Estimation Technique of Fixed Sensor Errors for SDINS Calibration

Tae-Gyoo Lee and Chang-Ky Sung

Abstract: It is important to estimate and calibrate sensor errors in maintaining the performance level of SDINS. In this study, an estimation technique of fixed sensor errors for SDINS calibration is discussed. First, the fixed errors of gyros and accelerometers, excluding gyro biases are estimated by the navigation information of SDINS in multi-position. The SDINS with RLG includes flexure errors. In this study, the gyros flexures are out of consideration, but the proposed procedure selects certain positions and rotations in order to minimize the influence of flexures. Secondly, the influences of random walks, flexures and orientation errors are verified via numerical simulations. Thirdly, applying the previous estimated errors to SDINS, the estimation of gyro biases is conducted via the additional control signals of close-loop self-alignment. Lastly, the experiments illustrate that the extracted calibration parameters are available for the improvement of SDINS.

Keywords: Fixed sensor errors, flexures, gyro biases, RLG, SDINS calibration.

1. INTRODUCTION

In order to realize the navigation and alignment algorithms of the INS (Inertial Navigation System), the calibration of sensor errors has to be done prior to the actual flight. It is important to calibrate sensor errors in maintaining the performance of INS. Two calibration approaches can be used for the estimation of calibration parameters [1-5]. The first approach employs the raw data of accelerometers and gyros. However this approach deals with the small magnitude of earth rotation rate that leads to difficulties in gyro parameter extraction, and requires precise orientation with respect to the local-level frame. Otherwise the orientation errors will affect calibration accuracy. In order to remove the above disadvantages the second calibration procedure must be employed. The second one deals with the velocity (acceleration) indications of the INS on the local-level frame. In this case, the IMU block is also turned in different angles, but this procedure deals with the INS output in the navigation mode during all calibration procedures. The orientation accuracy of the IMU block with respect to the local-level frame will not be critical, because the velocity (acceleration) indications of the INS are available following completion of system alignment. Any misalignment errors take place as unknown ones, which have to be estimated together with other parameters. Particularly, the SDINS (Strapdown INS) frequently employs this calibration procedure to improve accuracy with an inexpensive turning table. The SDINS, which is compared to the GINS (Gimbaled INS) of the same navigation accuracy, requires a more accurate calibration of sensor errors. The reason for this is because the SDINS sensors are attached to the body of the vehicle and all evaluations have direct influenced system output.

This study describes the second approach for the extraction of desired calibration parameters such as in [1-5]. Generally, assuming the flexure errors have first been compensated, the system will behave as if the g-sensitive misalignments are zeros. Then the estimation of remaining coefficients is accomplished by their procedures. In this study, the flexures of gyros are out of consideration, but the proposed procedure is to select 15 positions and rotations in order to minimize (separate) the influence of flexures. The advantage of the proposed procedure is that the calibration can be independently performed without the consideration of flexures. The simulations indicate the influences of random walks and flexures of gyros and orientation errors. And the estimation technique of gyro biases is introduced through the close-loop self-alignment procedure. The experiments illustrate that the calibration parameters estimated using the suggested procedures improve the performance of SDINS with RLG.

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2. CALIBRATION PARAMETERS

The goal of calibration is to estimate unknown constant errors and to compensate for these errors. Therefore first of all the sensor error models must be defined. The error models of the accelerometers and gyros (RLG) are known as follows [1,5]:

$$\begin{aligned}\delta a_x &= \alpha_x + \alpha_{xx}\cdot a_x + \alpha_{xy}\cdot a_y + \alpha_{xz}\cdot a_z,\\ \delta a_y &= \alpha_y + \alpha_{yx}\cdot a_x + \alpha_{yy}\cdot a_y + \alpha_{yz}\cdot a_z,\\ \delta a_z &= \alpha_z + \alpha_{zx}\cdot a_x + \alpha_{zy}\cdot a_y + \alpha_{zz}\cdot a_z,\end{aligned} \tag{1}$$

$$\begin{aligned}\delta\omega_x &= \beta_x + \beta_{xx}\cdot\omega_x + \beta_{xy}\cdot\omega_y + \beta_{xz}\cdot\omega_z\\ &\quad + (\beta_{xyx}a_x + \beta_{xyy}a_y + \beta_{xyz}a_z)\cdot\omega_y\\ &\quad + (\beta_{xzx}a_x + \beta_{xzy}a_y + \beta_{xzz}a_z)\cdot\omega_z,\\ \delta\omega_y &= \beta_y + \beta_{yx}\cdot\omega_x + \beta_{yy}\cdot\omega_y + \beta_{yz}\cdot\omega_z\\ &\quad + (\beta_{yxx}a_x + \beta_{yxy}a_y + \beta_{yxz}a_z)\cdot\omega_x\\ &\quad + (\beta_{yzx}a_x + \beta_{yzy}a_y + \beta_{yzz}a_z)\cdot\omega_z,\\ \delta\omega_{zx} &= \beta_z + \beta_{zx}\cdot\omega_x + \beta_{zy}\cdot\omega_y + \beta_{zz}\cdot\omega_z\\ &\quad + (\beta_{zxx}a_x + \beta_{zxy}a_y + \beta_{zxz}a_z)\cdot\omega_x\\ &\quad + (\beta_{zyx}a_x + \beta_{zyy}a_y + \beta_{zyz}a_z)\cdot\omega_y,\end{aligned} \tag{2}$$

where δa_i and $\delta\omega_i$ are accelerometer and gyro errors on the body frame, respectively. α_i is accelerometer bias, α_{ii} is accelerometer scale factor error, α_{ij} is accelerometer misalignment error ($i \neq j$), a_i is specific force on the body frame, β_i is gyro bias, β_{ii} is gyro scale factor error, and β_{ij} is gyro misalignment error ($i \neq j$). Also β_{ijk} is gyro flexure error, ω_i is absolute angular velocity and $i, j, k(= x, y, z)$ represents the body axes. Generally, the accelerometers and gyros include random errors. Though the random errors affect the performance of calibration, the calibration procedure excludes the infixed random errors. In this study, the gyro flexure errors are also not considered because the estimation of flexures leads to difficulty in the extraction of other gyro parameters. But the influence of flexures and random walk errors upon the estimation accuracy is analyzed.

3. MEASUREMENT MODEL FOR SDINS CALIBRATION

In the analysis of practical applications over a short period of time (1~3[min]), it is expedient to use the simplified SDINS error model [5,6]:

$$\begin{aligned}\delta\dot{v}_E &= -g\Phi_N(0) + \delta a_E + g\int_{t_0}^{t}\delta\omega_N dt,\\ \delta\dot{v}_N &= g\Phi_E(0) + \delta a_N - g\int_{t_0}^{t}\delta\omega_E dt,\\ \delta\dot{v}_U &= \delta a_U,\end{aligned} \tag{3}$$

where δv_E, δv_N, δv_U are velocity errors, Φ_E, Φ_N are attitude errors, δa_E, δa_N are acceleration errors, $\delta\omega_E$, $\delta\omega_N$ are angular velocity errors on the local-level frame and g is the gravitational constant. $\Phi_N(0)$, $\Phi_E(0)$ are initial horizontal misalignment errors. After the horizontal alignment procedure, the initial horizontal misalignment errors can be defined as follows:

$$\begin{aligned}\Phi_N(0) &= \frac{1}{g}(\alpha_x + \alpha_{xz}g),\\ \Phi_E(0) &= -\frac{1}{g}(\alpha_y + \alpha_{yz}g).\end{aligned} \tag{4}$$

Consider the rotation of IMU about the pitch (θ, x-axis) axis and the roll (γ, y-axis). From (3), (4) and the transformation matrix between the body and the local-level frame, the velocity measurement models can be derived as [3,5]:

$$\begin{aligned}\delta\dot{v}_E &= g\sin\theta\cdot\alpha_{xy} - g(1-\cos\theta)\cdot\alpha_{xz}\\ &\quad + g\sin\theta\cdot\beta_{yx} - g(1-\cos\theta)\cdot\beta_{zx}\\ &\quad + 0.25g^2[(1-\cos 2\theta)(\beta_{yxy} - \beta_{zxz})\\ &\quad + (2\theta + \sin 2\theta)\beta_{yxz} - (2\theta - \sin 2\theta)\beta_{zxy}],\end{aligned} \tag{5}$$

$$\begin{aligned}\delta\dot{v}_N &= (-1+\cos\theta)\cdot\alpha_y - \sin\theta\cdot\alpha_z\\ &\quad + g\cos\theta\sin\theta\cdot\alpha_{yy} - g(1-\cos^2\theta)\cdot\alpha_{yz}\\ &\quad - g\sin^2\theta\cdot\alpha_{zy} - g\cos\theta\sin\theta\cdot\alpha_{zz} - g\theta\cdot\beta_{xx},\end{aligned} \tag{6}$$

$$\begin{aligned}\delta\dot{v}_U &= \sin\theta\cdot\alpha_y + g\sin^2\theta\cdot\alpha_{yy} + g\sin\theta\cos\theta\cdot\alpha_{yz}\\ &\quad + \cos\theta\cdot\alpha_z + g\cos^2\theta\cdot\alpha_{zz} + g\sin\theta\cos\theta\cdot\alpha_{zy},\end{aligned} \tag{7}$$

$$\begin{aligned}\delta\dot{v}_E &= -(1-\cos\gamma)\cdot\alpha_x + \sin\gamma\cdot\alpha_z\\ &\quad - g\cos\gamma\sin\gamma\cdot\alpha_{xx} - g(1-\cos^2\gamma)\cdot\alpha_{xz}\\ &\quad - g\sin^2\gamma\cdot\alpha_{zx}\\ &\quad + g\cos\gamma\sin\gamma\cdot\alpha_{zz} + g\gamma\cdot\beta_{yy},\end{aligned} \tag{8}$$

$$\begin{aligned}\delta\dot{v}_N &= -g\sin\gamma\cdot\alpha_{yx} - g(1-\cos\gamma)\cdot\alpha_{yz}\\ &\quad - g\sin\gamma\cdot\beta_{xy} - g(1-\cos\gamma)\cdot\beta_{zy}\\ &\quad + \frac{g^2}{4}[(1-\cos 2\gamma)(\beta_{xyx} - \beta_{zyz})\\ &\quad + (2\gamma + \sin 2\gamma)\beta_{xyz} - (2\gamma - \sin 2\gamma)\beta_{zyx}],\end{aligned} \tag{9}$$

$$\delta\dot{v}_U = -\sin\gamma\cdot\alpha_x + g\sin^2\gamma\cdot\alpha_{xx} - g\sin\gamma\cos\gamma\cdot\alpha_{xz} + \cos\gamma\cdot\alpha_z + g\cos^2\gamma\cdot\alpha_{zz} - g\sin\gamma\cos\gamma\cdot\alpha_{zx}, \quad (10)$$

where (5)-(7) are the measurement models for pitch rotation and (8)-(10) represent the case of roll rotation. The measurement models ignore gyro biases and the earth rotation rate. This is because the influence of gyro biases can be neglected for a short period of time and the earth rate may be very small in comparison to $\dot{\theta}$, $\dot{\gamma}$.

4. SDINS CALIBRATION AND SIMULATION STUDY

The main problem of the calibration is to select an appropriate rotation angle in order to provide the proper observation of all gyro and accelerometer error parameters [1,3,5]. The initial positions for observation are defined in Fig. 1. The rotation angles and axes from each initial position are shown in Table 1. The initial positions and rotations are summarized in Table 2. The calibration parameters are summarized in Table 3. Consequently, the suggested procedures can provide the necessary observation of the parameters in Table 3. Table 3 indicates that the calibration parameters include the combined flexure errors, which are separated from other parameters. It should be noted that α_{xy}, α_{xz}, α_{yz} can be defined as zeros [1,3,4].

The measurement equations that are derived through Table 2 can be expressed in the matrix equation form as follows:

$$z = Hx, \quad (11)$$

where $z \in \mathbf{R}^{45}$ is an acceleration error vector on the local-level frame that is the slope of the velocity errors, $H \in \mathbf{R}^{45\times 24}$ is a measurement matrix and $x \in \mathbf{R}^{24}$ is an unknown calibration parameter vector. The calibration parameters, x can be calculated as follows:

$$x = (H^T H)^{-1} H^T z. \quad (12)$$

To analyze the estimation accuracy of calibration parameters, 30 Monte Carlo simulations are performed according to the following conditions:

- The horizontal alignment time is 60 [sec] in each initial position.
- The stored heading is 0 [deg].
- The rotation rate is 20 [deg/sec].

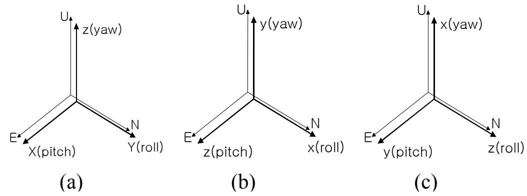

Fig. 1. Initial Positions.

Table 1. The rotation axis and the magnitude of angles.

Number	Axis	Angle
1	Pitch (θ)	90°
2	Pitch (θ)	180°
3	Pitch (θ)	360°
4	Roll (γ)	180°
5	Roll (γ)	360°

Table 2. Attitudes and rotations of IMU for calibration.

	Initial position			Rotation	Final position		
	x(θ)	y(γ)	z(ψ)	Axis & Angle	x(θ)	y(γ)	z(ψ)
1	E	N	U	x(θ) & 90°	E	U	S
2	E	N	U	x(θ) & 180°	E	S	D
3	E	N	U	x(θ) & 360°	E	N	U
4	E	N	U	y(γ) & 180°	W	N	D
5	E	N	U	y(γ) & 360°	E	N	U
	x(γ)	y(ψ)	z(θ)	Axis & Angle	x(γ)	y(ψ)	z(θ)
6	N	U	E	z(θ) & 90°	U	S	E
7	N	U	E	z(θ) & 180°	S	D	E
8	N	U	E	z(θ) & 360°	N	U	E
9	N	U	E	x(γ) & 180°	N	D	W
10	N	U	E	x(γ) & 360°	N	U	E
	x(ψ)	y(θ)	z(γ)	Axis & Angle	x(ψ)	y(θ)	z(γ)
11	U	E	N	y(θ) & 90°	S	E	U
12	U	E	N	y(θ) & 180°	D	E	S
13	U	E	N	y(θ) & 360°	U	E	N
14	U	E	N	z(γ) & 180°	D	W	N
15	U	E	N	z(γ) & 360°	U	E	N

Table 3. Calibration parameters.

Parameter	Unit	Specification	Parameter	Unit	Specification
α_x	$m/\sec^2$	Accelerometer Bias	β_{xy}	rad	Gyro Misalignment
α_y			β_{xz}		
α_z			β_{yx}		
α_{xx}	-	Accelerometer Scale Factor Error	β_{yz}		
α_{yy}			β_{zx}		
α_{zz}			β_{zy}		
α_{yx}	rad	Accelerometer Misalignment	$\beta_{yxz}-\beta_{zxy}$	rad/g	Gyro Flexure (is not used for calibration)
α_{zx}			$\beta_{zyx}-\beta_{xyz}$		
α_{zy}			$\beta_{xzy}-\beta_{yzx}$		
β_{xx}	-	Gyro Scale Factor Error	$\beta_{yxy}-\beta_{zxz}$		
β_{yy}			$\beta_{xzx}-\beta_{yzy}$		
β_{zz}			$\beta_{zyz}-\beta_{xyx}$		

Table 4. The estimation error (gyro biases are 1 σ = 0.5[deg/h], gyro random walks are 0.005[deg/hr$^{0.5}$], flexures are 1σ=10[asec/g] and instrument errors are 1σ=0.5[deg]).

Error element	Gyro		Accelerometer		
	scale factor [ppm]	misalignment [asec]	bias [μg]	scale factor [ppm]	misalignment [asec]
Applied error(1σ)	1000	360	1000	1000	360
Estimated error (1σ)	1.67433 1.70744 1.77592	2.8670 1.9969 1.3124 3.2069 1.3589 1.2775	3.0465 3.2985 3.6415	1.1174 1.0333 1.2924	2.3636 2.2185 2.6434

- The acquisition of velocity data is 60 [sec] in each final position.
- The acceleration errors are the average slopes of each velocity data.
- The sensors include the gyro random walks, the errors of (1) and (2). Moreover the orientations of instruments are not accurate.

Table 4 indicates the statistics of applied errors and estimation errors. In this case the estimation errors are very small in comparison with well-known run-to-run errors of high grade INS [3,4,6]. These results show that the accuracy of estimation is very precise and that other errors do not affect the accuracy.

5. GYRO BIAS ESTIMATION

In this study, an estimation approach of gyro bias is introduced by a close-loop self-alignment, which requires an additional control rate. The control rate includes the gyro errors that can be available for the estimation of gyro bias at a specific attitude.

The small misalignment errors in the alignment procedure are represented as follows [5-7]:

$$\begin{aligned}\dot{\Phi}_E &= -\omega_N^N \Phi_U + \omega_U^N \Phi_N + \Omega_E + \omega_E^c, \\ \dot{\Phi}_N &= -\omega_U^N \Phi_E + \omega_E^N \Phi_U + \Omega_N + \omega_N^c,\end{aligned} \tag{13}$$

where Φ_E, Φ_N, Φ_U are misalignment errors on the local level frame, ω_E^c, ω_N^c are control rates on the close-loop alignment, $\Omega_E, \Omega_N, \Omega_U$ are gyro biases on the local level frame, $\omega_E^N = 0$, $\omega_N^N = \Omega\cos\phi$ and $\omega_U^N = \Omega\sin\phi$ are earth rates on the level frame, and Ω, ϕ are absolute earth rate and latitude. After the calibration of the previous estimated parameters and the termination of the alignment procedure, the horizontal misalignment errors are sufficiently small. (13) is rewritten as follows:

$$\begin{aligned}\omega_E^c &= (\Omega\cos\phi)\Phi_U - (\Omega\sin\phi)\Phi_N - \Omega_E, \\ \omega_N^c &= (\Omega\sin\phi)\Phi_E - \Omega_N.\end{aligned} \tag{14}$$

The well-known alignment errors in steady state are as follows [5-7]:

$$\begin{aligned}\Phi_E(0) &= -\frac{A_N}{g}, \\ \Phi_N(0) &= \frac{A_E}{g},\end{aligned} \tag{15}$$

$$\Phi_U(0) = -\frac{\Omega_E}{\Omega\cos\phi} + \frac{A_E}{g}\tan\phi, \tag{16}$$

where A_E, A_N are accelerometer biases on the local level frame. If α_x, α_y, α_z are calibrated a priori and the body frame approximately coincides with the local-level frame, then A_E, A_N may be sufficiently small. (14) can be rewritten as follows:

$$\begin{aligned}\omega_E^c &= -2\Omega_E, \\ \omega_N^c &\approx -\Omega_N.\end{aligned} \tag{17}$$

As a result, the gyro biases on the local-level frame can be derived by the control rates with sufficient alignment time. However, the sensor errors of SDINS are defined on the body frame. The gyro bias using (17) is not equivalent to the body one because the body frame does not perfectly coincide with the local-level frame. Considering small angle approximation, the transformation matrix between the local-level and the body frame is given by the form [5,7]:

$$C_{ll}^B = \begin{bmatrix} 1 & \Phi_Z & -\Phi_Y \\ -\Phi_Z & 1 & \Phi_X \\ \Phi_Y & -\Phi_X & 1 \end{bmatrix}, \tag{18}$$

where Φ_X, Φ_Y, Φ_Z are small angles between the local-level and the body frame. The angular rates on the local-level frame include the earth rates, the gyro biases and the control rates. The difference in angular rates ($\Delta\omega_X$, $\Delta\omega_Y$, $\Delta\omega_Z$) between the body and the local-level frame can be calculated as follows:

$$\begin{bmatrix} \Delta\omega_X \\ \Delta\omega_Y \\ \Delta\omega_Z \end{bmatrix} = \begin{bmatrix} 1 & \Phi_Z & -\Phi_Y \\ -\Phi_Z & 1 & \Phi_X \\ \Phi_Y & -\Phi_X & 1 \end{bmatrix} \begin{bmatrix} -\Omega_E \\ \Omega\cos\phi \\ \Omega_U + \Omega\sin\phi \end{bmatrix}, \tag{19}$$

where Ω_U is up-direction gyro bias. Neglecting the second order terms, (19) can be rewritten as follows:

$$\begin{aligned}\Delta\omega_X &\approx \Omega\cos(\phi)\Phi_Z - \Omega\sin(\phi)\Phi_Y, \\ \Delta\omega_Y &\approx \Omega\sin(\phi)\Phi_X, \\ \Delta\omega_Z &\approx -\Omega\cos(\phi)\Phi_X.\end{aligned} \tag{20}$$

Generally, it is not complicated to achieve small horizontal angles (Φ_X, Φ_Y). On the other hand, it is difficult to maintain the small azimuth angle (Φ_Z). Consequently, y-axis bias can be exactly measured in comparison with other gyro biases as follows:

$$\beta_y \approx \omega_N^c. \tag{21}$$

Note that β_x and β_z can be estimated from the positions of Fig. 1(b) and Fig. 1(c). To minimize the effects of random errors and transient responses, the average value can be used:

$$\hat{\beta}_y = -\frac{1}{T - T_0}\int_{T_0}^{T} \omega_N^c dt, \tag{22}$$

where $T - T_0$ are the alignment times for gyro bias estimation. In order to attain better accuracy, a Kalman filter can be used. The Kalman filter is a more intellectual algorithm in comparison with the averaging due to the use of priory knowledge on measurement noise variance and the variance of a useful signal.

To analyze the performance, the suggested approach is compared with the raw measurement method through experiments.

The estimation procedure of gyro bias using the raw measurements is as follows. First, the IMU coincides with the local-level frame. The angular rate of the i-axis is expressed as follows [5]:

$$\omega_i^B(0) = \omega_{true} + \beta_i + f(\omega_{true}), \quad i = x, y, z, \tag{23}$$

where ω_{true} is actual angular rate and $f(\bullet)$ is gyro error relative to angular rate. Secondly, the i-axis rotates in 180[deg], then the angular rate of the i-axis becomes:

$$\omega_i^B(180) = -\omega_{true} + \beta_i - f(\omega_{true}), \quad i = x, y, z. \tag{24}$$

The i-axis gyro bias is estimated from the following formulation:

$$\beta_i = \frac{\omega_i^B(0) + \omega_i^B(180)}{2}, \quad i = x, y, z. \tag{25}$$

Table 5. The estimation results of gyro biases [deg/h].

	Case I	Case II	Case III
x-axis	-0.191671	-0.2225865	-0.197592
y-axis	-0.036624	-0.0535545	-0.034855
z-axis	-0.028228	-0.012273	-0.025745

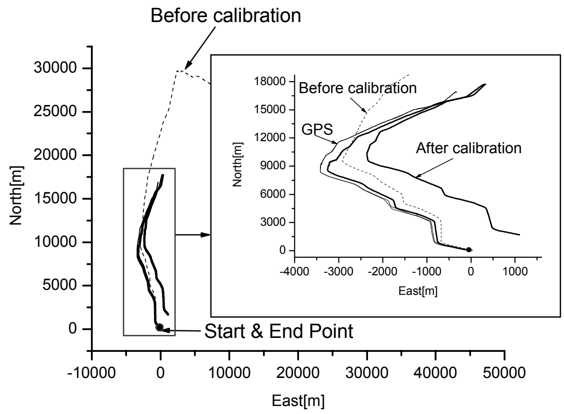

Fig. 2. The actual experiments of SDINS for calibration analysis 1.

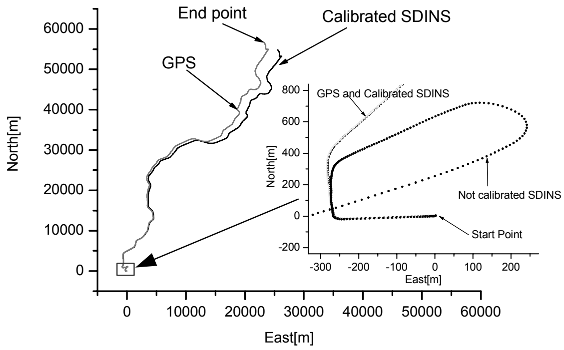

Fig. 3. The actual experiments of SDINS for calibration analysis 2.

This method requires an accurate rate table and obtains the measurements for a long period of time due to the small magnitude of the earth rotation rate and random errors. To analyze the estimation accuracy of gyro bias estimation, the experiments are performed as follows:

CASE 1: After the coarse alignment (160 sec), the proposed estimation is performed for 600 sec. In this case, the fine alignment of azimuth is not needed because the body coincides with the local-level frame as much as possible. T_0 is 200 sec.

CASE 2: The gyro biases are estimated by the raw measurement of 960(160+200+600) sec.

CASE 3: The gyro biases are estimated by the raw measurement of 3600 sec.

Table 5 presents the estimates of gyro bias in each case. CASE 3 appears reasonably better than other cases, since this case uses data acquired over a longer period of time. CASE 1 shows more similar results to CASE 3 than CASE 2. This implies that the proposed scheme is effective for the estimation of gyro bias.

6. IMPROVEMENT OF SDINS ACCURACY

In this study, the effectiveness of the proposed calibration technique is attained by the van tests. The test results do not include the effect of flexures because we are unfamiliar with the flexures of test SDINS. Therefore the calibrated SDINS includes the navigation errors by the flexures. The test results show the influence of the calibration of other parameters rather than the flexures. Generally, the effect of flexures is small in the land navigator.

Figs. 2 and 3 indicate that the performance of SDINS compared to GPS results is remarkably improved by the suggested calibration procedure. Fig. 2 demonstrates when the test van with SDINS returns to the starting point. Fig. 3 shows when the navigation time is comparatively long. Consequently, the importance of the calibration procedure can be emphasized by these experimental results.

7. CONCLUSION

The goal of calibration is to estimate unknown constant errors and to compensate for these errors. In this study, the calibration techniques to estimate SDINS error parameters are proposed. The first calibration procedure that is estimated by the velocity (acceleration) indications of SDINS navigation is to select the positions and rotations to minimize gyro flexure effects. The second estimation of gyro biases is derived through the control rates of SDINS alignment. The accuracy of estimation has been verified by simulations. The experiments illustrate that the extracted calibration parameters using the proposed scheme are highly effective for the improvement of SDINS performance.

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