ITEAM Project
State Estimation for Vehicle Dynamics
KU Leuven Concept Car Platform

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ITEAM Network Concept: Motivation

X-by-wire vehicles

Low-emission vehicles

Automated vehicles

Insufficient consideration of integration

Studies on Multi-Actuated Ground Vehicles (MAGV)
Consortium:
- 10 universities
- 2 research institutions
- 3 automotive OEMs
- 2 suppliers
- 2 SMEs

Global goals:
1. Advance the automotive postgraduate education
2. Improve career perspectives of PhDs in both public and private sectors
3. Create R&D group with determinant contributions to next generations of multi-actuated ground vehicles
ITEAM Network Concept: Clusters

Cluster MAGV Integration
- ESR2 and ESR3 (VOLVO)
- ESR4 (University of Pavia)
- ESR13 (Coventry University)
- **ESR14 (KU Leuven)**

Cluster Green MAGV
- ESR5 (Infineon)
- ESR6 (VIF)
- ESR7 (University Compiègne)
- ESR9 and ESR15 (TU Ilmenau)

Cluster MAGV Driving Environment
- ESR1 (VIF)
- ESR8 (SKODA)
- ESR10 (University Compiègne)
- **ESR11 (Flanders Make)**
- ESR12 (AVL)
Training objectives

- Develop an interdisciplinary project-based training network to enhance vehicle design quality and performance;
- Establish and sustain a new type of continuous, consecutive and successive research community, recognizable on an international scale, with the high potential to make significant contributions to next generations of intelligent, safe and energy-efficient multi-actuated ground vehicles;
- Establish and promote (i) professional advancement of the participating institutions in cutting-edge technologies through intersectoral collaboration and (ii) technical and cultural exchange between academic and non-academic environments.
Our project ITEAM was made possible thanks to #H2020 funding

€30 billion is still available in the 2018-20 Work Programme!

#InvestEUresearch
State Estimation – Motivation

Past and current: vehicle dynamics control

Source: Subaru
State Estimation – Motivation

Future: ADAS and automated driving

http://www.ti.com/applications/automotive/adas/overview.html
State Estimation – Motivation

Future: ADAS and automated driving

Source: General Motors
SyRI seminar

State Estimation – Motivation

However, some sensors are still too costly and/or intrusive.

Components of velocity
- Vehicle sideslip angle
- Tire forces

→ Virtual Sensing

State estimation for vehicle dynamics

Longitudinal tire force estimator
- Rotating wheel dynamics model
- + Wheel torque uncertainty
- Wheel torque adaptation
- Rolling resistance
- + Wheel torque uncertainty

Lateral tire force estimation
- Lat. velocity & cornering stiffness estimation
- Adaptive linear tire model (RW evolution)
- Cornering stiffness estimation
- Neural Networks
- + Differential terms

Vertical tire force estimator
- Load transfer model
- Body angle estimator
  - Vehicle kinematics model
- Road angle estimator
  - Decoupled roll & pitch model

Approaches:
- Kalman filter (KF)
- Neural networks + KF (NN)
- Sliding mode observer (SM)
Automotive state estimation environment

- IPG CarMaker
- Virtual ‘measurement’
- Concept Car
- Measurement
- cmread.m
- MATLAB
- Estimator
- MATLAB-AMESim interface
- Version 7
- Version 2018a
- Version 14.2
- AMESim
- Vehicle model
- Single track model
- Twin track model
- Multibody system model

13/11/2018
Automotive state estimation environment

Advanced Modeling Environment for performing Simulations of engineering systems: AMESim

Software tool for modeling and analysis of multi-domain systems (originally by Imagine S.A.; acquired by LMS International; acquired by Siemens AG)

Based on Modelica and bond graph theory

Causal: in- and outputs of icons are linked (in contrast to e.g. Simulink)
Automotive state estimation environment
Automotive state estimation environment

Standard set of sensors already available in current production vehicles

Virtual sensing approach based on dynamic vehicle model to correct for sensor inaccuracies

Tire cornering stiffness estimation with random walk (adds robustness against unknown and variable tire/road behavior)

‘Adaptive linear tire model’

Source: Tire and Vehicle Dynamics (Pacejka)
Automotive state estimation environment

- **IPG CarMaker**
- **Virtual ‘measurement’**
- **Concept Car**
- **Measurement**

**Version 7**

- cmread.m

**Version 2018a**

- MATLAB
- Estimator

**MATLAB-AMESim interface**

**Version 14.2**

- AMESim
- Vehicle model

- Single track model
- Twin track model
- Multibody system model

**MATLAB: state estimation library (Kalman filter)**

**MATLAB-AMESim interface**
SyRI seminar

Automotive state estimation environment

IPG CarMaker
SyRI seminar

Flanders Make electrified Evoque test vehicle
State estimation results – vehicle sideslip angle
State estimation results – longitudinal tire forces

- $F_{z, FL}$ vs. $t$ [s]
- $F_{z, FR}$ vs. $t$ [s]
- $F_{z, RL}$ vs. $t$ [s]
- $F_{z, RR}$ vs. $t$ [s]
State estimation results – lateral tire/axle forces

Front

Rear

$F_y$ [N]

$t$ [s]
Estimation framework

**Longitudinal tire force estimator**
- Rotating wheel dynamics model
- + Wheel torque uncertainty
- Wheel torque adaptation
- Rolling resistance
- Load proportionality principle

**Lateral tire force estimation**
- Lat. velocity & cornering stiffness estimation
- Adaptive linear tire model (RW evolution)
- Cornering stiffness estimation
- Neural Networks
- Bicycle model
- + Differential terms

**Vertical tire force estimator**
- Load transfer model
- Body angle estimator
  - Vehicle kinematics model
- Road angle estimator
  - Decoupled roll & pitch model

**Vehicle Sensors**
- $\omega_{whl}$
- $T_{whl}$
- $P_{brk}$
- $\nu_x$
- $\delta$

**Vehicle kinematics model**
- $a_{imu}$
- $z_{ij}$
Body and Road angle estimation & Vertical tire force estimation

Body angle estimator
Vehicle kinematics model

Road angle estimator (EKF + RW)
Decoupled roll & pitch model

Measurement correction
\[ a_x = a_{x,IMU} + g \sin(\theta_v + \theta_r) \]
\[ a_y = a_{y,IMU} - g \sin(\phi_v + \phi_r) \]

Load transfer model

\[ F_z \]
Body and Road angle estimation & Vertical tire force estimation

\[ \phi_{v,ij} = \cos^{-1} \frac{N_{ij}^y}{\|N_{ij}\|} \]

\[ \theta_{v,ij} = \cos^{-1} \frac{N_{ij}^x}{\|N_{ij}\|} \]

\[ a_x = a_{x,IMU} + g \sin(\theta_v + \theta_r) \]

\[ a_y = a_{y,IMU} - g \sin(\phi_v + \phi_r) \]

\[ F_z \]
Body and Road angle estimation & Vertical tire force estimation

\[
\begin{bmatrix}
\dot{\phi}_v \\
\dot{\theta}_v \\
\alpha_x \\
\alpha_y \\
\phi_v \\
\theta_v
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & -g & 0 & -g & 1 \\
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\phi_v \\
\phi_v \\
\alpha_x \\
\alpha_y \\
\phi_v \\
\theta_v
\end{bmatrix} +
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{v}_y + \psi \dot{v}_y \\
-\dot{v}_x + \psi \dot{v}_x
\end{bmatrix}
\]
Body and Road angle estimation & Vertical tire force estimation

\[
\begin{align*}
\dot{a}_x &= a_{x,IMU} + g \sin(\theta_v + \theta_r) \\
\dot{a}_y &= a_{y,IMU} - g \sin(\phi_v + \phi_r)
\end{align*}
\]
Body and Road angle estimation & Vertical tire force estimation

\[
F_{zi,j} = \frac{(L - l_i) mg}{2L} \pm \Delta F_{\phi_i} \pm \Delta F_{\theta_i}
\]

\[
\Delta F_{\phi_i} = \frac{1}{t_i} \left( \frac{k_{\phi_i}}{k_{\phi_f} + k_{\phi_r} - mgh'} + \frac{L - l_i}{L} h_{\phi_i} \right) ma_y
\]

\[
\Delta F_{\theta_i} = \pm \frac{ma_x h}{2L}
\]
State estimation results
10 DOF Vehicle Model

Legend:
F = Force
T = Torque
X = Position
V = Velocity
θ = Angle
ω = Wheel speed
R = Rotation matrix
Y = Yaw

Use case
Road angle estimation

Motion control

13/11/2018
Nonlinear suspension stiffness:

\[ F = e^{ax} + bx \]

Suspension strokes:

\[ x = x_{CoM} + R_{v2e} \times r \]
Calculated normal tire forces (Limit handling test)
Concept Car Platform – Introduction

Modular powertrain architecture
Including conventional, hybrid, and fully electric options

Goal: creation of automotive platform for versatile research and validation purposes

In cooperation with *Punch Powertrain*, Belgian supplier of powertrain technology

Supported by a number of Master’s theses

Development/optimization is ongoing
Concept Car Platform – Student work

2016/2017: initial frame design; hybrid controller for energy optimization; powertrain implementation strategy & battery pack design

2017/2018: Brake-By-Wire; Electric Power Assisted Steering

2018/2019: suspension redesign; vehicle dynamics controller (ABS, TCS, ESC)
Concept Car Platform – High voltage battery

Lithium Ferro Phosphate (LiFePO4)

- 12 kWh usable
- 360 V
- 60 kW peak
- 50+ km full electric range
- 160+ kg

Junction box interfacing internal/external connections and hosting safety features

Complete battery pack assembled from seven modules and a total of 112 cells
Concept Car Platform – Energy optimization

Constrained optimization of (equivalent) fuel consumption

Rule-based mode selection
- Combustion only
- Hybrid mode
- Full electric mode

‘High level’ control

<table>
<thead>
<tr>
<th>Performance</th>
<th>limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE</td>
<td>engine map (fuel consumption)</td>
</tr>
<tr>
<td>CVT</td>
<td>CVT losses</td>
</tr>
<tr>
<td>Motor</td>
<td>motor map (efficiency)</td>
</tr>
<tr>
<td>Battery</td>
<td>Charge/discharge efficiency</td>
</tr>
</tbody>
</table>
Concept Car Platform – Energy optimization

Constrained optimization of (equivalent) fuel consumption

Rule-based mode selection
- Combustion only
- Hybrid mode
- Full electric mode

‘High level’ control

<table>
<thead>
<tr>
<th>Transition</th>
<th>Conditions</th>
<th>Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>$T_{\text{request}} &lt; 0$</td>
<td>switch to braking mode stop engine</td>
</tr>
<tr>
<td>a2</td>
<td>$T_{\text{request}} &lt; 0$</td>
<td>switch to braking mode</td>
</tr>
<tr>
<td>b</td>
<td>hybrid trigger</td>
<td>start engine</td>
</tr>
<tr>
<td>c1</td>
<td>engine ready</td>
<td>no action</td>
</tr>
<tr>
<td>c2</td>
<td>engine speed sufficient</td>
<td>switch to hybrid mode close clutch</td>
</tr>
<tr>
<td>d</td>
<td>clutch is closed</td>
<td>no action</td>
</tr>
<tr>
<td>e</td>
<td>electric trigger</td>
<td>switch to electric mode open clutch</td>
</tr>
<tr>
<td>f</td>
<td>clutch is open</td>
<td>stop engine</td>
</tr>
<tr>
<td>g</td>
<td>engine off</td>
<td>no action</td>
</tr>
<tr>
<td>h1</td>
<td>$T_{\text{request}} &gt; 0$</td>
<td>switch to electric mode</td>
</tr>
<tr>
<td>h2</td>
<td>$T_{\text{request}} &gt; 0$ engine ready clutch closed</td>
<td>switch to hybrid mode</td>
</tr>
<tr>
<td>h3</td>
<td>$T_{\text{request}} &gt; 0$ engine ready</td>
<td>switch to hybrid mode close clutch</td>
</tr>
<tr>
<td>h4</td>
<td>$T_{\text{request}} &gt; 0$ engine not ready</td>
<td>switch to electric mode</td>
</tr>
</tbody>
</table>
Concept Car Platform – Energy optimization

‘Low level’ control: instantaneous optimization based on look-up tables

Global optimization not possible as we do not know the future trajectory

→ Offline optimization (also less demanding on computational power)

<table>
<thead>
<tr>
<th></th>
<th>Combustion Mode</th>
<th>Hybrid Mode</th>
<th>Percentual reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFC ICE [g/kWh]</td>
<td>304,99</td>
<td>249,41</td>
<td>18.22%</td>
</tr>
<tr>
<td>SFC ICE during charging [g/kWh]</td>
<td>-</td>
<td>243,99</td>
<td>-</td>
</tr>
<tr>
<td>Total fuel consumption [g]</td>
<td>1793,64</td>
<td>1705,47</td>
<td>4.92%</td>
</tr>
<tr>
<td>Equivalent electric consumption [g]</td>
<td>-</td>
<td>-483,48</td>
<td>-</td>
</tr>
<tr>
<td>Total consumption [g]</td>
<td>1793,64</td>
<td>1221,99</td>
<td>31.87%</td>
</tr>
<tr>
<td>Fuel consumption 6x MOL [g]</td>
<td>10817,4065</td>
<td>7249,80</td>
<td>32.98%</td>
</tr>
</tbody>
</table>
Concept Car Platform – Tubular vehicle frame

Manufactured by local supplier *Engie Fabricom*, Antwerp

Combined tubular/sheet metal structure, welded and bolted

Experimental modal analysis is planned

Assembly of subsystems: suspension, brakes, steering, powertrains including battery pack, seats

Control systems
Thank you for your attention!