TECHNISCHE UNIVERSITÄT WIEN
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Smartphone sensor based orientation determination for indoor navigation

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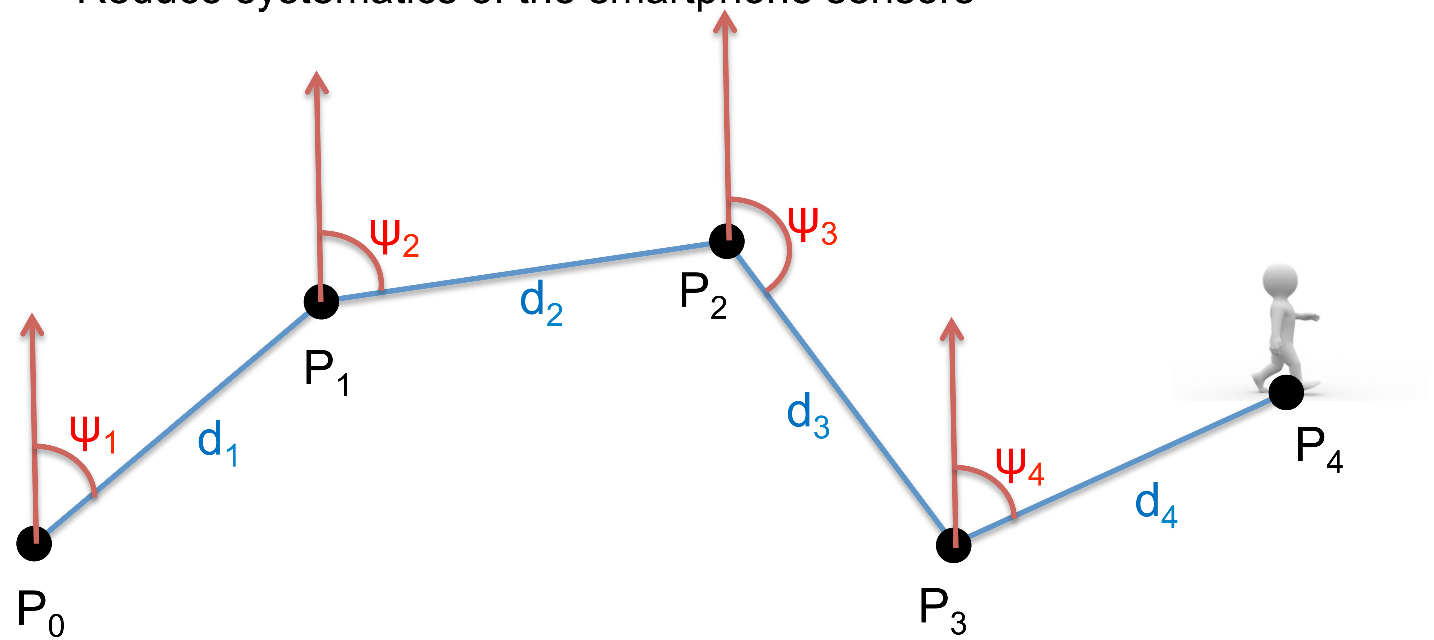
Outline

- Motivation and Methodological approach
- Orientation and Smartphone Measurement Data
- Kalman Filter for Orientation Determination
- Test Measurements and Results
- Conclusion and Outlook

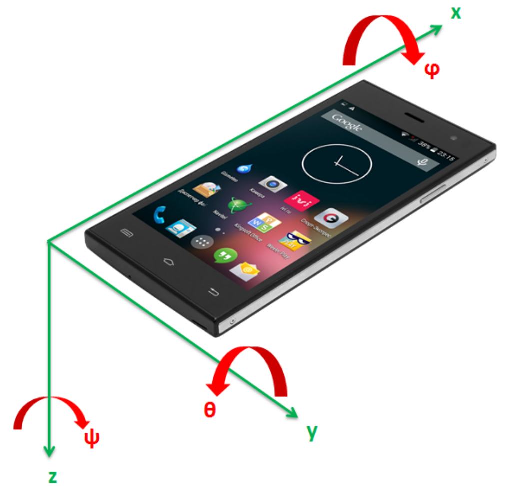
Motivation and Methodological approach

- Indoor navigation
  - Applications are augmented by 2D-PDR (“Pedestrian Dead Reckoning”)
    - Distance d_i and yaw ψ_i → Position P_i
  - Critical part → calculation of users moving direction respectively yaw
- Methodological approach
  - Calculate yaw with Kalman filter
  - Detect turns of the user
  - Smooth trajectory when user is walking straight
  - Reduce systematics of the smartphone sensors

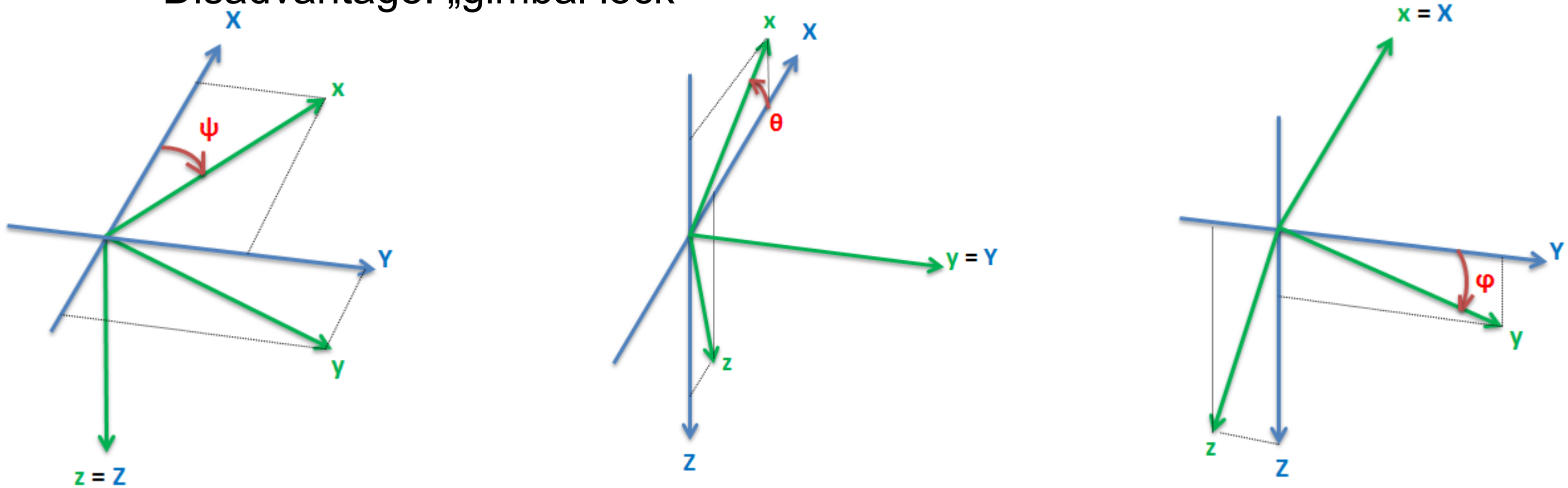


Orientation and Smartphone Measurement Data

- Orientation
  - Rotation of Sensor-Coordinate System x, y, z according to a superordinate Coordinate System X, Y, Z



- Different representations of orientation
  - Elements of the Direction-Cosine-Matrix
  - Euler angles
  - Quaternions
- Euler angles
  - pitch θ, roll φ and yaw ψ
  - Disadvantage: „gimbal lock“



Orientation and Smartphone Measurement Data

- Pitch and Roll
  - Part of the orientation
  - Used to level measurement data
  - Necessary for calculation of yaw
- Accelerometer: a_x, a_y, a_z
  - Calculation of roll and pitch directly

$$\varphi_k = f\left(a_{y,k}, a_{z,k}\right) \qquad \tan\left(\varphi\right) = \frac{a_y}{a_z}$$

$$\theta_k = f\left(a_{x,k}, a_{y,k}, a_{z,k}\right) \qquad \tan\left(\theta\right) = \frac{-a_x}{a_y \sin\left(\varphi\right) + a_z \cos\left(\varphi\right)}$$

  - Gravity → low-pass filter
- Gyroscope: ω_x, ω_y, ω_z
  - Calculation of the angular <u>changes</u> of roll and pitch

$$\dot{\varphi}_k = f\left(\omega_{x,k}, \omega_{y,k}, \omega_{z,k}, \varphi_{k-1}, \theta_{k-1}\right) \qquad \dot{\varphi}_k = \left(\omega_y \sin\left(\varphi_{k-1}\right) + \omega_z \cos\left(\varphi_{k-1}\right)\right)\tan\left(\theta_{k-1}\right) + \omega_x$$

$$\dot{\theta}_k = f\left(\omega_{y,k}, \omega_{z,k}, \varphi_{k-1}\right) \qquad \dot{\theta}_k = \omega_y \cos\left(\varphi_{k-1}\right) - \omega_z \sin\left(\varphi_{k-1}\right)$$

  - Initial values are necessary

$$\varphi_k = \varphi_{k-1} + \Delta t \cdot \dot{\varphi}_k$$

$$\theta_k = \theta_{k-1} + \Delta t \cdot \dot{\theta}_k$$

Orientation and Smartphone Measurement Data

- Yaw
- Magnetometer: m_x, m_y, m_z
  - Calculation of yaw directly

$$\psi_k = f\left(m_{x,k}, m_{\mathrm{y,k}}, m_{\mathrm{z,k}}, \varphi_{\mathrm{k}}, \theta_{\mathrm{k}}\right)$$

$$\begin{pmatrix} m_X \\ m_Y \\ m_Z \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta\sin\phi & \sin\theta\cos\phi \\ 0 & \cos\phi & -\sin\phi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{pmatrix} \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}$$

$$\tan(\psi) = \frac{-m_Y}{m_X}$$

- Gyroscope: ω_x, ω_y, ω_z
  - Calculation of angular <u>change</u> of yaw

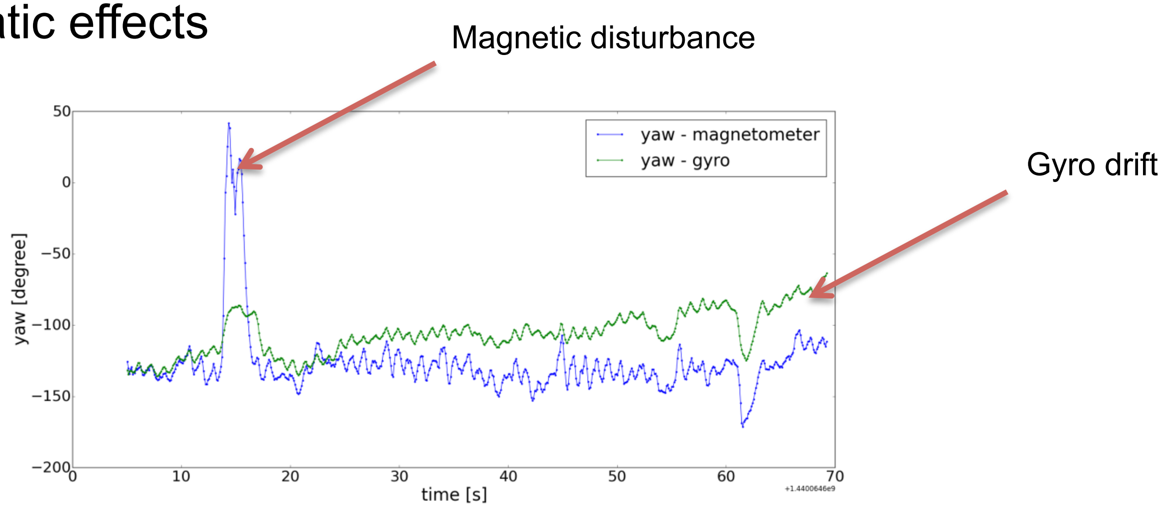
$$\overset{g}{\psi}_k = f\left(\omega_y, \omega_z, \varphi_{k-1}, \theta_{k-1}\right)$$

  - Initial value necessary

$$\overset{g}{\psi}_k = \left(\omega_y \sin\left(\varphi_{k-1}\right) + \omega_z \cos\left(\varphi_{k-1}\right)\right)\cos\left(\theta_{k-1}\right)^{-1}$$

$$\psi_k = \psi_{k-1} + \Delta t \cdot \overset{g}{\psi}_k$$

- Systematic effects



Kalman Filter for Orientation Determination

- System equations
  - State vector contains φ, θ and ψ
  - Control inputs: gyro measurements ω_y and ω_z
  - Disturbance: w_φ, w_θ and w_ψ

Random walk model

$$f_1 : \varphi_k = \varphi_{k-1} + w_{k-1,\varphi}$$
$$f_2 : \theta_k = \theta_{k-1} + w_{k-1,\theta}$$
$$f_3 : \psi_k = \psi_{k-1} + w_{k-1,\psi}$$

→ User walks straight

$$f_3 : \psi_k = \psi_{k-1} + \frac{\Delta t}{\cos\theta_{k-1}} \left[\sin\varphi_{k-1} * \omega_{y,k} + \cos\varphi_{k-1} * \omega_{z,k} \right] + w_{k-1,\psi}$$

↓ User is turning

$$\boldsymbol{T}_k = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \frac{\delta f_3}{\delta\varphi} & \frac{\delta f_3}{\delta\theta} & 1 \end{pmatrix}$$ Transition

$$\boldsymbol{B}_k = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{\delta f_3}{\delta\omega_y} & \frac{\delta f_3}{\delta\omega_z} \end{pmatrix}$$ Control

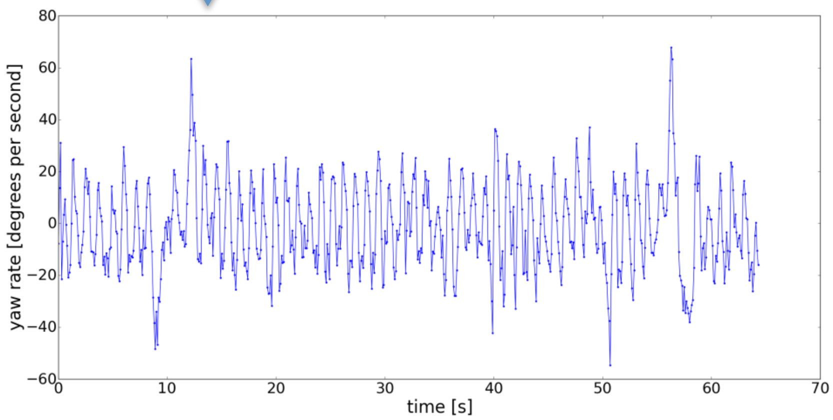
$$\boldsymbol{C}_k = \Delta t \cdot \boldsymbol{T}_k$$ Disturbance

- Propagation of covariance

$$\sum\nolimits_{\bar{x}\bar{x},k} = \boldsymbol{T}_k \sum\nolimits_{\hat{x}\hat{x},k-1} \boldsymbol{T}_k^T + \boldsymbol{B}_k \sum\nolimits_{uu} \boldsymbol{B}_k^T + \boldsymbol{C}_k \sum\nolimits_{ww} \boldsymbol{C}_k^T$$

Kalman Filter for Orientation Determination

- Indicators for changing system equation
  - Statistical test on innovations d_k
  - Yaw-rate

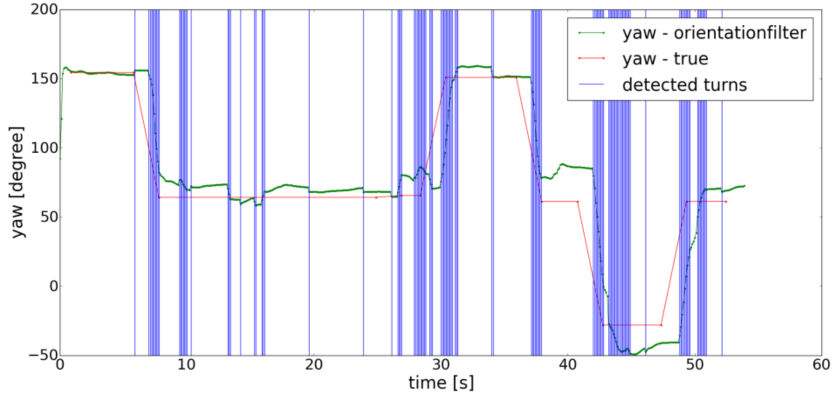


$$H_0 : E(d_k) = 0$$

$$H_A : E(d_k) \neq 0$$

$$P\{\frac{d_\psi^2}{\sigma_{d_\psi}^2} \leq \chi^2_{1;1-\alpha} \mid H_0\} = 1 - \alpha$$

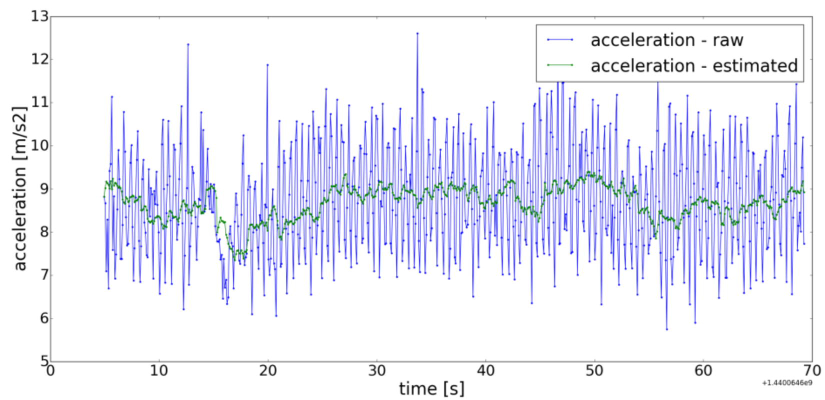
Innovation test responds > 0.3s
Yaw-rate > 30°/s



Kalman Filter for Orientation Determination

- Observations
  - Pitch, roll and yaw are introduced as directly observed
  - Separate Kalman filter for acceleration measurements
    → $\hat{a}_{x,k}, \hat{a}_{y,k}, \hat{a}_{z,k}, \Sigma_{\hat{a}\hat{a},k}$

$$\boldsymbol{l}_k = \begin{pmatrix} \varphi_k \\ \theta_k \\ \psi_k \end{pmatrix} = \begin{pmatrix} g_1\left(\hat{a}_{y,k}, \hat{a}_{z,k}\right) \\ g_2\left(\hat{a}_{x,k}, \hat{a}_{y,k}, \hat{a}_{z,k}\right) \\ g_3\left(m_{x,k}, m_{y,k}, m_{z,k}, \hat{a}_{x,k}, \hat{a}_{y,k}, \hat{a}_{z,k}\right) \end{pmatrix}$$



- Adaptive covariance matrix of the observations

$$\Sigma_{ll,k} = \boldsymbol{F}_k \begin{pmatrix} \Sigma_{\hat{a}\hat{a},k} & 0_{3\times3} \\ 0_{3\times3} & \bar{\sigma}^2_{m,k} * I_{3\times3} \end{pmatrix} \boldsymbol{F}_k^T$$

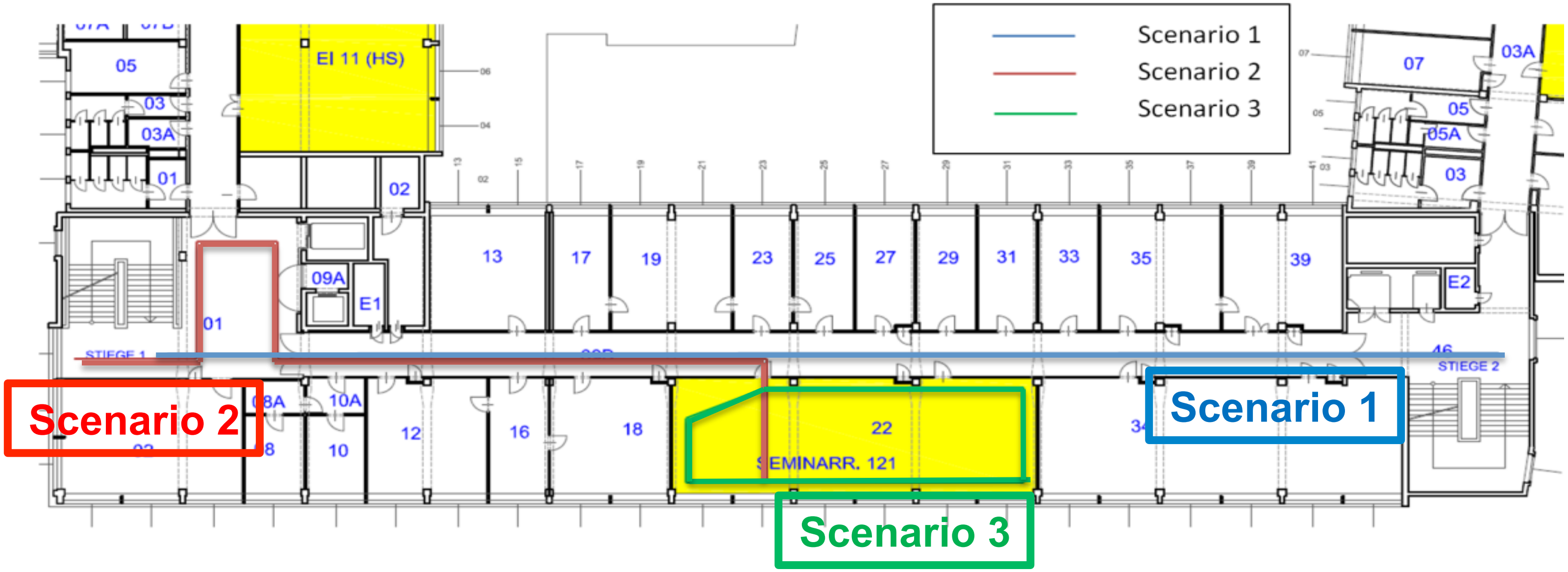
$$\boldsymbol{F}_k = \begin{pmatrix} \frac{\partial g_1}{\partial \hat{a}_{x,k}} & \cdots & \frac{\partial g_1}{\partial m_{z,k}} \\ \frac{\partial g_2}{\partial \hat{a}_{x,k}} & \cdots & \frac{\partial g_3}{\partial m_{z,k}} \\ \frac{\partial g_3}{\partial \hat{a}_{x,k}} & \cdots & \frac{\partial g_3}{\partial m_{z,k}} \end{pmatrix}$$

$$\bar{\sigma}^2_{m,k} = \left(\sigma_m + \Delta m_{k-1,k}\right)^2$$

$$\Delta m_{k-1,k} = \left\| \left\| \vec{m}_k \right\| - \left\| \vec{m}_{k-1} \right\| \right\|$$

Test Measurements and Results

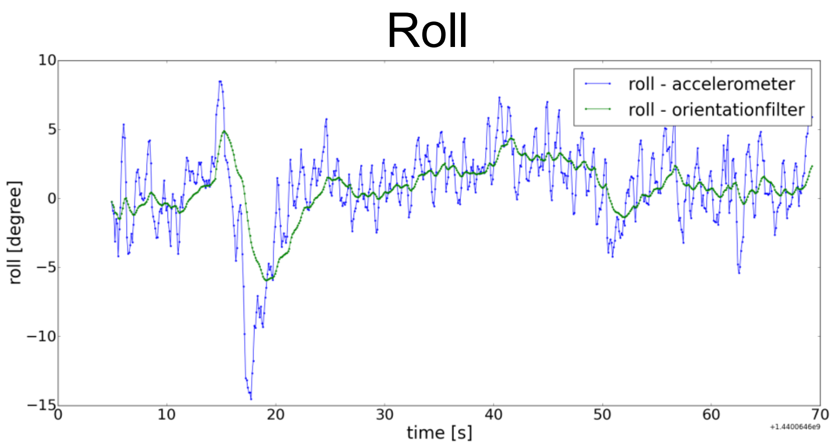
- 3 scenarios
- One smartphone → Samsung Galaxy S4
- Ground truth from indoors mobile toolkit
- Evaluation
  - Inner and outer accuracy
- Comparison to results from orientation sensor of android

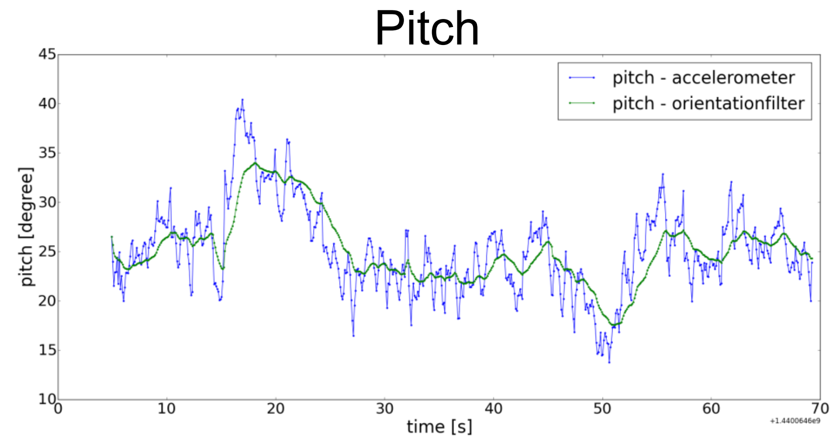


Test Measurements and Results

Scenario 1

- Random walk model
  - Smooth filter result
  - Time shift ~2s
- No reference values
  - Smartphone was held in texting mode
  - Results are reasonable

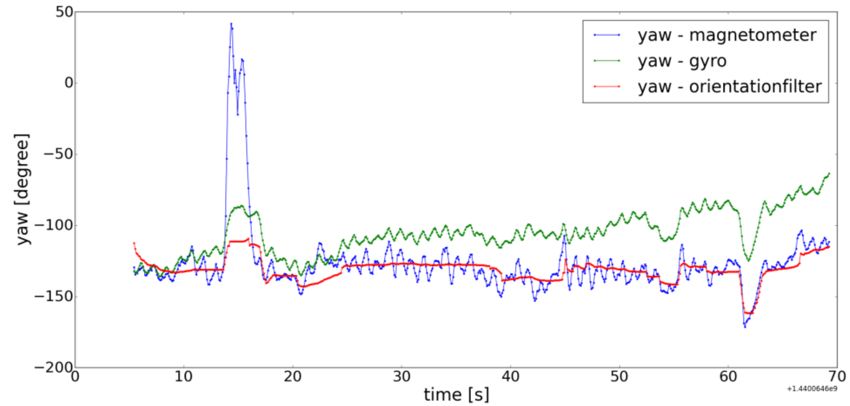


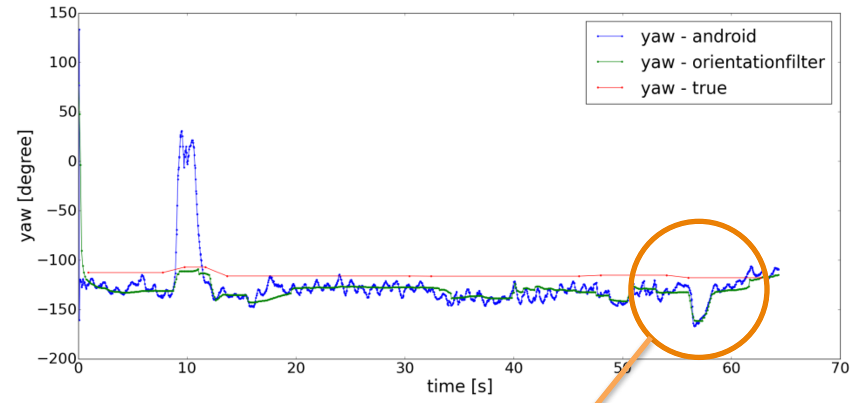


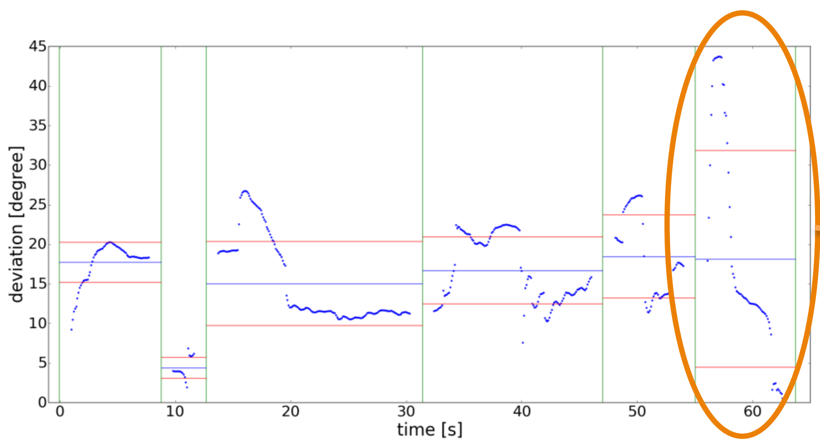
Test Measurements and Results

Scenario 1

- Yaw – filter result
  - No drift
  - Minimized influence of magnetic disturbance
  - Constant offset
- Outer accuracy: 16.2°
  - Mean deviation from ground truth
- Inner accuracy: 5.4°
  - Mean standard deviation of deviations





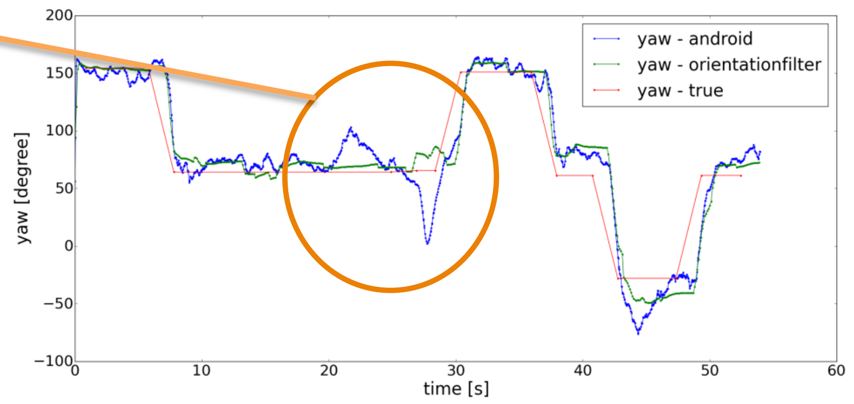


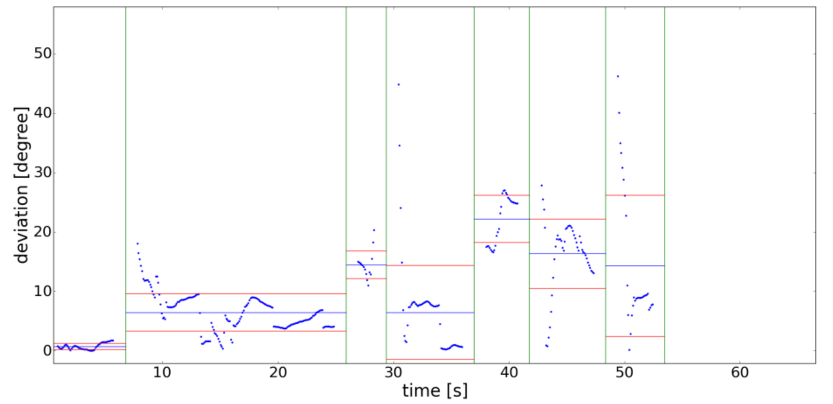
Error in ground truth

Test Measurements and Results

Scenario 2

Reduced influence of
magnetic disturbance



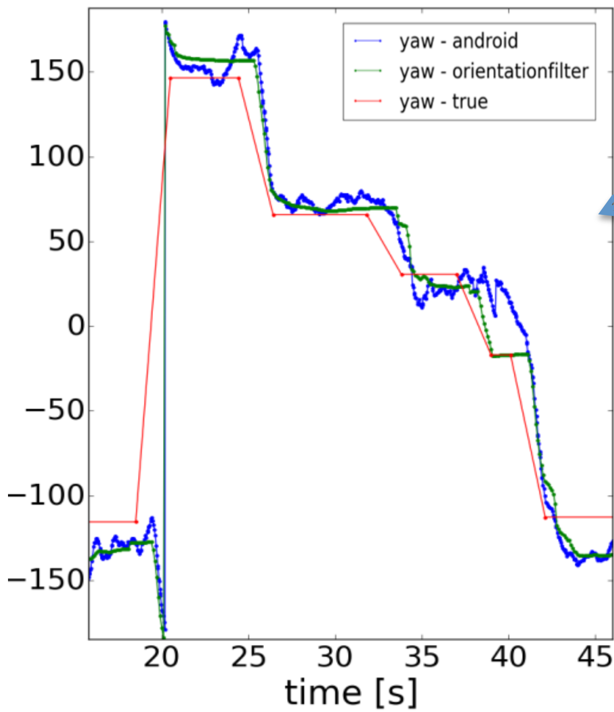


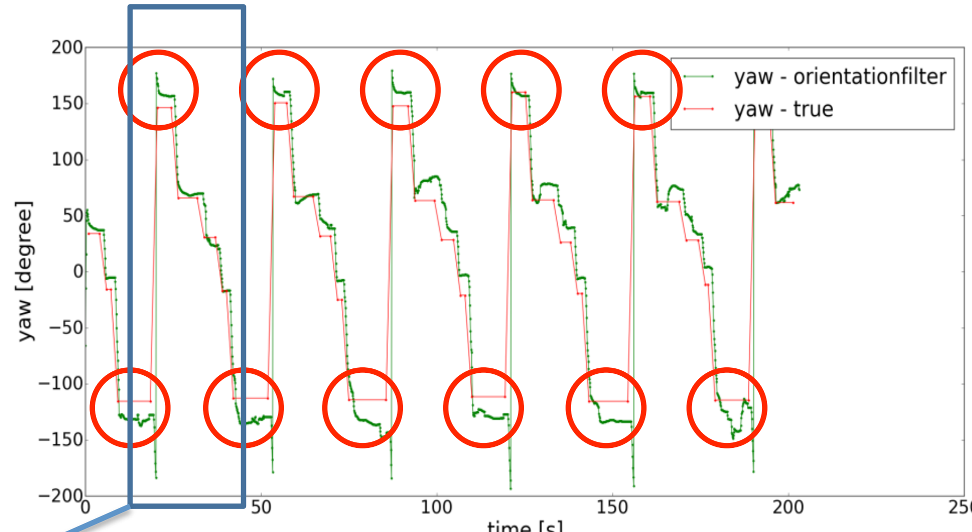
- Outer accuracy
  - 8.9°
- Inner accuracy
  - 5.1°

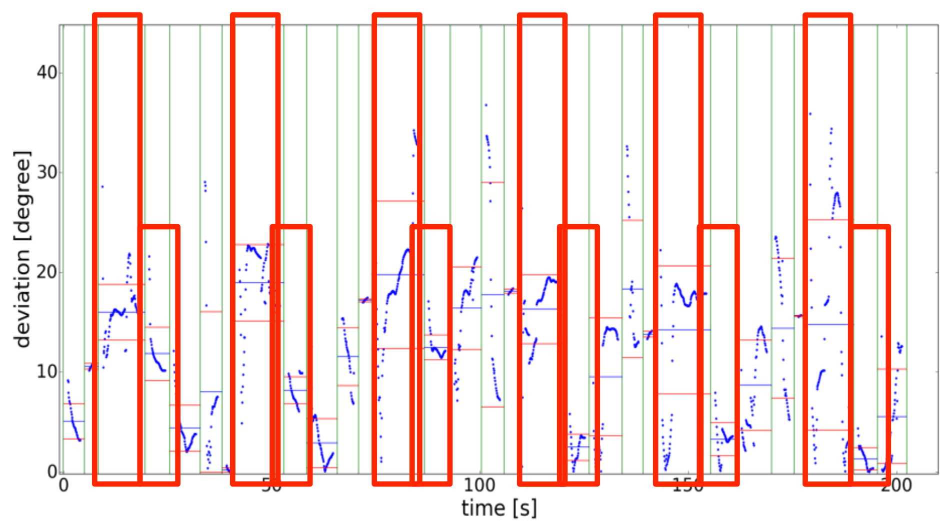
Test Measurements and Results

Scenario 3

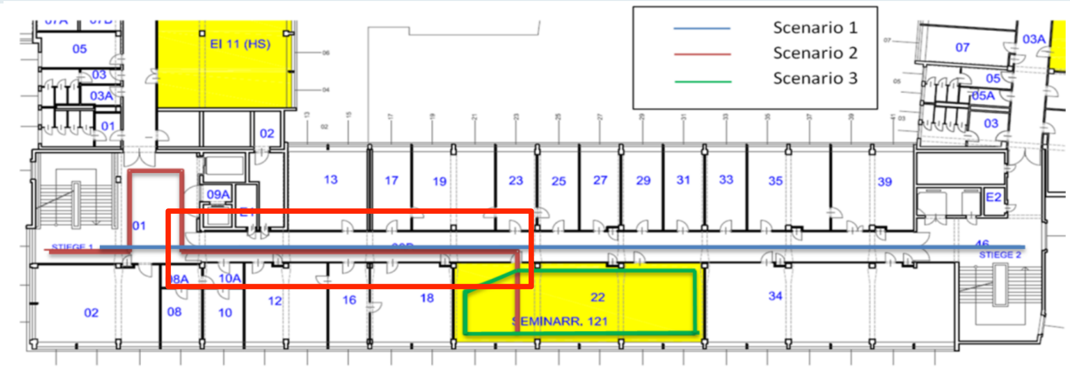
- Outer accuracy
  - 12.2°
- Inner accuracy
  - 3.6°
- Properties of deviations
  - Varying most of the time

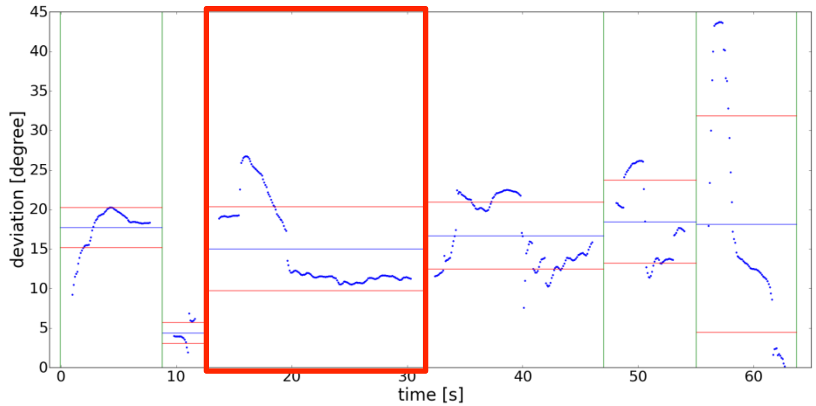


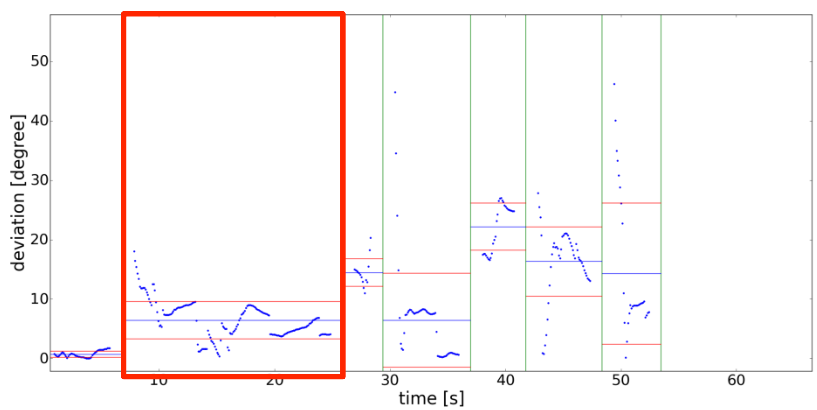




Results – *Comparison of Scenario 1 and Scenario 2*







- Offset and residuals differ

Conclusion and Outlook

- Conclusions
  - Systematic effects of the sensors are minimized
  - Turns are detected correctly
  - Residuals are rarely reproducible and not normally distributed
  - Filter result ~20% better than android solution
  - Inner accuracy ~60% better than outer accuracy

Scenario	Outer accuracy		Inner accuracy
	Orientation filter	Android	Orientation filter
1 (straight)	16.2°	18.5°	5.4°
2 (straight with turns)	8.9°	12.4°	5.1°
3 (polygonal, repeatedly)	12.2°	14.5°	3.6°

- Outlook
  - Tests on different smartphones
  - Improving ground truth
  - Additional orientation information to overcome remaining systematic effects
  - Adaption of test statistics

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