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A Comparative Analysis of Attitude Estimation for Pedestrian Navigation with Smartphones

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Indoor Positioning and Indoor Navigation
October 13-16, 2015 - Banff, Alberta, Canada

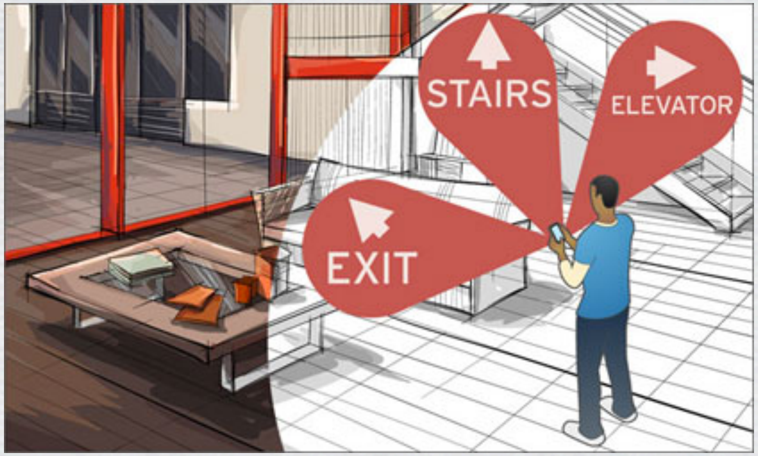
gipsa-lab

Inria informatics mathematics

LIG

Improving Augmented Reality with more Precise Localization

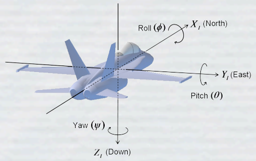
- **Goal**
  - Obtaining precise **localization** and **orientation** of the smartphone

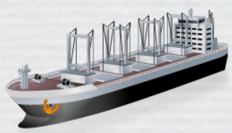


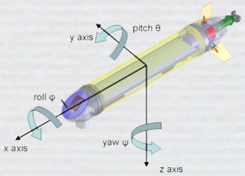
- **Difficulties**
  - Magnetic perturbations
  - External accelerations
  - Hard to compare algorithms
  - No ground truth to evaluate algorithm precision

Outline

- Introduction
- A set-up for attitude estimation algorithms evaluation
  - Ground truth using a motion lab
  - Several motions using a smartphone
- A comparative study of 6 well-known algorithms
  - Theoretical comparison
  - Experimental evaluation







- Conclusions and perspectives

Attitude

Attitude is the orientation of the Smartphone with respect to the Earth local frame

- Quaternion

$$\mathbf{q} = \begin{bmatrix} \mathbf{w} & \mathbf{x} & \mathbf{y} & \mathbf{z} \end{bmatrix}^T$$

- Euler Angles (yaw, pitch, roll)

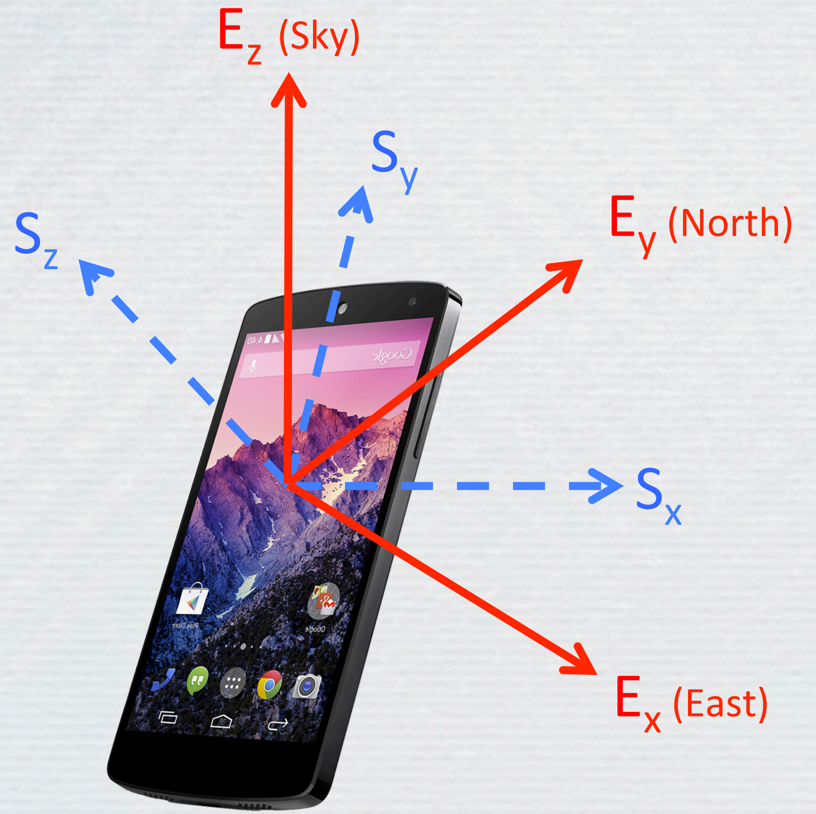
xyz, xzy, yxz, yzx, zxy, zyx

- Rotation Matrix

$$\mathbf{R} = \begin{bmatrix} \mathbf{x}_1 & \mathbf{y}_1 & \mathbf{z}_1 \\ \mathbf{x}_2 & \mathbf{y}_2 & \mathbf{z}_2 \\ \mathbf{x}_3 & \mathbf{y}_3 & \mathbf{z}_3 \end{bmatrix}$$

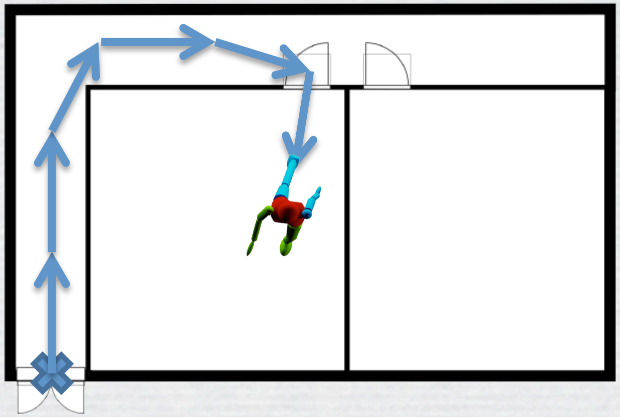
- Axis-Angle

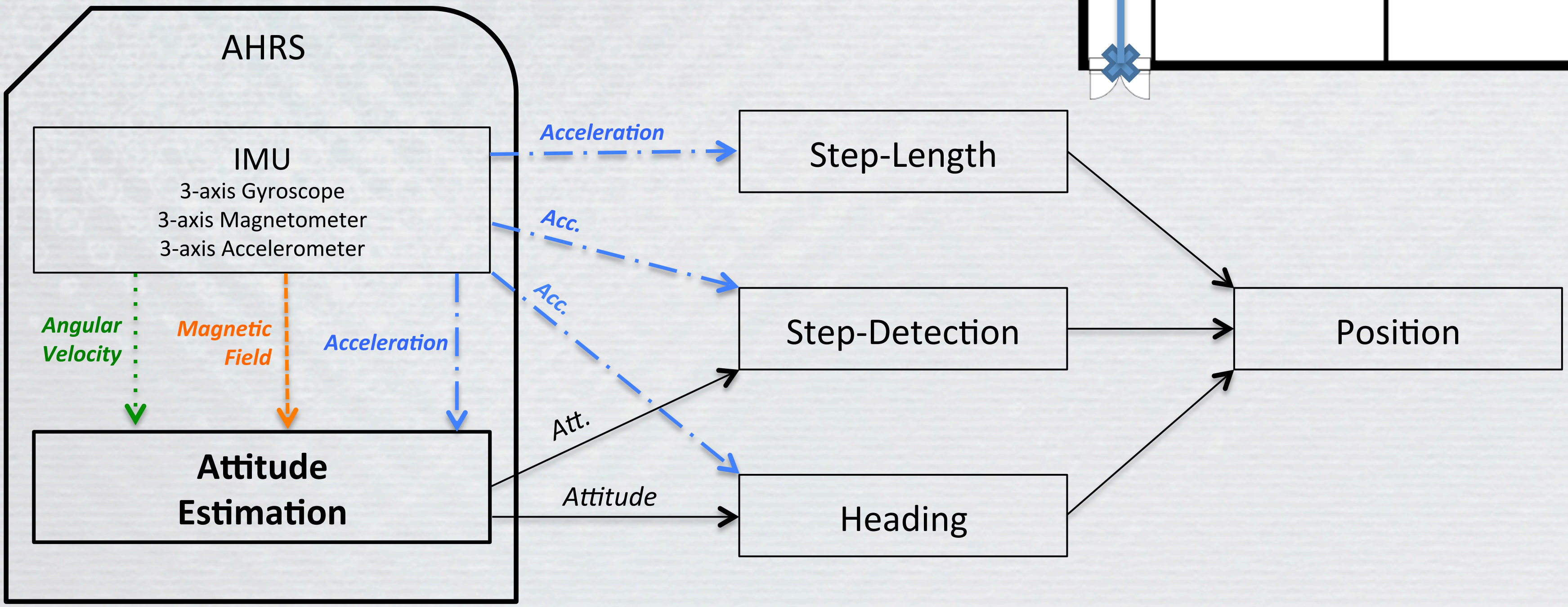
$$(axis, angle) = \left(\begin{bmatrix} \mathbf{a}_x \\ \mathbf{a}_y \\ \mathbf{a}_z \end{bmatrix}, \theta \right)$$



Attitude Estimation Impact

- Estimation from 3 sensors of the smartphone
- Attitude is the core of Pedestrian Dead Reckoning (PDR)
- Large impact on final position





How judge the **attitude** precision ?

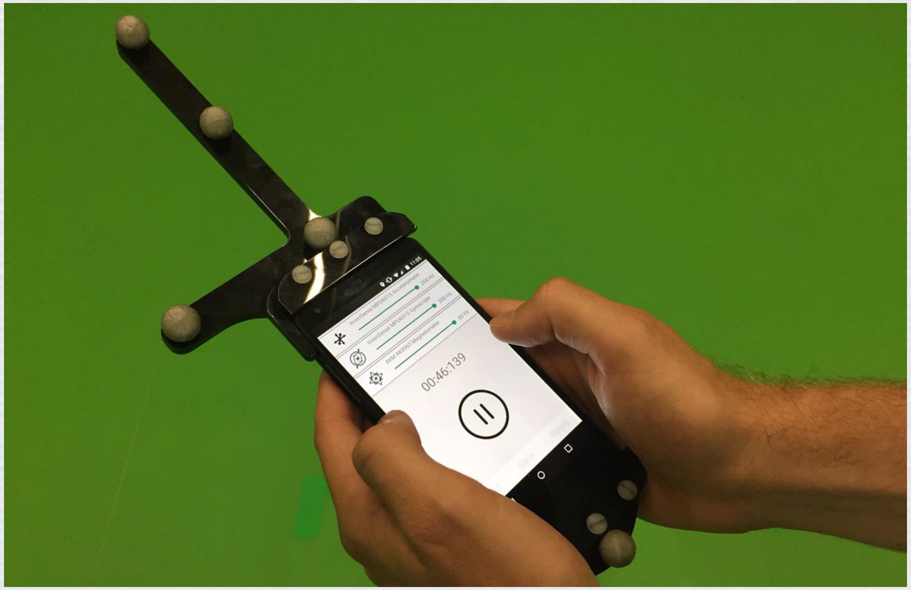
Using a Motion Lab to establish a Ground Truth

- 20 infra-red cameras, connected to Qualisys system, precision error < 1°
- Motion lab frame aligned with earth frame
- Hypotheses: Magnetic field is considered as static (vary from *40μT* to *43μT*)

Device

- Smartphone: Nexus 5
  - InvenSense MPU6515 (Accelerometer, Gyroscope) at *200Hz*
  - AKM AK8963 (Magnetometer) at *60Hz*

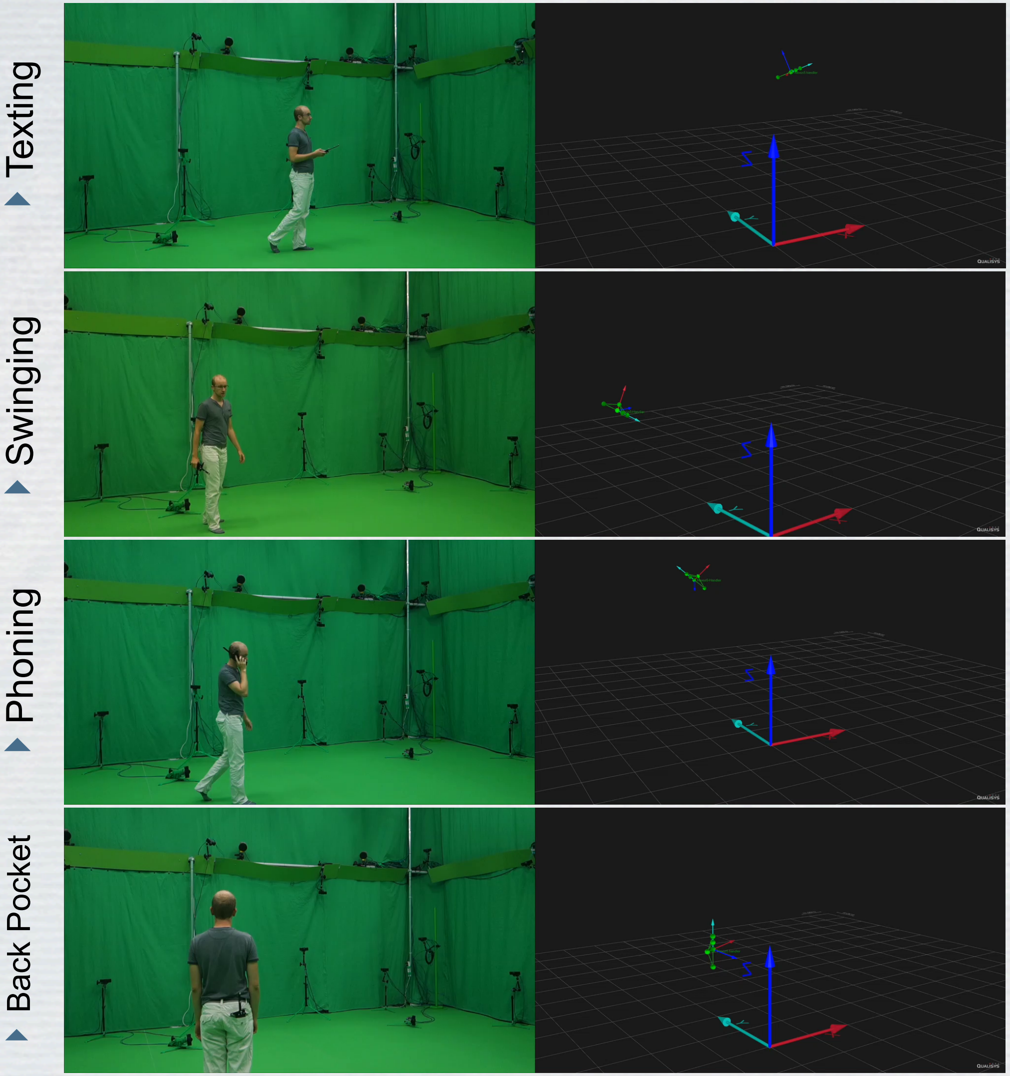
- Smartphone's handler with markers
  - Designed for this experiment
  - Handler and smartphone have the same frame



- Android sensors recorder
  - Record raw and calibrated data from sensors
  - GitHub sensors-monitoring-android

Datasets retrieved

- 4 motions, 180 seconds recording for each
- Data from sensors
  - timestamp
  - accelerometer raw
  - gyroscope raw
  - magnetometer raw
  - gyroscope calibrated
  - magnetometer calibrated
- Data from motion lab
  - timestamp
  - quaternions



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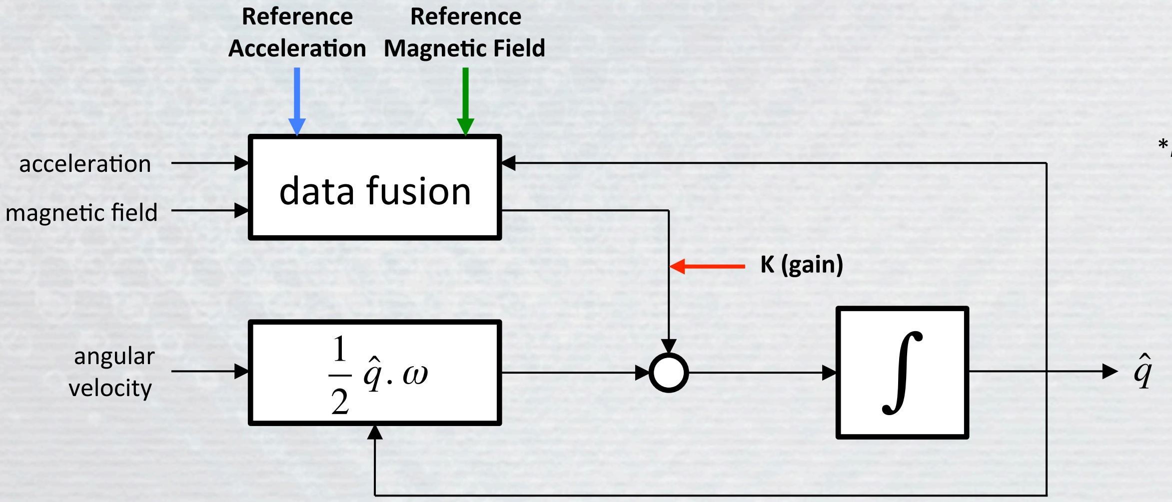
Overview of Compared Algorithms

Authors	Designed for	Method
Choukroun et al., *IEEE Transactions on Aerospace and Electronic Systems*, vol 42, no. 1, 2006	Aerospace	Kalman Filter
Mahony et al., *IEEE Transactions on Automatic Control*, vol 53, p1203-1218, 2008	UAV	Complementary Filter
Martin et al., *Control Engineering Practice*, vol 18, p712-722, 2010	UAV	Observer
Madgwick et al., *IEEE Rehabilitation Robotics*, 2011	Pedestrian	Gradient Descent Algorithm
Fourati et al., *IEEE Sensors Journal*, p233-244, 2011	Foot-mounted	Complementary Filter
Renaudin et al., *Sensors*, vol.14, no. 12, 2014	Pedestrian	Extended Kalman Filter

Algorithms design



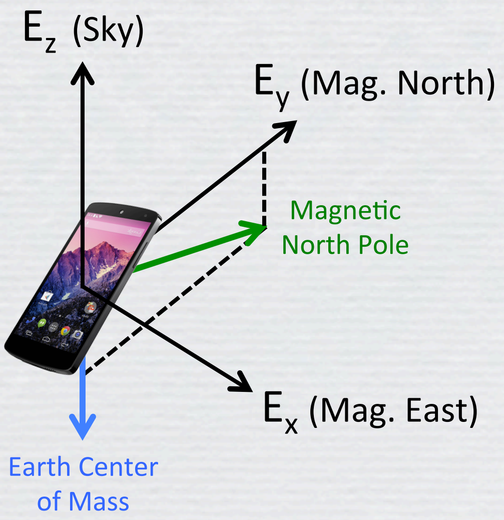
- If the smartphone is static:

  → $acc_{ref} = \begin{bmatrix} 0 & 0 & -9.8 \end{bmatrix}$

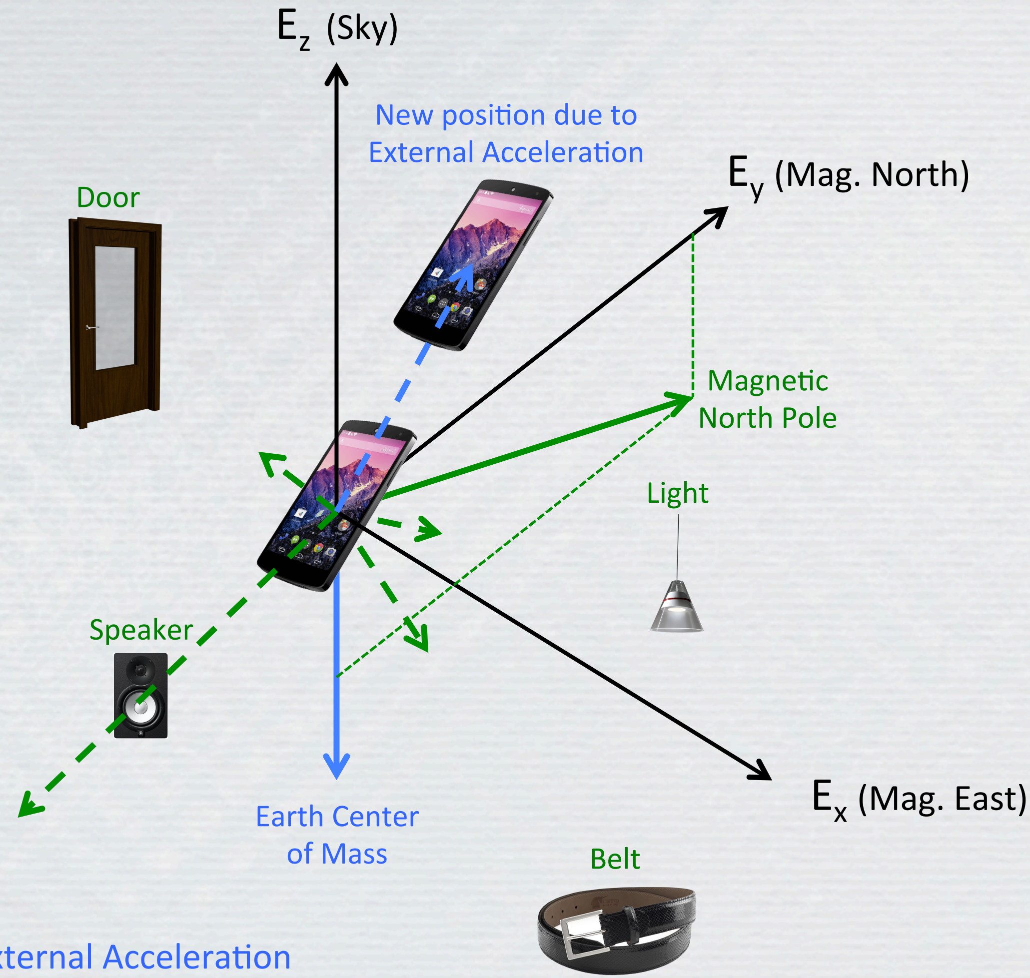
- If there is no magnetic perturbation, earth magnetic field* can be used:

  → $mag_{ref} = \begin{bmatrix} 0 & m_2 & m_3 \end{bmatrix}$

*m_2 and m_3 can be found using World Magnetic Model (WMM)



Problem of the design



acc_{ref} = Earth Gravity + External Acceleration

mag_{ref} = Earth Magnetic Field + $\sum$ Magnetic Objects Door + Speaker

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Comparison of Algorithms

Author	→ Acceleration Reference	→ Magnetic Field Reference
Choukroun et al.	No recommendation	No recommendation
Mahony et al.	No recommendation	No recommendation
Martin et al.	Use $acc_{ref} = \begin{bmatrix} 0 & 0 & -9.8 \end{bmatrix}$	Use following trick: $acc_{ref} \wedge mag_{ref}$ to prevent deviation on pitch and roll
Madgwick et al.	Use $acc_{ref} = \begin{bmatrix} 0 & 0 & -9.8 \end{bmatrix}$	Use following trick: $mag_{ref} = \hat{q}^{-1} \times mag \times \hat{q}$ This consider magnetic field as static
Fourati et al.	Use $acc_{ref} = \begin{bmatrix} 0 & 0 & -9.8 \end{bmatrix}$ → gain is modified during high accelerations	Use $mag_{ref} = \begin{bmatrix} 0 & m_2 & m_3 \end{bmatrix}$
Renaudin et al.	Use $acc_{ref} = \begin{bmatrix} 0 & 0 & -9.8 \end{bmatrix}$ There is no Kalman Filter update during high accelerations	Use $mag_{ref} = \hat{q}^{-1} \times mag \times \hat{q}$ during low magnetic field variations. There is no Kalman Filter update in others cases

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Results and Analyses

- Quaternion Angle Difference is used for precision errors:

$$\theta = \cos^{-1}(2\langle \hat{q}, q_{ref} \rangle^2 - 1)$$

q_{ref} *is the quaternion provided by Motion Lab*

$\hat{q}$ *is the quaternion to be compared*

- Mean Absolute Error (MAE)

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | \theta_i |$$

All results can be found at *http://tyrex.inria.fr/mobile/benchmarks-attitude/benchmarks.html*

Calibration

Calibration			
	Uncalibrated	Android Calib.*	Own Calib. **
Mean of MAE	92.6°	10.5°	5.3°

* Gyroscope and magnetometer calibration from Android (black-box)

** Magnetometer calibration from: *Renaudin et al., New method for magnetometers based orientation estimation, 2010*
Acceleration calibration from: *Frosio et al., Autocalibration of MEMS accelerometers, 2013*

- At least magnetometer calibration should be done due to internal components magnetic field
- Own calibrations are better than Android's one
- Accelerometer calibration slightly enhance the precision by 1°

External Accelerations

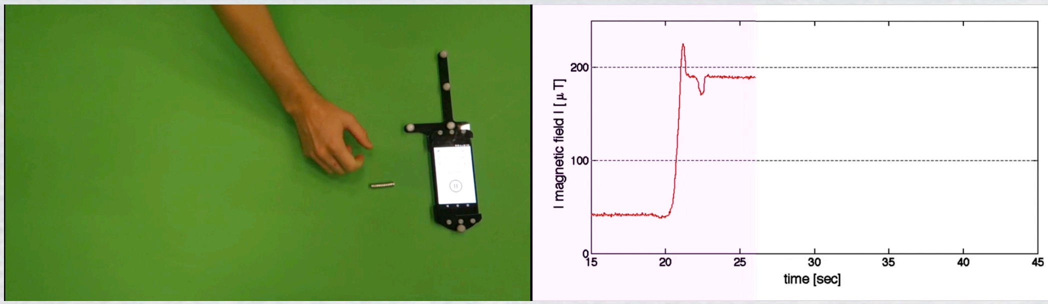
Attitude Estimation According to External Acceleration (MAE)					
	Texting	Phoning	Back Pocket	Swinging	Mean
Mean absolute of **External Acc.** norms	0.60 $m.s^{-2}$	0.52 $m.s^{-2}$	1.14 $m.s^{-2}$	1.58 $m.s^{-2}$	0.96 $m.s^{-2}$
Mahony	5.8°	5.0°	5.5°	7.5°	6.0°
Madgwick	4.7°	4.4°	6.8°	8.1°	6.0°
Choukroun	3.5°	4.3°	5.0°	9.1°	5.5°
Renaudin	2.4°	3.0°	8.5°	7.6°	5.4°
Martin	3.1°	3.9°	5.0°	7.1°	4.8°
Fourati	3.6°	4.6°	5.2°	5.3°	4.7°
Mean*	3.8°	4.2°	6.0°	7.5°	5.4°
Android**	3.8°	22.1°	7.0°	4.8°	9.4°

* Mean is provided without value from Android algorithm

** Results provided by embedded algorithm with Android calibration (black box)

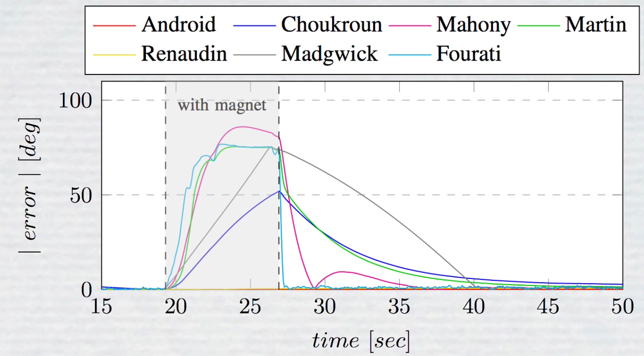
Magnetic Deviations

- 6 magnets put at *19s* and removed at *27s*

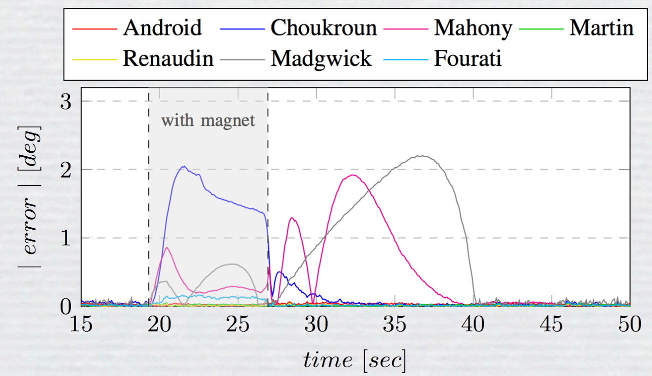


- For all algorithms *Yaw* is more impacted than *Pitch* and *Roll*
- *Android* and *Renaudin*'s algorithms are not impacted by magnetic deviations during this test.
- *Martin*'s algorithm is only impacted on yaw
- *Fourati*'s algorithm recover faster than others

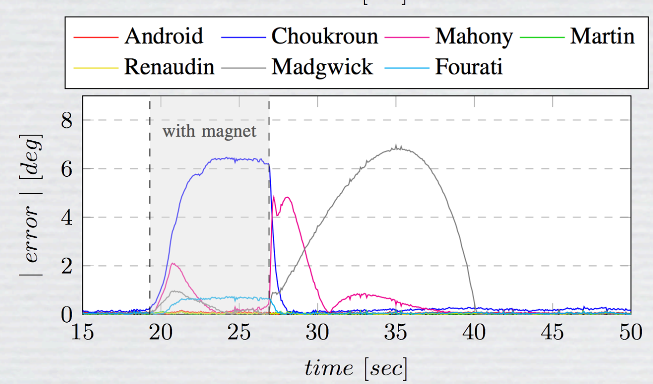
Yaw



Pitch



Roll



Conclusions and Perspectives

- **Summary**
  - A set-up for attitude estimation algorithms is provided. This set-up can be reused by anyone
  - 6 algorithms + Sensor's black box have been compared

- **Conclusions**
  - Open problems:
    - Supporting external accelerations, it can be partially corrected by modifying gain
    - Dealing with magnetic deviations, only variations of magnetic field can be detected
  - Calibration from *Renaudin*'s and *Frosio*'s papers enhances attitude precision by 5°
  - Quality of quaternions from compared algorithms is better than Android API's ones

- **Perspectives**
  - Enrich the set-up by recording more datasets
  - Investigate hybrid algorithms (QSF detector, dynamic gain…)

End

Thank you.

http://tyrex.inria.fr/mobile/benchmarks-attitude

Comparison based on Algorithms

Sensors biases and noises considerations						
	Gyroscope		Accelerometer		Magnetometer	
	Bias	*Noise*	*Bias*	*Noise*	*Bias*	*Noise*
Choukroun et al.	X*	X		X		X
Mahony et al.	X					
Martin et al.	X		X		X	
Madgwick et al.	X					
Fourati						
Renaudin et al.	X	X	X	X		X

*not implemented in our version

Number of parameters of each algorithm					
Choukroun	Mahony	Martin	Madgwick	Fourati	Renaudin
0	2	6	2	0	2

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Processing Time

Processing Time (Quaternion/sec)					
	Choukroun	Mahony	Martin	Madgwick	Fourati
Quaternion gen./sec*	2148	2762	1257	4052	2559
Relative to the best	1.88	1.47	3.22	1.00	1.59

* Benchmarks have been done with matlab

- Madgwick is the best (no matrix inversion)
- Martin is really slow