Automotive Control Systems
-Past, present, and future-

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Institute of Automatic Control and Mechatronics
Darmstadt, Germany
Automotive Control Systems

- Introduction
- Mechatronic components and driver assistance systems
- Control structures for automobiles
- Modelling and parameter estimation of vehicle dynamics
- From driver assistance systems to automatic driving
- Collision avoidance systems
- Fault tolerant issues
- Outlook
Some general drivers for the development of automobiles

1. Shortage of fossil energy and raw material resources:
   - Increasing energy and raw material prices
   - Increased use of regenerative energy sources (wind, biofuel, solar), and storage
Some general drivers for the development of automobiles

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2. Increasing transportation and mobility
   - More traffic (ground, air, sea)
   - Energy/time efficient mobility concepts
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   • Passive safety
   • Active safety
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3. Improvement of safety for automobiles
   • Passive safety
   • Active safety

4. Increasing electrification and electronification
   • Electronic sensors, electrical actuators, electronic control units
   • Integration to mechatronic components
   • Power trains with combustion engines and/or electrical motors
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Electrical system of a passenger car in 1958

- Alternator
- Battery
- Starter
- Ignition
- Lights
- Blinker
- Horn

... No electronics, except the radio

Source: Rainer Kallenbach, Bosch 2010: DSC Conference. Cambridge (historical Bosch archive)
**Sensors**

wheel speed
pedal position
yaw rate
lateral & longitudinal acceleration
susp. deflection
brake pressure
steering angle
steering torque
ultra sonic
Radar system
video camera system
stereo camera system

**Mechatronic components and driver-assistance systems**

**Actuators**

hydraulic pump
magnetic switching valves
electronic throttle valve
electro-pneumatic brake booster
magnetic proportional valves
semi-active shock absorbers
electric power steering
rear axle steering
torque vectoring
electro-hydraulic or electromotoric stabiliser

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Development of driver-assistance systems
**Sensors**
- wheel speed
- pedal position
- yaw rate
- lateral & longitudinal acceleration
- susp. deflection
- brake pressure
- steering angle
- steering torque
- ultra sonic
- Radar system
- video camera
- system
- stereo camera
- system

**Mechatronic components and driver-assistance systems**

- Antilock brakes (ABS, 1979)
- Traction control (TCS, 1986)
- Electronic stability program (ESP, 1995)
- Brake assist (BA, 1996)
- Electrical power steering (EPS, 1996)
- Electronic air suspension control (EAS, 1998)
- Adaptive cruise control (ACC, 1999)

**Actuators**
- hydraulic pump
- magnetic switching valves
- electronic throttle valve
- electro-pneumatic brake booster
- magnetic proportional valves
- semi-active shock absorbers
- electromotoric actuator for active front steering
- electro-hydraulic or electromotoric stabiliser

**Development of driver-assistance systems**
- Highly automated driving (20xxx)
- Anti-collision-avoidance (20xx)
- Parking assistance (2003)
- Dynamic drive control (DDC, 2003)
- Active front steering (AFS, 2003)
- Continuous damping control (CDC, 2002)
- Electro-hydraulic brake (EHB, 2001)
- Active body control (ABC, 1999)
From hydraulic brake systems to mechatronic brake systems

Conventional hydraulic brake with vacuum booster

Electronic modulation ABS, ASC

Deceleration, acceleration with ACC

ACC plus steering system, expanded VMC

Electric booster, redundancy for steering

Source: Alexander Haeussler; Bosch; Automated Driving …, ATZ Conf. ChassisTec, Munich 2015

VMC: Vehicle Motion Control
Brake-by-wire systems

Electrohydraulic brake control (EHB), Bosch; (2001, serial production until ~ 2010)

Electromechanical brake (EMB), Continental Teves (2000), prototype
Brake System Software Functions

- ESC
  - Yaw Rate Control
  - Yaw Moment Distribution
  - Actuator Arbitration
  - Actuator Control (Valves, Pump, Booster)

- ABS
- TCS
- HSA

1984
1989
1997
2003

1 2 3 4

- ABS
- BTCS
- TCS
- ABS
- ABS Plus
- ESC
- EBV
- BA
- EDC
- BTCS
- TCS
- ABS

- EPB
- GMK
- DSR
- ARF
- ACC
- EBA
- HDC
- AVH
- EBV
- HSA
- Soft Stop
- MBS
- FBS
- Reduced Stooping Dist.
- OHB (booster failure)
- OHB Cold Start Support
- HBA
- RBS
- PBA
- BAS
- ARR
- VDS
- BBV
- TPM
- DDS
- ESC – Adaptive STM
- ESC – Beta Control
- ESC - TSP
- ESC - UCL
- ESC - LDE
- ESC - YRC
- TCS Comfort Features
- TCS - EDC
- BTCS
- TCS
- ABS Comfort Features
- ABSPlus
- ABS
Hydraulic Power Steering (HPS)

Electrical Power Steering (EPS)

Electrical Power Assisted Steering (HPS + EPS)

Active Front Steering (AFS)

Steer-by-Wire (SbW)

Mechatronic steering systems
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3 - level vehicle guidance (basic, driver control), Donges 1982
Signal flow: manual driving, some driver assistance systems
→ „peaceful coexistence“
Modern chassis with actuators and advanced driver assistance systems

- **AFS**
  - Active front axle steering

- **ARK**
  - Active rear axle steering

- **EAS, ABC**
  - Active suspension level control

- **ARS, ABC**
  - Vertical force control

- **EAD, ABC**
  - Pitch and roll control

- **TPMS, DDS**
  - Tire pressure control

Mathematical equation:

\[ M_\Psi = \sum (r_i \times F_i) \]

**Source:** Peter Lauer, Continental AG, Frankfurt

\[
\text{max. horizontal tire force } F_1 = \mu F_{z1} = \sqrt{F_{x1}^2 + F_{y1}^2}
\]

**Controlled longitudinal drive train torque**

**Controlled longitudinal lock**

**Controlled differential torque**

**Toe-in angle control**
Signal flow: with advanced driver assistance systems and decentralized control
Signal flow: with advanced driver assistance systems and integrated chassis control
• **AUTOSAR**: Standardized automotive software architecture
• Basic software layer: hardware dependent services (bus connect., microcontrollers)
• Runtime environment (RTE): virtual function bus, decouples application software from hardware
• Application layer: software functions, hardware independent

**Layered AUTOSAR structure for interconnection of ECUs**

Source: Andreas Marx, TRW; iQPC 2007,
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Simulation tool chain for the virtual development of drive dynamics (OEM)

Simulation tool chain for the virtual development of drive dynamics (OEM)

Integration of vehicle models and ECUs

Source: Michael Kochem (Opel) : Virtual tool chain, VDI-GMA Ausschuss AUTOREG, 5_2016
Example: Modeling of lateral dynamics, basic model structure

(1) Non-linear Two Track Model

Non-linear system description:
\[ x = [v, \beta, \psi] \]
\[ \dot{x} = f(x, u) = \begin{bmatrix} \dot{v}(x, u) \\ \dot{\beta}(x, u) \\ \dot{\psi}(x, u) \end{bmatrix} \]

Velocity of center of gravity:
\[ \dot{v} = \cos(\beta) \cdot \frac{\sum F_x^V}{m} + \sin(\beta) \cdot \frac{\sum F_y^V}{m} \]

Side slip angle dynamics:
\[ \dot{\beta} = -\frac{\sin(\beta)}{v} \cdot \frac{\sum F_x^V}{m} + \frac{\cos(\beta)}{v} \cdot \frac{\sum F_y^V}{m} - \dot{\psi} \]

Yaw dynamics:
\[ \ddot{\psi} = \frac{1}{J_z} \left[ (F_y^V \cdot l_f) - (F_y^V \cdot l_r) \right] \]

Introducing non-linear lateral and longitudinal tire model:
\[ F_{y,ij} = f(\alpha_{ij}, \lambda_{ij}, F_{z,ij}) \quad F_{x,ij} = f(\alpha_{ij}, \lambda_{ij}, F_{z,ij}) \quad j = l, r \quad i = f, r \]

Bechtloff, J.: Cornering stiffness and sideslip estimation … IFAC-AAC 2016, Norrköping
Modeling of lateral dynamics: tire forces

(2) Non-linear One Track Model

Non-linear axle force models for front and rear axle:

\[ F_{y,f} = \alpha_f c_{\alpha,f} \]  
\[ F_{y,r} = \alpha_r c_{\alpha,r} \]  

(Rear axle)

(Front axle)

Linearized region \( \rightarrow \) cornering stiffness

\[ F_{y,f} = f(F_{z,f}, \alpha_f, \lambda_f, c_{\alpha,f}, \alpha_{f,max,f}, F_{y,max,f}) \]

\[ F_{y,r} = f(F_{z,r}, \alpha_r, \lambda_r, c_{\alpha,r}, \alpha_{f,max,r}, F_{y,max,r}) \]
Modeling of lateral dynamics: simplification for low lateral dynamics

(3) Linear One Track Model

Side slip angles at front and rear axle:

\[ \alpha_f \approx \delta - \beta - \frac{l_f \psi}{v} \]
\[ \alpha_r \approx -\beta + \frac{l_r \psi}{v} \]

With constant velocity, linear tire model and side slip angles the linear state space description of the single track model is derived:

\[ \dot{x} = A \begin{bmatrix} \alpha_f \\ \beta \\ \psi \end{bmatrix} + B \begin{bmatrix} \frac{c_{\alpha,f}}{m \cdot v} \\ \frac{c_{\alpha,r} - l_r c_{\alpha,f}}{J_z} \\ \frac{\frac{c_{\alpha,r} - l_r c_{\alpha,f}}{J_z \cdot v} - 1}{m \cdot v} \end{bmatrix} \begin{bmatrix} \frac{\frac{c_{\alpha,f}}{m \cdot v}}{l_r c_{\alpha,f}} \frac{\frac{c_{\alpha,r} - l_r c_{\alpha,f}}{J_z} \frac{\frac{c_{\alpha,r} - l_r c_{\alpha,f}}{J_z \cdot v} - 1}{m \cdot v}}{l_f} \end{bmatrix} \delta \]

[slip angle]
[yaw rate]
Modeling of lateral dynamics: ranges for linear and nonlinear tire forces

(4) Non-linear One Track Model

Non-linear axle force models for front and rear axle:

linear one track model:
\[ \dot{x} = Ax + Bu \]

area that is covered by the non-linear one track model:
\[ \dot{x} = f(x, u) = \begin{bmatrix} \dot{\psi}(x, u) \\ \dot{\beta}(x, u) \end{bmatrix} \]
Model based design, Estimation and Control of lateral dynamics (yaw rate and slip angle): low and high dynamics

Structure

desired vehicle behavior

\[ \delta_f \]

\( X_d \)

desired states

feed forward control (inverted model)

\( [\hat{\beta}, \hat{\psi}] \)

feed back control

\[ u = \begin{bmatrix} \delta_f + \Delta \delta_f \\ \delta_r \\ M_B \end{bmatrix} \]

actual vehicle

\( \delta_f^+, \delta_r, \ldots \)

with additional steering angles and brake torques the axle forces are generated

\( u = [\delta_f^+, \delta_r, \ldots] \)

Extended Kalmanfilter

(non-linear two track model)

\[ \hat{\alpha}_f, \hat{\alpha}_r \]

ESC functions

\( h(\hat{x}, u) \)

\( \omega_{ij} \)

\( M_{ij} \)

\( a_y \)

\( \ddot{\psi} \)

wheel speeds

calc. wheel torques

lateral acceleration

yaw acceleration

\[ z = \begin{bmatrix} \omega_{ij} \\ M_{ij} \\ a_y \\ \ddot{\psi} \end{bmatrix} \]
Estimation (Experimental Results)
Side Slip Angle $\beta$

Slalom maneuver with over-steering on plane road:

The side slip angle estimation follows the reference signal (measured with optical Correvit sensor)
Estimation (Experimental Results)

Cornering Stiffnesses $c_\alpha$ Adaption

($c_\alpha$: part of non-linear one track axle force model)

Normal driving on country roads for about 26 minutes:

- $a_y$ in m/s$^2$
- $c_\alpha$ in kN/rad
- $t$ in s

Graph showing:
- Front reference
- Rear reference
- Front estimation
- Rear estimation
Control design (Simulation)

Example for Active Front Steering

- based on non-linear one-track model
- cornering stiffness at the front and steering ratio is settable

\[
\begin{align*}
\delta_f \quad & \text{desired vehicle behavior} \\
\delta_f^+ \quad & \text{desired states} \\
\hat{c}_{\alpha,f}, \hat{c}_{\alpha,r} \quad & \text{feed forward control (inverted model)} \\
\delta_f^+ \quad & \text{based on non-linear one-track model} \\
\delta_r \quad & \text{cornering stiffness at the front and steering ratio is settable} \\
\end{align*}
\]

\[
\begin{align*}
x_d \quad & \text{desired states} \\
\end{align*}
\]

\[
\begin{align*}
\text{desired states} & \quad \begin{bmatrix} \hat{c}_{\alpha,f}, \hat{c}_{\alpha,r} \end{bmatrix} \\
\end{align*}
\]

\[
\begin{align*}
\text{actual vehicle} & \quad \begin{bmatrix} a_y, \psi \end{bmatrix} \\
\text{with additional steering angles} & \quad \text{the axle forces are generated} \\
\end{align*}
\]

\[
\begin{align*}
u & \quad \begin{bmatrix} \delta_f + \delta_f^+, \delta_r, ... \end{bmatrix} \\
\end{align*}
\]

Bechtloff, J.: Cornering stiffness and sideslip estimation …IFAC-AAC 2016, Norrköping

TU Darmstadt → Tuesday, 10:40 Hrs
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From assisted driving to automated driving

Source: Alexander Haeussler; Bosch; Automated Driving ..., ATZ Conf. ChassisTec, Munich 2015
Signal flow: Manual Driving (1)
Signal flow: Driver and electronic control systems (2a)
Signal flow: Electronic hierarchical control levels for automatic driving (2b)

### AUTOMATIC VEHICLE CONTROL SYSTEMS

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<th>Electronic vehicle control systems</th>
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<th>ADAS</th>
<th>DAS</th>
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<td>highly automatic driving</td>
<td>automated driving control</td>
<td>vehicle control level 2</td>
<td>vehicle control level 1</td>
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<td>partially automatic driving</td>
<td>slow maneuvers</td>
<td>parking control</td>
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<td>limited maneuvers</td>
<td>lane-keeping control</td>
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<td>continuous driving</td>
<td>braking control</td>
<td>TCS</td>
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<td>accident avoidance</td>
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</table>

- Component control:
  - engine control
  - transmission control
  - power steering control (HPS, EPS)
  - brake control (ABS)
  - suspension control

- GPS

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<table>
<thead>
<tr>
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<th>Driver Assistance System (DAS)</th>
<th>Advanced Driver Assistance System (ADAS)</th>
<th>Automatic Driving (partially)</th>
<th>Automatic Driving (fully)</th>
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</table>

References: VDA, Ruchatz (AUTOREG 2013)

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<tr>
<th>M A N E U V E R S</th>
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<td>NORMAL</td>
<td>KIND OF DRIVING</td>
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<td>longitudinal control</td>
<td>lateral control</td>
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<td>· steering (parking)</td>
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<td>· braking</td>
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<td>· jam assistant (stop &amp; go)</td>
<td>parking assistant (lateral)</td>
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<td>MANEUVERS WITH LIMITED DURATION</td>
<td>lane keeping assistant</td>
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<td>· emergency braking</td>
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<tr>
<td>DRIVER</td>
<td>ROLE OF SYSTEM &amp; DRIVER</td>
<td>· assistance for longitudinal and/or lateral control</td>
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references: VDA, Ruchatz (AUTOREG 2013)

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<td>Kind of Driving</td>
<td>assisted driving</td>
<td>advanced assisted driving</td>
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<td>Longitudinal control</td>
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<tr>
<td>Acceleration</td>
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<td>SLOW MANEUVERS</td>
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<td>Parking pilot (front, back, lateral)</td>
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<td>MANEUVERS WITH LIMITED DURATION</td>
<td>Lane keeping assistant</td>
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<td>Continuous Driving</td>
<td>Speed / Distance control assistant (ACC)</td>
<td>Highway assistant - speed / Distance control</td>
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<td>Accident Avoidance Maneuvers</td>
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<td>ROLE OF SYSTEM &amp; DRIVER</td>
<td>Assistance for longitudinal and/or lateral control</td>
<td>Longitudinal automatic control for defined cases</td>
<td>Longitudinal automatic control for defined cases for other cases</td>
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## Degrees of Automatic Driving

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<td>• parking assistant (lateral)</td>
<td>• parking pilot (front, back, lateral)</td>
<td>• jam pilot</td>
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<td>SLOW MANEUVERS</td>
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<td>• lane change pilot</td>
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<td>• speed / distance control assistant (ACC)</td>
<td>• highway assistant - speed / distance control</td>
<td>• highway assistant - lane keeping control</td>
<td>• highway pilot</td>
<td>• rural road pilot</td>
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<td>DRIVER</td>
<td>ROLE OF SYSTEM &amp; DRIVER</td>
<td>• assistance for longitudinal and/or lateral control</td>
<td>• longitudinal automatic control for defined cases</td>
<td>• longitudinal automatic control in many cases</td>
<td>• longitudinal &amp; lateral automatic control in many cases</td>
</tr>
<tr>
<td>• driver supervises all time, takes over for other cases</td>
<td>• driver does not have to supervise all time, takes over on request</td>
<td>• driver does not have to supervise all time, takes over on request</td>
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</tr>
</tbody>
</table>

References: VDA, Ruchatz (AUTOREG 2013)

TU Darmstadt
## DEGREES OF AUTOMATIC DRIVING

<table>
<thead>
<tr>
<th>MANEUVERS</th>
<th>GENERAL DESCRIPTION</th>
<th>Driver Assistance System (DAS)</th>
<th>Advanced Driver Assistance System (ADAS)</th>
<th>Automatic Driving (partially)</th>
<th>Automatic Driving (fully)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KIND OF DRIVING</td>
<td>assisted driving</td>
<td>advanced assisted driving</td>
<td>highly automatic driving (HAD)</td>
<td>fully automatic driving (FAD)</td>
<td></td>
</tr>
<tr>
<td>NORMAL</td>
<td>longitudinal control · acceler. · braking</td>
<td>lateral control (parking)</td>
<td>lateral control</td>
<td>driver inside · longitudinal control · lateral control</td>
<td>driver inside · driver outside</td>
</tr>
<tr>
<td>SLOW MANEUVERS</td>
<td>jam assistant (stop &amp; go)</td>
<td>parking assistant (lateral)</td>
<td>parking pilot (front, back, lateral) · jam pilot</td>
<td>parking pilot · jam pilot</td>
<td>parking pilot · valet parking pilot · shunting pilot (HLV)</td>
</tr>
<tr>
<td>MANEUVERS WITH LIMITED DURATION</td>
<td>lane keeping assistant</td>
<td>lane keeping control</td>
<td>lane change pilot · overtaking pilot · crossing pilot</td>
<td>driving maneuver pilot</td>
<td></td>
</tr>
<tr>
<td>CONTINUOUS DRIVING</td>
<td>speed / distance control assistant (ACC)</td>
<td>highway assistant · speed / distance control</td>
<td>highway assistant · lane keeping control</td>
<td>highway pilot · rural road pilot · city pilot</td>
<td></td>
</tr>
<tr>
<td>CONFLICT</td>
<td>ACCIDENT AVOIDANCE MANEUVERS</td>
<td>WARNINGS</td>
<td>WARNINGS</td>
<td>WARNINGS</td>
<td>WARNINGS</td>
</tr>
<tr>
<td></td>
<td>emergency braking</td>
<td>emergency braking</td>
<td>emergency braking · emergency steering</td>
<td>emergency braking · emergency steering</td>
<td>emergency braking · emergency steering · freespace maneuver</td>
</tr>
<tr>
<td></td>
<td>blind spot warning</td>
<td>emergency braking (evasion)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DRIVER</td>
<td>ROLE OF SYSTEM &amp; DRIVER</td>
<td>assistance for longitudinal and/or lateral control</td>
<td>longitudinal automatic control for defined cases · driver supervises all time, takes over for other cases</td>
<td>longitudinal &amp; lateral automatic control in many cases · driver does not have to supervise all time, takes over on request</td>
<td>performs complete driving · driver does not have to drive</td>
</tr>
</tbody>
</table>

References: VDA, Ruchatz (AUTOREG 2013)

R. T.
TU Darmstadt
Surround sensors: near and long range radar: front and rear, near and long range infrared, stereo camera, ultra sonic

Source: Gottscholl, VDI/GMA Techn. Committee Meeting 7.62 A UTOREG, 2015
Sensor data fusion for assisted and automated driving

Source: Alexander Haeussler; Bosch; Automated Driving …, ATZ Conf. ChassisTec ,Munic h 2015
Highly precise position requirements

1. Planning Map:
   “Your lane ends at GPS position \(x \ y\) \((+/-10m_{long})\)”

2. Localization Map:
   “You are currently at GPS position \(\xi \ \psi\) \((+/-10m_{long})\)”

3. Decision Algorithm:
   “Merge right within the next 150mtrs”

→ Precise, up-to-date maps with high resolution obtained by GPS and link to cloud data

Security for cyber attacks: anomaly detection

- Information exchange via the cloud is expected for
  - navigation
  - teleservice (remote diagnosis)
  - Infotainment connections (internet, smart phones, …)
- Automotive control domain must be protected against external attacks
- **Security measures** have to be implemented (like known from IT-world), see Ihle, M. Glas, B., Bosch/ETAS (2016):
  - Layer 4: protect the vehicle as a node in a global network (firewalls)
  - Layer 3: protection of the internal E/E communication architecture (e.g. via the central gateway, connecting several bus systems)
  - Layer 2: security of vehicle internal communication (e.g. by new cryptographic protection)
  - Layer 1: protection of the individual ECU (preventing the misuse of functions, e.g. by building blocks, keys, special hardware security modules)
- Present access points: OBD plug, bluetooth, keyless entry
4 layer security levels

RB Vehicle Security Approach – 4 Layers

Layer 1: Individual ECU
- Protect integrity of ECU SW & data
- Hardware Security Module

Layer 2: In-vehicle network
- Protect integrity of critical in-vehicle signals

Layer 3: E/E Architecture
- Protect and separate domains by E/E architectures and gateways

Layer 4: Connected vehicle
- Vehicle firewalls and security standards for external interfaces

Source: Markus Ihle; Bosch Center of Competence Security, ATZ Conf. Diver Assist. Syst., Frankfurt, April 2016
Automotive Control Systems

- Introduction
- Mechatronic components and driver assistance systems
- Control structures for automobiles
- Modelling and parameter estimation of vehicle dynamics
- From driver assistance systems to automatic driving
- Collision avoidance systems
- Fault tolerant issues
- Outlook
Collision avoidance systems: research projects at TU Darmstadt

- Accident type: in longitudinal direction

**Vehicles move same direction**

- Other Vehicles:
  - move ahead
  - stop

- Other Vehicles:
  - move laterally
  - cutting in
  - crossing

**Vehicles move opposite direction**

**Overtaking:**

- rural road
  - 2 lanes
  → oncoming vehicle

- autobahn
  - ≥ 2 lanes
  → oncoming vehicle, wrong way

**Straight driving:**

- own vehicle turns to left
- other vehicle turns to left

**CAV actions:**

- warning
- braking
- swerving to free lane

- warning
- braking and
  - swerving back

- warning
- braking and
  - swerving to the right

- warning
  - braking & swerving: to the right
to free lane

**PRORETA 1 (2003 – 2006)**

Driver assistance system for obstacle collision avoidance (PRORETA 1: 2003-2006)

R. Isermann, R. Bruder, H. Winner
E. Bender, M. Darms, M. Schorn, U. Stählin

In Cooperation with Continental

Collision avoiding system: automatic braking and steering
Considered collision cases: obstacle in lane

→ Automatic intervention in the last possible instant

a) Blocked lane

b) Cutting-in vehicle

Emergency Evasion

Emergency Braking
Testing and system validation

• Emergency steering (driver keeps steering wheel straight)
Driver assistance system for collision avoidance during overtaking maneuvers, PRORETA 2 (2006-2009)

- Used environmental sensors:
  - RADAR-System: Continental ARS 300, wide range, 77 GHz
  - Video-System: Continental CSF 200, mono, resolution 752 x 480 pixels
3. Situation analysis

1. Odometry: Position on road
2. Maneuver detection: detection of an overtaking maneuver
3. Hazard evaluation: detection of hazards during overtaking

• Input data:
  – Drive dynamic sensors
  – Camera based lane detection
  – Object-tracking based on radar and camera
4. Warnings and automatic actions
- planning of overtaking break-off -

\[ \tau_{\text{required}} = \tau_{\text{steer}} + \tau_{\text{nosteer}} \]

**break-off of overtaking, if:**

\[ \tau_{\text{required}} \geq \tau_{\text{available}} \]

- 1. **Warnings:**
  - driver brakes: ok
- 2. **Automatic Braking:**
  - if the driver does not brake
- 3. **Cutting in:**
  - by the driver
Overtaking assistant: PRORETA 2
Overtaking maneuver: warning and automatic braking
Available collision avoiding systems

• **Automatic emergency braking (AEB):**
  
  • for in front driving or stopping vehicles:
    • forward collision warning
    • activation of brake system
    • automatic full braking
  
  • for crossing vehicles
  
  • for pedestrians

• **Automatic evasion**

  • Evasive steering assist (MB)
  • In development, depends on surrounding information

• **Overtaking assistance:**

  • ?
Automotive Control Systems

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Conventional vs. automatic driving

- **Conventional driving:** driver is always in a control loop for driving
  - Controls the vehicle along a route
  - Supervises the right functioning of the vehicle
  - Obtains warnings for specified faults of some components
  - Takes appropriate actions in the case of faults

- **Highly automatic driving:** driver is temporarily not in a control loop
  - Electronic automatic closed loop control systems drive the car
  - This is based on sensor signals, digital control algorithms, electrical commanded actuators
  - Appearing faults in sensors and actuators influence immediately the closed loop behavior
    - Small faults may be compensated by the closed loop for some time
    - Larger faults may result in control deviations, sluggish behavior, instable behavior (monotonic or oscillatory)

  → **safety critical components** (sensors, communication channels, electrical board net, actuators)

  need a fault tolerant design
Different kinds of redundancy

a) Static redundancy: 
   $n$-out-of $m$ voting
   $n = 3$; 1 fault tolerated
   $n = 5$; 2 faults tolerated

b) Dynamic redundancy: hot standby 
   (small transfer time) $n = 2$; 1 fault tolerated

c) Dynamic redundancy: cold standby 
   (larger transfer time) $n = 2$; 1 fault tolerated
Degradation steps of fault-tolerant systems

Fail Operational (FO)
• System remains operational (after 1 failure)
• Possible, if the component has analytical or hardware redundancy
• In the case of a fault, the system switches from a defect component to an intact one ➔ system reconfiguration

Fail Silent (FSIL)
• Component is switched off in case of fault
• With regard to other components, the faulty components is silent, i.e. other components are not affected by the faulty component

Fail Safe (FS)
• Component is brought to safe state and is switched off
• Differentiation: active and passive fail-safe
• Operation cannot be maintained in case of a fault

Fail (F)
• Permanent interruption of operation
Required fault tolerant chassis components

- Brake system
  - Electromechanic booster → redundancy by ESC
  - Hydraulic brake circuits → redundancy by 2 brake circuits
  - Electromagnetic valves
  - Brake system sensors (positions, currents, pressure, wheel speeds: (4 wheels))
  - ECU software functions (ABS, ESC)
- Power steering system (EPS)
  - Electromotor
  - Steering gear (pinion-rack, ball-recirculation …)
  - Steering system sensors (steering angle (redundant), torque, …)
  - EPS-ECU software functions
- Chassis sensors
  - Acceleration (lateral, longitud.
  - Yaw rate
  - Longitudinal speed
- Electric power supply:
  - Generation and batteries

→ redundancy is presently only partially implemented,
→ general hardware redundancy or analytical redundancy has to be developed
Electrical Power Steering System (Example)

Motor+ECU

Technical Data
Interface: CAN
Current demand: $\leq 80$ A
Speed: $\pm 8000$ rpm
Torque: $\pm 6$ Nm
Electrical Power: $\leq 960$ W

Steering wheel angle sensor (redundant, FO-F)

Technical Data
Interface: CAN
Measuring range: 1560 °

Torque Sensor

ZF Servolectric: Paraxial servo unit

Source: ZF Lenksysteme
Fault-tolerant structures for EPS systems with increasing redundancy

<table>
<thead>
<tr>
<th>faults</th>
<th>redundancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors</td>
<td>-</td>
</tr>
<tr>
<td>ECU</td>
<td>-</td>
</tr>
<tr>
<td>Inverter</td>
<td>-</td>
</tr>
<tr>
<td>Motor</td>
<td>-</td>
</tr>
<tr>
<td>Gear</td>
<td>-</td>
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</tbody>
</table>
Test bench for a duplex EPS (case E) at IAT, TU Darmstadt

a) PC system

b) dSPACE system

highspeed serial link
Conclusions and Outlook

• Mechatronic components, electrification and surrounding sensor systems are the basis for advanced driver assistance systems and automatic driving

• The introduction of (partial) automatic driving occurs step by step, taking into account reliability, safety and (current) liability

• Virtual development is required and includes:
  – Mathematical models (components, vehicle) with different degrees of granularity (research, suppliers, OEMs)
  – Development platforms with SiL, MiL and HiL-Simulation
  – Hardware and software prototypes

• Testing and validation: virtual by simulation and by experiments on testing grounds and with real traffic scenarios

• Electronic architecture changes: real time buses (Flexray, Ethernet), more integrated control → centralized hierarchical control

• Safety issues: fault-tolerance with redundancy, cyber-security

• Similar developments for model and computer based control of powertrains (combustion engines, hybrid and electric drives and transmissions)