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## Personal navigation with handheld devices

Valérie Renaudin

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# IPIN 2015 TUTORIAL

## Personal Navigation with Handheld Devices

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Banff, Canada, 13 October 2015



IFSTTAR

# Instructor Bio: Valérie Renaudin

## Current

- Head of GEOLOC Lab at the French institute of science and technology for transport, development and networks (IFSTTAR)

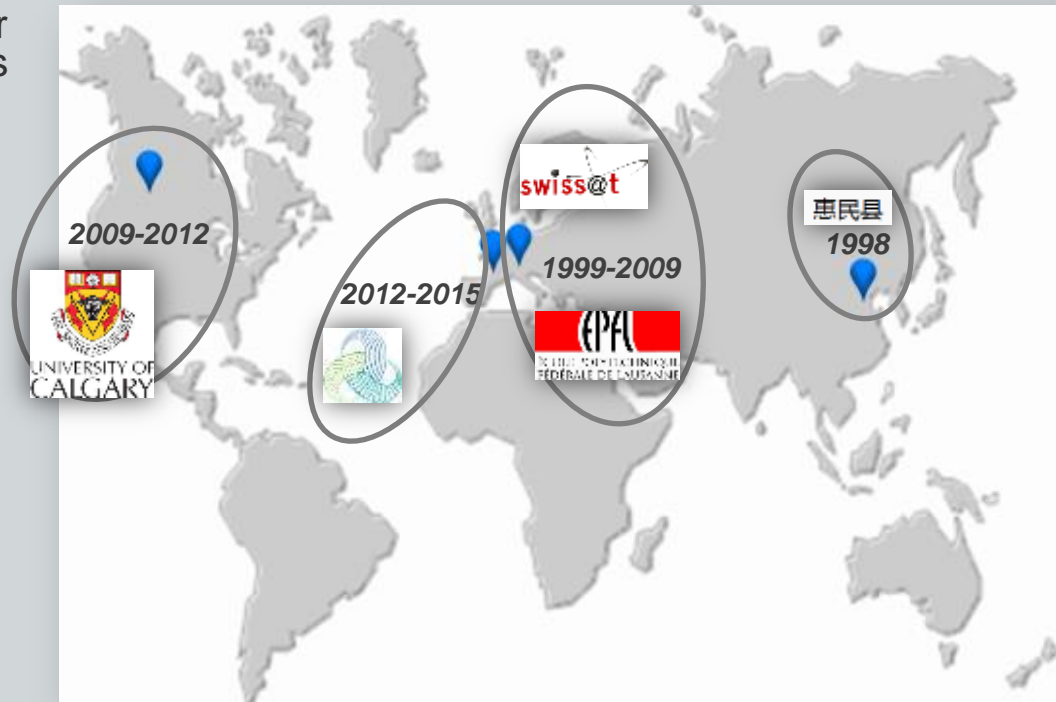
## Graduation

- MSc in Geomatic Eng. from the ESGT, France
- PhD in Computer, Communication and Information Sciences from the EPFL, Switzerland

## Research Focus is on

- Methods and systems for personal mobility in multimodal transport
- Pedestrian navigation using signals from Global Satellites Navigation Systems, inertial and radio telecommunication technologies in indoor spaces

## Past Positions



# IFSTTAR

FRENCH INSTITUTE  
OF SCIENCE AND TECHNOLOGY  
FOR TRANSPORT, DEVELOPMENT  
AND NETWORKS



# Overview and motivation

Background on strapdown inertial navigation system (INS)

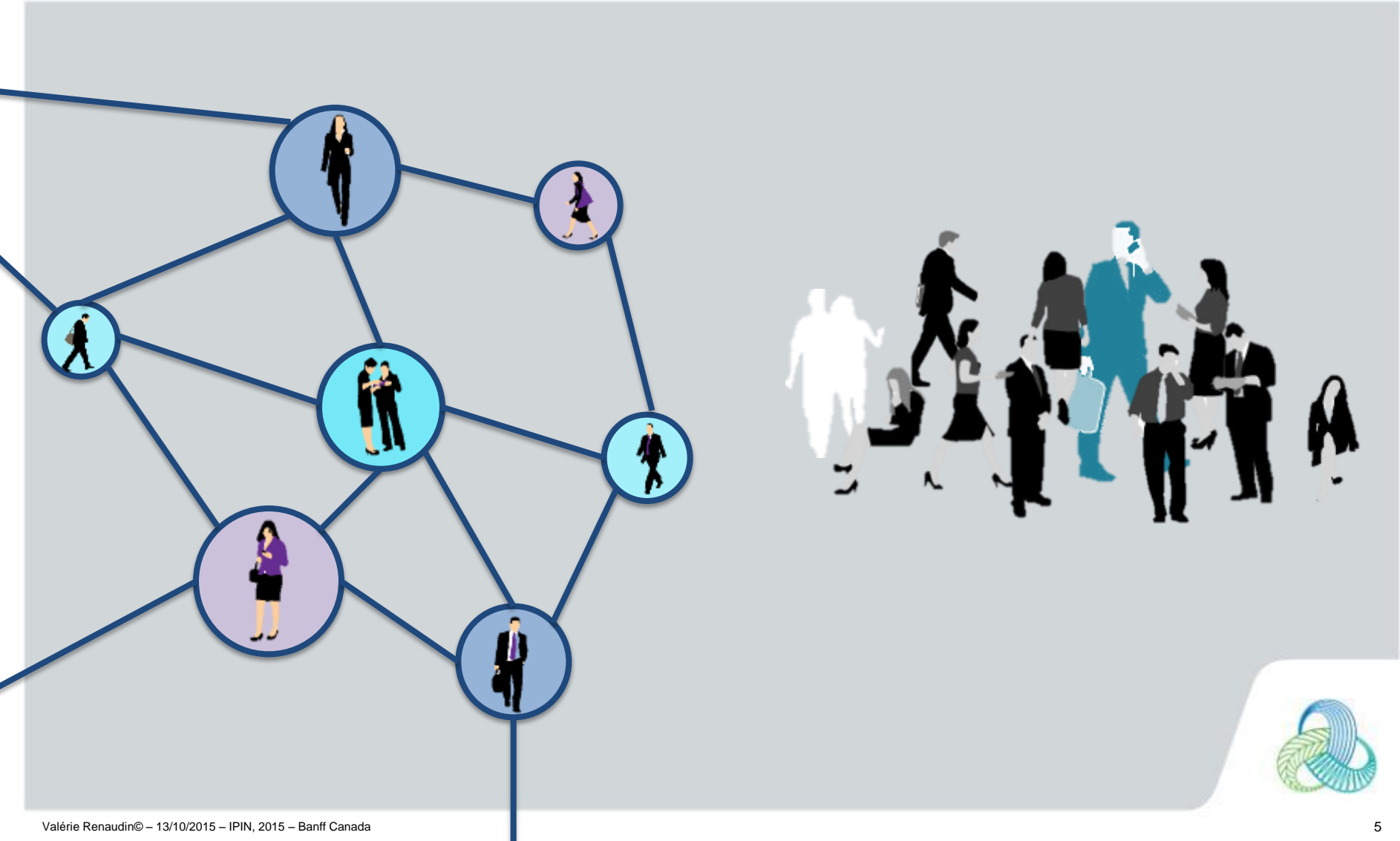
The challenge of personal navigation with handheld device

Alternative positioning strategies



## Conclusion

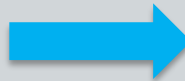
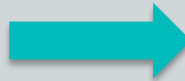
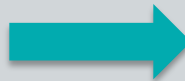
# A Paradigm Shift!



# Why navigating with handheld devices?

## PAST/PRESENT

- Strapdown navigator in motorized bodies → physics of solid
- Principally outdoors
- One device for each application: to guide private car, one to hike, etc.
- General navigation functionalities



## FUTURE

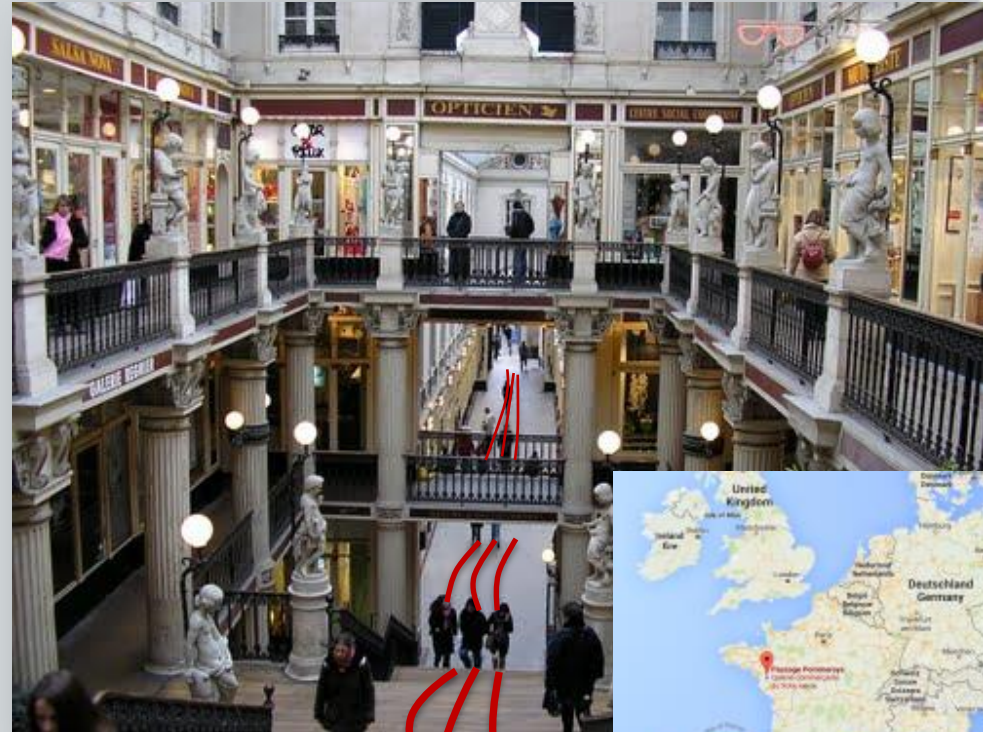
- Connected human → not well known human kinematic
- Indoors → 70% of mobile phone calls and 80% of data telecom in indoor spaces [*Strategy Analytics 2012*]
- The smartphone is a toolkit for everything including navigation
- We want the connected object to understand my particularities: Who am I? Physiological parameters?



# Targeted performances

- Continuous, reliable and accurate
- In figures
  - 1 m accuracy
  - 95% percentile of the error distribution law
  - 99% coverage
- Applications from recreational use up to safety critical services

*Shopping Mall in Nantes : Passage Pommeraye*





# Beyond Navigation Expectations

- Adaptive to all dynamics
  - Different motion modes
    - Comfortable walking
    - walking disabilities
  - Active transport
    - walk, run, bike
  - Motorized transport
    - private car
    - public transit
- Providing personal (positive) feedback
  - on physiological performance: a training tool
  - on general health: a medical diagnostic tool





**The development of consumer navigation systems is more and more pedestrian's centered**

# Overview and motivation

## Background on strapdown inertial navigation system (INS)

The challenge of personal navigation with handheld device

Alternative positioning strategies

Conclusion

# ***GEOGRAPHICAL FRAMES***



# Many different coordinate frames

- Inertial Navigation involves several coordinate frames
  - Inertial Frame (Inertial Signals)
  - Earth Centered Earth Fixed Frame (GNSS)
  - Local Frame (Map)
  - Body Frame (IMU)
  - Pedestrian Frame (Handheld Sensor)
- Preliminary comments
  - The definition of these frames may differ depending on the application and the context
  - These choices impact the mechanization equations of inertial navigation



# Inertial Frame (i-frame)

- The inertial frame is close to a Galilean frame
  - non-rotating & non accelerating frame
- The approximation comes from the fact that the earth is accelerating while it orbits the sun
- Accelerometer and gyroscope measurements are given in this frame



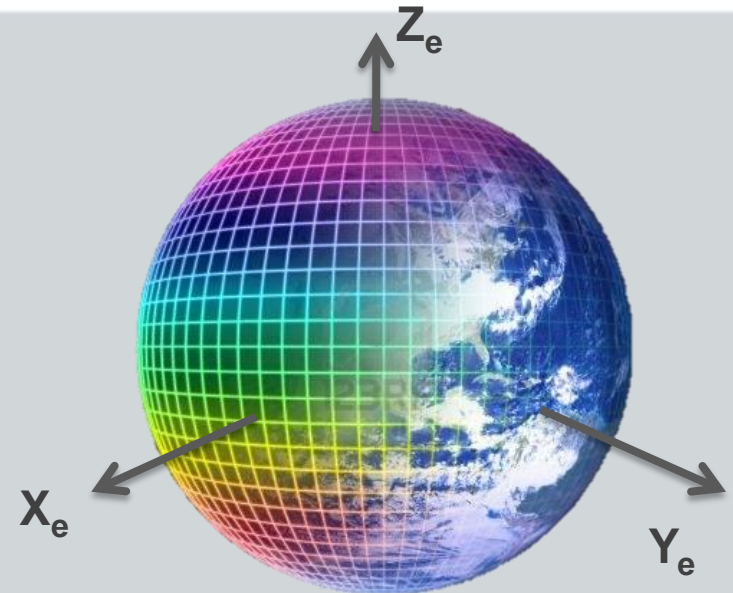
<http://hronrad.wordpress.com/>

Parameter	Description
Origin	Earth's Center of Mass
Z axis	Parallel to the earth spin axis
X axis	Pointing toward mean vernal equinox
Y axis	Form a right handed orthogonal frame



# Earth Centred Earth Fixed Frame (e-frame)

- Principally used for satellite signals based navigation (GPS, GLONASS, Beidou, Galileo) because orbital data are computed in this frame
- Also called terrestrial equatorial frame
- Satellite signals and inertial navigation are often combined in this frame

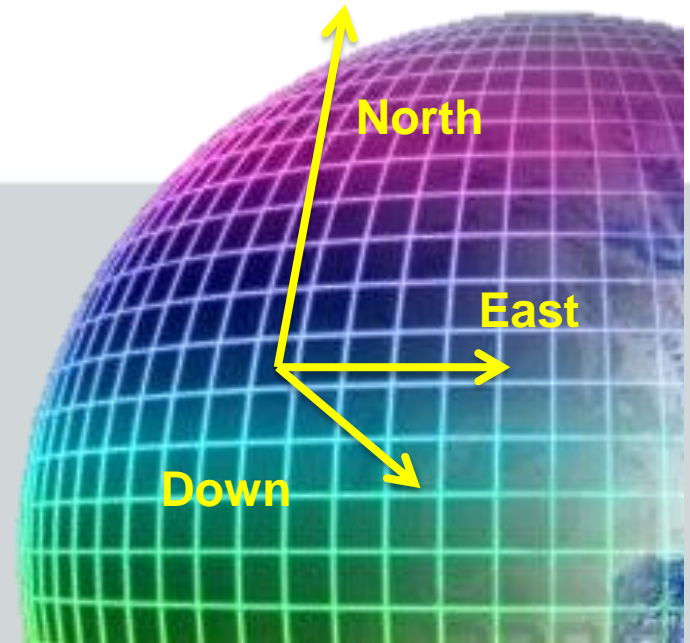


Parameter	Description
origin	Earth's Centre of Mass
Z axis	Parallel to earth spin axis
X axis	Pointing towards mean meridian of Greenwich
Y axis	Completing right-handed orthogonal frame



# Local Frame (l-frame)

- Its choice and axis convention depend on the application
- On the illustration: North, East, Down (N,E,D)
- Often linked to the geographic information system used to display the navigation solution



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Parameter	Description
origin	Arbitrary: point on the earth surface
Z axis	Orthogonal to the reference ellipsoid
Y axis	Directed to the geodetic north
X axis	Completing right-handed orthogonal frame

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# Transformation between e-frame and i-frame

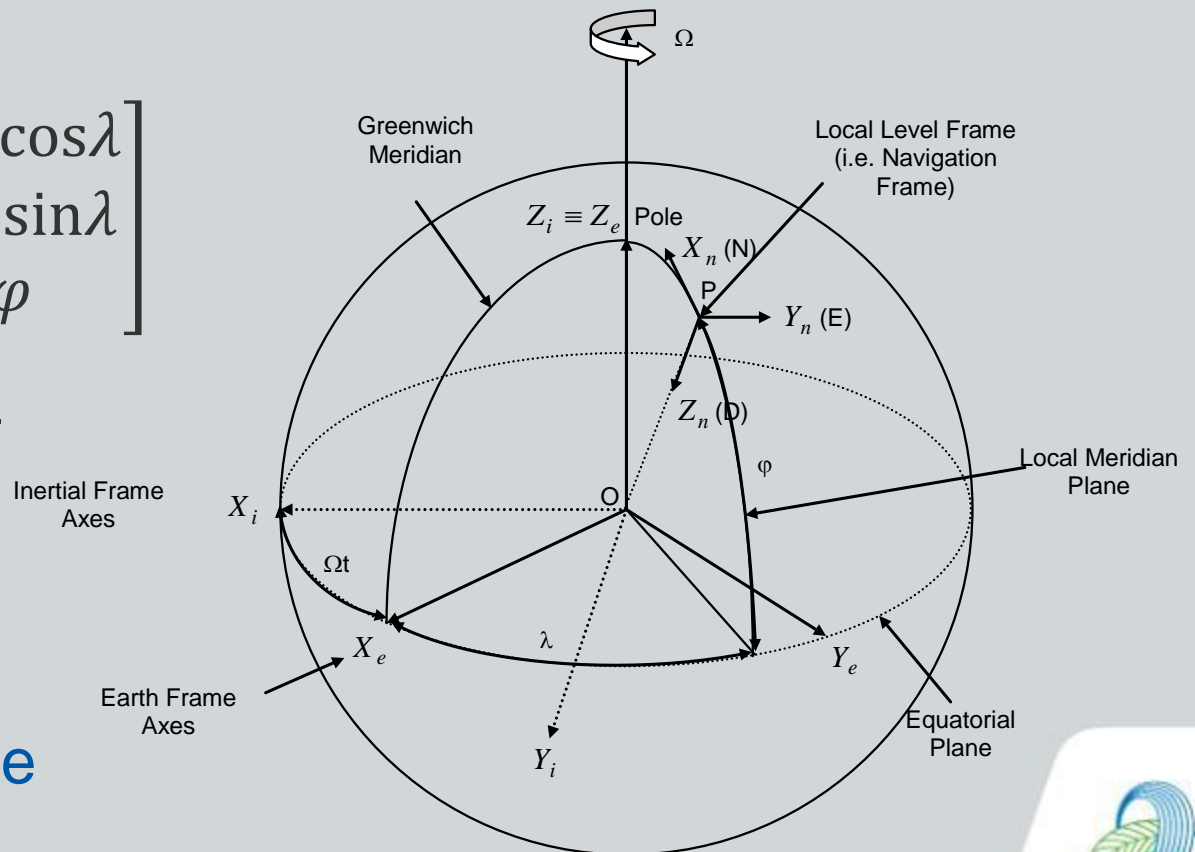
- The  $X_n, Y_n, Z_n$  axes of the I-frame are expressed in the e-frame with

$$- Z_n = \begin{bmatrix} -\cos\varphi\cos\lambda \\ -\cos\varphi\sin\lambda \\ \sin\varphi \end{bmatrix}$$

$$- X_n = \frac{1}{\cos\varphi} \frac{\partial Z_n}{\partial \lambda}$$

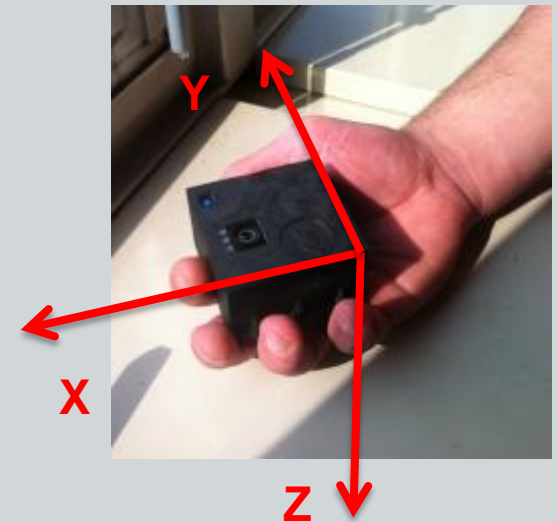
$$- Y_n = -\frac{\partial Z_n}{\partial \varphi}$$

- $\varphi$  is the latitude
- $\lambda$  is the longitude



# Body Frame (b-frame)

- The body frame can be defined in many different ways
- Usually right-handed 3D Cartesian frame related to an object
- In strapdown applications, the body frame is considered as rigidly attached to the vehicle
- This hyp. doesn't always hold for pedestrian navigation applications

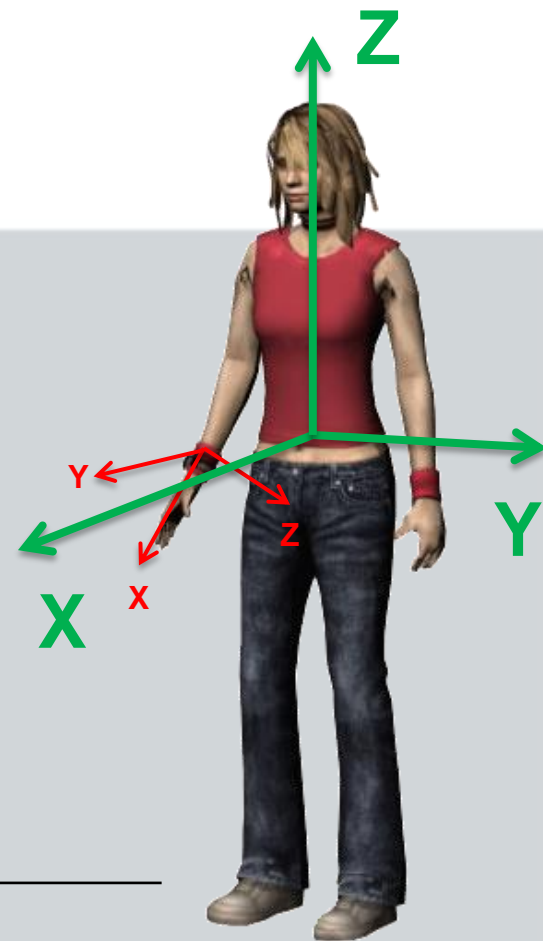


Parameter	Description
origin	Specific point within the object
X axis	Pointing along the forward direction
Y axis	Pointing along the lateral axis of the IMU
Z axis	Completing right-handed orthogonal frame



# Pedestrian Frame

- The pedestrian frame is attached to the “skeleton” of the human body
- Its origin describes the pedestrian position on the map
- Intermediate frame between the body and the local frames
- Usually right-handed 3D Cartesian frame



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## Parameter

## Description

origin	Human Body Center of Mass
X axis	Pointing along the forward direction
Y axis	Pointing along the lateral axis of the IMU
Z axis	Completing right-handed orthogonal frame

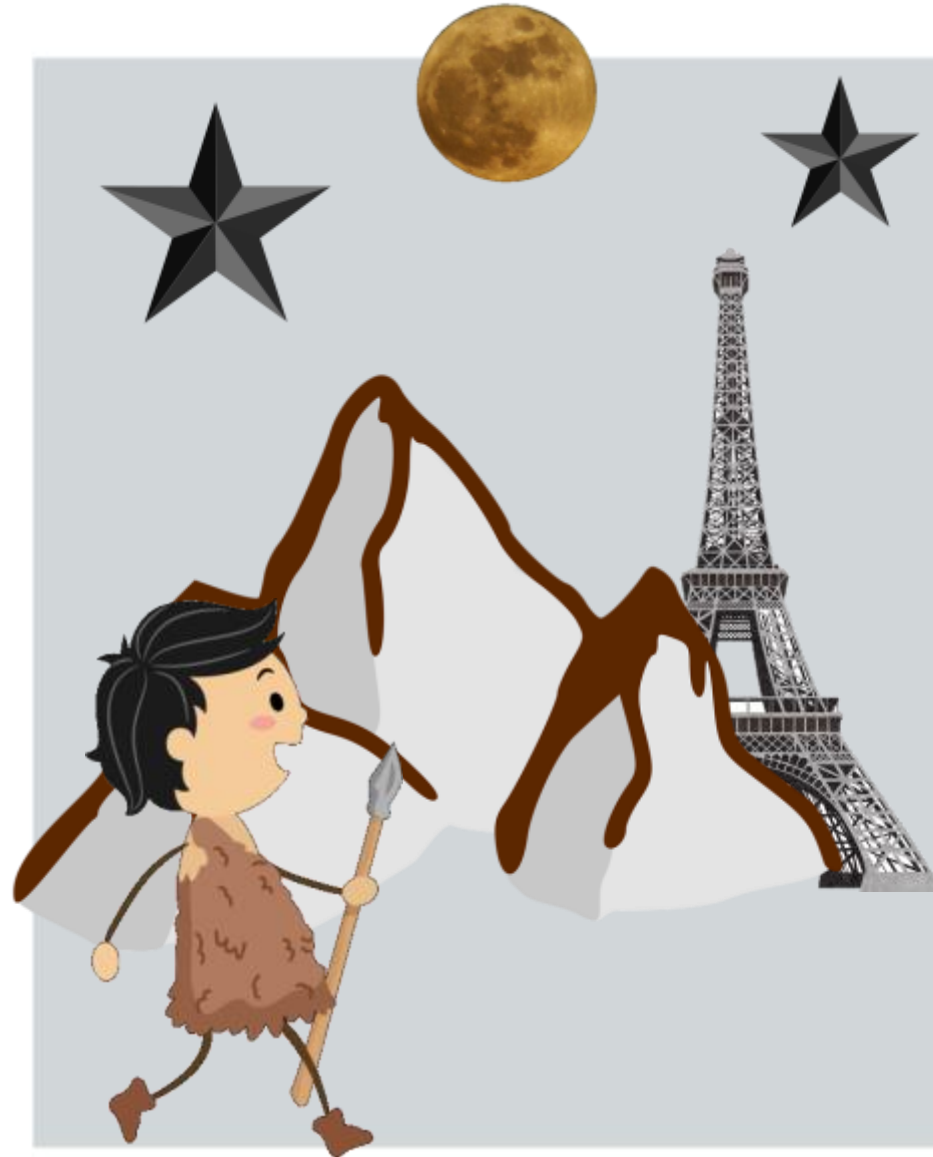
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# ***HISTORY OF NAVIGATION***

# History of Navigation



- **Landmarks Navigation**
  - Stone age practice
  - Recognizing landmarks to deduct geographical locations & find routes
- **Celestial Navigation**
  - Observing the geometrical configuration of celestial objects for deriving location and guidance data
  - Triangulation: angle measurements between the observer's local vertical and the star (sun or moon)



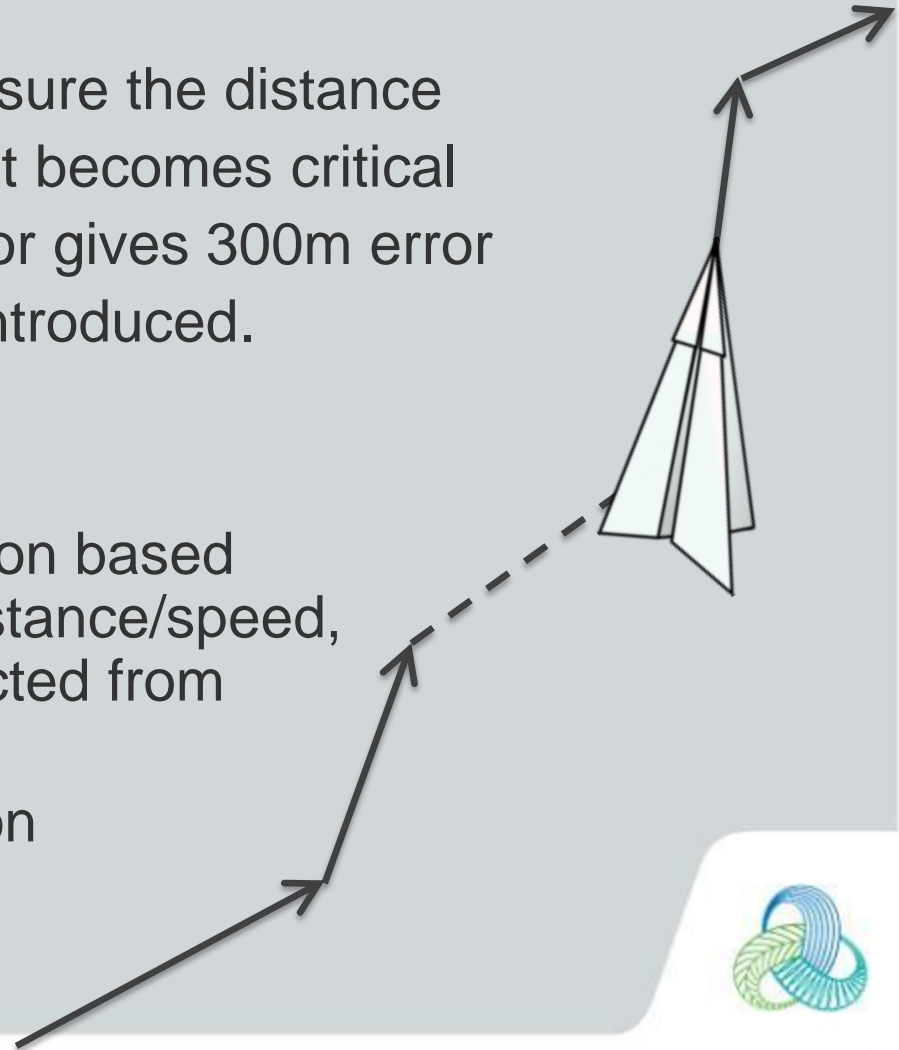
# History of Navigation

- Radio Navigation

- Use of radio signals to measure the distance
- Accurate time measurement becomes critical
- At speed of light:  $1\mu\text{sec}$  error gives 300m error
- Trilateration positioning is introduced.

- Dead Reckoning

- Estimates the current position based on the previous one and distance/speed, angle measurements extracted from embedded sensors
- A recursive process common for aircraft navigation



# History of Navigation

- Inertial Navigation
  - Is a dead reckoning navigation
  - The measurements are **accelerations** and **angular rates** relative to an inertial navigation frame
  - Processing
    - Estimates the Position, Velocity and Attitude changes of a body
    - Its mechanization is based on Newton's 1st and 2nd law of motion
  - Definition
    - INS → Inertial Navigation System
    - IMU → Inertial Measurement Unit



# Inertial Sensors

## Stable platform

- A triad of acc. is kept physically aligned with respect to the local vertical and north axes
- Mechanically complicated, bulky

## Strapdown sensors configuration

- Introduced in the early 80s
- The stabilization is achieved mathematically
- Smaller size, weight and consumption

## Micro-Electro-Mechanical Systems: MEMS

- Latest introduced inertial sensors
- Small and less expensive
- Mass production
- Embedded in daily life equipment (smartphone, remote control, ...)
- Consumer Grade sensors

## Solid State Inertial Sensors

- Solid state optics
- Nanotechnology
- Atomic Physics

Operate without reference to an external signal  
→ Autonomous with respect to its environment





# Gyroscope

- Gyroscopes are angular rate sensors
- Measure the rotation rates of the body frame relative to the inertial frame
- Parameterized in the body frame, it is  $\omega_{ib}^b$

Foucault's gyroscope



© Science Museum / Science & Society Picture Library



# Gyro. Main Operation Principles

- **Spinning Mass**
  - Uses the principle of conservation of angular momentum
  - Directions in inertial space are defined by bodies/particles rotating with constant momentum
  - One example is the rotor gyro designed for stable platform
- **Optical Gyros**
  - Uses Sagnac effect
  - Based on relativistic principle that speed of light is conserved in rotating body
  - Widely used in automotive applications
- **Vibratory or Resonator Gyro**
  - Uses Coriolis principle
  - An oscillating inertial body will preserve the plane of vibration even under rotation
  - Angular rates are derived from rotating accelerometers to which a high frequency vibration is applied
  - Primary choice for MEMS



# Accelerometer

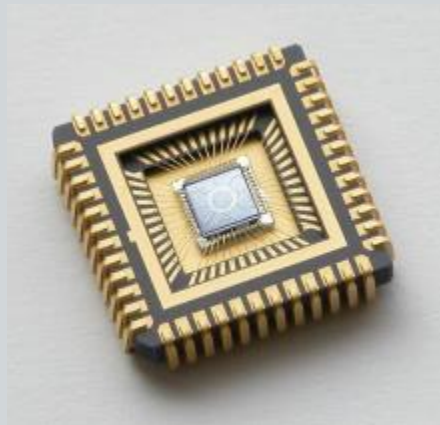
- They are specific force sensors

- measure the acceleration plus the gravity:

$$f^i = \ddot{x}^i - g^i$$

- free fall:  $\ddot{x}^i = -g^i$

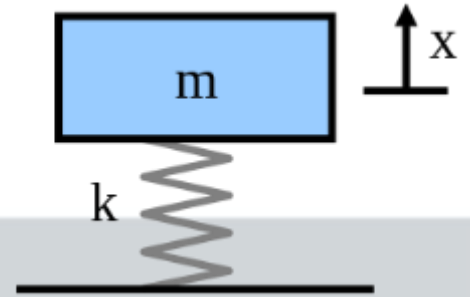
- the gravitational acceleration needs to be removed from the accelerometer data prior to using it for inertial navigation



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# Acc. Main Operation Principles

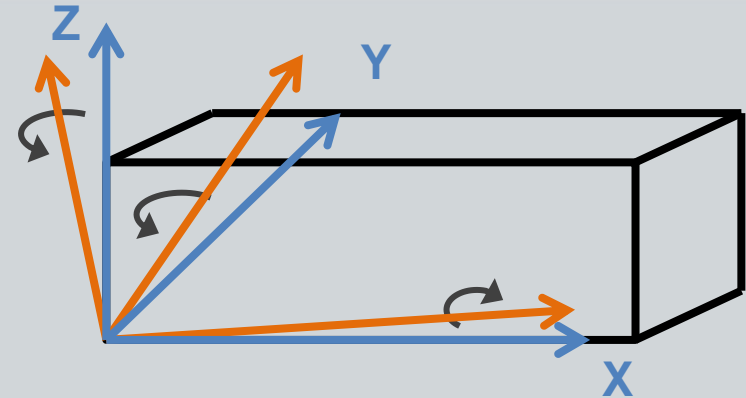


- **Force-rebalanced accelerometer**
  - These servo acc. restrain a proof of mass and measure the electrical current needed to supply the restoring force, which is proportional to the acceleration
  - “standard” translational or pendulous design still used
- **Vibratory accelerometer (MEMS)**
  - Measure the acc. as a frequency difference in a pendulous system
  - Vibrating string acc., quartz resonator or integrated silicon acc.
  - Not as accurate as the force-balanced acc.
- **Electrostatic levitated accelerometer (MEMS)**
  - Position change of a suspended small element by electrostatic is sensed by a capacitance in a closed-loop servo system
  - High performance acc.



# IMU Errors

- All sensors are affected by errors:
  - deterministic & stochastic
- Sensor assembly error linked to orthogonal tri-axis arrangement
  - Sensor axis misalignment
  - Non-orthogonality
  - Nominal scale factor
- For the others, their behavior is described with statistical terms (stochastic processes)
  - in run bias
  - scale factor



- Inertial sensors performances vary a lot depending on the technology and the application
- The quality of inertial sensors depend on
  - the accuracy
  - the dynamic range
  - the sensitivity



# Gyroscope Error Model

- A sample single axis gyroscope signal modeling is

$$\omega(t) = b_\omega + S_\omega \omega(t) + C_\omega(t) + W_\omega(t)$$

- $b_\omega$  is the turn on to turn on bias term
  - $S_\omega$  is the scale factor error term
  - $C_\omega(t)$  is the correlated noise term
  - $W_\omega(t)$  is the white noise
- The correlated noise is for example described by a Gauss-Markov process:

$$\dot{C}_\omega(t) = \frac{-1}{\tau_{C_\omega}} C_\omega(t) + W_{C_\omega}(t)$$

- $\tau_{C_\omega}$  is the correlation time
- $W_{C_\omega}(t)$  is the white noise



# Accelerometer Error Model

- A simple single axis accelerometer signal modeling is

$$f(t) = b_f + S_f f(t) + C_f(t) + W_f(t)$$

- $f(t)$  is the specific-force measurement
  - $b_f$  is the turn on to turn on bias term
  - $S_f$  is the scale factor error term
  - $C_f(t)$  is the correlated noise term
  - $W_f(t)$  is the white noise
- Allan variance analysis is often conducted to estimate the parameters of the noise stochastic processes (described in textbooks)



# Inertial Sensors Performances

Sensor	Error	Tactical Grade	Consumer Grade
Gyro	Bias Stability	0.01 °/hr	15-100 °/hr
	Noise	0.2-0.5 °/hr/√Hz	N/A
Acc	Bias Stability	0.1 mg	1-10 mg
	Noise	0.2-0.4 mg/√Hz	N/A
<b>Applications</b>		Tactical Missile, Automotive, ...	Consumer, Pedestrian Navigation, ...





# INERTIAL NAVIGATION EQUATIONS

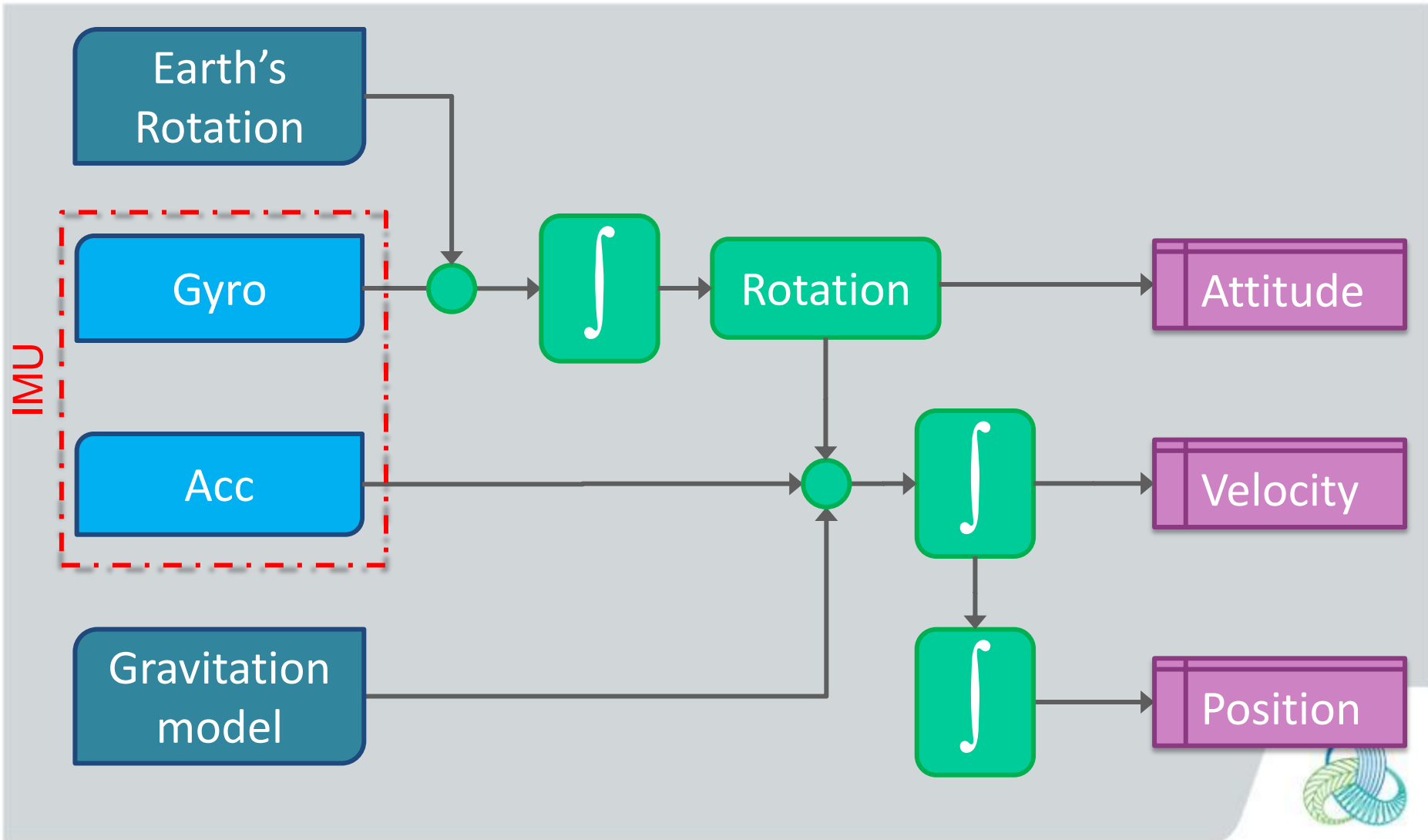


et



On peut utiliser

# Inertial Navigation Algorithm

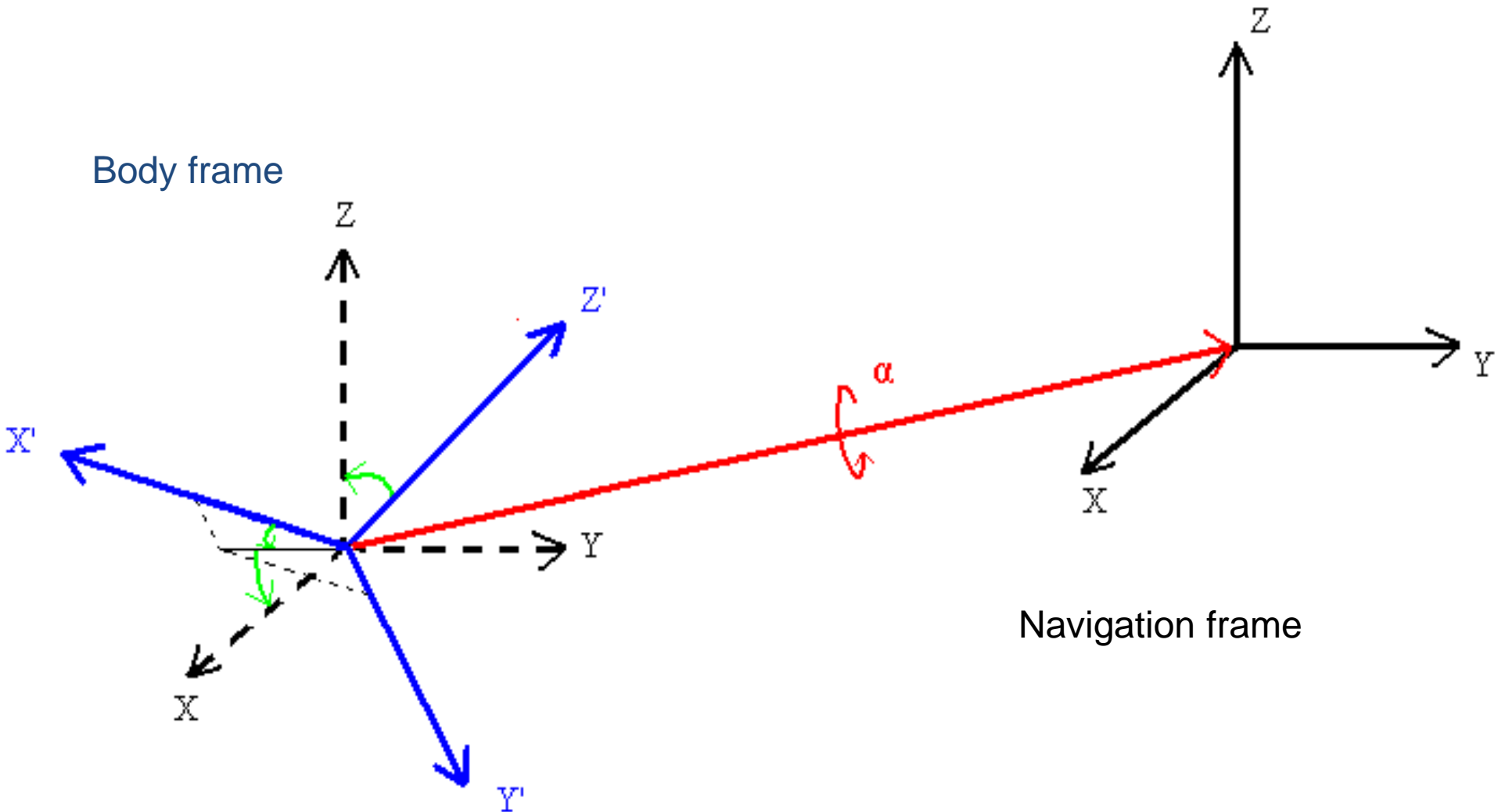


# INS Equations: Position and Velocity

- Evolution of the velocity ( $\dot{\mathbf{x}}$ ) of the mobile in time
  - $\forall u \in [t, \Delta t]$
  - $\dot{\mathbf{x}}_{t+\Delta t}^n = \int_t^{t+\Delta t} \ddot{\mathbf{x}}^n du = \dot{\mathbf{x}}_t^n + \ddot{\mathbf{x}}^n \Delta t$
- Evolution of the position ( $\mathbf{x}$ ) of the mobile in time
  - $\forall u \in [t, \Delta t]$
  - $\mathbf{x}_{t+\Delta t}^n = \int_t^{t+\Delta t} \dot{\mathbf{x}}^n du = \mathbf{x}_t^n + \dot{\mathbf{x}}_t^n \Delta t + \frac{1}{2} \ddot{\mathbf{x}}^n \Delta t^2$
- With only an accelerometer bias error modeling
  - $\ddot{\mathbf{x}} = \mathbf{f} - \mathbf{g} - \mathbf{b}_f + \mathbf{w}_f$
  - $\mathbf{g}$  is known in local map frame and  $\mathbf{f}$  measured in the body frame  $\rightarrow$  orientation ?



# INS Equations: Orientation



# INS Equations: Quaternion

- Quaternion modeling of the rotation  $\theta$  around the vector  $\mathbf{u}$

$$\mathbf{q}_a^b = \left( \cos\left(\frac{\theta}{2}\right), \sin\left(\frac{\theta}{2}\right)\mathbf{u} \right)$$

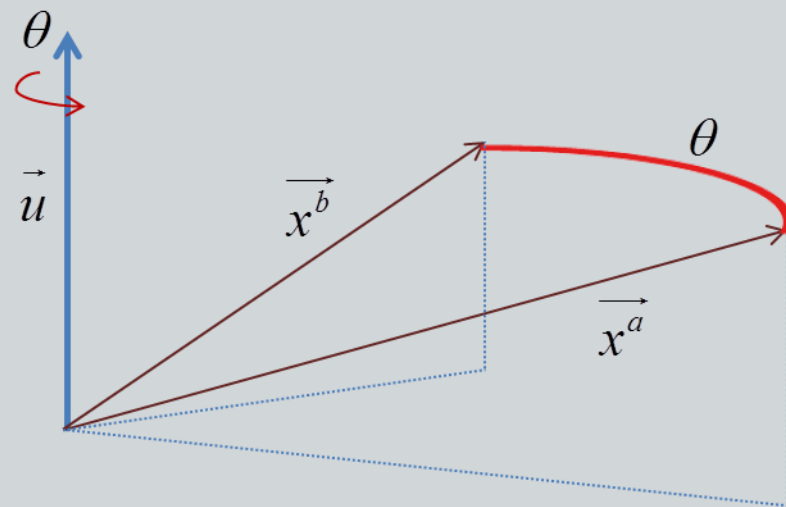
- Multiplication in vector form

$$(0, \mathbf{x}^b) = \left( \cos\left(\frac{\theta}{2}\right), \sin\left(\frac{\theta}{2}\right)\mathbf{u} \right) \circ (0, \mathbf{x}^a)$$

$$\circ \left( \cos\left(\frac{\theta}{2}\right), -\sin\left(\frac{\theta}{2}\right)\mathbf{u} \right)$$

$$(0, \mathbf{x}^b) = \mathbf{q}_a^b \otimes (0, \mathbf{x}^a) \otimes \bar{\mathbf{q}}_a^b$$

- $\bar{\mathbf{q}}$  is the conjugate of  $\mathbf{q}$



# INS Equations: Orientation

- Acceleration in the local frame
  - $(0, \ddot{\mathbf{x}}^n) = \mathbf{q}_b^n \circ (0, \ddot{\mathbf{x}}^b) \circ \bar{\mathbf{q}}_b^n - (0, \mathbf{g}^n)$
- Evolution of the attitude angles quaternion
  - $\mathbf{q}_b^n(t + \Delta t) = \mathbf{q}_b^n(t) \circ \mathbf{q}_\omega^b(t)$
- Relation between quaternion and angular rates

$$- \mathbf{q}_\omega^b(t) = \begin{pmatrix} \cos\left(\frac{\|\boldsymbol{\omega}_{nb}^b\| \Delta t}{2}\right) \\ \sin\left(\frac{\|\boldsymbol{\omega}_{nb}^b\| \Delta t}{2}\right) \frac{\boldsymbol{\omega}_{nb}^b \Delta t}{\|\boldsymbol{\omega}_{nb}^b \Delta t\|} \end{pmatrix} + \mathbf{w}_{q_\omega}^b$$

- With only a gyroscope bias error modeling
  - $\boldsymbol{\omega} = \boldsymbol{\omega} + \mathbf{b}_\omega + \mathbf{w}_\omega$



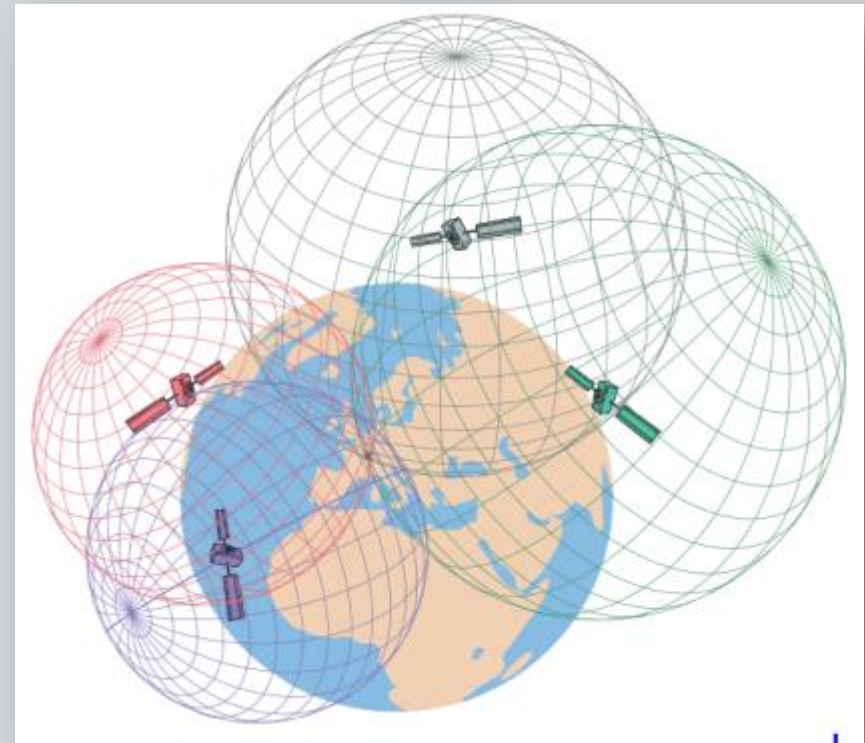
# Impact of IMU errors

- Assuming a non-rotating earth and a single plane body dynamic
  - a constant acc. bias error impacts the position ( $\mathbf{x}$ ) at time square rate:  $\Delta t^2$
  - a constant gyro. bias error will impact the position ( $\mathbf{x}$ ) at time cubic rate:  $\Delta t^3$
- A correlated problem: azimuth errors are propagated in the horizontal velocity via the specific force
- Solutions consists in
  - adopting aided navigation solution : GNSS, Map, Telecom signals, Opportunistic signals, ...
  - estimating the instrument errors with augmented state equations



# Hybridization with GNSS signals

	PROS	CONS
GNSS	Bounded errors Self initialization	Lower attitude accuracy Vulnerable to interference, jamming Lower data rate
INS	Self contained Attitude estimation Higher data rate	Unbounded error growth Needs Initial state is needed



© White Paper <http://www.sappart.net/>





# Zero Velocity Update



- Biomechanics features in walking gait captured by foot mounted IMU (widely adopted)
- Main principle: during the stance phase, the foot velocity equals zero:  $\dot{\mathbf{x}}^n = \mathbf{0}$
- Observation Equations

–  $\delta$  is the perturbation of the state

$$- \begin{bmatrix} 0 \\ \delta \dot{\mathbf{x}}^n \end{bmatrix} = \mathbf{q}_b^n \circ [0 \quad (\mathbf{f}^n - \mathbf{b}_f^n)^T]^T \circ (\mathbf{q}_b^n)^{-1} \delta t + \begin{bmatrix} 0 \\ \mathbf{g}^n \end{bmatrix} \delta t$$

$$- \begin{bmatrix} 0 \\ \delta \mathbf{x}^n \end{bmatrix} = \dot{\mathbf{x}}^n \delta t + \frac{\mathbf{q}_b^n}{2} \circ [0 \quad (\mathbf{f}^n - \mathbf{b}_f^n)^T]^T \circ (\mathbf{q}_b^n)^{-1} \delta t^2 + \begin{bmatrix} 0 \\ \mathbf{g}^n \end{bmatrix} \delta t^2$$

- Following the same strategy, Zero Angular Rate Update has been proposed



# Mature Technologies ?

- With “body fixed” sensors
  - on foot (smart insole), waist, trunk
  - the closest to foot motion, the better
- Biomechanics for calibration
  - Stance phase (Foot)
    - Zero Velocity Update (ZUPT)
    - Zero Angular Rate Update (ZARU)
  - Trunk Roll Constraint
- Aiding
  - Principal Building Directions
  - Visual Odometry/Gyro
  - Magnetometer Gradient



# Overview and motivation

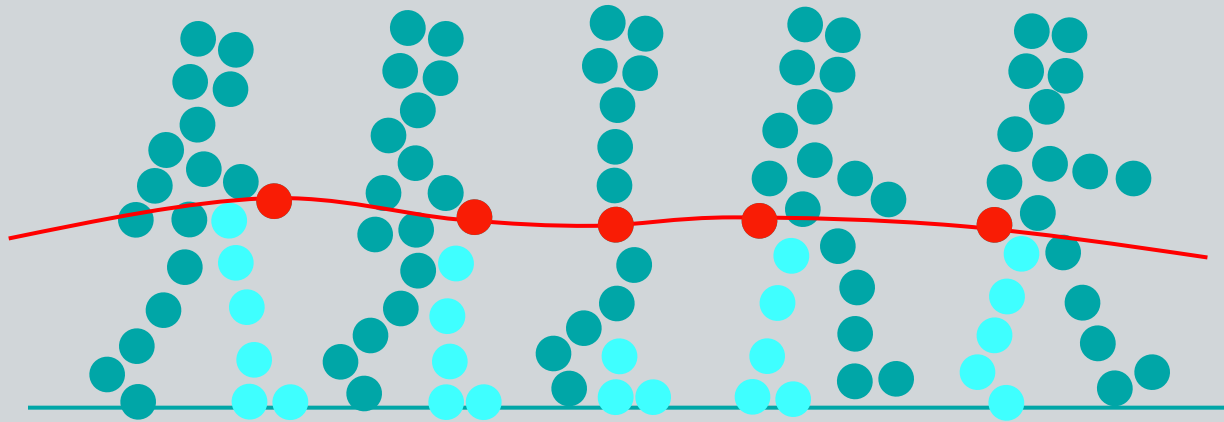
## Background on strapdown inertial navigation system (INS)

### The challenge of personal navigation with handheld device

### Alternative positioning strategies

### Conclusion

# Dead Reckoning with Handheld IMU



- Hand motion can hide global pedestrian locomotion
- “Strapdown” Mechanization cannot be applied
  - Algo. (freely carried devices) can take several forms
  - Sensors & context dependent
- Common Assumption
  - The user is watching the screen while walking
  - ‘body fixed’ like case



# Strapdown INS with Handheld IMU

- **Motion Lab**
  - Multi-Camera tracking system with optical markers
  - Tree marker attached to the handheld IMU
  - High-accuracy
  - 60 Hz
- **IMMU: inertial and magnetic mobile unit**
  - ADIS 16488



# Strapdown INS with Handheld IMU

- 5km/hr walk on a treadmill with texting and swinging hand

Texting Mode

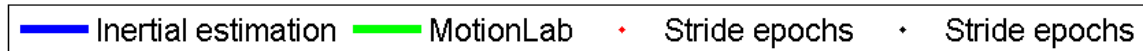
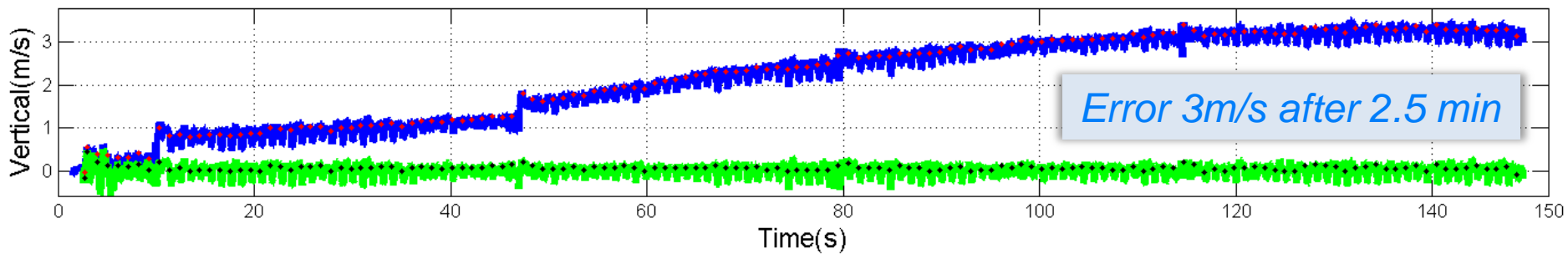
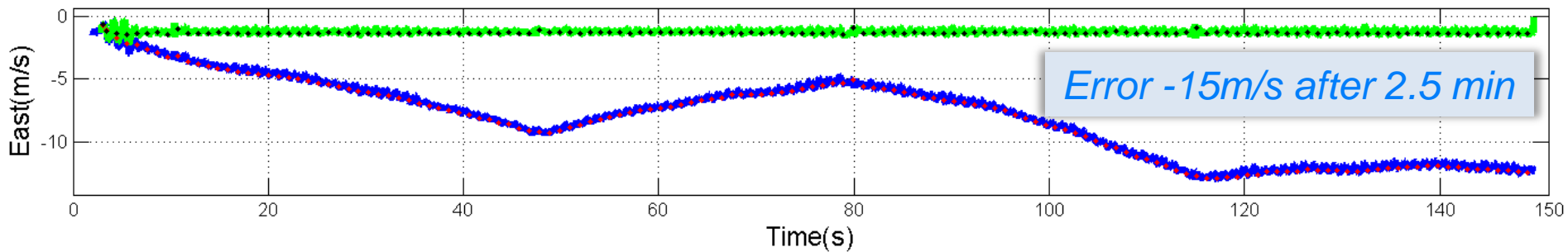
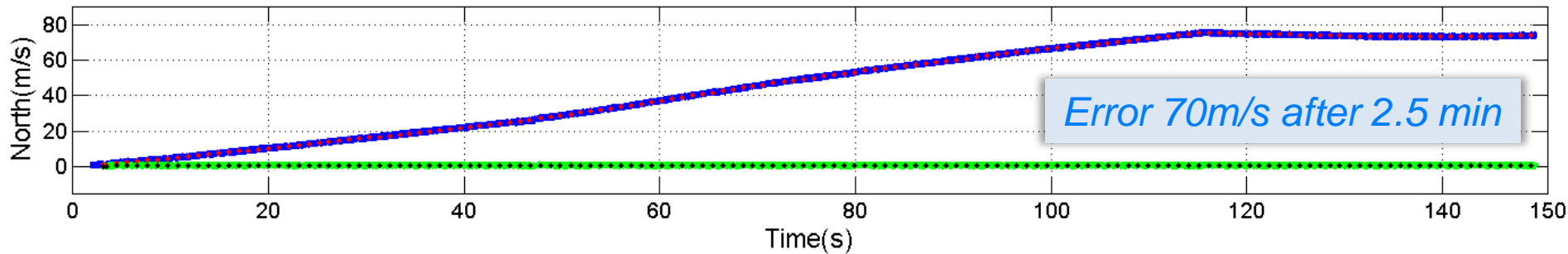


Swinging Mode

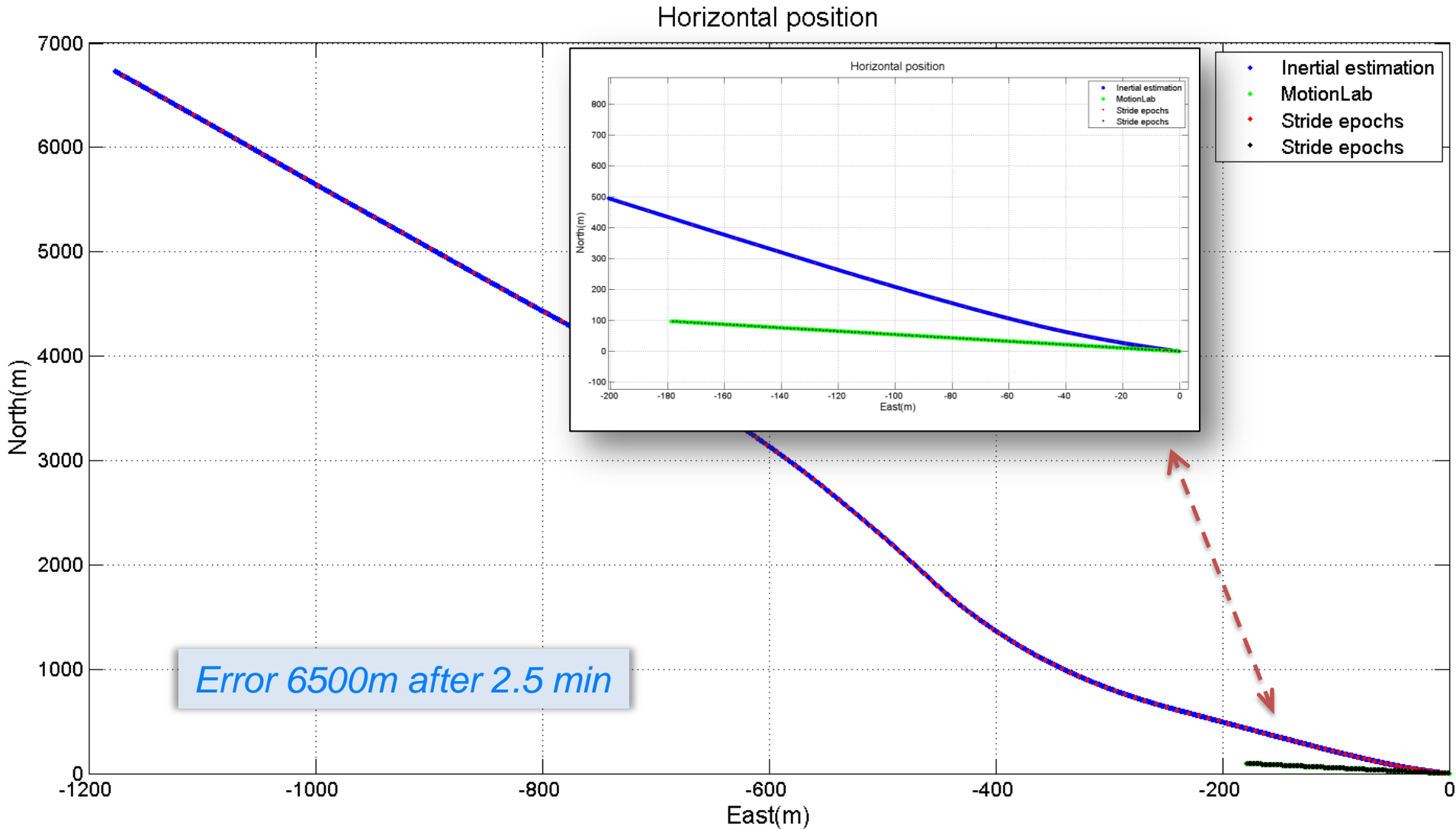


# Strapdown INS with "Texting" Hand

Velocity estimation



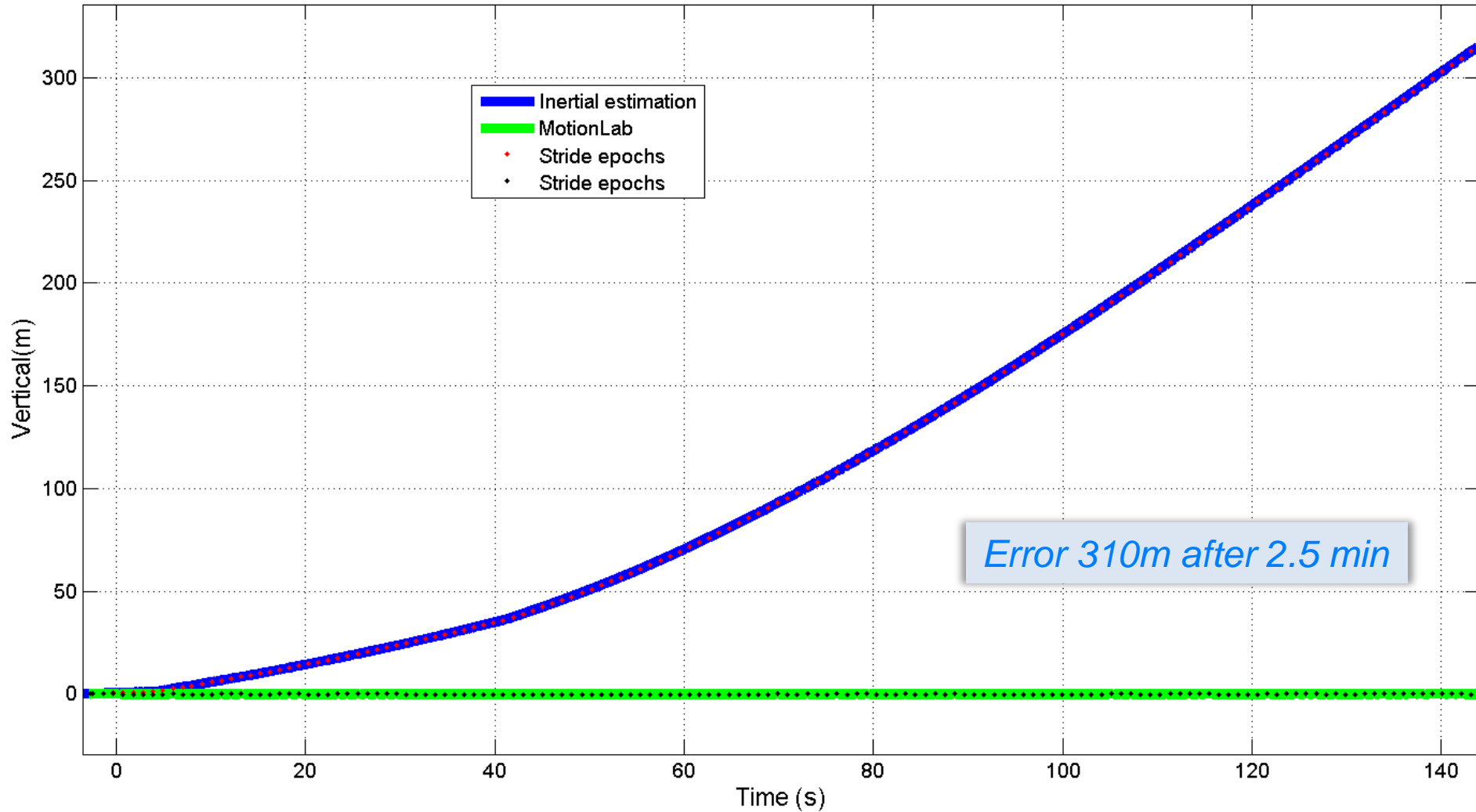
# Strapdown INS with “Texting” Hand





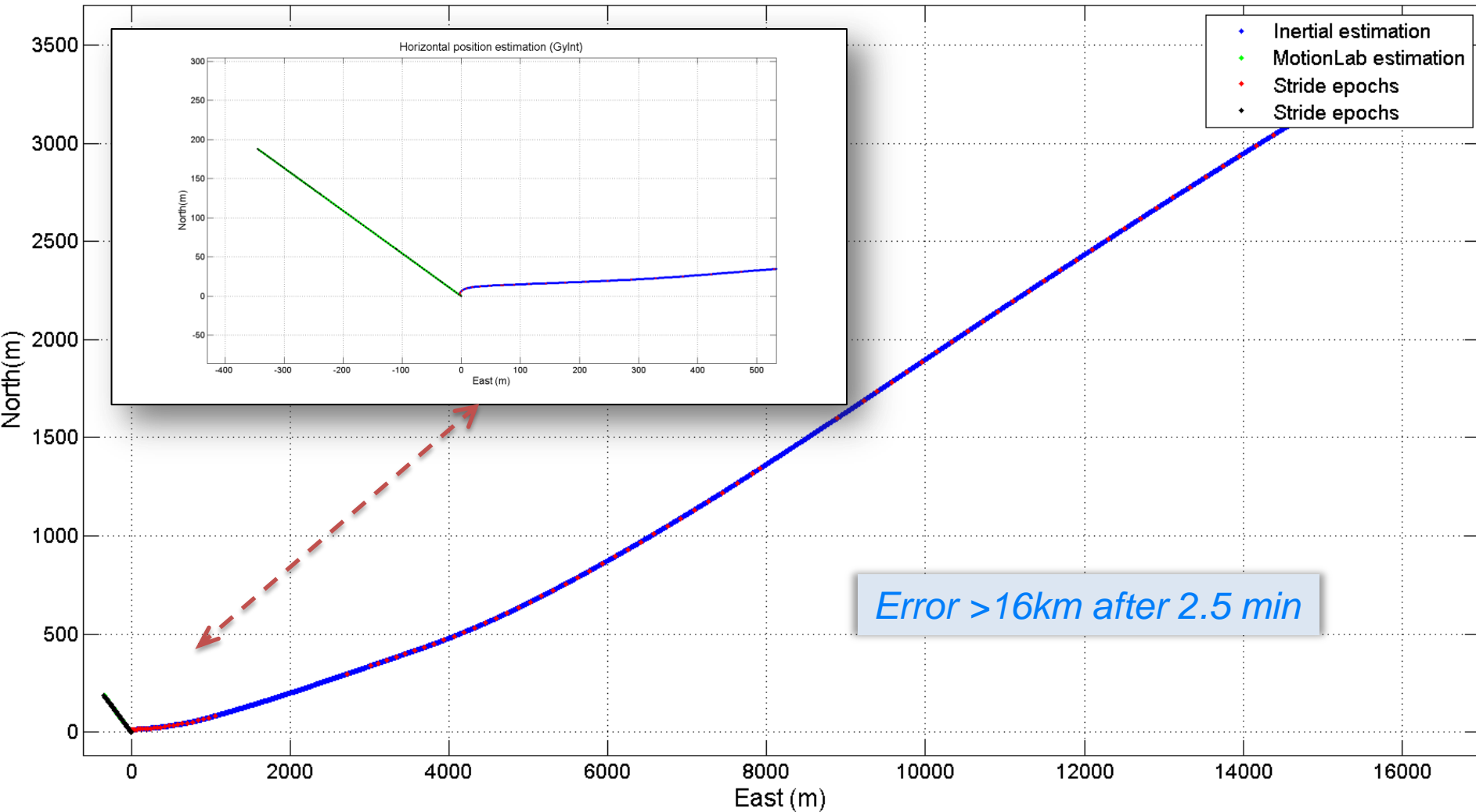
# Strapdown INS with “Texting” Hand

Vertical position



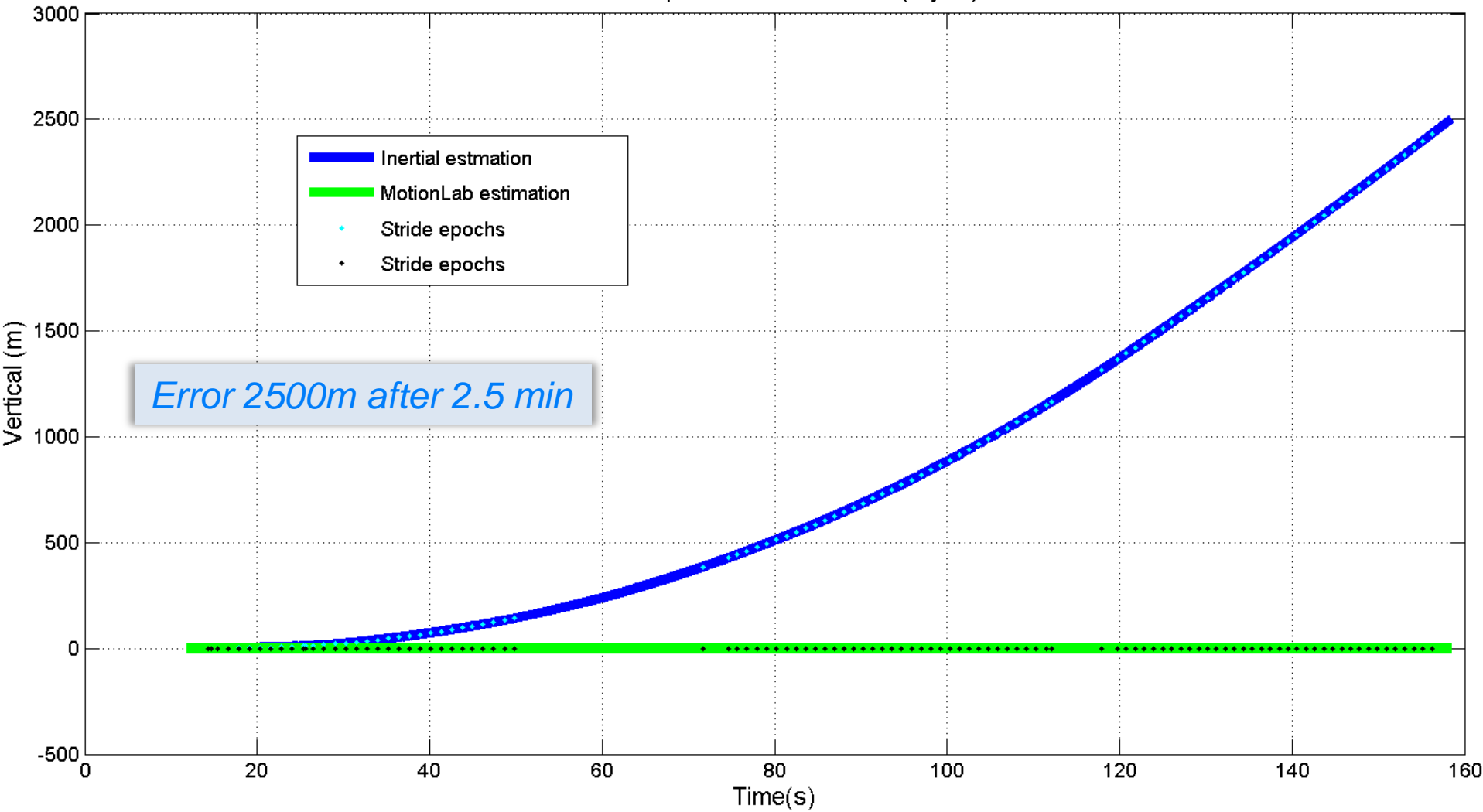
# Strapdown INS with “Swinging” Hand

Horizontal position estimation (Gylnt)



# Strapdown INS with “Swinging” Hand

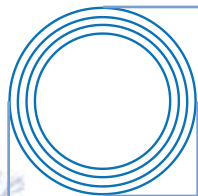
Vertical position estimation (Gylnt)



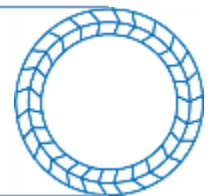
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Alternative positioning strategies



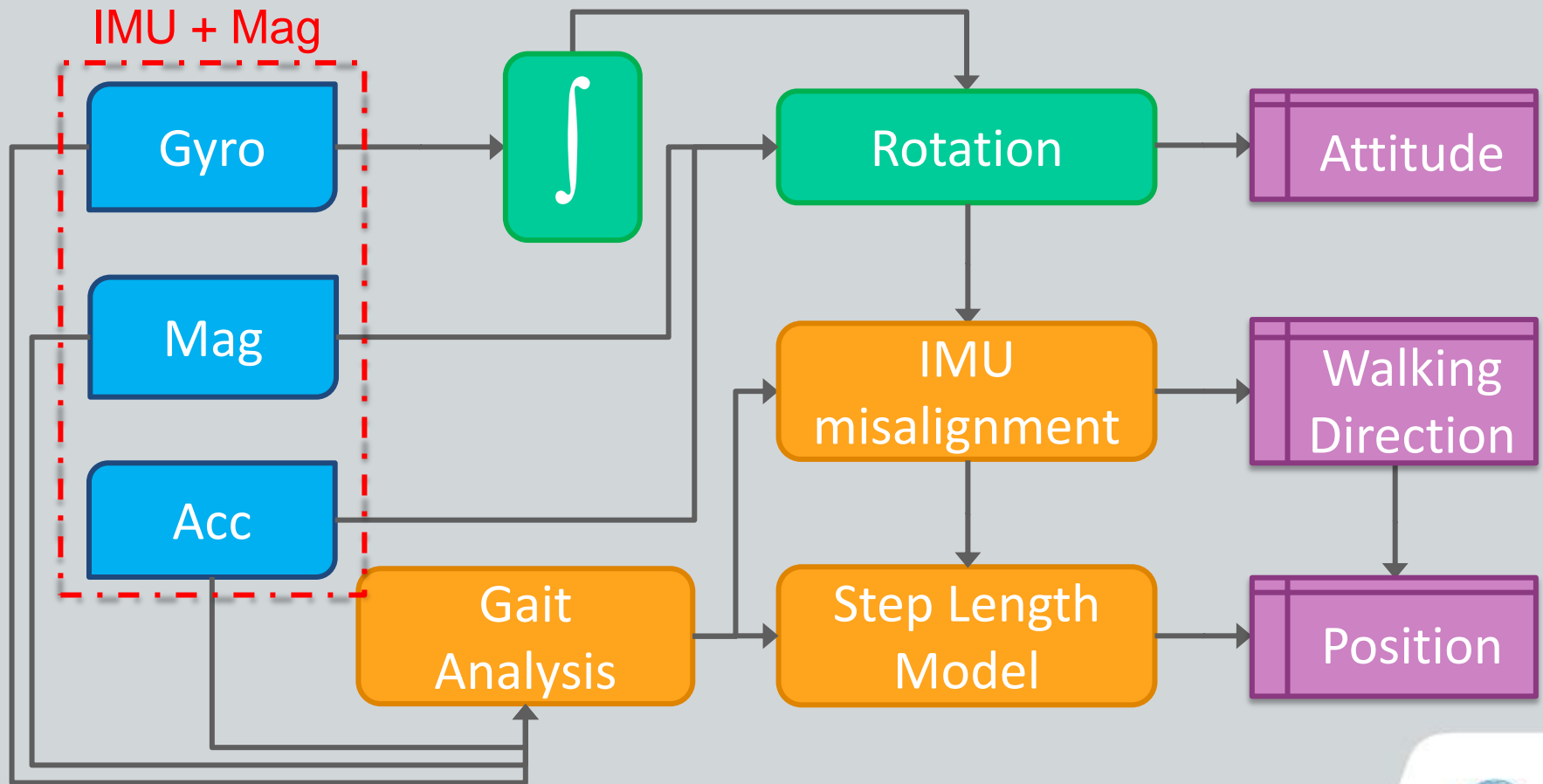
Conclusion

# Review of Alternative INS Strategies

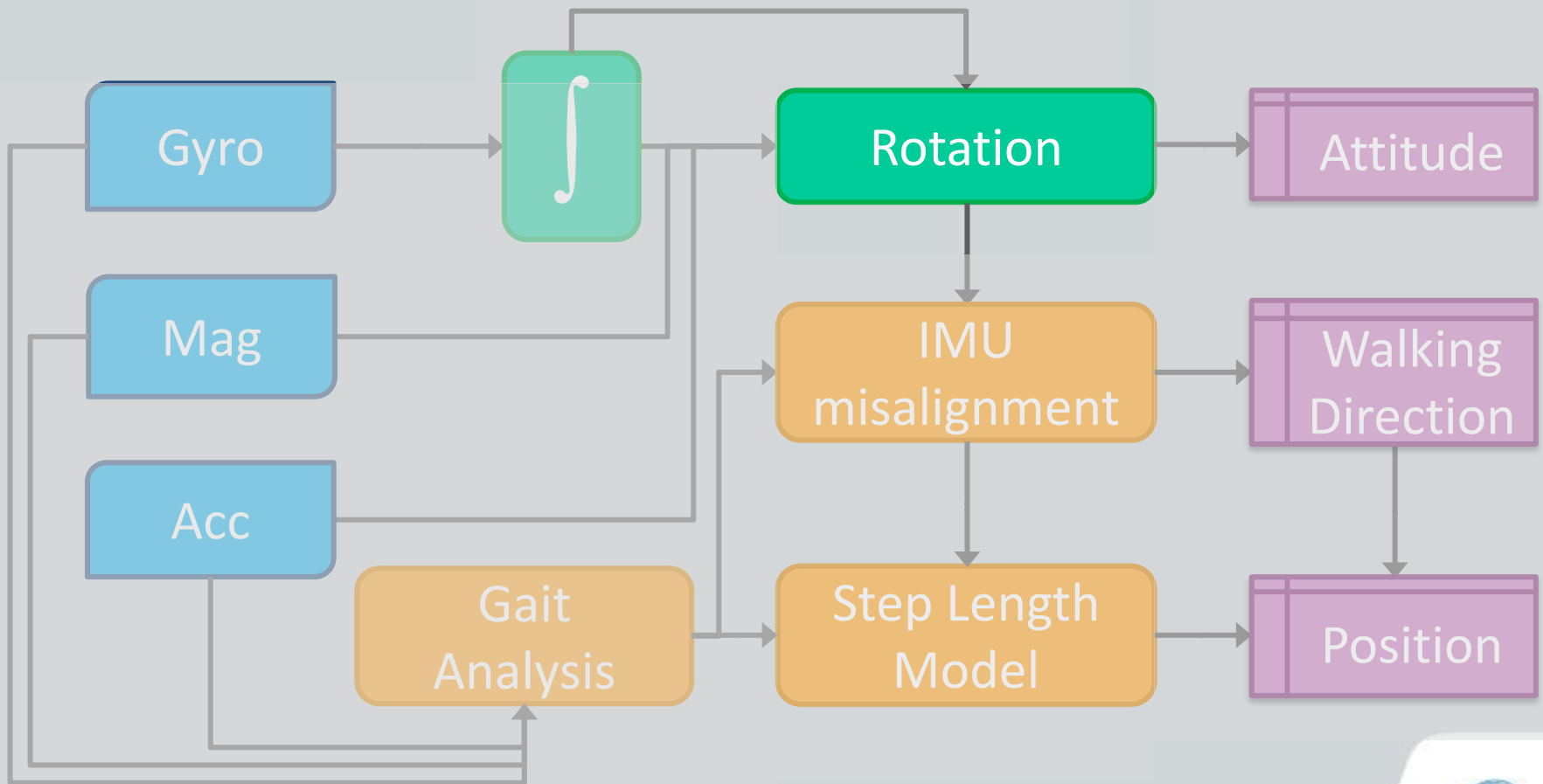
- **Biomechanics of human walking gait**
  - Repetitive steps
  - Assumed symmetry between right and left step
  - Upper body part contribute to the equilibrium
  - Repetitive arm motion during the displacement
- **Alternative processing strategies**
  - Different forms of algorithms (freely carried devices)
  - Sensors & context dependent
- **Existing methods**
  - Classification of activity and sensor carrying modes
  - Step/stride length modeling (no integration)
  - Sensor calibration with opportunistic signal (artificial magnetic field) or motion (quasi-static acceleration)
  - Hybridization with other sensors: camera, microphone, etc.



# Pedestrian Dead Reckoning



# Walking Direction



# Accurate Attitude Angles

## Rotation

- Accurate attitude estimation is limited primarily by gyroscopes errors which can be controlled by
  - GNSS updates
  - New sensor configuration
  - Magnetometer
  - Reducing the filter error propagation (quaternion space)
  - New sensors
  - Opportunistic IMU motion
  - Unknown sensor orientation relative to body/user





# Error Modeling in Quaternion Set

Rotation

- Differential equation ?  
$$\mathbf{q}_b^n(t + \Delta t) = \mathbf{q}_b^n(t) \circ \mathbf{q}_\omega^b(t)$$

$$\mathbf{q}_\omega^b = \begin{bmatrix} \cos\left(\frac{\|\boldsymbol{\omega}_{nb}^b\|}{2} \Delta t\right) \\ \sin\left(\frac{\|\boldsymbol{\omega}_{nb}^b\|}{2} \Delta t\right) \frac{\boldsymbol{\omega}_{nb}^b \Delta t}{\|\boldsymbol{\omega}_{nb}^b \Delta t\|} \end{bmatrix}$$

- Angular rate error model

$$\boldsymbol{\omega}_{nb}^b = \boldsymbol{\omega} + \mathbf{b}_\omega + \mathbf{w}_\omega$$

- Error model in the quaternion set

$$\mathbf{q}_{\omega_{nb}^b}^b = \mathbf{q}_\omega^b + \mathbf{b}_{q_\omega^b} + \mathbf{w}_{q_\omega^b}$$

?

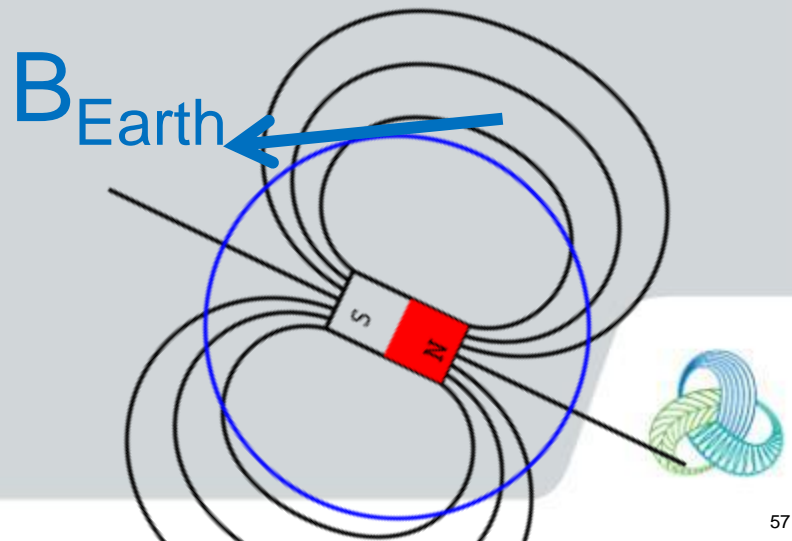
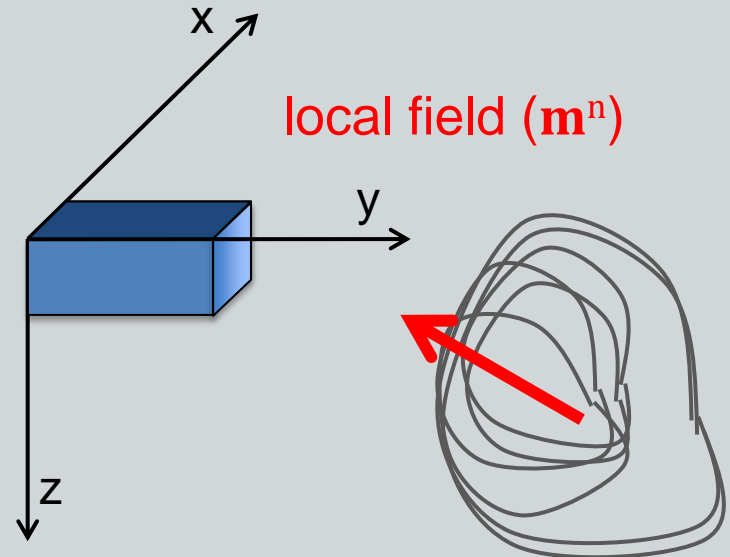
Allan Variance Analysis



# Magnetic Field Update

Rotation

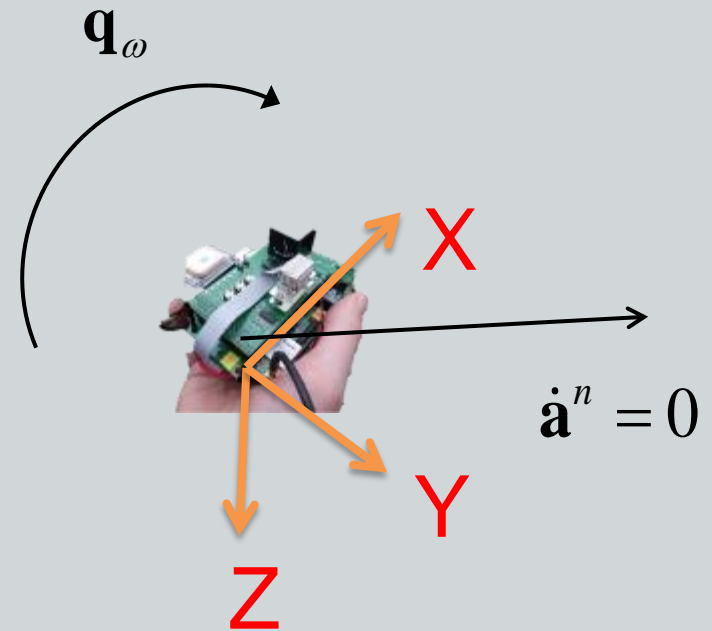
- When local magnetic field is constant over  $\Delta t$ :  
2 updates
  - QSF: all  $\mathbf{m}^n$  are equal
  - MARU: quaternions derived from the magnetic and gyroscope angular rates over  $\Delta t$  are the same



# Acceleration Field Update

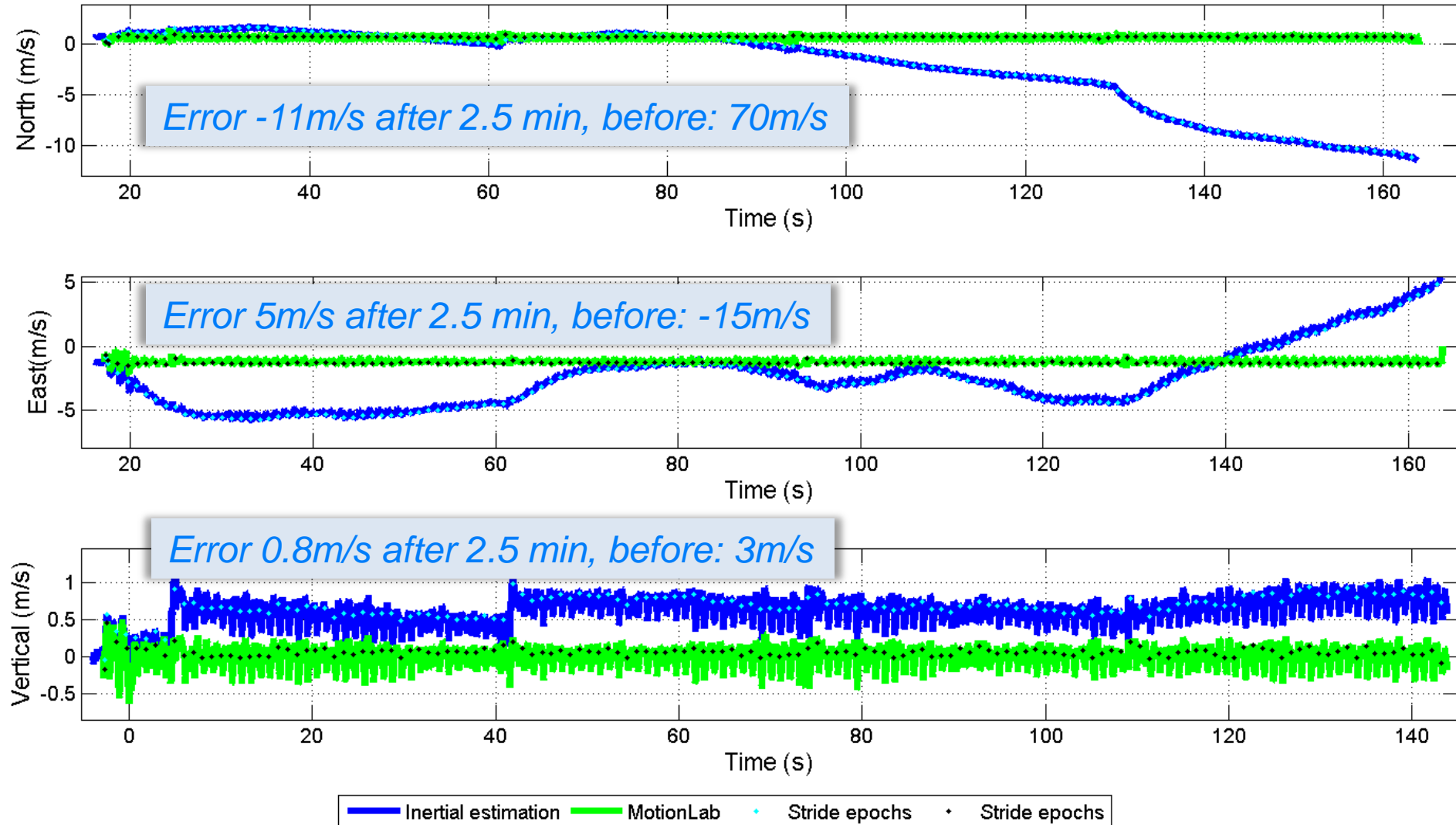
Rotation

- When the acceleration is Constant, over  $\Delta t$ : 2 updates
  - QSF: all an acc. are equal
  - AGU (Acceleration Gradient Update): the quaternions derived from the gyroscope and the QSF acceleration should be the same

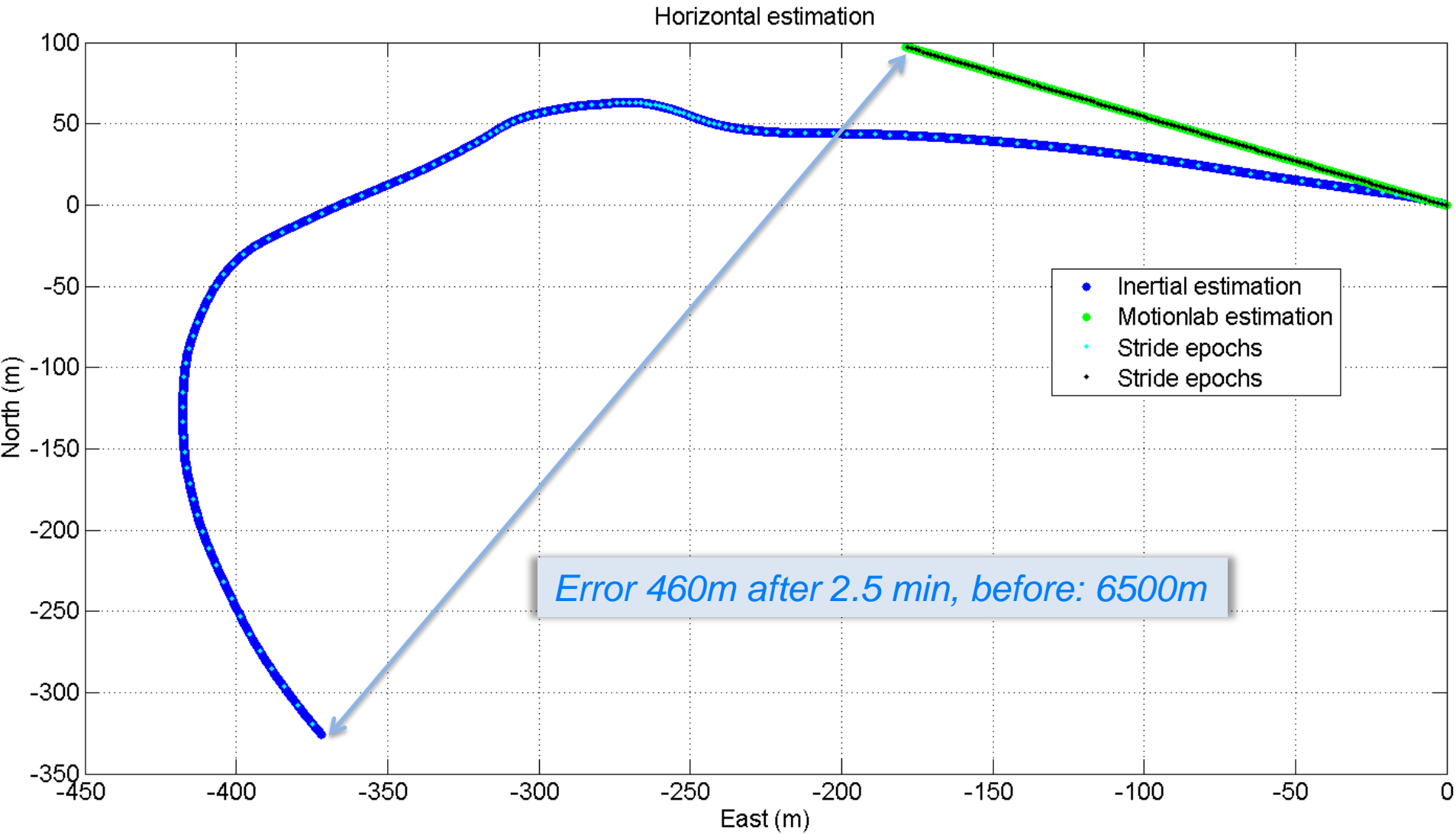


# MAGYQ with "Texting" Hand

Velocity estimation

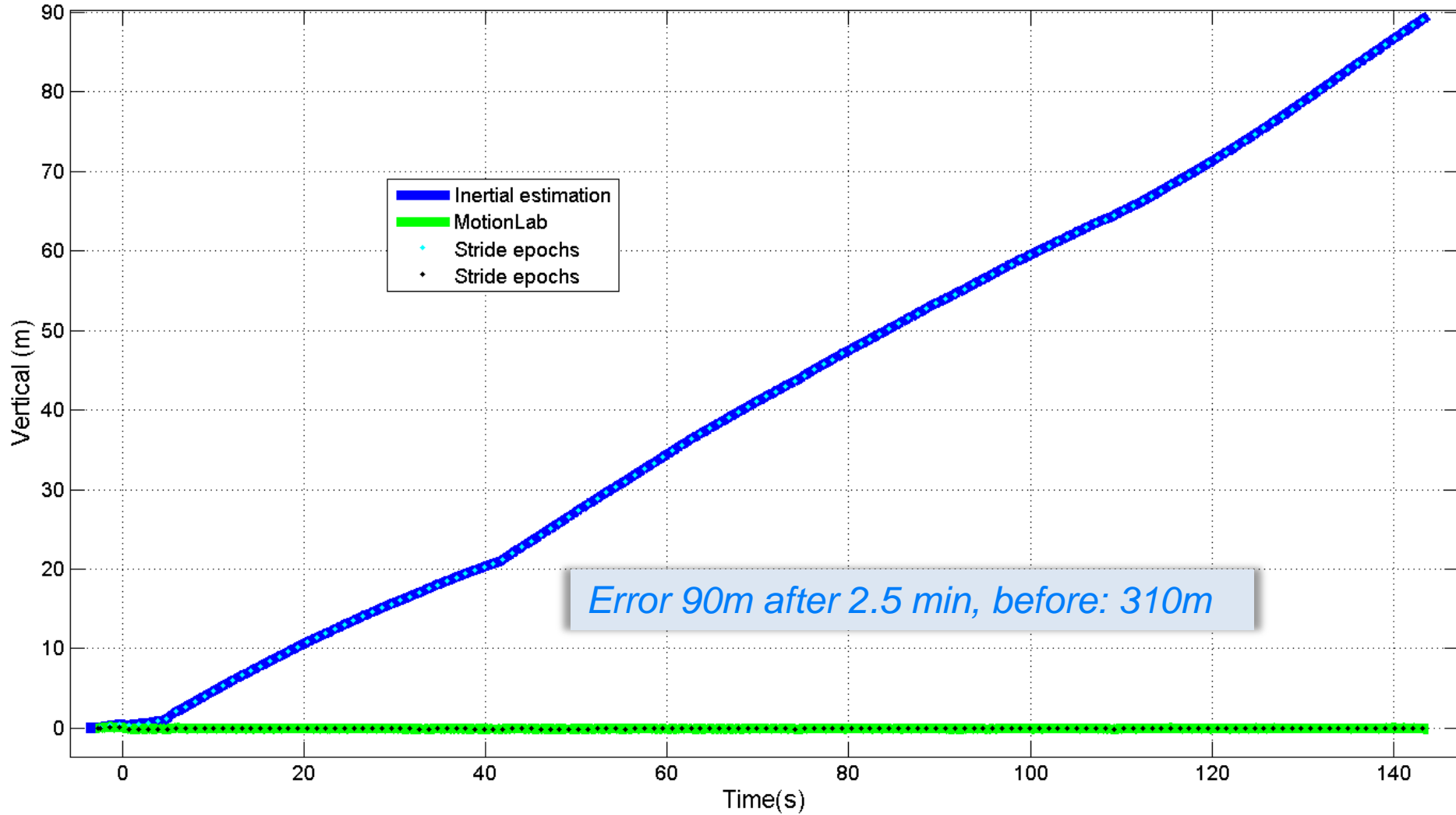


# MAGYQ INS with “Texting” Hand



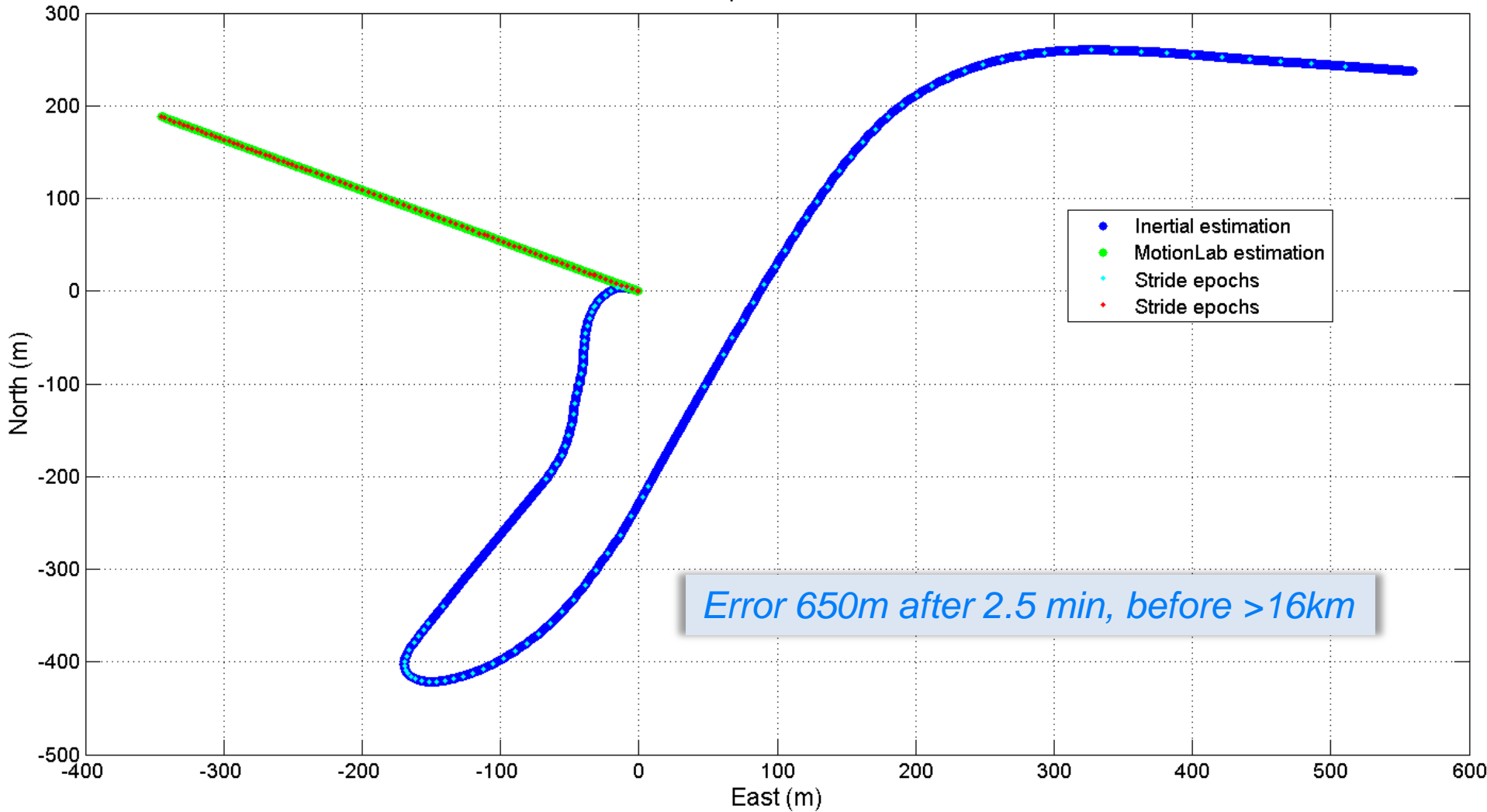
# MAGYQ INS with “Texting” Hand

Vertical estimation



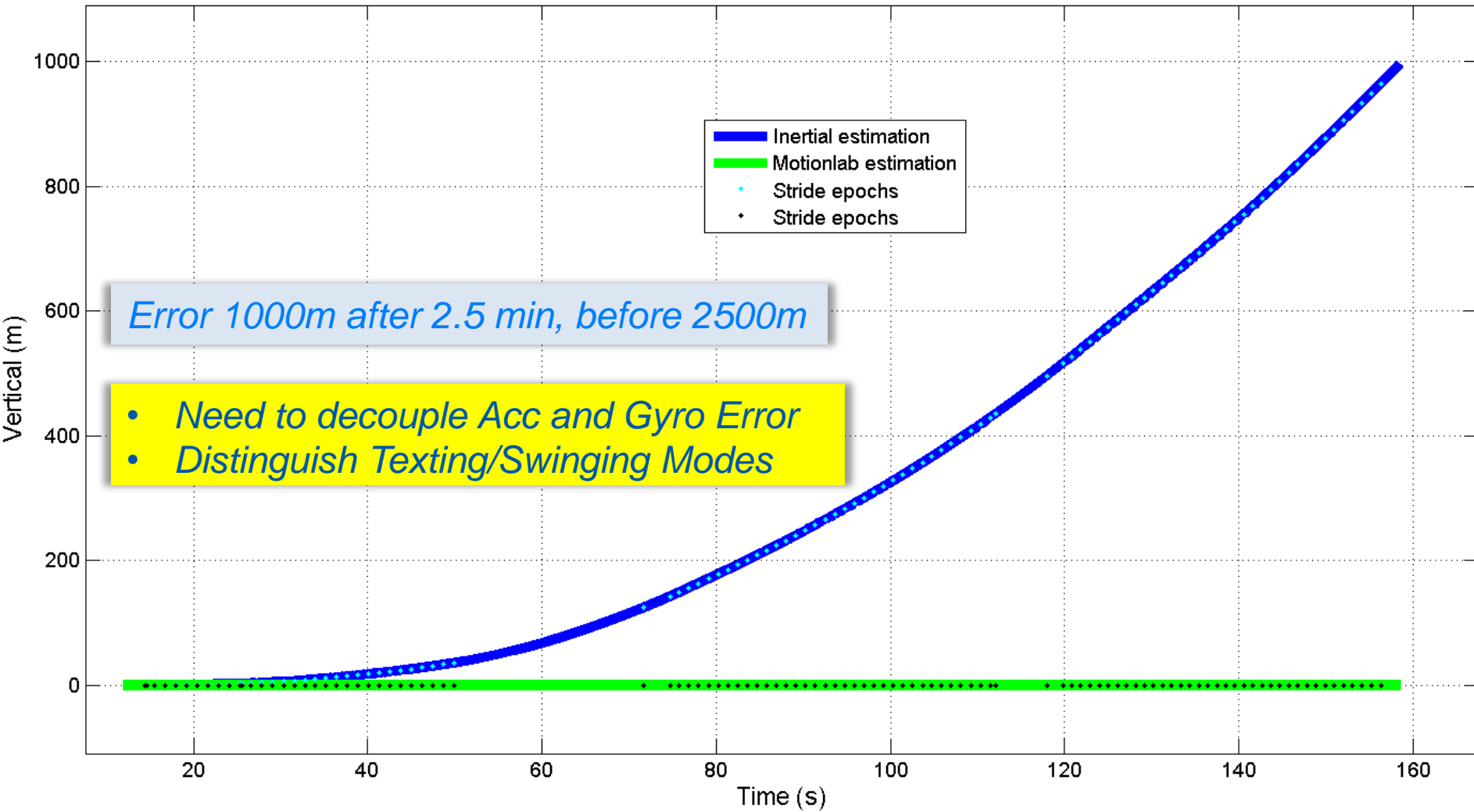
# MAGYQ INS with “Swinging” Hand

Horizontal position estimation



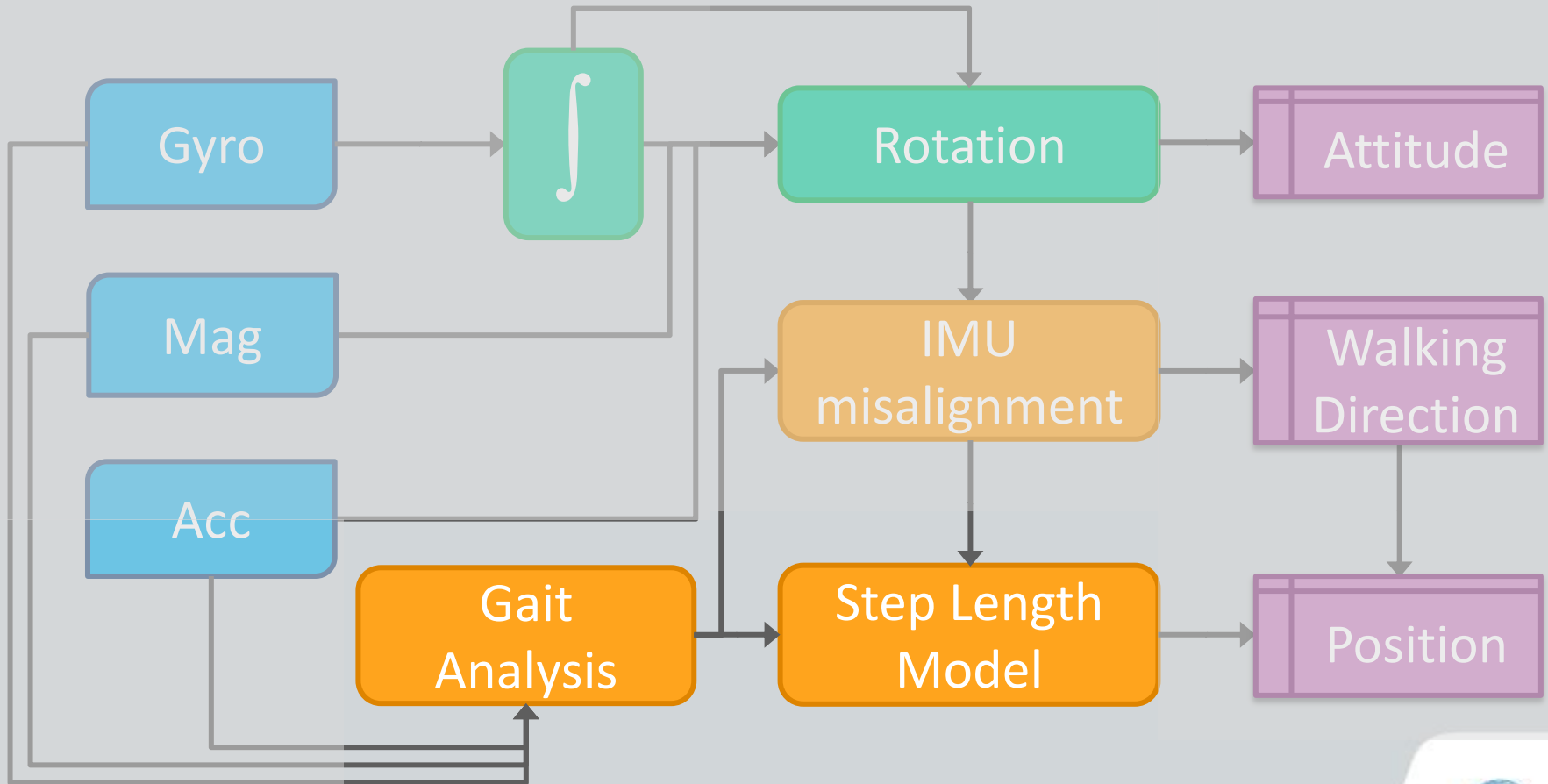
# MAGYQ INS with “Swinging” Hand

Vertical position estimation (Magyq)





# Human Gait Analysis



# Motion and Carrying Mode Recognition

Gait  
Analysis

**Input Space**

$$X = [x_1, x_2, \dots, x_n]$$

*IMU Signal Features*

$f(X)$

**Decision Rule:**

$$X \rightarrow f(X) \rightarrow y_k \in Y$$

*mapping function*

**Output Space**

$$y_{k \in \{1, m\}} \in Y = [y_1, y_2, \dots, y_m]$$

**Classifier**

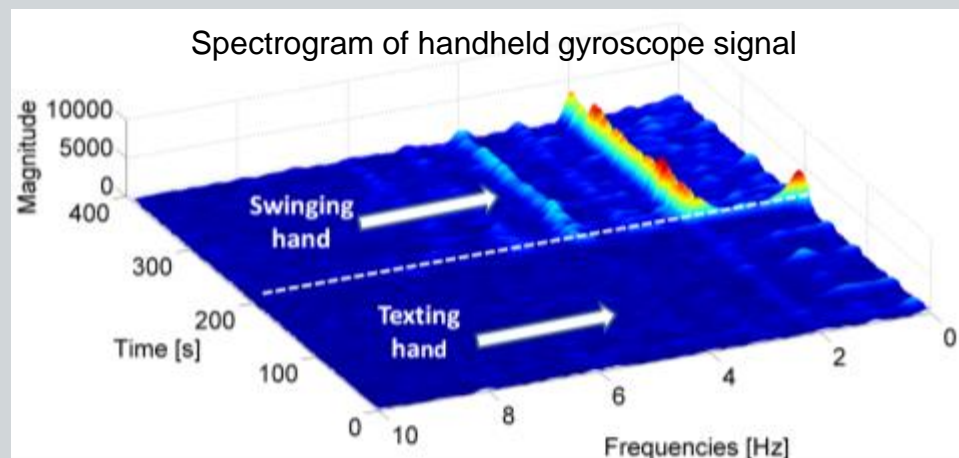
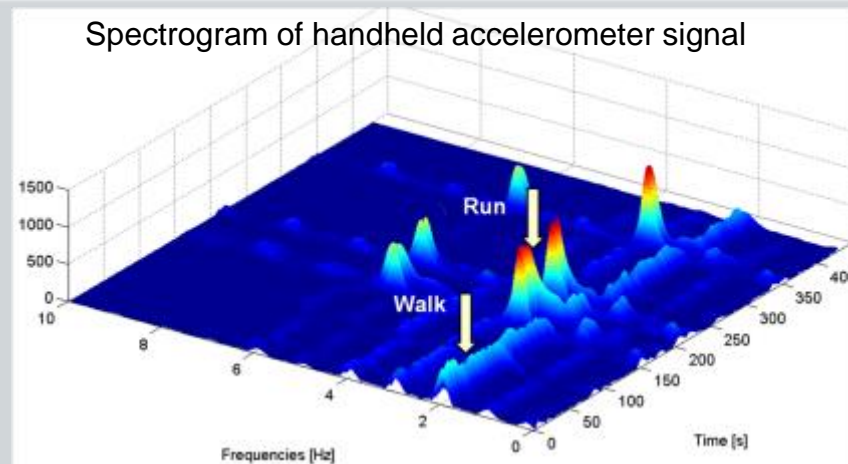
- Adapt the algorithms to the context to bound positioning error
- A classification problem
  - Pre-processing → Feature extraction → Decision Making
- Motion states
  - User: Standing, Running, Walking, Up/Down Stairs
  - IMU/Hand: Phoning, Texting, Bag Carrying, Swinging, Irregular Motion



# Selecting Features

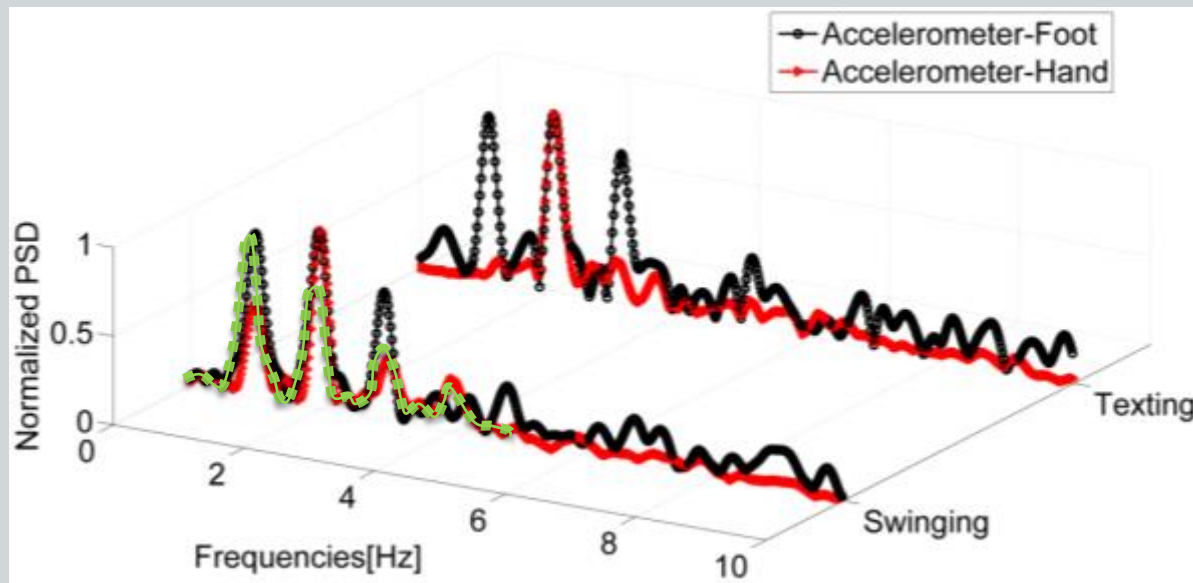
## Gait Analysis

- **Manifold features**
  - Energy
  - Variance
  - Standard deviation
  - Frequencies in sub-bands
  - STFT coefficients
- **Pattern Extraction**
  - Faster Motion modes migrate the signal energy toward highest frequencies (acc. signal)
  - Periodic arm rotation induce frequency peaks (gyro signals)



# Step Frequency Extraction

- Estimated independently from step detection: remove correlation in the filter, more robust
- Extraction of dominant frequencies with Short Time Fourier Transform (STFT) over 2 sec. sliding window
  - Three peaks
- Coupling problem of the strongest hand frequency with step or stride
  - Binary Detector based on biomechanics feature of walking gait



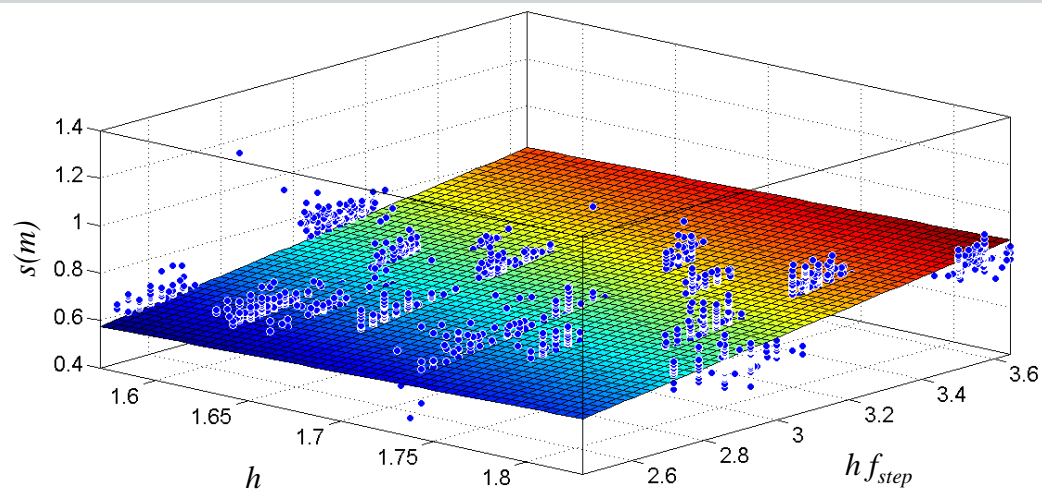
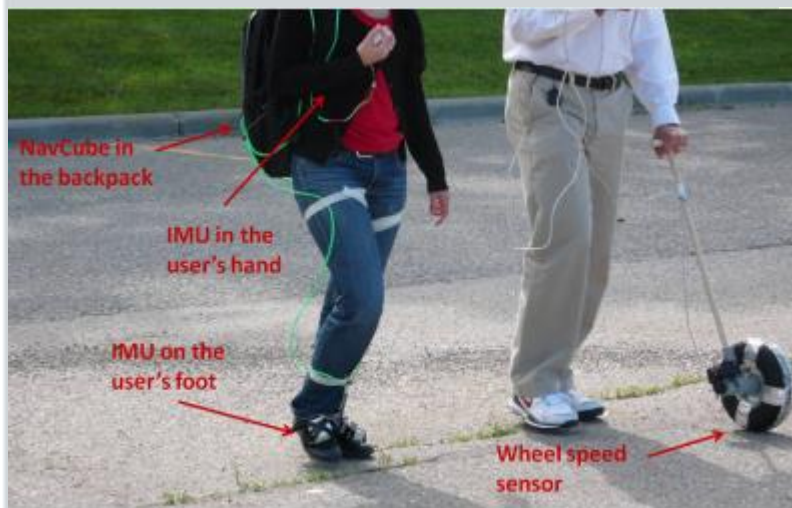
# Defining a Model

## Step Length Model

- Experimental approach with controlled walking pace

$$s = h(af_{step} + b) + c$$

- $s$ : step length
- $\{a, b, c\} \in \mathbb{R}$ : individual parameters set
- $h$ : the pedestrian's height



Renaudin et al., Step Length Estimation Using Handheld Inertial Sensors, Sensors, 2012.



# Evolutionary Gait

## Step Length Model

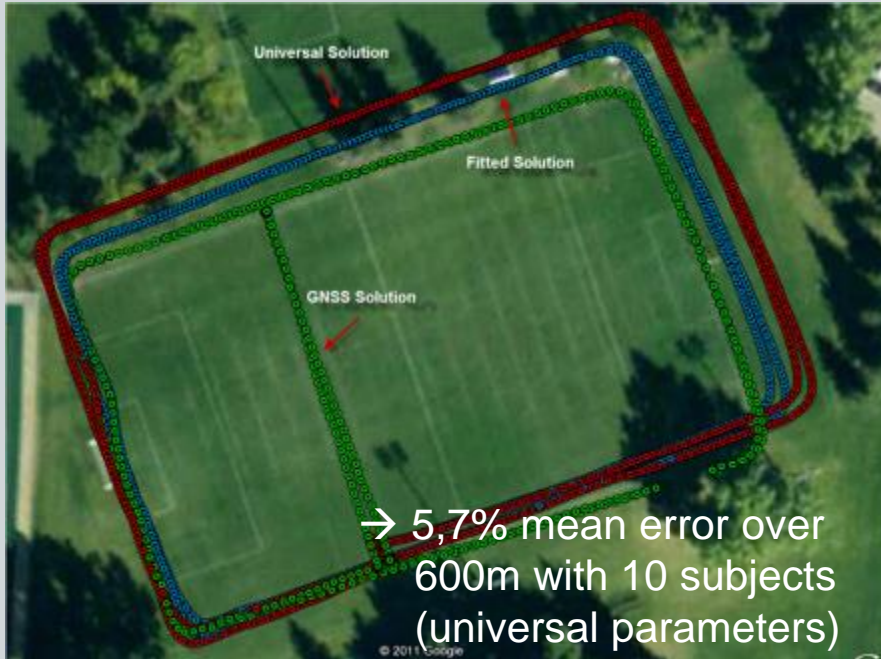


- Walking Gait influenced by varying physiological conditions tiredness, injuries, carrying a bag, ...
  - Frequent calibration is needed
- Several approaches are possible depending on the application
  - Walking along a known footpath
  - Use departure / destination info
  - Hybridization with opportune signal (GNSS, WiFi, etc.)

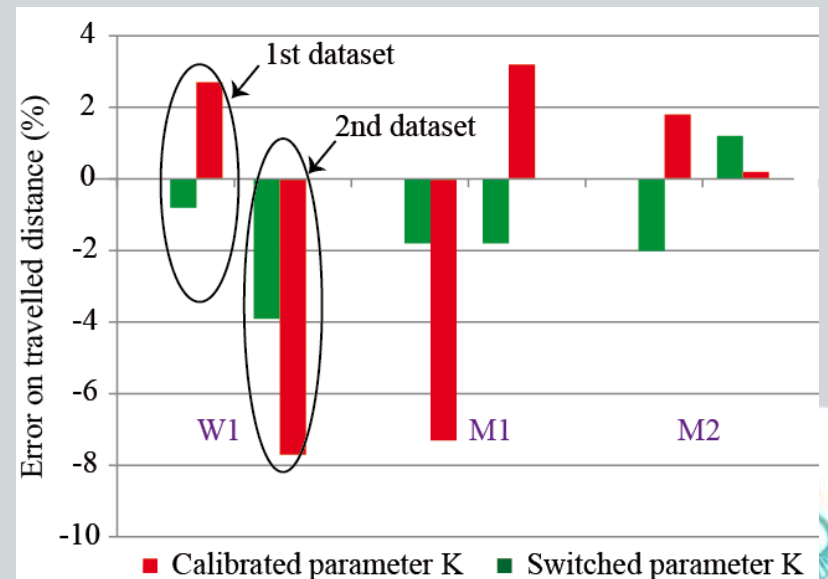
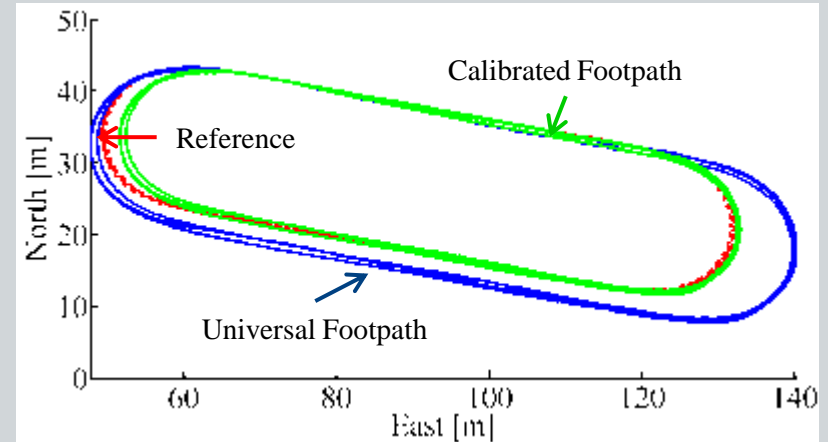


# Distance Estimation Performance

Step Length  
Model



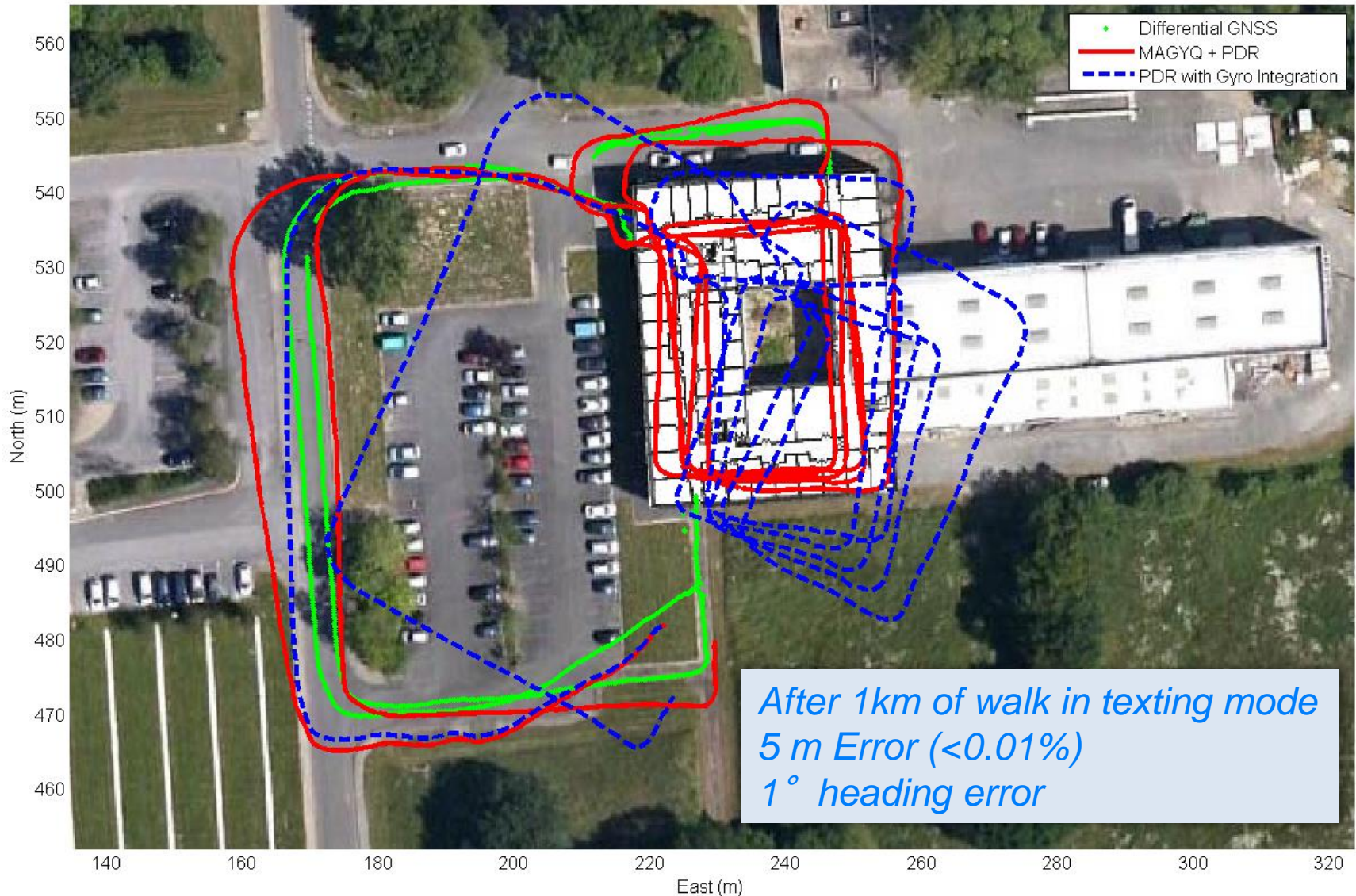
- Calibration using GNSS Doppler
  - 10 sec. PDR/GPS Doppler hybridization
  - 2% mean error over 700m with 4 test subjects with freely carried device (texting, swinging)



Renaudin et al., Adaptive Pedestrian Displacement Estimation with a Smartphone for Free Inertial Navigation, IPIN, 2013.

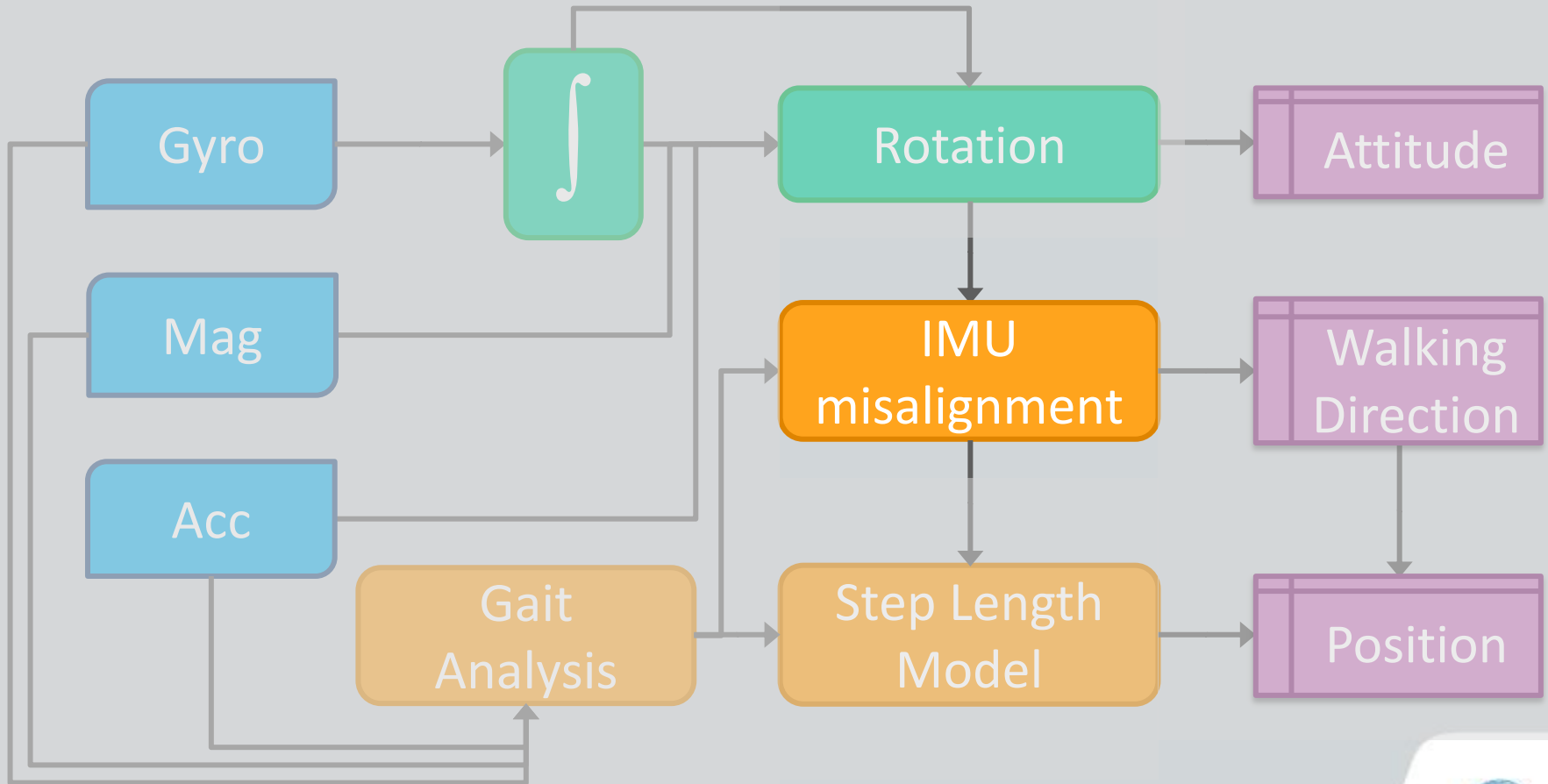


# MAGYQ + PDR





# Estimating the Walking Direction



# Deformable Model

IMU  
misalignment

- Features extraction from the accelerations dataset, in navigation frame, over a step
- Fundamental assumptions
  - $\mathcal{H}1$ : Pedestrian Gravity Center dynamic is observable
  - $\mathcal{H}2$ : Acceleration in the navigation frame are unbiased



# Three Strategies

IMU  
misalignment

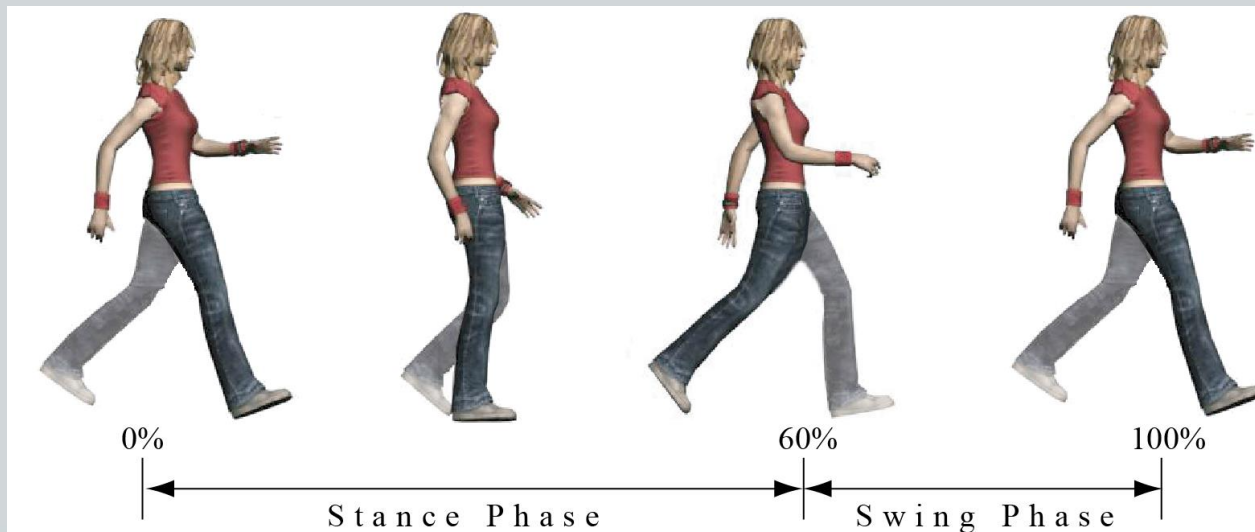
- Principal component analysis of the accelerations
  - *Algo*: find the direction of the horizontal oscillations in the estimated acceleration
  - *Ht*: constant misalignment over a step (even several)
- « Pattern Matching » on a reference acceleration signal signature in the forward and lateral directions
  - *Algo*: minimize of the distance between the pre-determined shape and the estimated acceleration
  - *Ht*: availability and validity of a universal model walking model
- Frequency analysis of inertial signals inspired by biomechanics
  - *Algo*: find the direction of oscillations by using the periodicity of the human walking
  - *Ht*: robust gait analysis is possible



# Common Elements

IMU  
misalignment

- Pre-processing
  - Estimation of the IMU's attitude angles
  - Estimation of the IMU's acceleration: removing the gravity component
- Biomechanics Outcomes
  - The motion of the pedestrian's center of mass is cyclic
  - Analysis can be conducted over several steps or stride



# Principal Component Analysis (PCA)

IMU  
misalignment

- Observations

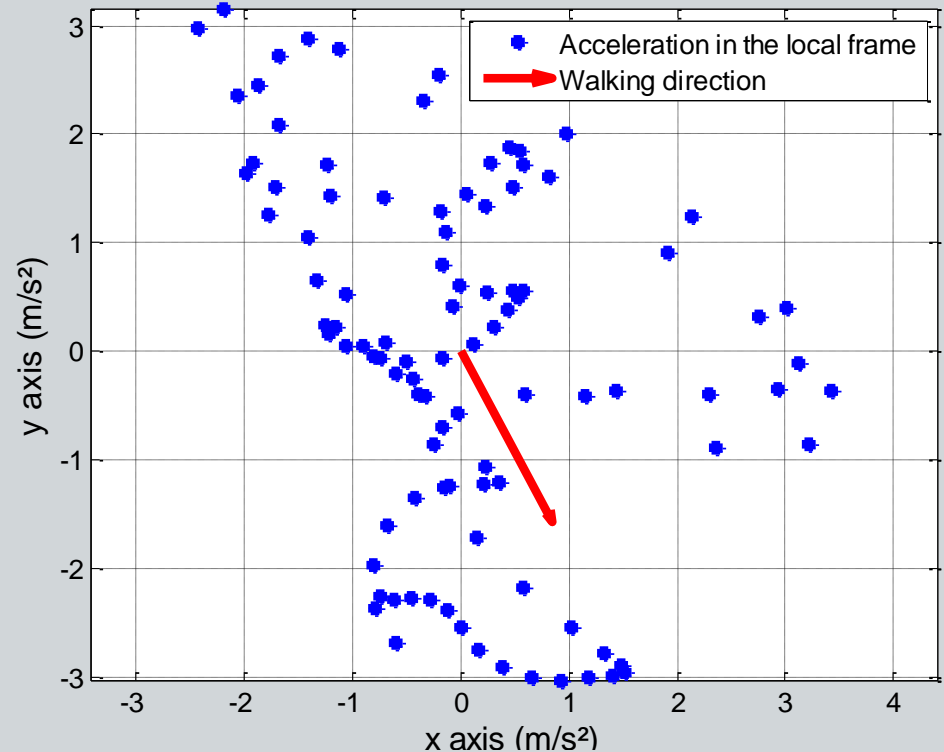
- Variance of horizontal acc. is maximum along the forward direction
- Variance of horizontal acc. is minimum along the lateral direction

- Problem statement

- find the horizontal unit vector  $\mathbf{u}$  that maximizes

$$\max_{\|\mathbf{u}\|=1} \left( \sum_{i=1}^n \langle \mathbf{u}, \ddot{\mathbf{x}}_H(i) \rangle^2 \right)$$

over a  $n$  samples  
step/stride



# Forward and Lateral Acc. Modeling (FLAM)

IMU  
misalignment

- Assumption

- Forward and Lateral acc. models over a stride/step exist

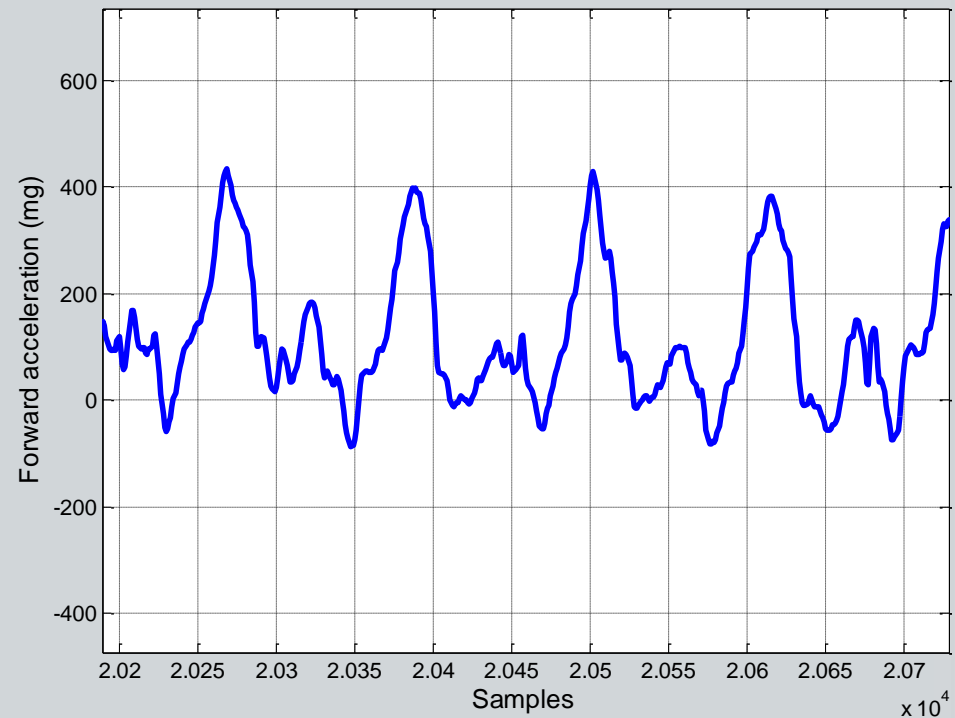
$$\ddot{\mathbf{x}}_m(t) = \sum_{i=1}^n \ddot{\mathbf{x}}_H \sin(tb_i + c_i)$$

- Problem statement

- Find  $\theta$  that maximizes the correlation

$$\max_{\theta} \sum_i \ddot{\mathbf{x}}_m(i) \left( \ddot{\mathbf{x}}_H^T(i) \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} \right)$$

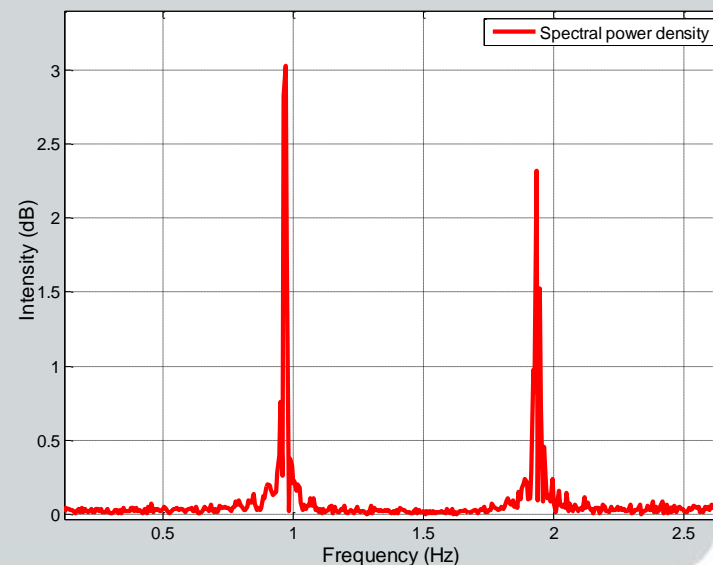
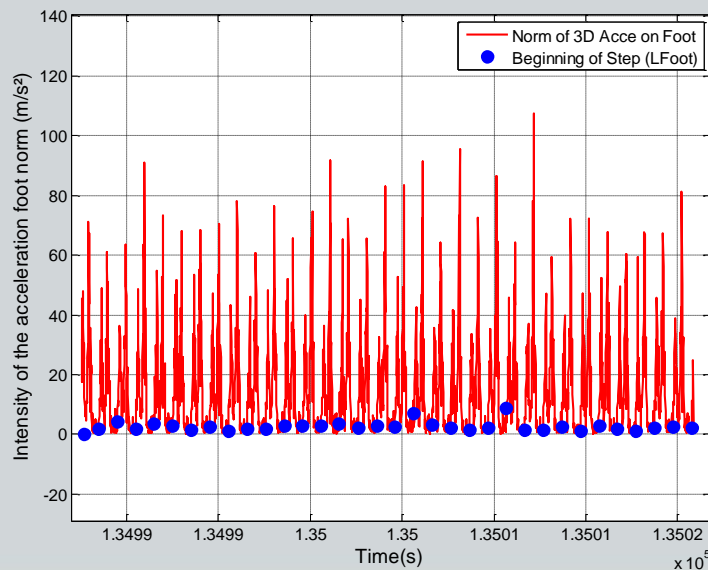
- Waking direction  $\theta$  is the weighted sum of the 2 angles found for the 2 models



# Frequency analysis of Inertial Signals (FIS)

IMU  
misalignment

- Observation
  - The energy of the signal is maximum along the forward direction at step/stride frequency
- Problem statement
  - Find  $\theta$  that maximizes the spectral density of the acc. and gyro. signals energy at step/stride frequency
  - Acc. and gyro freq. and phase components  $\ddot{X}(\omega)$  and  $W(\omega)$  estimated by STFT
  - Compute forward and lateral power spectral densities ( $P_{\ddot{X}_f}$ ,  $P_{\ddot{X}_l}$ ) and ( $P_{W_f}$ ,  $P_{W_l}$ )
  - $\max_{\theta}(w_1 P_{\ddot{X}_f}(\theta) + w_2 P_{\ddot{X}_l}(\theta) + w_3 P_{W_f}(\theta) + w_4 P_{W_l}(\theta))$



# Comparative Analysis

IMU  
misalignment

- Overall experimental results in Motion Lab (see previous videos)
  - Swinging mode : error  $< 10^\circ$
  - Texting mode: mean error  $< 30^\circ$

Parasite oscillations

Gait Analysis

Large hand/arm motion

- PCA

- sensitive to oscillations

- FLAM

- need a large database
- IMU carrying mode dependent
- Person dependent (gender, weight, etc.)

- FIS

- globally more robust
- Gait Analysis dependent
- Accuracy is not sufficient



Combettes et al., Comparison of misalignment estimation techniques between handheld device & walking directions, IPIN, 2015.





# Overview and motivation



Background on strapdown inertial navigation system (INS)

The challenge of personal navigation with handheld device

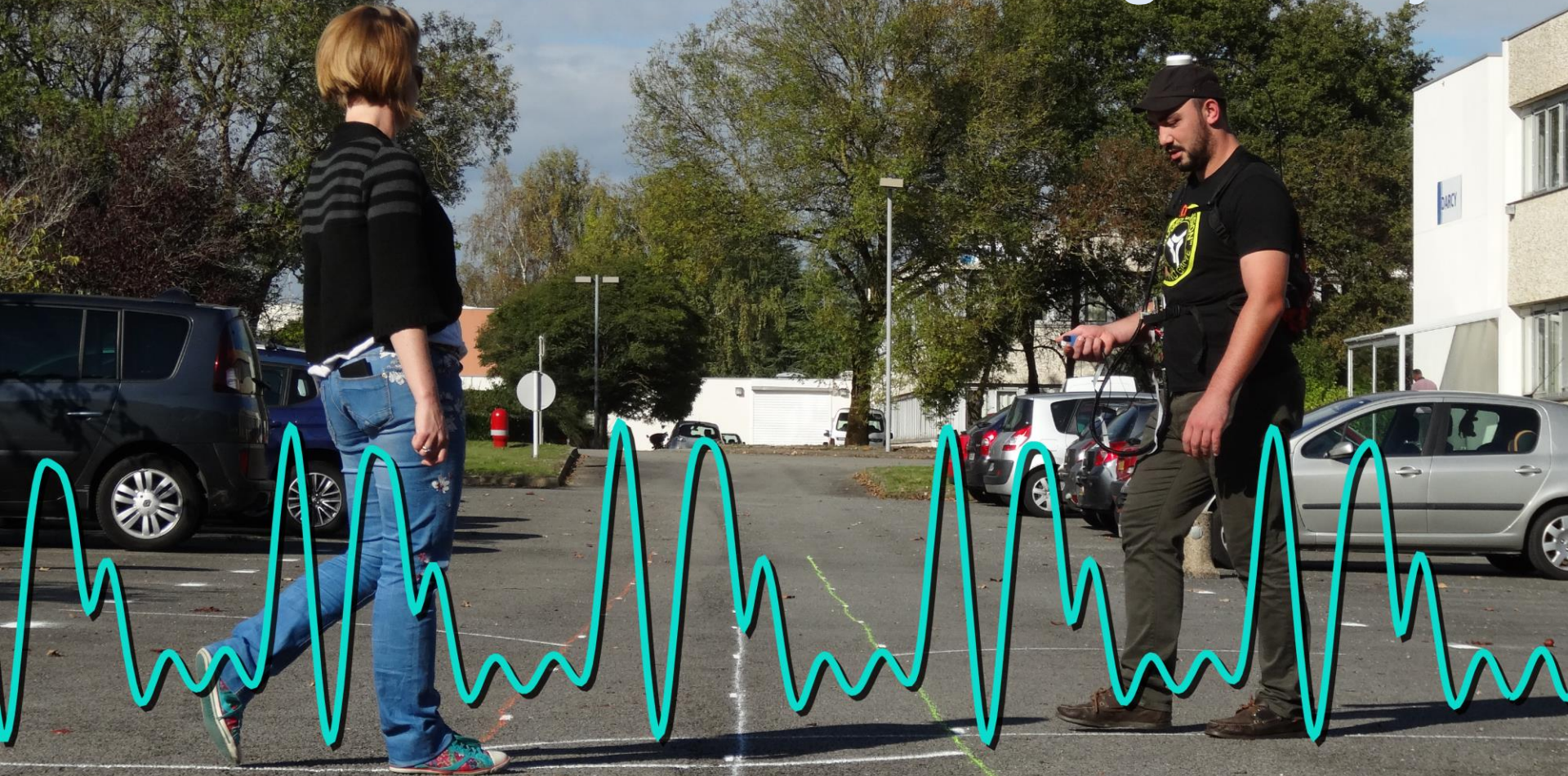
Alternative positioning strategies



**Conclusion**



# *Personal Inertial Navigation System with Handheld Devices is becoming a reality*



*Opens the way to new research fields*



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**IFSTTAR**