

Control Theory of Autonomous Vehicles

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Control of Ground Vehicles

Research Focus

• Vehicle dynamics and drivetrain. Variable geometry suspensions systems and their related control problems, rollover prevention and detection of heavy-duty vehicles.

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- Cooperative transportation systems. One of the main focus of vehicle and transportation applications is related to cooperative, intelligent transportation systems (C-ITS). Theory of cooperative systems, distributed vehicle coordination, integrated design methods, moder network communication methods, fault tolerance in connection with on-board control systems.
- *Hybrid and electric vehicles*. Research of distributed and decentralized vehicle control architectures for hybrid and fully electric vehicles. Sensor fusion and communication based robust, integrated vehicle control systems enabling special needs of electromobility applications.
- ADAS systems. Driver assistance systems, using vision based sensors for road signals, road surface and environment sensing, as a part of Robert Bosch Knowledge Center. Visual environment perception and obstacle detection methods. Methods for monitoring driver awareness.
- Control problems of semi- and fully autonomous vehicles. Specification and analysis of autonomous control systems. Automated assembly of formations and control of platoons with respect to stability and performance guarantees. Handling modelling uncertainty and the network topology and constraints in inter-vehicular control networks. A demonstartion for platooning of heavy duty vehicles for economical reasons have been developed, respecting the manufacturer (Knorr Bremse Fékrendszerek Kft.) specifications and the operators expertise.
- Modelling and control of road transportation networks. Highway modelling, urban city traffic modelling and control, data sharing and control over cloud (Bosch), traffic optimized intelligent cruise control system (Knorr Bremse).

SENSORS of the AUTONOM VEHICLE



Observability Analysis

Observability: determination of the system state from future Input – Output observations.

The state equations in general are nolinear (input affine):

 $\dot{x} = f_0(x) + \sum_{i=1}^m f_i(x)u_i$ $\dot{y} = h(x)$

The observability distribution is composed from the Lie – derivatives $dL_{f_{i_1},\ldots,f_{i_k}}^kh$ Lie - rank observability condition can be derived (Kalman, Isidori): the dimension of observability co – distribution is equal to the state dimension.

Kálmán-filtering



For linear systems the state estimates has the "smallest" covariance among all linear estimation.







Kálmán Rudolf Emil Published in 1960

A New Approach to Linear Filtering and Prediction Problems¹

 R.E. KALMAN Reaches a starting of the second of production productin production production production production production produ

Transactions of the ASME-Journal of Basic Engineering, 82 (Series D): 35-45. Copyright © 1960 by ASME



- Extended Kalman Filter (EKF)
- Robust Kalman Filter (RKF)
- Unscended Kalman Filter (UKF)

Autonomous vehicle motion estimation with KF

- Measured Signals: longitudinal and lateral speeds with GPS and IMU (acceleration sensor) devices
- Speed esitmates:

$$\hat{x}(k) = F(k)\hat{x}(k-1) + B_2 u(k) P(k) = F(k)P(k-1)F^T(k) + Q(k)$$

u(k) is the speed provided by the IMU (available with high frequency).

• the higher precision GPS measurements z(k) will correct the speed estimates

$$x_{up}(k) = x(k) + K(k)(z(k) - Hx(k))$$
$$P_{up}(k) = P(k)(I - K(k)H)$$

• Further calculations are based on the new speed signals.



All-wheel steering: a control example for a vehicle's lateral dynamics and tracking



 β side slip angle

Ψ́ yaw rate

State equation of a simplified single track bycicle model:

$$mv(\dot{\beta} + \dot{\Psi}) = F_1 + F_2 + F_w$$
$$J\ddot{\Psi} = F_1 l_1 - F_2 l_2 + F_w l_w + M_1 + M_2$$

The control criterion:

$$J(x_0, u) = \int_0^\infty (e^T Q e + u^T R u) dt$$

where

$$e = x - x_v = \begin{bmatrix} \beta - \beta_v \\ \dot{\Psi} - \dot{\Psi}_v \end{bmatrix}$$

is the error between the real and virtual state.

Lane Departure Detection and Tracking - 1996



- Eliminate driver's shortcomings which leads to the unintented abandonment of the current track.
- Requirements for video system and tasks to be solved:
- Detect the lane even if they are not clearly indicated.
- Determine the position of the vehicle within the detected lane.
- Predict the movement of the vehicle taking into account the boundaries of the lane (using other sensors) and calculate the time to intersection of these boundaries and the predicted trajectory.
- Actuation: by unilateral operation of the brakes.

Longitudinal Dynamics - Speed profile control

- The control systems of the vehicle are also integrated into the environment. The control design leads to a multi-objective task, in which several factors are taken into consideration:
 - Global factors (traveling time, energy requirement, fuel consumption, terrain characteristics, traffic conditions)
 - Local factors (road stability, traffic regulations, motions of the preceding/follower vehicles, congestions, road maintenances)





The purpose of the method is to design the speed of the vehicle, which reduces control energy and fuel consumption, keeps speed limits and traveling time.

Integrated vehicle control



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The purpose of the integrated vehicle control is to create a balance among active control components to guarantee the operation conditions and improve reliability.

Control design principles:

- Guarantee state-dependent priorities and a hierarchy among the actuators.
- Reconfiguration: adaptation to the change in the different inner/outer conditions.
- Fault Tolerance: adaptation to faulty operations or performance degradations.



Design of integrated vehicle control

State-dependent weighting functions are designed and applied to create a balance between control systems, handle priorities and integrate performance specifications.





Vret

Control design of steering system

Analysis of the actuator selection

 The aim of the analysis is to identify the similarities and differences between the different actuator interventions. A nonlinear polynomial Sum-of-Squares (SOS) programming method is applied to calculate the shape of the Controlled Invariant Sets of actuators.

Tyre characteristics - Polynomial approximation 4000 Linear approximation Lateral tyre force (N) 2000 -2000 -4000 -6000 └─ -15 -10 10 15 -5 5 0 α (deg)

The ellipsoidal cylinders show the outer approximation of the reachable sets in the functions of the state variables, the velocity and the adhesion coefficient. The shape and the size of the ellipsoidal cylinders of the steering and the brake systems differ.



 $\mu = 0.9 \qquad \qquad \mu = 0$

 $\mu = 0.4$

Reconfiguration strategy: depending on the adhesion factor, by choosing a suitable steering or braking function, we can increase the vehicle's stability range while maneuvering.

Reconfiguring control strategies



During the operation of the vehicle it is a frequent problem that one of the performances must be guaranteed even at the cost of the degradation of the other performances.

Example: A fault in the suspension system requires a reconfiguration to the active anti-roll bar.

• Initially the active actuator is λ_1 , in which a reachable set approximation is the R_1 ellipsoid. x_{ref} can not be reached by λ_1 , because it is out of its reachable set. However, x_{ref} can be reached by actuator λ_2 , where the reachable set approximation is the R_2 ellipsoid. Thus it is necessary to reconfigure the actuator of the system.



Environment Detection using LIDAR laser scanners



• Data acquisition

Velodyne HDL 64E

Test vehicle

Street House wall and columns Street objects

Parking vehicles

Moving vehicles and pedestrians



Safety and Economic Platform for Partially Automated Commercial Vehicles

Aim: to define and implement a set of automated control functions for commercial vehicles in order to reduce the fuel consumption and the emission of air pollutants, as well as to improve road safety and driver comfort







Autonomous vehicle control experiment

Aim: to add autonomous features to a production electric car by fitting it up with sensors (RGB cameras, LIDARs, communication units, etc.) and implementing autonomous functions on the control computer.

Applications of Aerospace Research Focus



- Adaptive, electro mechanical actuators and intelligent sensors. Smart actuators with embedded computing units are becoming standard in aerospace, but the built-in processing power allows for implementing model based control and monitoring functions, especially on Electro-Mechanical-Actuators, which are built and developed by the lab. The other end of control systems are the sensors which are also becoming smart – the lab is working on developing IMUs, advanced GNSS units and their intelligent fusion which allows sensor monitoring and fault detection (UTC Aerospace, Dassault, RICOH, Airbus cooperation).
- Fault tolerant control systems. Research on active fault tolerant systems helps increasing the safety of commercial aircraft. We are
 working on methods, which are able to provide flight envelope protection and the same flight performance in case of actuator and sensor
 faults what the pilot expects from a healthy aircraft.
- Unmanned Aerial Vehicles (UAV). Safe insertion of UAVs into the national airspace is a key question, we are working on optimizing the design of redundant aircraft avionics and flight dynamics to be applicable for fault tolerant control. Camera based collision avoidance modules allow the flight control system to react for threats in time and perform avoidance. Payload driven trajectory generation methods allow for optimizing the mission even for uncertainties, like windgust in surveying. (UofM, ONR).
- Aero-servo-elastic interaction and active aeroelastic control Active flutter suppression promises the advantage, that aircraft wings can be designed to be less stiff, saving significant structural weight. Basded on the very high dimensional flexible mathematical models of aircraft active control methods and the overall active mode supression system for commercial aircraft is being set up. While the underlying questions of sensor placement, model order reduction, model abstraction level and multi-disciplinary optimisation are providing rich playground for theoretical problems in basic reserach. (Airbus, FACC)

VISION Aided Landing in case of GPS/ILS error







Sense and Avoid (SAA) System

- SAA capability required for future UAS insertion into the common airspace
- Demonstrate the feasibility of a low-cost vision only SAA system
- Multi-processor, ultra low consumption onboard architecture based on FPGA
- Coupled estimation and guidance problem to improve fidelity
- Funded by the US Office of Naval Research





Examples: Books

J. Bokor, P. Gáspár, Z. Szabó, *Robust Control Theory with Automotive Applications*, Typotex, 2013.

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P. Gáspár, Z. Szabó, J. Bokor, *Járműdinamika és irányítás*, Széchenyi University Press, 2014.

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A. Edelmayer, Fault detection in dynamic systems: from state estimation to direct input reconstruction. Széchenyi University Press, 2013.



Thank You for Your Attention!