Master's Thesis

Economic MPC for Transient Diesel Engine Applications

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Abstract

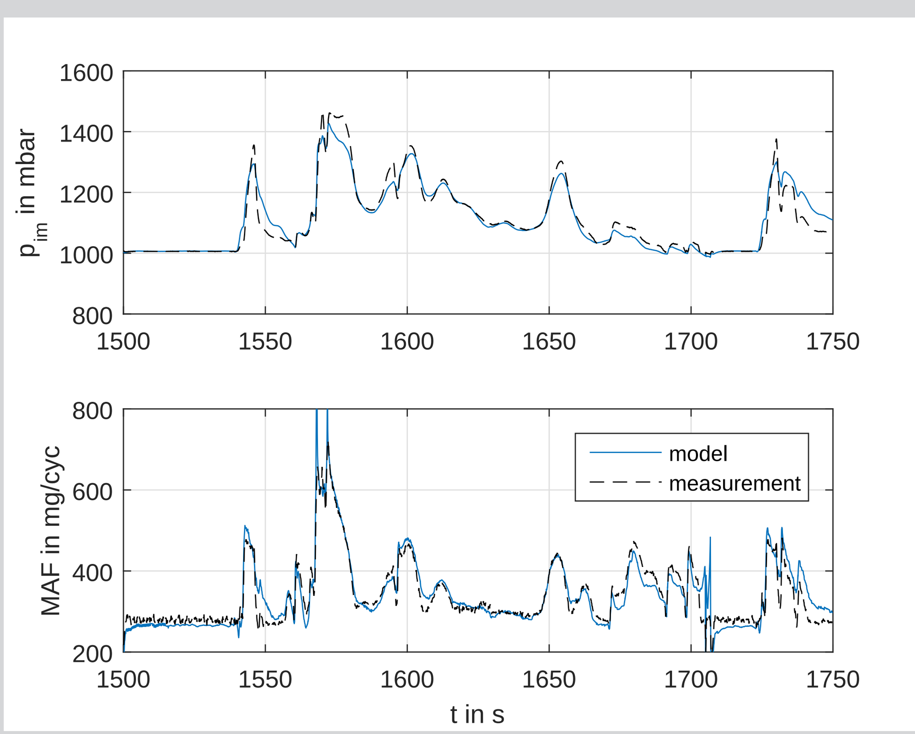
In times of more and more stringent emission regulations and heightened public awareness of the negative impact of pollutants, car manufacturers have an incentive to find improved control strategies to reduce the emissions generated by the combustion process.
The industrial standard approach attempts to capture the behaviour of internal combustion engines for a multitude of operating conditions in steady state realizing a feedforward control that is augmented by separate feedback loops. This approach disregards both the dynamic behaviour and the coupled nature of a turbocharged Diesel engine with EGR.
The focus of this thesis is the development of an economic model predictive control based on a nonlinear model of the engine that considers the system dynamics as well as the cross-influence of the MIMO structure.
In order to solve the optimal control problem on which the model predictive control is based, a control oriented model, i.e. a simplified system description comprising the major influences on the airpath and combustion, is derived. Measurements from the test bench in steady state and during transients are used to identify the model parameters and validate the resulting model.
Based on this model, an economic model predictive control is formulated that attempts to minimize the economic objective, i.e. a cost consisting of fuel consumption and amount of emissions, by predicting the future system trajectories and control actions necessary to achieve this goal, while complying with the constraints imposed by the model dynamics and limited actuator actions.
The performance of the economic model predictive control was then compared with the strategy applied by the engine control unit for the Federal Test Procedure on a provided simulation environment. A reduction of over 30% in the nitrogen oxide emissions during transient manoeuvres was achieved, while hardly increasing the fuel consumption.

Control Oriented Model

An internal combustion engine can be divided into two main subsystems. On the one hand, the airpath system has the task of providing the air or air-exhaust gas mixture necessary for the combustion process. On the other hand the energy for this exothermic reaction is delivered by the fuel system, which injects the diesel fuel necessary to meet the torque demand. A mean value model, i.e. a continuous representation of the reciprocating process is derived by combining first principles and databased submodels.
An analysis of the main influences and dynamics resulted in the formulation of a 5th-order ODE, where the dynamics solely originate from the airpath system as the combustion process is much faster in comparison. The model has a MIMO structure with the inputs $u = [q_f, x_{EGR}, x_{VGT}]^T$, measured disturbances $d = [N_{eng}, x_{SWIRL}]^T$, outputs $y = [T_{eng}, NO_x, \lambda]^T$ and states $x = [p_{im}, p_{em}, T_{em}, N_{tc}, x_{O2,im}]^T$:

$$
\begin{aligned}
\dot{p}_{im} &= \frac{T_{im} R_{im}}{V_{im}} \cdot (W_{ci} + W_{xi} - W_{ie}) \\
\dot{p}_{em} &= \frac{\kappa_{em} R_{em}}{V_{em}} \cdot [(W_{ie} + q_f) \cdot T_{exh} - (W_{xi} + W_{xt}) \cdot T_{em}] \\
\dot{T}_{em} &= \frac{T_{em} R_{em}}{p_{em} V_{em} c_{v,em}} \cdot [\, c_{p,em} \cdot (W_{ie} + q_f) \cdot T_{exh} - c_{p,em} \cdot (W_{xi} + W_{xt}) \cdot T_{em} \\
&\quad - c_{v,em} \cdot (W_{ie} + q_f - W_{xi} - W_{xt}) \cdot T_{em} \,] \\
\dot{N}_{tc} &= \left(\frac{30}{\pi}\right)^2 \frac{1}{J_{tc} N_{tc}} (P_t - P_c - P_{fric}) \\
\dot{x}_{O2,im} &= \frac{T_{im} R_{im}}{p_{im} V_{im}} \cdot [(x_{O2,amb} - x_{O2,im}) W_{ci} + (x_{O2,exh} - x_{O2,im}) W_{xi}]
\end{aligned}
\tag{1}
$$

While the dynamics can be described by physical relations, the physics behind processes like the NO_x generation or the mass flow through the compressor are much more complex and are thus described by black-box models. The resulting nonlinear model has then been further improved by using the model parameters θ as decision variables in an optimization. The objective was to minimize the quadratic error of both the manifold absolute pressure and mass air flow, which are typically used to characterize the state of an engine airpath.



Optimal Control

The constrained minimization problem states the mathematical problem the EMPC is supposed to find an approximate solution for. The controllers goal is to minimize the economic cost over a finite horizon T, while complying to the constraints originating from the system and the requirement. The weighting c_{qf} makes it possible to shift the optimization between a more fuel saving or NO_x reducing strategy. Besides minimizing the economic cost, the controlled system has to deliver the demanded torque and ensure that the air-fuel ratio does never drop beneath a critical level. Applying a direct optimization, the multiple shooting method leads to the discretization of both the inputs and states of the underlying model along the horizon. This results in a nonlinear program with $(n_u + n_x) \times N$ decision variables $w = [s_0, q_0, s_1, q_1, \ldots, s_{N-1}, q_{N-1}, s_N]$, where q_k is the piecewise constant input on the interval $[t_k, t_{k+1}]$ and s_k the artificial starting point of the ODE at each discretization point along the grid.

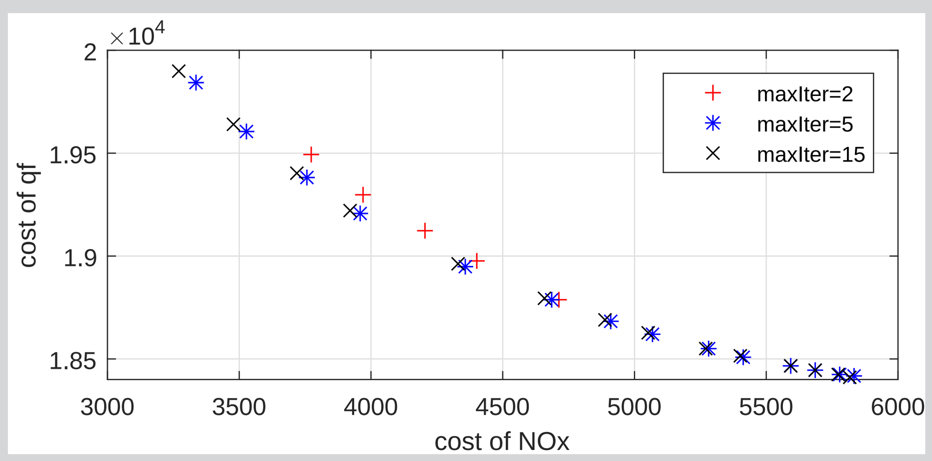
$$
\begin{aligned}
&\min_u \int_0^T (c_{qf} \cdot q_f + NO_x)\, dt \\
&\text{s.t.} \\
&x(0) = x_0 \\
&\dot{x} = f(x, u, d, \theta) \\
&T_{eng} = T_{dem} \\
&\lambda_{lb} \le \lambda \\
&lbu \le u \le ubu
\end{aligned}
$$

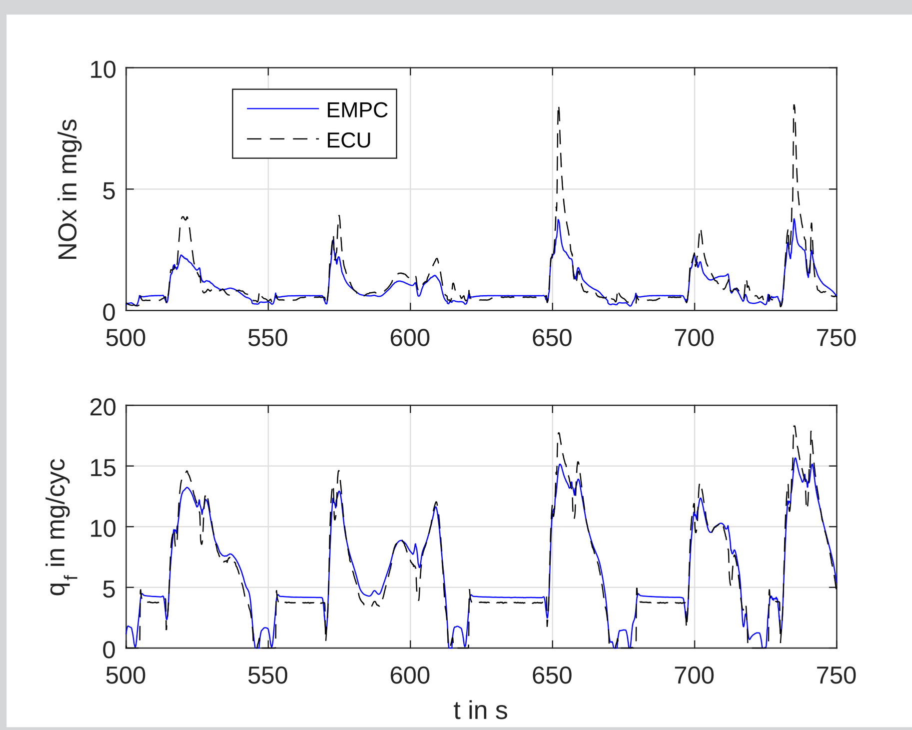
$$
\begin{aligned}
&\min_w \; F(w) \\
&\text{s.t.} \\
&lbw \le w \le ubw \\
&lbg \le G(w) \le ubg
\end{aligned}
$$

While multiple shooting ends with a higher number of optimization variables than single shooting, the special structure of the objective function F leads to sparse Hessian $\nabla^2 F$. The applied interior point solver IPOPT can exploit this structure to improve the optimization. Additionally to the constraints imposed by the original optimal control problem, continuity, path and terminal constraints have to be added to the function G to improve convergence of the EMPC algorithm. The control algorithm has been implemented with the symbolic framework provided by CasADi, which also computes the necessary gradients, Jacobians and Hessians and has an interface to multiple optimization solvers like e.g. IPOPT.

Results

An evaluation of the control for multiple weightings c_{qf} shows the expected trade-off behaviour between the generated NO_x-emission and the fuel consumption. However, the pareto curve can be shifted towards lower levels of economic costs by different measures, like e.g. longer horizons or enabling a look-ahead. Due to a warm start of the NLP by providing good initial points for the primal as well as the dual variables, a fast convergence to a local optimum has been achieved.





The expectation that the industrial control approach lacks performance during transient operations has been confirmed, as the EMPC were able to significantly reduce emissions and also fuel consumption during fast transients. The EMPC has predicted the emission peaks caused by the rapidly changing system state and reacted accordingly to reduce the overall economic cost. However, the standard approach performed consistently better in steady state operation, which can be explained by the extensive calibration in these conditions.

Conclusion and Outlook

An economic model predictive control based on a reduced order model of a turbocharged Diesel engine with EGR was proposed, aiming to reduce fuel consumption and NO_x-emissions especially during transient manoeuvres. Fuel consumption and NO_x-output have been simulated for the first 1000s of the FTP-cycle using different foci shifting between fuel saving and minimization of the emitted NO_x. The simulation yielded promising results with a reduction of the nitrogen oxide emissions up to 31.87%, while delivering the torque demanded by the driver and complying with the constraints imposed on the control.
A major advantage of the control formulated is its easy extension with additional objectives and constraints. An obvious extension of the problem would be the consideration of particulate matter, as it is the second major pollutant generated by Diesel engines.