Technique of constructing a measuring base for determining the azimuthal attitude of the dynamic test-bench Actidyn “ST2356C”

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Abstract. Calibration of inertial sensors is one of the most important tasks in the development of inertial navigation systems. The solution to this problem is impossible without achieving the required level of accuracy of dynamic modeling test-benches used in their development. The paper describes a technique of constructing a measuring base for determining the azimuthal attitude of the precision dynamic test-bench. This technique uses industrial geodesy technologies for providing ability to calibrate all major types of modern inertial measuring units in a wide temperature range. The azimuthal attitude determining is based on measuring the angular attitude of the mirror placed on the test-bench’s turntable by an autocollimation measurements technique by using a high-precision reflectorless total station, the coordinates of which are determined by rangefinder-goniometric measurements to reflectors with known coordinates, mounted on the room's walls. The calculation results show that the proposed technique of constructing a measuring base allows to ensure the measurement accuracy for carrying out research and calibration of highly accuracy inertial measuring systems.

1. Introduction

The calibration of measuring sensors of inertial reference systems (IRS), performed using precision reference dynamic simulators equipped with climatic chamber, is the main way to validate their required accuracy performance at the stages of development, production and operation [1-6].

In the Moscow Aviation Institute based "Inertial reference system research and testing laboratory" witch engaged to research in the field of avia-space systems. The laboratory has research equipment that provides calibration of the main types of IRS in the full operating temperature range. The laboratory includes a high-precision biaxial dynamic test-bench Actidyn “ST2356C”™ (Actidyn Systemes, France), equipped with a climatic chamber (figure 1), designed for calibrating inertial navigation and orientation systems and properties study of its inertial sensors in wide temperature range. The test-bench is capable to create a complex highly dynamic motion trajectory for inertial orientation algorithms properties study.
Information about the exact angular azimuthal attitude of the dynamic test-bench is one of the most important parameters required for researching of IRS and gyro sensors. Usually, for the attitude determination, additional autocollimation optical equipment is used, which is stationary placed on the fixed base in front of dynamic stand's turntable [7-10]. The placement of additional autocollimation equipment in close proximity to dynamic simulators is difficult for many test laboratories equipped a similar test-benches. In paper is proposed a method for constructing a measuring basis of azimuthal attitude which does not require permanent placement of additional measuring optical equipment in front of the turntable of the dynamic testbench. The proposed technique of constructing a measuring base allows to ensure the measurement accuracy for carrying out research and calibration of highly accuracy IRS.

2. Methodology
The dynamic test-bench, providing ability to calibrate the inertial measuring sensors and systems based on them at various temperatures. The main technical characteristics are shown in table 1. The periodic measurements of the azimuthal orientation of the test-bench rotation axes with the maximum reachable accuracy is required for providing the possibility of carrying out a full range of tests of IRS of various accuracy classes.

| Parameter                        | Inner axis | Outer axis |
|----------------------------------|------------|------------|
| Payload mass [kg]                | 100        |            |
| Payload diameter [mm]            | 600        |            |
| Payload height [mm]              | 540        |            |
| Orthogonality of rotation table [arc sec.] | ±2         |            |
| Wobble of rotation table [arc sec.] | from ±1 to ±2 | ±1        |
| Position accuracy [arc sec.]     | ±1         |            |
| Position command increment [arc sec.] | ±0.036        | ±0.2      |
| Rate range [deg./sec.]           | ±1800      | ±600       |
| Rate accuracy [%]                | ±0.001     | ±0.05      |
| Rate command increment [deg./sec.] | 0.00001    |            |
| Rate speed stability [%]         | from 0.05 to 0.0001 |            |
| Temperature range [°C]           | from -55 to +85 | ±1        |
| Temperature stability [°C]       |            | ±1         |
The dynamic test-bench is mounted at the ground floor of the building on the highly stability monolithic reinforced concrete base, located on an anti-vibration sand and gravel cushion at the bottom of a waterproof reinforced concrete well. Figure 2 shows the laboratory room with layout of the test-bench.

Figure 2. Layout of the test-bench Actidyne “ST2356C” in the laboratory.

The technological features of dynamic test-bench exploitation, as well as the peculiarities of its location in a room with a limited area, impose a number of restrictions, the most critical of which are:

- inability to sight the mirror, placed on the turntable of the test-bench, with the use of an electronic total station outside the room (building);
- the inability to open the door of the test-bench’s climatic chamber when the electric drive of the external axis of rotation is on;
- the impossibility of installing a column for placing a reference measuring device in front of the turntable of the test-bench to ensure sighting of the mirror placed on the turntable;
- small distance from the optical measuring device to the turntable of the dynamic test-bench.

The most expedient from the point of view of technical feasibility way of constructing a measuring base for determining the test-bench's azimuthal attitude was chosen with taking into account above restrictions. This way consists in determining azimuthal orientation of the geodetic mirror placed on the turntable of the test-bench by an autocollimation method with using an electronic total station.

The electronic total station Leica “TS 06 plus R500 (1 “EGL)”TM (Leica Geosystems AG, Switzerland) is chosen as most preferable measuring system. The point in front of the door of the test-bench climatic chamber was chosen as a place for location electronic total station, as shown at figure 2.

Since it is not technically possible to place the total station stationary in the laboratory on the point with previously measured coordinates due to the floor structure, it becomes necessary to measure its coordinates with high accuracy at each installation. To do this, it is proposed to install the device on a
tripod, the legs of which are installed on the concrete monolithic foundations of the building and the supporting structure under the floor, which will be accessed through technological holes in the floor covering (figure 3).

**Figure 3.** Total station setting up in the laboratory.

**Figure 4.** Spherical magnetic reflector Leica “1.5” BRR™ (Leica Geosystems AG, Switzerland).

It is proposed to place reflectors on the walls of the laboratory room and measure their coordinates to create a network of control points used to measure the coordinates of an electronic total station (figure 2). As reflectors, it was decided to place high-precession spherical reflectors Leica “1.5” BRR™ (Leica Geosystems AG, Switzerland) (figure 4), placed on the walls using magnetic ring mounts [11]. The locations of the reflectors are marked at installation points R1-R5 in figure 2.

The geographic coordinates of the reflectors R1-R5 in the room can be determined in a local coordinate system using an absolute laser tracker eg Leica "AT960"TM (Leica Geosystems AG, Switzerland) [12]. The attitude of the local and geographic coordinate systems can be determined using a high-precision gyroscopic measuring system Leica “Gyromat 5000”TM (Leica Geosystems AG, Switzerland) [13]. For angle measurement of the inclination of the test-bench's turntable plane is used the precision electronic inclinometer Leica “Nivel N210”TM (Leica Geosystems AG, Switzerland).

Taking into account the small measured distances to the spherical reflectors located on the walls of the laboratory room (figure 2), it is advisable to assess the influence of the error in determining the coordinates of the total station on the value of the measured azimuthal angle of orientation of the turntable of the dynamic stand. Since the spherical reflectors have a slight excess over the level of the installation of the total station, it is possible to calculate the coordinates of the total station by reverse angular intersection using the Pranis-Pranevich method [14].

Figure 5 shows the layout of the reflectors and the point of total station installation (N) with coordinate marks in the local OXY system, the origin of which coincides with point T3. Points are numbered and angles are counted in counterclockwise direction (left circle). As the control points were selected points T1, T2, T3, corresponding to the locations of the reflectors R1, R2, and R5. It is necessary to answer that this article considers the case of using a minimum sufficient number of reflectors placed in the laboratory in order to conduct an analytical assessment of the measurement accuracy of the azimuthal orientation of the stand. By using more reflectors, the measurement accuracy can be improved.
The calculation of the ideal coordinates of the searching point N is performed according to the relations (1-8):

\[
\begin{align*}
\text{ctg}(\gamma) &= \frac{(Y_2 - Y_1)\text{tg}^{-1}(\alpha) - (Y_3 - Y_2)\text{tg}^{-1}(\beta) + X_1 - X_3}{(X_2 - X_1)\text{tg}^{-1}(\alpha) - (X_3 - X_2)\text{tg}^{-1}(\beta) - Y_1 + Y_3} \\
Z_1 &= (Y_2 - Y_1)(\text{tg}^{-1}(\alpha) - \text{ctg}(\gamma)) - (X_2 - X_1)(1 + \text{tg}^{-1}(\alpha)\text{ctg}(\gamma)) \\
Z_2 &= (Y_3 - Y_2)(\text{tg}^{-1}(\beta) - \text{ctg}(\gamma)) - (X_3 - X_2)(1 - \text{tg}^{-1}(\beta)\text{ctg}(\gamma)) \\
Z &= \frac{Z_1 + Z_2}{2}
\end{align*}
\]  

Calculation of corrections to the coordinates of the required point N in the plan, mm:

\[
X_n = \frac{Z}{1 + \text{ctg}^2(\gamma)}
\]  

Calculation of the ideal coordinates of the required point N in the plan, mm:

\[
\begin{align*}
X_n &= X_2 + X_n \\
Y_n &= Y_2 + Y_n
\end{align*}
\]  

Parameters values of observed points arrangement for the diagram shown in figure 5 are given in table 2.

**Table 2.** Parameters of observed points arrangement.

| Point | Angle (grad.) | Coordinates (mm) | Distance (mm) |
|-------|---------------|------------------|---------------|
| T1    | 78.5404<sup>a</sup> | X: 6921.02, Y: -3070.55 | 1435.05       |
| T2    | 85.4802<sup>b</sup> | X: 7321.02, Y: 1582.94 | 4734.74       |
| T3    | 164.1696<sup>c</sup> | X: 0.00, Y: 0.00    | 6181.00       |

<sup>a</sup> Angle α between points T1,N,T2.

<sup>b</sup> Angle β between points T2,N,T3.

<sup>c</sup> Angle γ between points T1,N,T3.
Calculation of the desired point's N real plan coordinates, obtained taking into account the influence of errors of the used measuring geodetic instruments, taking into account their measuring accuracy.

Errors in measuring the coordinates of points Ti are determined by the ratios (9,10):
\[
\delta X_i = 0.015 + 0.006L_{Ti} \quad (9)
\]
\[
\delta Y_i = 0.015 + 0.006L_{Ti} \quad (10)
\]

Errors of angular measurements to reflectors corresponding to the measuring accuracy of the total station, for the angles between T1-N-T2 and T2-N-T3 can be set equal (11,12):
\[
\delta \alpha = 2\arccos(\alpha) \quad (11)
\]
\[
\delta \beta = 2\arccos(\beta) \quad (12)
\]

Real measurements of the coordinates of points Ti, for the reflector layout shown in figure 5, can be calculated by the following ratios (13,14):
\[
X_{\text{real}} = X_i + \delta X_i \quad (13)
\]
\[
Y_{\text{real}} = Y_i + \delta Y_i \quad (14)
\]

The real values of the angles between the points T1-N-T2 and T2-N-T3 are calculated by the ratios (15,16):
\[
\alpha_{\text{real}} = \alpha + \delta \alpha \quad (15)
\]
\[
\beta_{\text{real}} = \beta + \delta \beta \quad (16)
\]

The calculation of corrections to the measured coordinates of the desired point N in the plan is carried out according to the ratios (17,18):
\[
X_{n\text{real}} = \frac{Z_{\text{real}}}{1 + \text{ctg}^2(y)} \quad (17)
\]
\[
Y_{n\text{real}} = X_{n\text{real}} \text{ctg}(y_{\text{real}}) \quad (18)
\]

The measured coordinates of point N in the plan are calculated according to the ratios:
\[
X_{n\text{real}} = X_{2\text{real}} + X_{n\text{real}} \quad (19)
\]
\[
Y_{n\text{real}} = Y_{2\text{real}} + Y_{n\text{real}} \quad (20)
\]

The error in measuring the coordinates of point N in the plan is calculated according to the relations (21,22):
\[
\delta X_n = X_n - X_{n\text{real}} \quad (21)
\]
\[
\delta Y_n = Y_n - Y_{n\text{real}} \quad (22)
\]

Coordinate values calculated from the ratios were: $\delta X_n = 0.025342$ mm, $\delta Y_n = -0.001985$ mm.

The circular error in measuring the coordinates of point N in the plan is calculated by the ratio (23):
\[
\delta_N = \sqrt{\delta X_n^2 + \delta Y_n^2} \quad (23)
\]

The component of the error in measuring the angular attitude of the mirror from point N, caused by the error in determining the coordinates of the geodetic optical measuring device in the plan using the basis of spherical reflectors, can be calculated by the ratio (24):
\[
\delta A_y = \arctg\left(\frac{\delta x}{L}\right) \quad (24)
\]

In relation (24) L is the distance to the mirror, which have value 2 139.01 mm for the circuit shown in figure 5.

3. Results and discussion

For the considered arrangement of spherical reflectors, the circular error have value: $\delta_N = 0.02542$ mm.
The calculated value of the component of the error in measuring the angle of the mirror caused by coordinates measuring error for the considered of observed points (spherical reflectors) arrangement was: \( \delta A_r = 2.45 \text{ arc sec.} \)

The estimation of the azimuth measurement accuracy \( \delta A \) is carried out according to the following simplified equation (25):

\[
\delta A = \sqrt{\delta A_{MIRR}^2 + \delta A_{REF}^2 + \delta A_t^2 + \delta A_{GYR}^2}
\] (25)

In relation (25) components of the azimuth measurement error is:

- \( \delta A_{MIRR} \) - is a error in measuring the angle of the geodetic mirror, caused by inaccuracy in the manufacture of the mirror, mounting equipment and errors in its installation;
- \( \delta A_{REF} \) - is a reflectors coordinates measuring error for measurements with absolute laser tracker;
- \( \delta A_t \) - is a error in measuring the angle of the mirror for measurements with using total station;
- \( \delta A_{GYR} \) - is a local and geographic coordinate systems attitude error with using gyroscopic measuring system.

The components of the azimuth measurement error and calculation results (25) are given in table 3. As shown in table 3 the value of component errors \( \delta A_{MIRR} , \delta A_{REF} , \delta A_t , \delta A_{GYR} \) are indicate with taking into account the accuracy characteristics of proposed measuring instruments. The minimum and maximum calculated value of azimuth measurement error \( \delta A \) meets the requirements for calibration of inertial measuring systems of high accuracy classes. This way allows to achieve the test-benche's azimuthal attitude measurements accuracy at the level of results of similar approaches, based on the use of stationary placed autocolimation equipment which is stationary placed in front of dynamic test-bench's turntable [7,8,10]. For example, in paper [10] shows that the achievable accuracy level of angular attitude has value is 3 arc sec. The achieved in [10] level significantly exceeds the requirements for the test accuracy of IRS and gyroscopic sensors and allows to calibrate gyro theodolites and gyro north-seekers systems.

**Table 3. The calculation results of the azimuthal attitudes measurement accuracy achievable level.**

| Azimuth error components                       | Value (1 RMS), arc sec. | Note                                      |
|-----------------------------------------------|-------------------------|-------------------------------------------|
| Error in measuring the angle of the geodetic mirror \( \delta A_{MIRR} \) | 2.00 10.00 Approximate error for calculation |
| Reflectors coordinates measuring error \( \delta A_{REF} \) | 1.50 Technical specification accuracy |
| Error in measuring the angle of the mirror \( \delta A_t \) | 1.00 technical specification accuracy |
| Local and geographic coordinate systems attitude error \( \delta A_{GYR} \) | 2.592 16.20 Approximate error value of measuring |
| Azimuth measurement error \( \delta A \) | 3.737 19.123 |

4. Conclusion

The obtained calculated results confirm the possibility of providing research and calibration of inertial measuring systems of high accuracy classes.

The proposed way for determining the dynamic test-benches azimuthal attitude can be widely used in the creation of laboratories for the calibration and study of the properties of inertial measuring systems
and their sensors. Its distinctive feature is the absence of the need for permanent placement of reference storage systems and optical instruments in the laboratory. This allows you to significantly reduce the requirements for laboratory premises.

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