MULTIVARIABLE CONTROL OF DUAL LOOP EGR DIESEL ENGINE WITH A VARIABLE GEOMETRY TURBO

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Overview

• Introduction
• Control Problem Specification
• Control Design and Implementation
• Experimental Results
• Robustness Analysis
• Summary
Developed within ATLAS Program

- Department of Energy sponsored program for light duty engine application

- Goals: Fuel economy improvement with simultaneous demonstration of Tier 2 Bin 2 emissions

- Dual Loop EGR selection for the air handling architecture created the need for an innovative transient controller
Modified Cummins 2.8L Engine

- Added 2000 bar Bosch piezo fuel system
- Swapped turbocharger to variable geometry turbo
- Added low pressure, cooled EGR circuit to existing high pressure EGR circuit
- Added aftertreatment system with DOC, ammonia doser, SCR catalyst on particulate filter (SCRF®), and underfloor SCR catalyst
Control Problem Specification - Air Handling Configuration

Control of Four Actuators
- HP EGR Valve
- LP EGR Valve
- Exhaust Throttle
- VGT
Model-Based Control Design with Honeywell OnRAMP Software to:

- Handle complex multivariable interactions
- Account for actuator and engine state constraints
- Develop a systematic and scalable approach
- Reduce development time
Model Identification Procedure

- **Component Level Identification**
  - Identification of individual components

- **System Level Identification (Steady-State)**
  - Identification of all components assembled together
  - Improve model accuracy

- **System Level Identification (Transient)**
  - Identification of dynamic part of model

Constrained Nonlinear Least-Squares Problem

\[
\frac{dx_t}{dt} = f(x_t, u_t, p)
\]

\[
y_t = g(x_t, u_t, p)
\]

\[
\min_p \sum_k ||y_k - g(x_k, u_k, p)||
\]

s.t. \( \forall f(x_k, u_k, p) = 0 \)
Controller Configuration

Controller Structure

- Feedforward action for fast response during heavy transients (map based model inversion)
- Feedback action for disturbance rejection, offset-free steady-state tracking and constraints handling
Model Predictive Control (MPC) for Feedback Control

- 36 scheduled local linear MPC controllers (regular grid)
  - Engine speed (800 to 2600 rpm)
  - Fuel injection quantity (0 to 60mg/stroke)

\[
J(u, x(t)) = \sum_{k=0}^{N} \|y(t+k|t) - y_{sp}(t)\|^2_Q + \sum_{k=1}^{N_c} \|\Delta u(t+k|k)\|^2_R
\]

subject to

\[
y = G(x, u)
\]

\[
u_{min} \leq u(t+k) \leq u_{max}
\]

- Prediction horizon: \(f(\text{settling time of linearized models})\)
- Robustness: small gain theorem for a given level of model uncertainty
- Performance: weights for each actuator/controlled variable
- ECU suitable MPC solver: explicit solution
Test Cell Hardware and Setup

- Developed controller embedded in a dSpace® MicroAutoBox® 1401
- MicroAutoBox communicates with ECM of engine via CAN line
- Sampling period for controller: 0.1 seconds
Steady-State Testing of MPC

- Engine speed set to 1800 rpm and total injection quantity to 52.5 mg/stroke
- Step-changed setpoint of charge pressure and total EGR mass flow
- Result: Coordinated control of all actuators
Transient Testing of MPC

- EPA Urban Dynamometer Driving Schedule (UDDS) used

Three Flavors of Same Controller with different Tuning Weights

- Aggressive charge pressure tracking
- Balanced tuning
- Aggressive EGR mass flow tracking
MPC Transient Testing

Experimental Results

Aggressive charge pressure tracking

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<tr>
<th>Time [sec]</th>
<th>Charge pressure [kPa]</th>
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<tr>
<td>260</td>
<td>100</td>
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<tr>
<td>280</td>
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<th>Time [sec]</th>
<th>Total EGR mass flow [Kg/min]</th>
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Measured vs. Setpoint

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Monte-Carlo Simulation

- Six parameters randomly varied to simulate plant uncertainties:
  - VGT, HP and LP EGR valves, and ET command offsets
  - Effective flow area of DPF
  - Charge air cooler effectiveness

- Nonlinear model was used as the plant

- Aggressive EGR mass flow tracking controller tuning

- 2000 LA-4 cycle simulations
Monte-Carlo Simulation

- MPC successfully reduced variability of the tracking error.

- Root-mean square errors (RMSE) of total EGR mass and charge pressure was reduced by 73.7% and 66.7%, respectively.

- MPC had better tracking capability as compared to the Open-Loop Control.
Key Points

- Proposed a systematic approach for Model-Based Control of Dual Loop EGR air-handling architectures

- Control performance and robustness of different control configurations evaluated through experimental validation and simulations

- Total of ten days to go from data collection for model identification to controller implementation and transient testing

- Honeywell OnRAMP Model-Based Control Design provides a scalable and fast process to assess capability of different engine architectures

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