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A Seamless Positioning System using GPS/INS/Barometer/Compass

GPS/INS/기압계/방위계를 이용한 연속 측위시스템

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Abstract

In this contribution, an integration of seamless navigation system for the pedestrian is introduced. To overcome the GPS outages in various situations, multi-sensor of GPS, INS, electronic barometer and compass are considered in one Extented Kalman filter. Especially, the integrated system is designed for low-cost for the practical applications. Therefore, a MEMS IMU is considered, and the low quality of the heading is compensated by the electronic compass. In addition, only the pseudoranges from GPS measurements are considered for possible real-time application so that the degraded height is also controlled by a barometer. The mathematical models for each sensor with systematic errors such as biases, scale factors are described in detail and the results are presented in terms of a covariance analysis as well as the position and attitude errors compared to the high-grade GPS/INS combined solutions. The real application scenario of GPS outage is also investigated to assess the feasible accuracy with respect to the outage period. The description on the current status of the development and future research directions are also stated.

Keywords : Seamless Positioning, GPS/INS/Barometer/Compass

要　旨

본 연구에서는, 보행자의 연속적이고 정확한 위치결정을 위한 보행자 측위시스템의 알고리즘을 소개하고 그 정확도를 분석하였다. 다양한 환경에서의 GPS 신호의 두절에 따른 위치의 불연속성을 해결하기 위하여, GPS, INS, 기압계와 방위계를 강결합의 형태인 중앙 집중형 칼만필터에서 융합하였다. 특히, 저가의 실질적인 시스템을 구성하기 위하여, MEMS IMU를 사용하였고, 실시간 계산의 용이성을 위하여 의사거리를 처리하였다. 이때 저가기기의 선택에 따른 높이와 방위값의 정확도를 보완하기 위하여 압력계와 방위계로부터 측정된 값을 이용한다. 편이, 스케일 오차 등의 상세한 수학적 모델과 융합방법을 소개하였고, 그 결과를 고성능의 GPS/INS 로부터 나온 결과와 비교 검토하였다. 특히 GPS 신호가 단절되었을 경우에 대한 위치 및 자세의 결과 비교를 통하여 위치 획득 정확도 및 가능성을 분석하였고, 향후 연구 방향을 소개하였다.

핵심용어 : 연속 측위시스템, GPS/INS/기압계/방위계

1. Introduction

Although GPS provides the continuous precise position information on and around earth, it also has a serious inevitable shortcoming, namely the signal blockage. When GPS signal is being blocked by an obstruction such as trees, tunnels, and buildings, the quality of the position is drastically degraded. To overcome this problem, GPS has been combined with other sensors such as Inertial Navigation System (INS), speedometer, odometer, etc. for continuous positioning especially in urban area. Among them, the integration of GPS/INS was heavily studied for the past ten years, and proved as an operational system nowadays (Da, 1997; Grejner-Brzezinska and Wang, 1998; Grejner-Brzezinska et al., 2005). Of course, the GPS/INS integration had been studied in Korea as well, and developed various algorithms in loosely/tightly coupled mode and produced some operational system like 4-S Van (Moon et al., 1999, 2000; Lee et al., 2006). Indeed, the performance of integrated GPS/INS systems still depends on the quality of GPS measurements because the long-term accuracy of a stand-alone INS is not good

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anyway. Therefore, another sensor is needed for such hostile environments.

In this paper, a preliminary result of the study on a seamless positioning system using GPS, INS, barometer, and electronic compass is presented. The purpose of the study is to generate an optimal position and attitude by the integration of those sensors especially for the personal navigation. The system is designed for low-cost so that a MEMs IMU (Micro-ElectroMechanical Systems; Inertial Measurement Unit) is integrated for which the barometer and the compass aid the low quality estimates of height and heading. In addition, only the pseudoranges from GPS measurement are considered for possible real-time application. The system is designed as an open-architecture to assure the possibility of augmenting the system by additional sensors. GPS pseudoranges, velocity and attitude from INS, height from barometer, and heading from the compass are being used as measurement updates in the Kalman filer.

As an initial step of the development, the mathematical model to combine the various measurements is constructed and a priori covariance analysis is performed through a suitable algorithm such as a tight integration filter. In fact, the modules used in this study mainly extracted and modified from the earlier developed the AIMS system (Airborne Integrated Mapping System), which combines GPS phase and INS measurements in a tightly coupled mode and provides a continuous in-flight calibration of the INS solution and IMU measurement errors (Bar-Itzhack et. al, 1988; Carlson, 2002; Moafipoor et. al., 2004). In this way, the time for the development is saved and stability of the filter was more or less assured.

To verify the developed mathematical model and algorithm, a synthetic data is constructed based on measurements of GPS phases and navigation grade LN-100 as well as the positions and attitudes estimates from AIMS with those measurements. In other words, the raw data for MEMS IMU, barometer, and compass are simulated by intentionally degrading the reference data and solution. For example, one can construct the raw data of MEMS IMU by adding appropriate systematic and random errors to the raw data of LN100. Similarly, the height and heading for barometer and compass can be simulated by adding corresponding instruments' specs to the height and heading solutions from AIMS.

From next section, a detailed description on the filter design, mathematical models, and synthetic data construction is presented. A preliminary result with some analysis with glimpse on the future research direction concludes this paper.

2. Design of the Seamless Positioning System

Figure 1 shows the tightly coupled filter architecture for the seamless navigation system which is under development. Four types of measurements are used in one central Extended Kalman filter which predicts and updates the states such as positions, velocities and attitudes. It should be noted that the INS measurements are not considered as measurement in the observation model. That is, it is not the elements in the observation vector, but the increments of velocities and angles from IMU, are integrated as a form of attitude and position, and feed into the filter to provide the approximation values.

Basically, the filter is an augmented version of the GPS/INS integration with barometer and compass. As in the usual integrated system, the position and attitude are determined mainly from GPS and INS, respectively. However, the quality of positions and attitudes are much poorer in this case, since a MEMs IMU and only pseudoranges from GPS is used in the system. Especially, the poor quality is expected to appear in heading and height, thus the outputs from barometer and compass mainly controls those quantities.

2.1 Measurement Model

In this section, the measurements model used in the system is described. Mainly, the pseudoranges from GPS,

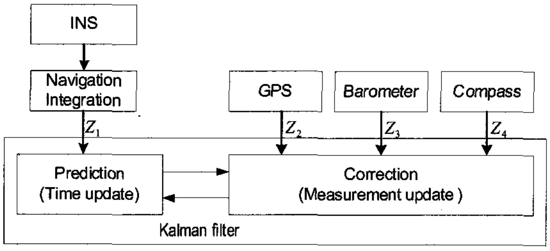

Figure 1. Tight integration filter, Z indicates sensor observation.

height from the barometer, and the angle from the electronic compass compose the measurement.

The GPS measurements are used in the form of double differenced pseudo ranges:

$$P_{ij}^{kl} = \rho_{ij}^{kl} + T_{ij}^{kl} + I_{ij}^{kl} + e_{ij}^{kl}, \quad (1)$$

where ρ_{ij}^{kl} is the double differenced range between the stations i,j and satellites k,l, T_{ij}^{kl} is the tropospheric delay, and I_{ij}^{kl} is the ionospheric effect.

Considering the station *i* is fixed, the equation (1) can be linearlized as:

$$P_{ij}^{kl} = \rho^{0}{}_{ij}^{kl} + T_{ij}^{kl} \frac{\partial \rho_{ij}^{kl}}{\partial x_{j,0}} dx_j + \frac{\partial \rho_{ij}^{kl}}{\partial y_{j,0}} dy_j + \frac{\partial \rho_{ij}^{kl}}{\partial z_{j,0}} dz_j + I_{ij}^{kl} + e_{ij}^{kl}, \quad (2)$$

where $\rho^{0}{}_{ij}^{kl}$ is the approximated double differenced range which is calculated from the navigation solution from INS measurements.

Since the output from the barometer is the pressure, the height should be calculated by following formula:

$$P_h = P_0 e^{-mgh/kT} \Rightarrow h = -\frac{kT}{mg} \ln(P_h / P_0), \quad (3)$$

where

P_h : atmospheric pressure at height h, P_0 : atmospheric pressure at mean sea level = 1013.25hpa, m : mass of one molecule = 29 amu (atomic mass unit) = 29 x 1.66057×10-27 kg (29 is average molecular mass), g : acceleration of gravity = 9.80665 m/s^2, k : Boltzmann's constant = 1.380622×10^{-23}, $J \cdot k^{-1}$, T : absolute temperature.

As can be seen in equation (3), the height can be changed due to the change of the air density and temperature over the surface of the earth. In addition, average atmospheric conditions and standard temperature and pressure are assumed for the height above mean sea level. Therefore, the height from the barometer can be seriously biased and should be modeled in the observation equation:

$$H_b = H^0 + B_b + e_B; \quad e_b \sim N(0, \sigma_b^2), \quad (4)$$

where,

H_b : height observation from barometer,

H_0 : initial values calculated from INS or GPS,

B_b : barometric height bias,

e_b : observation error with standard deviation of σ_b^2.

The output from the electronic compass is the heading angle which can be directly modeled as:

$$\Theta_c = \Theta^0 + e_c, \quad e_c \sim N(0, \sigma_c^2), \quad (5)$$

Where Θ^0 is the approximation value from INS, and e_c is the random error with standard deviation of σ_c^2.

2.2 Kalman Filter

As stated in the previous sections, four kinds of the measurements are feed into a Kalman filter to estimate an optimal solution for the positions and attitudes. Three equations, namely the measurement equation, system dynamic equation and initial equation constitute Kalman filter. The derived measurements model of equations (2), (4), and (5) in the previous section constitutes the measurement/observation equation of Kalman filter which has the general form of [4]:

$$z_k = H_k x_k + \nu_k, \quad \nu_k \sim N(0, \textstyle\sum). \quad (6)$$

Here, the subscript k is the index for the epoch, z is the measurement vector, H is the design matrix, x is the state vector, and ν is the observation error which is assumed to be normally distributed with zero mean and variance of $\sum$.

The state vector considered in this study is composed as follows:

$$x(t) = [NAV \ IMU \ \ GRAVITY \ LEVER-ARM \ BB \ IONO]^T \quad (7)$$

where NAV is the position, velocity, and attitude error; IMU is the accelerometer bias, accelerometer scale factor, gyro bias; Gravity is the error in the gravity vector; Lever_arm is the lever-arm, that is the position difference between the GPS antenna and INS center; BB is the barometer bias; and IONO is the ionospheric error.

Therefore, each component in the measurement equation of Kalman filter can be constructed as :

$$Z = \begin{bmatrix} P_{ij,1}^{kl} - \rho^{0}{}_{ij}^{kl} - T_{ij}^{kl} \\ \vdots \\ P_{ij,2}^{kl} - \rho^{0}{}_{ij}^{kl} - T_{ij}^{kl} \\ \vdots \\ H - H^0 \\ \theta_{heading} - \theta_{heading}^0 \end{bmatrix}. \quad (8)$$

Note that dual frequency GPS pseudoranges, denoted with subscript 1 and 2, are used in the observation vector.

The dynamic equations show the behavior of the states in terms of the linear (linearized) differential equations. Basically, the dynamic equation for the navigation solution (positions, attitudes) is obtained from the linear perturbation of the navigation equation. Since the dynamics of the navigation equation are available in many literatures, it is not derived here but the resulting equations are presented. For detailed derivation of the equations, refer to Jekeli [4]:

$$\delta\dot{v}^n = \delta a^n - \delta(\Omega^n_{in} + \Omega^n_{ie})v^n - (\Omega^n_{in} + \Omega^n_{ie})\delta v^n + \delta\bar{g}^n$$

$$= C^n_s\delta a^s + a^n \times \psi^n - (\Omega^n_{in} + \Omega^n_{ie})\delta v^n + \delta\bar{g}^n, \tag{9}$$

$$\dot{\psi}^n = -\omega^n_{in} \times \psi^n - C^n_s\delta\omega^s_{is} + \delta\omega^n_{in}, \tag{10}$$

where superscript n denotes the quantities are coordinatized in n-frame, δv^n is the velocity error, δa^n is the acceleration error, δa^s is the accelerometer sensor error, Ω^n_{in}, Ω^n_{ie} are the skew-symmetric matrices corresponding the rotation of the n-frame and e-frame with respect to i-frame, respectively, $\delta\bar{g}^n$ is the error of the gravitational acceleration, ψ^n is the orientation error, $\delta\omega^s_{is}$ is the gyros sensor error in indicated angular rates, $\delta\omega^n_{in}$ is the orientation error of the n-frame with respect to the i-frame.

Table 1. IMU error specifications

		IMU400C-100
IMU Error	Acceleration Bias	8.5 mg 8.5e-3*g = 8.3132e-2
	Acceleration Scale Factor	1%
		1.0e-2
	Gyro Bias	1 deg/s
		1*π/180 = 1.745e-2
Random walk	Velocity	0.1 m/s/$\sqrt{hr}$
		0.1/60 = 1.667e-3
	Attitude	2.25 deg/$\sqrt{h}$
		2.25*π/180/60 = 6.5450e-4
	Acceleration Bias	0.05 m/s/$\sqrt{h}$
		0.05/60 = 8.333e-4
	Acceleration Scale Factor	0.0
		0.0
	Gyro Bias	0.85 deg/$\sqrt{h}$
		0.85*π/180/60/3600 = 6.8682e-8

For the dynamics of other states such as IMU sensor errors and ionospehric error, mainly the random constant model and random walk is used (Table 1). Considering the equations (9), (10), error specs on Table 1, the dynamic equation given below can be constructed.

$$\underline{x}_k = \Phi_{k-1}x_{k-1} + w_{k-1},\ w_{k-1} \sim (\underline{0}, Q_{k-1}), \tag{12}$$

where Φ_{k-1} is the state transition matrix, w_{k-1} is the random error for the system with zero mean and variance of Q_{k-1}.

The initial equation of Kalman filter has the form of:

$$x_0 = \hat{x}_0 + e_0 \qquad e_0 \sim (0, P_0), \tag{13}$$

where $\hat{x}_0$ is the initial value and e_0 is its error with zero mean and variance of P_0.

The uncertainty of the initial value used in this study is described in Table 2.

Table 2. The variance of the initial values for the states

states	Initial value
σ_P	100.0
σ_V	1.0
$\sigma_{A_{r,p}}$	0.015×π/180 = 2.6179e-4
σ_H	0.05×π/180 = 8.7266e-4
σ_{AccB}	8.5e-3 g = 8.3132e-2
σ_{AccS}	1×10^{-2}
σ_{GyroB}	1×π/180 = 1.745e-2
σ_G	2.5×10^{-5}×g = 2.4451e-4
σ_L	0.05
σ_B	100.00
σ_{Iono}	0.05

3. Feasibility Test

Since the hardware of the system is still under development, a test data set is artificially generated by degrading an existing raw IMU data from high-degree IMU (LN-100) for feasibility test. One way to accomplish that task is to take the estimates of IMU systematic errors, such as biases and scale factors from AIMS, then remove these effects from the LN-100 raw data, and assume these data as the true values. Then, we add proper systematic as well as random errors correspond to the low-degree IMU specification to the LN-100 raw data. Figure 2 shows the detailed procedures to construct the test data.

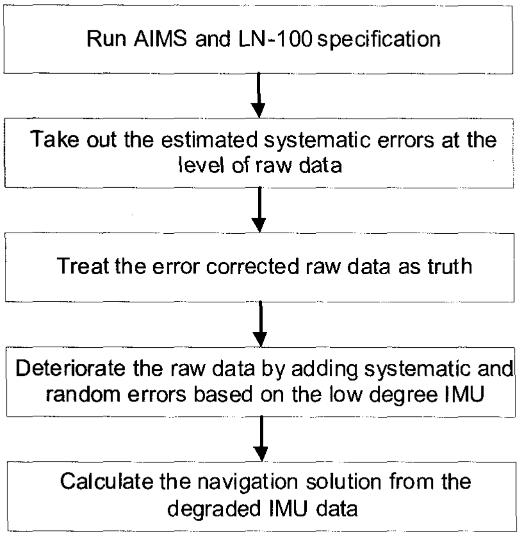

Figure 2. The procedure for degradation of IMU raw data.

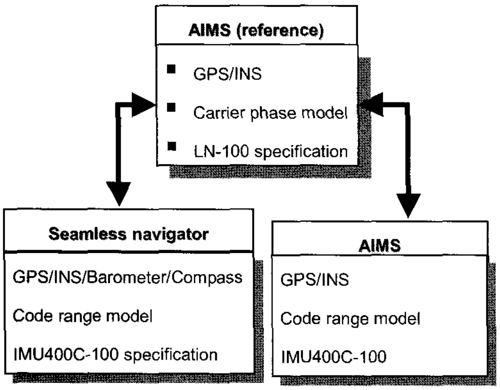

Figure 3. Analysis of the system with respect to AIMS solution.

To analyze the developed system, the navigation solution is computed from the integration of the LN-100 raw data and GPS phases through AIMS software. Since the accuracy of the solution from the AIMS is verified many times in previous studies, it is considered as a reference/truth solution in this test. With respect to the truth solution, the solution from AIMS using only GPS code and low-degree IMU, and the solution from the developed seamless positioning system using GPS code, low-degree IMU, barometer, and compass are compared (Figure 3).

In the following figures, the results from two cases are compared with respect to the reference solution. The first

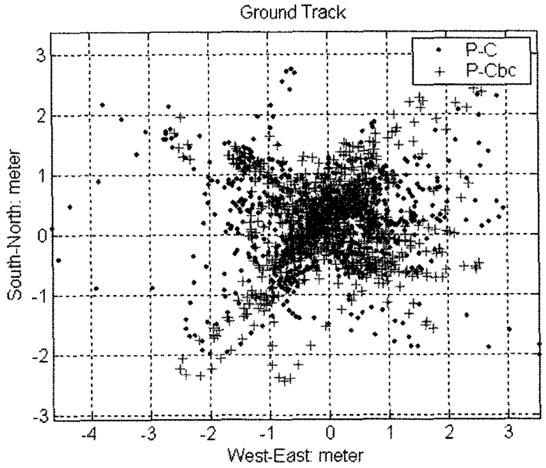

Figure 4. The horizontal position error with respect to the reference solution.

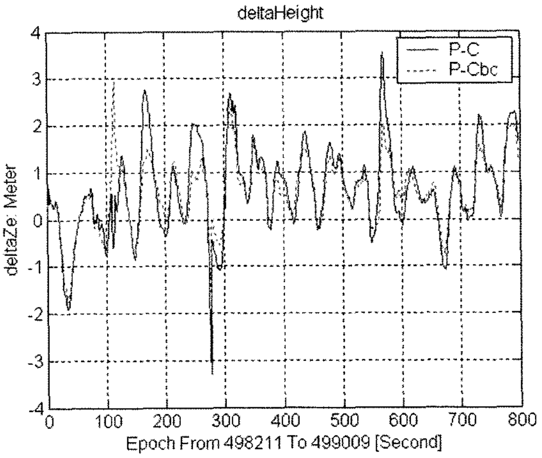

Figure 5. The vertial position error with respect to reference solution.

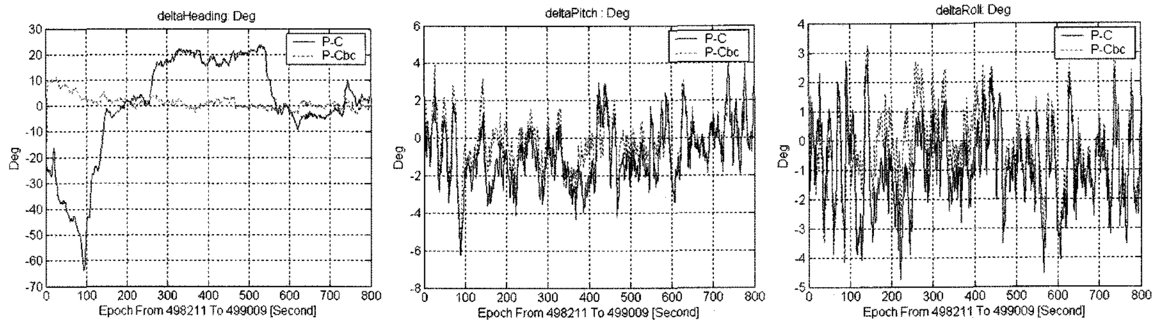

Figure 6. Attitude error with respect to the reference solution.

one denoted as P-C, and it is the difference of the solution from the integration of GPS code and low-degree IMU with respect to the reference solution. The other one is denoted as P-Cbc, and it is the difference of the integrated solution of GPS code range, low-degree IMU, barometer and compass of the developed seamless positioning system with respect to the reference solution.

As can be seen in figure 4-6, the seamless positioning system performs much better than the GPS/INS system as expected. It should be noted that the pitch/roll is coupled with heading, so that some portion in pitch/roll could show partly degraded results caused by the large improvement on heading. Using the developed system, the position accuracy of better than 1 meter, and the attitude better than 1 degree is achievable in most of the time. Indeed, the accuracy is much poorer at the beginning because the filter needs some time to be stabilized. Based on the analysis, one can see that about 100 seconds are needed for the system to be stabilized.

4. GPS outage

Since the purpose of this study is to develop a seamless positioning system, intentional GPS outage in the data is assumed and the remaining data is processed in the system. To investigate the effect of the outage duration, 30, 60, 120, and 240 seconds of GPS gaps are simulated and the results are presented in Table 3. As expected, the position with barometer and compass shows much better performance in case of the GPS outage than that with INS only. Especially, the up component remains very stable with high accuracy due to the height information from the barometer.

Similarly, the accuracy of the attitude from the integrated system is better than that from the INS only, and the heading is maintained with good accuracy because of the compass. Obviously, the accuracy of the horizontal position and roll and pitch is not enough for the independent navigation. Therefore, it would be necessary to integrate other systems or develop algorithm to compensate the horizontal position, pitch, and roll. For example, a body motion modeling is being currently conducted for this purpose by analyzing the IMU output and modeling the motion with a differential equation.

5. Conclusions and Future Study

In this study, the initial analysis on the seamless personal positioning system is presented. Four sensors, namely GPS, INS, barometer, and compass are considered in a Kalman filter to generate a continuous navigation solution. The measurements from those equipments are mathematically modeled to include systematic errors such as biases and scale factor errors as well as the random white noises. Therefore, the system generates navigation solution with estimates on the systematic errors. Comparing the results to the precise reference solution from AIMS, it was found that the position accuracy of 1meter and attitude of 1 degree is achievable. In the test of GPS outage, however, the horizontal position and pitch and roll are seriously degraded since those are mainly affected by IMU only while heading and height are compensated from compass and barometer, respectively. For example, the horizontal position and attitude deviates up to 22 meter and 0.2°, respectively even with barometer and compass in GPS outage of 60 seconds. For this problem, a human body

Table 3. Position and attitude error during GPS gap (comparisons are based on the AIMS solution)

		30sec		60sec		120sec		240sec	
		Mean	Std	Mean	Std	Mean	Std	Mean	Std
INS Only	N [m]	5.127	3.771	31.378	21.265	155.934	105.410	982.272	749.159
	E [m]	2.793	1.542	13.683	8.561	53.143	28.249	120.384	65.219
	U [m]	0.798	0.359	2.921	1.748	12.488	7.608	54.986	33.987
INS +Barometer +Compass	N [m]	4.101	3.394	22.995	17.086	108.26	78.099	601.877	451.237
	E [m]	2.587	1.402	10.577	7.323	39.424	28.537	181.973	134.709
	U [m]	0.331	0.104	0.440	0.201	0.395	0.203	0.414	0.205
INS Only	R [°]	0.121	0.050	0.255	0.118	0.422	0.217	0.663	0.244
	P [°]	0.191	0.084	0.267	0.101	0.398	0.209	0.694	0.332
	H [°]	0.815	0.270	1.518	0.555	4.964	15.973	8.206	17.650
INS +Barometer +Compass	R [°]	0.120	0.049	0.232	0.104	0.366	0.167	0.527	0.190
	P [°]	0.179	0.081	0.255	0.100	0.371	0.188	0.504	0.208
	H [°]	0.004	0.003	0.006	0.004	0.011	0.008	0.010	0.008

motion modeling is being currently conducted. Based on the sensors output with various body motion such as walking, running, and turning, the motions could be either mathematically modeled or defined by a look up table. It is expected that this body motion modeling will significantly improves the performance of the system especially in GPS outage so that provides continuous navigation solution with proper accuracy.

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