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Long term robust AUV control
using a gyro-compassing Inertial Navigation System

Geoff Lawes
CTO Sea Operations—Australasia

geoff.lawes@ixblue.com

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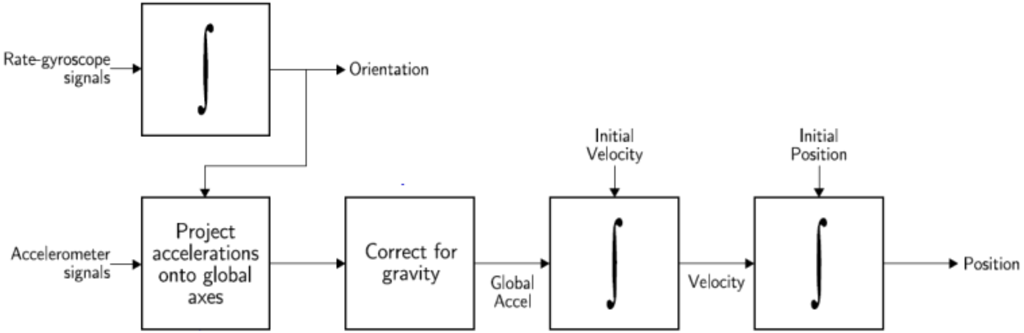
Principles of inertial navigation

Initial state, rotation, acceleration & integration

- Navigating any vehicle in space without external aiding requires:
  - A starting position/orientation/velocity state
  - Dynamic pitch, roll and yaw rates
  - Vertical (heave), longitudinal (surge), lateral (sway) accelerations
  - Integration of these values to generate orientation, velocity and absolute position
- On Earth, there are two more observable phenomena in the frame:
  - Earth rotation
  - Gravity

An Inertial Measurement Unit has 3 x orthogonal rate gyroscopes and 3 x orthogonal accelerometers



Principles of inertial navigation

Gyroscope errors

- Sensors have two error types
    - Systematic (biases) – which can also vary slowly with time (bias drift)
    - Random errors (noise)
- Random error impacts instantaneous (local) accuracy
- Bias reduces system accuracy progressively over time – but static bias can be compensated
- Bias drift generates a “residual bias” which causes sensor accuracy to degrade over time – residual bias is *uncompensated*
- Without correction to a reference direction, observations will drift:
    - For pitch and roll, the best reference is the vertical direction (gravity vector)
    - For yaw, the best reference is north

Principles of inertial navigation

Gyro-compassing

- IMUs are classed as “Gyro-compassing” **only** if they can seek north, without any other direction finding source
- North-seeking is a misnomer – actually they find east!
- East is direction of resultant vector difference between consecutive gravity vector observations as Earth rotates
- North is derived from east, on a plane tangent to Earth’s surface
- To provide heading (rather than just dynamic yaw) at better than 0.5° accuracy, the IMU must be capable of resolving rotations to an accuracy of 1/100th of Earth’s rotation rate
- **Needs rate sensitivity of better than 0.15°/hr**
- Sensors that can’t achieve this, will not be north seeking and will need aiding (normally from GNSS)

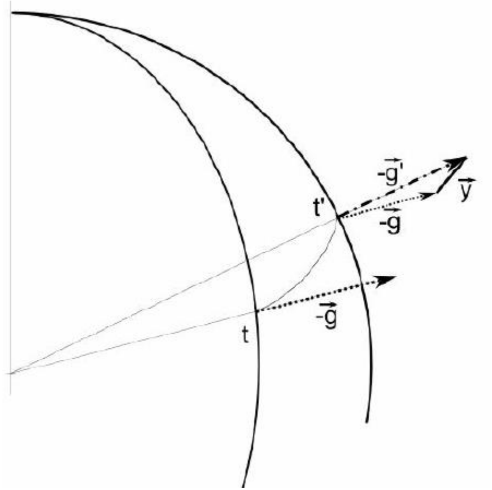
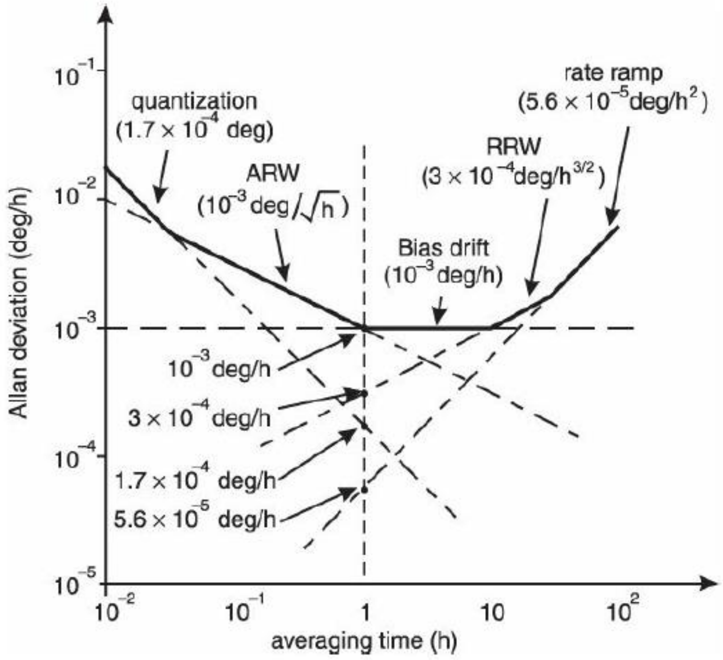


Image: Lefevre, H. (2014) *The Fibre Optic Gyroscope*

Principles of inertial navigation

North sensing accuracy limits

- Gyrocompass heading accuracy is limited by the averaging necessary to deal with noise and bias drift
- For 0.5 degrees – need 10^{-1} °/h
- For 0.05 degrees – need 10^{-2} °/h
- For 0.01 degrees – need 10^{-3} °/h
- Current technological performance:
  - **iXblue FOG ~ 1×10^{-6} °/h (and not yet reached technology limit)**
  - RLG ~ 5×10^{-5} °/h (at technology limit)
  - HRG ~ 3×10^{-4} °/h (approaching technology limit)
  - MEMS ~ 10^{1} °/h (at technology limit – cannot be an autonomous navigation gyrocompass)



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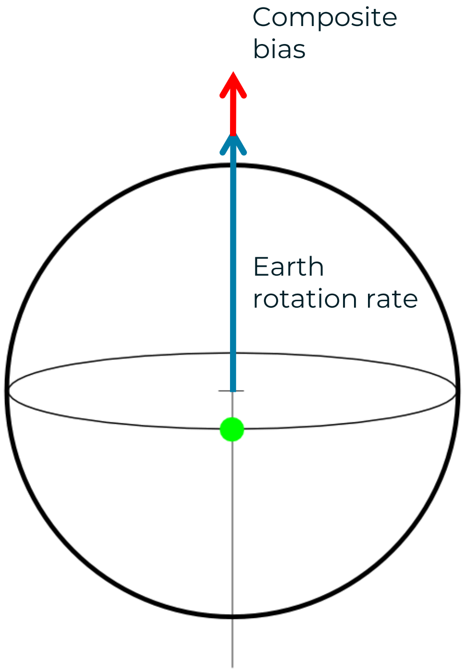
Principles of inertial navigation

Effect of bias on INS position error

- To achieve unaided position accuracy of 1NM/day the INS requires bias stability (and scale factor) better than better than 10^{-3} °/hr!

Gyroscope composite bias	Longitude angular drift over 24 hours (arc minutes)	45 degrees latitude equivalent
0.01 deg/h	14.4	10 Nm in 1 day
0.001 deg/h	1.44	1 Nm in 1 day
0.0001 deg/h	0.14	1 Nm in 10 days
0.000015 deg/h	0.021	1 Nm in 15 days
0.000010 deg/h	0.014	1 Nm in 14 weeks



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Principles of inertial navigation

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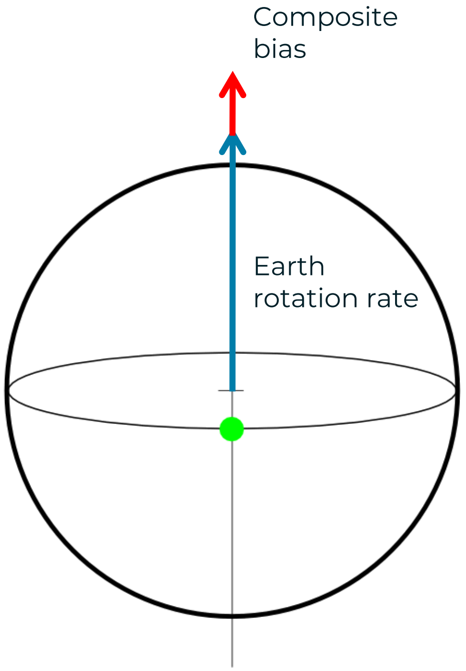

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Principles of inertial navigation

Key points

- Low dynamic range Attitude and Heading Reference Systems (AHRS) are non-gyrocompassing and rely on “dual-GNSS” compasses or magnetic compasses to provide a north reference

- A non-gyrocompassing AHRS will drift away from north as soon as the external reference is removed – i.e. in a subsea environment

- A gyro-compassing INS will maintain heading awareness, with predictably distributed uncertainty .

- A gyro-compassing INS with very low bias instability will maintain better position and heading awareness with predictable uncertainty distribution

Why are these factors important for robustness of AUV control systems?

Robust control

Predictable outcomes from unpredictable inputs

- **Control theory** – The design of a robust controller explicitly deals with uncertainty in inputs (i.e. positioning/orientation) to create predictable outputs (i.e. AUV control signals)
- Many control systems incorporate **Kalman filters** to ensure that the controller is fed a **predictive stream of data** irrespective of variable sensor rates, periodic losses
- Kalman filters offer an organic means to **generate uncertainty estimates** from prediction step covariances
- The output **uncertainty estimates benefit from input uncertainties that are "predictable"** and conform well to some expected apriori distribution
- Sensor inputs that "wander" and exhibit **stochastic behaviours are problematic** as they will invalidate the output uncertainty estimate of the Kalman filter (in addition to negatively impacting the navigation solution)

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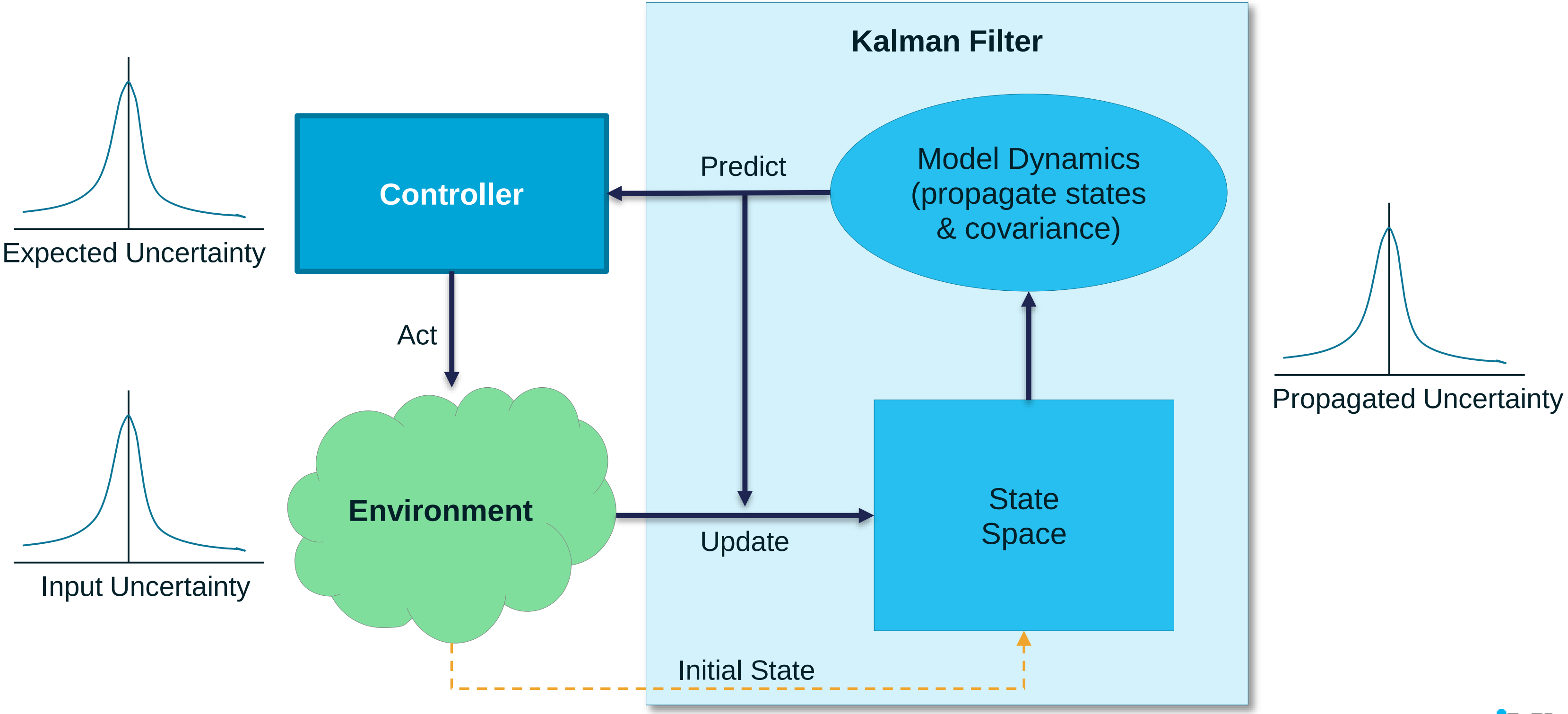
Robust control

In context – AUV control with known sensor uncertainty distribution



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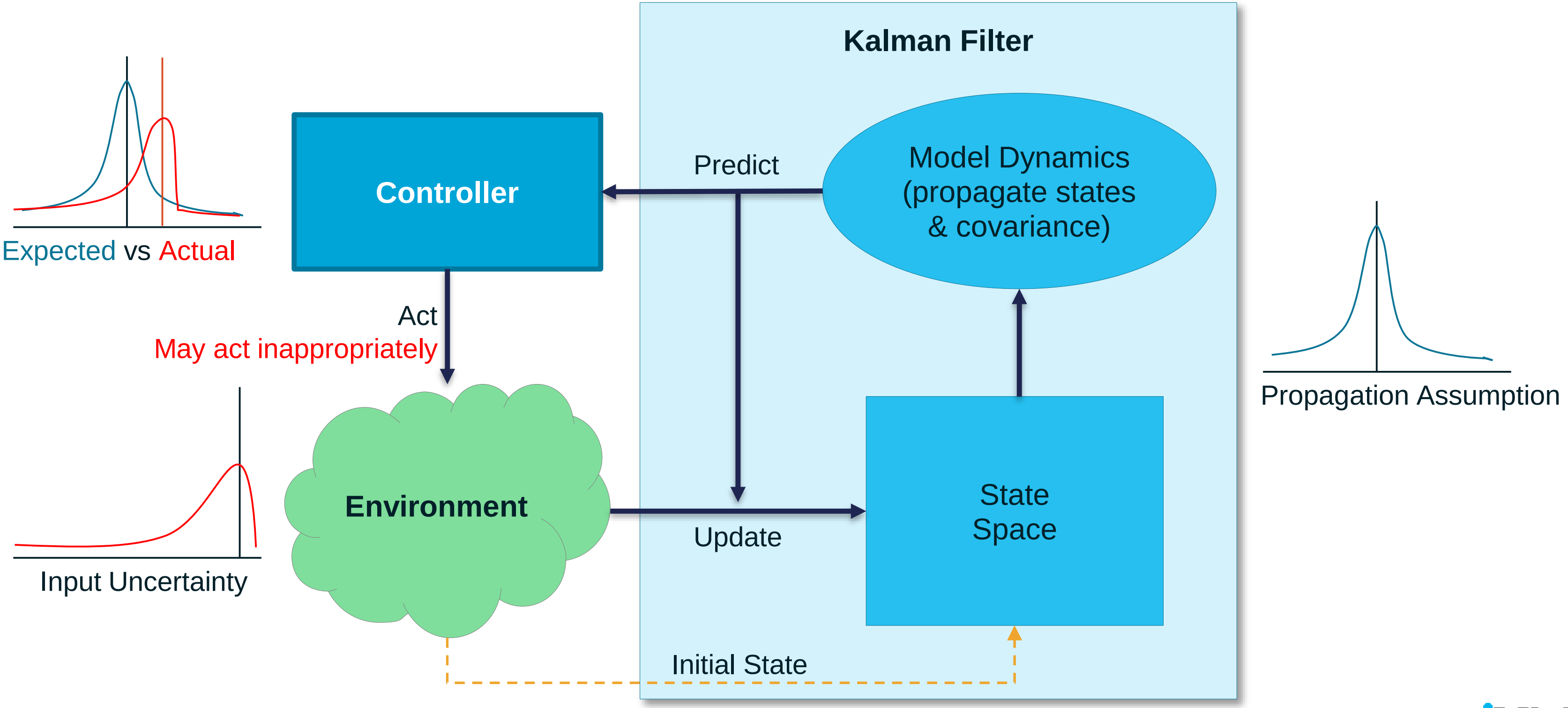
Robust control

In context – stochastic sensor error effects on control



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Conclusion

In other words

To achieve long-term robust control in an AUV it requires a **gyro-compassing INS** that provides:

- Pitch and roll referenced to an external fixed orientation (up) with predictably distributed measurement errors
- Non-drifting heading, not derived from external sensors, continually referenced to an internal computation of true north, with predictably distributed measurement errors
- Positioning output with predictable uncertainty distributions
- Lowest possible bias instability (preferably at or below 10^{-3} °/hr)

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