Control Design of Vehicle Dynamics to Improve Safety and Economy

Péter Gáspár

Associate head of SCL, MTA SZTAKI
Head of research area, JKK, SZE

Basic Research for the Development of Hybrid and Electric Vehicles Section

Hungarian Academy of Sciences
Budapest, 31 January 2014

Outline of the Presentation

Challenges in Vehicle Control

- Requirements concerning vehicles have significantly increased.

  Some examples: road holding, passenger comfort, efficiency of transport, safety, reliability of components, reduction of fuel consumption and travelling time.

  Complex and difficult tasks must be handled by vehicle control systems.

  $\Downarrow$

  Research and development of new methods and algorithms.

- The solutions are constrained by the possibilities and limitations in the individual control systems.

  $\Downarrow$

  Research and development of integrated vehicle control systems.

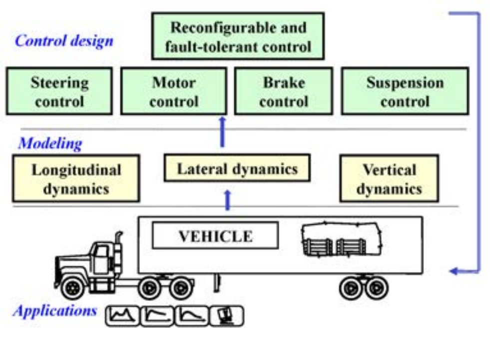
- Requirements for the safe and economical operation of the control of vehicle groups or traffic systems.

  $\Downarrow$

  Research and development of cooperative vehicle control systems.

Vehicle-Oriented R&D

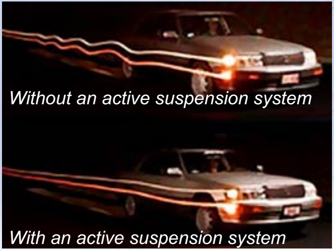
- Component design
- Integrated design in vehicles
- Cooperative design in transport systems



Components to Improve Stability

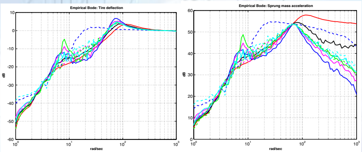
Semi-active suspension systems:

Performance specifications, e.g., road stability, passenger comfort, physical constrains, must be guaranteed.
Robust control design methods must be developed.



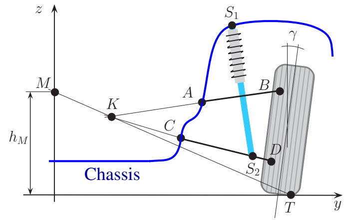
Without an active suspension system

With an active suspension system



Variable-geometry suspension systems

The camber angle can be integrated into the steering angle
⇒ trajectory control, road stability
The roll center can be modified
⇒ comfort
The half-track change can be modified
⇒ tire wear



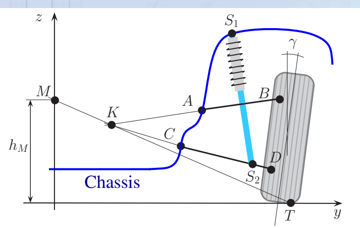
Control of Variable-Geometry System

The lateral force of the vehicle depends on the tire side-slip angle α and the wheel camber angle γ:

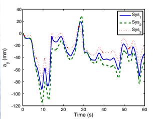
$$F_y = C\alpha + C_\gamma \gamma$$

Performance specifications of vehicle dynamics:

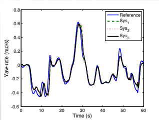
- Trajectory tracking:
  $z_1 = |\dot{\psi}_{ref} - \dot{\psi}| \rightarrow min$
- Minimization of the chassis roll angle:
  $z_2 = |\Delta h_M| = |\xi_2 t_z + \varepsilon_2 a_y| \rightarrow min$
- Minimization of input displacement:
  $z_3 = |a_y| \rightarrow min$
- Minimization of half-track change:
  $z_4 = |\Delta B| = |\xi_3 t_z + \varepsilon_3 a_y| \rightarrow min$



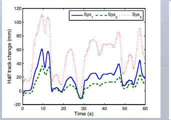
a_y



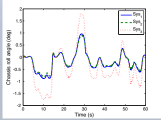
$\dot{\psi}$



ΔB



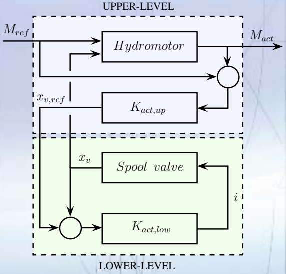
Δh_M



The control design is based on a **multi-objective optimization criterion**.

Control of Active Anti-roll Bars

The control of active anti-roll bars is designed in a **hierarchial structure**, in which the reference value of the control torque is defined at the highest level, while the actual torque is realized by the spool valve of a hydraulic actuator at the low level.

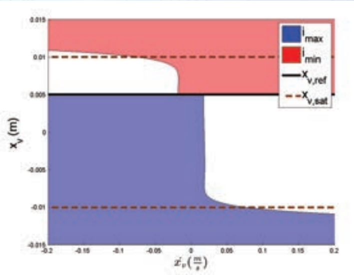


Valve control can only take discrete control input values $(i_{min}, 0, i_{max})$.
$\Rightarrow$ Discrete control of the electro-hydraulic valve.

The selection of the discrete control input is based on the Control Lyapunov Function approach.

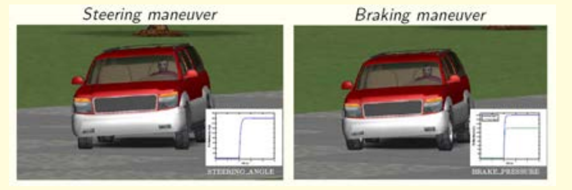
Sets in which control inputs stabilize the plant and achieve the required control performance are calculated:

$$x_{v,ref} - x_v \Rightarrow Min!$$



Integrated Vehicle Systems

Several control components and actuators operate simultaneously. They affect both the horizontal and the vertical dynamics of the vehicle.



The purpose of the **integrated vehicle control** is to coordinate the operations of the active control systems in order to guarantee performance specifications and improve safety and reliability. The integration of control systems also ensures the management of resources.

Principles of the design

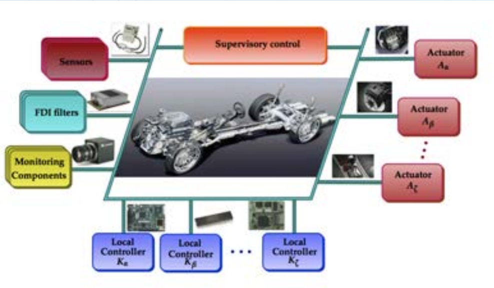
- Coordination of the control systems
- Priority among components
- Reconfiguration and adaptation to the changing conditions
- Fault-tolerance against performance degradation and faulty conditions

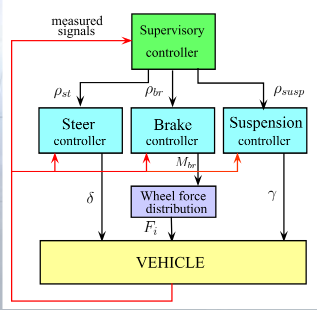
Architecture of Integrated Control

Hierarchical control levels

High-level control (supervisory control) ensures the coordination of control systems and functions.

Local control guarantees the specific performances of individual control components.





The supervisor performs the coordination of local control components and creates a priority among them based on signals of the monitoring components.

Components:

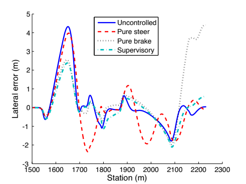
Sensors, Actuators, Control systems, Communications.

Example: Integrated Control

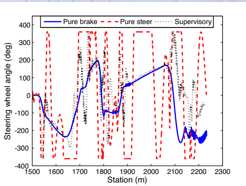
In the simulation example a vehicle with varying velocity is driven along the road. The driver is not able to keep the vehicle on the track without a **driver assistance system**.

- When the **steering system** is used only, the driver needs to turn the steering wheel in the entire steering range, which is uncomfortable and dangerous.
- When the **brake system** is used only, the differential braking torque sometimes increases. Moreover, the braking torque sharply increases due to the skidding effect. The longitudinal slip of the rear right wheel exceeds 1.

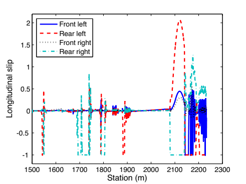
Lateral error



Steering wheel angle



Slip in brake control



Example: Integrated Control

In the example the driver without an assistance system is not able to follow the track. The lateral error increases and the vehicle leaves the road.

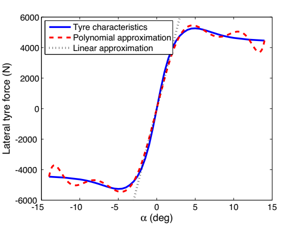
steering control ⇔ integrated control

When the steering system is used only, the driver needs to turn the steering wheel in the entire steering range.

brake control ⇔ integrated control

When the brake system is used only, the slip of the rear tires increases, which leads to a loss of stability.

The reachability characteristics of vehicle actuators are examined in order to analyse their abilities for the entire vehicle system.



Lateral tire force

The **set of reachable states** $\mathcal{R}$ with unit-energy inputs for a linear system is

$$\mathcal{R} \triangleq \left\{ x(T) \middle| \begin{array}{c} x, u \text{ satisfy } \dot{x} = A(\rho)x + B(\rho)u, \quad x(0) = 0 \\ \int_0^T u^T u dt \leq 1, \quad T \geq 0 \end{array} \right\}$$

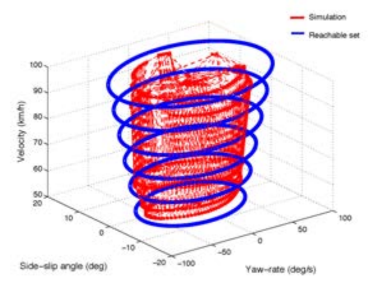
The reachable set is approximated by using ellipsoid forms:

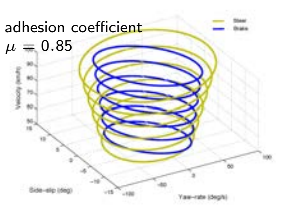
$$\varepsilon = x \left\{ x^T P(\rho) x \leq 1 \right\}.$$

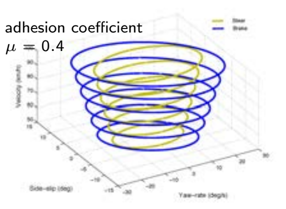
The solution leads to a linear matrix inequality.

Example: Actuator Priority

Simulation experiments are carried out in order to formulate the shape of the outer approximation of the reachable sets of actuators.



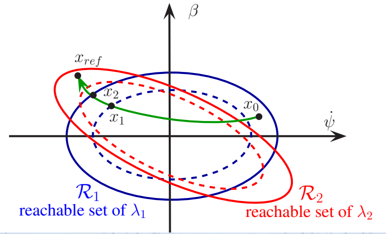




Reachable sets of braking and steering *with varying velocities and road conditions are illustrated. Both the shape and the volume of elliptical cylinders differ.*

Reconfigurable Control

The reconfigurable control is able **change its operation and adapt to new conditions** in order to focus on other performances instead of the current performances.



The initial state vector of the system is x_0 and the reference state vector is x_{ref}. Since x_{ref} is outside the reachable set $\mathcal{R}_1$, it cannot be achieved by actuator λ_1. However, actuator λ_2 is able to achieve x_{ref}, which is in its reachable set $\mathcal{R}_2$.

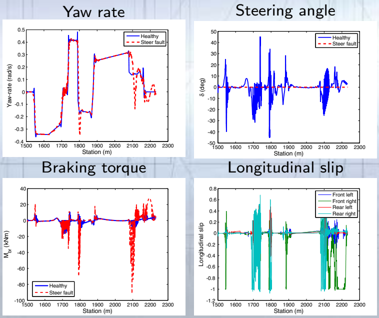
Thus, in order to achieve x_{ref} the reconfiguration from actuator λ_1 to actuator λ_2 must be carried out.

Example: Design of in-wheel-motor vehicles

Example: Reconfigurable Control

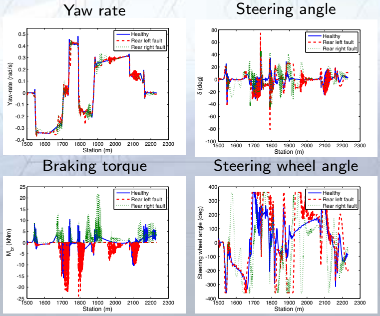
Degradation in steering:

A deterioration of steering induces an increase in brake yaw moment to perform the maneuver. The integrated control system can tolerate a steering fault.



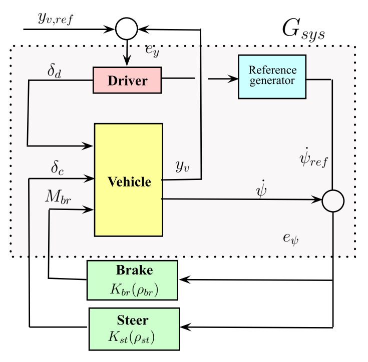
Degradation in a brake circuit:

In right bends the fault of the rear right-hand-side brake circuit increases the lateral error. A deterioration of braking induces an increase in front wheel steering.



Driver In-the-Loop Control System

The control solutions create a **balance between driving (or road holding) and comfort**. This balance often leads to a compromise between vehicle functions, which may not be suitable for all the drivers.



⇒ The integrated control is combined with a driver model in order that the driver behaviors and requirements are incorporated in the design of the control system.

⇒ Consequently, in the driver assistance system the interaction between the vehicle and driver is taken into consideration.

Driver In-the-Loop Control System

A **hardware-in-the-loop (HIL) simulation environment** is built in such a way that the simulator tends to the real vehicle functions as much as possible and the driver model can be analyzed.

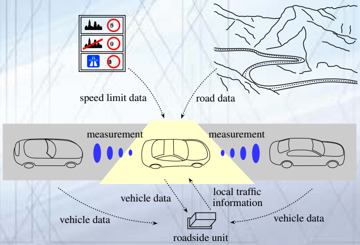
The simulation environment contains several components such as a HMI (Human Machine Interface), a high-accuracy validated simulation software operated on a PC and a visual system with real-time graphics.

The proposed integrated control system is able to assist the driver in his operation and reduce both the lateral error and the yaw rate error significantly.

Control to Improve Economy

The **speed of vehicles** must be designed in such a way that control energy and fuel consumption are minimized while the following factors are taken into consideration:

- travelling time ($|v_{ref} - \dot{\xi}| \rightarrow min$)
- topographic data ($|F_l(\alpha)| \rightarrow min$) and speed limits ($\dot{\xi} \leqq v_{lim}$)
- emission ($|e^p| \rightarrow min$)
- local traffic information, i.e., preceding vehicle ($\dot{\xi} \leqq v_{pre}$) and following vehicles ($\dot{\xi} \geqq v_{foll}$)

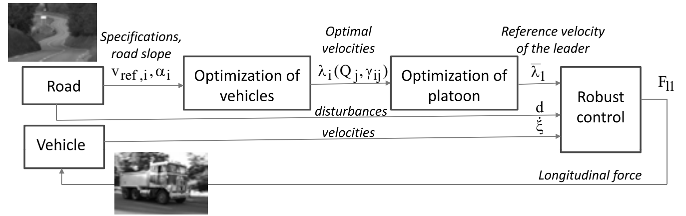


The energy-efficient predicted cruise control strategy is based on a **multi-objective optimization criterion**.

Design of Platoon Velocity

In the platoon, the **velocity of the leader vehicle** determines the velocity of all the vehicles. The goal is to determine the velocity at which the velocities of the members are as close as possible to their own optimal velocity:

$$\sum_{j=1}^{m} |\bar{\lambda}_1 - \dot{\xi}_j|^2 \rightarrow Min.$$



THANK YOU FOR YOUR ATTENTION.

Péter Gáspár

Associate head of SCL, MTA SZTAKI

Contact

Email: gaspar.peter@sztaki.mta.hu

Tel: +361 2796171

Web: www.sztaki.hu

COOPERATION BETWEEN HIGHER EDUCATION, RESEARCH INSTITUTES AND AUTOMOTIVE INDUSTRY

TÁMOP-4.1.1.C-12/1/KONV-2012-0002

BASIC RESEARCH FOR THE DEVELOPMENT OF HYBRID AND ELECTRIC VEHICLES

TÁMOP-4.2.2.A-11/1/KONV-2012-0012

"SMARTER TRANSPORT" - IT FOR CO-OPERATIVE TRANSPORT SYSTEM

TÁMOP-4.2.2.C-11/1/KONV-2012-0012

Nemzeti Fejlesztési Ügynökség
www.ujszechenyiterv.gov.hu
06 40 638 638

HUNGARY'S RENEWAL

The projects are supported by the European Union and co-financed by the European Social Fund.

Hungarian Academy of Science
Budapest, 31 January 2014