Performance Testing of Integrated Strapdwon INS and GPS

Sang-Jong Lee*, Chang-Sun Yoo, Yo-Han Shim** and Jong-Chul Kim*****
Aircraft Division
Korea Aerospace Research Institute, Taejon, Korea 305-600

Abstract

In recent navigation system, the profitable solution is to integrate the GPS and Stapdwon INS (SDINS) system and its integration allows compensation for shortcomings of each system. This paper describes the hardware preparation and presents the test results obtained from the automobile test of the developed system. The automobile tests was conducted with two kinds of inertial sensors and GPS receivers : short range and middle range test, to verify and evaluate the performance of the integrated navigation system. The reference of position is given by the Differential GPS(DGPS) which has cm-level accuracy to compare the accuracy of system. Kalman filtering is used for integrating GPS and SDINS and this filter effectively allows the long-term stability of GPS to correct and decrease the time deviation error of SDINS.

Key Word : Strapdown INS, GPS, integrated navigation system, Kalman filter

Introduction

For many vehicle requiring a navigation capability, and many users and designers are considering to achieve more high accuracy with low costs. One major efforts and trends to satisfy these requirements is to integrate the Strapdown Inertial Navigation System (SDINS) with Global Positioning System (GPS). Each of these navigation systems has its own advantages and disadvantages when it would be used as sole means of navigation system. As well known, inertial navigation system(INS) is characterized by a time dependent drift in the accuracy of the position and velocity information it provides. On the other hand, GPS can provide stable accuracy of position for long periods of time. This main advantage leads a variety of efforts to develop the integrated navigation system for many application.

Korea Aerospace Research Institute(KARI) has been endeavoring to develop the integrated SDINS/GPS system and several research papers have already been published : calibrating errors of an inertial measurement unit(IMU) in [1], developing algorithm for SDINS in [2], performance testing for SDINS in [3] and developing algorithm for the integrated SDINS/GPS in [4]. The purpose of this paper is to evaluate and show the performance of the integrated SDINS/GPS navigation system which was developed in [4]. To verify the performance of system, two kinds of real IMUs are used, tested and compared ; First system is composed of Fiber optic gyro(FOG) with bias 7.2 °/h and a silicon micro-machined accelerometer with ±30mg of bias. Second one consists of the same FOGs and a pendulous torque-feedback type accelerometer which has ±17mg of bias. Though the level of bias is not so accurate and high as to be used in airborne navigation application. NovAtel GPS receiver

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* Researcher
E-mail : albert@kari.re.kr, TEL: 042-860-2342, FAX : 042-860-2009
** Senior Researcher
*** Principal Researcher

was used for external navigation aids for the integrated SDINS/GPS navigation system and also provides the high accuracy of position as the reference outputs of Differential GPS (DGPS) to compare the outputs of the integrated SDINS/ GPS navigation system. By using the automobile two types of tests were performed : one is the short range test about 1.7 Km for about 7 minutes and second is the middle range test about 7.0 Km for about 17 minutes. All test results are reported in this paper and the position output was compared with DGPS results which has a cm-level positioning.

Mechanization of Navigation System

Inertial navigation is the process of calculating position by integration of velocity and computing velocity by integration of total acceleration. Basic structure of integrated SDINS/GPS navigation system is depicted in Fig. 1. Error state estimation for determining the navigation outputs can be updated through Kalman filtering with optimal correction control input.

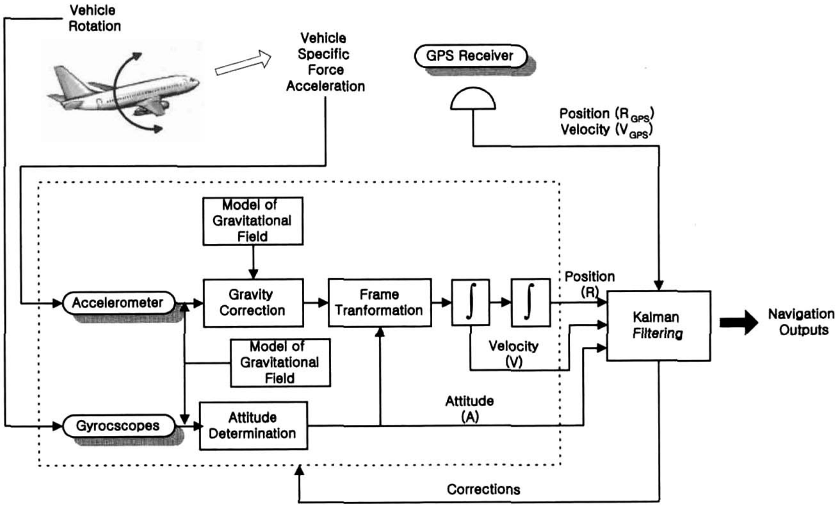

Fig. 1. Structure of integrated navigation system

Strapdown INS Mechanization

The SDINS consists of two parts of calculation ; rotational mechanization(attitude determination) and translational mechanization [2]. Brief description of each part of navigation is defined following equations (1) and (2) ;

- rotational mechanization $\dot{\boldsymbol{\lambda}}(t) = \frac{1}{2}\boldsymbol{\Phi}(\boldsymbol{\omega})\cdot\boldsymbol{\lambda}(t)$ where $\boldsymbol{\Phi}(\boldsymbol{\lambda}) = \begin{bmatrix} \alpha & -\mathbf{q}^{T} \\ \mathbf{q} & \alpha\cdot\mathbf{I}-\mathbf{q}\times \end{bmatrix}$ (1)

- translational mechanization $\begin{bmatrix} \mathbf{r}(t) \\ \mathbf{p}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A}_{\varphi}(t) & t\cdot\mathbf{A}_{\varphi}(t) \\ \mathbf{0} & \mathbf{A}_{\varphi}(t) \end{bmatrix} \begin{bmatrix} \mathbf{r}_0 \\ \mathbf{p}_0 \end{bmatrix} + \begin{bmatrix} \mathbf{A}_{\varphi}(t)\cdot\mathbf{r}_{\Delta}(t) \\ \mathbf{A}_{\varphi}(t)\cdot\mathbf{v}_{\Delta}(t) \end{bmatrix}$ (2)

$$\mathbf{p}_0 = \mathbf{v}_0 + \mathbf{u}_{\varphi}\times\mathbf{r}_0, \quad \mathbf{r}_{\Delta}(t) = \int_0^t (t-s)\cdot\mathbf{a}_g(s)ds, \quad \mathbf{v}_{\Delta}(t) = \int_0^t \mathbf{a}_g(s)\,ds$$

$$\mathbf{a}_g(t) = \mathbf{A}^{T}(t)\cdot\mathbf{a}(t) + \mathbf{A}_{\varphi}^{T}(t)\cdot[\mathbf{g}(t)-\mathbf{w}_{\varphi}]$$

where $\boldsymbol{\lambda} = [\alpha \quad \mathbf{q}]^{\mathrm{T}}$ is the quaternion that describes the rotation of vehicle into the inertial frame, $\boldsymbol{\omega}$ is the angular rate vector of the vehicle with respect to the inertial frame. $\mathbf{r}$ and $\mathbf{v}$ are the position and velocity vectors with respect to the navigation frame. $\mathbf{u}_{\varphi} = \Omega[\cos\varphi \quad 0 \quad -\sin\varphi]^{\mathrm{T}}$ is a vector of the earth angular rate and φ is a latitude. Transformation matrices, $\mathbf{A}$ and $\mathbf{A}_{\varphi}$, represent ones from the inertial to the body frame and from the inertial to the navigation frame respectively.

Integrated SDINS/GPS Mechanization

Discrete error equation of SDINS is derived as equation (2) and when implemented in integrated SDINS/GPS navigation system, the vectors, $\delta\boldsymbol{\theta}(t)$, $\delta\mathbf{r}(t)$ and $\delta\mathbf{p}(t)$, are error states to be estimated. This estimation will be determined by a method of Kalman filtering using a difference between the computed SDINS and the observed GPS values of the vehicle's navigation information : position and velocity [4].

$$\begin{bmatrix} \delta\boldsymbol{\theta}(t) \\ \delta\mathbf{r}(t) \\ \delta\mathbf{p}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{I} & \mathbf{0} & \mathbf{0} \\ \mathbf{A}_{\varphi}(t)\cdot\mathbf{V}_r(t) & \mathbf{A}_{\varphi}(t) & t\cdot\mathbf{A}_{\varphi}(t) \\ \mathbf{A}_{\varphi}(t)\cdot\mathbf{V}_v(t) & \mathbf{0} & \mathbf{A}_{\varphi}(t) \end{bmatrix} \begin{bmatrix} \delta\boldsymbol{\theta}(t_0) \\ \delta\mathbf{r}(t_0) \\ \delta\mathbf{p}(t_0) \end{bmatrix} + \begin{bmatrix} t\cdot\widehat{\mathbf{A}}_k^{\mathrm{T}}\cdot\mathbf{u}_{\omega k} \\ t^2\!/_2\cdot\mathbf{A}_{\varphi}(t)\cdot\widehat{\mathbf{A}}_k^{\mathrm{T}}\cdot\mathbf{u}_{ak} \\ t\cdot\mathbf{A}_{\varphi}(t)\cdot\widehat{\mathbf{A}}_k^{\mathrm{T}}\cdot\mathbf{u}_{ak} \end{bmatrix} + \begin{bmatrix} \tilde{\boldsymbol{\varepsilon}}_{\theta\omega} \\ \tilde{\boldsymbol{\varepsilon}}_{ra} \\ \tilde{\boldsymbol{\varepsilon}}_{va} \end{bmatrix} \tag{3}$$

$$\mathbf{V}_r(t) = -\int_{t_0}^{t}(t-s)\cdot\widehat{\mathbf{A}}^{\mathrm{T}}(s)\cdot\mathbf{a}_0(s)\,ds\times \quad , \quad \mathbf{V}_v(t) = -\int_{t_0}^{t}\widehat{\mathbf{A}}^{\mathrm{T}}(s)\cdot\mathbf{a}_0(s)\,ds\times$$

where the second term on the right hand side is the first approximation of corresponding integral and $\widehat{\mathbf{A}}_k$, $\mathbf{u}_{\omega k}$ and $\mathbf{u}_{ak}$ are the mean value of the function $\mathbf{A}(t)$, $\mathbf{u}_{\omega}(t)$ and $\overline{\mathbf{u}}_{\mathbf{a}}(t)$ in the integration interval. The corrected vector for attitude, position and velocity can be found to be the solution of the Riccati equation of optimal control problem [5][6].

$$\overline{\mathbf{u}}_{\omega,k} = -c_{\omega}\cdot\delta\widehat{\boldsymbol{\theta}}_k \quad , \quad \overline{\mathbf{u}}_{\mathbf{a},k} = -c_r\cdot\delta\widehat{\mathbf{r}}_k - c_p\cdot\delta\widehat{\mathbf{p}}_k$$

The coefficient of the corrected vector, c_{ω}, c_r and c_p, should be selected by trial and error and its value is set to be 5.0, 8.0, and 4.0 in this test.

Hardware System Description

The developed integrated SDINS/GPS naviagtion system is composed of a three KVH's 1-axis Fiber Optic Gyros(FOG), one 3-axis Crossbow's accelerometer, three 1-axis Ramenskoye's accelerometers as well as two NovAtel MiLLennium GSPCard$^{\mathrm{TM}}$ GPS receivers and its basic block diagram is presented in Fig. 2. The inertial measurement unit assembles three FOGs with both two kinds of accelerometers. For convenience sake, we refer to two combination as SDINS-1 and SDINS-2 as below. The result will show the difference between two systems could not be large and it would indicate the advantage of the integrated navigation system.

o SDINS-1: three 1-axis FOGs, three 1-axis Accelerometers
o SDINS-2: three 1-axis FOGs, one 3-axis Accelerometer

Inertial Measurement Unit and GPS receiver

For SDINS-1 set, three interferometric type FOGs have a 7.2 °/h gyro drift and a torque-feedback accelerometer has ±17mg of bias (Ramenskoye accelerometer). For SDINS-2 set, the same FOGs are used and a silicon micro- machined type accelerometer that has ±30mg of bias is used (Crossbow accelerometer) . Both IMU sets are installed on the one triad mounting frame which makes orthogonal axes and was shown on Fig. 3.

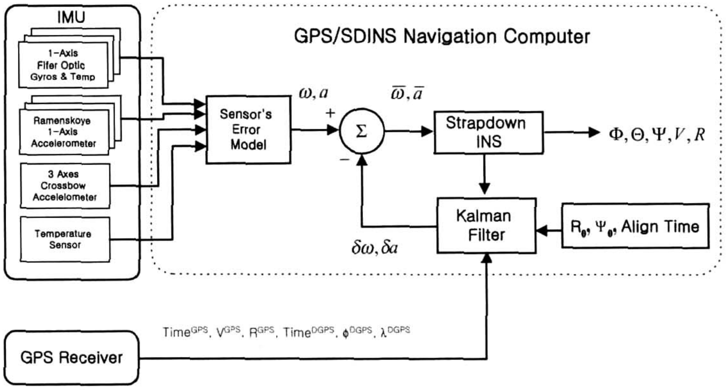

Fig. 2. Basic block diagram of hardware structure

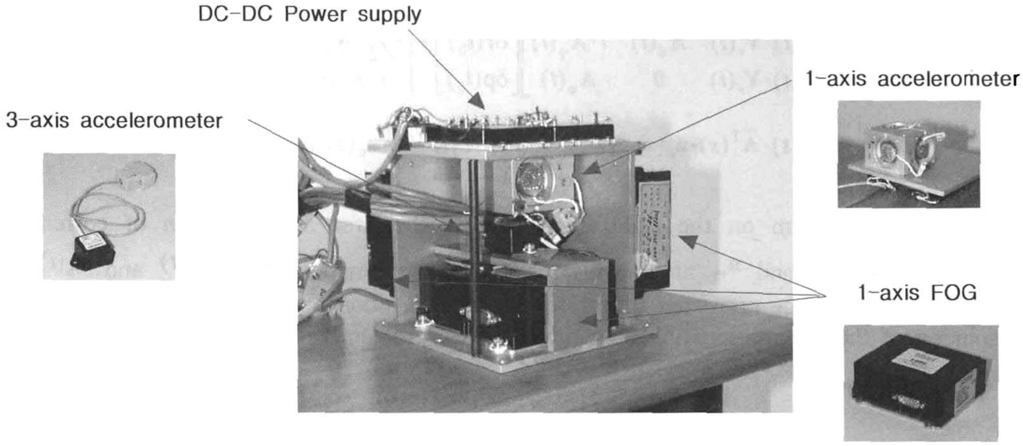

Fig. 3. Inertial Measurement Unit

The MiLLennium GPSCard, GPS receiver, is a high-performance GPS receiver capable of receiving and tracking the L1 C/A code, L1 and L2 carrier phase of up to 12 GPS satellites. it will function with an active or passive dual-frequency GPS antenna. It requires only one regulated power input of DC +5 V and communication with RS232C serial data format via two ports, COM1 and COM2. Fig. 4 shows the GPS receiver and antenna. Two GPS receivers were used in this test ; one was installed on the moving automobile and the other in reference station for DGPS. Position accuracy is about 15 m for stand-alone mode in SA off condition and velocity accuracy is about 0.2 m/s.

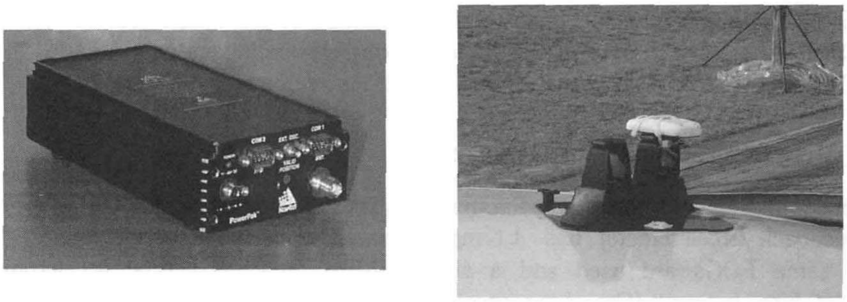

Fig. 4. GPS receiver and antenna

Data Acquisition System

The data acquisition system(DAQ) consists of an industrial computer equipped with the 32-channel 16-bit AD converter as well as the IBM notebook computer. Industrial computer's CPU is a Pentium MMX 233 MHz with 64MB DRAM and it collects all raw data from FOGs and two accelerometers. Collected data from IMU is used for calculating all numerical algorithm defined in previous section inside the running time of 40 Hz sampling frequency. GPS data is saved simultaneously during the testing period by a notebook computer shown on Fig. 4. It provides both the external navigation information for correcting the navigation output of SDINS and precise DGPS positioning output as the reference one to compare the results. DGPS positioning result can be obtained from the post-processing software and its accuracy is so accurate as to be used as a reference value. GPS receiver's two communication ports support user-selectable bit rates of 300 - 115,200 bps. In real test, we chose 38,400 bps and the updating rate is 10 Hz.

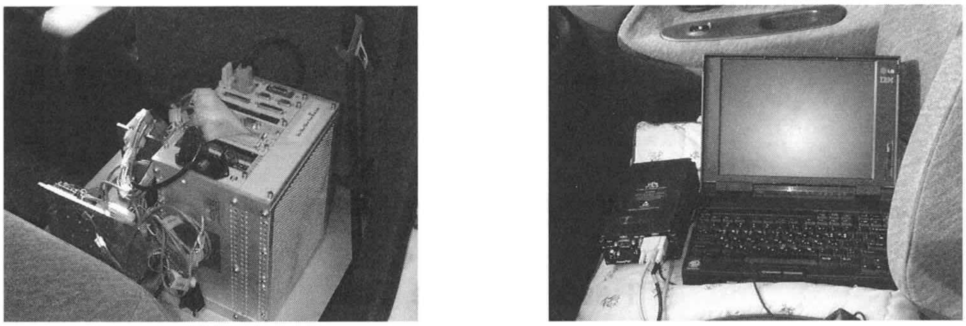

Fig. 5. Data acquisition system for IMU and GPS receiver

Test Description

Automobile tests were conducted and all system described above were installed in automobile. To verify the developed system two types of test were performed. The First test was the short range test ; it was done on the rectangular route inside KARI. The distance covered was about 1.7 Km and total elapsed time was about 7.0 minutes including the initial alignment. Starting point was the same as the stop one. Next test was the middle range test ; it took about 17 minutes to run the route near the Daeduk Science Town. The trajectory of the middle rage test was selected as following and shown on Fig. 6 : KARI→Entrance of KAIST→Taejon fire station of northern part→EXPO park→Doryong-dong Intersection→ETRI→Science Town Park→KARI.

Before operating the integrated navigation system, it should be considered to calibrate the IMU and compensate it in a sensor level. As well known, the performance of a SDINS is largely affected by a number of error-sources, where most of which are related to the IMU. Therefore the main cause of SDINS's errors are caused by each sensor's error and the compensation of sensor's error should be considered and try to find the adequate error parameters of gyro and accelerometer and compensate the measurement of them by using the compensation algorithm [1]. The error models for interferometric fiber optic gyro and 3-axis accelerometer have been determined. These error parameters of them can be estimated by linear regression method during the 24-multiposition and rate test. Correspondingly the described procedures in [1] have been used for calibrating the Strapdown INS sensor unit and was used for developing the integrated SDINS/GPS system.

One more consideration is to doing the initial alignment. In the procedure of automobile test the initial alignment was conducted for 200 seconds before the car started to run. But one problem is that the resolution of FOG is not so accurate to measure the earth rotation rate. It means that it can not provide the initial yaw angle of the vehicle, so user needs either to input it artificially or input it from other information source such as magnetometer to supply it.

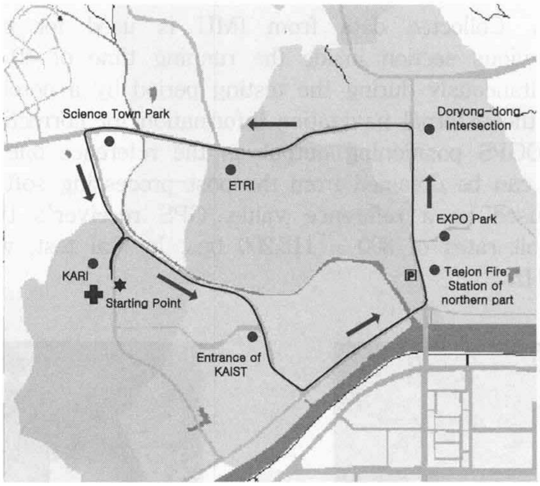

Fig. 6. Trajectory of the middle range test

Results of the Test

Short Range Test Results

Fig. 7 depicts the trajectory result of the short range test. Compared to the trajectory result of the pure SDINS navigation in Fig. 8, the integrated SDINS/GPS navigation provides the more accurate and stable outputs. That is, it compensates the time dependent error of SDINS and decrease the error of position. Final value of position of SDINS was r_x=27.08m, r_y=-13.74m for SDINS-1 and r_x=41.47m, r_y=-49.24m for SDINS-2. These final position error decrease to r_x=1.49m, r_y=-6.87m for integrated SDINS/GPS system. One interesting feature is that difference between integrated system with SDINS-1 and SDINS-2 is very little and can be neglected.

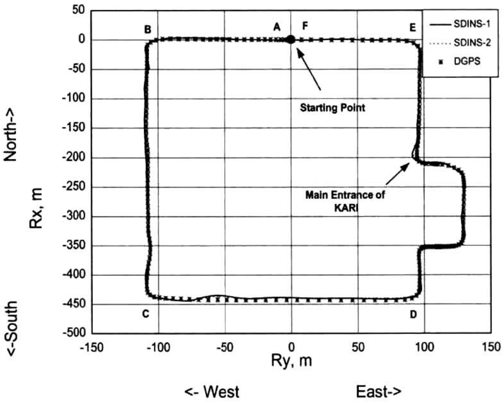

Fig. 7. Trajectory of short range test of SDINS/GPS

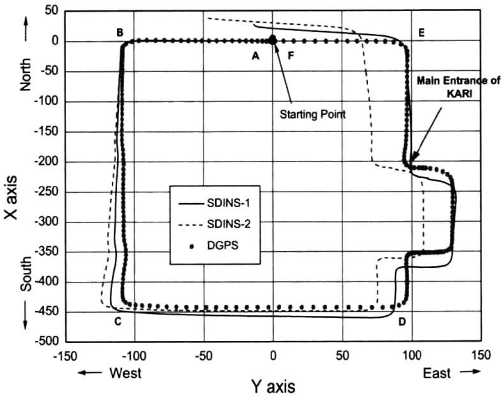

Fig. 8. Trajectory of short range test of SDINS

The attitude results are shown on Fig. 9. After 200 seconds of initial alignment time, the initial roll and pitch angle was φ=1.053° and θ=4.577° for SDINS-1 and φ=1.063° and θ=4.576° for SDINS-2 respectively. The automobile stated to the direction of west(ψ=-90°) ; ψ=0° designates north direction, ψ=90° east direction, ψ=180° south direction. At B, C, D and E point, it is identified four turning of automobile in comparison to Fig. 7 and similarly automobile turned 4 times during the periods of D-E.

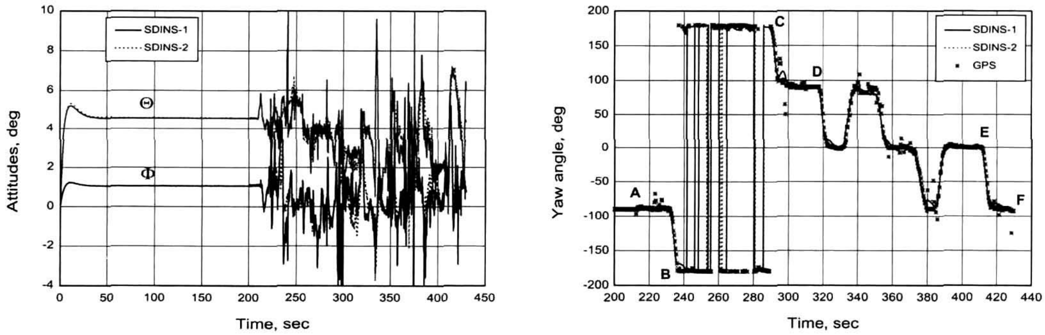

Fig. 9. Attitude result of short range test of SDINS/GPS

The velocity result of integrated SDINS/GPS system is presented on Fig. 10 and the position one on Fig. 11. The velocity and position result of vertical axis is worse than the horizontal results and it is originated from the external information of GPS which has the same characteristics. The statistics of position result is summarized in Table 1, which compared with the reference, DGPS position result.

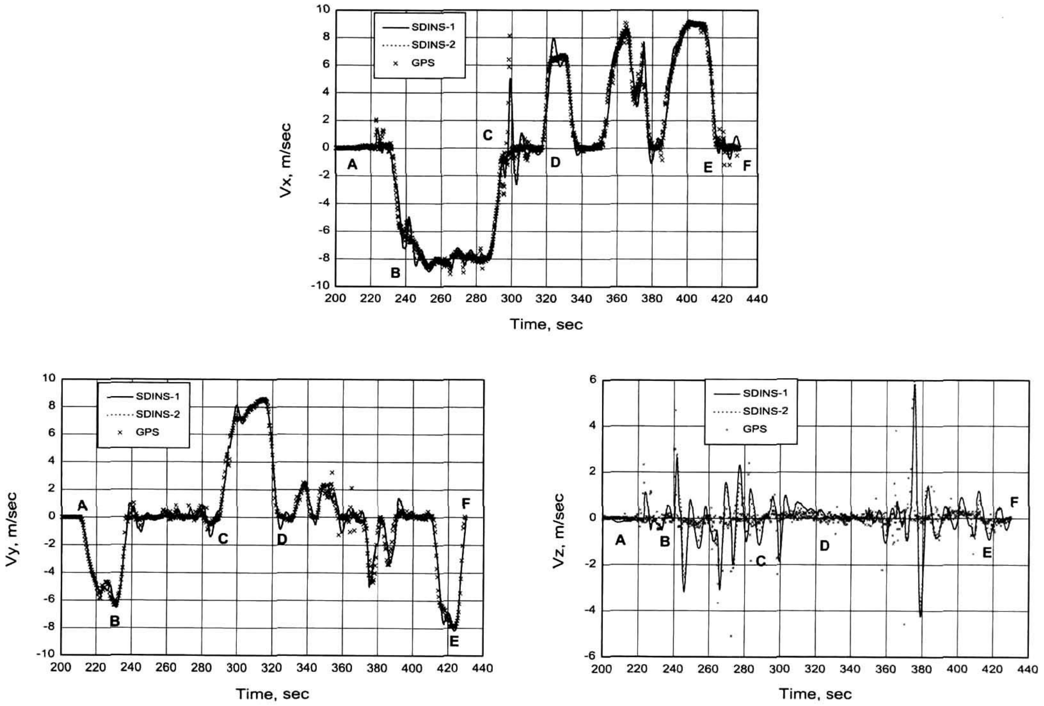

Fig. 10. Velocity result of short range test of SDINS/GPS

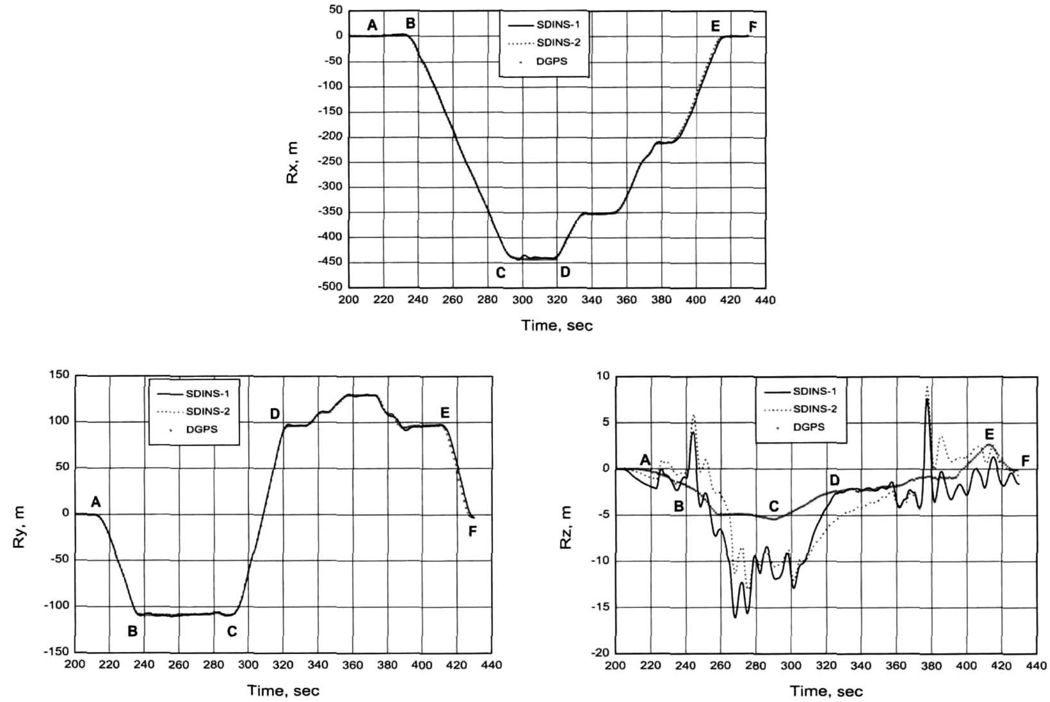

Fig. 11. Position result of short range test of SDINS/GPS

Table 1. Statistics of position difference of short range test

Period		Integrated SDINS/GPS		
		δr_x (m)	δr_y (m)	δr_z (m)
A-B	*mean*	-0.2264	1.5373	0.8670
	std (σ)	1.0825	1.5538	0.7521
B-C	mean	2.7205	0.5622	3.2101
	std (σ)	2.6125	0.9413	4.2170
C-D	mean	-1.5722	-2.7133	5.2251
	std (σ)	2.8060	2.5792	1.7612
D-E	mean	-0.5251	0.1287	0.7724
	std (σ)	4.0337	1.5391	1.9121
E-F	mean	0.2515	-4.1670	1.5224
	std (σ)	1.2958	2.5961	0.6926

From Table 1, error of position r_x is less than about 2.8m and error of r_y less than about 4.2m. For error of r_z, its maximum deviation is about 5.3m.

Middle Range Test Result

The middle rage test was performed on the roads of inside Daeduk Science Town in Taejon. At the starting point the car was aligned to the north direction (ψ=0°) and done the initial alignment procedure for 200 seconds. Fig. 12 shows the trajectory of the middle range test for 17 minutes. The initial attitude after alignment was φ=0.812° and θ=-0.780° for SDINS-1 and φ=1.183° and θ=-0.728° for SDINS-2. Though it might be difficult to compare the results between the starting and ending point because two points were not same, the final attitude after the car stopped was φ=1.668° and θ=-0.734° for SDINS-1 and φ=1.715° and θ=-0.674° for SDINS-2. Final velocity at ending point was v_x=0.642m/s, v_y=0.674m/s, v_z=-0.350m/s for SDINS-1 and v_x=0.619m/s, v_y=0.712m/s, v_z=-0.373m/s for SDINS-2. The final position that could be conjectured was r_x=98.78m, r_y=3.94m and r_z=0.54m. It can be sure that it was closely right value because DGPS result was 99.63m, 1.411m and 1.189m respectively for r_x, r_y and r_z.

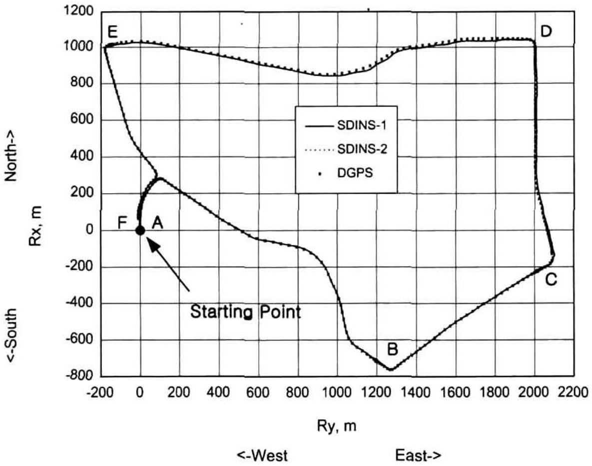

Fig. 12. Trajectory of middle range test of SDINS/GPS

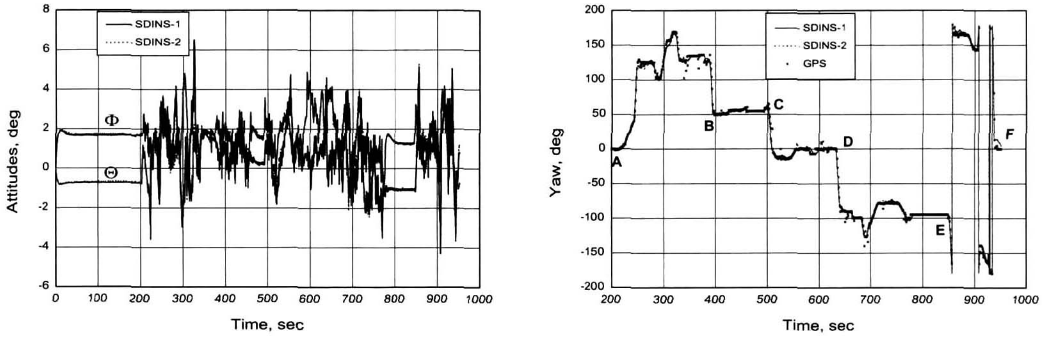

Fig. 13. Attitude result of middle range test of SDINS/GPS

Fig. 13 shows the result of attitude during the whole testing time and Fig. 14 presents the velocity result of integrated navigation system. Same as the short range test, the whole testing trajectory divided into 5 periods, A-B, B-C, C-D, D-E and E-F : A is the starting point and F is the ending point. Position of integrated navigation system can be compared with DGPS reference position and the mean and standard deviation of position are summarized in Table 2 as well as Fig. 15.

The error of r_y in D-E period and r_x in E-F period gives a poor accuracy and this may be caused by coarse information from GPS. Except these error elements, maximum error deviation of r_x is about 9.1m and r_y is about 6.6m. Last item of error of r_z is less than 5.4m.

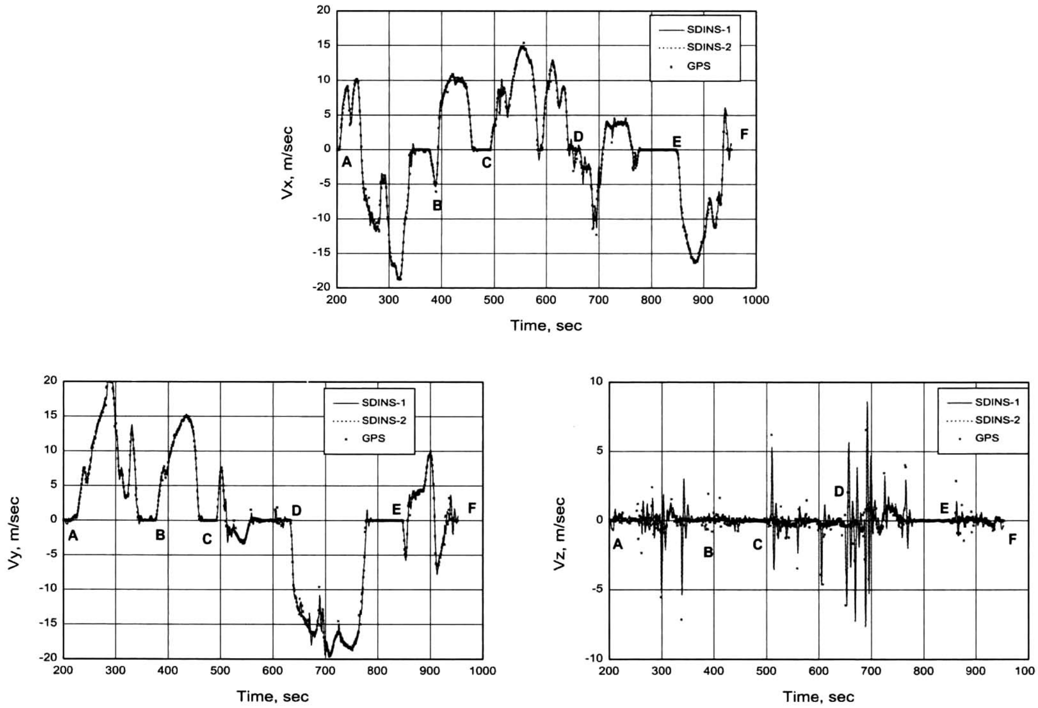

Fig. 14. Velocity result of middle range test of SDINS/GPS

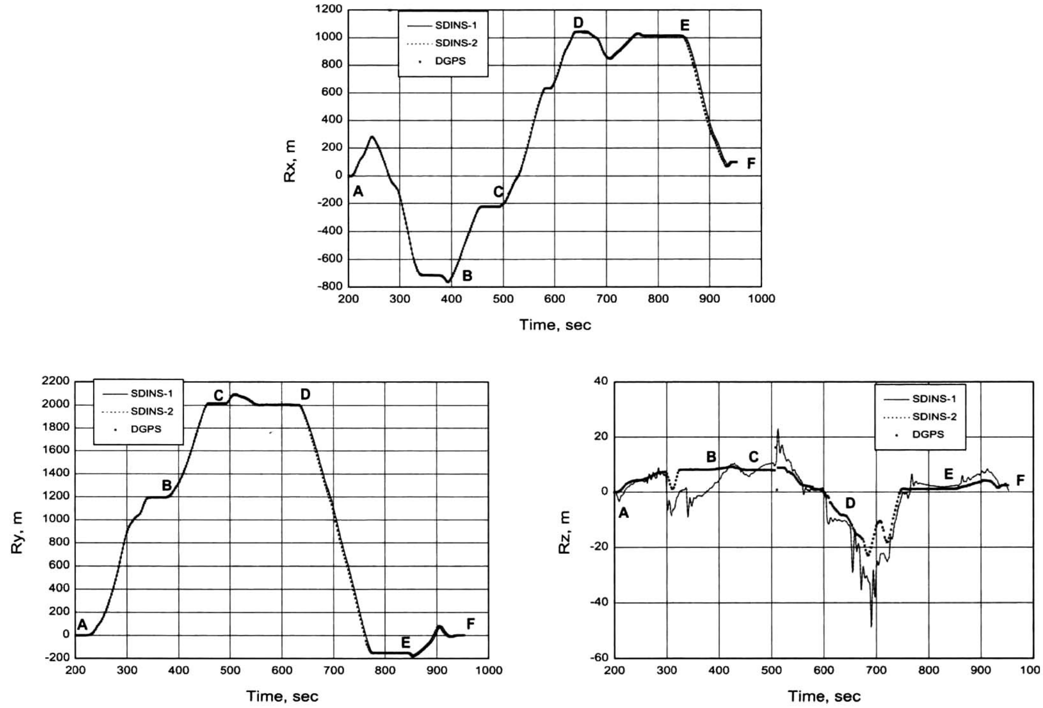

Fig. 15. Position result of middle range test of SDINS/GPS

Table 2. Statistics of position difference of middle range test

Period		Integrated SDINS/GPS		
		δr_x (m)	δr_y (m)	δr_z (m)
A-B	mean	0.1563	-2.0436	4.8414
	std (σ)	4.3548	4.3023	4.3378
B-C	mean	-4.1140	-4.6659	0.4898
	std (σ)	3.2862	3.4980	2.0238
C-D	mean	9.0662	-6.5153	-0.3832
	std (σ)	4.4695	2.0777	4.5908
D-E	mean	6.7169	-24.1905	5.3665
	std (σ)	4.9869	13.6930	6.6057
E-F	mean	-19.006	3.5515	-1.6698
	std (σ)	23.5526	13.4711	1.1439

Conclusions

The integrated SDINS and GPS navigation system has been developed on the base of the chosen reference coordinates. This mechanization uses GPS as the external aids information system with Kalman filtering. This integrated SDINS and GPS navigation system was tested through two kinds of the automobile test with the IMU and GPS receivers. GPS external information can improve the performance of pure navigation system : Strapdown INS. The ability of integrated navigation system to detect and correct the time dependent drift of SDINS was demonstrated and verified.

Based on field test data collected during the tests, the achievable position error is between 2.8 to 5.3m for time periods up to 7 minutes in short range test. Under middle range test conditions, integrated navigation system provides position accuracy of 9.1m in x axis, 6.6m in y axis and 5.4m in z axis.

In this paper investigation into improvement of SDINS/GPS for correcting GPS cycle slips was not proved and demonstrated. This typical feature is also important advantage of integrated SDINS./GPS navigation system. And also some deficiency of observable capability to correct the yaw angle of vehicle should be considered to be implemented especially on airborne applications.

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