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IMU error calibration of strapdown inertial navigation system

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Abstract

In view of the accuracy of strapdown inertial navigation system to the turntable, the difficulty of installation leveling and North alignment, as well as the various factors such as temperature rise, temperature change of hardware circuit board and components for a long time, the IMU is proposed to take the reference north angle, roll angle and pitch angle of the three-axis turntable as the reference, the actual movement speed of the system as the observation measurement, and the minimum is adopted Two multiplication fitting system level calibration algorithm, through three axis turntable multi-position static measurement, rotation angle measurement, rapid measurement of 24 parameters such as installation error and orthogonal error of inertial unit, sensor zero deviation, scale factor, etc., the system level calibration time is not more than 2h, and the course and attitude progress is better than 0.012°. This method is not only convenient and simple, but also convenient to improve the system accuracy and rapid batch production.

Keywords: IMU; Zero Bias; Installation Error; Least Square Method; Three Axis Turntable;

1. INTRODUCTION

The IMU of laser gyro strapdown inertial navigation system is composed of three laser gyroscopes and three accelerometers. Its non orthogonal installation, sensor bias, scale factor and other errors directly affect the accuracy of the system. Therefore, IMU error calibration is a very important link in the development and use of strapdown inertial navigation system. At home and abroad, discrete calibration method and system level calibration method are often used. The discrete calibration method needs to provide the attitude reference [1] through the precise test equipment, take the earth's rotation speed, gravity acceleration and rotation platform angular speed as the reference quantity, and compare with the actual output of gyroscope and accelerometer, so as to solve various error coefficients, but when the laser gyroscope works, it will produce jitter itself, thus affecting the calibration accuracy. The system level calibration method mainly uses the output of the inertial instrument to solve the navigation problem, and takes the navigation error as the observation measurement to determine the error parameters, avoiding the use of the precision instrument, but its calculation is large, the filtering algorithm is complex, and the calibration time is long [2].

In view of the shortcomings of the above two methods, as well as the difficulty of the turntable in the process of calibration to the north and to adjust equally [3], this paper proposes a system level multi position 24 parameter calibration method, which can identify all the parameters through the rotating position of the manual or automatic three-axis turntable, and the whole calibration process takes about 2 hours. This method takes velocity as the observation measurement, uses the least square method to calibrate 24 parameters, such as the orthogonal installation of three-axis laser gyro and accelerometer, sensor bias, scale factor, etc. its algorithm is simple and efficient, and improves the accuracy of the system IMU.

2. IMU ERROR MODEL BUILDING

There are errors in the mechanical installation of the three laser gyroscopes and three accelerometers of the main components of the laser gyro strapdown inertial navigation system. The laser gyro coordinate system and the accelerometer sensor itself cannot be completely orthogonal in the engineering installation, and there is a certain deflection angle [4]. The two coordinate systems of laser gyroscope and accelerometer can not overlap completely, and they are also non orthogonal error sources. In addition, the output value of the angular velocity of the laser gyro fixed on the turntable rotating 360 ° is inconsistent with the theoretical value, and the output value of the accelerometer in the positive and negative directions is inconsistent with the corresponding value of the theoretical value, so the calibration factor needs to be calibrated; at the same time, the output value of the sensor in the zero position has errors. The system level calibration with the least square fitting method is adopted. Through the three-axis turntable with multiple positions: static rotation static [5], the laser gyro strapdown inertial navigation system remains static in the fixed position. After the initial heading is given and the calibration preparation is completed, it rotates or rotates to the designated position according to the pre-designed direction. After the system remains static, the data of the system is measured. The test time is t, and through observation The change of the system speed and the change of the sensor in the process of rotation are measured, 24 error parameters are calibrated, and a total of 14 steps are carried out.

In the calibration process, the northeast sky coordinate system is defined as the reference coordinate system [4], and the error equation of laser gyro is:

$$\begin{cases} \omega_{tx} = b_{11}\omega_x + b_{12}\omega_y + b_{13}\omega_z - B_{01} \\ \omega_{ty} = b_{21}\omega_x + b_{22}\omega_y + b_{23}\omega_z - B_{02} \\ \omega_{tz} = b_{31}\omega_x + b_{32}\omega_y + b_{33}\omega_z - B_{03} \end{cases} \quad (1)$$

Formula: ω_{tx}、ω_{ty}、ω_{tz} is the output angular velocity of the laser gyro after the calibration parameters are brought in; B_{01}、B_{02}、B_{03} is the laser gyro bias; b_{11}、b_{22}、b_{33} is the laser gyro scale factor, also known as the scale factor; b_{12}、b_{13}、b_{21}、b_{23}、b_{31}、b_{32} is the installation error of the laser gyro.

The error equation of accelerometer is:

$$\begin{cases} a_{tx} = a_{11}a_x + a_{12}a_y + a_{13}a_z - A_{01} \\ a_{ty} = a_{21}a_x + a_{22}a_y + a_{23}a_z - A_{02} \\ a_{tz} = a_{31}a_x + a_{32}a_y + a_{33}a_z - A_{03} \end{cases} \quad (2)$$

Formula: A1 is the speed increment of the accelerometer output after the calibration parameters are brought in; A2 is the accelerometer bias; A3 is the accelerometer scale factor, also known as the accelerometer scale factor; A4 is the accelerometer installation error.

3. IMU calibration scheme design

After the inertial components of the laser gyro strapdown inertial navigation system are installed in the fixed box structure, due to various errors, three laser gyro and three accelerometers have certain error angles with the northeast of the theoretical coordinate system. The system is fixed on the calibrated three-axis turntable, and the installation error of laser gyro and acceleration and turntable error are controlled within 3 '. The error between the actual position of IMU and the theoretical value of navigation coordinate system is shown in Figure 1. Definition of IMU and navigation coordinate system: $E_1N_1U_1$ is the actual position of the inertial combination of laser gyro strapdown navigation system; ENU is the navigation coordinate system of northeast sky, and there is a certain deviation angle between them. The system is fixed on the manual three-axis turntable as shown in Figure 2.

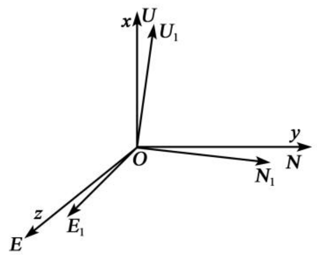

Figure 1. Comparison between IMU component installation and theoretical coordinate system

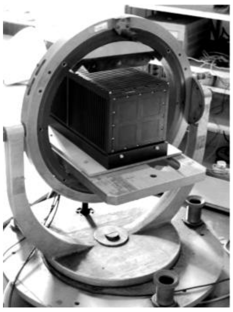

Figure 2. The system is fixed on the manual three-axis turntable

The IMU speed error is:

$$\begin{aligned}\delta\dot{V}^n &= -\phi^n \times f^n - (-2\omega_{ie}^n + \omega_{en}^n)\times\delta V^n \\ &\quad - (2\delta\omega_{ie}^n + \omega_{en}^n)\times V^n + C_b^c\delta f^b\end{aligned} \quad (3)$$

During the calibration process, the system does not displace, so, $V^n = 0, \omega_{en}^n = 0$ 。

The rotation velocity of the earth is very small compared with that of the turntable , $-2\omega_{ie}^n \times \delta V^n$ ignored，So the velocity error equation is：

$\delta \dot{V}^{n} = -\phi^{n} \times f^{n}$ (4)

Before IMU calibration, the fixed system shall be installed, and the initial position of the turntable shall be aligned with the north direction, that is, the turntable shall be fixed at 0 degrees position, and the system heading, roll and pitch shall be aligned with 0 degrees. Pre installed 24 calibration parameters, the scale factor of x axis, y axis, z axis laser gyro is 0.932920, the scale factor of x axis, y axis, z axis accelerometer is 1.0, and the initial value of other parameters is 0. The data acquisition period τ = 5 ms, that is, τ = 0.005 s for three laser gyroscopes and three accelerometers. When each position is stationary, the data acquisition period is 100s, that is, the acquisition number n = 20000, ΔV_{e1} and ΔV_{e2} are the eastward velocity at T1 and T2, and the constant K = 180/π. The steps of IMU calibration are as follows:

1) Calibrate the scale factors a_{11}, a_{22} and a_{33} of the accelerometer, and zero bias A_{01}, A_{02} and A_{03}. First, fix the system, rotate the three-axis turntable to the position of heading 0 degrees, roll 0 degrees, pitch 0 degrees, and keep the system still. Given the heading 0 degrees, collect the data for 100s after the north seeking is completed. Then, slowly and uniformly rotate 90 degrees along the pitch direction, i.e., rotate the pitch from 0 degrees to 90 degrees, keep the static collection data for 100s. then rotate -180 degrees in the pitch direction, rotate to -90 degrees, collect the data for 100 s. Then rotate 90 degrees in the pitch direction to 0 degrees , rotate 90 degrees in the roll direction to 90 degrees , and collect data for 100s; rotate -180 degrees in the roll direction, that is, rotate the roll from 90 degrees to -90 degrees , collect data for 100s; finally return to the initial position. The position of the system on the three-axis turntable is shown in Figure 3 to figure 7 in turn, and finally returns to figure 3. The heading, roll and pitch are respectively represented by H, R and P.

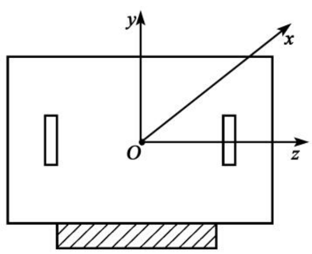

Figure 3. H=0° R=0° P=0°

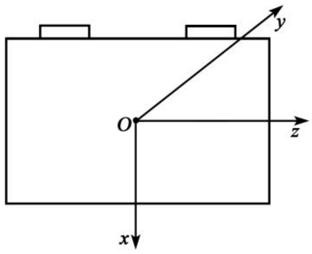

Figure 4. H=0° R=0° P=+90°

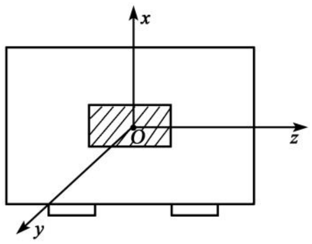

Figure 5. H=0° R=0° P=-90°

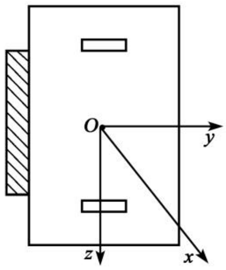

Figure 6. H=0° R=+90° P=0°

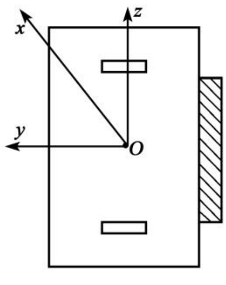

Figure 7. H=0° R=0° P=-90°

The bias parameter and accelerometer scale factor are as follows:

$$\begin{cases} A_{01} += (\sum_{i=1}^{20000} a_{x\_p(i)} + \sum_{i=1}^{20000} a_{x\_m(i)}) / T_{100} / 2 \\ A_{02} += (\sum_{i=1}^{20000} a_{y\_p(i)} + \sum_{i=1}^{20000} a_{y\_m(i)}) / T_{100} / 2 \\ A_{03} += (\sum_{i=1}^{20000} a_{z\_p(i)} + \sum_{i=1}^{20000} a_{z\_m(i)}) / T_{100} / 2 \end{cases} \quad (5)$$

$$\begin{cases} a_{11} = a_{11} / ((\sum_{i=1}^{20000} a_{x\_p(i)} - \sum_{i=1}^{20000} a_{x\_m(i)}) / T_{100} / 2) \\ a_{22} = a_{22} / ((\sum_{i=1}^{20000} a_{y\_p(i)} - \sum_{i=1}^{20000} a_{y\_m(i)}) / T_{100} / 2) \\ a_{33} = a_{33} / ((\sum_{i=1}^{20000} a_{z\_p(i)} - \sum_{i=1}^{20000} a_{z\_m(i)}) / T_{100} / 2) \end{cases} \quad (6)$$

Formula: a_{x_p} , a_{y_p} and a_{z_p} are the corresponding accelerometer 90 degrees position measurement values; a_{x_m} , a_{y_m} and a_{z_m} are the corresponding accelerometer -90 degrees position measurement values; the sensor data acquisition cycle of laser gyro strapdown inertial navigation system is 5ms, and the data measurement time of each position is T_{100} equals 100s.

2) Calibrate the scale factor n_{11} of the x-axis laser gyro. The system rotates to the position of heading 0 degrees, roll 0 degrees, pitch 0 degrees and remains still (see Figure 3); then the given heading is 0 degrees, after initialization, the system rotates slowly and uniformly 360 degrees along the pitch direction and collects data for 100s; then it rotates slowly and uniformly -360 degrees along the pitch direction, i.e. returns to the starting position and collects data for 100s.

$$n_{11} = n_{11}(1.0 - ((\Delta V_{e1} - \Delta V_{e2}) / 2) / (2\pi \times g \times T_{100} \times \tau) \quad (7)$$

3) Calibrate the scale factor n_{33} of z-axis laser gyro. The system rotates to the position of heading -90 degrees, roll 0 degrees, pitch 0 degrees, and remains stationary, as shown in Figure 8. When the given heading is -90 degrees and initialization is completed, the data shall be collected for 100 seconds by slowly and uniformly rotating 360 degrees along the pitch direction; then the data shall be collected for 100s by slowly and uniformly rotating -360 degree along the pitch direction, and then returned to the initial position.

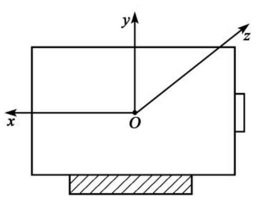

Figure8. H=-90° R=0° P=0°

$n_{33} = n_{33}(1.0 - ((\Delta V_{e1} - \Delta V_{e2})/2)/(2\pi \times g \times T_{100} \times \tau)$ (8)

4) Calibrate the scale factor n_{22} of y-axis laser gyro. The system rotates to the position of heading -90 degrees, roll -90 degrees, pitch 0 degrees and remains stationary, i.e. from the initial position (see Figure 8) to the calibration preparation position (see Figure 9). The given heading is -90 degrees, after initialization, the data will be collected for 100s by slowly and uniformly rotating 360 degrees along the pitch direction, and then slowly and uniformly rotating -360 degrees along the pitch direction, and the data will be collected for 100s, and then return to the initial position.

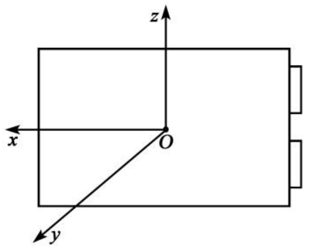

Figure9. H=-90° R=-90° P=0°

$n_{22} = n_{22}(1.0 - ((\Delta V_{e1} - \Delta V_{e2})/2)/(2\pi \times g \times T_{100} \times \tau)$ (9)

5) Calibrate the zero deviation A_{03} of z-axis accelerometer. The system rotates to the position of heading 0 degrees, roll 0 degrees, pitch 0 degrees, and remains still. Then the heading 0 degrees is given. After initialization, the system slowly and uniformly rotates 180 degrees along the roll direction and collects data for 100s; then it slowly and uniformly rotates -180 degrees along the roll direction and returns to the initial position and collects data for 100s; then it continues to slowly and uniformly rotate -180 degrees along the roll direction and collects data for 100s. Then slowly and uniformly rotate 180 degrees along the rolling direction to return to the initial position.

$A_{03} - = [(\Delta V_{e1} + \Delta V_{e2})/2]/(2 \times g \times T_{100})$ (10)

6) Calibrate the zero deviation A_{01} of x-axis accelerometer. The system rotates to the position of heading - 90 degrees, roll 0 degrees, pitch 0 degrees, and remains still. Given the heading - 90 degrees, after initialization, the system slowly and uniformly rotates 180 degrees along the pitch direction and collects data for 100s; then it slowly and uniformly rotates -180 degrees along the pitch direction and returns to the initial position and collects data for 100s; then it continues to slowly and uniformly rotate -180 degrees along the pitch direction and collects

data for 100s; then it rolls along the roll direction Slowly and uniformly rotate 180 degrees to return to the initial position.

$$A_{01} + = [(\Delta V_{e1} + \Delta V_{e2}) / 2] / (2 \times g \times T_{100}) \quad (11)$$

7) Calibrate the zero deviation A_{02} of y-axis accelerometer and the installation error a_{23} of y-axis accelerometer and z-axis accelerometer. The system rotates to the position of heading 0 degrees, roll 0 degrees, pitch 0 degrees and remains still. Then the heading 0 degrees is given. After initialization, the system slowly and uniformly rotates 90 degrees along the roll direction and collects data for 100s. Then it slowly and uniformly rotates -90 degrees along the roll direction and returns to the initial position and collects data for 100s. Then it continues to slowly and uniformly rotate -90 degrees along the roll direction and collects data for 100s. Finally, slowly and uniformly rotate 90 degrees along the rolling direction to return to the initial position.

$$A_{02} + = [(\Delta V_{e1} - \Delta V_{e2}) / 2] / (2 \times g \times T_{100}) \quad (12)$$

$$a_{23} + = ((\Delta V_{e1} + \Delta V_{e2}) / (2 \times g \times T_{100})) \quad (13)$$

8) Calibrate the installation error a_{12} of x-axis accelerometer and y-axis accelerometer. The system rotates to the position of heading -90 degrees, roll 0 degrees, pitch 0 degrees, and remains still. Then the given heading - 90 degrees is given. After initialization, the system slowly and uniformly rotates 90 degrees along the pitch direction and collects data for 100s; then slowly and uniformly rotates -90 degrees along the pitch direction and returns to the initial position and collects data for 100s. Then continue to slowly and uniformly rotate -90 degrees along the pitch direction to collect data for 100s; then slowly and uniformly rotate 90 degrees along the pitch direction to return to the initial position.

$$a_{12} - = ((\Delta V_{e1} + \Delta V_{e2}) / (2 \times g \times T_{100})) \quad (14)$$

9) Calibrate the installation error of x-axis accelerometer and z-axis accelerometer a_{13}. The system rotates to the position of heading -90 degrees, roll -90 degrees and pitch 0 degrees to keep still, and then gives the heading -90 degrees. After initialization, the system slowly and uniformly rotates 90 degrees along the pitch direction (around the y-axis), and collects data for 100 s; then slowly and uniformly rotates -90 degrees along the pitch direction, and returns to the initial position to collect data for 100 s. Then continue to slowly and uniformly rotate -90 degrees along the pitch direction to collect data for 100s; finally, slowly and uniformly rotate 90 degrees along the pitch direction to return to the initial position.

$a_{13}- = ((\Delta V_{e1} + \Delta V_{e2})/(2\times g\times T_{100}))$ (15)

10) The installation errors of y-axis laser gyro and x-axis laser gyro are n_{21} and n_{31} respectively. The system rotates to the position of heading -90 degrees, roll 0 degrees, pitch 0 degrees, and remains still. Then the given heading is -90 degrees. After initialization, the system slowly and uniformly rotates 90 degrees along the roll direction and collects data for 100s; then it slowly and uniformly rotates -90 degrees along the roll direction and returns to the initial position and collects data for 100s; then it continues to slowly and uniformly rotate -90 degrees along the roll direction and collects data for 100s. Finally, slowly and uniformly rotate 90 degrees along the rolling direction to return to the initial position.

$n_{21}- = ((\Delta V_{e1} + \Delta V_{e2})/(2\times g\times T_{100}))$ (16) $n_{31}- = ((\Delta V_{e1} + \Delta V_{e2})/(2\times g\times T_{100}))$ (17)

11) The installation errors of the x-axis laser gyro and the y-axis laser gyro are n_{12} and n_{32} respectively. The system rotates to the position of heading -90 degrees, roll 0 degrees, pitch 0 degrees, and remains still, then gives the heading -90 degrees. After initialization, it slowly and uniformly rotates 90 degrees along the heading direction and collects data for 100s; then it slowly and uniformly rotates -90 degrees along the heading direction and returns to the initial position and collects data for 100s; then it continues to slowly and uniformly rotate -90 degrees along the heading direction and collects data for 100s. Finally, slowly and uniformly rotate 90 degrees along the heading direction to return to the initial position.

$n_{32}+ = ((\Delta V_{e1} + \Delta V_{e2})/(2\times g\times T_{100}))$ (18)

$n_{12}+ = ((\Delta V_{e1} + \Delta V_{e2})/(2\times g\times T_{100}))$ (19)

12) The installation errors of y-axis laser gyro and z-axis laser gyro are calibrated to be n_{23}, and that of x-axis laser gyro and z-axis laser gyro to be n_{13}.The system rotates to the position of heading 0 degrees, roll 0 degrees, pitch 0 degrees, and remains still, and then sets the heading 0 degrees. After initialization, the system slowly and uniformly rotates 90 degrees along the pitch direction and collects data for 100s; then slowly and uniformly rotates -90 degrees along the pitch direction and returns to the initial position and collects data for 100s; then continues to slowly and uniformly rotate -90 degrees along the pitch direction and collects data for 100s. Finally, slowly and uniformly rotate 90 degrees along the pitch direction to return to the initial position.

$n_{23}+ = ((\Delta V_{e1} + \Delta V_{e2})/(2\times g\times T_{100}))$ (20)

$n_{13} += ((\Delta V_{e1} + \Delta V_{e2})/(2 \times g \times T_{100}))$ (21)

13) Calibrate the bias N_{01} of x-axis laser gyro, N_{02} of y-axis laser gyro and N_{03} of z-axis laser gyro. The system rotates to the position of heading 0 degrees, roll 0 degrees and pitch 0 degrees to keep still, and then gives the heading 0 degrees. After initialization, keep still to collect data for 600s, and the system automatically calculates the zero deviation N_{01}, N_{02} and N_{03} of the X -, Y - and z-axis laser gyro as follows:

$N_{01} += 3600 \times K \times V_e / 2\mathrm{R}$ (22)

$N_{02} -= 3600 \times K \times \psi / T_{10}$ (23)

$N_{03} -= 3600 \times K \times V_n / 2R$ (24)

Formula: R is the long half axis of the earth; V_e is the East speed; V_N is the North speed; T10 = 600s.

14) Calibrate the bias N_{02} and N_{03} of y-axis and z-axis laser gyro. The system rotates to the position of heading - 90 degrees, roll 0 degrees, pitch 0 degrees and keeps still, then gives the heading -90 degrees, and after initialization, keeps still to collect data for 600s. based on the thirteen steps, the system automatically calculates the zero deviation N_{02} and N_{03} of Y-axis and z-axis laser gyro as follows:

$N_{02} -= 3600 \times K \times ((\psi - ik0 / K) / T_{10})$ (25)

$N_{03} += 3600 \times K \times V_e / 2R$ (26)

Formula: ψ is the heading at the time of data acquisition; ik0 = - 90° is the given initial heading.

4. IMU error calibration and application of strapdown inertial navigation system

IMU of strapdown inertial navigation system adopts three-axis laser gyro and three-axis quartz accelerometer components, and its system accuracy is verified by using high-precision three-axis digital display turntable to verify the attitude repeatability and orthogonality.

4.1 IMU error calibration of strapdown inertial navigation system

The IMU of strapdown inertial navigation system is installed and fixed on the three-axis turntable. The IMU heading is fixed according to the turntable's heading. After the initialization of the system's starting heading is completed, 24 parameters are calibrated according to the above 14 steps, and parameter files are automatically generated and written into the configuration files. Each time the system opens 24 configuration files are automatically read and loaded into the corresponding parameters. See Table 1 for details.

Table 1. Comparison between initial value of IMU calibration and calibration completion parameters

number	*Calibration parameter*	*variable*	*Calibration results*
1	Zero deviation of x-axis laser gyro(°/h)	N_{01}	-0.078921
2	Zero deviation of y-axis laser gyro(°/h)	N_{02}	+0.025013
3	Zero deviation of z-axis laser gyro	N_{03}	+0.084675
4	Zero deviation of x-axis accelerometer(g)	A_{01}	+0.003576
5	Zero deviation of y-axis accelerometer(g)	A_{02}	-0.0016021
6	Zero deviation of z-axis accelerometer(g)	A_{03}	-0.0059875
7	X-axis laser gyro scale factor	n_{11}	+0.932978
8	X-axis laser gyro installation error	n_{12}	+0.001801
9	X-axis laser gyro installation error	n_{13}	-0.000801
10	Y-axis laser gyro installation error	n_{21}	-0.001657
11	Y-axis laser gyro scale factor	n_{22}	+0.932801
12	Y-axis laser gyro installation error	n_{23}	+0.000914
13	Z-axis laser gyro installation error	n_{31}	+0.000510
14	Z-axis laser gyro installation error	n_{32}	-0.004321
15	Z-axis laser gyro scale factor	n_{33}	+0.932801
16	X-axis accelerometer scale factor	a_{11}	+0.980101
17	X-axis accelerometer installation error	a_{12}	+0.000801
18	X-axis accelerometer installation error	a_{13}	-0.000330
19	Y-axis accelerometer installation error	a_{21}	+0.000000
20	Y-axis accelerometer scale factor	a_{22}	+1.080798
21	Y-axis accelerometer installation error	a_{23}	+0.000986
22	Z-axis accelerometer installation error	a_{31}	+0.000000
23	Z-axis accelerometer installation error	a_{32}	+0.000000
24	Z-axis accelerometer scale factor	a_{33}	+0.953105

Note: except the marked calibration parameters have units, the rest are dimensionless.

4.2 IMU accuracy verification of strapdown inertial navigation system

The error of the three-axis high-precision digital display turntable is better than 0.0001 degrees, Level the high-precision digital display turntable, fix the IMU on the turntable [6], prepare for the corresponding test, turn on the power to seek the North twice and take the average value, set it as the initial value of the scale of the three-axis high-precision digital display turntable, and automatically seek the north four times for each quadrant, as shown in table 2-5.

Table 2. test data of 0°, 90°,180°and 270°position of turntable. unit: °

number	*0°*			*90°*			*180°*			*270°*		
	Head	Roll	Pitch	Head	Roll	Pitch	Head	Roll	Pitch	Head	Roll	Pitch
1	0.010329	0.002115	-0.001641	90.009189	0.002678	0.000563	180.000315	0.001952	0.002138	270.005671	0.003548	0.002896
2	-0.010653	0.002893	-0.001273	90.007654	0.002018	0.000781	180.000363	0.001631	0.003159	270.005751	0.003179	0.002765
3	-0.005672	0.003542	-0.002101	89.999781	0.002671	0.000603	180.000403	0.002152	0.001876	270.006012	0.003019	0.002514
4	0.002389	0.003679	-0.001978	90.0032167	0.0030189	0.000451	180.000158	0.0019871	0.002819	270.005138	0.003998	0.003065
average value	-0.000902	0.003057	-0.00175	90.00496	0.002596	0.0006	180.0003	0.001931	0.002498	270.0056	0.003436	0.00281
Mean square deviation	0.0092159	0.000716	0.000372	0.004282	0.000418	0.000137	0.000107	0.000218	0.000593	0.000367	0.000435	0.000232

4.3 Verify the stability of IMU of strapdown navigation system

The IMU of laser gyro strapdown inertial navigation system is fixed on the chassis of the vehicle body [7], and the central axis of the vehicle body is roughly consistent with the central axis of the vehicle body. The experimental vehicle is equipped with a high-precision azimuth extraction device and a digital level, without accumulated error. The accuracy of the azimuth extraction device is higher than 0.006 degrees, the course stability is verified; the accuracy of the digital level is better than 0.0006 degrees. After the initialization of IMU, the binding initial heading value of azimuth extraction device and the binding roll and pitch value of digital level are consistent with the initial value of IMU equipment. The closed-loop sports car test results in a certain place are shown in Table 3.

Table 3. test data of 270 ° position of turntable. unit: °

number	*IMU*			*Azimuth lead*	*Digital level*		*error*		
	Head	Roll	Pitch	Head	Roll	Pitch	Head	Roll	Pitch
1	20.186751	0.009256	-0.017475	20.186751	0.009256	-0.017475	0.000000	0.000000	0.000000
2	74.261759	0.017019	0.052811	74.262023	0.017211	0.052833	-0.000264	-0.000192	-0.000022
3	156.123621	0.009978	0.039101	156.124101	0.009981	0.039131	-0.000480	-0.000003	-0.000030
4	254.556781	0.019298	0.029012	254.557014	0.019301	0.029112	-0.000233	-0.000003	-0.000100
5	246.017871	0.008066	-0.027013	246.018541	0.008054	-0.027128	-0.000670	0.000012	0.000115
6	20.017897	0.012601	-0.013012	20.017913	0.012871	-0.014151	-0.000016	-0.000270	0.001139

From the test data in Table 3, it can be seen that the heading stability is better than 0.009 degrees and the roll and pitch accuracy is better than 0.06 degrees.

5. Concluding remarks

In this paper, the IMU error calibration method based on the laser gyro strapdown inertial navigation system is proposed, which solves the difficulties of the system calibration due to the accuracy of the turntable, the alignment of the base to the north and the leveling, the dithering of the laser gyro, the rise of the working temperature for a long time and the complexity of the algorithm. The system level calibration method based on the IMU output speed is proposed Through multi position measurement of three-axis turntable: static rotation static, 24 error parameters such as orthogonal installation error of three-axis laser gyro and three-axis accelerometer, zero deviation of sensor and scale factor are identified quickly. The calibration process is shortened to 2 hours, and the attitude accuracy is better than 0.012 degrees. The experiment shows that the algorithm is simple and the operation process is convenient. It can effectively solve the influence of turntable error on IMU calibration accuracy, thus improving the accuracy of laser gyro strapdown inertial navigation system and providing reference value for IMU error calibration.

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