HydrOs – An Integrated Hydrographic Positioning System for Surveying Vessels

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Motivation

Current State:

- Positioning of surveying vessels: GNSS or GNSS-INS coupled systems
  → referencing of multibeam echo sounder
- **Problems:**
  GNSS: Shadowing, Multipath effects, loss of RTK solution
  IMU: drift effect
  ➔ Insufficient positioning accuracy close to obstacles
  ➔ regions without valid RTK positions

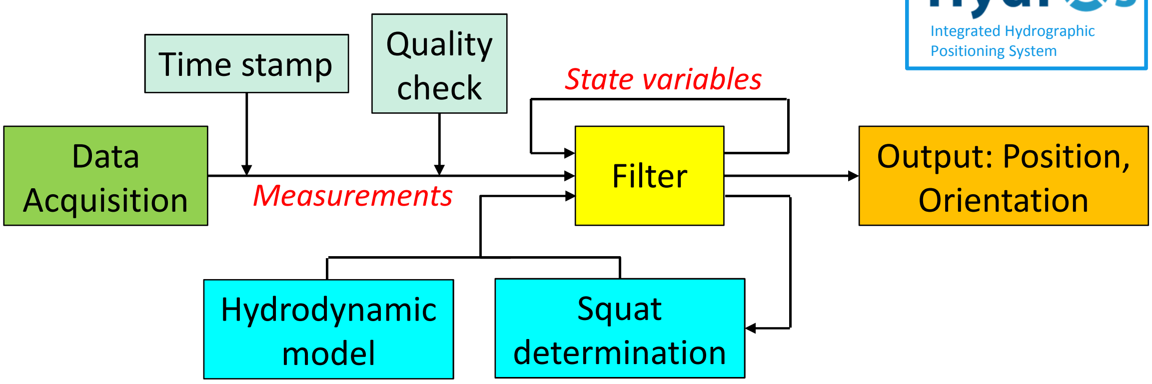
Outline

Project HydrOs

- Project partners: German Federal Institute of Hydrology (BfG), Institute of Engineering Geodesy, University of Stuttgart
- Objective: Improvement of the GNSS-Positioning of surveying vessels on German inland waterways.

➔ Development of a Multi-Sensor System and Data processing with an Extended Kalman Filter.

HydrOs
Integrated Hydrographic Positioning System



Multi-Sensor System

Integrated Sensors:

- **GNSS**
  - different antenna configurations
  - RTK solution: CORS network service ***SAPOS*** (Germany)
    → Virtual Reference Station (VRS)
  - also: part of GNSS-INS system
  - output: *coordinates, Speed and Course over ground*

- **IMU**
  - short time: high accuracy,
    long time: drift effects
  - currently: part of the coupled system
  - output: *turning rates, orientation angles, velocity components, heave*

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Multi-Sensor System

Integrated Sensors:

- **Compass**
  - here: GNSS compass, part of the coupled system
  - output: *heading*

- **Doppler Velocity Log** (DVL):
  → type of Acoustic Doppler Current Profiler (ADCP)
  - Workhorse Navigator: four sending/receiving units
  - output: *velocity components (over ground and relative to defined water layers)*

Source: www.rdinstruments.com

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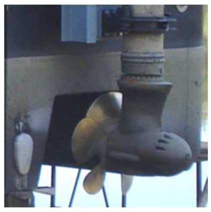
Multi-Sensor System

Integrated Sensors:

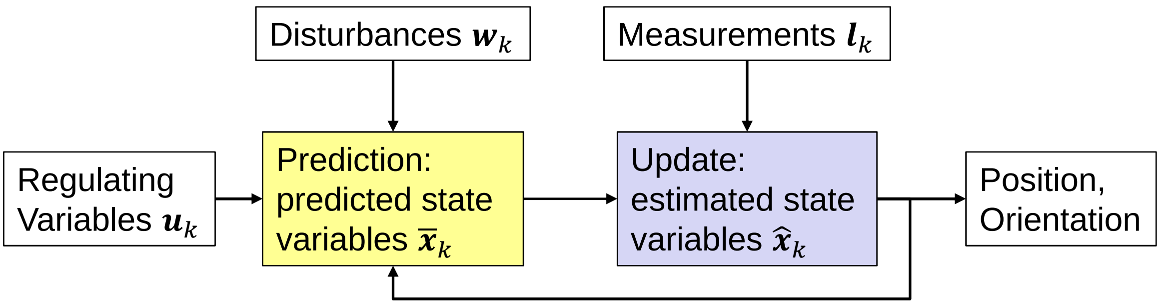
- **Ship propulsion**
  - Schottel rudder propellers → pulls the vessel
  - can be rotated for 360°
  - analog measurements
  - output: *pull direction and revolution speed*



- **Hydrodynamic Models**
  - information about water level
  → pseudo-observations
  → also: Improvement of existing models
  - output: *height*

Data Processing

Extended Kalman Filter (EKF)



- Prediction Model

$$\bar{\boldsymbol{x}}_k = f_{k,k-1}\left(t_{k,k-1}(\hat{x}_{k-1}), b_{k,k-1}(u_{k-1})\right)$$

$$\boldsymbol{\Sigma}_{\bar{x}\bar{x},k} = \boldsymbol{T}_{k,k-1} \cdot \boldsymbol{\Sigma}_{\hat{x}\hat{x},k-1} \cdot \boldsymbol{T}^T_{k,k-1} + \boldsymbol{B}_{k,k-1} \cdot \boldsymbol{\Sigma}_{uu,k} \cdot \boldsymbol{B}^T_{k,k-1} + \boldsymbol{C}_{k,k-1} \cdot \boldsymbol{\Sigma}_{ww,k-1} \cdot \boldsymbol{C}^T_{k,k-1}$$

- Measurement Equations

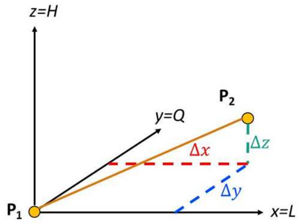
$$\hat{\boldsymbol{x}}_k = \bar{\boldsymbol{x}}_k + \boldsymbol{K}_k \cdot (\boldsymbol{l}_k - \boldsymbol{a}_k(\bar{\boldsymbol{x}}_k))$$

$$\boldsymbol{\Sigma}_{\hat{x}\hat{x},k} = \boldsymbol{\Sigma}_{\bar{x}\bar{x},k} - \boldsymbol{K}_k \cdot \boldsymbol{\Sigma}_{dd,k} \cdot \boldsymbol{K}^T_k$$

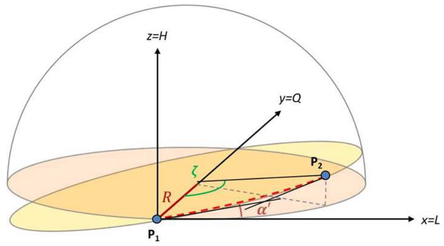
Data Processing

Prediction model:

- **State variables:** Turning rates, velocity components, orientation, coordinates
- 2 Approaches are considered:



Linear Approach



Spherical approach

- Evaluation of simulated data

Scenario	Line (σ_{Lage}/σ_H)		Curve (σ_{Lage}/σ_H)	
	Linear Approach	Spherical Approach	Linear Approach	Spherical Approach
2 x GNSS, IMU, DVL	1.5 cm / 1.9 cm	1.5 cm / 1.5 cm	1.4 cm / 1.7 cm	2.0 cm / 1.4 cm
3 x GNSS, IMU, DVL	1.3 cm / 1.6 cm	1.3 cm / 1.3 cm	1.2 cm / 1.4 cm	1.6 cm / 1.2 cm
2 x GNSS, IMU, DVL + hydrodyn. model	1.3 cm / 1.5 cm	1.3 cm / 1.2 cm	1.2 cm / 1.4 cm	1.6 cm / 1.2 cm

Data Processing

Measurement Equations

- Flexible for different sensor configurations
- Output frequency of 10 Hz
- Extra- and Interpolation of measurement data
  → Differentiation: Data gap or delayed incoming data

Precondition:

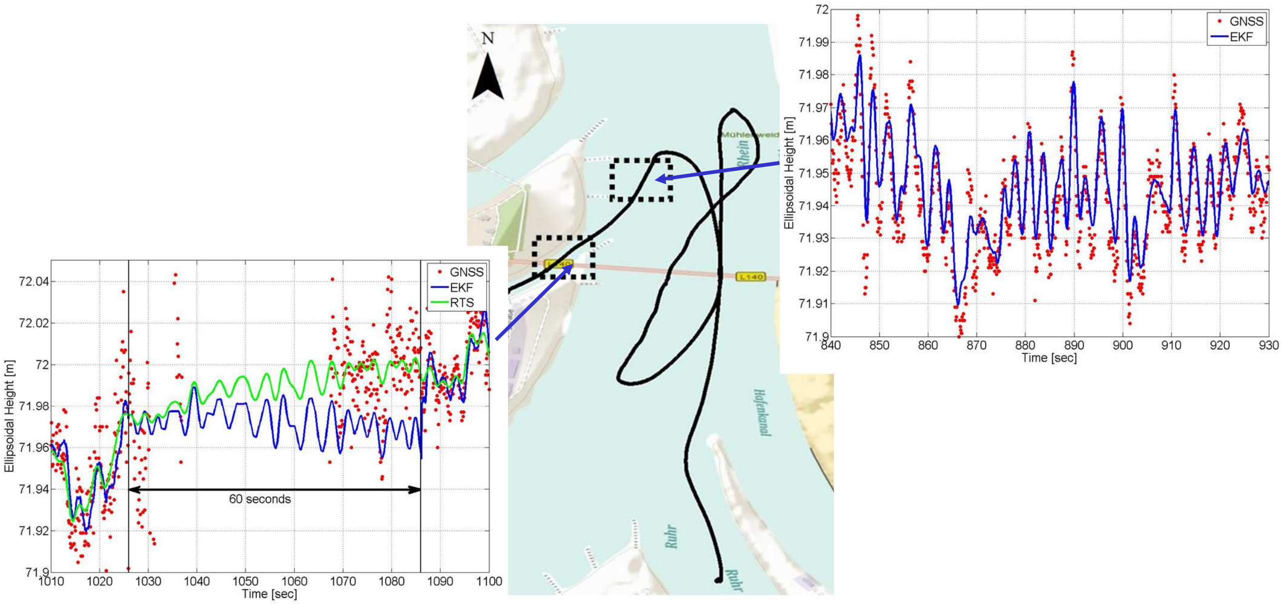
- Detection of unreliable measurements
- Check of GNSS-Measurements
  - single receiver: quality parameters
  - multiple receivers: base length, comparison of measured speed over ground (SOG)

Data Processing

Example:

Evaluation of measurements on the Rhine, close to Duisburg (Germany)

Sensor configuration: GNSS, IMU, DVL



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Squat Determination

Background

- Integration of hydrodynamic models
  → offset of the reference point (vessel) must be known
- Squat effect: Subsidence of the vessel caused by velocity relative to the water (v_{rel}), according to under keel clearance (h_{ukc}), shape of the hull, etc.
- Existing algorithms: - Suitable for special vessels (e.g. cargo-ships)
  - Pessimistic prediction: safety aspects

Considered surveying vessels: smaller, with twin hulls
→ Different squat behavior compared to mono hull ships is expected

➔ Experimental determination of the squat effect

➔ Use of GNSS-RTK (Lon, Lat, H) and DVL (v_{rel}, h_{ukc})

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Squat Determination

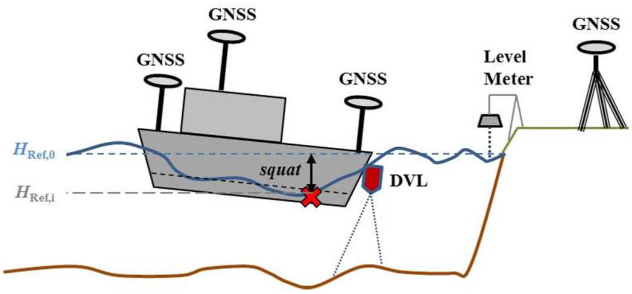
Idea:

Measurements along a trajectory (h_{ukc}) with undisturbed water level:

1. Vessel drifts downstream (engines idle) ➔ $H_{ref,0}(Lon, Lat)$
2. Vessel drives with different velocities $v_{rel,i}$ ➔ $H_{ref,i}(Lon, Lat, v_{rel,i})$

→ measured heights of GNSS antennas are transformed to a reference point

$$\boldsymbol{squat_i = H_{ref,0} - H_{ref,i}(v_{rel,i}, h_{ukc,i})}$$



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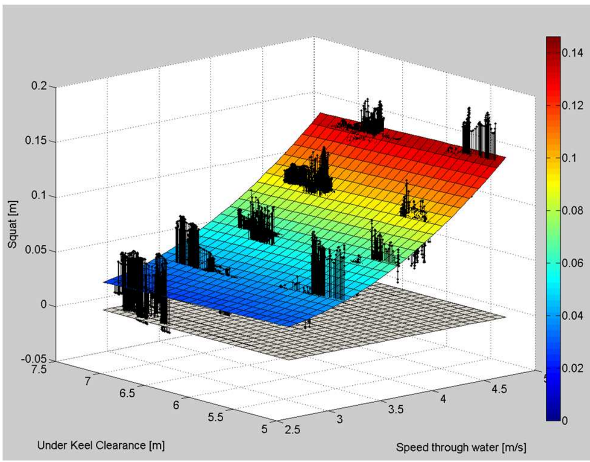
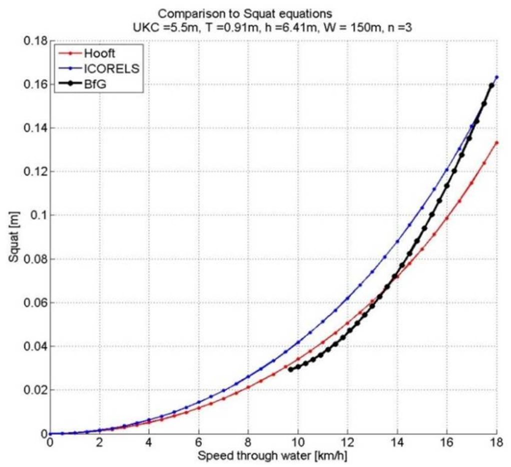
Squat Determination

Characteristic model:

$$squat_i = a + b \cdot v_{rel,i} + c \cdot h_{ukc,i} + d \cdot v_{rel,i}^2$$



Characteristic model of surveying vessel "Mercator"



Comparison: Equations of Hooft resp. ICORELS and characterstic model

Conclusion + Outlook

Conclusion:

- Multi-sensor system: Integration of multiple sensors and models
  → Determination of Position and Orientation
- Data processing: Extended Kalman Filter
- Integration of additional height information by using squat determination: → Method to determine the squat effect
- Avoiding land-based measurements.

Outlook:

- Integration of additional (geodetic) sensors, e.g. total station, laser scanner and further hydrodynamic models
- Adapting the prediction model to vessels: individual calibration

➔ Georeferencing of data from the multibeam echo sounders is also possible in areas without (reliable) GNSS positions

Thank you for your attention!

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Data Processing

Prediction Model

$$\begin{bmatrix} \Delta\bar{\omega}_{x,k+1} \\ \Delta\bar{\omega}_{y,k+1} \\ \Delta\bar{\omega}_{z,k+1} \\ \Delta\bar{v}_{x,k+1} \\ \Delta\bar{v}_{y,k+1} \\ \Delta\bar{v}_{z,k+1} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \cdot \begin{bmatrix} \hat{\omega}_{x,k} \\ \hat{\omega}_{y,k} \\ \hat{\omega}_{z,k} \\ \hat{v}_{x,k} \\ \hat{v}_{y,k} \\ \hat{v}_{z,k} \end{bmatrix} + \begin{bmatrix} a_{1\delta} \\ a_{1\delta} \\ a_{1\delta} \\ a_{1\delta} \\ a_{1\delta} \\ a_{1\delta} \end{bmatrix} \delta_{res,k+1}$$

$$\begin{bmatrix} \Delta\bar{\varphi}_{k+1} \\ \Delta\bar{\theta}_{k+1} \\ \Delta\bar{\psi}_{k+1} \end{bmatrix} = T\left(\hat{\varphi}_k, \hat{\theta}_k, \hat{\psi}_k\right) \cdot \begin{bmatrix} \hat{\omega}_{x,k} \\ \hat{\omega}_{y,k} \\ \hat{\omega}_{z,k} \end{bmatrix} \cdot \Delta t$$

$$\begin{bmatrix} \Delta\bar{E}_{k+1} \\ \Delta\bar{N}_{k+1} \\ \Delta\bar{U}_{k+1} \end{bmatrix} = R_z(\hat{\psi}_k) R_y\left(\hat{\theta}_k\right) R_x(\hat{\varphi}_k) \cdot \begin{bmatrix} \Delta L \\ \Delta Q \\ \Delta H \end{bmatrix} \quad \begin{cases} \begin{bmatrix} \Delta L \\ \Delta Q \\ \Delta H \end{bmatrix} = \begin{bmatrix} \hat{v}_{x,k} \\ \hat{v}_{y,k} \\ \hat{v}_{z,k} \end{bmatrix} \cdot \Delta t \\ \begin{bmatrix} \Delta L \\ \Delta Q \\ \Delta H \end{bmatrix} = R_y(\alpha') \cdot \begin{bmatrix} R \cdot \sin\varsigma \\ R \cdot (1 - \cos\varsigma) \\ 0 \end{bmatrix} \end{cases}$$