INS/GNSS and INS/GNSS with analytic constraints were implemented. To evaluate the performance of the proposed method, visual and numerical analyses were applied.

Fig. 4 Testing platform.

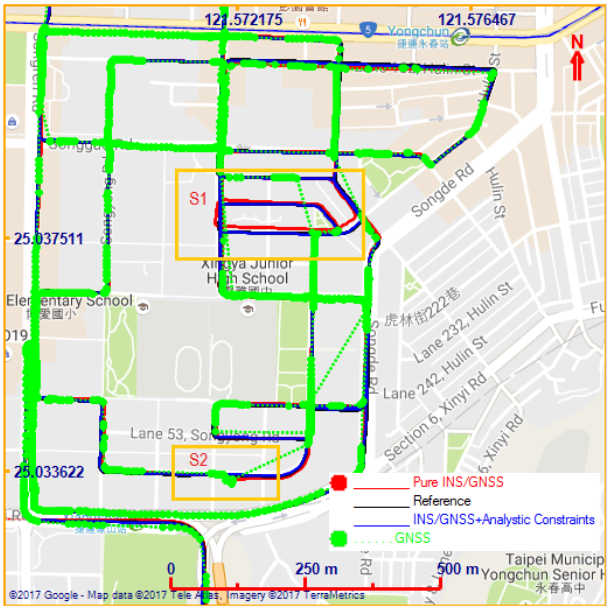

Fig. 5 Testing trajectory.

For visual analysis, the enlargement of two typical scenarios including when the long outages of GNSS solution and when vehicle stop were extracted as shown in the Figs. 6 and 7. The graphical comparison between pure INS/GNSS and INS/GNSS with analytic constraints in terms of position, velocity and attitude are shown in the Figs. 8-10.

The visual result indicates that in the urban area, GNSS outages appear frequently due to the limitation of sky view. In addition, when vehicle stops, the GNSS solution is noisy and inaccurate. In these scenarios, the solution provided by pure INS/GNSS degrades due to the effect of bad GNSS's solution. Conversely, the solution provided by INS/GNSS with analytic constraints performs better with significant improvement.

For the numerical analysis, RMSE (Root Mean Square Error) in terms of position, velocity and attitude of solutions provided by INS/GNSS and INS/GNSS with analytic constrains are calculated. The improvement of the proposed method compared to the pure INS/GNSS is also estimated as shown in Table 1. The analysis indicates that with the support of the analytic constraints such as NHC and ZUPT, the performance of the system improves significantly compared to the pure INS/GNSS in terms of position velocity and attitude.

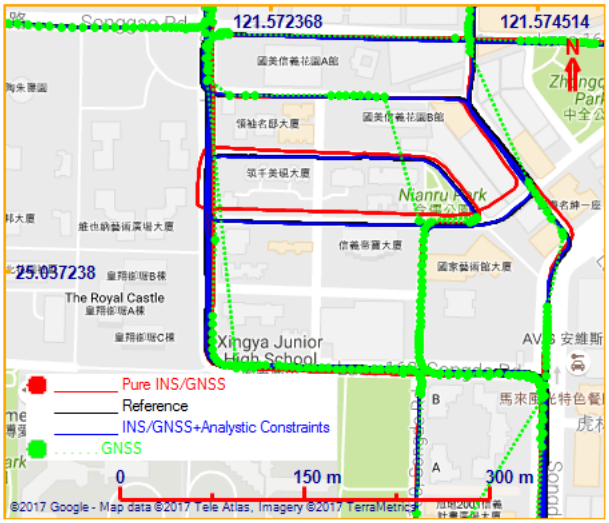

Fig. 6 Enlargement of scenario 1 (S1).

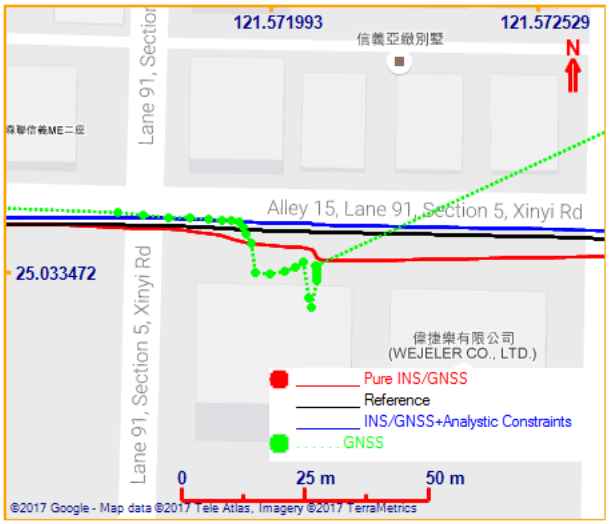

Fig. 7 Enlargement of scenario 2 (S2).

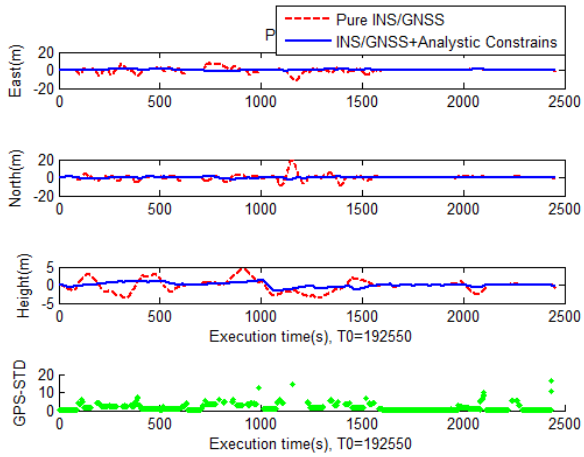

Fig. 8 Comparison of positional error.

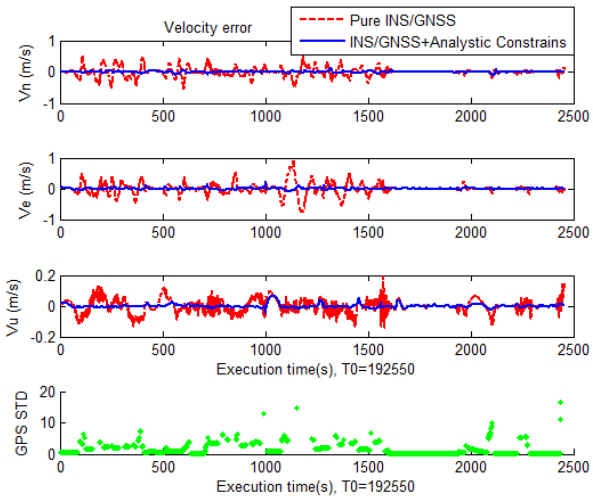

Fig. 9 Comparison of velocity error.

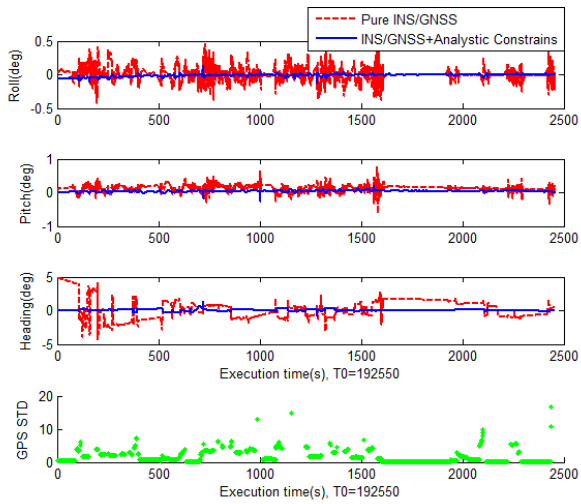

Fig. 10 Comparison of attitude error.

Table 1 Comparison of RMSE in two integration strategies.

RMSE	INS/GNSS	INS/GNSS + analytic constraints	Improvement %
East (m)	2.542	0.694	73
North (m)	2.994	0.627	79
Up (m)	1.646	0.610	63
3D (m)	4.259	1.117	74
Ve (m/s)	0.137	0.029	79
Vn (m/s)	0.179	0.026	86
Vu (m/s)	0.040	0.013	69
Roll (o)	0.084	0.022	73
Pitch (o)	0.149	0.047	69
Heading (o)	1.559	0.848	46

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 improves significantly compared to the pure INS/GNSS in terms of position and attitude. The results also demonstrate 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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