Paper

Int'l J. of Aeronautical & Space Sci. 18(3), 565–573 (2017)
DOI: http://dx.doi.org/10.5139/IJASS.2017.18.3.565

IJASS
International Journal of Aeronautical and Space Sciences

A Multistage In-flight Alignment with No Initial Attitude References for Strapdown Inertial Navigation Systems

WoonSeon Hong*

Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul 08826, Republic of Korea, and the 3rd R&D Center, Agency for Defense Development, Daejeon 34186, Republic of Korea

Chan Gook Park**

Department of Mechanical and Aerospace Engineering/ Automation and System Research Institute, Seoul National University, Seoul 08826, Republic of Korea

Abstract

This paper presents a multistage in-flight alignment (MIFA) method for a strapdown inertial navigation system (SDINS) suitable for moving vehicles with no initial attitude references. A SDINS mounted on a moving vehicle frequently loses attitude information for many reasons, and it makes solving navigation equations impossible because the true motion is coupled with an undefined vehicle attitude. To determine the attitude in such a situation, MIFA consists of three stages: a coarse horizontal attitude, coarse heading, and fine attitude with adaptive Kalman navigation filter (AKNF) in order. In the coarse horizontal alignment, the pitch and roll are coarsely estimated from the second order damping loop with an input of acceleration differences between the SDINS and GPS. To enhance estimation accuracy, the acceleration is smoothed by a scalar filter to reflect the true dynamics of a vehicle, and the effects of the scalar filter gains are analyzed. Then the coarse heading is determined from the GPS tracking angle and yaw increment of the SDINS. The attitude from these two stages is fed back to the initial values of the AKNF. To reduce the estimated bias errors of inertial sensors, special emphasis is given to the timing synchronization effects for the measurement of AKNF.

With various real flight tests using an UH60 helicopter, it is proved that MIFA provides a dramatic position error improvement compared to the conventional gyro compass alignment.

Key words: In-flight alignment, Helicopter, SDINS, Adaptive kalman navigation filter

1. Introduction

A strapdown inertial navigation system (SDINS) performs alignment to estimate the initial attitude of vehicles before navigation. Gyro compass alignment (GCA) for stationary vehicles or in-flight alignment (IFA) for moving vehicles is common for this. For a tactical grade INS - position error of 0.8-1.0nm/hr- it takes 4 to 15 minutes to complete the GCA depending on the gyro performance, and 4-10 minutes to complete IFA depending on the maneuvering trajectory of the vehicles.

For every case of IFA, the Kalman navigation filter (KNF) which has various structures to enhance the estimated attitude accuracy is essential. The observability analysis that discriminates the observable states of the SDINS error model is also important because the maneuvering pattern of a vehicle should be determined from the analysis results. A piece-wise constant system assumption was introduced in [1, 2] for observability analysis of an INS error model during IFA. The nonlinear error model of the INS was simplified as a piece-wise constant system and analyzed according to its dominant trajectory segments. A carrier maneuver such as an S-turn to increase the observability was investigated in [3]-[5].

* Ph. D Student, Principal Researcher
** Professor, Corresponding author: chanpark@snu.ac.kr

Received: September 28, 2016 Revised: July 25, 2017 Accepted: September 4, 2017

http://ijass.org pISSN: 2093-274x eISSN: 2093-2480

When configured with a GPS or up-linked radar system as a measurement reference, the KNF much improves the performance, offering more precise initial attitude. Many studies on the IFA focused on KNF improvement under large initial attitude errors, especially heading errors. The Attitude Dilution of Precision (ADOP) metric was derived and augmented to improve IFA performance of a theater defense missile that has a large initial attitude error in [6]. For a low grade SDINS with a large initial heading error, the attitude error model was divided into two parts, horizontal and heading errors, and the large heading error was modeled as a perturbed sinusoidal term in [7]. This was effective to coarsely estimate a heading with a large error of as much as 40 degrees. The authors in [8] introduced an innovation-covariance estimation-based adaptive extended Kalman filter (AEKF) under a priori incorrect knowledge of measurement noise. It directly applied the covariance of innovation into gain instead of adjusting the measurement covariance and proved considerable performance enhancement under an initial large heading error and noisy GPS measurement.

Although impressive approaches under large initial attitude errors were introduced in the above-mentioned studies, we still determine the rough initial attitude no matter how large the attitude error is. It is impossible to assume the initial attitude for the moving vehicles. The initial attitude error can cause the divergence of AKNF because it sometimes exceeds the linearized limit of nonlinear error models.

This paper presents the multistage in-flight alignment (MIFA) for the moving vehicles, which is composed of a coarse horizontal alignment, coarse heading alignment, and fine alignment with an adaptive Kalman navigation filter (AKNF).

At the first stage the second order damping loop formulates the acceleration differences between the SDINS and GPS as damping coefficients to estimate the horizontal attitude roll and pitch. And the dedicated scalar filter is introduced to shape the fluctuating GPS acceleration. At the second stage the coarse heading alignment which uses the SDINS yaw increment and GPS tracking angle as inputs determines the coarse heading. At the third stage the AKNF estimates the fine attitude of moving vehicles. With the adaptive innovation process for the measurement noise, the AKNF converges faster than the usual KNF and guarantees stability against uncertain large initial attitude errors.

Because there is no attitude reference during MIFA in real tests, the estimated attitude accuracy cannot be investigated directly from the attitude errors. The accuracy for MIFA can be investigated by the position error of a pure navigation because the estimated heading error is nearly proportional to the position error. Various real tests with a UH60 helicopter equipped with SDINS and GPS verifies that the proposed MIFA improves the position error by 53.75% compared to the gyro compass alignment.

2. Multistage In-flight Alignment

The multistage in-flight alignment (MIFA) presented in

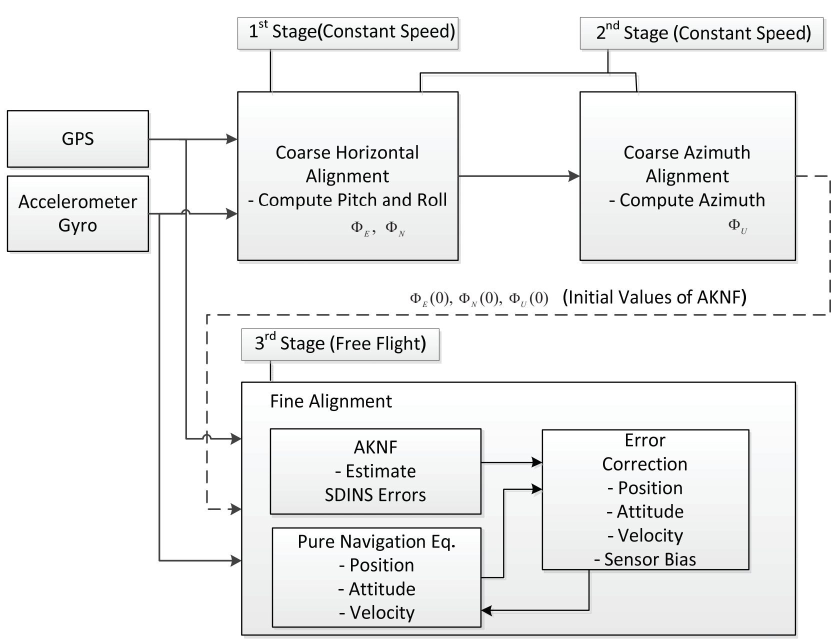


Fig. 1. Multistage in-flight alignment

DOI: http://dx.doi.org/10.5139/IJASS.2017.18.3.565

this study is for the case of no initial attitude, such as an abrupt power cycle, no gyro compass alignment, or recovery from the malfunction of SDINS on moving air vehicles. In these cases it is hard to estimate the precise attitude from the KNF because there is no initial attitude reference. The proposed MIFA to solve these problems consists of the coarse horizontal alignment and coarse heading alignment for the initial attitude and the AKNF for the fine attitude estimation. The only constraint for this study is nearly straight maneuvering to determine the initial attitude which takes maximum of 60 seconds at the beginning of MIFA. The 1st stage takes 20 seconds for the estimation of the coarse horizontal attitude and the 2nd stage takes 40 seconds for estimation of the coarse heading. All the stages of MIFA are depicted in Fig. 1.

In the first two stages, the alignment concept is similar to the gyro compass alignment on the ground except that the velocity of a SDINS is not stationary but nearly constant, that is, the acceleration is almost zero. In the first stage in Fig. 1, the alignment is performed with the input of the acceleration differences between the SDINS and GPS. The GPS acceleration derived from the velocity difference is too fluctuant for the damping loop input. A scalar filter is used to shape the acceleration because the major dynamics of the SDINS must be distinguished from the fluctuating noises. If the acceleration is not shaped properly, it causes large initial attitude errors that degrade the SDINS performance. In the second stage the coarse heading alignment which substitutes a yaw increment and GPS tracking angle as damping loop input estimates the coarse heading of the SDINS. The estimated attitude in the first two stages act as initial attitude of the third stage AKNF. In the third stage the AKNF which shapes the measurement covariance in real time estimates the error state vector. It converges rapidly because the measurement residuals are directly reflected into the error state estimation.

The time synchronization error between the SDINS and GPS causes the estimation errors which degrade severely the SDINS performance. It causes the estimated attitude error in the 1st and 2nd stages, so that is why we need a nearly constant velocity. It also causes the accelerometer bias estimation errors to the on-going direction for the AKNF, increasing the position errors toward that directional vector. The effect of timing mismatch for KNF was analyzed for the constant and circular velocity trajectories in [9]. The accelerometer bias and attitude errors according to trajectory segments were simulated and it proved the time mismatch dominantly affects the accelerometer biases. The influence of time synchronization error for MIFA is discussed in the following section.

3. Coarse Horizontal and Heading Alignment

In the first stage the vehicle moves straight with a constant speed to maintain nearly zero acceleration and the minimum time synchronization error between the SDINS and GPS. The acceleration difference between the SDINS and GPS is used as a control input to estimate the attitude. It is similar to gyro compassing on the ground except that the specific force of the acceleration difference is projected onto the local level frame. The observability at this stage is the same as the ground alignment because the stationary condition and zero acceleration have the same observability. The block diagram of a coarse horizontal alignment for a single channel is in Fig. 2.

The alignment equation in the navigation frame can be represented as

$$\begin{aligned} \Phi_E + \Phi_U \omega_N - \omega_U \Phi_N &= \omega_E^C + \omega_E^{dr} \\ \Phi_N + \Phi_E \omega_U - \omega_E \Phi_U &= \omega_N^C + \omega_N^{dr} \end{aligned}, \tag{1}$$

where Φ_E, Φ_N, and Φ_U represent misalignment angles of the east, north, and up direction, ω_E^C and ω_N^C gyro control rates of the east and north direction, ω_E^{dr} and ω_N^{dr} gyro drift rates, and ω_E, ω_N, and ω_U the earth rate projections to the ENU frame. To formulate the second order damping loop, the control rates ω_E^C and ω_N^C are described as

$$\begin{aligned} \omega_E^C &= -K^b \delta V_N \\ \omega_N^C &= K^b \delta V_E \\ \delta V_E &= \Delta\Lambda_E - K\delta V_E \\ \delta V_N &= \Delta\Lambda_N - K\delta V_N \\ \Delta\Lambda_E &= a_E^{INS} - a_E^{GPS} = -g\Phi_N + B_E - \delta a_E \\ \Delta\Lambda_N &= a_N^{INS} - a_N^{GPS} = g\Phi_E + B_N - \delta a_N \end{aligned}, \tag{2}$$

where K^b and K are damping coefficients, $\Delta\Lambda_E$ and $\Delta\Lambda_N$ are the east and north acceleration differences between the SDINS and GPS, a_E^{INS} and a_N^{INS} the east and north accelerations of the SDINS, a_E^{INS} and a_N^{INS} the ease and north accelerations of the GPS, δa_E and δa_N the east and north acceleration difference errors between the SDINS and GPS, B_E and B_N the east and north accelerometer biases, g gravity, V_E^{GPS} and V_N^{GPS} the east and north GPS horizontal velocities. Substituting Eq. 2 into Eq. 1, the horizontal alignment equation can be expressed as

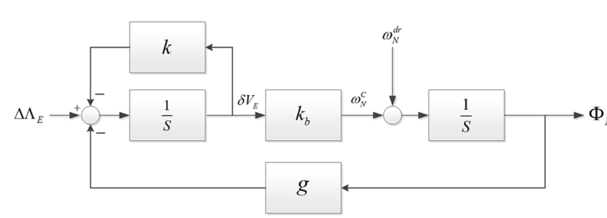


Fig. 2. Coarse horizontal alignment for the single channel

a second order damping loop,

$$\begin{aligned} \Phi_E + K\Phi_E + K^b g\Phi_E &= -K^b B_N + K^b \delta a_N + K\omega_E^{dr}, \\ \Phi_N + K\Phi_N + K^b g\Phi_N &= -K^b B_E + K^b \delta a_E + K\omega_N^{dr} \end{aligned} \tag{3}$$

where $K=2\zeta\omega_0$, $K^b g=\omega_0^2$.

The settling time of the damping loop is chosen by K^b and K. Because the vehicle maneuvers straight with a constant speed, the variation of the horizontal attitude is small enough, therefore the effect of the time mismatch that causes the horizontal attitude error is minimized.

The GPS acceleration derived from the velocity differences is too fluctuant to substitute for the damping loop input and can cause the large attitude error if it is not shaped properly. The scalar filter for the 1st and 2nd stage of MIFA is presented to prevent an excessive fluctuation of GPS velocities. The scalar filter equations are as follows:

$$\begin{aligned} v_{k,gps} &= v_{k-1,gps} + k_k(z_{k,gps} - v_{k-1,gps}) \\ p_{k/k-1} &= p_{k-1} + q \\ k_k &= \frac{p_{k/k-1}}{p_{k/k-1} + r} \\ p_k &= (1-k_k)p_{k/k-1} \end{aligned} \tag{4}$$

Where $\hat{v}_{k,gps}$ is the smoothed GPS velocity, k_k is the filter gain, $Z_{k,gps}$ is the velocity measurement, p_k is the error covariance, q is the process noise, and r is the measurement noise.

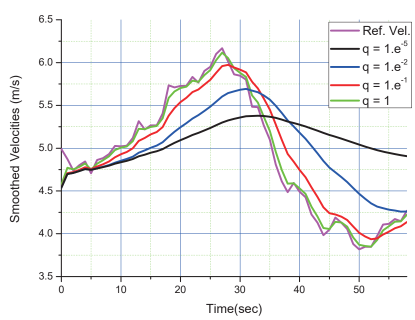
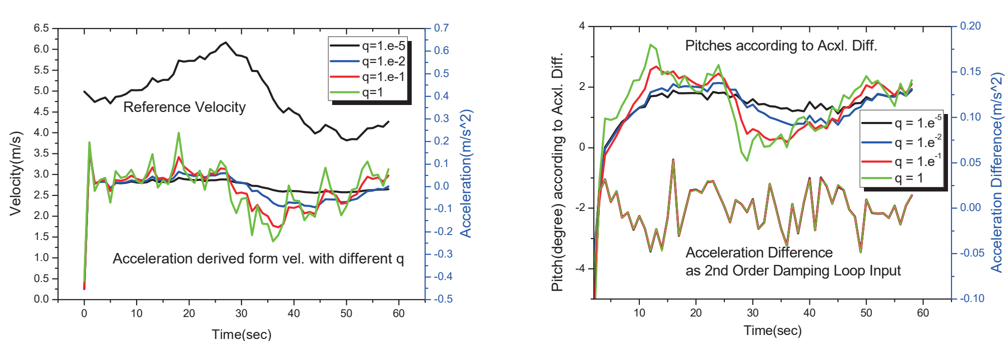


Fig. 3. Scalar filter output w.r.t the reference velocity

Because the process noise q attenuates the velocity, it is very important to choose a proper q to reflect the true vehicle dynamics. If q is too small, the acceleration variation of a vehicle is not distinguishable, so the horizontal attitude does not match the real vehicle dynamics. To investigate the effect of q the sensitivities on the performance corresponding to different q are simulated with the real flight data acquired from the UH-60 helicopter for its full operation sequences. The filter sensitivity has been defined the ratio of the filter output w.r.t the reference input for the analysis purpose. The scalar filter outputs are shown in Fig. 3. The filter sensitivity for q=1 is 0.9888, for $q=10^{-1}$ 0.9644, $q=10^{-2}$ 0.9197 and $q=10^{-5}$ 0.8719. For q=1 the response keeps track of the reference GPS velocity but is too fluctuant to use as a horizontal attitude damping loop. On the other hand, for $q=10^{-5}$ the output is over smoothed, which has not reflected the true helicopter dynamics and caused the large horizontal attitude error.

The estimated horizontal pitch angles for the different q are shown in Fig. 4 as an example. The GPS velocity is attenuated by a scalar filer, then converted to accelerations in Fig. 4(a). The acceleration differences between a GPS and SDINS are fed back into the 2nd order horizontal attitude damping loop in Fig. 4(b). The velocity residual with respect to the average velocity always exists because no platform can maintain an ideal constant speed in the practical maneuvering. As shown in Fig. 4, the higher q responds well to the velocity change, but the pitch which should be smoothed to suppress the noise is too fluctuant. For the helicopter velocity is normally over 100kts, we have to consider q to prohibit an abrupt change and over smoothing of a horizontal attitude and to keep track of the fast velocity. The adequate q for helicopter dynamics is chosen 0.1 based on the analysis and test results.

The coarse azimuth alignment of MIFA estimates the coarse heading of a SDINS under constant speed as well. The



(a) GPS velocity and acceleration

(b) SDINS attitude and acceleration difference

Fig. 4. Attitude estimation corresponding to the different scalar filter gains

closed loop composed of a GPS tracking angle and SDINS yaw increment is implemented to calculate the SDINS heading,. The tracking angle of a GPS can be calculated as follows

$$H^{GPS} = \arctan\left(\frac{V_E^{GPS}}{V_N^{GPS}}\right). \tag{5}$$

Using a GPS tracking angle, the SDINS heading can be calculated from the closed loop.

$$H_K = H_{K-1} + \Delta H^{INS} + K(H_{K-1}^{GPS} - H_{K-1}), \tag{6}$$

where H_k is an INS/GPS integrated heading, ΔH^{INS} is an INS heading increment, and H^{GPS} is a GPS tracking angle. With sufficiently large gain K the coarse azimuth can converged within short time.

4. Fine Alignment

In the third stage of MIFA, the precise attitude is estimated by the AKNF which uses the GPS as an aiding source. There are generally two kinds of coupling method for a SDINS and GPS: a loosely coupled method or a tightly coupled method. A loosely coupled system can be easily implemented using the GPS solution, but there must be more than four satellites to maintain 3D status. A tightly coupled system which uses pseudo ranges and pseudo range rates as measurements is complex for their configuration but shows good performance. Though a tightly coupled GPS/INS has the advantage of using less than four satellites, a loosely coupled GPS/INS system is usual because tight coupling needs the embedded system configuration and mass data transportations between the SDINS and GPS, and it also increases system failure rates because of its complexity. This study configures the loosely coupled GPS/INS system for its simplicity. The 14th error state model of the SDINS for the fine alignment is given as

$$x(k+1) = \Phi x(k) + Gw(k), \tag{7}$$

$$z(k+1) = Hx(k+1) + \upsilon(k), \tag{8}$$

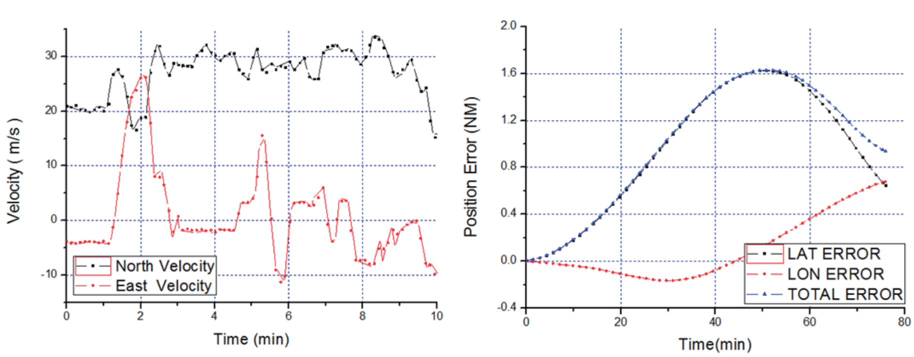
where $\hat{x}(k)$ is the error state vector, Φ is the state transition matrix, G is the input matrix, $w(k)$ is the input white noise vector with a zero mean and covariance $Q = E\{w(k)w(k)^T\}$, $z(k)$ is the measurement vector, H is the measurement matrix, $\upsilon(k)$ is the measurement white noise vector with zero mean and covariance $R = E\{\upsilon(k)\upsilon(k)^T\}$.

The error state variables of a SDINS are described as

$$\begin{aligned} x(t) &= \begin{bmatrix} x_f & x_a & \delta_t \end{bmatrix} \\ x_f &= \begin{bmatrix} \delta\phi & \delta\lambda & \delta v_e & \delta v_n & \varepsilon_e & \varepsilon_n & \varepsilon_u \end{bmatrix} \\ x_a &= \begin{bmatrix} \delta A_x & \delta A_y & \delta A_z & \delta B_x & \delta B_y & \delta B_z \end{bmatrix} \end{aligned}, \tag{9}$$

where x_f is the error vector of the position, velocity, and attitude, x_a is the error vector of the accelerometer and gyro biases, δ_t is the time delay, $\delta\phi$ is the latitude error, $\delta\lambda$ is the longitude error, δv_e is the east velocity error, δv_n is the north velocity error, ε_e is the east attitude error, ε_n is the north attitude error, ε_u is the upper attitude error, δA_x is the x axis accelerometer bias error, δA_y is the y axis accelerometer bias error, δA_z is the z axis accelerometer bias error, δB_x is the x axis gyro bias error, δB_y is the y axis gyro bias error, and δB_z is the z axis gyro bias error.

In a GPS/INS system it is very common to use the GPS PPS (pulse per second) signal for time synchronization but an inherent time delay exists between the INS and GPS. This timing mismatch mainly causes error in an ongoing directional accelerometer bias. If the vehicle moves to the north direction, the north accelerometer bias is over estimated so the latitude error is dominant. The time delay effects are analyzed by the real driving test with a car which equips the SDINS. The time delay variable δ_t is excluded intentionally from the SDINS error



(a) GPS velocity (b) SDINS pure navigation error after IFA

Fig. 5. Time delay effects between the SDINS and GPS

model. The results are depicted in Fig. 5. In Fig. 5(a), the vehicle moves to the north direction with an average speed of 27m/s, and to the east with 0.8m/s. In Fig. 5(b), a latitude error of 1.6 nm within the first Schuler cycle is dominant because the velocity mismatch caused by the time delay involves the large north accelerometer bias. The SDINS error specification used for this test is about 1.0nm/hr. It is obvious that the time delay effect between a SDINS and GPS mainly affects the position error in real situations.

In real time implementation, the SDINS saves the data necessary for aiding at the Kth PPS reception, which is delayed by δ_t from its occurrence, and we need to compensate for the GPS data for the Kth measurement because it is very hazardous to compensate for all variables of the state transition matrix of a SDINS data back by -δ_t. The PPS time delay is depicted in Fig. 6. We have to estimate the time delay of the PPS reception from SDINS error models and compensate for the GPS measurement by δ_t.

The measurement at the Kth update of SDINS and its Tayler series expansion can be written as follows:

$$\begin{aligned} z(k) &= P_{INS}(k) - P_{GPS}(k+\delta t) \\ &\cong P_{INS}(k) - (P_{GPS}(k) + P_{GPS}(k)\delta t) \end{aligned}, \tag{10}$$

$$z(k) = \begin{bmatrix} \phi_{INS} - (\phi_{GPS} + \dfrac{V_{N,GPS}\delta t}{R}) \\ \lambda_{INS} - (\lambda_{GPS} + \dfrac{V_{E,GPS}\delta t}{R\cos(\phi_{GPS})}) \end{bmatrix}. \tag{11}$$

The measurements of the AKNF is position only because the GPS velocity calculated from the Doppler frequency can be interfered by the rotation of helicopter rotors. The linearized INS error models cause the estimation errors from theoretical values, and these estimation errors are not reflected exactly in the error covariance P in practice. The innovation is fed back into the measurement error covariance R to minimize the estimation errors and this makes the R keep up with the error residuals. Making R flexible gives rise to the fast convergence of an error estimation. The windows for this are five samples (N = 5). The major update sequences of the AKNF can be written in a form

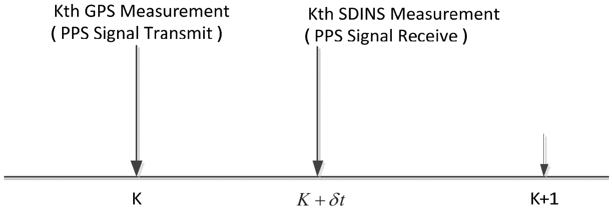


Fig. 6. Time delay between the GPS and SDINS

$$\begin{aligned} v_k &= z_k - H\hat{x}_{k/k-1} \\ \hat{W}_k &= \frac{1}{N}\sum_{i=k-N+1}^{k} v_k v_k^T \\ \hat{R}_k &= \hat{W}_k - HP_{k/k-1}H^T \\ K_k &= P_{k/k-1}H^T(HP_{k/k-1}H^T + \hat{R}_k)^{-1} \\ P_k &= (I - K_k H)P_{k/k-1} \end{aligned}. \tag{12}$$

Here v_k is the innovation sequence, $\hat{W}_k$ is the windowed covariance matrix of the innovation sequence, $\hat{R}_k$ is the adaptive covariance matrix of measurement noise, K_k is the Kalman gain matrix, and P_k is the error covariance matrix.

The AKNF determines the optimal measurement covariance in real time from its innovation sequence. At the beginning of the AKNF the measurement residual is relatively large because of the rough attitude; therefore this is reflected in the Kalman gain and error state vector. This makes the measurement residual errors get small after a few seconds.

5. Real Flight Test

The SDINS used to verify the proposed paper is configured with digita1 self-running gyroscopes and semiconductor type pendulous accelerometers. The gyroscopes and accelerometers output the angle increments and linear accelerations via the RS422 serial communications. The typical gyro bias is 0.01deg/hr, accelerometer 100ug, and gyro random walk 0.007$\mathrm{deg}/\sqrt{hr}$. The position accuracy of the stand-alone GPS is 6m SEP. The true heading error of this grade SDINS is less than 0.05° and the corresponding maximum position error of a pure navigation is 1NM/hr (1.8 km/hr). The position error of a pure navigation is proportional to the estimated heading error at the alignment. For the real flight test the alignment accuracy is verified with the position error of a pure navigation because there is no attitude reference during MIFA.

The SDINS is mounted on the passenger room of an UH-60 helicopter and interfaces with a stand-alone GPS via serial communication. The reference position and velocity for these tests are from the stand-alone GPS because the small deviation of GPS position from the true position is negligible for a long-time operation. If the MIFA proposed in this paper is not properly worked, the position error shall increase easily over 1NM for one Schuler cycle. The test set mounted on the UH-60 helicopter is shown in Fig. 7.

All the cables are wrapped with an aluminum foil to prevent electro-magnetic interference and the batteries for the SDINS, GPS and CDU (control and display unit) are

Fig. 7. GPS/INS mounted on an UH-60 helicopter for flight tests

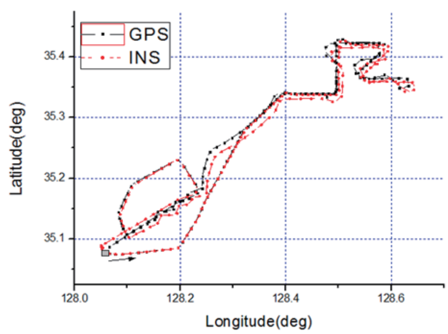


Fig. 8. Typical trajectory of pure navigation after GCA

equipped independently from the helicopter power.

A typical trajectory for the experiments is shown in Fig. 8. To compare the pure navigation performance, the conventional gyro compass alignment and MIFA are performed three times. The minimum flight time is over one Schuler cycle (84.4minutes).

The estimated attitude during the coarse horizontal and azimuth alignment is depicted in Fig. 9. The helicopter velocity is nearly 200km/hr to the south-west direction. Because of the high speed of the helicopter, the small velocity variation may cause the horizontal attitude divergence. It is evident that the of the scalar filter is properly tuned because the excessive fluctuation is suppressed, and the 2nd order damping loop for horizontal attitude maintains well the pitch and roll. After the 20 seconds of a maneuvering, the coarse heading matches well the flight direction.

The position errors of the pure navigation after MIFA and conventional gyro compass alignments are depicted in Fig. 10 and Fig. 11. We performed MIFA for 10minutesand then changed the SDINS mode to the pure navigation. The magnitude of position error is calculated with RSS (Root Sum Square) of latitude and longitude errors.

Figure 10 shows the maximum RSS position errors as 0.9nm, 0.74nm, and 0.75nm within the first Schuler cycle. The average maximum RSS error is 0.8nm and its circular error probable (CEP) is 0.66nm. The position error matches the standard navigation unit specification well.

The maximum RSS position errors of the MIFA are 0.53nm, 0.37nm, and 0.4nm respectively in Fig. 11. The average of maximum RSS error is 0.43nm and its CEP is 0.35nm. The test results are summarized in Table 1. Because properly designed MIFA estimates and compensates for the error state variables, it is possible to dramatically improve the

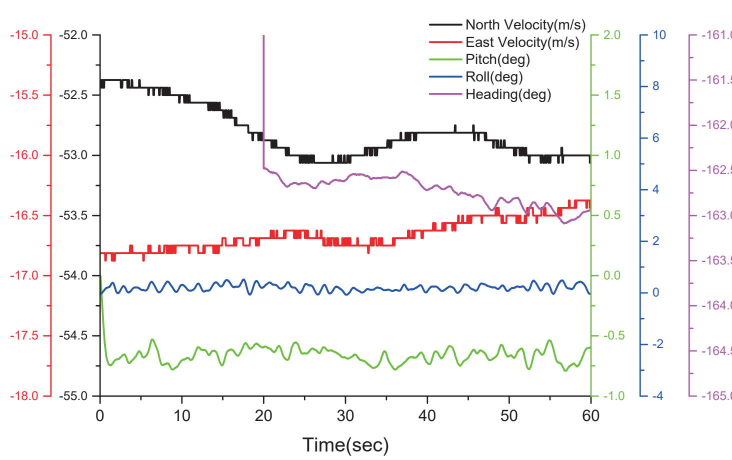
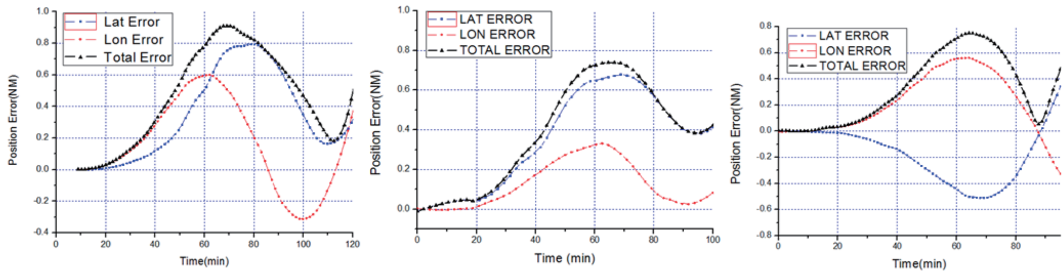
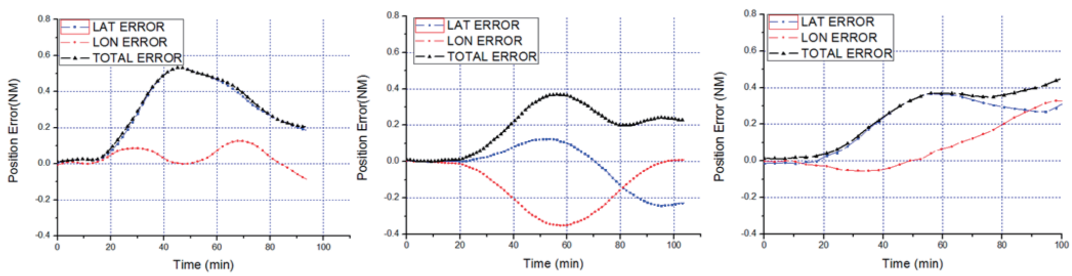


Fig. 9. Estimated attitudes during 1st and 2nd stages



(a) first flight test (b) second flight test (c) third flight test

Fig. 10. Pure navigation error after GCA



(a) first flight test (b) second flight test (c) third flight test

Fig. 11. Pure navigation error after MIFA

Table 1. Maximum position error within one Schuler cycle (UH60 flight test)

Test		1st	2nd	3rd	Average
MIFA	RSS(nm)	0.53	0.37	0.4	**0.43**
	CEP(nm)	0.44	0.31	0.33	**0.36**
GCA	RSS(nm)	0.9	0.74	0.75	**0.8**
	CEP(nm)	0.75	0.61	0.62	**0.66**

navigation performance. The MIFA navigation performance is better by 53.75 percent over the conventional gyro compass alignment.

6. Conclusion

This paper presented a multistage in-flight alignment (MIFA) for moving vehicles with no initial attitude reference, composed of the coarse horizontal alignment, coarse heading alignment, and fine alignment using the AKNF. The scalar filter to smooth accelerations from the noisy GPS velocity and the effects of the filter gain corresponding to process noise for the attitude estimation were discriminated for moving vehicles. The time synchronization effects between SDINS and GPS were described as a term of position error.

We confirmed the performance of the proposed MIFA by real flight tests with a UH60 helicopter which mounted the SDINS and the stand-alone GPS. All the algorithms described in this paper were implemented with the real-time software. With six real flight tests, the results confirmed that the position error of MIFA was reduced by 54 percent compared with that of the conventional gyro compass alignment for one Schuler cycle.

References

[1] Drora, G. M. and Bar-Itzhack, I. Y., "Observability Analysis of Piece-Wise Constant Systems Part I: Theory",

IEEE Transaction on Aerospace and Electronic Systems, Vol. 28, No. 4, 1992, pp. 1056-1067.

[2] Drora, G. M. and Bar-Itzhack, I. Y., "Observability Analysis of Piece-Wise Constant Systems Part II: Application to Inertial Navigation In-Flight Alignment", *IEEE Transaction on Aerospace and Electronic Systems*, Vol. 28, No. 4, 1992, pp. 1068-1075.

[3] Salychev, O. S., *Applied Inertial Navigation: Problems and Solution*, Moscow: BMSTU Press, 2004.

[4] Siouris, G. M., *Aerospace Avionics System: A Modern Synthesis*, New York: Academic Press, 1993.

[5] Maybeck, P. S., *Stochastic Models, Estimation, and Control*, New York: Academic Press, Vol. 2, 1979.

[6] Johnson, C, Ohlmeyer, E. J. and Pepitone, T. R. "Attitude Dilution of Precision-A New Metric for Observability on In-Flight Alignment Errors", *AIAA Guidance, Navigation, and Control Conference and Exhibit*, 2000, AIAA-2000-4277.

[7] Hong, H. S., Lee, J. G. and Park, C. G., "Performance Improvement of In-Flight Alignment for Autonomous Vehicle Under Large Initial Heading Error", *IEE proceedings Radar, Sonar and Navigation*, Vol. 151, 2004, pp. 57-62.

[8] Jiancheng, F. and Sheng, Y., "Study on Innovation Adaptive EKF for In-Flight Alignment of Airborne POS", *IEEE Transaction on Instrumentation and Measurement*, Vol. 60, No. 4, 2011, pp. 1378-1388.

[9] Lee, H. G., Lee, J. G. and Jee, G. I., "Effects of GPS Measurement Delay on SDINS", *IEEE 2000 Position Location and Navigation Symposium*, 2000, pp. 464-471.