In the Name of GOD

Guidance and Navigation I: INS Tests and Calibration

Hadi Nobahari
Sharif University of Technology
Department of Aerospace Engineering

Objectives

- To check the performance of the overall system
- To see if the system behaves as predicted from the knowledge of the components.
- To see if the system can work well in real environment.
- To investigate the adverse interactions between the components.
- To calibrate the INS (***)
- A manufacturer will wish to check that the units built on a production line will meet the design specification
- The customer will wish to confirm that the inertial system will fulfill his or her requirements.

Components of each error terms

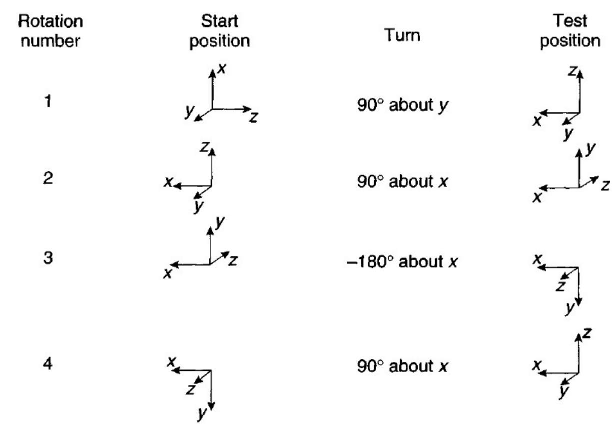
Each error term include some or all of the following components:

- fixed or repeatable terms
- temperature induced variations
- switch-on to switch-on variations
- in-run variations

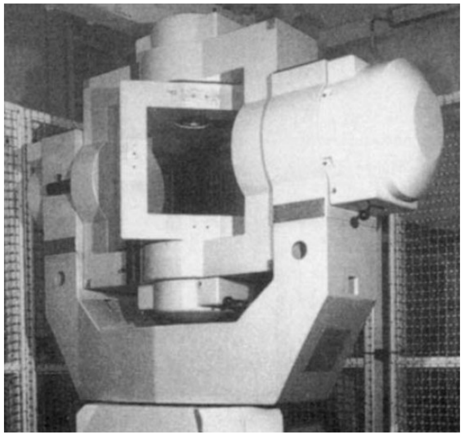
The first two ones can be calibrated.

Switch-on to switch-on variation and in-run effects, that is, the random effects caused by instabilities within the gyroscope, can not be calibrated before the operation of the system

Typical test rotations for a strapdown inertial measurement unit (IMU)

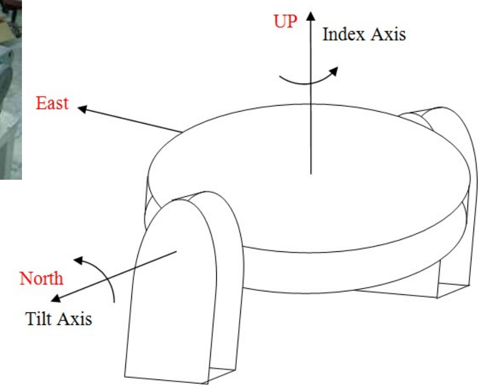


Three-axis Test Table



- Video 1
- Video 2

Two-axis test table



Two-axis test table

- Tilt axis is always fixed WRT the earth (toward the geographic North)
- Index axis is always perpendicular to the rotating plane
- Initially the rotating plane is aligned WRT the local level
- After installation of the IMU on the table, $[\mathbf{T}]^{B_0N}$ is known
- After any tilt and index motion of the table $[\mathbf{T}]^{BN}$ is known as a function of the tilt angle (θ) and the index angle (ψ)

=> the expected accelerometer output ($-\mathbf{g}^B$) is known

- During any tilt and index motion of the table, $\boldsymbol{\omega}_{NB}$ is known as a function of tilt rate (dθ/dt) and index rate (dψ/dt)

The expected rate gyro outputs

$$\boldsymbol{\omega}_{IB}^{B} = \boldsymbol{\omega}_{IE}^{B} + \boldsymbol{\omega}_{EN}^{B} + \boldsymbol{\omega}_{NB}^{B}$$

- Position of the table is fixed WRT the earth =>

$$\boldsymbol{\omega}_{IE}^{N} = \begin{bmatrix} \omega_e \cos L \\ 0 \\ -\omega_e \sin L \end{bmatrix} \qquad \boldsymbol{\omega}_{EN} = 0$$

- The instantaneous ω_{NB} is known as a function of the tilt rate (dθ/dt) and the index rate (dψ/dt)

=> The expected rate gyro outputs ($[\boldsymbol{\omega}_{IB}]^B$) are known

The expected accelerometer outputs

$$\mathbf{a}^{\mathrm{N}} = \begin{bmatrix} 0 \\ 0 \\ -\mathrm{g} \end{bmatrix}$$

- After any tilt and index motion of the table, $[T]^{BN}$ is known as a function of the tilt angle (θ) and the index angle (ψ)
- the expected accelerometer outputs can be calculated from:

$$\mathbf{a}^{\mathrm{B}} = [\mathbf{T}]^{\mathrm{BN}} \mathbf{a}^{\mathrm{N}}$$

Calibration of the INS accelerometers

- Since there is always installation misalignments, the expected acceleration in x direction is a function of all accelerometers outputs:

$$\hat{a}_{\mathrm{x}} = \mathrm{B}_{\mathrm{ax}} + \mathrm{S}_{\mathrm{axx}} a_{\mathrm{x}} + \mathrm{M}_{\mathrm{axy}} a_{\mathrm{y}} + \mathrm{M}_{\mathrm{axz}} a_{\mathrm{z}} + \mathrm{n}_{\mathrm{ax}}$$

- It can also be written as:

$$\hat{a}_{\mathrm{x}} = C^{\mathrm{T}} x_{\mathrm{x}} + \mathrm{n}_{\mathrm{ax}} \qquad \text{where}: \; C = \begin{bmatrix} 1 \\ a_{\mathrm{x}} \\ a_{\mathrm{y}} \\ a_{\mathrm{z}} \end{bmatrix} \; , \; x_{\mathrm{x}} = \begin{bmatrix} \mathrm{B}_{\mathrm{ax}} \\ \mathrm{S}_{\mathrm{axx}} \\ \mathrm{M}_{\mathrm{axy}} \\ \mathrm{M}_{\mathrm{axz}} \end{bmatrix}$$

- x_x: the unknown vector

Calibration of INS accelerometers

- In the same way:

$$\hat{a}_{\mathrm{y}} = \mathrm{B}_{\mathrm{ay}} + \mathrm{S}_{\mathrm{ayy}} a_{\mathrm{y}} + \mathrm{M}_{\mathrm{ayx}} a_{\mathrm{x}} + \mathrm{M}_{\mathrm{ayz}} a_{\mathrm{z}} + \mathrm{n}_{\mathrm{ay}}$$

$$\hat{a}_{\mathrm{z}} = \mathrm{B}_{\mathrm{az}} + \mathrm{S}_{\mathrm{azz}} a_{\mathrm{z}} + \mathrm{M}_{\mathrm{azx}} a_{\mathrm{x}} + \mathrm{M}_{\mathrm{azy}} a_{\mathrm{y}} + \mathrm{n}_{\mathrm{az}}$$

- 12 unknown parameter can be defined for 3 accelerometers.
- 3 equation can be written for each tilt and index (each test)

⇒ At least 4 independent test must be run to obtain a system of 12 equations and 12 unknowns (4 different sets of tilt and index)

⇒ More tests can result better accuracies using the method of least square.

Calibration of INS accelerometers

- the expected acceleration in x direction may also be considered to depend to higher order terms of the accelerometers outputs:

$$\mathrm{a}_{\mathrm{xind}} = \mathrm{B}_{\mathrm{ax}} + \mathrm{S}_{\mathrm{axx}} a_{\mathrm{x}} + \mathrm{S}_{\mathrm{2x}} a_{\mathrm{x}}^{2} + \mathrm{M}_{\mathrm{axy}} a_{\mathrm{y}} + \mathrm{M}_{\mathrm{axz}} a_{\mathrm{z}} + \mathrm{n}_{\mathrm{ax}}$$

- Here, at least 5 independent test must be run to obtain a system of 15 equations and 15 unknowns

Calibration of the INS rate gyros

- Since there is always installation misalignments, the expected angular rate around x_B axis is a function of all rate gyros outputs:

$$\hat{\omega}_x = B_{gx} + S_{gxx}\omega_x + M_{gxy}\omega_y + M_{gxz}\omega_z + n_{gx}$$

- Considering higher-order error terms and g-dependent errors:

$$\hat{\omega}_x = B_{gx} + B_{ax}a_x + B_{ay}a_y + B_{az}a_z + S_{gxx}\omega_x + S_{gxx2}\omega_x^2 + S_{gxx3}\omega_x^3 + M_{gxy}\omega_y + M_{gxz}\omega_z + n_{gx}$$

- Some gyros (e.g. FOGs) are not sensitive to accelerations