MHE for 3D Motion Tracking

Sensor Fusion for AWE Systems

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Xsens Technologies B.V. &
Systems Control and Optimization Lab

AWESCO Kick-off Event
March 3rd, 2016

UNI FREIBURG

AWESCO
Airborne Wind Energy
System Modelling, Control & Optimisation

xsens

Overview

1. Institutions and locations
2. Motivation
3. State Estimation for AWE applications
4. Current research project
5. Research focus

Xsens Technologies - Basic Facts

- Founded in 2000
- Leading innovator in 3D motion tracking technology and products.
- 65 employees (7 researchers)
- Headquarter in Enschede, the Netherlands
- A Fairchild company

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  FAIRCHILD
- Xsens offices are directly next to the campus
  - Collaborations and discussions.
  - PhD and project students

Enschede - Basic Facts

- ca. 160.000 inhabitants
- located in the eastern part of the Netherlands.
- part of the region Twente
- University of Twente
  - founded in 1961
  - ca. 10.000 students
  - faculties in electrical engineering, mathematics and computer science

Freiburg - Basic Facts

- PhD position in collaboration with Systems Control and Optimization laboratory, Imtek, University Freiburg.
- Expertise of the group of Moritz Diehl in realtime optimization.
- First secondment from January 2016 until today.
- ...

Motivation
On the Edge to to the Fully Autonomous Age

Fully autonomous systems are on the rise

- Cars and robots
- Consumer electronics
- Renewable Energies

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State estimation is a key technology to guarantee a robust and fail-safe operation for these **complex** systems.

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State estimation is a key technology to guarantee a robust and fail-safe operation for these **complex** systems.

- State estimation
- Control algorithms

State Estimation - The Main Components

Sensor information

- Measured quantities
- Measurement error
- Network topology
- Different frequencies

Estimation algorithm

- Estimate representation
- Online vs. offline
- Underlying model
- Error and uncertainty representation

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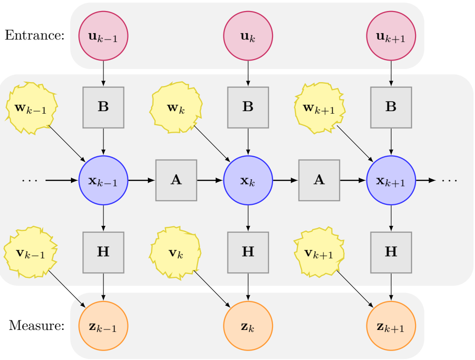
State estimation for complex systems

- Sensor network
  - Capture dynamics
  - Reduce measurement errors
- Advanced estimation algorithm
  - Complex dynamics of system
  - Estimate parameters
  - Cope with uncertainty

State Estimation - The Work Horse

Kalman-Bucy filter (KF)

- Rudolf E. Kálman
- based on the Bayes-Filter



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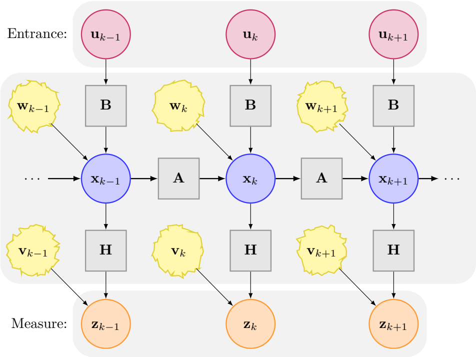

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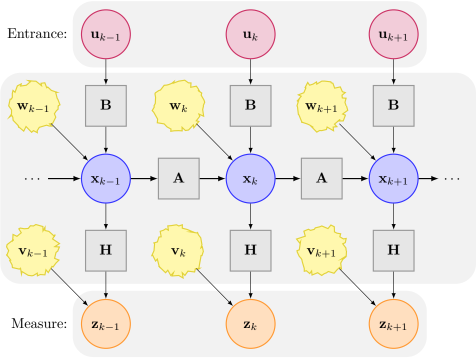
Assumptions:

- Linear system dynamics
- Noise sources are Gaussian distributed



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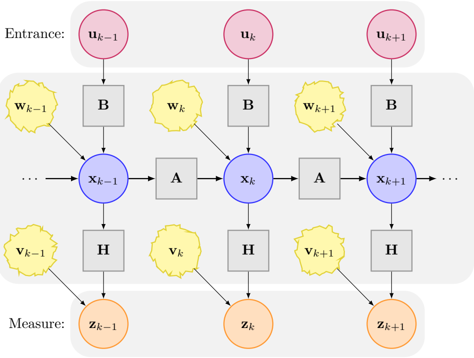
Extensions:

- Extended Kalman filter
- Unscented Kalman filter
- Particle filter



Moving Horizon Estimation solves a possibly constrained optimization problem in each filter iteration of the form:

$$\begin{aligned} \underset{x,w}{\text{minimize}} \quad & \frac{1}{2}\sum_{k=1}^{N} \left\| \bar{y}_{t_k} - y_{t_k}(x_k, w_k) \right\|^2 \\ \text{subject to} \quad & \dot{x} = F(x, w) \\ & g(x) = 0 \\ & h(x) \geq 0 \end{aligned}$$

- linear, non-linear
- convex, non-convex

State Estimation

The Kalman Filter vs. Moving Horizon Estimation

Moving Horizon Estimation solves a possibly constrained optimization problem in each filter iteration of the form:

$$
\begin{aligned}
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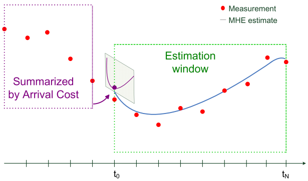

- Measurements in estimation window of horizon N.
- History can be summarized by imposing an arrival cost term.

Combination of state and parameter estimation in one optimization problem.

State Estimation for AWE Applications

- Challenging autonomous systems with high degree of freedom.
- Flexible structures subject to deformation.
- Fast dynamics.
- Many important values of interest which are hard to observe:
  - Angle of attack
  - Aerodynamic forces

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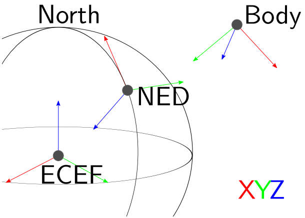
Conclusion

AWE applications represent a perfect application for new state estimation approaches due to the variety of the field (soft and rigid kites) and the complexity of the motion and underlying models.

Current Research Project



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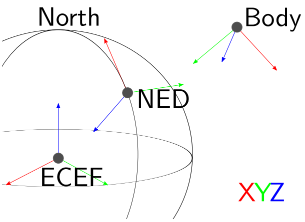


Estimate Orientation

- Dead-reckoning
- Sensor fusion

GPS

- Measurements in earth frame
- Low frequency $4\mathrm{Hz}$

IMU

- Measurements in body frame
- High frequency $400\mathrm{Hz}$

Current Research Project

Estimate Orientation using MHE

Model: Rigid Unit Ball

$$x(t) = \begin{bmatrix} p^e(t) \\ \dot{p}^e(t) \\ \omega^e(t) \\ q^{be}(t) \\ \delta_{\mathrm{ACC}} \\ \delta_{\mathrm{GYR}} \end{bmatrix} \quad , \quad w(t) = \begin{bmatrix} F^e(t) \\ \tau^e(t) \end{bmatrix}$$

ODE

$$\dot{x}(t) = \begin{bmatrix} \dot{p}^e(t) \\ \frac{F^e(t)}{m} \\ (I^{e-1}\tau(t)) \\ \frac{1}{2}\begin{bmatrix} 0 \\ \omega^e(t) \end{bmatrix} \odot q^{be}(t) \\ [0,\ 0,\ 0]^\top \\ [0,\ 0,\ 0]^\top \end{bmatrix}$$

Current Research Project

Estimate Orientation using MHE

NLP: Multiple Shooting

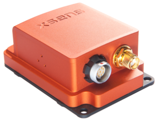
$$\min_{x_1 \dots x_N, w_1 \dots w_{N-1}} \quad \frac{1}{2} \sum_{k=1}^{N} \Big(\|\bar{y}_{k,\mathrm{GPS}} - y_{\mathrm{GPS}}(x_k, w_k)\|_Q^2 + \sum_{j=1}^{M} \|\bar{y}_{j,\mathrm{IMU}} - y_{j,\mathrm{IMU}}(x_k, w_k)\|_W^2 \Big)$$

$$\text{s.t.} \quad \dot{x} = F(x, w_k) \quad \forall t \in [t_k, t_{k+1}]$$

$$(Z_q x_1)^\top (Z_q x_1) = 1$$

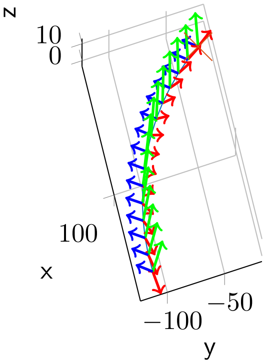
$$x_{k+1} = \phi(x_k, w_k) \qquad k = 1 \dots N-1$$

Current Research Project
Estimate Orientation using MHE



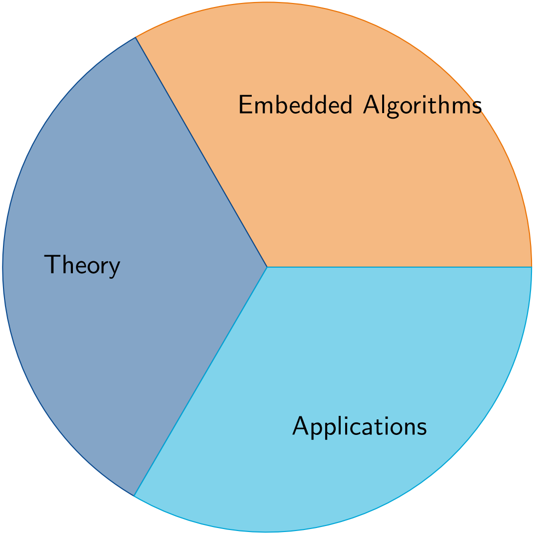
- Introduction to main concepts like observability, rotations in 3D, MHE and numerical optimization.
- Comparison to Kalman filter based approach for the problem.
- Formulation of arrival cost for decreasing computational burden of MHE.
- High performance solvers for realtime feasability on embedded devices.

→ Possible publication for MSC 2016



Research Focus

About finding the niche ...



Research Focus

About finding the niche ...

Theoretical Approaches

- Calibration approaches
- Formulation of arrival cost.
- Information hopping in sensor network

- ALU-FR
- Chalmers
- EPFL

Embedded Realization

- Embedded numerical optimization for residual prob
- Numerical solvers for FPGA-architectures
- SOC-architectures for parallelization and realtime feasibility

- Xsens
- ALU-FR

Application for Systems

- Challenging systems with flexible structures
- Cope with the uncertainty of the system
- Optimized sensor network information flow

- Ampyx, Enerkite, Skysails
- TUD, ETH

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Questions ???

Thank you for your Attention!