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Accuracy Improvement of Low Cost GPS/INS Integration System for Digital Photologging System

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Abstract

The accuracy of the Digital Photologging System, designed for the construction of the road Facility Database, highly depends on the positions and attitudes of the cameras from GPS/INS integration. In this paper, the development of a loosely coupled GPS/INS is presented. The performance of the system is verified through a simulation as well as a real test data processing. Since the IMU used in this study shows large systematic errors, the possible accuracy of the positions and attitudes of this low-performance IMU when combined with precise GPS positions are assigned. Currently, the integrated system shows the positional accuracy better than 5cm in real data processing. Although the accuracy of attitude based on real test could not be assigned at this time, it is expected that better than 0.5 degrees and 1.8 degrees for horizontal and down component are achievable according to the simulation result.

Keywords : GPS, INS, Navigation, Integration, Photologging

1. Introduction

For efficient management of the road and traffic control, the construction of the Road Facility Database is very important and necessary. One of the ways to acquire the data for the database is to take images along the target road, and extract necessary features and objects. Obviously, if this data acquisition and processing is fully automatic, the construction, management and update of the database could be easy and efficient.

The Digital Photologging System(DPS) is an Mobile Mapping System integrated by the Global Positioning System(GPS), Inertial Navigation System(INS) and CCD camera for the purpose of automatic data acquisition and processing[1]. The exterior orientations of the CCD camera is provided by GPS and INS so that the obtained images can be processed in near-real time. Therefore, the accuracy of the product from the DPS is highly depend on the accuracy of positions and attitudes from the GPS/INS integration.

As well known, the GPS and INS have complementary characteristics in signal stability and behavior. For example, the GPS pseudorange measurements are available at anytime in all weather conditions but with relatively low sample rates. In addition, GPS may experience short-term loss of the GPS signals because of signal blockage, interference, or jamming. The INS estimates are calculated based on the outputs of inertial sensors that are not dependent on the external fields and are therefore essentially immune to external interference. However, the systematic errors of INS increase exponentially with respect to time. Therefore, by the combination of GPS and INS, one can achieve stable and accurate determination of positions and attitudes. Especially for the low-cost INS which systematic errors are significantly large, the combination with GPS significantly improves the position and attitude result [3-5].

In this paper, an algorithm and results from simulation and real test for the loosely coupled GPS/INS integration are presented. The integration is performed by 15 states Kalman filter with estimation of the

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accelerometer and gyro biases. The achievable accuracy for the positions and attitudes for the integrated system especially with a low-performance INS is assigned based on the real data processing and simulation.

2. GPS/INS Integration Algorithm

2.1 Initial Fine Alignment Algorithm

Before INS navigates in a 3-dimensional space, the orientation of the sensors(accelerometers and gyros) should be determined so that the observed accelerations can be properly mapped in a pre-defined coordinate system. During the alignment procedure, the navigation system is stationary with respect to the Earth so that the accurate position of the system is assumed to be known. Using the earth's gravity and rotation as input, the system can be aligned with respect to the navigation system which is defined by north-east-down axes.

The alignment and calibration procedure through a Kalman filtering for the stationary case are well described in [3]. The state vector comprises the orientation errors, the gyro biases, and the velocity errors. Let the system state vector be denoted by ε

$$\varepsilon = (\phi_N \; \phi_E \; \phi_D \; \triangle\omega_N \; \triangle\omega_E \; \triangle\omega_D \; \delta v_N \; \delta v_E)^T. \tag{1}$$

Then, the dynamics of the state vector is given as:

$$\dot{\varepsilon} = F\varepsilon, \tag{2}$$

where,

$$F = \begin{bmatrix} 0 & -\omega_e \sin\phi & 0 & -1 & 0 & 0 & 0 & \frac{1}{r} \\ \omega_e \sin\phi & 0 & \omega_e \cos\phi & 0 & -1 & 0 & -\frac{1}{r} & 0 \\ 0 & -\omega_e \cos\phi & 0 & 0 & 0 & -1 & 0 & \frac{1}{r}\tan\phi \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \bar{g} & 0 & 0 & 0 & 0 & 0 & -2\omega_e \sin\phi \\ -\bar{g} & 0 & 0 & 0 & 0 & 0 & 2\omega_e \sin\phi & 0 \end{bmatrix} \tag{3}$$

ω_e is the rotational velocity of the earth, r is the mean radius of the earth and ϕ is the latitude of the platform in the earth-centered earth-fixed system.

The linear relationship between observations of zero velocities and states is given by

$$y = H\varepsilon + v, \tag{4}$$

where, the design matrix H is given as

$$H = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \tag{5}$$

2.2 GPS/INS Integration Algorithm

Among numerous approaches for the integration of GPS and INS, a loosely-coupled mode was developed in this study(Fig. 1). The INS and the GPS calculates the navigation solution and positions independently, and then those two solutions are combined in a Kalman filter to estimate and correct the systematic errors of IN generating a blended solution.

As seen, the filter is implemented as a form of the extended Kalman filter in which the estimated INS systematic errors are fed back to the INS navigation procedure so that the systematic effects are calibrated.

The state vector of 15 states is comprised of the three orientation errors, three velocity errors with respect to NED geographic navigation system, three position errors with respect to WGS-84 coordinate system, three gyro bias, and three accelerometer bias.

Following the typical dynamic form of a Kalman filter, the dynamic equations in this case is given as:

$$\dot{x}(t) = F \cdot x(t) + w(t), \tag{6}$$

or in a matrix form

$$\begin{bmatrix} \dot{x}_i \\ \dot{x}_f \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} \\ 0_{6\times9} & 0_{6\times6} \end{bmatrix} \cdot \begin{bmatrix} x_i \\ x_f \end{bmatrix} + \begin{bmatrix} w_i \\ 0_{6\times1} \end{bmatrix}. \tag{7}$$

The observation equation is given as

$$z(t) = H \cdot x(t) + v(t), \quad v \sim N(0, R), \tag{8}$$

where,

$$x_i = [\delta\alpha \;\; \delta\beta \;\; \delta\gamma \;\; \delta Vn \;\; \delta Ve \;\; \delta Vd \;\; \delta\phi \;\; \delta\lambda \;\; \delta h]^T \tag{9}$$

$$x_f = [\delta Wn \;\; \delta We \;\; \delta Wd \;\; \delta fn \;\; \delta fe \;\; \delta fd]^T \tag{10}$$

$$w_i = [Wg \;\; Wg \;\; Wg \;\; Wa \;\; Wa \;\; Wa]^T \tag{11}$$

$$H = [0_{3\times3} \;\; 0_{3\times3} \;\; I_{3\times3} \;\; 0_{3\times3} \;\; 0_{3\times3}] \tag{12}$$

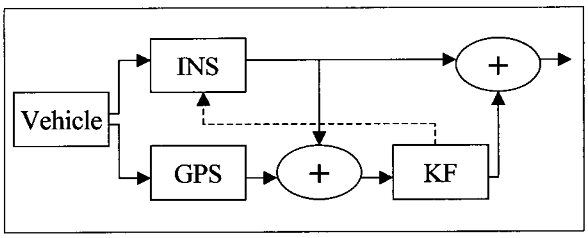

Fig. 1. The loosely-coupled System.

$$F_{12} = \begin{bmatrix} -C_b^n & 0_{3\times3} \\ 0_{3\times3} & C_b^n \\ 0_{3\times3} & 0_{3\times3} \end{bmatrix} \quad (13) \qquad G = \begin{bmatrix} -C_b^n & 0_{3\times3} \\ 0_{3\times3} & C_b^n \\ 0_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & 0_{3\times3} \\ 0_{3\times3} & 0_{3\times3} \end{bmatrix}. \quad (14)$$

Note that the submatrix F_{11} would be the same as the matrix F in equation (3). Also note that only biases of accelerometers and gyros are modeled in this case for simple feasibility test.

3. GPS/INS Integration Simulation

3.1 Simulation S/W development

The GPS/INS Integration software package GICI version 1.0 is developed through this study. It is the software to integrate GPS solution and INS navigation solution to obtain the blended solution of the accurate attitudes and positions. In addition, the systematic errors of INS are estimated and calibrated through the filter.

A simulation data was constructed and the algorithm is applied to verify the developed loosely-coupled GPS/INS integration. Fig. 2 shows the procedures of the simulation with all modules in the developed software GICI-1.

The first module GICI1 SimulationData creates the error-free accelerometer and gyro data, namely the increments of velocities and angles. Later, this data would be intentionally contaminated by the systematic errors to generate the deteriorated navigation solution.

The second module GICI1Initialization defines the initial constant values such as the initial attitudes from alignment procedure and the initial position of the system from GPS data. In addition, the initial covariance matrices for the states and system errors P, Q for Kalman Filtering are defined in this module. Obviously, the values for the covariance matrices should be based on the system specification to be used in the study.

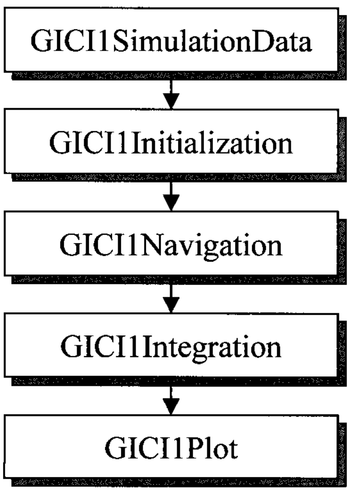

Fig. 2. GPS/INS Integration Procedure.

The third module GICI1Navigation calculates the attitude, velocity and position through navigation equation using the error-free data that created in the first module.

The fourth module GICI1Integration integrates the GPS and IMU data using the Kalman Filter. The Navigation data created in the third module is used as GPS data and the intentional systematic errors are added to generate the deteriorated IMU data. Then, the Kalman filtering is performed to estimate the systematic errors and generate the blended solution.

The fifth Module GICI1Plot draws figures for estimates, blended solutions, residuals, and covariances etc.

3.2 Error-Free INS Data Creation

The first step in the simulation is to create the raw data of IMU composed of increments of velocities and angles. Fig. 3 and 4 show the simulated error-free

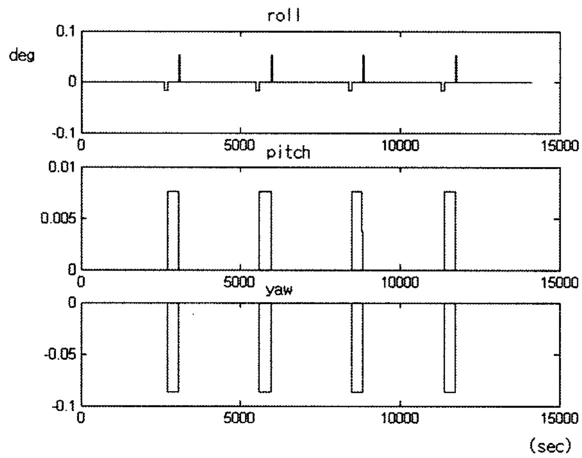

Fig. 3. Simulation data angle rate.

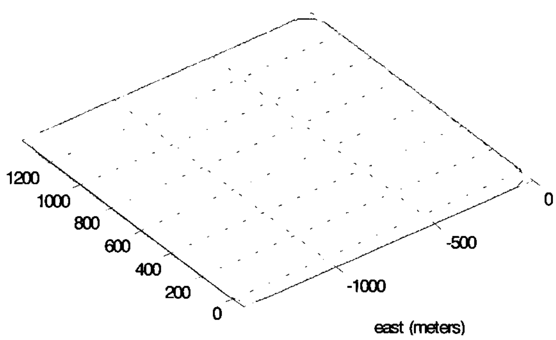

Fig. 4. Trajectory.

increments of angles and the designed trajectory, respectively. As noticed, the angular data shows clear four turns, corresponding to the rectangular loop on the trajectory.

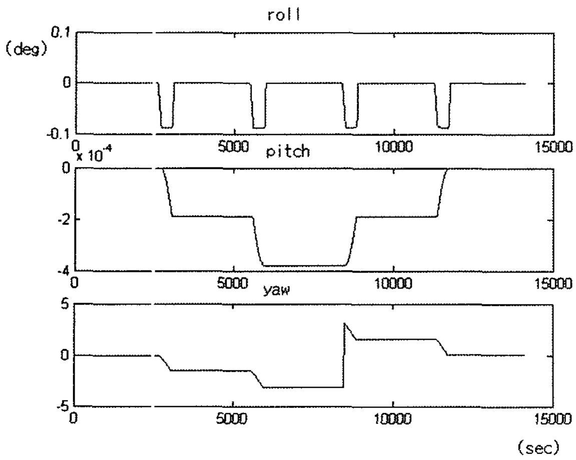

Fig. 5. Navigation Solution - attitude.

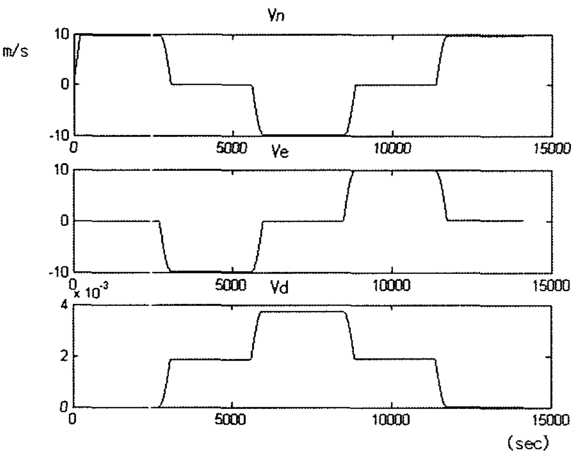

Fig. 6. Navigation Solution - Velocity.

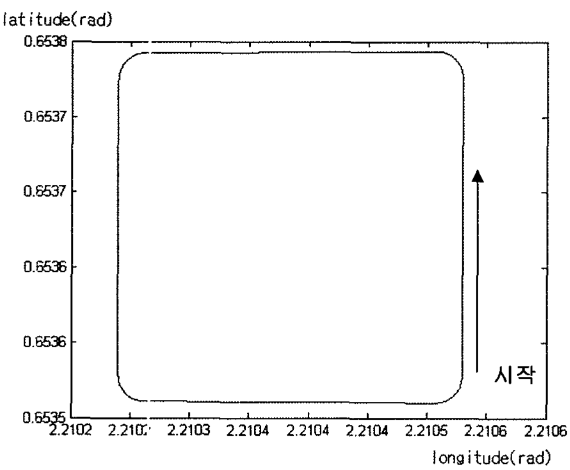

Fig. 7. Navigation Solution - Position.

3.3 Navigation solution

Using the simulated IMU raw data constructed in the previous step, the navigation solution (attitude, velocity, position) is calculated. The calculated error-free position is to be used as true position, namely GPS position in the filter. And, the calculated error-free attitude and velocity would be used as basic data in which the intentional systematic error are imposed.

Fig. 5, 6 and 7 shows the pure navigation solutions. Clear four turns are reflected in the attitudes as well as in the velocities. Of course, the position solution is a rectangular loop designed for the simulation. When the vehicle makes turns, the velocities are changed while it is a constant when the vehicle is on straight motion.

3.4 Contaminated Data Creation

To verify the performance of the developed filter, a contaminated IMU data should be created. This can be done by adding the systematic errors to the error free simulated data. It is obvious that the amount of the systematic error to be added should be based on a IMU specification; DMU-FOG in this case (Table 1).

In this study, the accelerometer and gyro biases and random errors modeled as random walk are added to the error-free data as the following procedure.

Contaminated Data = Error-free simulated data + bias + random walk

Table 1. IMU(Crossbow DMU-FOG) Specification

Specification (Performance)		
Angle Rate	Bias: Roll, Pitch, Yaw (°/sec)	<±0.03
	Random Walk (°/hr1/2)	< 1.25
Accelerometer	Bias: X/Y/Z (mg)	<± 8.5
	Random Walk (m/s/hr1/2)	< 0.1

3.5 Initial Fine Alignment

The test data for initial fine alignment is the contaminated data that created in section 3.4 with stationary condition. In addition, an intentional misalignment are added in the procedure of navigation equation as is shown in Table 2. Then, the fine

Table 2. Fine Alignment test Initial value

Time		12,000 sec
Initial misalignment angle	roll	8 °
	pitch	5 °
	yaw	0 °

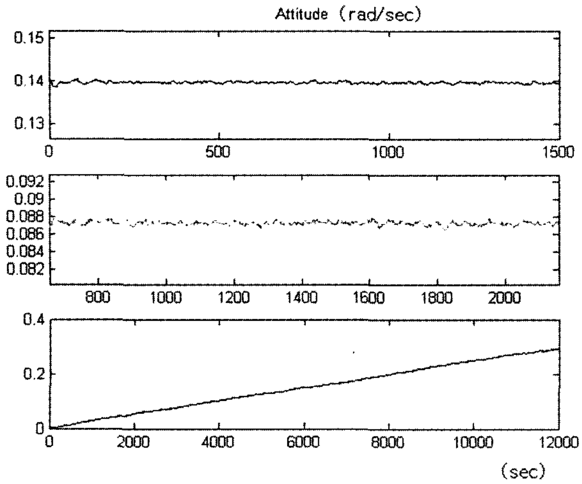

Fig. 8. Initial Fine Alignment.

alignment described in section 2.1 is performed to check if the mis-alignment is estimated.

Fig. 8 shows the result of the alignment procedure. Note that the north and east mis-alignments are well estimated from the beginning of the filter. The down mis-alignment (yaw), however, was not estimated due to the insensitivity of the down gyro to the earth's rotation and no yaw motions.

3.6 GPS/INS Integration

The contaminated INS data is combined with simulated GPS position in the Kalman filter. The filter estimates the systematic errors of IMU, correct the effect and generate the blended solution. Fig. 9-13 shows the navigation solution before and after the GPS/INS integration. As seen, the attitudes and velocities are well corrected through the filtering.

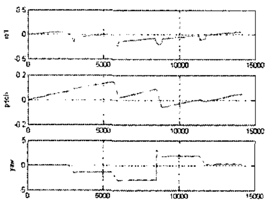

Fig. 9. before-attitude.

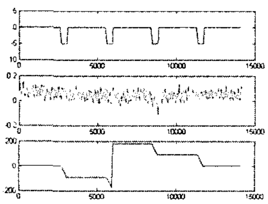

Fig. 10. after-attitude.

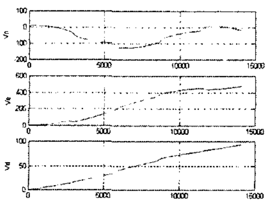

Fig. 11. before-velocity.

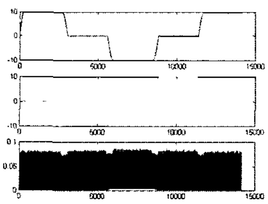

Fig. 12. after-velocity.

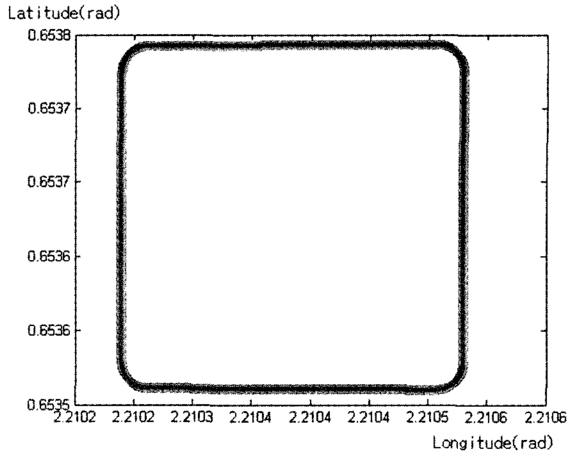

Fig. 13. GPS/INS Integrated position.

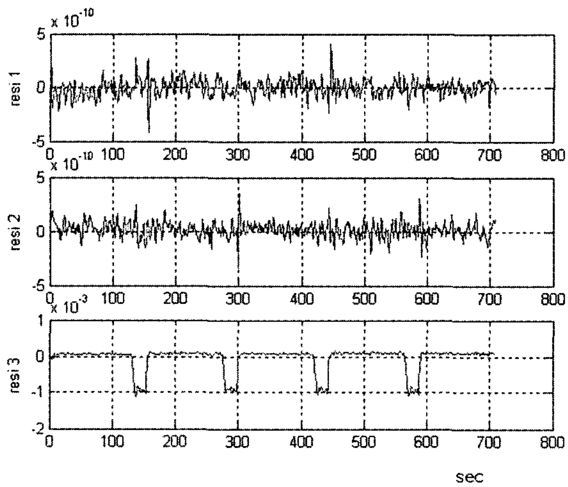

Fig. 14. Residual.

Based on this simulation, it has been shown that the attitude better than 0.2 degrees in horizontal and 1.2 degree in vertical is achievable in the integration of the low-cost IMU and GPS.

4. GPS/INS Field Test and Result

4.1 Field Test

Since the simulation shows the good feasibility of the algorithm, a field test is carried out for the final verification.

We use the experiments car that was originally designed for Digital Photologging System(Fig. 15). The description on the field test is as follows.

- Test area : Taejun, Korea (Fig. 16.)
- Test date : 2002-09-05
- IMU : Crossbow DMU-FOG (84 Hz)

- GPS : Trimble 4000ssi (Event marker possible) (1Hz)
- Initial Position and Attitude from initial fine alignment:

	Initial position(。)		Initial Attitude(。)
ϕ	36.4374078	roll	0.434
λ	127.4130672	pitch	-4.406
h	55.919	yaw	135

Fig. 15. Experiment Car.

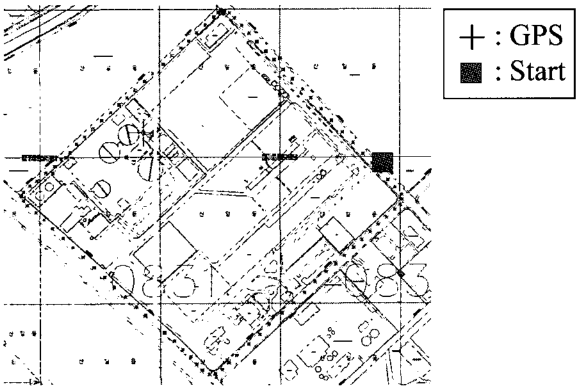

Fig. 16. Field Test Area.

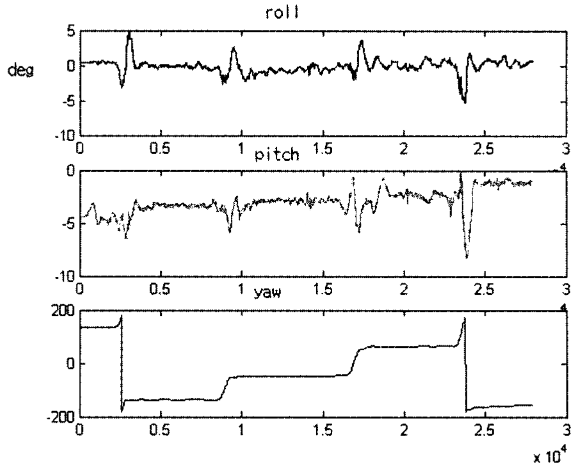

Fig. 17. Field Test - Attitude.

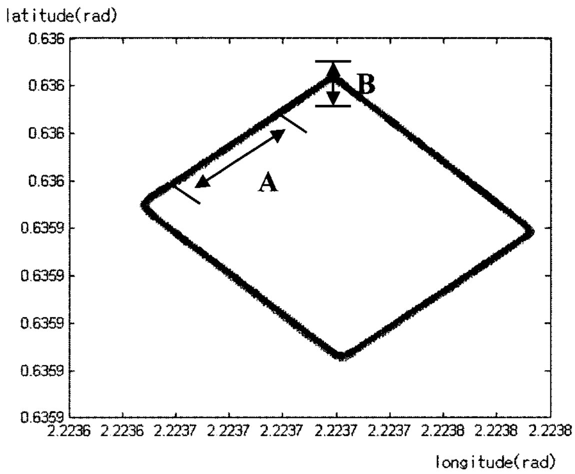

Fig. 18. Field Test - Position.

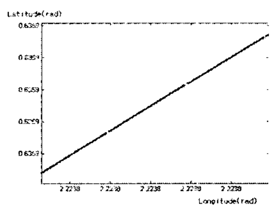

Fig. 19. area 'A'.

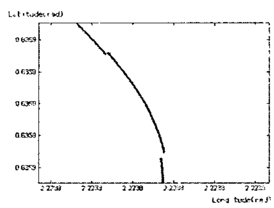

Fig. 20. area 'B'.

4.2 Result

Fig. 17 and 18 shxow the result of the integration using the field test data. Although the attitudes show much more vibrations reflecting the road condition and vehicle vibration, the turns are clearly detected by gyros. Fig. 19 and 20 present the comparison between the DGPS solution and the blended solution from the integration while the vehicle is on straight motion and on turns, respectively. Clearly, the integrated solution shows bigger errors during the turns than on a straight motion because of high dynamics of the vehicle.

The comparison of the position showed that the accuracy better than 5 cm is achieved through the integration. For further analysis, the position update rate is set to two seconds to see the effect of GPS outage to the blended position (Fig. 21, 22). As expected, the standard deviation of the difference between the GPS and blended solution increased up to 50 cm because of the low-performance of the IMU.

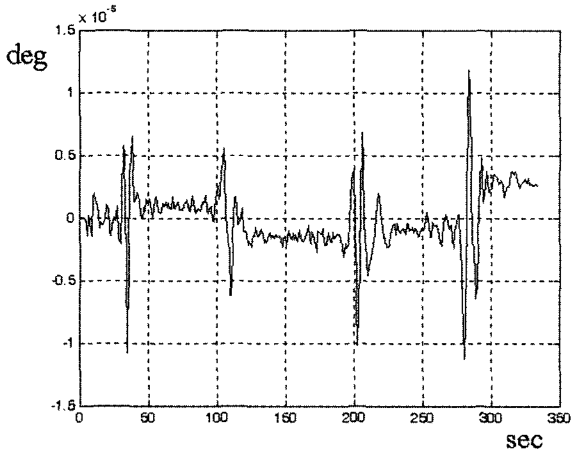

Fig. 21. Position Errors(ϕ).

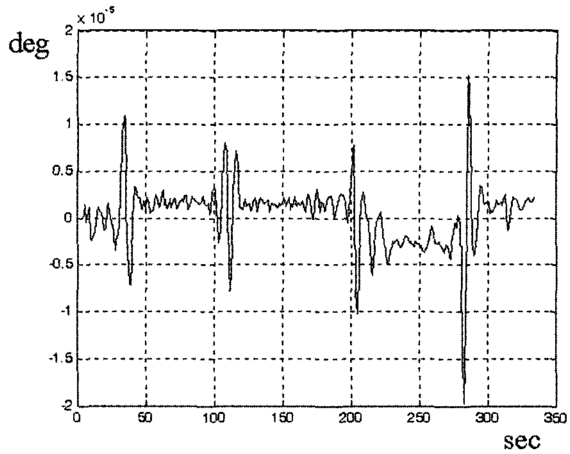

Fig. 22. Position Errors(λ).

5. Conclusion

In this paper, an algorithm and results of a loosely-coupled GPS/INS integration were presented. The developed algorithm was verified through a simulation as well as a real field test showing better than 5 cm of positional accuracy.

The accuracy of the attitudes cannot be assigned through the field test because of the lack of the control data. Based on the simulation, however, it is expected that better than 0.5 and 1.2 degrees in horizontal and vertical direction can be achieved.

The obtained blended solution would be used to provide an exterior orientation of the CCD camera mounted on the Digital Photologging System, so the accuracy of the object extracted from images in DPS is highly depend on the accuracy of the blended solution.

It has been shown that the positional accuracy are degraded to 50 cm if GPS outage occurs at every one second. This reflects that the low-performance IMU is not sufficient for the precise mapping even after the integration with GPS in loosely coupled mode.

Therefore, a tightly integration should be developed for the immunity of the GPS solution outage. Also, the accuracy of the attitude should be verified based on the real control data.

Acknowledgment

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