Image-based navigation

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E.T.S.I.Geodesica, Cartografíca y Topográfica

Image-based navigation

- ✓Introduction
- ✓ Definitions
- ✓ Navigation techniques
- ✓ Conclusions

Introducción INS

OBJECTIVE OF THIS UNIT

- ✓ Provide an overview of the different types of sensors available.
- ✓ Provide a description of error sources (biases and noise)
- ✓ Explain how errors in individual gyroscopes and accelerometers propagate through the navigation system as a whole.

DRAWBACKS

- ✓ Lack of readable introduction into the subject which does not oversimplify or ignore the error properties of inertial navigation systems.

- ✓ For the sake of conciseness we focus on INS of the type → MEMS (micro-machined electromechanical systems)

Introducción INS

Inertial navigation

Inertial navigation is a self-contained navigation technique in which measurements provided by IMUs (accelerometers and gyroscopes) are used to track the position and orientation of an object relative to a known starting point, orientation and velocity.

Inertial navigation is used in a wide range of applications including the navigation of aircraft, tactical and strategic missiles, spacecraft, submarines and ships barcos, etc.)

UNIT 2 $\rightarrow$ we studied the principles of inertial navigation

$$\frac{d}{dt}\begin{pmatrix} v_N \\ v_E \\ v_D \end{pmatrix} = \begin{pmatrix} a_N + g_N - 2\omega_e v_E \operatorname{sen}\varphi + \dot{\varphi} v_D - \dot{\lambda}\operatorname{sen}\varphi v_E \\ a_E + g_E - 2\omega_e \operatorname{sen}\varphi v_N + 2\omega_e \cos\varphi v_D + \dot{\lambda}\operatorname{sen}\varphi v_N + \dot{\lambda}\cos\varphi v_D \\ a_D + g_D - 2\omega_e \cos\varphi v_E - \dot{\lambda}\cos\varphi v_E - \dot{\varphi} v_N \end{pmatrix}$$

Mechanizations

INS

Inertial navigation systems (INS) typically contain three orthogonal rate-gyroscopes and three orthogonal accelerometers, measuring angular velocity and linear acceleration respectively.

Not to be confused → INS with IMU (*Inertial Measurement Unit*)

POSSIBLE INERTIAL SYSTEM CONFIGURATIONS

Stable platform systems (gimbaled)
IMUs are mounted on a platform which is isolated from any external rotational motion. The mesaured data are refered to a global frame (***n-frame/i-frame)***
Have mechanical complexity, and little software is used.

Strapdown systems → have become the dominant type of INS
IMUs are mounted rigidly onto the device, and therefore output quantities measured in the body frame (***s-frame/b-frame***) rather than the global frame.
Have reduced mechanical complexity, tend to be physically smaller, though increased computational load (software)

Stable Platform Systems

•The platform is held in alignment with the global frame.

•This is achieved by mounting the platform using gimbals (frames) which allow the platform freedom in all three axes.

•The platform mounted gyroscopes detect any platform rotations.

•These signals are fed back to torque motors which rotate the gimbals in order to cancel out such rotations,hence keeping the platform aligned with the global frame.

•To track the orientation of the device the angles between adjacent gimbals can be read using angle pick-offs.

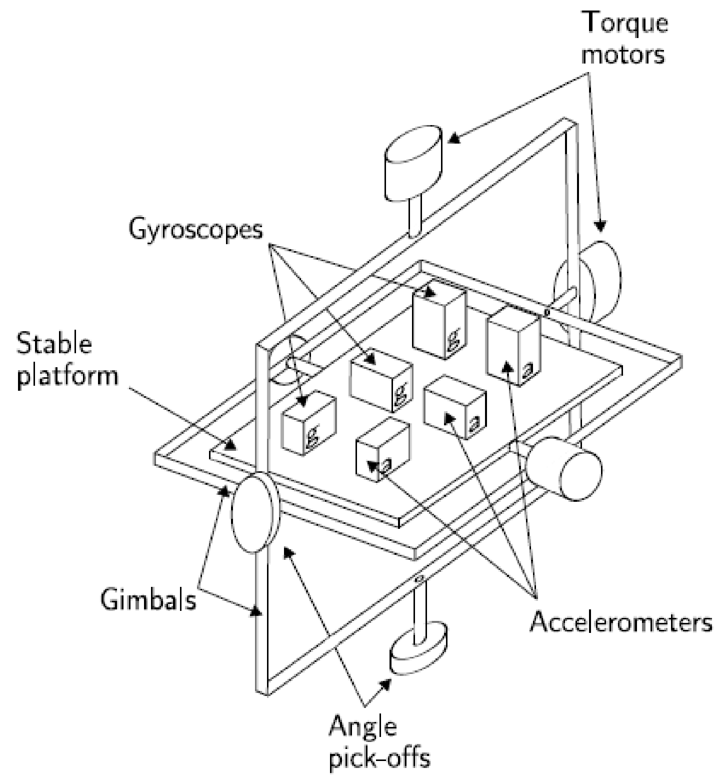


Figure 2: A stable platform IMU.

Stable Platform Systems

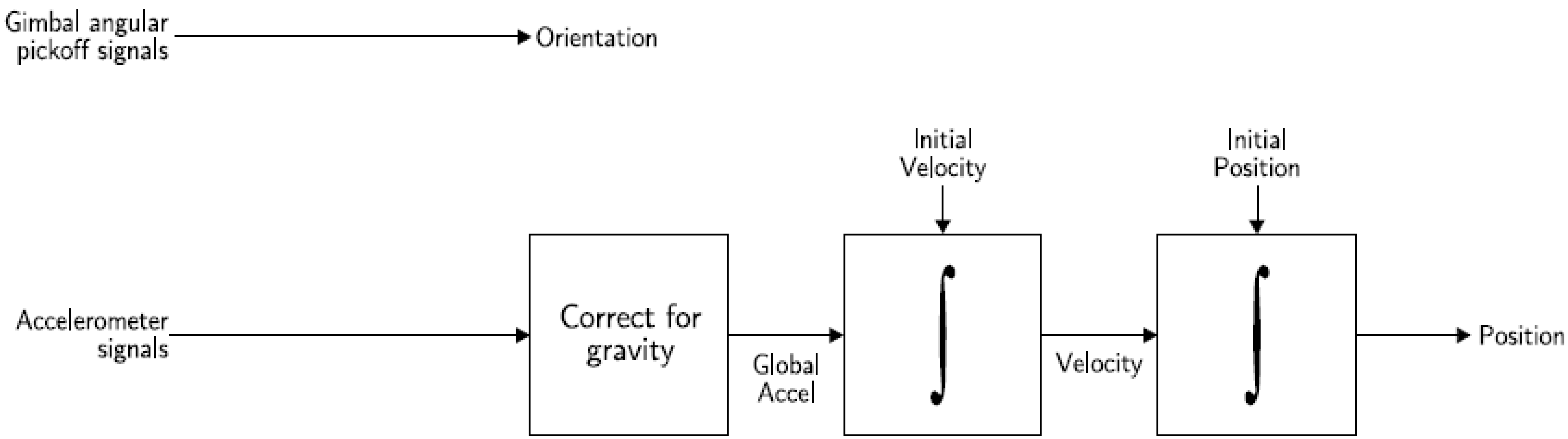


Figure 3: Stable platform inertial navigation algorithm.

Examples os stabilized platforms

https://www.youtube.com/watch?v=T0SFAdPUUYs
https://www.youtube.com/watch?v=xjZod2SWvz4

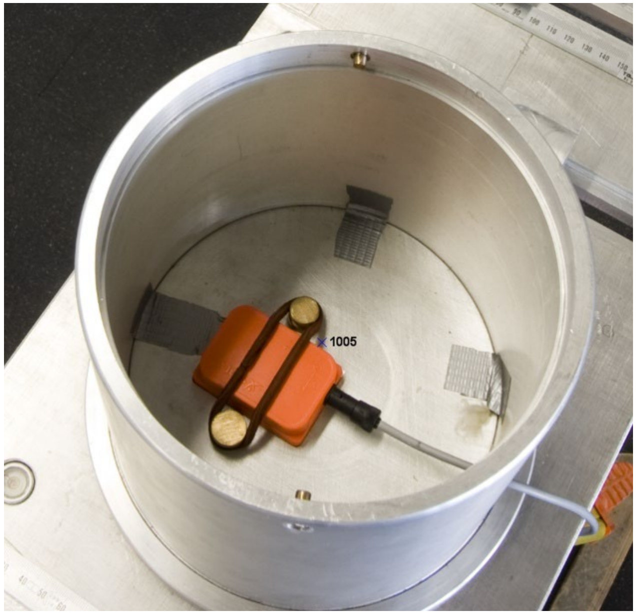
Strapdown systems

- In strapdown systems the inertial sensors are mounted rigidly onto the device.

- Output quantities measured in the body frame (b-frame/s-frame).

- To keep track of orientation the signals from the rate gyroscopes are integrated $\rightarrow$ rotation matrix (Euler angles) is obtained.

- To track position the three accelerometer signals are resolved into global coordinates using the known orientation, as determined by the integration of the gyro signals.



- The global acceleration signals are then integrated as in the stable platform algorithm.

Strapdown systems

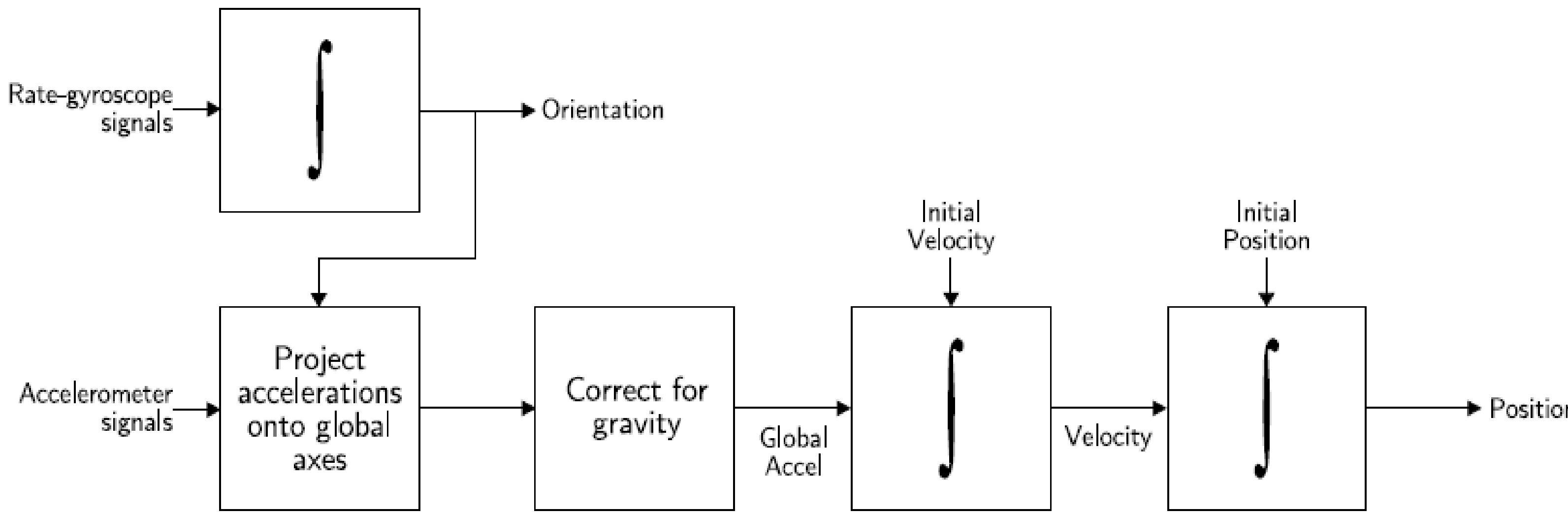
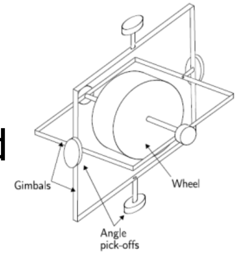


Figure 4: Strapdown inertial navigation algorithm.

Gyroscopes

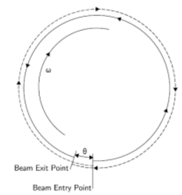
Types of gyroscopes

Mechanical



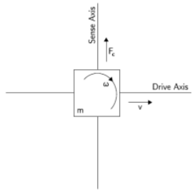
A conventional gyroscope consists of a spinning wheel mounted gimbals which allow it to rotate in all three axes
(SDF – Single degree of freedom)

Optical



FOGs – Fibre optic gyroscope
RLGs – Ring laser gyroscope

MEMS (micro electro-mechanical systems)



Use silicon micro-machining techniques

Mechanical gyroscopes

- Based on the effect of the conservation of angular momentum.

- A spinning wheel resists changes in orientation.

- Hence when a mechanical gyroscope is subjected to a rotation the wheel will remain at a constant global orientation and the angles between adjacent gimbals will change.

- The angles between adjacent gimbals can be read using angle pick-offs → conventional mechanical gyroscopes measure rotation.

Disadvantages
Contain moving parts that cause friction → need mechanical maintenace
Require some warming up time.
More expensive (manufacture + maintenance)

Gyroscopes explanation
https://www.youtube.com/watch?v=cquvA_IpEsA
https://www.youtube.com/watch?v=eYlT30nfjn8
Mechanical Gyroscope 1952
https://www.youtube.com/watch?v=FYSHEhksBjk
INS Stabilized Platform 60s
https://www.youtube.com/watch?v=pvRsA-bk4b4

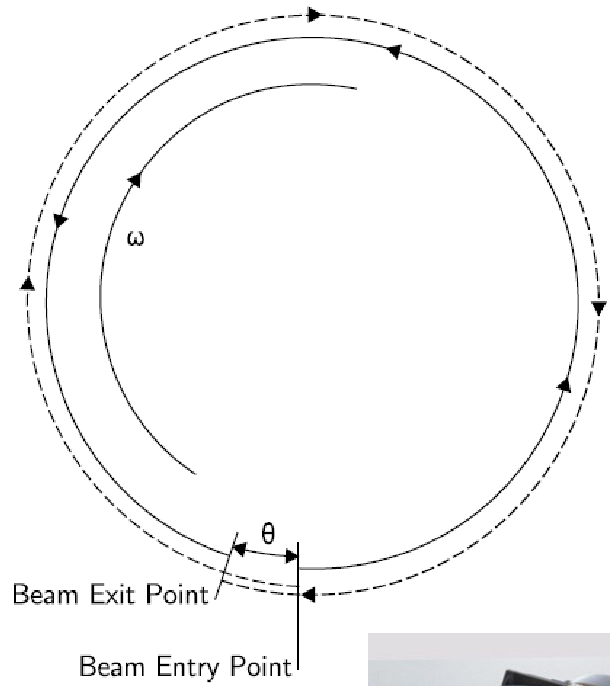
Optical Gyroscopes (FOGs)

FOG – fiber optical gyroscopes

- A FOG consists of a large coil of optical fibre two light beams are fired into the coil in opposite directions

- Uses the interference of light to measure angular velocity.

- If the sensor is undergoing a rotation then the beam travelling in the direction of rotation will experience a longer path to the other end of the fibre than the beam travelling against the rotation $\rightarrow$ Sagnac effect

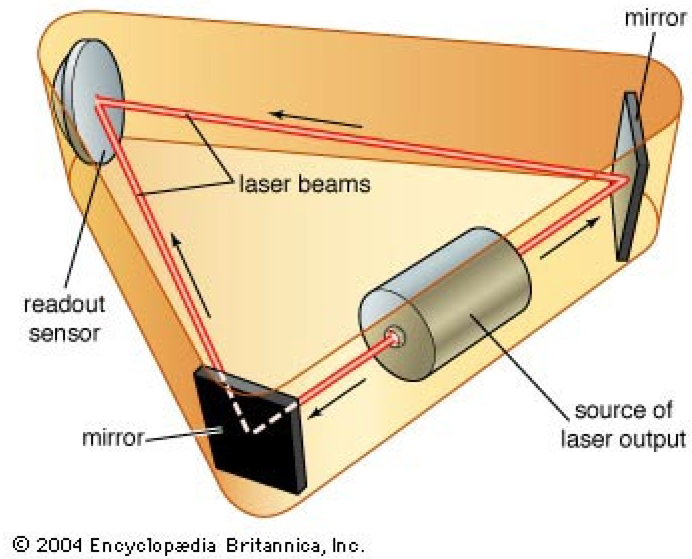


Optical Gyroscopes (RLGs)

RLGs - Ring laser gyroscopes

- Are also based on the Sagnac effect.

- The difference is that in a RLG laser beams are directed around a closed path using mirrors rather than optical fibre.



Sagnac effect- FOG
https://www.youtube.com/watch?v=eXahNBBxqS0
https://www.youtube.com/watch?v=aO0pCbKSpvE

RLG
https://www.youtube.com/watch?v=eu4ZrzG-7ik
https://www.youtube.com/watch?v=jcexE7cWaWA

Optical Gyroscopes

They measure angular velocity.

The accuracy of an optical gyro is largely dependent on the length of the light transmission path (larger is better), which is constrained by the size of the device.

Advantages

→ contain no moving parts.
→ require only a few seconds to start-up.

Disadvantages

→ have high part counts and require parts with high-precision tolerances and intricate assembly techniques.
→ they remain expensive.
→ they are bigger and demand more energy consumption than MEMS .

MEMS gyroscopes

•Small
•Have low part counts (a MEMS gyroscope can consist of as few as three parts)
• Relatively cheap to manufacture
• They cannot match the accuracy of optical devices, however they are expected to do so in the future.

They measure the angular velocity.

Advantages → small size, low weight, rugged construction, low power consumption, short start-up time, inexpensive to produce (in high volume), high reliability, low maintenance, and compatible with operations in hostile environments.

MEMS explanation
https://www.youtube.com/watch?v=eqZgxR6eRjo
https://www.youtube.com/watch?v=zwe6LEYF0j8

Laser/MEMS

	GG1320AN (Laser Gyro)	GG5300 (MEMS 3xGyro)
Size	88 mm $\times$ 88 mm $\times$ 45 mm	50 mm $\times$ 50 mm $\times$ 30 mm
Weight	454 g	136 g
Start-Up Time	< 4 s	< 1 s
Power	15 Vdc, 1.6 watts nominal 5 Vdc, 0.375 watts nominal	5 Vdc, < 800 mA
Operating Temperature Range	-54 °C to 85 °C	-45 °C to 85 °C
Angular Random Walk	$0.0035°/\sqrt{\mathrm{h}}$	$0.2°/\sqrt{\mathrm{h}}$
Bias Stability	0.0035°/h	< 70°/h

Table 1: Specifications for the Honeywell GG1320AN and GG5300 gyroscopes.

MEMS gyro error characteristics

- ✓Constant bias
- ✓Thermo-mechanical white noise / Angle random walk
- ✓Flicker noise / Bias stability
- ✓Temperature effects
- ✓Calibration errors
- ✓Summary

MEMS gyro errors

✓Constant bias

Average output from the gyroscope when it is not undergoing any rotations

It is measured in º/h

Offset of the output from the true value.

A constant error ε ,when integrated,causes an angular error which grows linearly with time

$$\theta(t) = \epsilon \cdot t$$

It can be estimated by taking a long term average of the gyro's output whilst it is not undergoing any rotation (static).

Once the bias is known it is trivial to compensate for it by simply subtracting the bias from the output.

MEMS gyro errors

✓Thermo-mechanical white noise / Angle random walk

The output is perturbated by some thermo-mechanical noise which fluctuates at a rate much greater than the sampling rate of the sensor.

As a result the samples obtained from the sensor are perturbed by a white noise sequence.

$$(0, \sigma^2) \qquad \int_0^t \epsilon(\tau)\, d\tau = \delta t \sum_{i=1}^{n} N_i$$

$$\mathrm{E}\left(\int_0^t \epsilon(\tau)\, d\tau\right) = \delta t \cdot n \cdot \mathrm{E}(N) = 0$$

$$\mathrm{Var}\left(\int_0^t \epsilon(\tau)\, d\tau\right) = \delta t^2 \cdot n \cdot \mathrm{Var}(N) = \delta t \cdot t \cdot \sigma^2$$

MEMS gyro errors

Hence the noise introduces a zero-mean random walk error into the integrated signal, whose standard deviation is called *Angle Random Walk* (ARW)

$$\sigma_\theta(t) = \sigma \cdot \sqrt{\delta t \cdot t}$$

$$\mathrm{ARW} = \sigma_\theta(1) \quad {}^\circ/\sqrt{\mathrm{h}}$$

Example → Honeywell GG5300 ARW = $0.2^\circ/\sqrt{\mathrm{h}}$

Other measurements used to specify noise are:
Power Spectral Density (PSD)
FFT noise density

$$\begin{aligned}
\mathrm{ARW}\ ({}^\circ/\sqrt{\mathrm{h}}) &= \frac{1}{60} \cdot \sqrt{\mathrm{PSD}\ (({}^\circ/\mathrm{h})^2/\mathrm{Hz})} \\
\mathrm{ARW}\ ({}^\circ/\sqrt{\mathrm{h}}) &= \frac{1}{60} \cdot \mathrm{FFT}\ ({}^\circ/\mathrm{h}/\sqrt{\mathrm{Hz}})
\end{aligned}$$

MEMS gyro errors

✓Flicker noise / Bias stability

•The bias of a MEMS gyroscope wanders over time due to flicker noise in the electronics and in other components susceptible to random flickering

•Flicker noise is noise with a 1/f spectrum.

•At high frequencies flicker noise tends to be overshadowed by white noise.

•Bias fluctuations which arise due to flicker noise are usually modelled as a random walk.

$$\mathrm{BRW}\ (^\circ/\sqrt{\mathrm{h}}) = \frac{\mathrm{BS}\ (^\circ/\mathrm{h})}{\sqrt{t\ (\mathrm{h})}}$$

•Bias stability measurement describes how the bias of a device may change over a specified period of time, typically around 100 seconds, in fixed conditions (usually including constant temperature)

MEMS gyro errors

✓ Temperature effects

•Temperature fluctuations due to changes in the environment and sensor self heating induce movement in the bias.

•That such movements are not included in bias stability measurements which are taken under fixed conditions.

•Any residual bias introduced due to a change in temperature will cause an error in orientation which grows linearly with time.

•The relationship between bias and temperature is often highly nonlinear for MEMs sensors.

•Most inertial measurement units (IMUs) contain internal temperature sensors which make it possible to correct for temperature induced bias effects (e.g. Xsens Mtx).

MEMS gyro errors

✓ Calibration errors

•The term 'calibration errors' refers collectively to errors in the scale factors, alignments, and linearities of the gyros.

•Such errors tend to produce bias errors that are only observed whilst the device is turning.

•Such errors lead to the accumulation of additional drift in the integrated signal, the magnitude of which is proportional to the rate and duration of the motions.

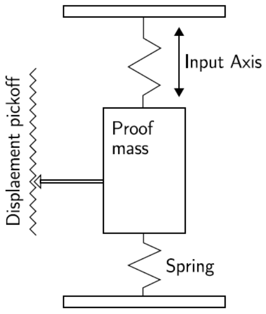
•It is usually possible to measure and correct calibration errors (e.g. Xsens Mtx apply internal corrections for calibration errors).

MEMS gyro errors

- ✓ Summary

Error Type	Description	Result of Integration
Bias	A constant bias ϵ	A steadily growing angular error $$\theta(t) = \epsilon \cdot t$$
White Noise	White noise with some standard deviation σ	An angle random walk, whose standard deviation $$\sigma_\theta(t) = \sigma \cdot \sqrt{\delta t \cdot t}$$ grows with the square root of time
Temperature Effects	Temperature dependent residual bias	Any residual bias is integrated into the orientation, causing an orientation error which grows linearly with time
Calibration	Deterministic errors in scale factors, alignments and gyro linearities	Orientation drift proportional to the rate and duration of motion
Bias Instability	Bias fluctuations, usually modelled as a bias random walk	A second-order random walk

Types of accelerometer



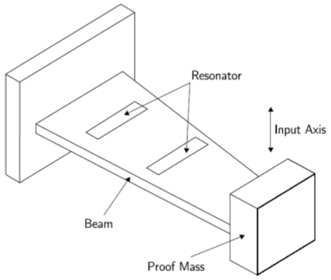
Linear accelerometers

Mechanical

Consists of a mass suspended by springs. The displacement of the mass is measured using a displacement pick-off, giving a signal that is proportional to the force F acting on the mass in the direction of the input axis.

Solid state

Solid-state accelerometers can be broken into various sub-groups:
Surface acoustic wave (SAW)
Vibratory
Silicon/quartz devices.



MEMS (micro electro-mechanical systems)
Mechanical
Solid state

MEMS accelerometer errors

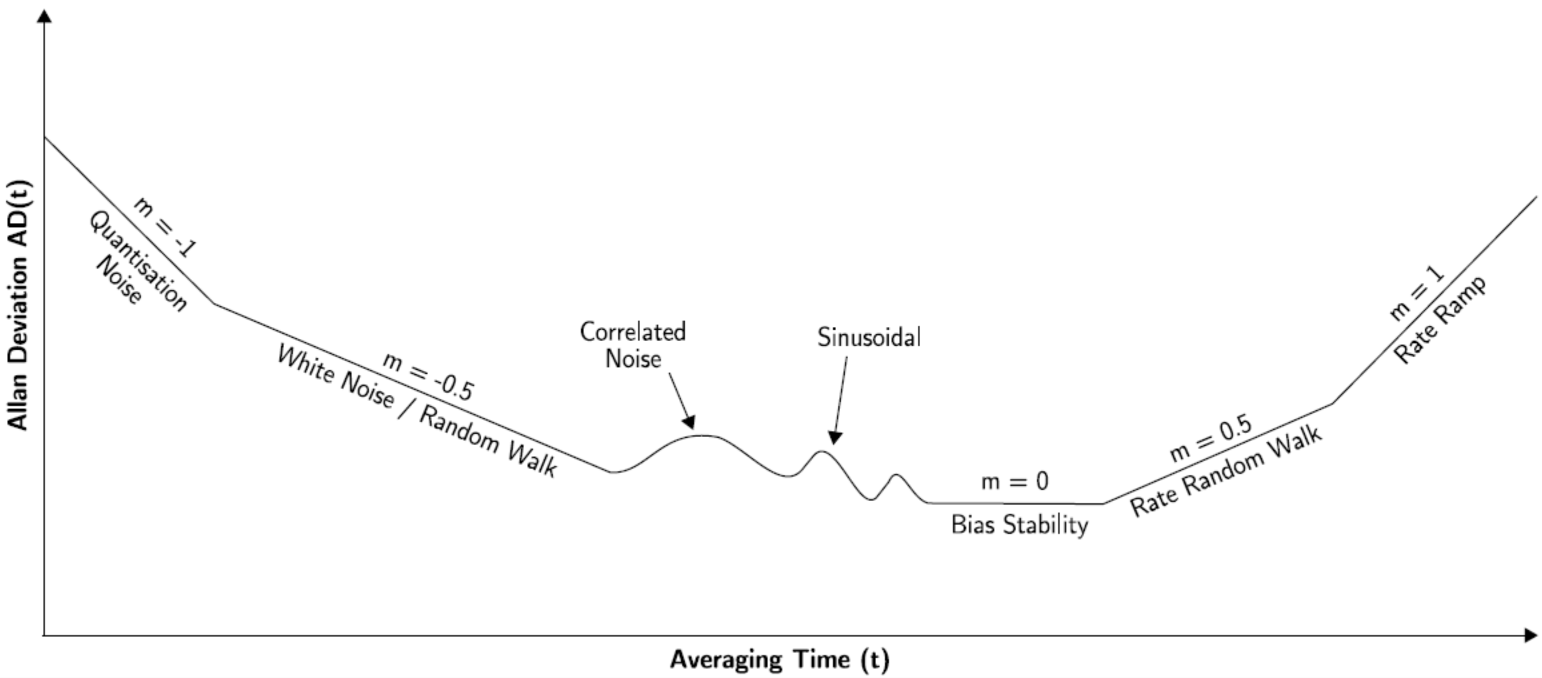
✓ Summary

Error Type	Description	Result of Double Integration
Bias	A constant bias ϵ in the accelerometer's output signal	A quadratically growing position error $$s(t) = \epsilon \cdot \frac{t^2}{2}$$
White Noise	White noise with some standard deviation σ	A second-order random walk. The standard deviation of the position error grows as $$\sigma_s(t) = \sigma \cdot t^{3/2} \cdot \sqrt{\frac{\delta t}{3}}$$
Temperature Effects	Temperature dependent residual bias	Any residual bias causes an error in position which grows quadratically with time
Calibration	Deterministic errors in scale factors, alignments and accelerometer linearities	Position drift proportional to the squared rate and duration of acceleration
Bias Instability	Bias fluctuations, usually modelled as a bias random walk	A third-order random walk in position

Signal Noise Analysis

✓ Allan Variance

Allan Variance is a time domain analysis technique that can be applied to any signal to determine the character of the underlying noise processes.



Allan Variance

✓ Description

Allan Variance is a time domain analysis technique originally designed for characterising noise and stability in clock systems.

1. Take a long sequence of data and divide it into bins of length t. There must be enough data for at least 9 bins (otherwise the results obtained begin to lose their significance).

2. Average the data in each bin to obtain a list of averages $(a(t)_1, a(t)_2, ..., a(t)_n)$, where n is the number of bins.

3. The Allan Variance is then given by

$$\mathrm{AVAR}(t) = \frac{1}{2 \cdot (n-1)} \sum_i \left(a(t)_{i+1} - a(t)_i\right)^2 \qquad (19)$$
$$\mathrm{AD}(t) = \sqrt{\mathrm{AVAR}(t)}$$

Finally, AD is plotted as a function of t on a log-log scale

Allan Variance

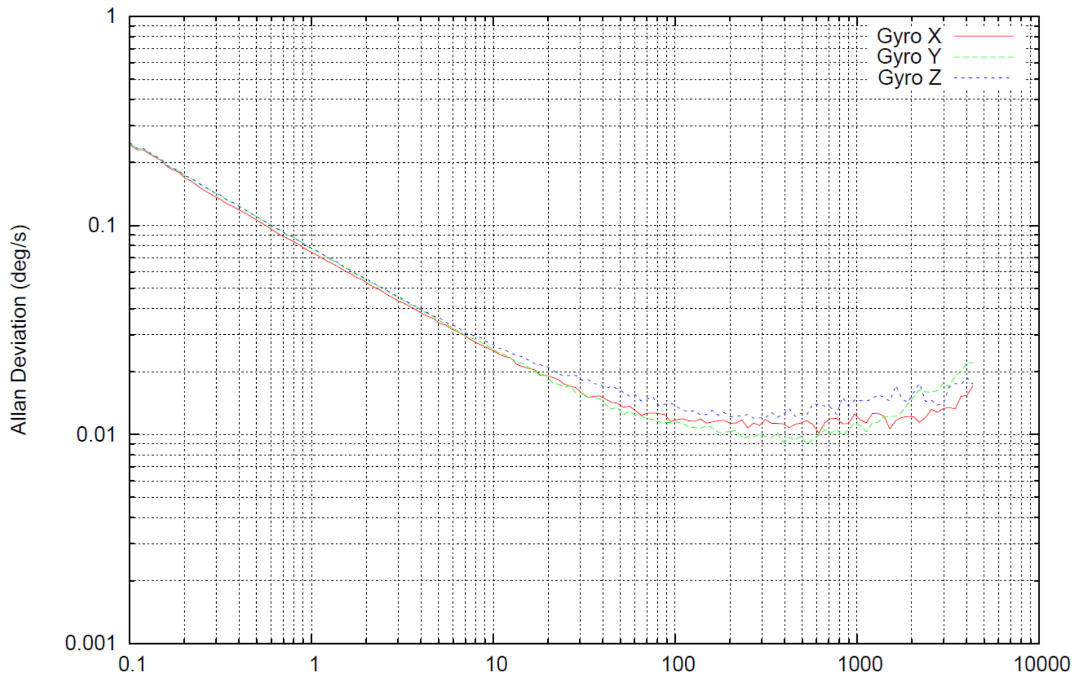
✓ Analysis of results for a MEMS device

For a MEMS device such as the Mtx the important processes that we want to measure are random walk and bias instability, which can be identified and read as follows

- White noise appears on the Allan Deviation plot as a slope with gradient -0.5. The random walk measurement for this noise (ARW for a rate-gyro, VRW for an accelerometer) is obtained by fitting a straight line through the slope and reading its value at $t = 1$.
- Bias Instability appears on the plot as a flat region around the minimum. The numerical value is the minimum value on the Allan Deviation curve.

Allan Variance (Xsens-MTx)

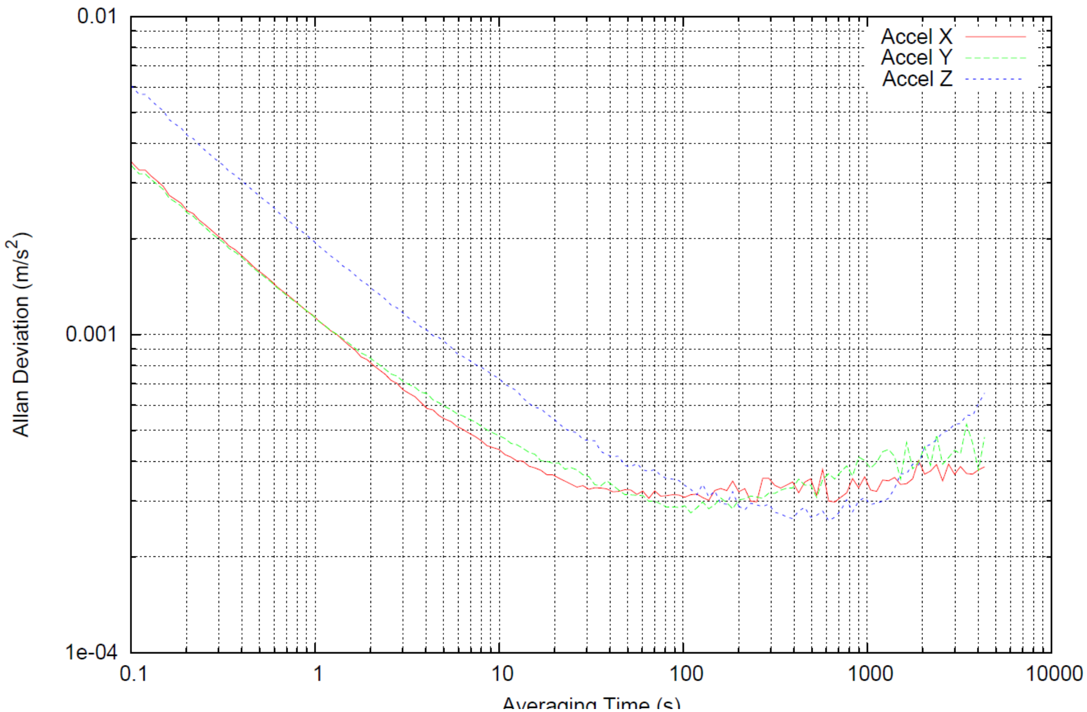
- ✓ Gyroscopes



	Bias Instability	Angle Random Walk
X Axis	$0.010°/\mathrm{s} = 36°/\mathrm{h}$ (at 620 s)	$0.075°/\sqrt{\mathrm{s}} = 4.6°/\sqrt{\mathrm{h}}$
Y Axis	$0.009°/\mathrm{s} = 32°/\mathrm{h}$ (at 530 s)	$0.078°/\sqrt{\mathrm{s}} = 4.8°/\sqrt{\mathrm{h}}$
Z Axis	$0.012°/\mathrm{s} = 43°/\mathrm{h}$ (at 270 s)	$0.079°/\sqrt{\mathrm{s}} = 4.8°/\sqrt{\mathrm{h}}$

Allan Variance (Xsens-MTx)

- ✓ Accelerometers



	Bias Instability	Velocity Random Walk
X Axis	$3.0 \cdot 10^{-4}$ m/s^2 = 1.1 m/h^2 (at 670 s)	0.0011 m/s$^2/\sqrt{\text{s}}$ = 0.066 m/s$^2/\sqrt{\text{h}}$
Y Axis	$2.8 \cdot 10^{-4}$ m/s^2 = 1.0 m/h^2 (at 110 s)	0.0011 m/s$^2/\sqrt{\text{s}}$ = 0.066 m/s$^2/\sqrt{\text{h}}$
Z Axis	$2.6 \cdot 10^{-4}$ m/s^2 = 0.94 m/h^2 (at 620 s)	0.0020 m/s$^2/\sqrt{\text{s}}$ = 0.12 m/s$^2/\sqrt{\text{h}}$

Propagation of errors

Gyroscopes

Angular velocity is integrated using the standard approach [Unit 2]

$$\boldsymbol{B} = \begin{pmatrix} 0 & -\omega_{bz}\delta t & \omega_{by}\delta t \\ \omega_{bz}\delta t & 0 & -\omega_{bx}\delta t \\ -\omega_{by}\delta t & \omega_{bx}\delta t & 0 \end{pmatrix}$$

$$\boldsymbol{\omega}_b = (\omega_{bx}, \omega_{by}, \omega_{bz})^T$$

$$\sigma = |\boldsymbol{\omega}_b \delta t|$$

$$\begin{aligned}
\boldsymbol{C}(t+\delta t) &= \boldsymbol{C}(t)\left(\boldsymbol{I} + \boldsymbol{B} + \frac{\boldsymbol{B}^2}{2!} + \frac{\boldsymbol{B}^3}{3!} + \frac{\boldsymbol{B}^4}{4!} + \ldots\right) \\
&= \boldsymbol{C}(t)\left(\boldsymbol{I} + \boldsymbol{B} + \frac{\boldsymbol{B}^2}{2!} - \frac{\sigma^2 \boldsymbol{B}}{3!} - \frac{\sigma^2 \boldsymbol{B}^2}{4!} + \ldots\right) \\
&= \boldsymbol{C}(t)\left(\boldsymbol{I} + \left(1 - \frac{\sigma^2}{3!} + \frac{\sigma^4}{5!}\ldots\right)\boldsymbol{B} + \left(\frac{1}{2!} - \frac{\sigma^2}{4!} + \frac{\sigma^4}{6!}\ldots\right)\boldsymbol{B}^2\right) \\
&= \boldsymbol{C}(t)\left(\boldsymbol{I} + \frac{\sin\sigma}{\sigma}\boldsymbol{B} + \frac{1-\cos\sigma}{\sigma^2}\boldsymbol{B}^2\right)
\end{aligned}$$

Propagation of errors

Gyroscopes

• Errors in the gyroscope signals propagate through to the calculated orientation, therefore diminishing the accuracy of the transformation matrix C that is used in the strapdown systems to convert accelerations from the del ***s-frame*** into the ***n-frame***

$$\vec{a}^a = C_b^a \vec{a}^b$$

• For most MEMS devices white noise and uncorrected bias errors are the main causes of an error in the orientation.

• White noise causes an **angle random walk** whose standard deviation grows proportionally to the square root of time.

• An uncorrected bias causes an error in orientation which grows linearly with time.

Propagation of errors

Tracking position

The acceleration signal obtained from the accelerometers is projected into the global frame of reference

$$\boldsymbol{a}_g(t) = \boldsymbol{C}(t)\boldsymbol{a}_b(t)$$

Acceleration due to gravity is then subtracted and the remaining acceleration is integrated once to obtain velocity, and again to obtain displacement [Unit 2]

$$\begin{aligned}\boldsymbol{v}_g(t) &= \boldsymbol{v}_g(0) + \int_0^t \boldsymbol{a}_g(t) - \boldsymbol{g}_g \, dt \\ \boldsymbol{s}_g(t) &= \boldsymbol{s}_g(0) + \int_0^t \boldsymbol{v}_g(t) \, dt\end{aligned}$$

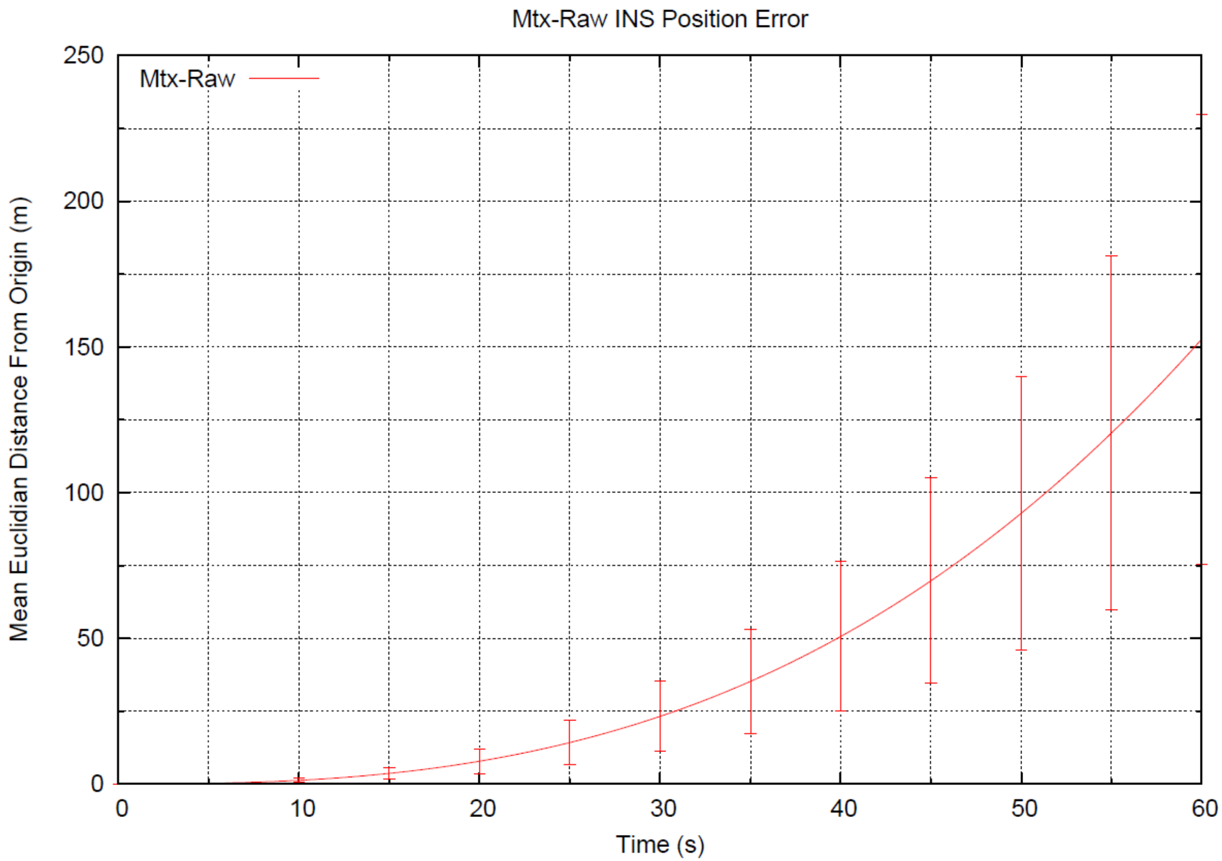
Errors in the angular velocity signals also cause drift in the calculated position.

This causes several problems.
Firstly, the accelerations of the device are integrated in the wrong direction.
Secondly, acceleration due to gravity can no longer be correctly removed.

"As a concrete example consider a tilt error of just 0.05°. This error will cause a component of the acceleration due to gravity with magnitude 0.0086 m/s2 to be projected onto the horizontal axes. This residual bias causes an error in the horizontal position which grows quadratically to 7.7 m after only 30 seconds."

Position error (Xsens-MTx)

- ✓ State case



Conclusions

✓ The propagation of orientation errors caused by noise perturbing the gyroscope signals as the critical cause of drift in strapdown INS systems.

✓A small tilt error in the calculated orientation causes a component of acceleration due to gravity to be projected onto the globally horizontal axes.

✓This residual error is then integrated twice, causing a rapidly growing error in the calculated position.

✓ Drift can also be reduced using sensor fusion techniques, often using additional data from absolute positioning systems and magnetometers, orby exploiting constraints which are known to apply to the movement of the IMU, such as known points in time at which the device must have a zero velocity.

✓ The stationary performance of the Xsens MTx system was shown to be suffering an average drift in position of 152.67 m after 60 seconds.