Improving localization & navigation with redundant sensors

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Navigare 2014
Fribourg, CH
01.04.2014

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Agenda

- Why redundant sensors (motivation)? (3)

- Configuration (3)
- Integrity (FDI) (1)
- Precision (noise reduction) (2)
- Processing approaches (3)

- Development & testing (3)

Motivation – UAV/MAV

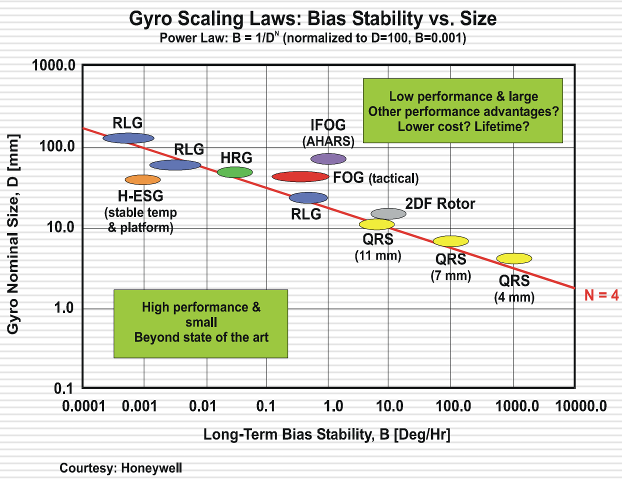
Dependence on:

- Waypoint /GNSS/ navigation
  - (One) **fragile** signal of low power (-157 dBW)
  - Removed by:
    - Intentionally (e.g. anti-tracking L1,L3,L3,L4,L5), >7W

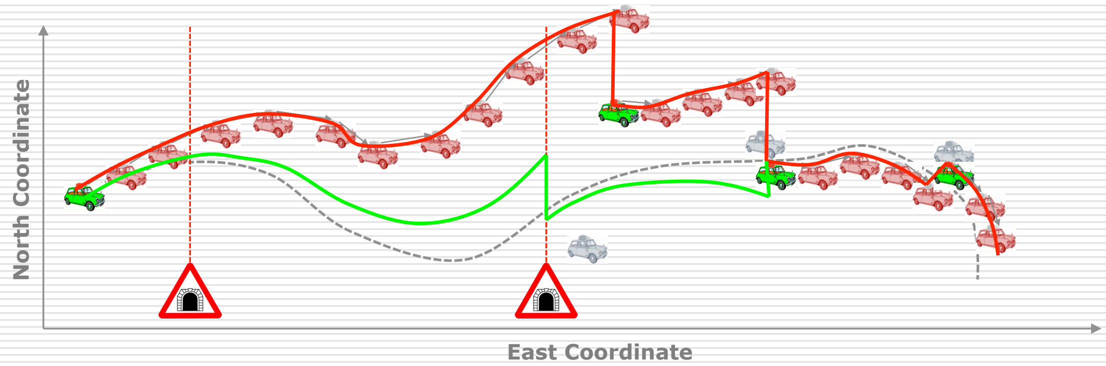
    - Non-intentionally
      - RF interference on board
      - External, e.g. communication lines, power lines, etc.

GNSS signal absence fallback solutions

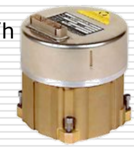
- Vision / texture & light dependency
  - Great – indoor, urban
  - Limited - forest, agriculture
  - Not functioning – night, fog, snow, water
- Inertial / size & weight
  - Murphy law in INS
    - < 2010:
    - > 2010:



Motivation – better autonomous performance

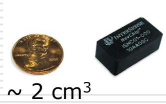


Nav/grade
~5000 cm^3
~4.5 kg
<0.01 °/h



Tactical
~2000 cm^3
~0.7 kg
<1 °/h

Low-cost

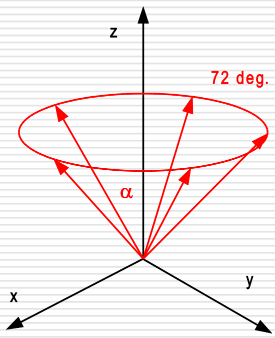


~ 2 cm^3
~ 10 grams
<10 °/h

Geometry of redundant "R"-IMU

- RIMUs
  - Not new, traditionally: safety critical applications, often 3 sensors/axis, high cost
  - A. Pejsa (1974) proposed a first theory based on variance minimization

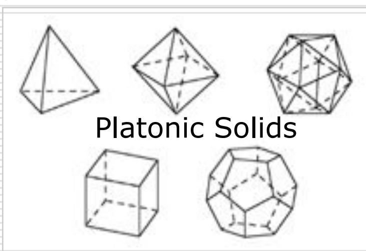
$$\alpha = \arccos\left(\sqrt{\frac{n-3}{3 \cdot n - 3}}\right)$$



  - S. Sukkarieh (2000) proposed a method based on information filter

$$\max(J) = \max\left(\det\left(\mathbf{H}^T \cdot \mathbf{R}^{-1}\mathbf{H}\right)\right)$$

$$J_{\max} = \left(\frac{n}{D}\right)^3$$



  - Sensor triads?

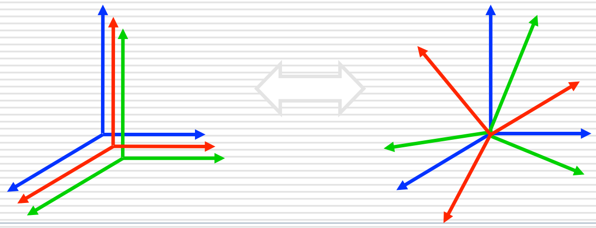
Geometry of RIMU / design with triads

- Approach based on partial redundancies (typically applied in geodetic networks)
  - each observation i has associated z_i (controllability)

$$\mathbf{Z} = \left(\mathbf{R} - \mathbf{H}\cdot\mathbf{P}\cdot\mathbf{H}^T\right)\cdot\mathbf{R}^{-1}$$
$$\mathbf{P} = \left(\mathbf{H}^T\cdot\mathbf{R}^{-1}\cdot\mathbf{H}\right)^{-1}$$

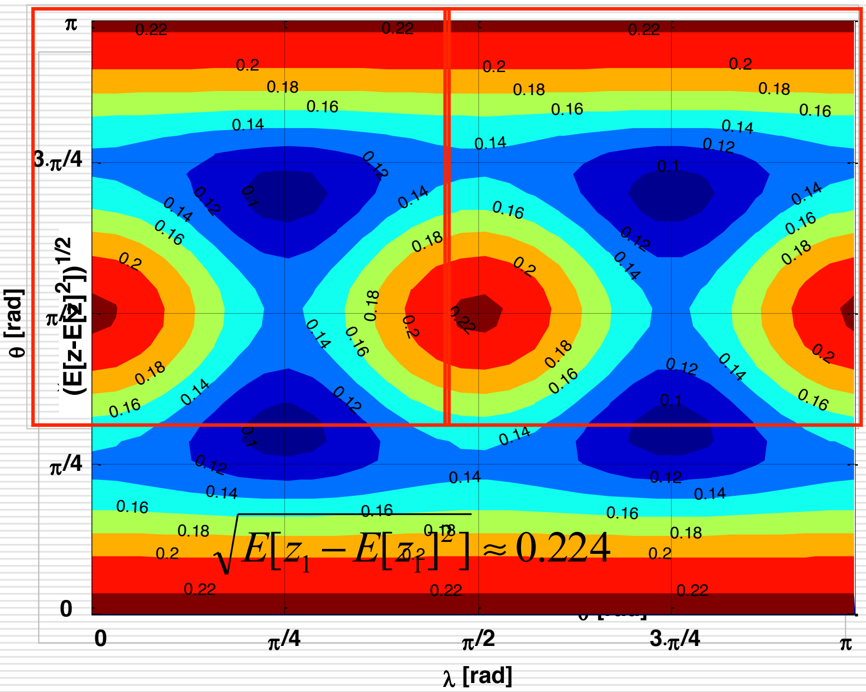
optimal config.: $\min \sqrt{E\left[\left(z_i - E\left[z_i\right]\right)^2\right]}$

- Sensor triads + same precision:
  - relative orientation is **unimportant** (analytically proven)



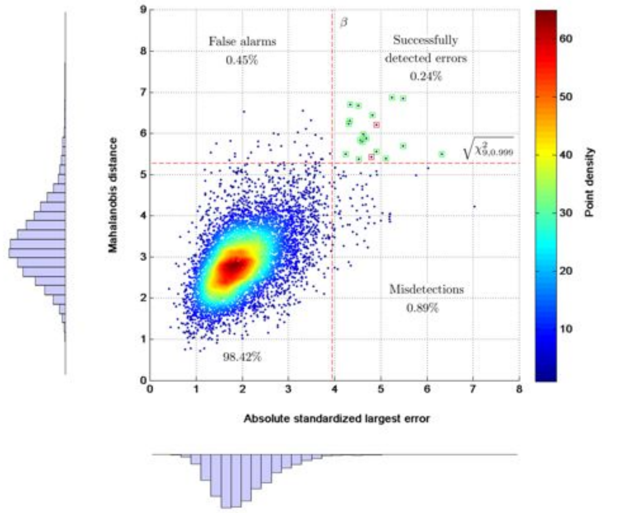
S. Guerrier (2009). *Improving Accuracy with Multiple Sensors: Study of Redundant MEMS-IMU/GPS Configurations.* ION GNSS-09, Savannah, GA.

Geometry of RIMU / impact of sensor failure



Fault Detection + Identification (FDI)

S. Guerrier, A. Waegli, J. Skaloud and M.-P. Victoria-Feser.
Fault Detection and Isolation in Multiple MEMS-IMUs Configurations,
in IEEE Transactions On Aerospace And Electronic Systems,
vol. 48, p. 2015-2031, 2012.

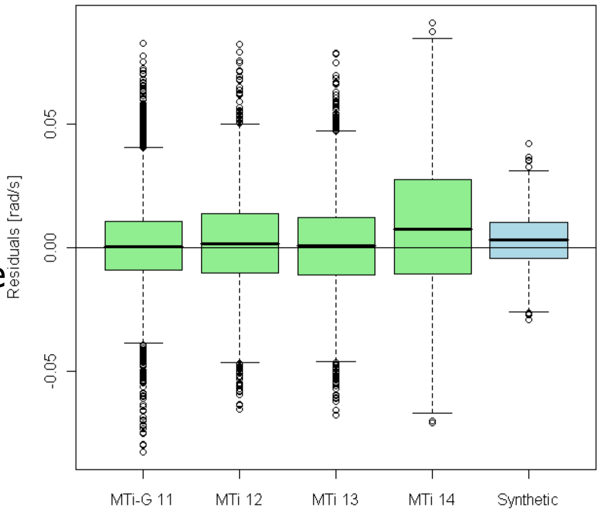


Noise reduction in RIMU

- Theory (constant variance)

$$\sigma_{\hat{x}}^2 = \sum_{i=1}^{n} w_i \sigma_i^2 = \frac{\sigma_x^2}{n}$$

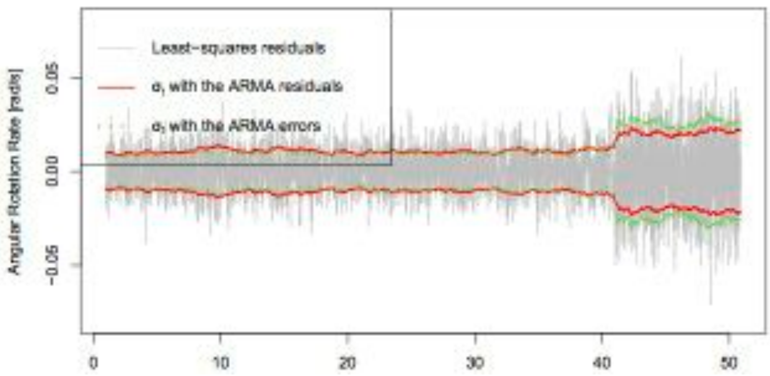
- Practice
  - Presence of "colored" noise
  - Variance not const. in time

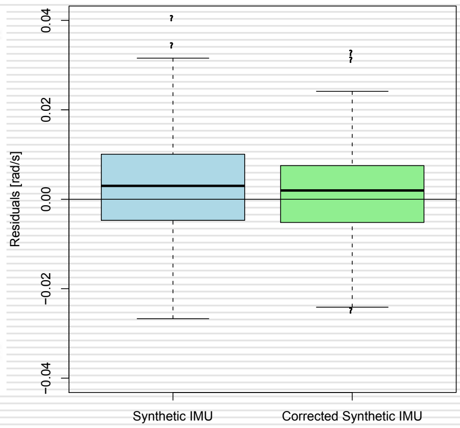


A. Waegli, J. Skaloud, S. Guerrier, E. Pares, I. Colomina.
Noise Reduction and Estimation in Multiple MEMS Inertial Systems,
in Measurement Science and Technology,
vol. 21, pp. 065201-065212, 2010.

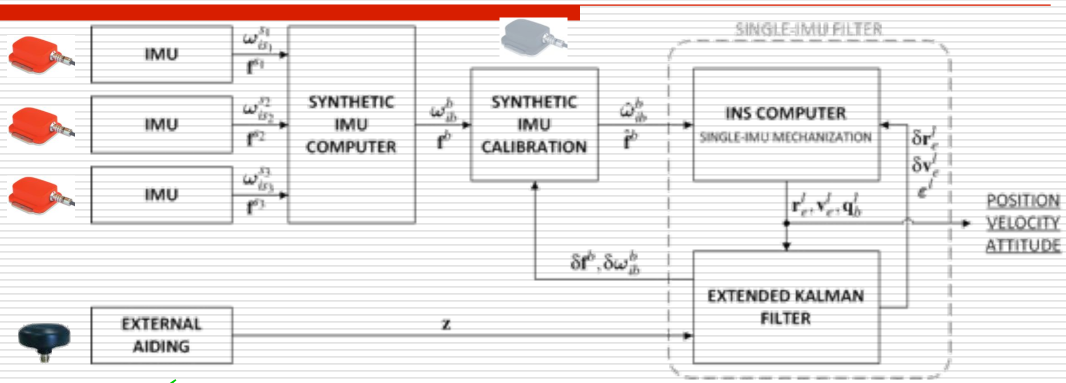
Noise reduction in RIMU - ARMA/GARCH

- ARMA (Auto-Regressive Moving-Average)
  - Remove the auto-correlated part
- GARCH (Generalized AR Conditional Heteroskedasticity)
  - Estimates the variance





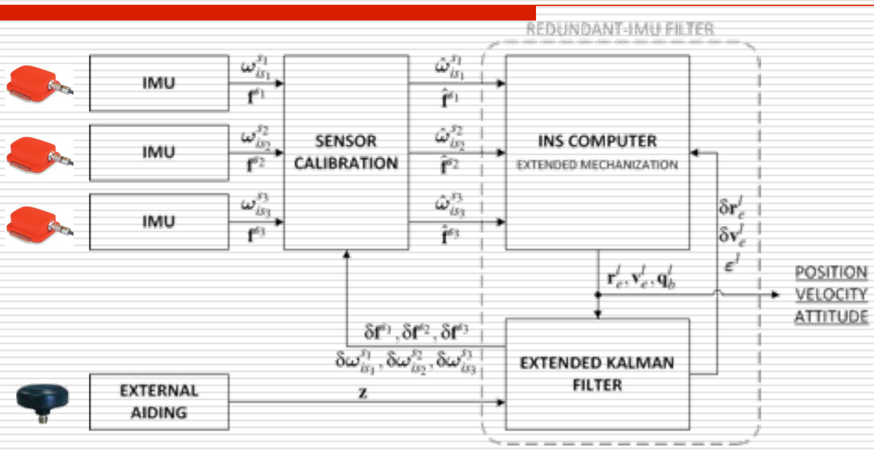
RIMU/GNSS (1): Synthetic IMU



- ✓ Applicable with standard GNSS/INS software
- ✓ Defective sensor detection
- ✓ Realistic estimation of noise
- ✓ Simple realization

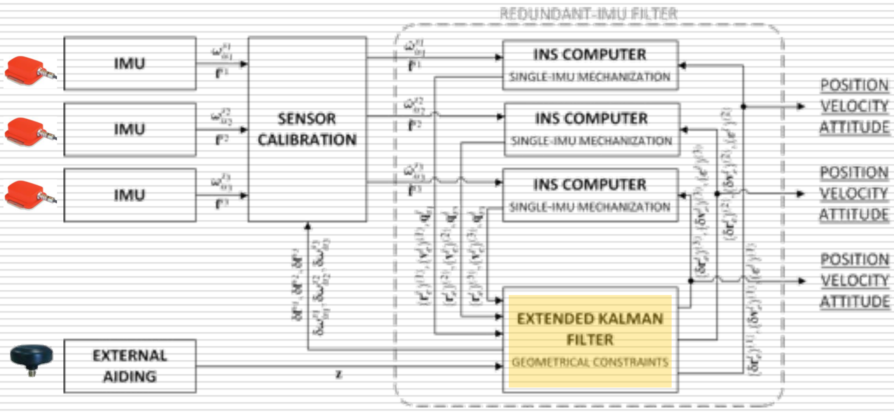
- ✗ Inertial error terms can not be back projected into the measurement space
  → not stochastically optimal

RIMU/GNSS (2): Extended IMU



- ✓ Estimation of individual sensor errors
- ✓ Defective sensor detection
- ✓ Realistic estimation of noise
- ✗ Requires modification of GNSS/INS software
- ✗ Requires knowledge of relative IMU orientation

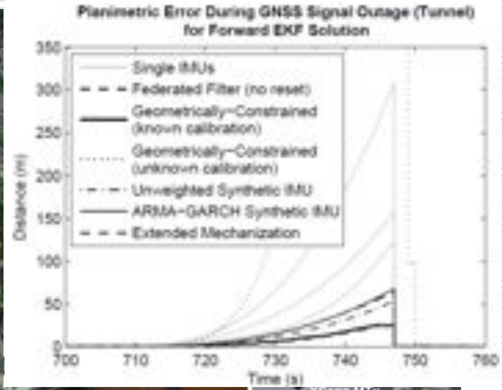
RIMU/GNSS (3): Constrained IMUs

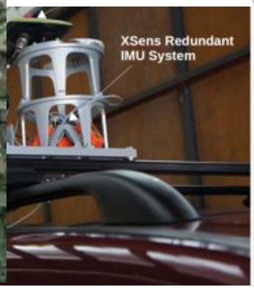


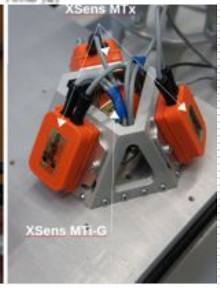
- ✓ Estimation of individual sensor errors
- ✓ Defective sensor detection + realistic noise
- ✓ Calibration of relative IMU orientation
- ✗ Requires modification of GNSS/INS software
- ✗ Increased computational effort

Development & testing – Xsens (R)IMUs

Single-IMU based INS/GPS Redundant INS/GPS Reference

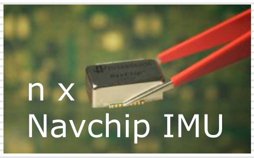




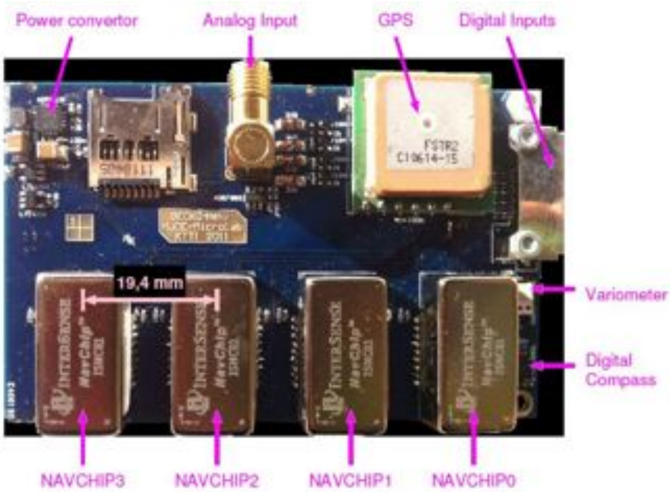


RIMU - Geko4Nav (Intersense/BFH/EPFL)

- Mother board
  - FPGA Geko, T. Kutler PhD @ EPFL / BFH



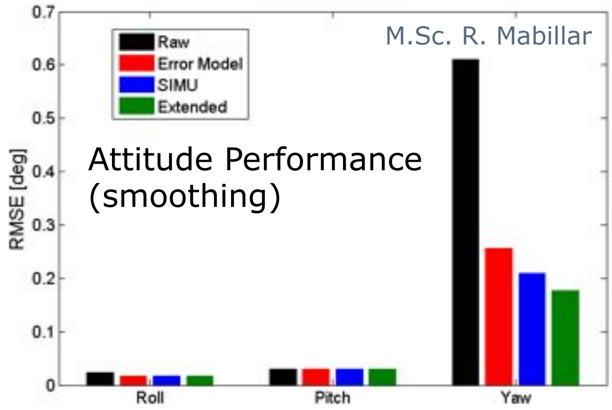
- Custom navigation board
  - Up to 4 MEMS-IMU
  - Sampling: 250–500 Hz
  - Barometer
  - Digital compass
  - Internal/external GPS



- Synchronization
  - scale: 1PPS -> Navchip
  - bias: NMEA/ZDA, soft.

RIMU - Geko4Nav: Calibration & Performance

- Offsets calibration
  - Accelerometers: multi-position static calibration
  - Gyroscopes: multi-position calibration on rotation table
- Error models
  - GMWM estimator (outperforms Allan Variance analysis)
- Testing
  - Dynamic
  - Drone / reference AT
    - Not-continuous
  - Vehicle / reference IMU
    - Continuous ->



Conclusion – R(MEMS)IMU

- Geometry
  - Sensor triads the relative geometry is not important unless sensor fails, which favors skew triads. (Many triads – geometry has minimal impact)
- Noise level
  - Can be determined (adapted in KF) & suppressed
  - ARMA/GARCH ideal but computationally demanding
- Processing
  - Calibration: geometrically constrained
  - Application: extended mechanization
  - Results: higher performance, redundancy & integrity
- Is RIMU answer to drone’s navigation autonomy?