Workshop

Model based calibration methodologies

Begrüßung, Einleitung

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General aspects

The new *Christian Doppler Laboratory* pursues the development of new and integrated methodologies for model based calibration of automotive systems: *Combustion engines, Powertrain systems, Hybrid components*

![Diagram of different input parameters and conflicting goals](image)

- **VVT-Timing**
  - Intake
  - Exhaust
- **Injection timing**
- **Spark advance**
- **A/F ratio**
- **EGR**
- **VTG**
- **Driver**
- **Environment**
- **load**
- **speed**
- **Conflicting goals**
  - Fuel Efficiency
  - Driveability
  - Performance
  - Emissions
Institute of Mechanics and Mechatronics
Faculty for Mechanical Engineering and Business Science

Five departments

Vehicle dynamics and biomechanics (multibody simulation in vehicle dynamics)
Applied mechanics (nonlinear stability theory)
Machine dynamics
Measurement and actuator technology
Control and process automation

Dept. of Control and Process Automation: 3 research areas

Active vibration damping, Process control, Automotive control

Methodology

Nonlinear system identification
State observation/Kalman Filters
Linear/nonlinear predictive control
$H_2$- and $H_\infty$-control (robust control)
Track geometry estimation with regular vehicles

Goals:
- Estimation of track geometry by measurements on the train
- Linear and nonlinear model identification
- Process and measurement noise estimation
- Nonlinear Kalman filter with constraints
- Sensor placement
- Virtual test bed (Multi-Body System)
- Valuation of safety limits
- Evaluation of track-vehicle interactions
MEMBAT
Modelling, Emulation and Management
of high complexity traction batteries

Goals:

- Precise and highly dynamic emulation of energy storage systems by battery simulators for hybrid powertrain testbeds
- Innovative concepts to control the output voltage despite the influence of uncertain loads
- Impedance emulation of real battery or supercap systems
- Complex battery models suitable for real-time simulation
BioNetControl
Predictive Control and optimization
of district heating networks with biomass power plants

Goals
- Modelling of relevant system components
- Higher-level optimal control of the total system
- Lower-level optimal control of the plant
- Modular design and structured configuration
- Robust MPC with respect to model mismatch

Diagram: A network showing the integration of grid, steam turbine, gas power plant, biomass power plants I and II, consumer nodes, and the district heating network.
# Team des CD-Labors

## TU-Wien, Inst. E325
- Laborleiter: Prof. Stefan Jakubek
- PostDoc: Dr. Christoph Hametner
- PhD 1: DI Christian Mayr
- PhD 2: DI Markus Stadlbauer

## AVL-List GmbH
- DI Horst Pflügl: Entwicklungsleiter *Powertrain Calibration Technologies*
- Dr.-Ing. Thomas Winsel: Research Manager *Powertrain Calibration Technologies*
- Dr.-Ing. Timo Combe: Fachteamleiter *Methodology, Development and Calibration*
- Dr. Mario Schweiger: Application manager *Hybrid testing systems and battery management systems*
- DI Manuel Nebel: Calibration of Diesel engines for series production of passenger cars

## Extern
- Prof. Stefan Volkwein (Univ. Konstanz): Hull Algorithms
- Team of Prof. Steindl (TUW): Stability Analysis
General aspects

The proposed CDL pursues two main targets which are organised in research topics:

### Research Topics of the CDL:

- **Research Topic A**: The basic development of methodologies for an integrated model based calibration workflow.
- **Research Topic B**: The systematic employment and enhancement of these methodologies to essential calibration tasks.
Research Topic A

Main Focus: Development of new methodologies and the related basic research for all steps in model based calibration. There are three research tasks:

- A1: Experiment design
- A2: Nonlinear system identification
- A3: Controller stability analysis and design
Research Topic B

Main Focus: Integration of Topic A results into application workflows for essential calibration tasks:

- **B1**: Battery Management System Calibration
- **B2**: Gasoline & Diesel engine calibration workflow
- **B3**: Cold start calibration
Interconnection of research topics A & B

Research Topic A
- Research Task A1: Experiment design
- Research Task A2: Nonlinear system identification
- Research Task A3: Controller stability analysis & design

Research Topic B
- Research Task B1: Battery Management System Calibration
- Research Task B2: Gasoline & Diesel engine calibration workflow
- Research Task B3: Cold start calibration
Research Task A1:
Experiment design

State of the art: Experiment design for static models
- Analytic representation of the area of operation (direct & indirect methods)
- Mixture criterion for candidate selection (A,S,D-optimality)
Research Task A1:
Experiment design

Research programme: Experiment design for dynamic models

- Determination of the dynamic area of operation (test based, model based)
- Analytic representation of the dynamic area of operation (local driveable areas)
- Creation of a dynamic experiment design (time space, distribution)
Model Based DoE

Optimal Design of Experiments based on a process model

**Motivation**
- DoE subsequent to component changes
- DoE for changed environmental conditions
- Use a model of a comparable process (e.g. a similar engine)
- Use a model from online training to optimize future process inputs (online DoE)
- Adherence to process constraints (inputs & outputs)
Model Based DoE
Optimality Criteria

The Fisher Information Matrix $\mathcal{I}$ is used as a measure:

$$
\mathcal{I}(\bar{\psi}) = \frac{1}{(k - n_{\text{max}})} \frac{1}{\sigma^2} \bar{\psi}^T \bar{\psi}
$$

Example for model structure: Dynamic multilayer perceptron network:
Research Task A2:
Nonlinear System Identification

State of the art: Nonlinear dynamic system identification
- Neural networks (black box), physical models (white box)
- Grey-Box: Incorporation of qualitative physical knowledge
- Advanced parameter estimation methods (GTLS)
Research Task A2: Nonlinear System Identification

Research programme: Nonlinear dynamic system identification

- Workflow of system identification for non experts
- User-defined performance criteria (relative error, data transformation)
- Operating regime based models (user-defined pre-partitioning)
- Constraints (= incorporation of quantitative knowledge)
- Model adaptation and extension (new operational conditions)

Inputs
- $N$, $Q_{\text{Main}}$
- $r_{\text{EGR}}$, $r_{\text{VNT}}$
- $P_{\text{Rail}}$, $\phi_{\text{MI}}$

Outputs
- $\text{NO}_x$, Soot, HC
- $m_{\text{fuel}}$, $m_{\text{Air}}$
- $p_2$, $p_3$, $T_2$, $T_3$
- $M_{\text{d}}$, $n_{\text{Turbo}}$

![Diagram of system identification process](image)
Operating Regime Model

Modelling strategy

**Local nonlinear models**
Embedded in the operating regime model

**User-defined pre-partitioning**
Split into segments representing the main physical effects (using load and speed)
Operating Regime Model
Training of the local nonlinear models

- One local nonlinear model in each operating regime
- Mean squared error (MSE) at the training data for each local model (exemplarily for $P_{max}$)
- Stem plot illustrates locally different complexity:
  - Highly nonlinear behaviour of the engine
  - MSE varies in a wide range which reflects locally different noise levels and input sensitivities
Research Task A3: Controller Stability Analysis and Design

State of the art:
- Gain scheduled PID control
- Gain scheduled observation/estimation (e.g. SoC)
- Manual tuning with simulation models

![Diagram showing linearised model and controller design for operating point dependent systems.](image)
Research Task A3: Controller Stability Analysis and Design

Research programme: Controller stability analysis and design

- Open loop stability analysis of dynamic model networks: Lyapunov stability theory
- Closed loop stability conditions (local controller network)
- Support for design of controllers/estimators
- Effect of model parameter uncertainties on controller design (robustness)
Global Stability
Motivational Example

Stable and unstable combinations of two stable local models

- Two stable State-Space models:
  \[ x(k + 1) = A_i x(k) \quad i = 1, 2 \]

- Global stability of the LMN depends on the partitioning!

Partitioning along \( x_1 \) direction:

\[ \begin{array}{c}
-2 & -1.5 & -1 & -0.5 & 0 & 0.5 & 1 \\
-2 & -1.5 & -1 & -0.5 & 0 & 0.5 & 1
\end{array} \]

Partitioning along \( x_2 \) direction:

\[ \begin{array}{c}
-15 & -10 & -5 & 0 & 5 & 10 \\
-15 & -10 & -5 & 0 & 5 & 10
\end{array} \]
Direct Lyapunov Methods
Three different approaches

Common Quadratic Lyapunov Function

Piecewise Quadratic Lyapunov Function

Fuzzy Lyapunov Function
Physical Engine Models

Reduction by Galerkin Projection

State of the art and challenges:
- Various physical engine models are available
- High complexity often prevents analytic insight
- Model based controller design requires reduced order models
- Realtime execution can be achieved with surrogate models

Research Programme:
- Flat Galerkin projection methods
- Sub-Manifold is obtained from snapshot approach
- Nonlinear Galerkin methods
- Applicable to both ODEs and PDEs
Research projects within Topic B

Research task B1: Battery Management System Calibration

- Model architecture for battery/cell models
- Experiment design for battery test system
- Related SoC estimation techniques
- Battery models used in battery simulator or hybrid vehicle simulation

Main Challenges

- Hysteresis
- Cell ageing
- Proper DoE
- Observer Robustness
Research projects within Topic B

Research task B2: Gasoline & Diesel engine calibration workflow

- Integrated workflow: DoE, identification, optimisation/calibration
- Dynamic models for torque, fuel consumption, $NO_x$, $HC$, $CO$, boost pressure, air mass flow
- Split of the overall system behaviour into static and dynamic submodels
- Integration of physical submodels

Inputs:
- $N$, $Q_{\text{Main}}$
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- $P_{\text{Rail}}$
- $\phi_{\text{MI}}$

Outputs:
- $NO_x$, Soot, HC
- $m_{\text{fuel}}$, $m_{\text{Air}}$
- $p_2$, $p_3$, $T_2$, $T_3$
- $Md$, $n_{\text{Turbo}}$
Research projects within Topic B

Research task B3: Cold start calibration

Iterative procedure comprising

- Cold start experiment: A single experiment with a fixed parameter setting
- Model adaptation: Adjustments of the process model based on experiment data
- ECU parameter adjustments: Optimisation of engine start reliability, engine speed overshoot, \( HC \) emissions and catalyst temperature
Summary

Christian Doppler Labor TU-Wien & AVL-List GmbH: 
*Model based calibration methodologies*

### Research Topic A: Basic research

- Experiment design
- Nonlinear system identification
- Controller analysis and design

### Research Topic B: Application oriented research

- Battery Management System Calibration
- Controller calibration workflow
- Cold start and warm up