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An Engineering Accuracy Estimation Method for Transfer Alignment

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Abstract: Aimed at characteristics of transfer alignment on a moving base-guided vehicle, a kind of accuracy estimation method was proposed. The navigation accuracy was mostly caused by attitude error and the simplified relation between transfer alignment error and velocity error was derived according to velocity error formula. After transfer alignment, the system entered into the navigation under similar flight and velocity error was measured in short time, further attitude alignment error was anti-derived. The yaw angle error was estimated by calculating reproducibility of the difference between major and slave inertial navigation system. Pitch and roll angle error were estimated by calculating reproducibility of velocity error between major and slave inertial navigation system. Experiments data show that the alignment accuracy meets the target and it is suitable for engineering application.

Keywords: Accuracy estimation, guided vehicle, transfer alignment, test analysis

INTRODUCTION

In early 1990s, precision-guided air vehicles first debut in the Gulf War and the new weapons have been widely used in the next several local wars. As guided vehicles are belong to the air projection class weapons, random relative motion exists between vehicles and the base and transfer alignment or air targeting of the onboard slave INS is necessary (Wen-long and Shu-Hua, 2009). Inertial transfer alignment is a basis of master INS, dynamic matching between two sets of data of INS to estimate the relative misalignment angle for the master INS and then corrected slave INS (SINS on concerned). Alignment accuracy directly impact on navigation accuracy, it is crucial to estimate its accuracy (Wang and Zheng-Long, 2010)

Strictly speaking, the navigation error at the different time on is the common total error responses for excitation source and alignment error. Although in theory it can be slave and master inertial navigation systems and data recording device placed in the carrier for composing of the new test system, after finishing alignment of slave INS into navigation and using Kalman smoothing process for more than one set of simultaneous observational data of master INS, separating the alignment error, accessing the average smoothed value of alignment error at the navigation start time, thus this method has a certain degree of difficulty in achieve engineering (Gu, 2008; Liu and Liu, 2011). Alignment accuracy based on air ammunition moving base is a new topic and this study proposes a project similar available test method.

ACCURACY ANALYSIS OF TRANSFER ALIGNMENT

Taking guided vehicle as an example, transfer alignment of guided vehicles is not rapid and less stringent requirement of mobility like air to air missiles, but it has not plenty of time like launching strategic weapons. Also due to cost constraints, the use of inertial MEMS devices requires an estimate of the gyro drift of transfer alignment.

In the transfer alignment the errors of inertial MEMS devices have been done approximate estimation and gyro drift estimation error is about 2.5°/h(1σ), then accelerometer accuracy is 1×10^{-4}g (1σ), in 2min flying process, attitude errors Δφ due to the gyro and accelerometer measurement error can be approximated as:

$$\Delta\varphi = \frac{2.5}{3600}\times(60\times2) = 0.083^{\circ}$$

$$\Delta\varphi = \nabla / g = 0.006^{\circ}$$

Compared with the initial heading, attitude deviation, they are smaller than an order of magnitude, so the navigation accuracy which is impacted by the attitude error caused by gyro and accelerometer error can be ignored.

Velocity error formulas:

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$$\begin{aligned}\delta\dot{V}_x^n &= -f_{mz}^n\varphi_y + f_{my}^n\varphi_z + (2\omega_{ie}\sin L + \frac{V_{mx}^n\tan L}{R_e})\delta V_y^n \\ &+ 2\omega_{ie}V_{my}^n\cos L + \frac{V_{mx}^n V_{my}^n}{R_e}\sec^2 L + (2\omega_{ie}V_{mz}^n\sin L)\delta L \\ &+ C_b^n(1,1)\nabla_x + C_b^n(1,2)\nabla_y + C_b^n(1,3)\nabla_z\end{aligned} \tag{1}$$

$$\begin{aligned}\delta\dot{V}_y^n &= f_{mz}^n\varphi_x - f_{mx}^n\varphi_z - (2\omega_{ie}\sin L + \frac{V_{mx}^n\tan L}{R_e})\delta V_x^n \\ &- \frac{V_{mz}^n}{R_e}\delta V_y^n - (2\omega_{ie}\cos L + \frac{V_{mx}^n}{R_e}\sec^2 L)V_{mx}^n\delta L \\ &+ C_b^n(2,1)\nabla_x^b + C_b^n(2,2)\nabla_y^b + C_b^n(2,3)\nabla_z^b\end{aligned} \tag{2}$$

where, $f^n{}_m$ is specific force of the master INS $C^n{}_b = C_{n'}{}^n$, $C^{n'}{}_b$ is attitude matrix between the vehicle body coordinate system and the navigation coordinate system and it is related with the deflection angle, misalignment angle and attitude angle error:

$$C_n^{n'} = \begin{pmatrix} 1 & \varphi_z & -\varphi_y \\ -\varphi_z & 1 & \varphi_x \\ \varphi_y & -\varphi_x & 1 \end{pmatrix}; \nabla^b = [\nabla_x^b \quad \nabla_y^b \quad \nabla_z^b]^T$$

is the bi as value of the accelerometer of the slave inertial navigation system.

By formula (1) and formula (2), we get: the velocity error is mainly caused by the attitude errors in a short time. Also according to flight conditions, the force f_x , f_y are very small in the horizontal direction and f_z is for about 1g, so the heading error $\delta\psi$ is not reflected in the east and north velocity error and the attitude error is the source of the error rate. If carrier aircraft keeps flying at uniform speed after the transfer alignment, excluding the impact of the value of the accelerometer bias, in the period of time, east, north velocity error are mainly caused by the initial alignment errors and they can be simplified. East velocity error is given by:

$$\begin{cases}\delta V_x = V_y \cdot \varphi_y - g\varphi_y \cdot t \\ \delta V_y = g\varphi_x \cdot t - V_x\varphi_z\end{cases} \tag{3}$$

where, t is autonomous flight time of the INS, φ_x, φ_y, φ_z for the transfer alignment pitch, roll, heading error, V_x, V_y is the east and north velocity of the carrier aircraft. Therefore, the error caused by the heading is:

$$\begin{cases}\delta V_x = V_y\varphi_z \\ \delta V_y = V_x\varphi_z\end{cases} \tag{4}$$

The error caused by the pitch is:

$$\delta V_y = g\varphi_x \cdot t \tag{5}$$

The error caused by the roll is:

$$\delta V_y = g\varphi_y \cdot t \tag{6}$$

The variance of east velocity is:

$$\sigma_x = \sqrt{(V_y\varphi_z)^2 + (g\varphi_y \cdot t)^2} \tag{7}$$

The variance of north velocity is:

$$\sigma_y = \sqrt{(V_x\varphi_z)^2 + (g\varphi_x \cdot t)^2} \tag{8}$$

If the carrier aircraft flying east, north velocity are 100 m/s, initial alignment heading, attitude accuracy are 0.1° and 0.2°, after 300 s and The variances of the east and north velocity are σ_E = 10.26 (m/s) and σ_N = 10.26 (m/s).

ESTIMATION METHOD

Heading accuracy estimation: At the end of each alignment process, the repeatability of the difference is to estimate the heading accuracy between the slave INS and master INS. After each alignment, the master INS heading angle $\psi^i{}_m$, the slave INS heading angle $\psi^i{}_s$ and the difference is $\Delta\psi_i$, $\psi^i{}_m$, $\psi^i{}_s$, 7 available values $\Delta\psi_1$, ψ_2, ψ_7 are obtained for 7 flight times. Calculate the mean value:

$$\overline{\Delta\psi} = \frac{\Delta\psi_1 + \Delta\psi_2 + \cdots + \psi\lambda_7}{7} \tag{9}$$

Then calculate the standard deviation:

$$\delta\psi = \sqrt{\frac{(\Delta\psi_1 - \overline{\Delta\psi})^2 + \cdots + (\Delta\psi_7 - \overline{\Delta\psi})^2}{7}} \tag{10}$$

Pitch and roll accuracy estimation: As the pitch and roll angle error is mainly caused by the initial alignment errors, essentially keep the uniform flight after turning into navigation, the pitch and roll accuracy estimation is determined by the north and east velocity error of the vehicle carrier slave INS after the 10s, 20s, 30s ..., 120s navigation. Supposed the north and east velocities of the master INS are $V^i{}_{my}$, and $V^i{}_{mx}$, and the north and east velocities of the slave INS are $V^i{}_{sv}$, and $V^i{}_{sx}$, T_i as the time, then the difference is:

$$\begin{cases}\Delta V_{iy} = V_{my}^i - V_{sy}^i \\ \Delta V_{ix} = V_{mx}^i - V_{sx}^i\end{cases} \tag{11}$$

And then turn into the pitch and roll angle error:

$$\begin{cases}\delta\theta_i = \dfrac{\Delta V_{iy}}{T_i \times g} \times \dfrac{180}{\pi} \\ \delta\gamma_i = \dfrac{\Delta V_{ix}}{T_i \times g} \times \dfrac{180}{\pi}\end{cases} \tag{12}$$

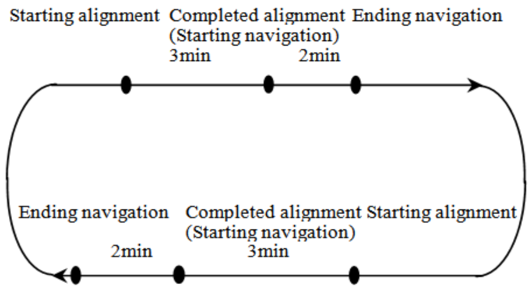

Fig. 1: Transfer alignment route

Thus the every seven values of $\delta\theta_1$, $\delta\theta_2$, …, $\delta\theta_7$, $\delta\gamma_1$, $\delta\gamma_2$, … , $\delta\gamma_7$ are gained and calculate the standard deviation:

$$\begin{cases} \delta\theta = \sqrt{\dfrac{\delta\theta_1{}^2 + \cdots + \delta\theta_7{}^2}{7}} \\ \delta\gamma = \sqrt{\dfrac{\delta\gamma_1{}^2 + \cdots + \delta\gamma_7{}^2}{7}} \end{cases} \tag{13}$$

Requirements of transfer alignment test: In alignment accuracy estimation the requirements are the following:

- Being ready to begin transfer alignment after starting the slave INS system.
- Flying the transfer alignment simulated route, shown in Fig. 1, start "Transfer Alignment" command and begin to download the master inertial navigation data.
- After 3 min, the carrier uploads "transfer alignment is good" signal, then the carrier begins to enter the autonomous navigation state.
- Carrier uniform motion, after 2 min the master inertial uploads "navigation end" signal, recording the master and slave inertial navigation data in the process and the end of one time of transfer alignment.
- The main INS received "navigation end" signal, return to 2) stage to the next alignment program delivery and the accuracy estimation after the completion of seven transfer alignments.

Test:

Static test: The master INS-XXX (gyro accuracy of 0.01°/h) and slave inertial navigation system installed on the same rigid plate and examine the performance by the following process after completing installation:

- The master INS starts, the signal is passed to the slave INS and complete the transfer alignment for 3 min and automatically enter the navigation mode, the transfer alignment attitude error can be estimated by the data which is recorded.

Table 1: Error of transfer alignment with static test

	Velocity error (m/s)			Attitude error (′)		
No	Vx	Vy	Vz	φx	φy	Φz
1	0.02	0.05	0.02	5.25	6.27	8.82
2	0.03	0.04	0.03	5.16	5.91	9.91
3	0.01	0.06	0.02	6.55	7.83	8.74
4	0.02	0.04	0.03	5.64	5.32	8.95
5	0.03	0.05	0.02	7.85	7.52	10.11
6	0.02	0.05	0.01	5.46	6.21	9.85
7	0.01	0.04	0.02	4.24	4.12	9.93

Fig. 2: Experiment of transfer alignment mounted vehicle

- Rotate the master INS to anther accurate angle, then take slave INS transfer alignment again and automatically enter the navigation mode, to analyze all the data recorded, which can estimate the heading error and attitude error of the transfer alignment.

Repeat this process about 7 times. After transfer alignment, the master and slave inertial INS velocity and attitude errors in Table 1.

Data from Table 1 shows that the mean velocity errors are 0.02, 0.05, 0.02 m/s and attitude errors are 5.74′, 6.17′, 9.47′ respectively.

Vehicle test: The vehicle test is with the same the static performance test and the master and slave INS installed with the same rigid plate and placed in the test vehicle, shown in Fig. 2.

Selecting the standard point A and standard point B, a distance two points A, B is about 5 min' fahrt, slave INS accuracy estimation method is as follows:

- Initial slave INS position at the point A and complete the initial alignment.
- Vehicle moves, slave INS starts transfer alignment
- Slave INS automatically enters the navigation mode after the completion of transfer alignment, the vehicle runs to the point B.

In order to truly simulate the actual condition, including sloping road traffic, road slope, *S* type of ring road (slope distance: 500 m, angle: 30°; slope distance: 3000 m, slope steepness: 30°; *S* type of road radius: 200 m).

The introduction of GPS signals, repeats the process about seven times, recording the data. After transfer alignment, the velocity and attitude errors of the master and slave INS in Table 2.

Table 2: Error of transfer alignment with vehicle mounted test

	velocity error (m/s)			Attitude error (')		
No	Vx	Vy	Vz	φx	φy	Φz
1	0.11	0.15	0.12	7.32	10.82	12.74
2	0.13	0.14	0.13	7.53	10.07	12.58
3	0.11	0.16	0.12	8.21	10.62	13.20
4	0.12	0.14	0.13	7.66	9.19	12.69
5	0.13	0.15	0.12	7.59	10.95	12.51
6	0.12	0.15	0.11	7.67	12.44	12.33
7	0.10	0.14	0.12	8.38	11.70	12.97

Table 3: Alignment statistics for 7 yaw tests

No	Ψ_is (o)	Ψ_is(o)
1	83.92	84.27
2	84.32	84.78
3	86.97	87.26
4	88.34	88.86
5	86.21	86.53
6	87.34	87.69
7	86.72	88.14

Data from Table 2 shows that the average errors were 0.12, 0.15, 0.12 m/s and attitude errors were 7.77′, 10.83′ and 12.71′.

SIMULATED FLIGHT TEST

After required transfer alignment, a simulated flight test measured the master and slave INS, heading angle statistics in Table 3, the velocity statistics in Table 4.

According to data of Table 3, heading angle error is calculated and according to formula (12) the pitch angle error and roll angle error are calculated, seeing Table 5.

According to the data from Table 5, according to formula (13) calculated heading alignment accuracy is 0.32º (required 0.5º), pitch alignment accuracy is 0.22º (required 0.3º) and roll alignment accuracy is 0.18º (required 0.3º) comprehensive analysis of the above results, transfer alignment accuracy is to meet the requirements.

Illustration for innovation and engineering application: Strictly speaking, the navigation error at

Table 4: Alignment statistics 7 velocity tests

Time (s)	Vsy (m/s)	Vmy (m/s)	ΔVy (m/s)	Vmx (m/s)	Vsx (m/s)	ΔVx (m/s)
(a) 1st velocity statistics						
10	-5.12	-4.98	-0.14	250.54	250.86	-0.32
30	-6.73	-5.34	-1.39	252.17	253.35	-1.18
60	-8.35	-6.17	-2.18	254.54	257.27	-2.33
90	-9.11	-6.24	-2.47	254.58	250.23	-5.25
120	-10.39	-6.53	-3.46	256.72	255.81	-9.09
(b) 2nd velocity statistics						
10	18.52	18.47	0.05	253.73	253.34	0.49
30	17.74	17.49	0.25	254.94	254.26	0.68
60	16.05	14.68	1.43	255.06	254.72	0.34
90	14.71	12.16	2.48	255.75	256.77	-1.02
120	12.92	9.05	3.87	253.91	256.65	-2.74
(c) 3rd velocity statistics						
10	4.26	4.37	-0.11	205.54	205.69	-0.15
30	3.15	2.66	0.49	206.28	206.75	-0.37
60	1.33	0.03	1.30	208.75	210.83	-2.08
90	0.62	-2.32	2.92	212.86	216.08	-3.24
120	-0.54	-4.39	3.94	214.06	219.57	-5.51
(d) 4th velocity statistics						
10	1.84	1.81	0	234.41	234.32	0.11
30	0.58	0.5	0.08	237.67	237.00	0.67
60	-0.56	-1.1	0.54	237.56	236.30	1.26
90	-1.28	-2.6	1.32	237.83	236.60	1.23
120	1.84	1.81	0	234.41	234.32	0.11
(e) 5th velocity statistics						
10	-4.92	-4.9	-0.02	240.53	240.85	-0.32
30	-5.72	-5.4	-0.32	242.15	243.37	-1.22
60	-6.11	-5.0	-1.11	244.50	247.26	-2.61
90	-7.67	-5.2	-2.47	244.58	250.28	-5.70
120	-10.39	-6.53	-3.46	256.72	255.81	-9.09
(f) 6th velocity statistics						
10	-15.97	15.93	-0.04	239.19	239.32	-0.14
30	-24.25	-24.6	0.35	236.06	238.12	2.06
60	-20.53	-21.6	1.07	239.83	242.53	3.70
90	-20.00	-22.8	2.80	244.33	248.55	4.22
120	-19.33	-24.7	5.37	251.14	256.81	5.67
(h) 7th velocity statistics						
10	12.57	12.56	0.02	150.23	150.06	0.17
30	18.75	18.42	0.33	150.95	150.37	0.58
60	18.53	17.30	1.23	151.86	153.21	1.65
90	17.00	14.70	2.30	153.04	155.72	3.32
120	16.33	12.10	4.20	153.82	158.76	-5.86

Table 5: Heading angle, pitch angle and roll angle error statistics

No	$\Delta\psi_i$ (o)	$\delta\theta_i$ (′)	$\delta\gamma_i$ (′)
1	0.35	2.68	2.25
2	0.46	3.36	3.80
3	0.29	5.30	8.56
4	0.52	7.94	8.64
5	0.32	9.33	9.53
6	0.35	12.22	10.25
7	0.42	13.41	12.04

the different time on is the common total error responses for excitation source and alignment error. Although in theory it can be slave and master inertial navigation systems and data recording device placed in the carrier for composing of the new test system, after finishing alignment of slave INS into navigation and using Kalman smoothing process for more than one set of simultaneous observational data of master INS, separating the alignment error, accessing the average smoothed value of alignment error at the navigation start time, thus this method has a certain degree of difficulty in achieve engineering.

The navigation accuracy was mostly caused by attitude error and the simplified relation between transfer alignment error and velocity error was derived according to velocity error formula. After transfer alignment, the system entered into the navigation under similar flight and velocity error was measured in short time, further attitude alignment error was anti-derived. The yaw angle error was estimated by calculating reproducibility of the difference between major and slave inertial navigation system. Pitch and roll angle error were estimated by calculating reproducibility of velocity error between major and slave inertial navigation system. Finally test data shows the method is feasible for engineering applications.

CONCLUSION

Aiming at the alignment requirements of guided air ammunitions delivery, analysis of the factors that affect the navigation accuracy, the gyro drift compensation and uniform carrier aircraft flight situation, design a alignment accuracy assessment for guided vehicle. In short time, the initial attitude error led to the velocity error of the main factors and the introduction of initial alignment errors by inverse derivation through the velocity error and calculate its variance and finally experimental data of the method is feasible for engineering applications.

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