Design of Adaptive Filtering Algorithm for Relative Navigation

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***Abstract*—Recently, relative navigation has been considered as one of the most important issues in navigation field. It is purposed to enable more accurate formation flying of aircrafts and satellites and more accurate monitoring of two-body ground vehicles carrying extremely hazardous materials. For the improvement of accuracy and consistency of navigation filter, adaptive method has been widely used to adjust system parameters and error models autonomously based on actual error statistics depicted in innovation sequences. This study aims to develop an efficient approach for adaptive filtering applicable to relative navigation between one master and multiple slave devices based on Global Positioning System (GPS) and Inertial Navigation System (INS). The proposed adaptive method is based on dual filters; One is the adaptive carrier-smoothed-code (CSC) filter in position domain and the other is the adaptive velocity-aided Kalman filter. The adaptive CSC filter takes the role of accurate position estimation and provides noise covariance matrix. The adaptive Kalman filter takes the role of GPS/INS integration with appropriate noise covariance received by adaptive CSC filter. Performance of the proposed adaptive method was evaluated by a simulation which considers a two-body land vehicle.**

***Index Terms*—Adaptive filtering, dual filter, relative navigation, GPS/INS integration**

I. Introduction

BY the complementing characteristics, integration of the Global Positioning System (GPS) and the Inertial Navigation System (INS) has become a standard approach for position and attitude determination of moving vehicles [1]-[4]. For GPS/INS integration, an efficient method based on dual filters was recently proposed [5] to avoid filter-driven-filter problem. Among the dual filters, one is the carrier-smoothed-code (CSC) filter in position domain and the other is the traditional Kalman filter. In the dual-filters method, computational burden is reduced by distributed processing and the filter-driven-filter problem is avoided since raw measurements are utilized as the input to each filter.

To improve the estimation accuracy in the presence of time-varying errors, adaptive filters [6]-[8] have been widely used. In the adaptive filtering, time-varying process and measurement error covariance matrices are estimated based on residuals. The estimated covariance matrices are utilized for time propagations and measurement updates. Related to the adaptive filtering applied to GPS/INS integration, A. H. Mohamed [9] proposed an adaptive Kalman filter based on the maximum likelihood criterion for the proper choice of filter weights, W. Ding [10] proposed an online stochastic modeling algorithm, and A. Almagbile [11] compared the performances of the innovation and residual based adaptive methods.

In GNSS applications, the CSC filtering approach proposed by Hatch [12] has been recognized to be more effective than Kalman filtering approach due to the unique characteristic that carrier-phase measurements can be utilized for accurate time propagation. Based on this characteristic, the adaptive CSC filter [13] estimates the noise covariance of carrier-phase measurements for time propagations and pseudorange measurements for measurement updates, respectively, based on innovation sequences.

This study aims to develop an efficient approach for adaptive filtering method applicable to relative GPS/INS navigation. The proposed adaptive method is based on dual filters; One is the adaptive CSC filter in position domain and the other is the adaptive velocity-aided Kalman filter. The adaptive CSC filter takes the role of accurate position estimation and provides GPS noise covariance matrix. The adaptive Kalman filter takes the role of GPS/INS integration with appropriate noise covariance received from the adaptive CSC filter. For the feasibility assessment of initial study results, performance of the proposed adaptive method is evaluated by a simulation which considers a two-body land vehicle where the tractor mounts a master device and the trailer mounts a slave device.

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II. Adaptive Filtering Method for Relative Navigation

A. *Overall adaptive filtering algorithm*

In the proposed adaptive relative navigation method, one master and multiple slave devices is considered. As shown in Fig. 1, the adaptive CSC filter takes the role of accurate position estimation and provides GPS noise covariance matrix. The velocity-aided Kalman filter takes the role of GPS/INS integration with appropriate noise covariance provided by the adaptive CSC filter. As shown in Fig.1, the proposed method utilizes instantaneous GPS velocities as the input to the Kalman filter. Thus, the filter-driven-filter problem can be avoided. The accuracy of position estimates can be maintained by extrapolating the CSC filter position estimates by the Kalman filter velocity estimates between the successive CSC filter position updates.

B. *Estimation of carrier-phase noise covariance for adaptive CSC filter*

In position domain CSC filtering, dimension of GPS measurement vector changes from time to time depending on the number of visible satellites. For time-propagation, the estimate $\Delta\hat{X}_k$ of the incremental position vector ΔX_k is obtained by the carrier-phase measurement vector Ω_{k+1} as follows.

$$\begin{aligned}\Delta\hat{X}_k &= H^{+}_{k+1}\Omega_{k+1} \\ &= \Delta X_k - H^{+}_{k+1}\Delta H_k \delta\hat{X}_k + H^{+}_{k+1}\left(N_{k+1} - N_k\right)\end{aligned} \tag{1}$$

where,

$$H^{+}_{k} = \left(\mathrm{H}^{T}_{k}\mathrm{H}_{k}\right)^{-1}\mathrm{H}^{T}_{k}$$

$\delta\hat{X}_k$ indicates a posteriori position error, H_k indicates the observation matrix, ΔH_k indicates the incremental observation matrix, and N_k indicates the carrier-phase measurement noise. The innovation vector $Z_{\Phi,k}$ for time-propagation is the difference between the indirect measurement Ω_{k+1} and its estimate $H_{k+1}\Delta\hat{X}_k$. The innovation vector $Z_{\Phi,k}$ can be obtained and modeled by

$$\begin{aligned}Z_{\Phi,k} &= \Omega_{k+1} - H_{k+1}\Delta\hat{X}_k \\ &= \left(I - H_{k+1}H^{+}_{k+1}\right)\left(N_{k+1} - N_k\right) \\ &\qquad - \left(I - H_{k+1}H^{+}_{k+1}\right)\Delta H_k \delta\hat{X}_k\end{aligned} \tag{2}$$

By (2), covariance of the innovation vector can be modeled by

$$\begin{aligned}&E\left\{Z_{\Phi,k}Z^{T}_{\Phi,k}\right\} \\ &= \left(I - H^{*}_{k+1}H^{*+}_{k+1}\right)R_{\Phi,k}\left(I - H^{*}_{k+1}H^{*+}_{k+1}\right)^{T} \\ &\qquad + \left(I - H^{*}_{k+1}H^{*+}_{k+1}\right)\Delta H^{*}_{k}\hat{P}_k\,\Delta H^{*T}_{k}\left(I - H^{*}_{k+1}H^{*+}_{k+1}\right)^{T}\end{aligned} \tag{3}$$

where,

$$R_{\Phi,k} = E\left\{\left(N_{k+1} - N_k\right)\left(N_{k+1} - N_k\right)^{T}\right\}$$

$$\hat{P}_k = E\left\{\delta\hat{X}_k \delta\hat{X}^{T}_k\right\}$$

As shown in (3), the covariance of the innovation vector is composed of the carrier-phase noise covariance $R_{\Phi,k}$, a posteriori noise covariance $\hat{P}_k$, and the observation matrix. Based on (3), the estimated noise covariance matrix $\hat{R}_{\Phi,k}$ can be computed by the following equation [13].

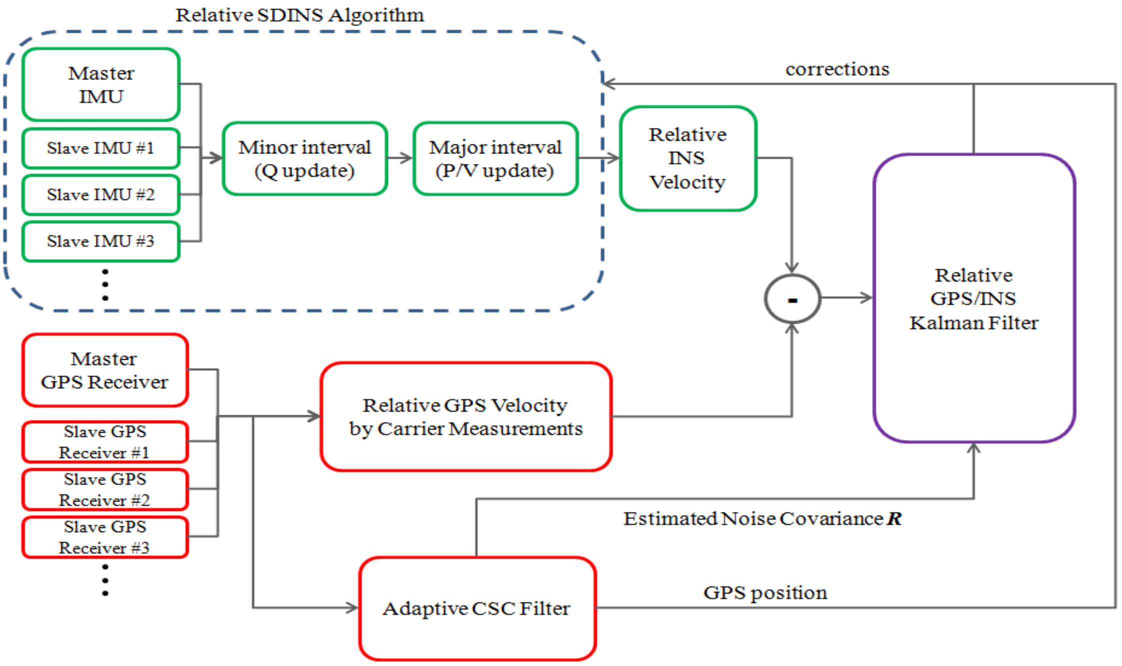

Fig. 1. Architecture of proposed adaptive GPS/INS algorithm.

$$\hat{R}_{\Phi,k} = \begin{bmatrix} E\left\{Z_{\Phi,k}Z_{\Phi,k}^{T}\right\} \\ -\left(I - H_{k+1}^{*}H_{k+1}^{*+}\right)\Delta H_{k}^{*}\hat{P}_{k}\ \Delta H_{k}^{*T}\left(I - H_{k+1}^{*}H_{k+1}^{*+}\right)^{T} \end{bmatrix} \cdot \left\{\left(I - H_{k+1}^{*}H_{k+1}^{*+}\right)\left(I - H_{k+1}^{*}H_{k+1}^{*+}\right)^{T}\right\}^{-1} \quad (4)$$

C. Estimation of measurement noise covariance for GPS/INS Kalman filter

The proposed relative GPS/INS Kalman filter utilizes relative GPS velocity measurements. The measurement noise covariance $\hat{R}_{\Lambda_{GPS},k}$ can be modeled by

$$\hat{R}_{\Lambda_{GPS},k} = E\left[\delta\Lambda_{GPS}^{n}\delta\Lambda_{GPS}^{nT}\right] \quad (5)$$

The relative velocity by GPS measurements is modeled by

$$\hat{\Lambda}_{GPS} = C_{e}^{n}H_{k}^{+}Y_{k} - C_{e}^{n}H_{k-1}^{+}Y_{k-1} \quad (6)$$

where,

$$Y_{k} = \left[\Phi_{1}^{b1} - \Phi_{1}^{b2} \quad \Phi_{2}^{b1} - \Phi_{2}^{b2} \quad \cdots \quad \Phi_{j}^{b1} - \Phi_{j}^{b2}\right]^{T}$$

Φ_{j} indicates carrier-phase measurement of the j-th satellite. Thus, the measurement noise covariance can be modeled by

$$\begin{aligned} \hat{R}_{\Lambda_{GPS},k} &= C_{e}^{n}H_{k}^{+}E\left[\delta Y_{k}\delta Y_{k}^{T}\right]H_{k}^{+T}C_{e}^{nT} \\ &\quad + C_{e}^{n}H_{k-1}^{+}E\left[\delta Y_{k-1}\delta Y_{k-1}^{T}\right]H_{k-1}^{+T}C_{e}^{nT} \\ &= C_{e}^{n}H_{k}^{+}\hat{R}_{\Phi,k}H_{k}^{+T}C_{e}^{nT} + C_{e}^{n}H_{k-1}^{+}\hat{R}_{\Phi,k-1}H_{k-1}^{+T}C_{e}^{nT} \end{aligned} \quad (7)$$

In (7), the carrier-phase measurement noise covariance $\hat{R}_{\Phi,k}$ can be obtained from the adaptive CSC filter as shown in (4).

III. Simulation

Performance of the proposed adaptive method was evaluated by a simulation. For the simulation, a land vehicle simulator and a GPS/INS signal generator were utilized. The land vehicle consists of a tractor and a trailer. The tractor of the vehicle was equipped with the master device consisting of a GPS receiver and an Inertial Measurement Unit (IMU). The trailer was equipped with the slave device consisting of a GPS receiver and an IMU. The sampling rate of GPS and IMU was set as 10 Hz and 100 Hz, respectively. The baseline between the tractor and trailer GPS antenna was 4.145 m. The initial values for pseudorange and carrier-phase noise terms were set as 0.1 m and 0.001 m, respectively. The vehicle followed a trajectory consisting of two circular turns in opposite directions.

Fig. 2 shows the estimated standard deviations of carrier-phase and pseudorange measurements. In the simulation, the intrinsic weakness of radio signals to signal path blocking, multipath, interference, and jamming was not considered. Thus, it is assumed that the carrier-phase and the pseudorange variance originating from different channels are the same and not correlated to each other. By the assumption, a scalar standard deviation was computed by averaging the diagonal terms of the error covariance matrix. Then, the covariance matrix is reconstructed in diagonal form.

Fig. 3 shows the relative velocity errors in north, east and down directions with or without the proposed adaptive method. Fig. 3(a) and 3(c) are errors generated without adaptive method and Fig. 3(b) and 3(d) are errors generated by the proposed adaptive method. As shown in Fig. 3, the proposed method generates more accurate relative velocity estimates than the method without adaptive filtering. It should be noted that the accuracy of position solution depends strongly on the accuracy of INS velocity estimates. According to the simulation result, the root-mean-square error (RMSE) of the relative velocity estimates by the proposed method in north, east and down directions are 0.02458, 0.01950 and 0.00838 m/s, respectively.

Fig. 4 shows the relative roll, pitch and yaw errors with or without the proposed adaptive method. Fig. 4(a) and 4(c) are errors generated by the method without adaptive filtering and Fig. 4(b) and 4(d) are errors generated by the proposed adaptive method. As shown in Fig. 4, yaw precision improves remarkably by the proposed method. The RMSE of

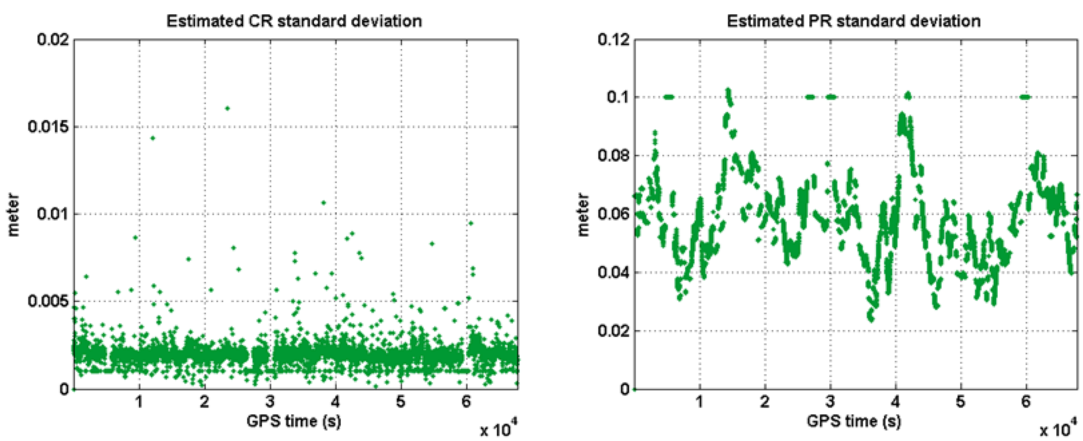

Fig. 2. Estimated standard deviations for carrier-phase and pseudorange noise terms.

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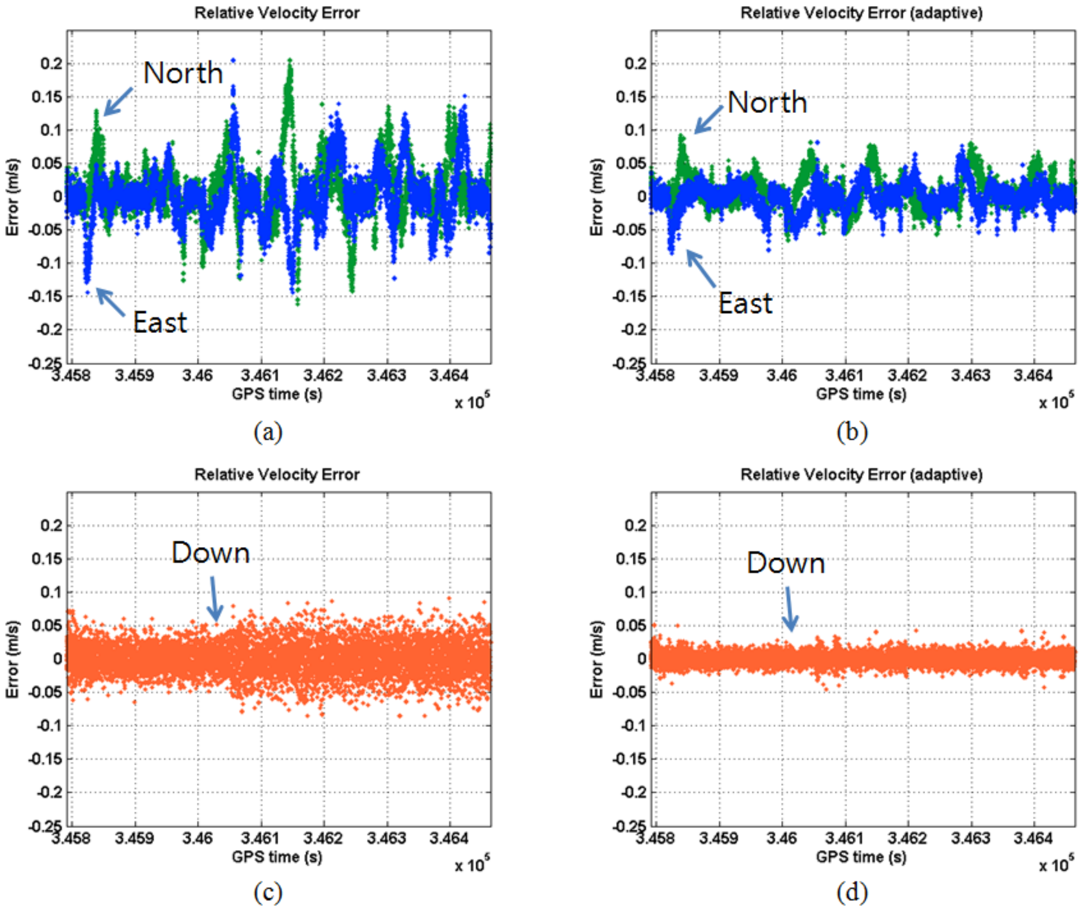

Fig. 3. Comparison of relative velocity errors in north, east and down directions

roll, pitch

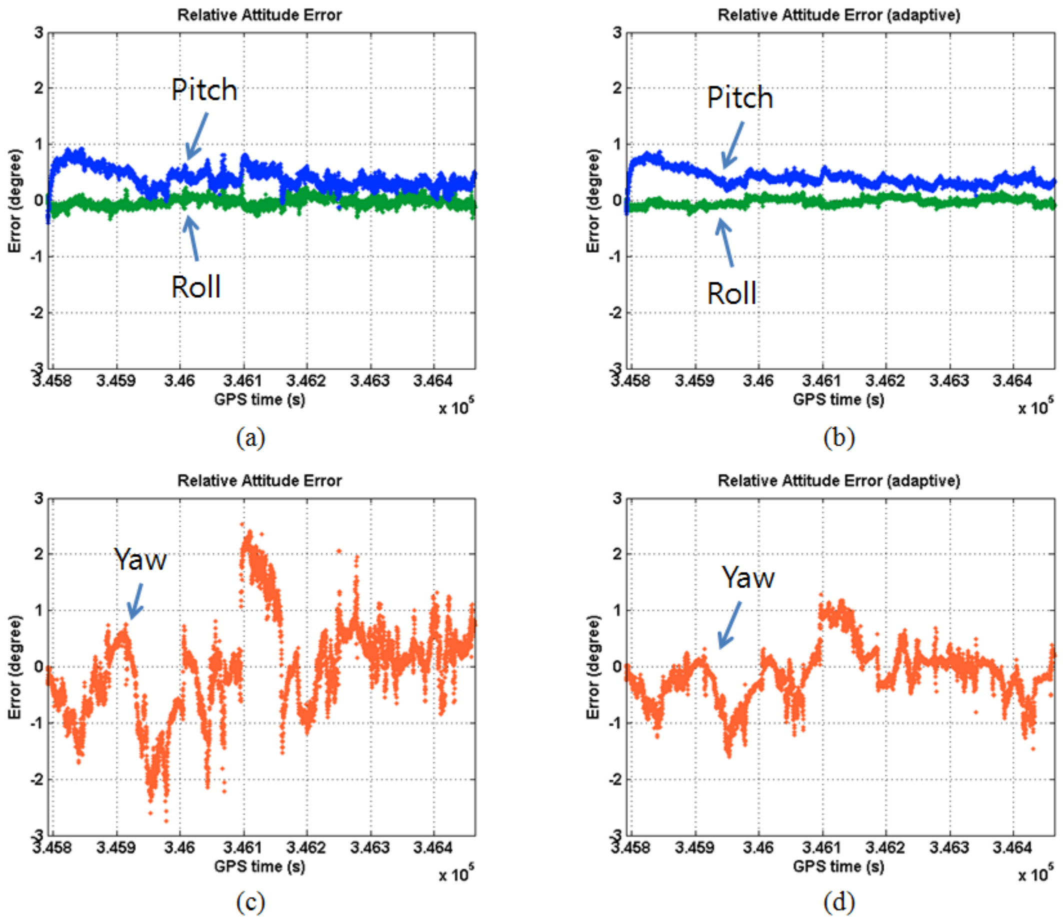

Fig. 4. Comparison of relative roll, pitch and yaw errors

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and yaw by the proposed method are 0.06725, 0.42146 and 0.49371 degree, respectively.

IV. Conclusion

In this paper, a new adaptive method applicable to relative GPS/INS was proposed. The proposed method consists of an adaptive position domain CSC filter and an adaptive velocity-aided Kalman filter. The performance of the proposed method was evaluated by a simulation considering a two-body land vehicle carrying a master device and a slave device. By the simulation, it was shown that the proposed adaptive method generates appropriate measurement noise covariance and provides accurate and precise velocity and attitude estimates.

References

[1] A. M. Fosbury and J. L. Crassidis, “Kalman filtering for relative inertial navigation of uninhabited air vehicles,” AIAA Guidance, Navigation, and Control Conference and Exhibit, Keystone, Colorado, Aug. 2006, AIAA-2006-6544.

[2] G. T. Schmidt and R. E. Phillips (2003a), “INS/GPS integration architectures,” Advances in Navigation Sensors and Integration Technology. AC/323(SET-064)TP/43, NATO TRO: 5-1-5-15.

[3] X. Yun et al., “Testing and evaluation of an integrated GPS/INS system for small AUV navigation,” IEEE J. Oceanic Eng., vol. 24, pp. 396-404, July 1999.

[4] Y. Zhang and Y. Gao, "Integration of INS and un-differences GPS measurements for precise position and attitude determination," The Journal of Navigation, vol. 61, pp. 87–97, 2008.

[5] J. D. Park, M. W. Kim, J. Y. Lee, H. S. Kim, and H. K. Lee, “An Integration Method for L1 GPS Receiver and MEMS IMU Based on Dual Filters,” International Science and Technology Conference, Istanbul, Dec. 2011.

[6] D. T. Magill, "Optimal adaptive estimation of sampled stochastic processes," IEEE Transactions on Automatic Control, AC-10, No. 4, pp. 434-439, 1965.

[7] R. K. Mehra, "On the identification of variance and adaptive Kalman filtering," IEEE Transactions on Automatic Control, AC-15, No. 2, pp. 175-184, 1970.

[8] R. K. Mehra, "On-line identification of linear dynamic systems with applications to Kalman filtering," IEEE Transactions on Automatic Control, AC-16, No. 1, pp. 12-21, 1971.

[9] A. H., Mohamed and K. P. Schwarz, "Adaptive Kalman filtering for INS/GPS," Journal of Geodesy, vol. 73, no. 4, pp. 193-203, 1999.

[10] W. Ding, J. Wang, C. Rizos, and D. Kinlyside, "Improving adaptive Kalman estimation in GPS/INS integration," Journal of Navigation, vol. 60, no. 3, pp. 517-529, 2007.

[11] A. Almagbile, J. Wang, and W. Ding, "Evaluating the performances of adaptive Kalman filter methods in GPS/INS integration," Journal of Global Positioning Systems, vol. 9, no. 1, pp. 33-40, 2010.

[12] R. R. Hatch, "The synergism of GPS code and carrier measurements," The Third International Geodetic Symposium on Satellite Doppler Positioning, New Mexico, 1982, pp.1213-1232.

[13] J. Y. Lee et al, "A study of covariance estimation to apply carrier-smoothed-code filter in GNSS," International Science and Technology Conference, Istanbul, Dec. 2011.

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