

3D Motion Tracking by Inertial and Magnetic sensors with or without GPS

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Outline

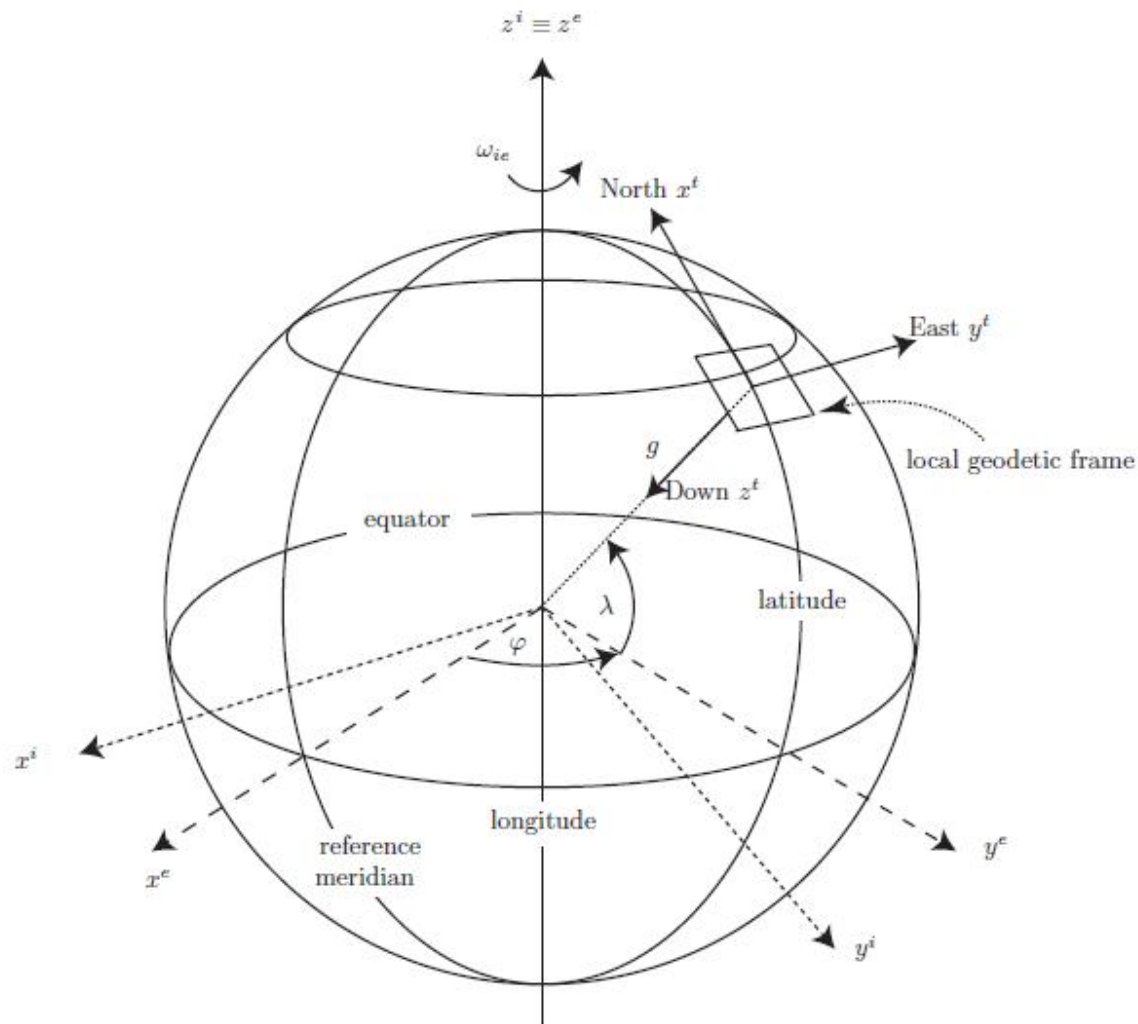
- Short introduction of Junping Cai
- Coordinate Systems
- Inertial Motion Tracking Working Principle
- On-site Calibration
- Extended Kalman Filter without GPS
- Extended Kalman Filter with GPS
- Experiment results
- Application examples
- Discussions

Short introduction of Junping

- Come from China
- 1988-1992, B.Sc., Automatic Control, Department of Automatic Control, Nanjing University of Aeronautics and Astronautics, China
- 1992-1996, Production Engineer, Canon (Tianjin) Ltd., China
- 1996-2002, Purchasing Engineer, Danfoss (Tianjin) Ltd., China
- 2002-2004, M.Sc., Mechatronics Engineering, Mads Clausen Institute (MCI), University of Southern Denmark (SDU), Denmark
- 2004-2007, PhD Student, Automation & Control, Department of Electronic Systems, Aalborg University, Denmark, Supervisors: Professor Jakob Stoustrup
- 2008 – 2009, Lead Development Engineer, Automatic Controls Laboratories, Danfoss A/S, Denmark
- 2009—now, R & D Engineer, Centre for Product Development (CPD), MCI, SDU



Coordinate systems



Earth-Centered Earth-Fixed Frame (ECEF, e-frame)

Inertial Frame (i-frame)

**Local Geodetic Frame (t-frame)
Local Tangent Plane (LTP)
(N-frame, global)**

North- East- Down (NED)
East- North- Up (ENU)

Body Frame (b-frame, local)

Forward
Right
Down

Relations between ECEF-frame (e), local geodetic-frame (t) and inertial-frame (i) .

Coordinate systems

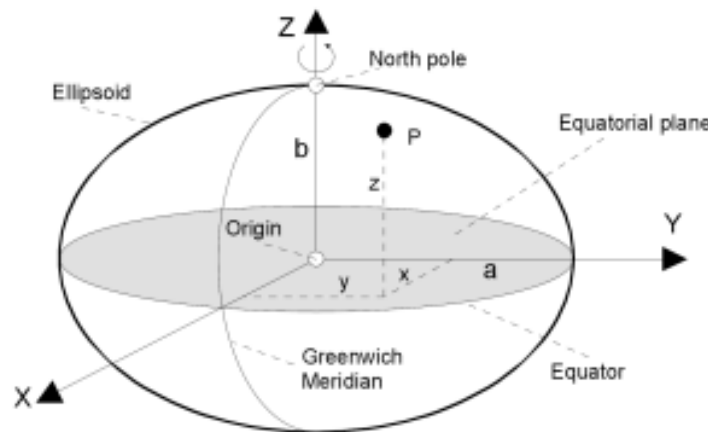
World coordinates WGS84 and LTP

Earth Centered Earth Fixed – ECEF

WGS-84 parameters:

$a=6,378,137$ m

$b=6,356,752$ m



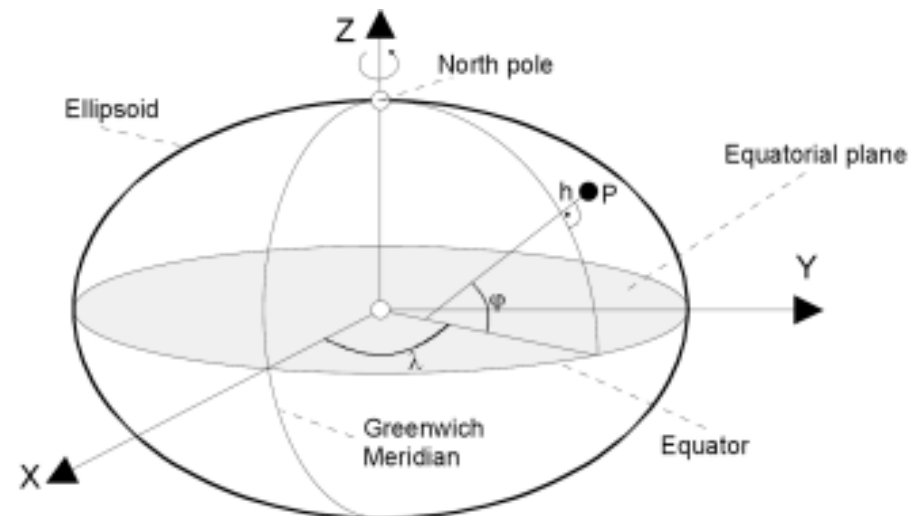
Earth-Centered Earth Fixed (ECEF)
Coordinate System

Spherical coordinates - LLA

λ – Longitude

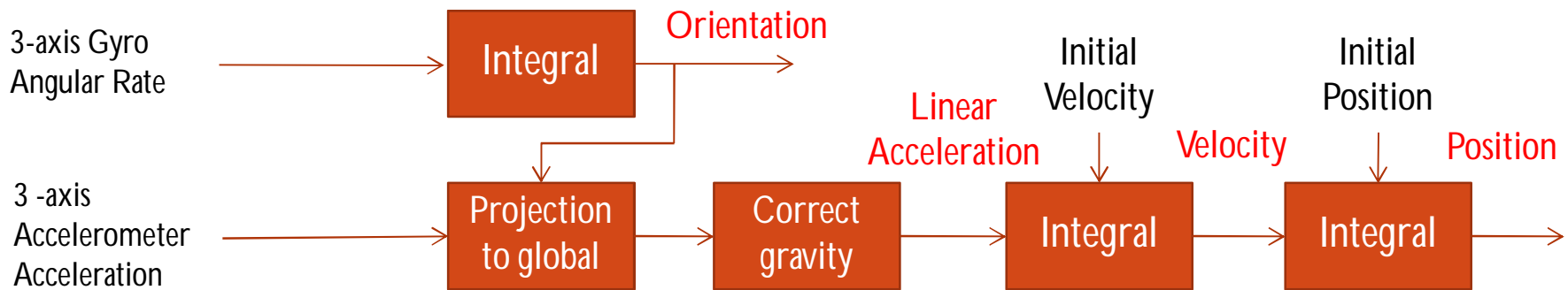
ϕ – Latitude

h – Altitude

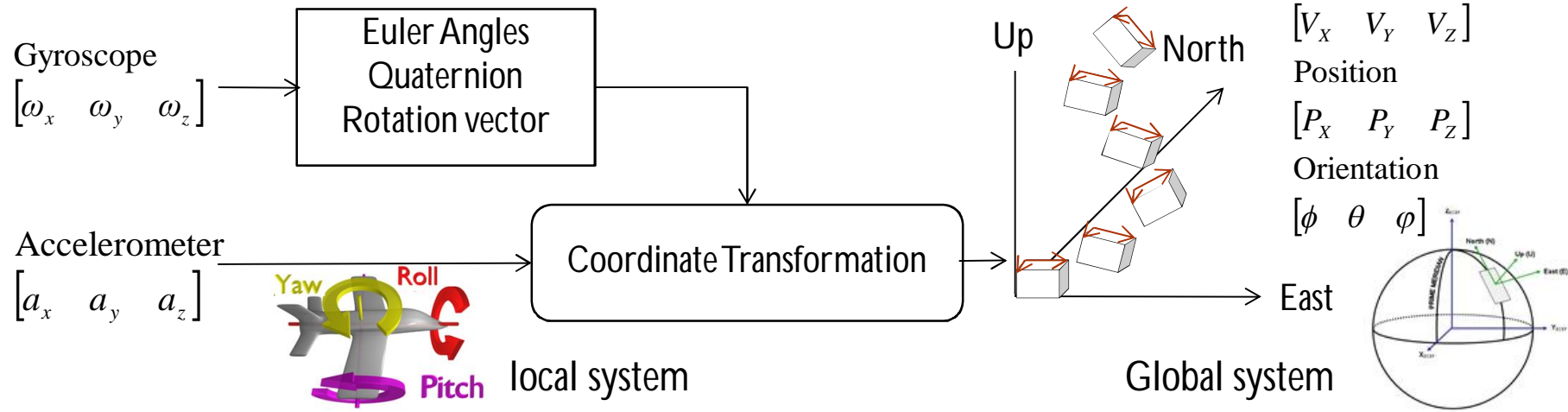


Definition of Ellipsoidal Coordinates (Latitude,
Longitude, Altitude) in WGS-84 Ellipsoid

Inertial motion tracking working principle



'The Devil is in the details'



Quaternion attitude representation-for example

Quaternion

$$\bar{q} = q_1 i + q_2 j + q_3 k + q_4$$

Transformation matrix (Global to Local)

$${}^L_G C(\bar{q}) = (2q_4^2 - 1)I_{3 \times 3} - 2q_4[\vec{q} \times] + 2\bar{q}\bar{q}^T$$

Quaternion update

$${}^{L(t)}_G \dot{\bar{q}}(t) = \frac{1}{2} \begin{bmatrix} \omega \\ 0 \end{bmatrix} \otimes {}^{L(t)}_G \bar{q} = \frac{1}{2} \Omega(\omega) {}^{L(t)}_G \bar{q}$$

$${}^L_G \bar{q}(t_{k+1}) = \Theta(t_{k+1}, t_k) {}^L_G \bar{q}(t_k) = (I_{4 \times 4} + \frac{\Delta t}{2} \Omega(\omega)) {}^L_G \bar{q}(t_k)$$

$$\Omega(\omega) = \begin{bmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{bmatrix}$$

Transformation

$$\begin{bmatrix} a_E \\ a_N \\ a_U \end{bmatrix} = {}^L_G C^{-1}(\bar{q}) \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$$

linear acceleration

$$a_{\text{linear}} = a^{ENU} - g$$

$$\text{velocity } V = V_0 + \int_{t_0}^{t_f} a_{\text{linear}} dt$$

$$\text{position } P = P_0 + \int_{t_0}^{t_f} V dt$$

g - gravity

$$\text{Roll} = \text{atan}_2({}^L_G C(2,3), {}^L_G C(3,3))$$

$$\text{Pitch} = \text{asin}(-{}^L_G C(1,3))$$

$$\text{Yaw} = \text{atan}_2({}^L_G C(1,2), {}^L_G C(1,1))$$

Calibration

Why:

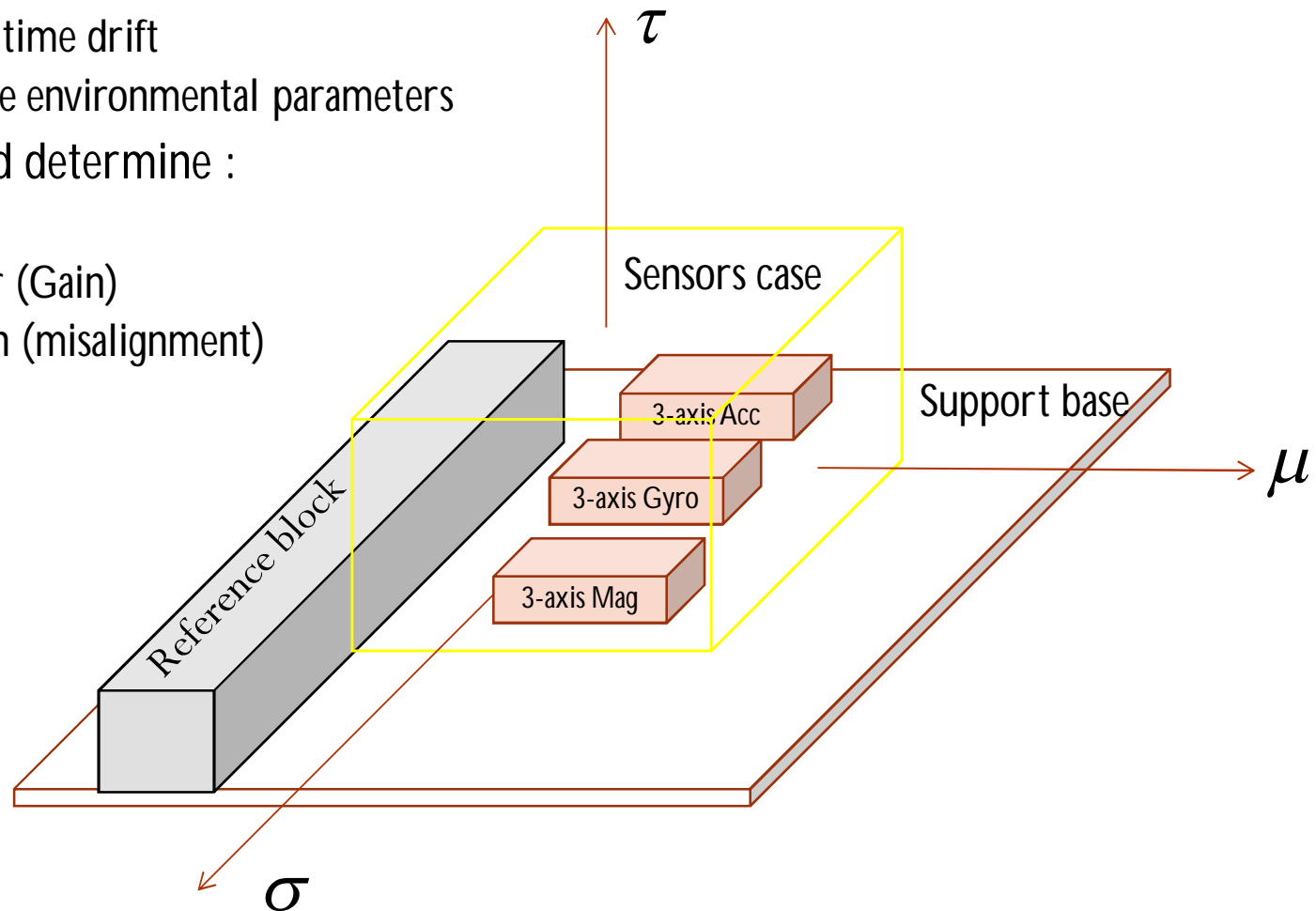
- Low cost
- Suffer from the time drift
- Sensitivity to the environmental parameters

Purpose is to in-field determine :

- The Bias
- The Scale factor (Gain)
- The Orientation (misalignment)

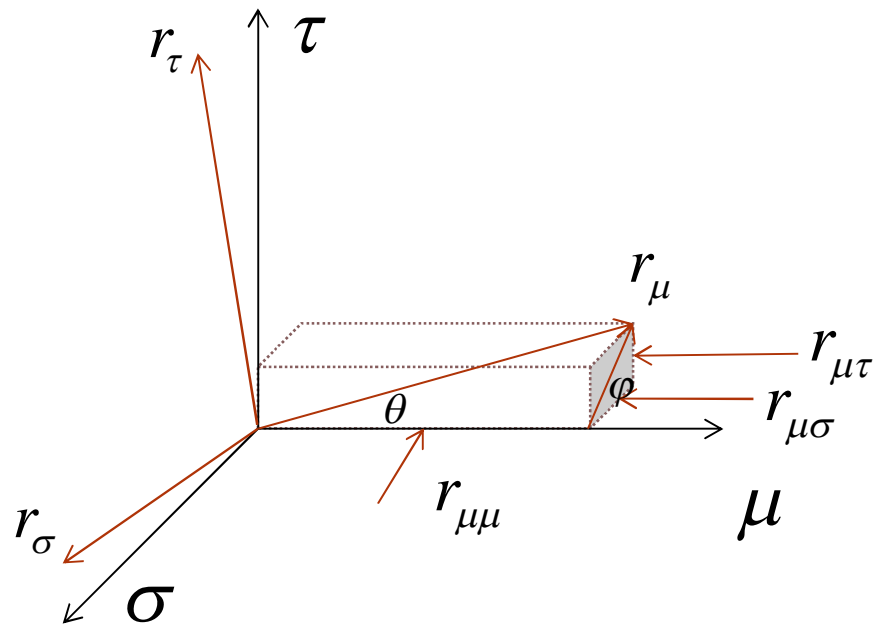
Requirement

- Time
- Complexity
- Instruments
- ...



Orientation - Misalignment

Misalignment: Nominal sensitivity axis vs. Actual sensitivity axis



Actual sensitivity axis

$$r_{\sigma}, r_{\mu}, r_{\tau}$$

Unit vector

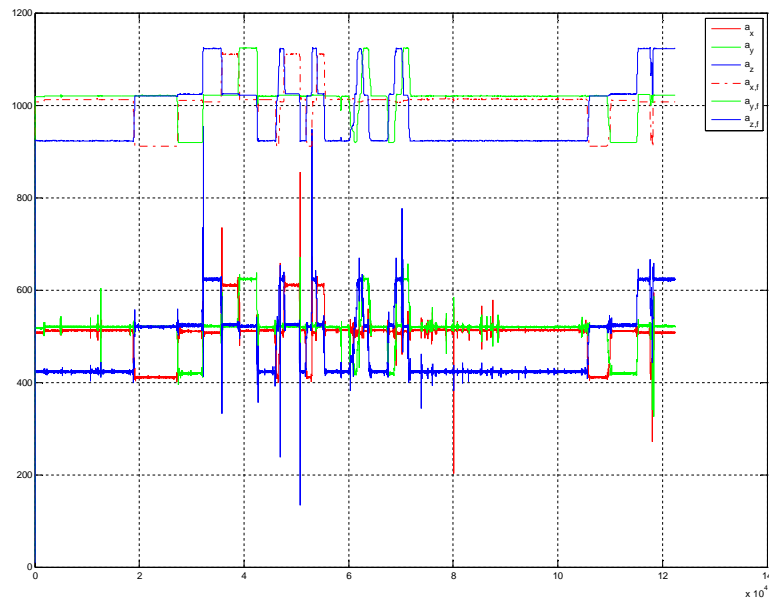
$$r_{\mu\sigma}^2 + r_{\mu\mu}^2 + r_{\mu\tau}^2 = 1$$

$$r_{\mu\mu} = r_{\mu} \cos \theta$$

$$r_{\mu\sigma} = r_{\mu} \sin \theta \cos \varphi$$

$$r_{\mu\tau} = r_{\mu} \sin \theta \sin \varphi$$

Accelerometer calibration example



Raw and filtered data

$$Ra = \begin{bmatrix} 0,9997 & 0,0050 & -0,0251 \\ 0,0049 & 0,9999 & 0,0098 \\ 0,0250 & -0,015 & 0,9996 \end{bmatrix}$$

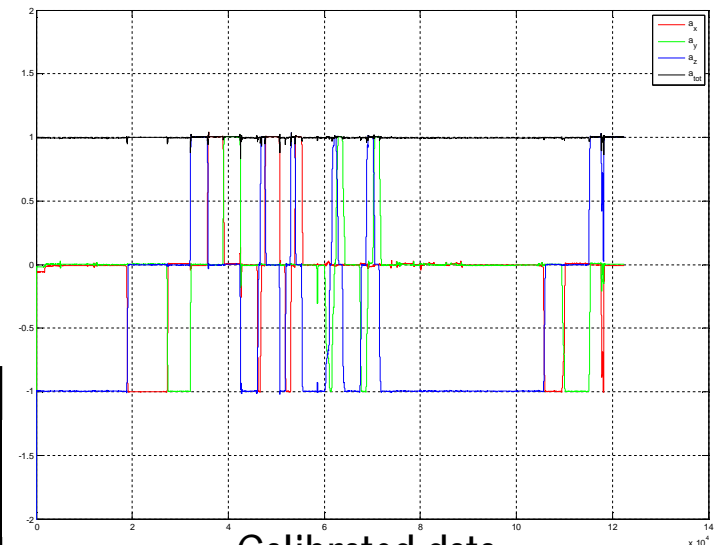
$$Ba = \begin{bmatrix} 1,4985 \\ 1,5288 \\ 1,5342 \end{bmatrix}$$

$$Ka = \begin{bmatrix} 291,6 & 0 & 0 \\ 0 & 298,8 & 0 \\ 0 & 0 & 293,1 \end{bmatrix}$$

Data sheet specification

[min typ max]

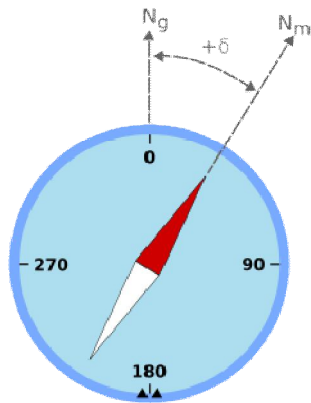
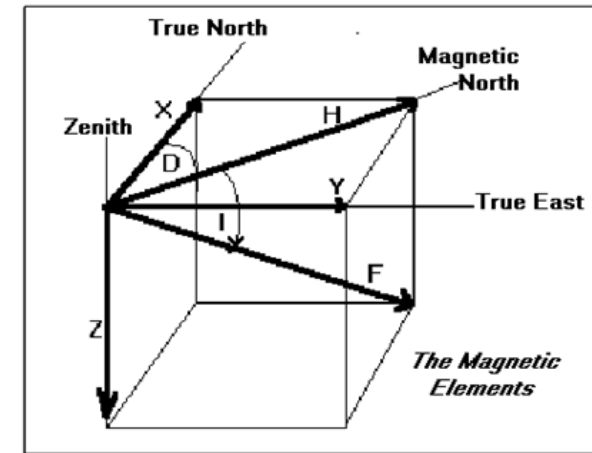
[270 300 330]



Calibrated data

On-field fast calibration -Magnetometers

- Method I: Using Earth Magnetic Field as Known Input, Publication ION 2010
- Method II: 3D Ellipsoid Curve Fitting
- Method III: 2D Mapping (boat & car)



Magnetic declination is the angle between magnetic north (the direction the north end of a compass needle points) and true north (north pole). The declination is positive when the magnetic north is east of true north.

Alsion 2 for example (WMM 2010)

Latitude = 54.91; % Degree N

Longitude = 9.78; % Degree E

Altitude = 0.00; % Km

Date = 2011.2;

F = 49826.4e-5; % nT 2 Gauss

H = 17513.6e-5; % nT 2 Gauss

X = 17506.3e-5; % nT 2 Gauss

Y = 505.1e-5; % nT 2 Gauss

Z = 46647.0e-5; % nT 2 Gauss

Decl = 1 + 39/60; % (Degree East)

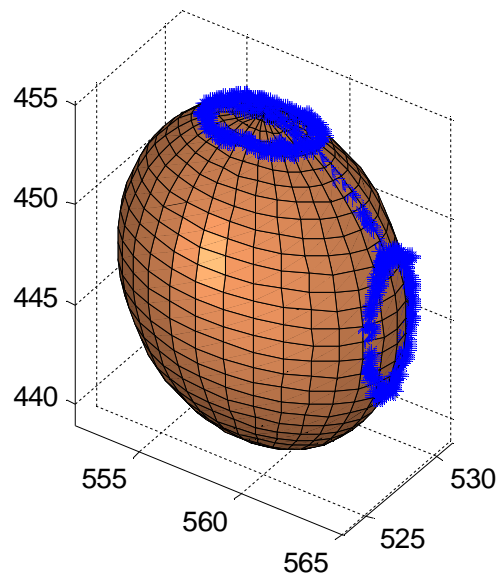
Incl = 69 + 25/60; % (Down) (Dip)

On-field fast calibration -Magnetometers

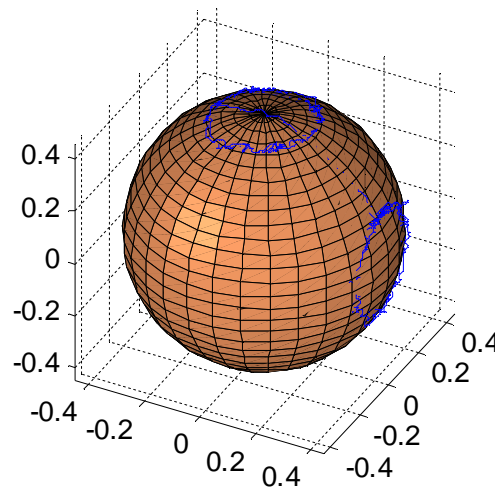
Method III : 3D mapping

$$F = \sqrt{\left(\frac{h_x - b_x}{k_x}\right)^2 + \left(\frac{h_y - b_y}{k_y}\right)^2 + \left(\frac{h_z - b_z}{k_z}\right)^2}$$

Magnetic field raw data



Magnetic field calibrated data

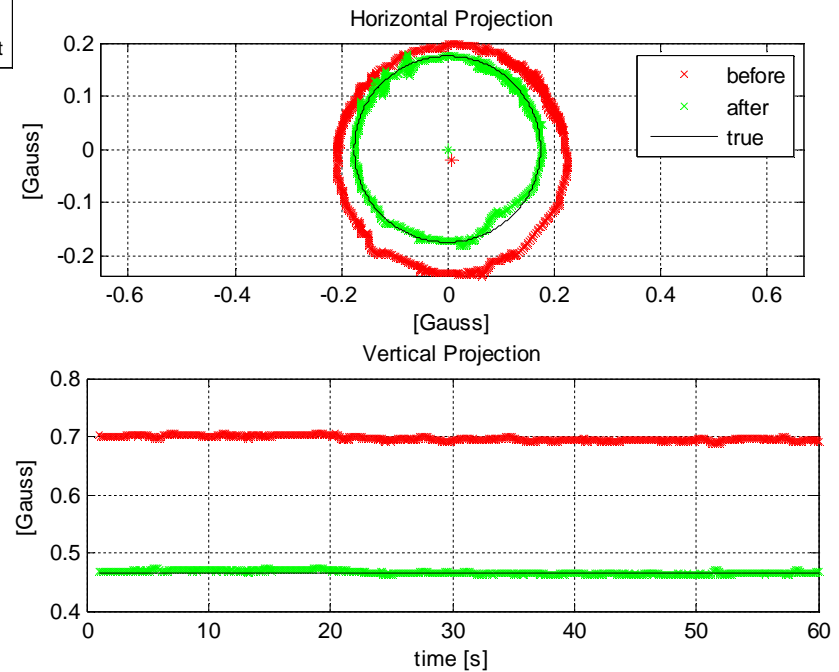
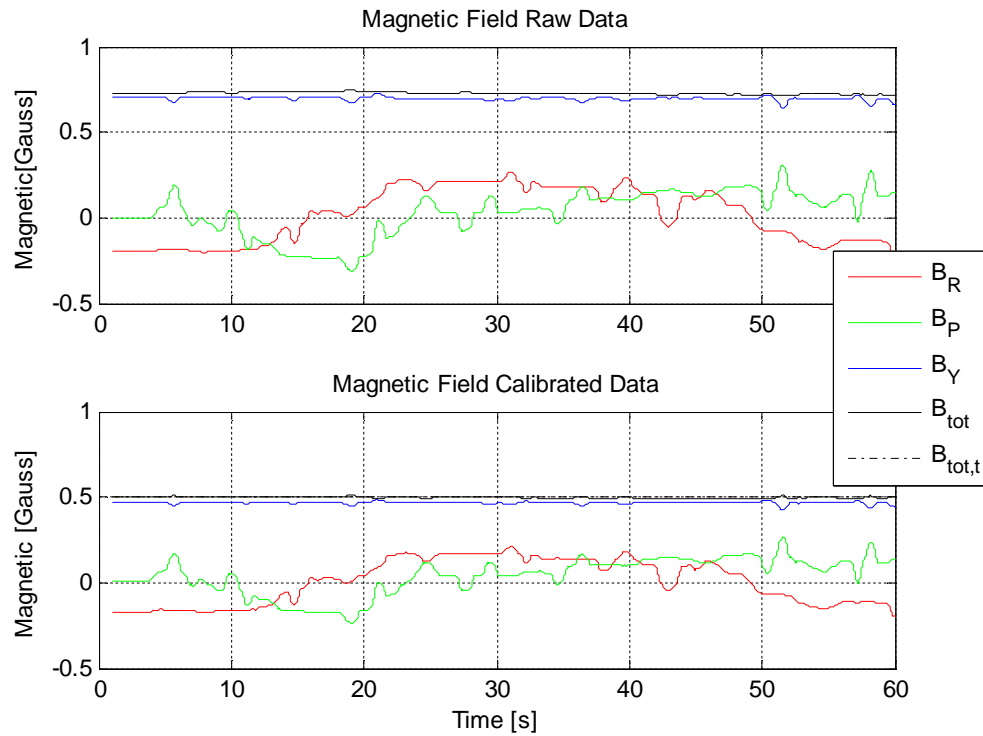


Requirement:

- Many different orientations as possible. e.g. keep the object still for a few seconds in at least 12 significantly different orientations, preferably more
- At least 3 meters from large ferromagnetic objects such as radiators and iron desks

On-field fast calibration

-Magnetometers 2D mapping example



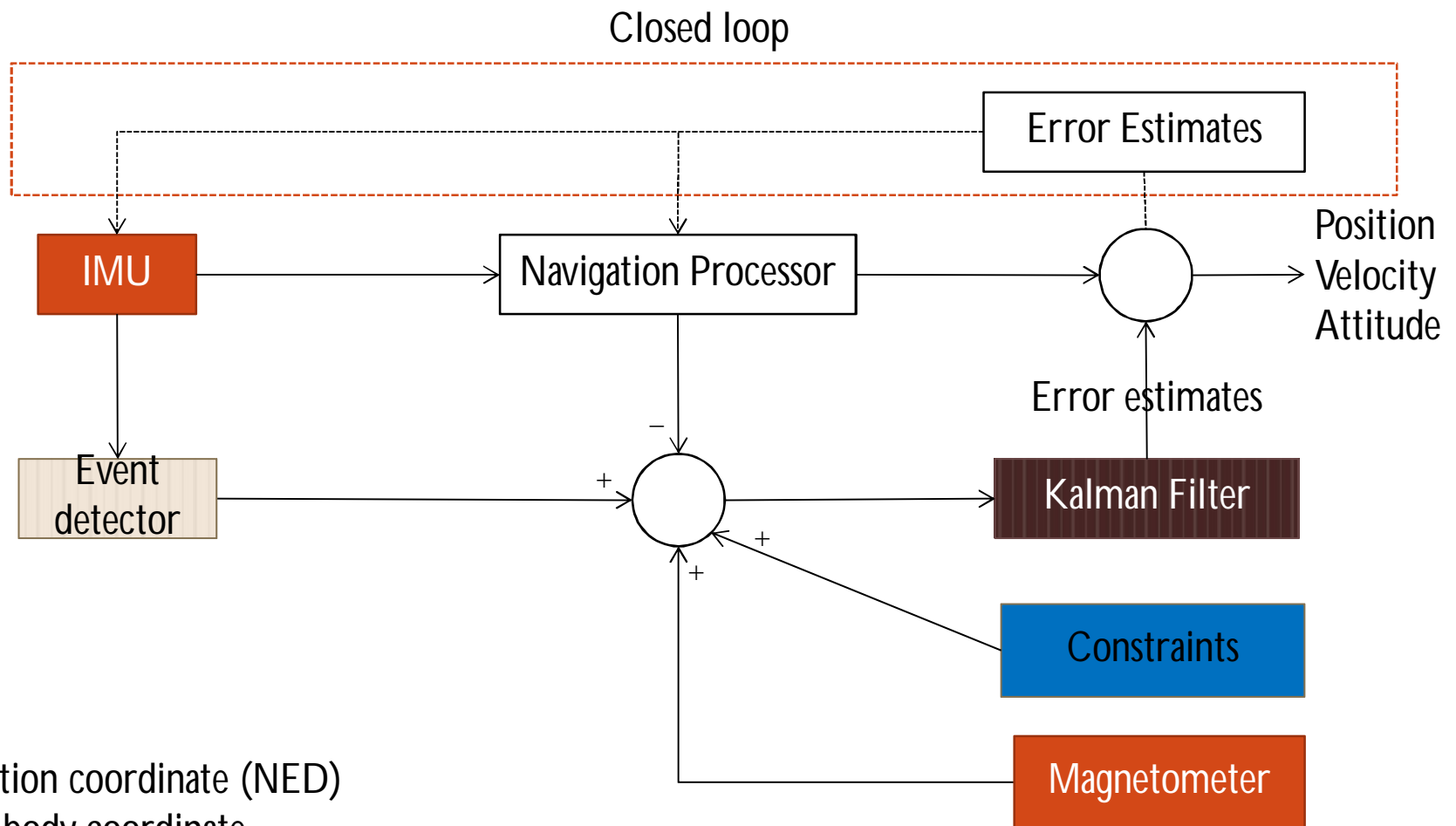
On-field calibration

- No special instrument is needed
- No special training is needed
- No strict sensor alignment (when mounting) is need
- First we do the factory calibration
- Then user do the on-site (on-use) calibration
 1. User need to stand still (if mounted) or hold the sensor set still for a few seconds
 2. User turns around 360 degree (if mounted) or rotate the sensor set in space

Automatic and fast!

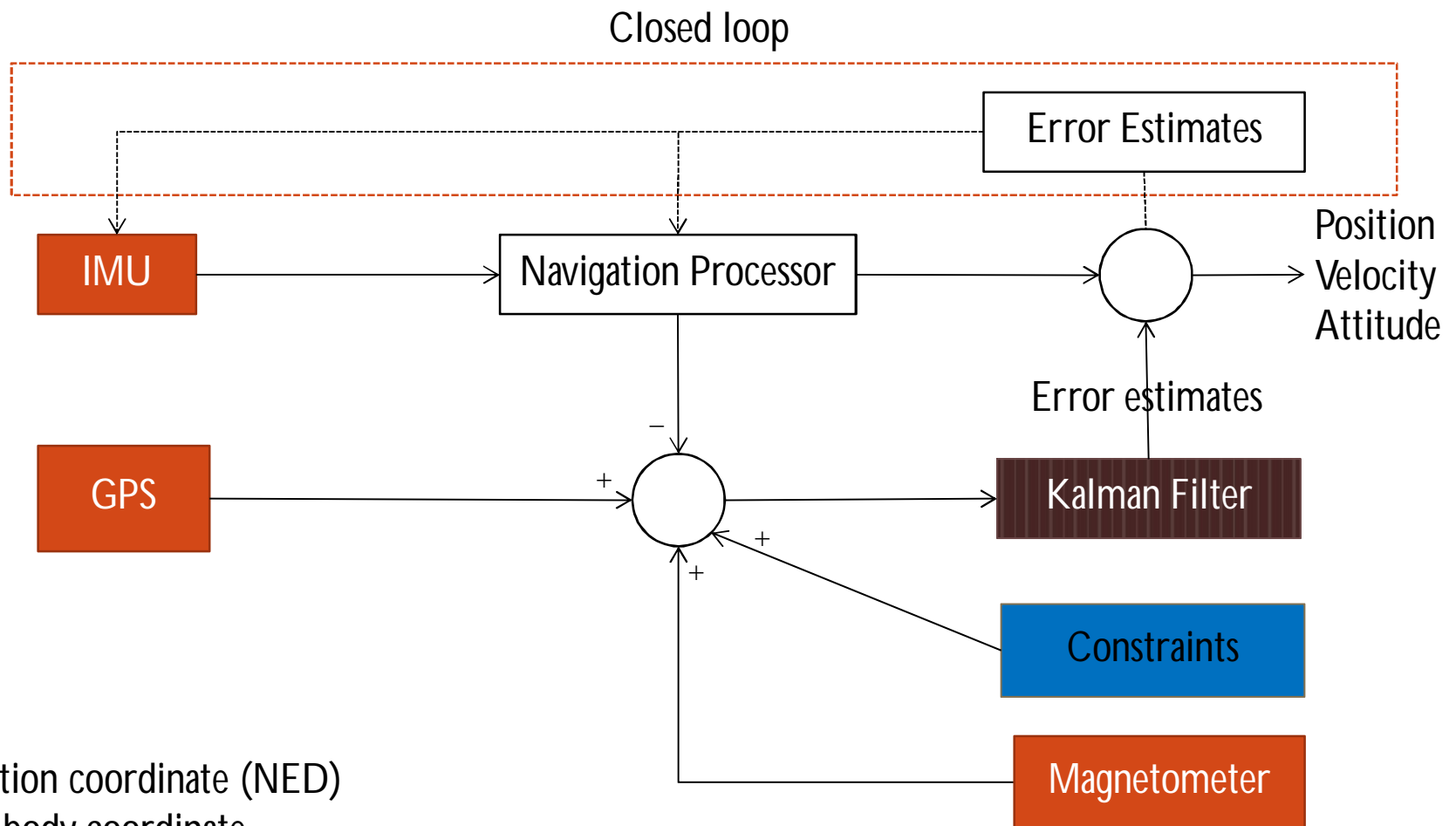
Extended Kalman Filter without GPS

Event detection and Constraints

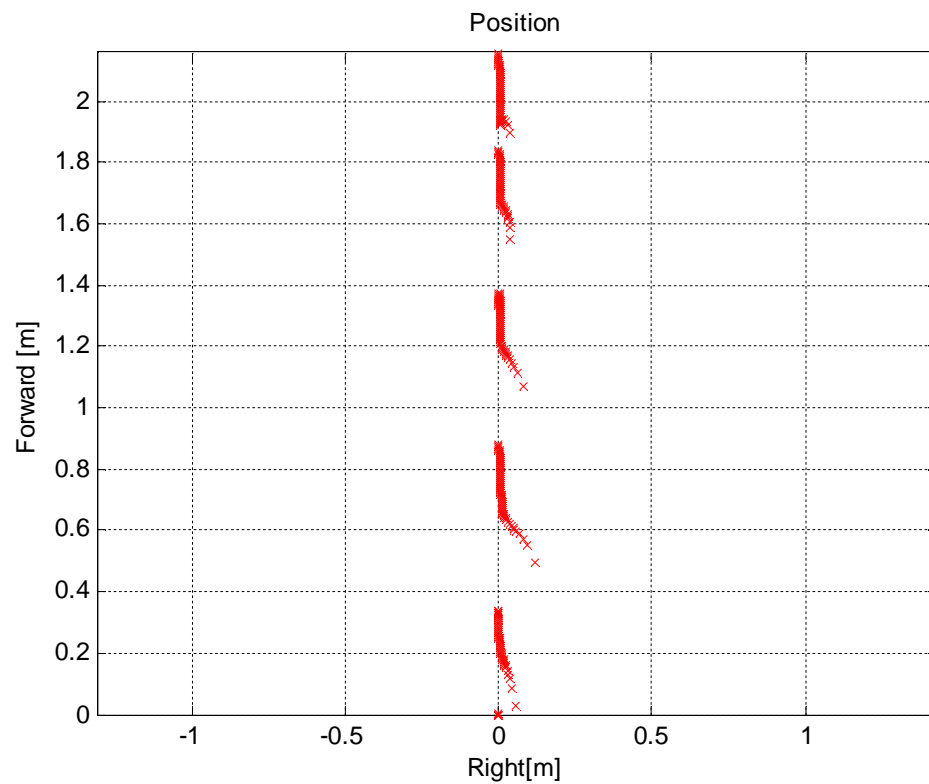


Extended Kalman Filter with GPS

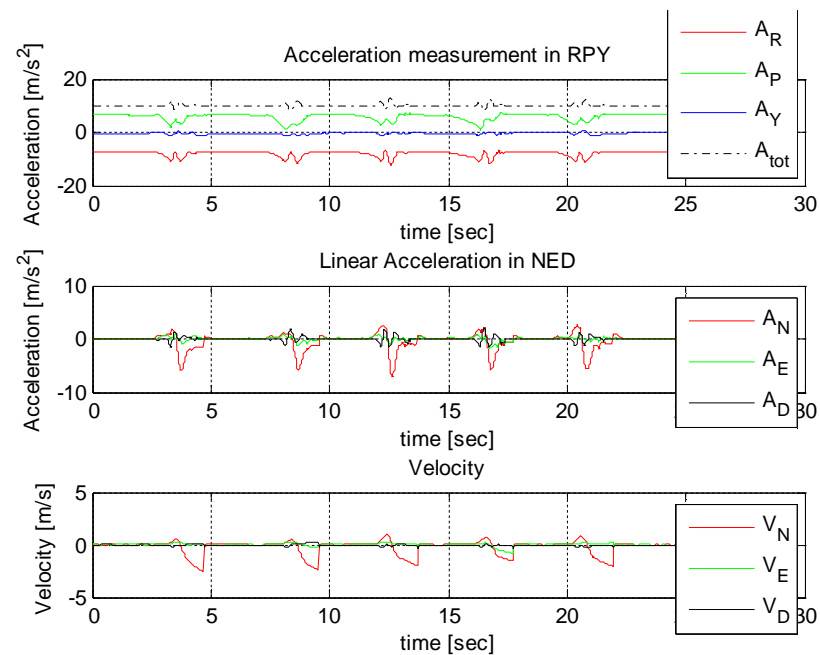
Loosely coupled integration strategy



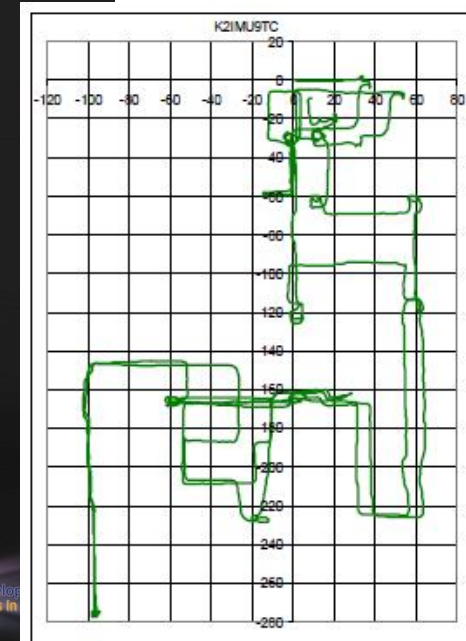
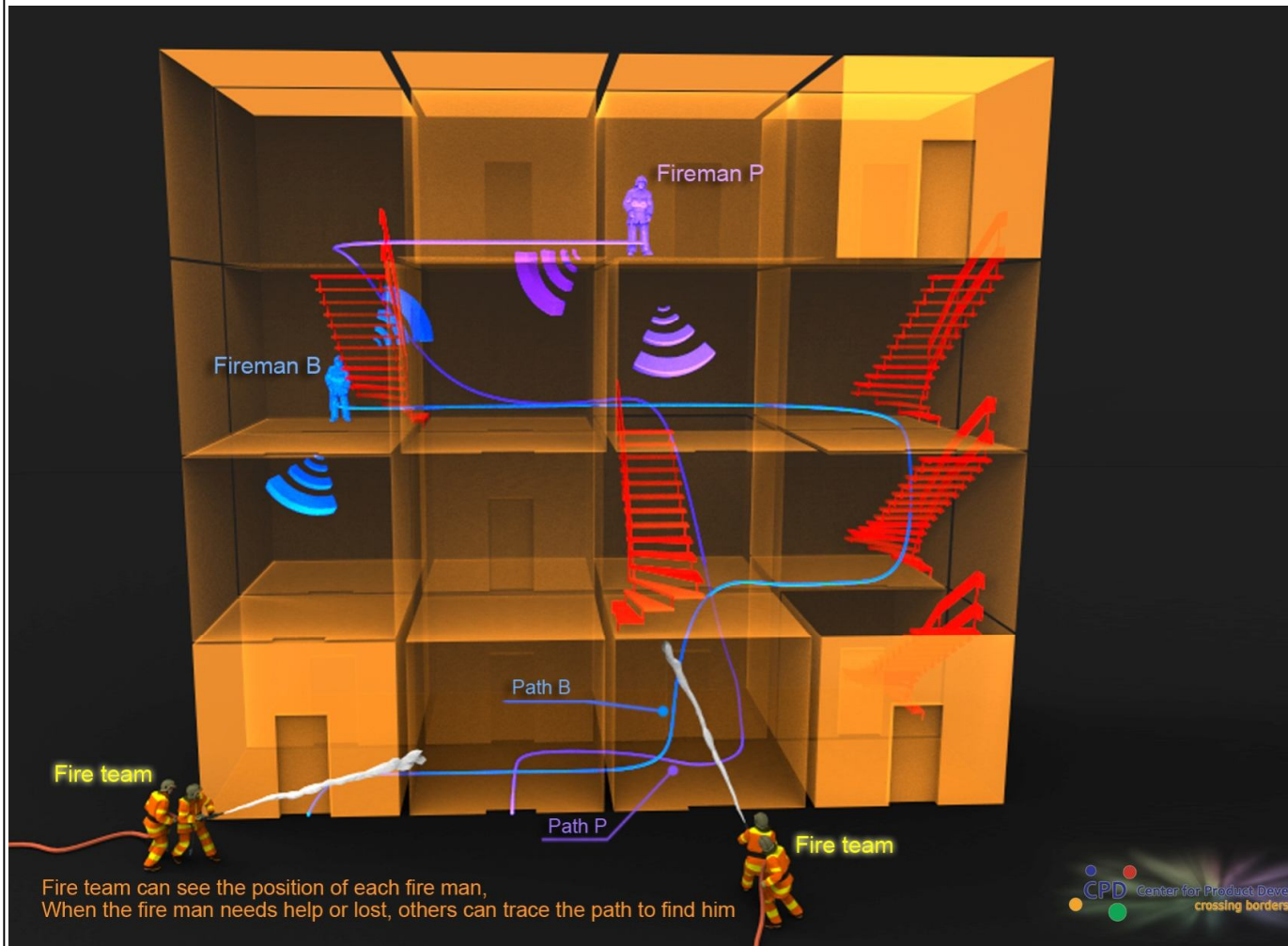
Experiments (indoor)



Walking a straight line



Indoor pedestrian tracking



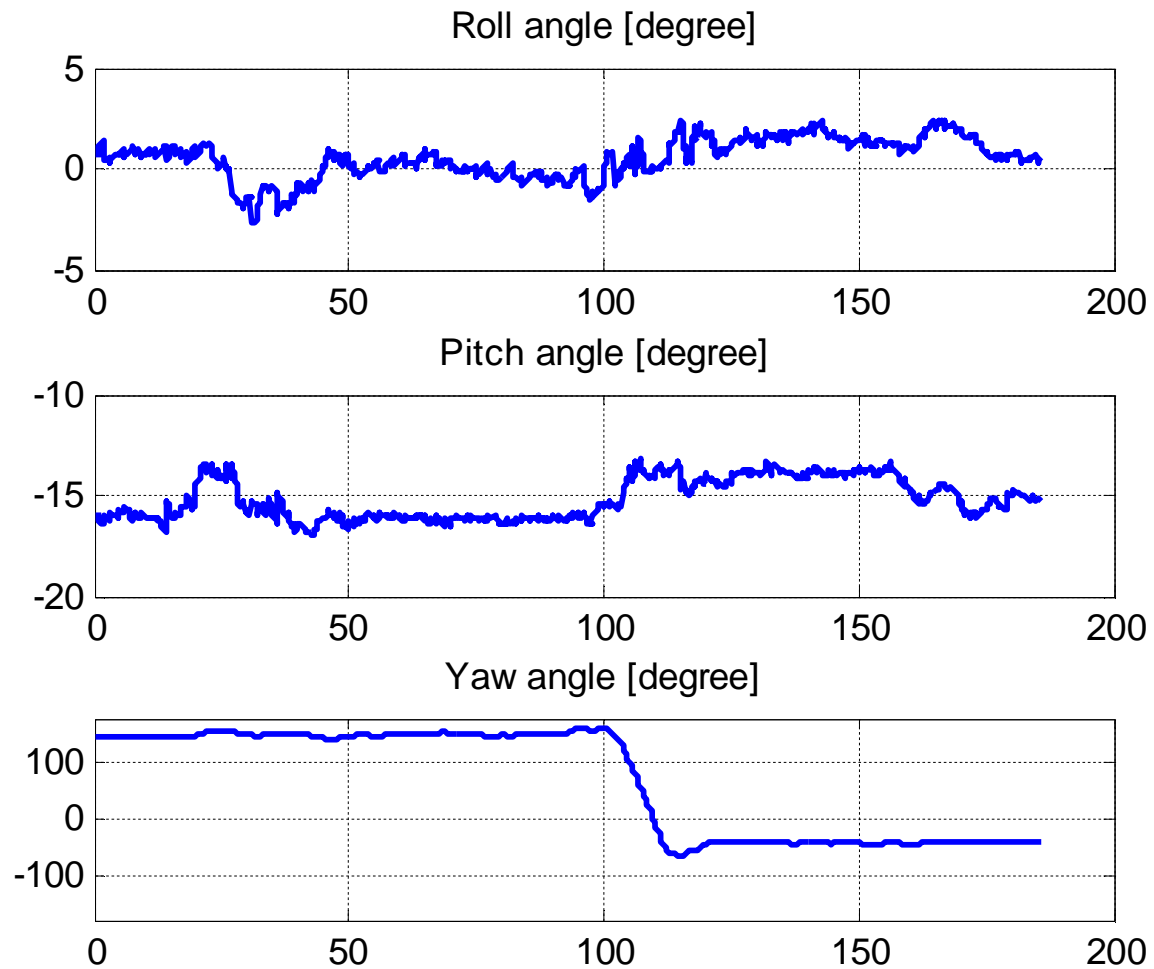
Experiment (outdoor)

Landyacht with GPS

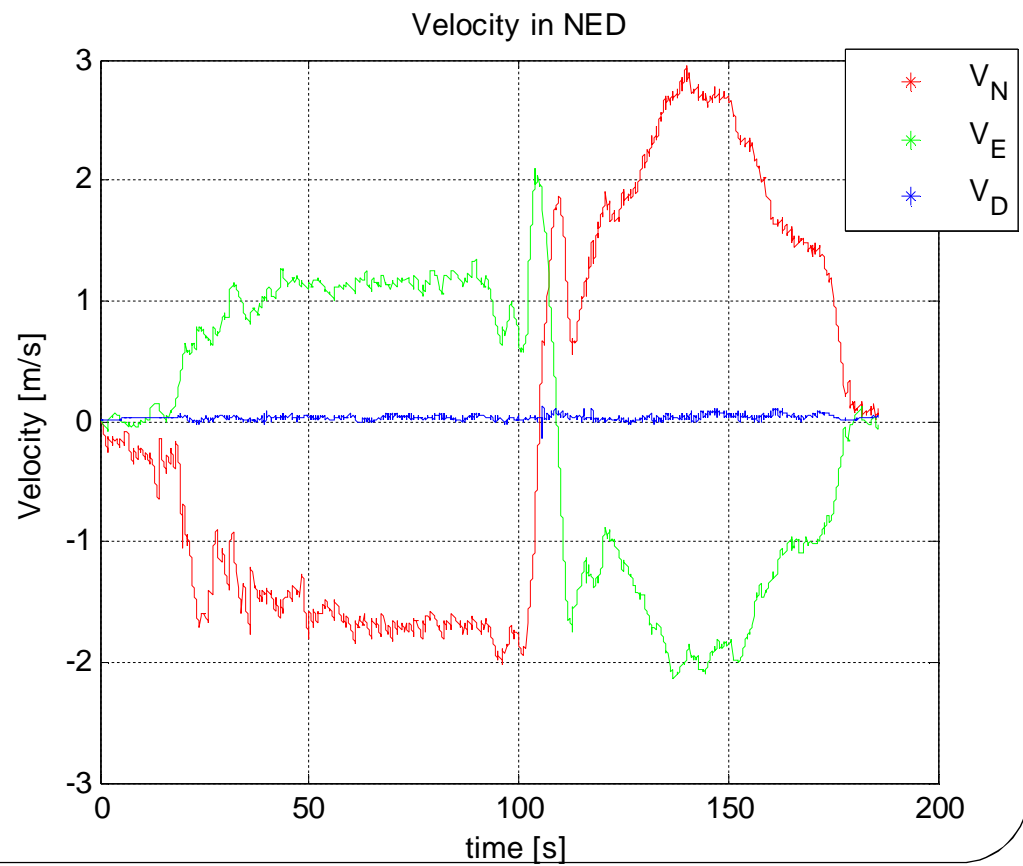
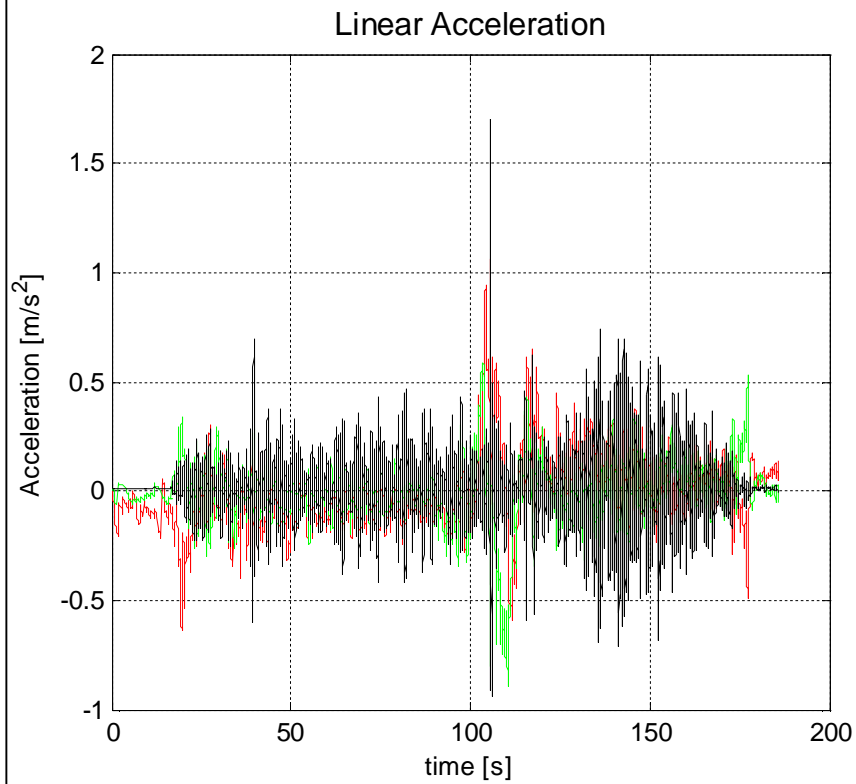


Alsion parking lot

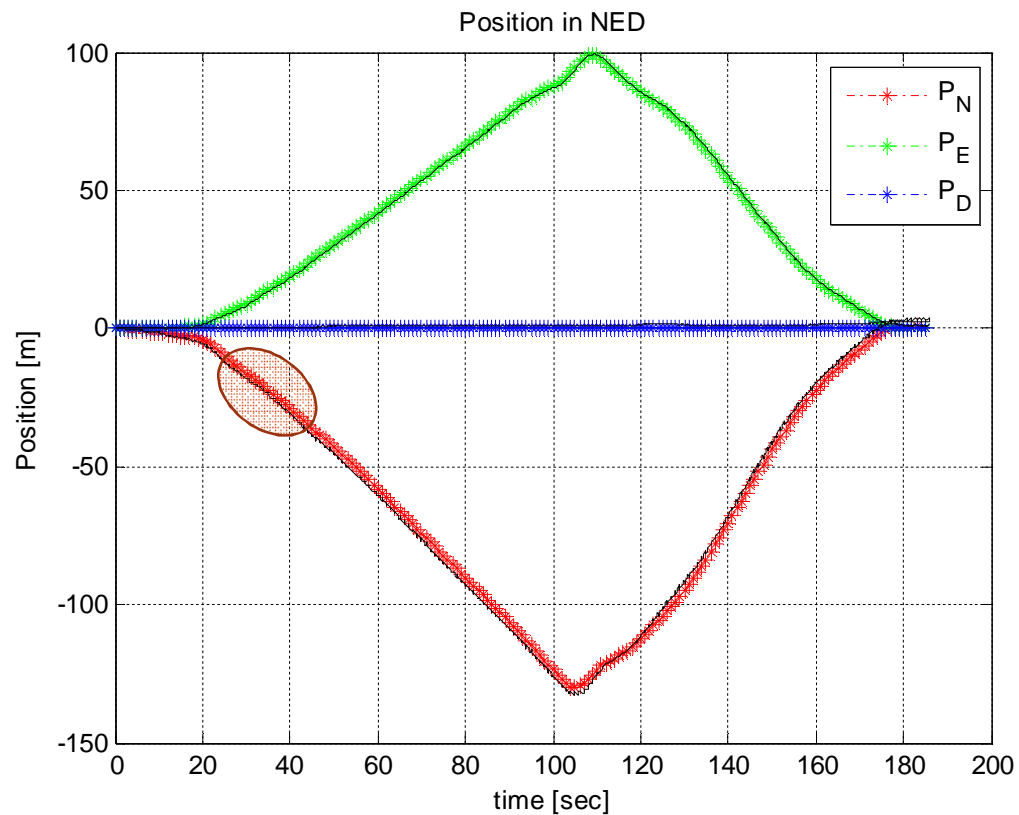
Experiment Results



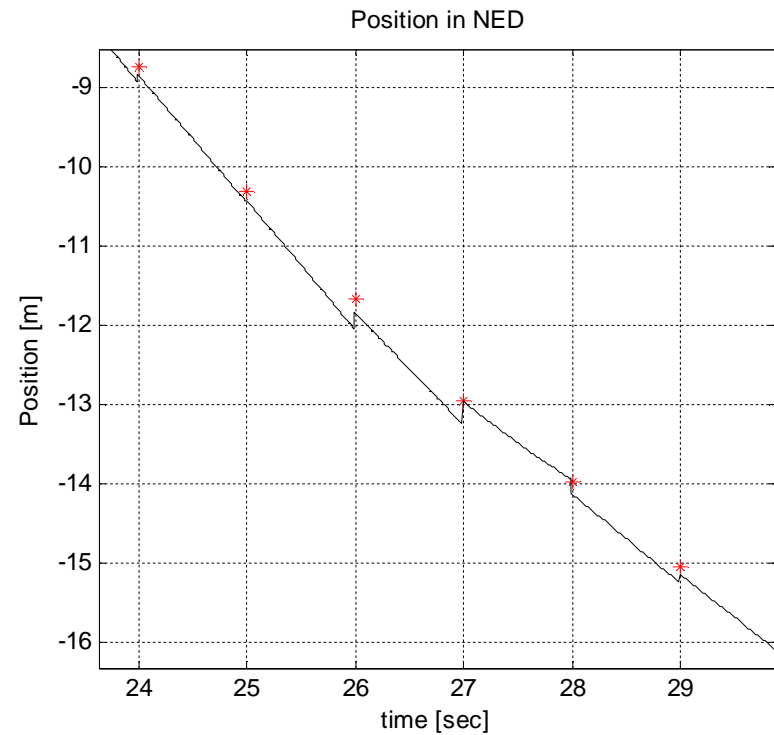
Experiment Results



Experiment Results

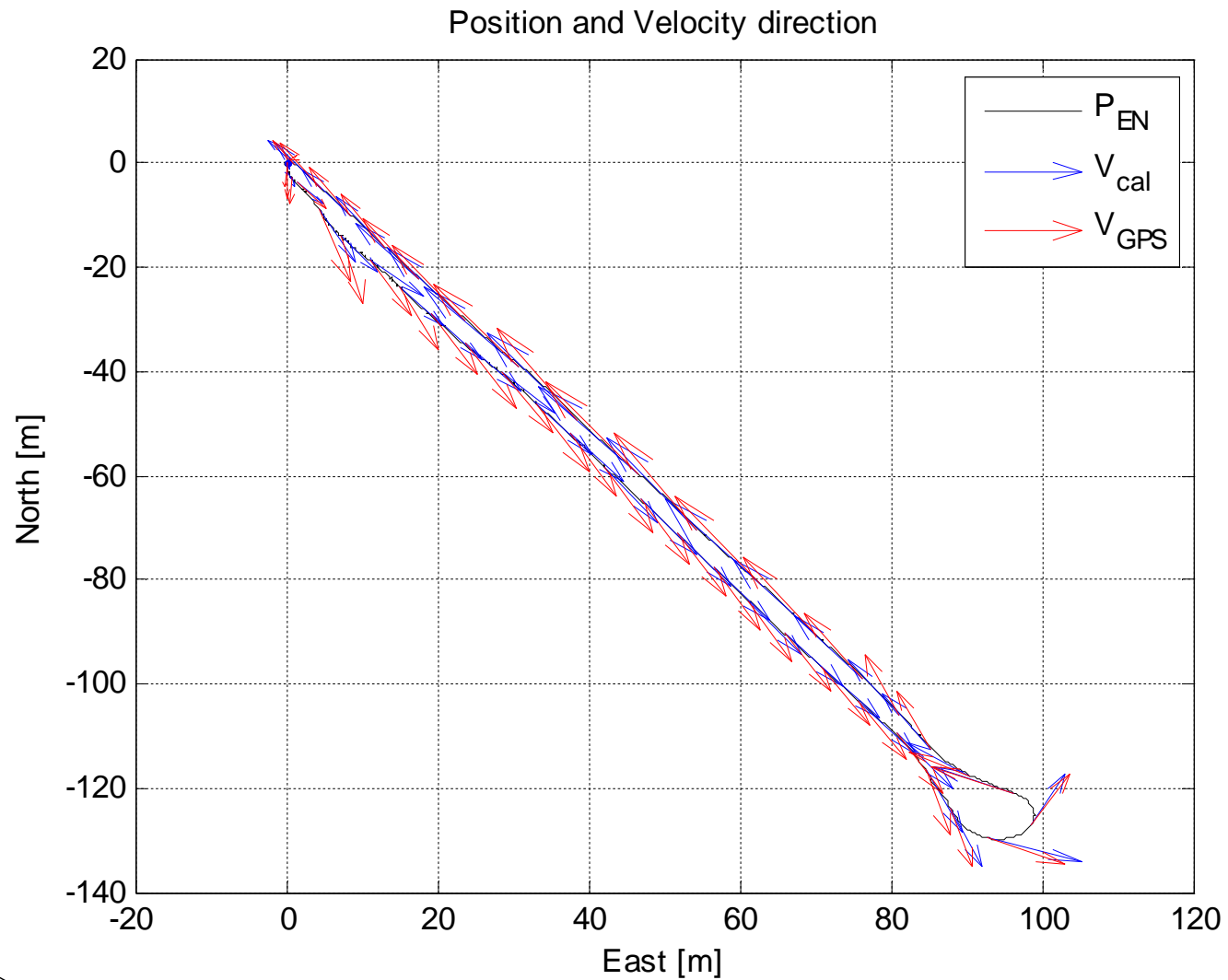


INS: $F_s=100$ Hz GPS: $F_s=1$ Hz
Black line -INS. Colored line-GPS



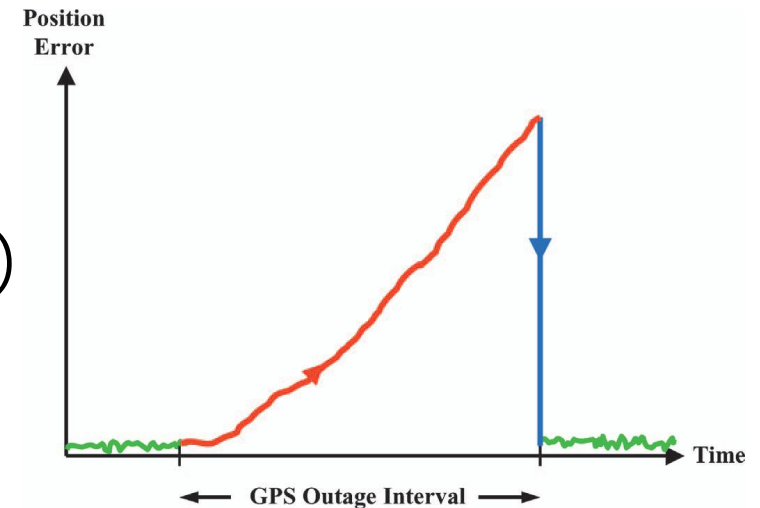
Zoomed in

Experiment results

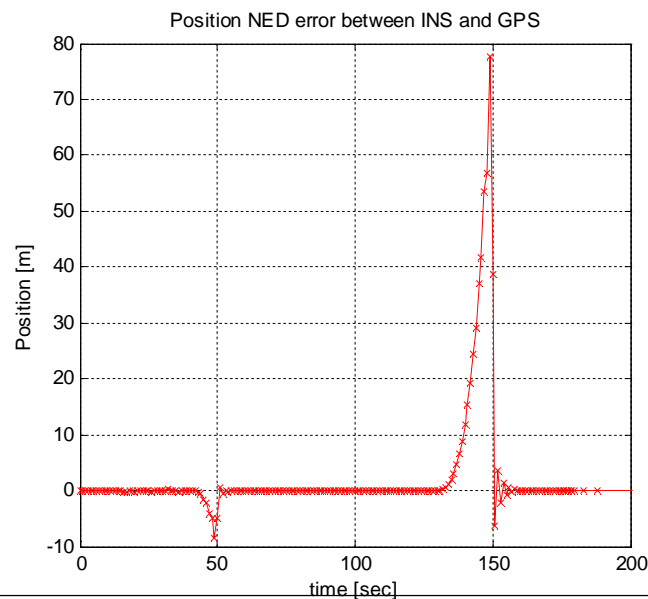


What during GPS signal blockage (outage) periods

- The consequence of GPS outage
- Bridging algorithm
 - Optimal Backward Smoothing (OBS)
 - DBM algorithm¹

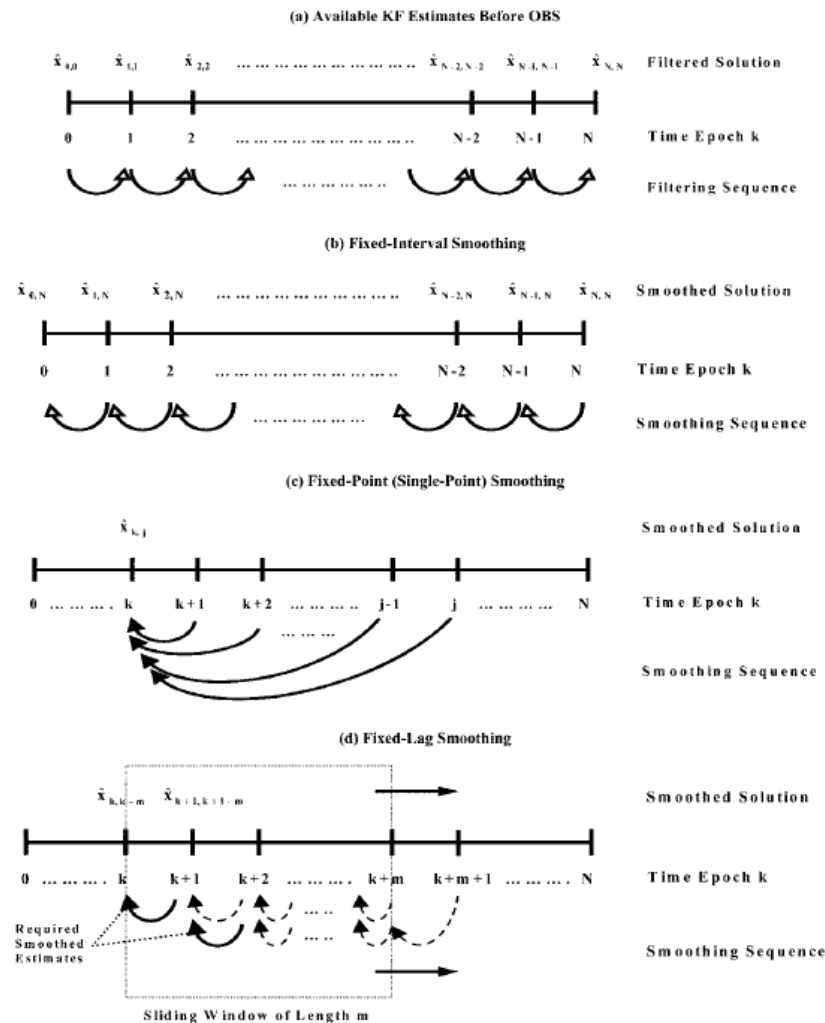


Positioning errors in INS/GPS navigation applications



Positioning (North) errors between INS/GPS with GPS outage at 40s-50s and 130s-150s

Optimal backward smoothing (OBS) algorithm



Three classes of OBS algorithms

- fixed-interval smoother
[0 N]
- fixed-point (single-point) smoother
 $j > k \quad j \in [k+1 N]$
- fixed-lag smoother
 $k < k+m \leq N$

Application dependent:

- Post-mission: the fixed-interval
- Near real-time: the fixed-lag
- Initial condition: the fixed-point

DBM algorithm

Acceleration error parameter during GPS outage

$$a_i = \frac{2(\delta r_{i,e} - \delta r_{i,b})}{(t_e - t_b)^2}$$

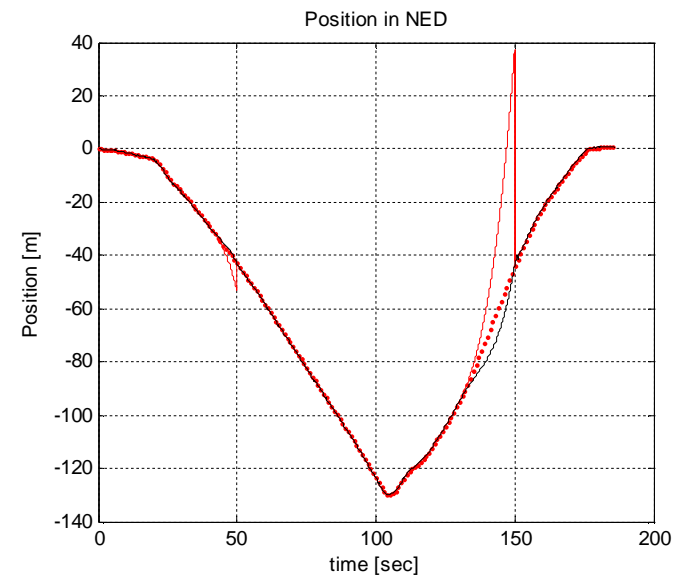
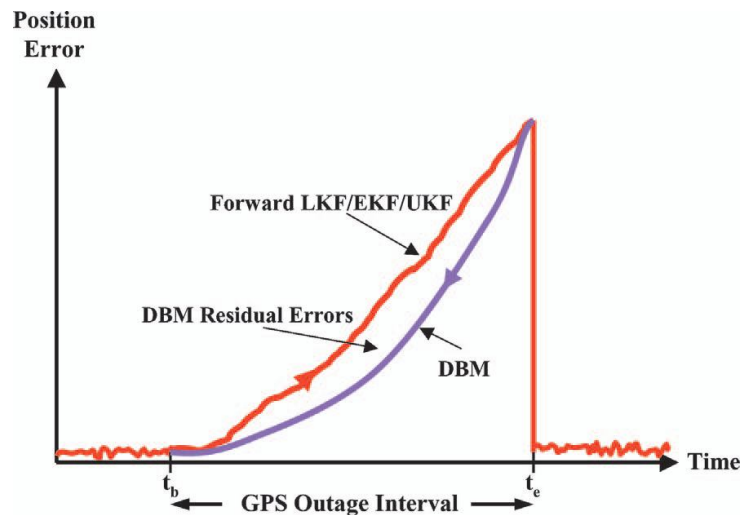
The expected position error during the outage

$$DBM_i = \frac{1}{2} a_i \cdot (t_e - t_b)^2$$

$$\delta r_{i,e} = r_{i,INS,e} - r_{i,GPS,e}$$

$$\delta r_{i,b} = r_{i,INS,b} - r_{i,GPS,b}$$

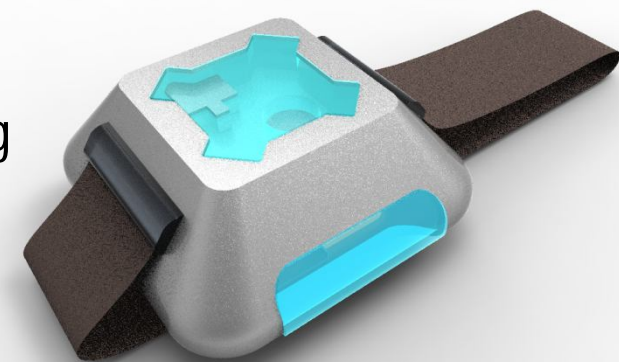
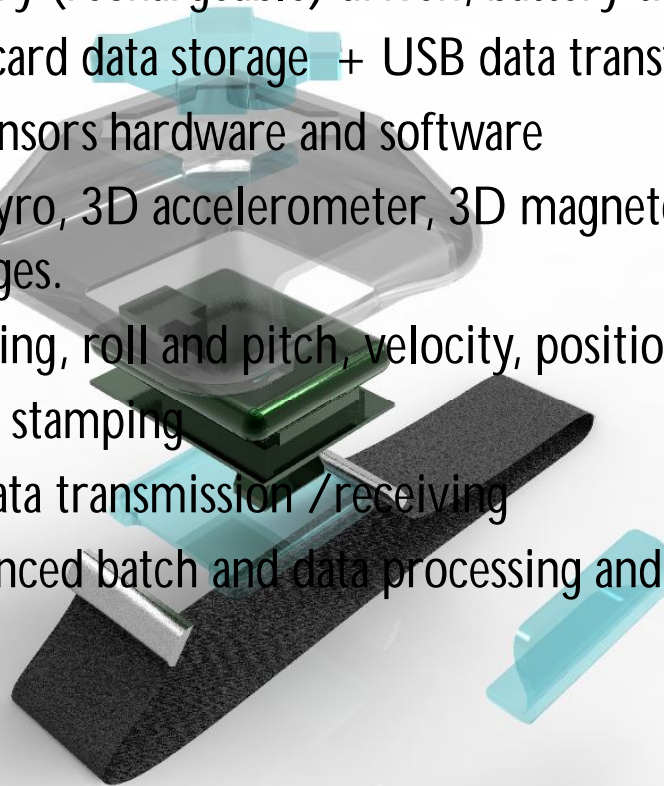
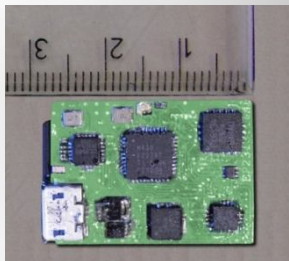
e – end b – beginning



Scenario shows the effect of backward smoothing
(Simulated data with manipulated GPS signal)
red solid line-when GPS outage. red dotted line- GPS
true position, black line -smoothed data

Uniqueness of the product

- Compact design: 27.9 x 19.5 x 4.8 mm³, 2 gram + battery
- Battery (rechargeable) driven, battery time: 4 - 200 hour
- SIM card data storage + USB data transfer/battery charging
- 25 sensors hardware and software
- 3D gyro, 3D accelerometer, 3D magnetometer, temperature and internal voltages.
- Heading, roll and pitch, velocity, position, angular velocity, acceleration.
- Time stamping
- RF data transmission /receiving
- Advanced batch and data processing and filtering

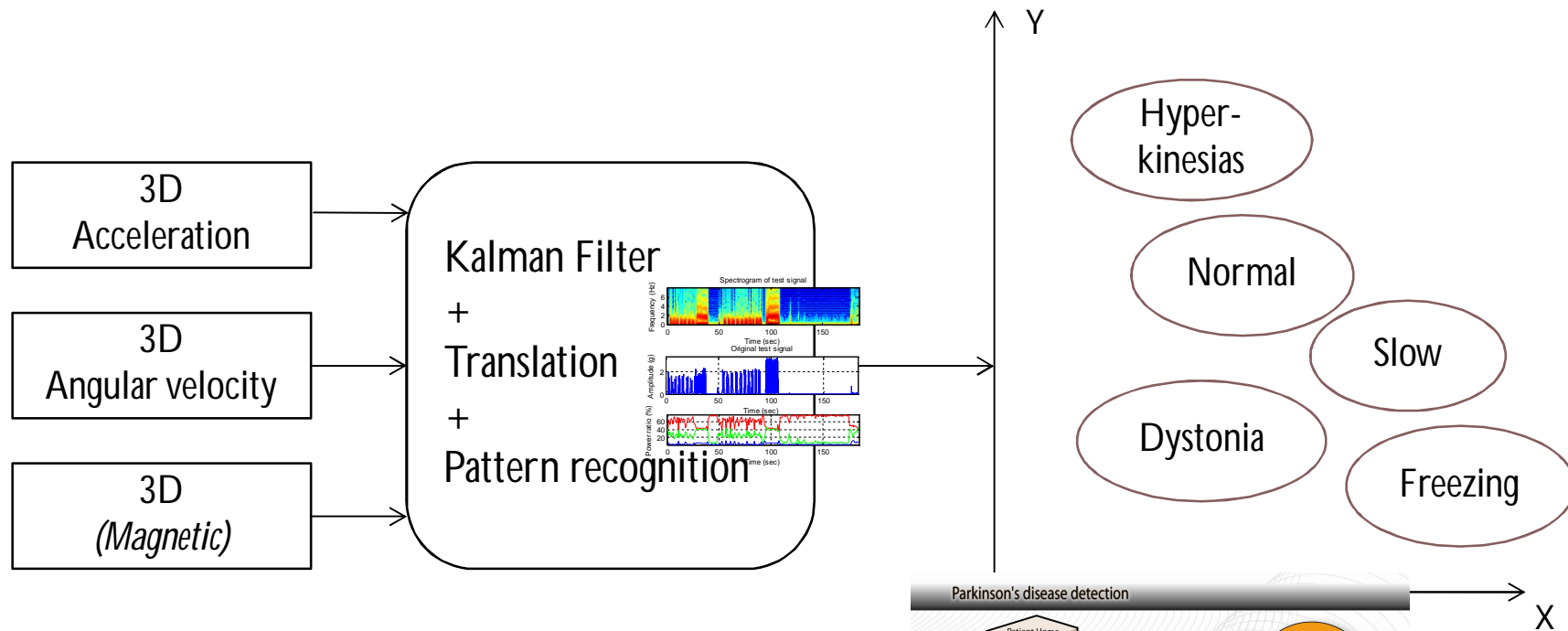


Applications

- Medical /Biomechanical study
- Rehabilitation
- Sport training
-

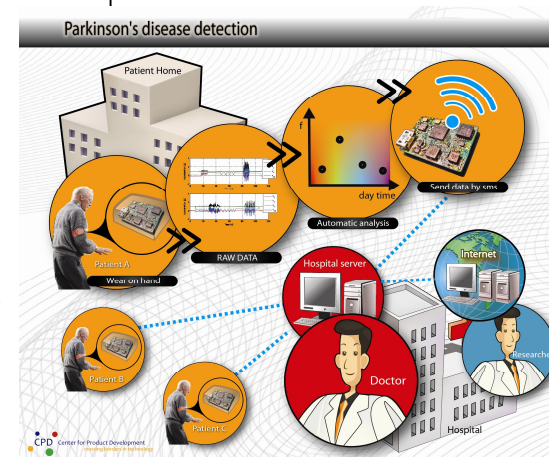
Application example: medical

Remote Monitoring of Patients With Parkinson's Disease (PD)



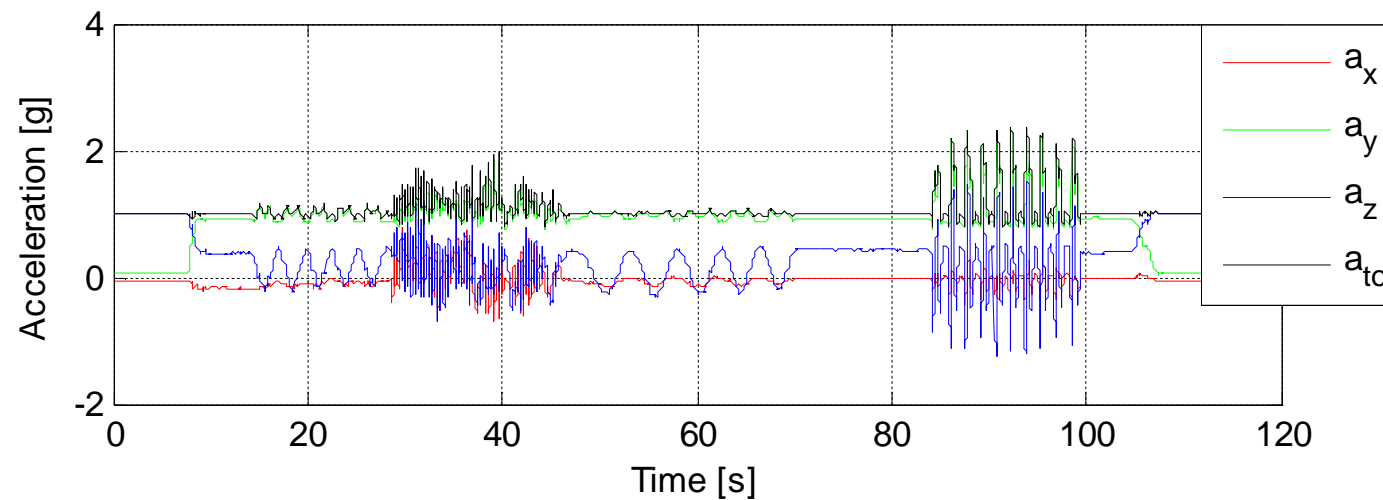
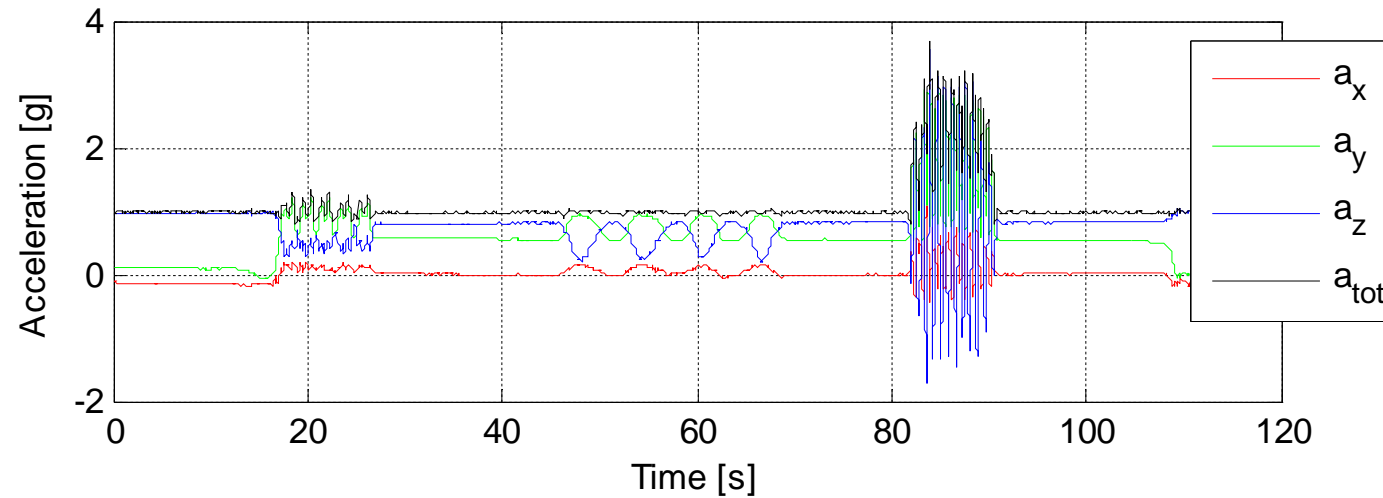
Movement pattern of PD patients

- normal movements
- slowing of movements
- hyperkinesias (exaggerated abnormal movements)
- dystonia (abnormal tone in a limb)
- freezing (no movements)



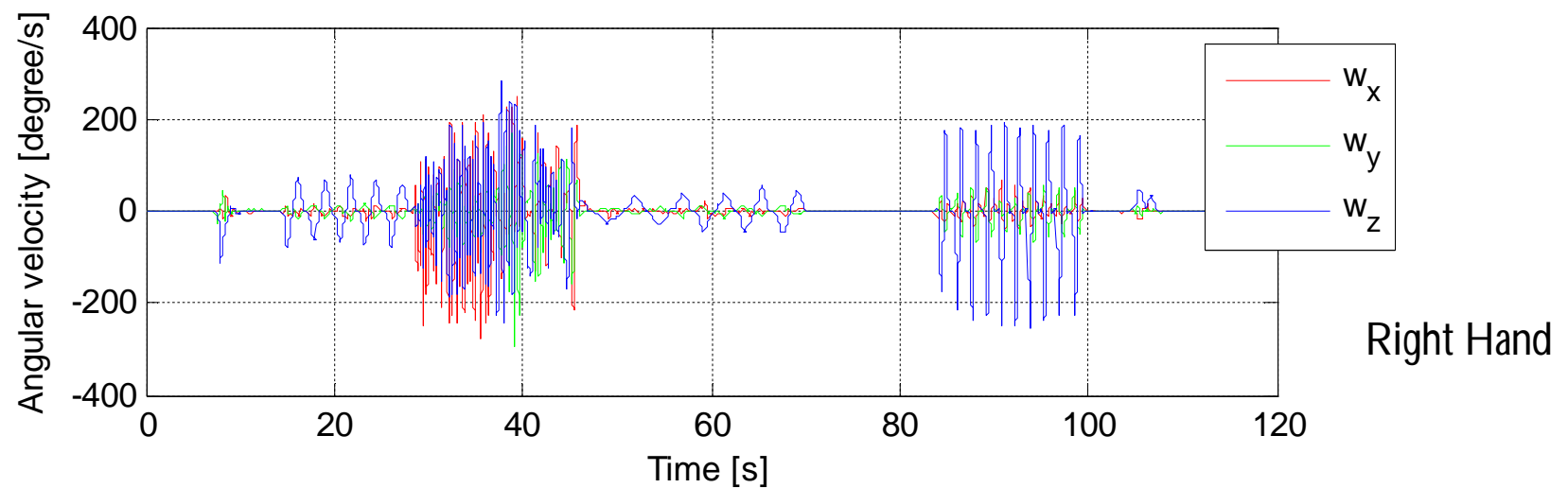
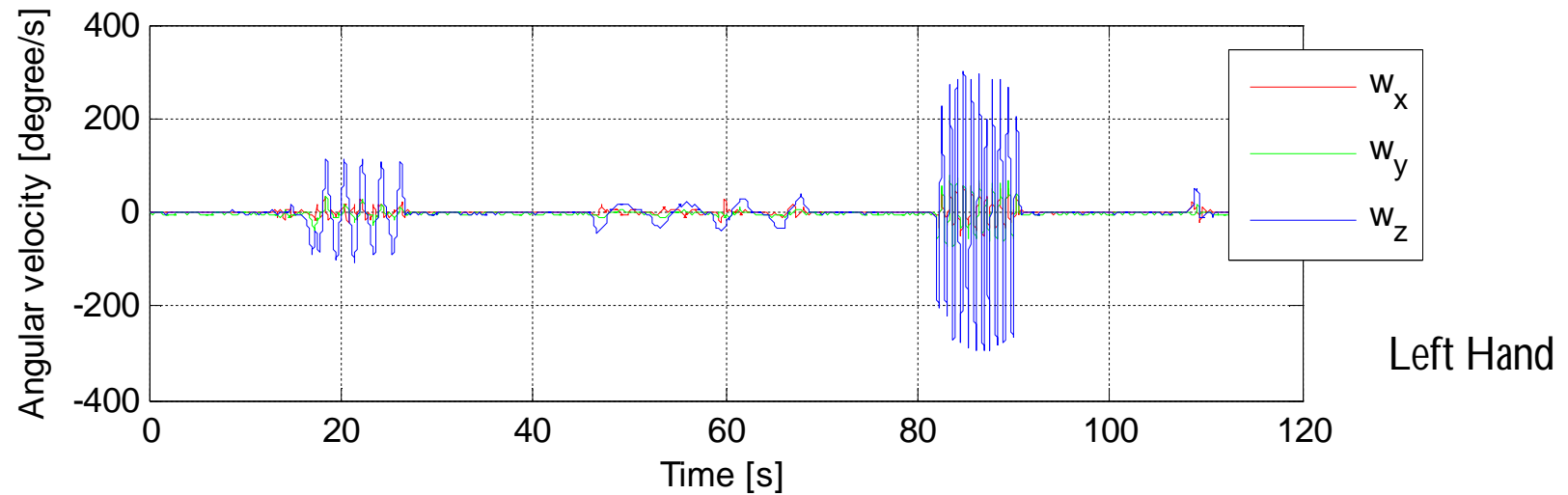
Remote Monitoring of PD Patients

-Preliminary Experiment -Accelerometer

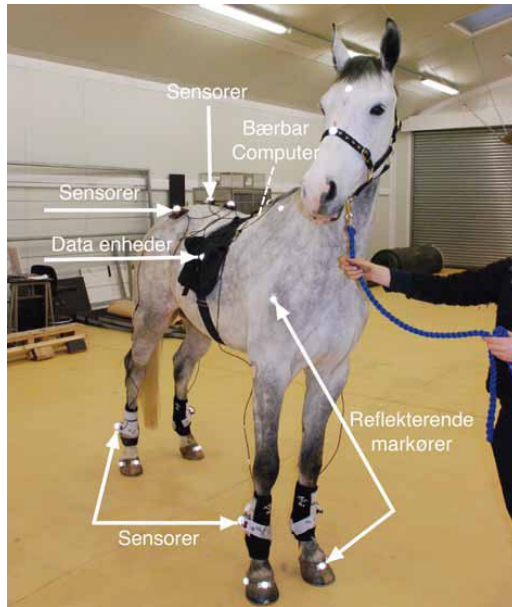


Remote Monitoring of PD Patients

-Preliminary Experiment –Gyroscope



Application example: Medical/ biomechanical study

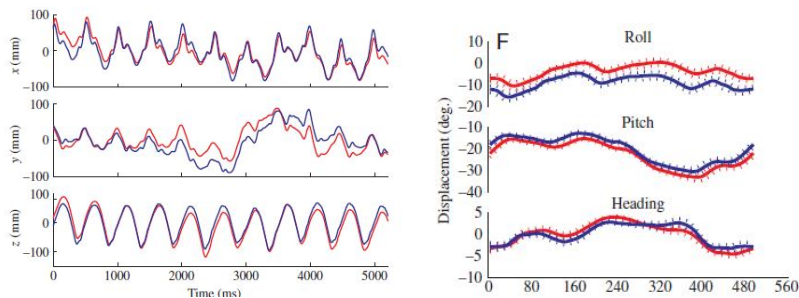


Life/KU (Copenhagen University)

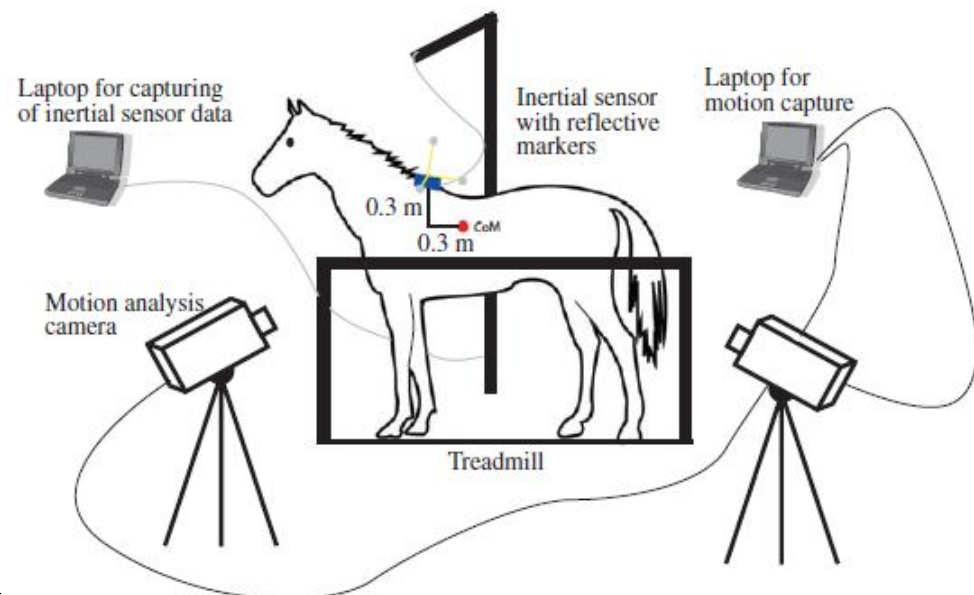
Detection and quantification of lameness in horses

Symmetric / Asymmetric

**Structure and Motion Laboratory,
The Royal Veterinary College, UK
Royal National Orthopaedic Hospital, UK**
Study of locomotion



Displacement data for x (craniocaudal), y (lateral) and z (dorsoventral) movement m , and orientation data, for optical motion capture (blue) and inertial sensor (red) for a series of strides at canter (9m/s)
Structure and Motion laboratory, UK



Application example: Sport training

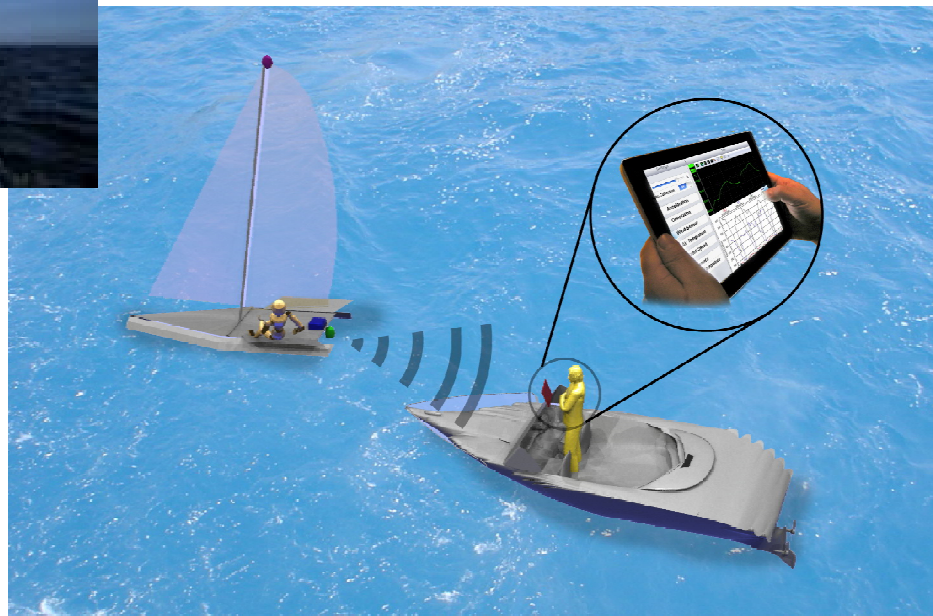
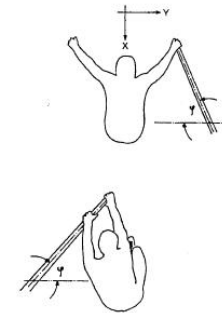


Figure 2

Measurement of the length of the stroke from pictures made looking down from a bridge.



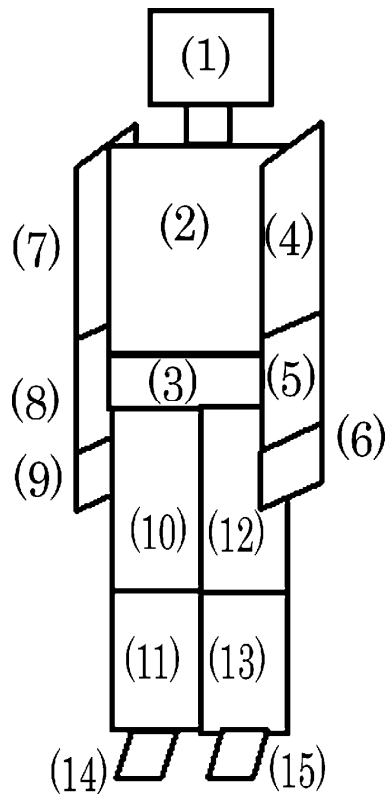
Application example: Rehabilitation/welfare



Application example: Rehabilitation/welfare



Applications: Sports/rehabilitation



Depiction of the 15 segments comprising stick figure for human body

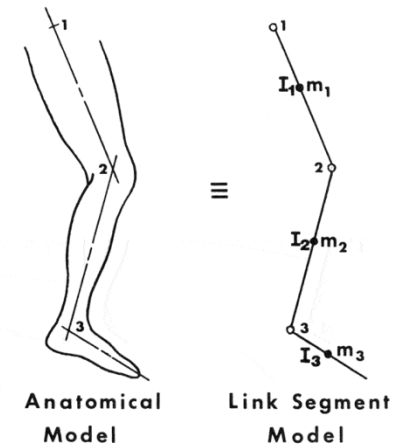
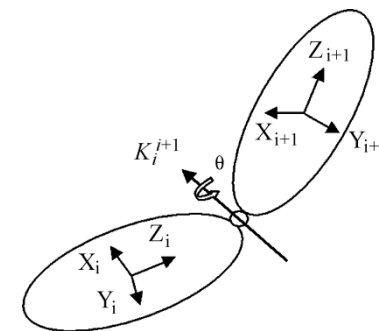


Figure 4.2 Relationship between anatomical and link-segment models. Joints are replaced by hinge (pin) joints and segments are replaced by masses and moments of inertia located at each segment's center of mass.



Physical segment model and the definition of its orthogonal frame

Applications: sports/rehabilitation

Relation between the measurements in segment (i) and segment (i+1)

$$\begin{bmatrix} g_x^{i+1} & g_y^{i+1} & g_z^{i+1} \end{bmatrix}^T = Rot(K_i^{i+1}, \theta) \cdot \begin{bmatrix} g_x^i & g_y^i & g_z^i \end{bmatrix}^T$$

$$\begin{bmatrix} H_x^{i+1} & H_y^{i+1} & H_z^{i+1} \end{bmatrix}^T = Rot(K_i^{i+1}, \theta) \cdot \begin{bmatrix} H_x^i & H_y^i & H_z^i \end{bmatrix}^T$$

where

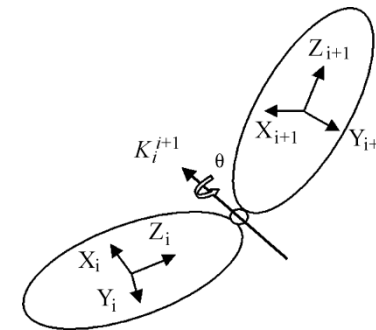
K_i^{i+1} is the rotation vector from segment $i \rightarrow i+1$

θ is the joint angle

g - gravity

H - magnetic field

T - Transpose



The whole body movement can be calculated by a series of Translation & Rotation.

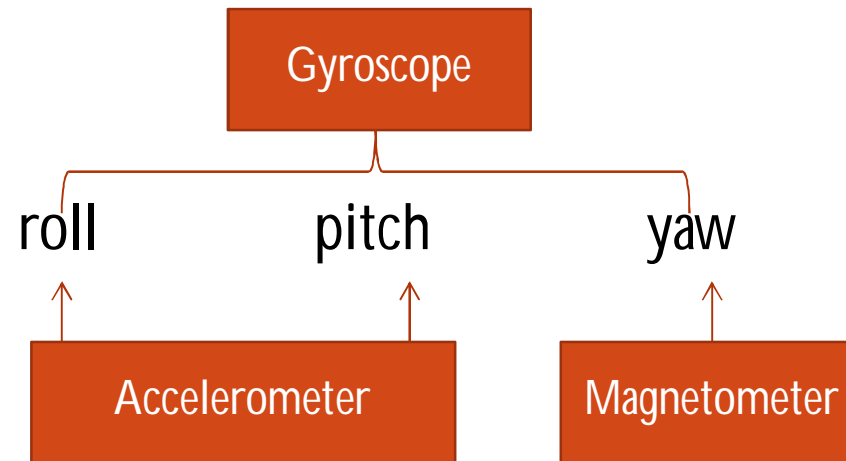
There is no need for strict sensor alignment.

Discussions

- Do we need so many sensors?
- What are the cost of sensors
- What is the accuracy of the measurement?

Discussion 1– Do we need so many sensors?

- Sensor dependent



Gyroscope

- Optical (Sagnac Effect)
 - Ring Laser Gyroscope (RLG)
 - Fiber Optic Gyroscope_(FOG)
- Mechanical
 - MEMS (Micro-Electro-Mechanical Systems) Gyroscope

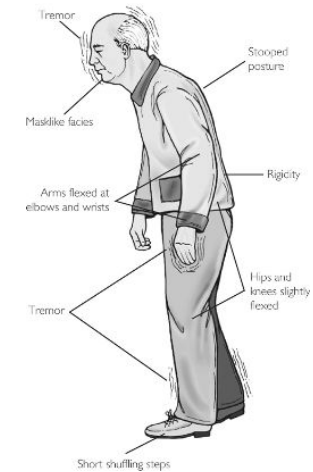
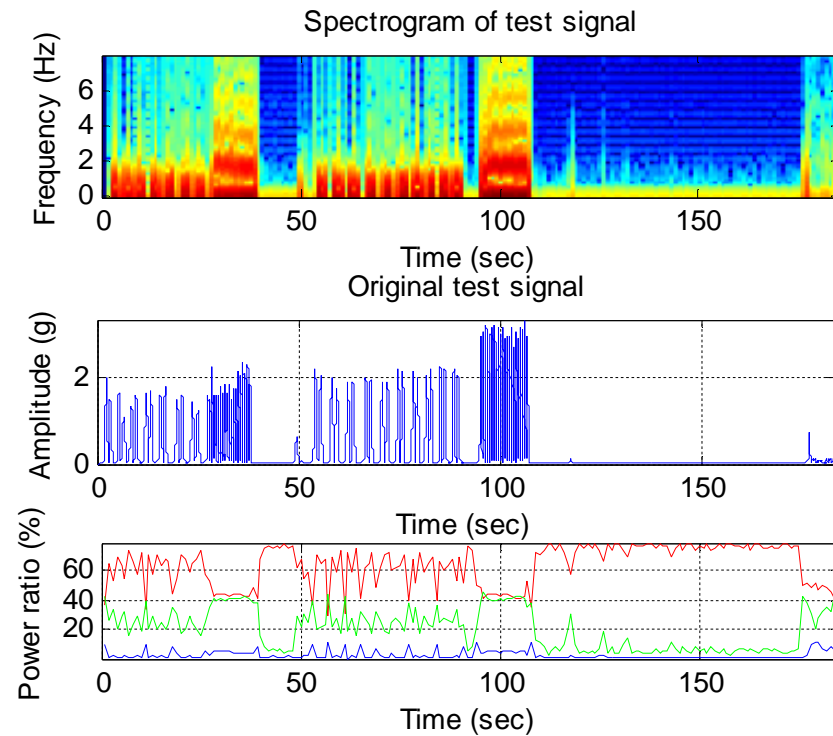
TABLE 1. Overview of Available Gyroscopes.

Gyroscope Technique	Products	Noise Level ($\text{rad}\cdot\text{s}^{-1}\cdot\text{Hz}^{-0.5}$)	Dimension (mm)	Price (k\$)
Ring Laser Gyro	Honeywell GG1320AN	1×10^{-6}	87 \varnothing , 45	27
Fibre Optic Gyro	KVH DSP-3000	2×10^{-5}	89 x 48 x 33	4
Solid State Vibrating Structure	BAE Systems VSG	3×10^{-3}	40 x 43 x 58	1
MEMS Gyro	O-Navi Gyropak 3	1×10^{-3}	20 x 20 x 4	0.1

Discussion 1 –cont.

Do we need so many sensors

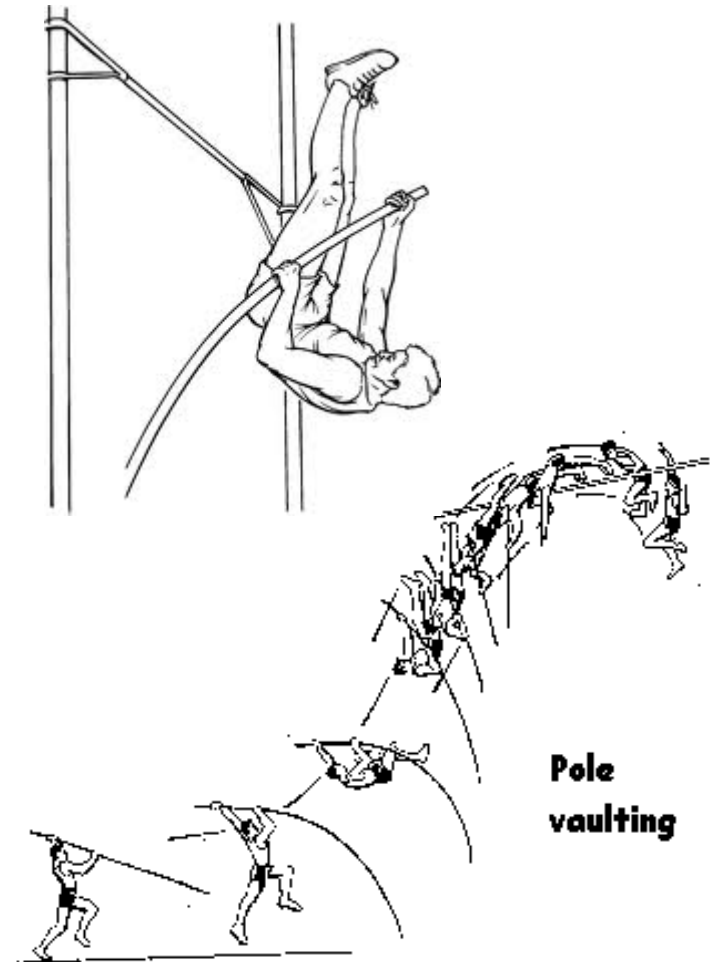
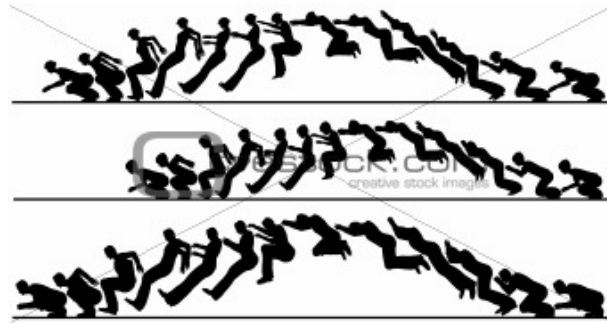
- **Application dependent**
When the time frequency matter – accelerometer only is enough



Discussion 1 –cont.

Do we need so many sensors

- Application dependent



When the angle and linear acceleration matter:
gyroscope+ accelerometer
+ magnetometer



Discussion 2


What are the cost of sensors



Accelerometers

Model	Package	Pins	Temp. Range	Packing, Qty	Price* (100-499)	Price* 1000 pcs	RoHS	View PCN/PDN
ADXL335BCPZ Status: Production	16 ld LFCSP (4x4mm, 2.40mm exposed pad)	16	Ind	Tray, 490	\$2.77	\$2.38	E Material Info	PCN
ADXL335BCPZ-RL Status: Production	16 ld LFCSP (4x4mm, 2.40mm exposed pad)	16	Ind	Reel, 4000	\$2.77	\$2.38	E Material Info	PCN
ADXL335BCPZ-RL7 Status: Production	16 ld LFCSP (4x4mm, 2.40mm exposed pad)	16	Ind	Reel, 1000	\$2.77	\$2.38	E Material Info	PCN

Honeywell Magnetometers

<p>HMC1043</p>  <p>click to see more</p>	<p>The HMC1043 is a 3-axis MR sensor in a 3x3x1.4mm LCC package. Field range is ± 6 gauss, resolution is 120 microgauss, and sensitivity is 1mV/Vgauss. ECCN Number: EAR99 Estimated Shipping Lead Time(s): 4 weeks for quantities ≥ 1000. 2 weeks for quantities < 1000.</p>	<p>50</p>	<p>\$15.00</p>
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Discussion 3

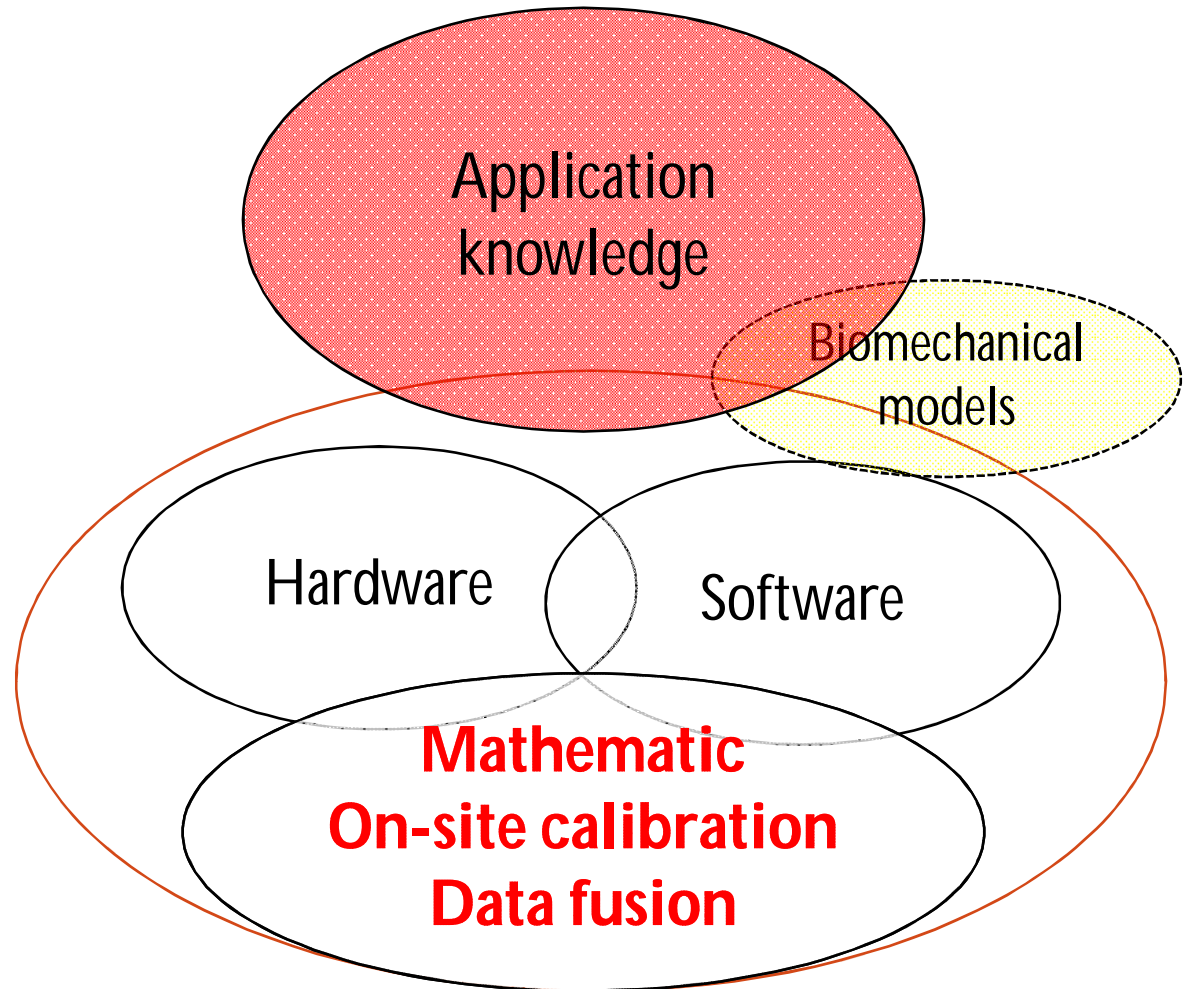
What is the accuracy of the measurement?

- Periodic (cyclic) movement
 - Walking (on one plane / on multi-plane)
 - Running
 - Hurdles
 - Pole jumping (vaulting)
- No cyclic / Random movement (outdoors with GPS)...
- No cyclic / Random movement (indoors, e g upper limb movement)
 - biomechanical model is need

Summary

We can fuse gyroscopes, accelerometers, magnetometers (and GPS data) to deliver accurate and reliable motion information, and output:

- Quaternion/
Transformation matrix
/Rotation vector
- Heading, pitch, and roll
- Linear acceleration
- Velocity
- Position



Some inspirations:

Click and play the video

<http://www.xsens.com/en/mvn-biomech>