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Modular Nonlinear Model Predictive Control for the Airpath of Internal Combustion Engines

Meeting the greenhouse gas emission targets in the coming decades requires a substantial decarbonization of the energy and mobility sector. Synthetic methane is a promising candidate to increase the share of new renewables energy production as it can be used as a long-term storage. Using the synthetic methane in internal combustion engines would allow for a 100% CO2-neutral mobility. Development on methane engines plays a vital role in the establishment of sustainable mobility. Due to the complexity of such engines, its airpath control states a challenge and demands for highly sophisticated algorithms. Within the project REAL, modular airpath control algorithms are developed, which are applicable to engines of variable fuel, size or airpath configuration. First results gathered on Diesel engines of different size and airpath configuration are promising. As a next step, the algorithms will be implemented on a methane engine.

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Introduction

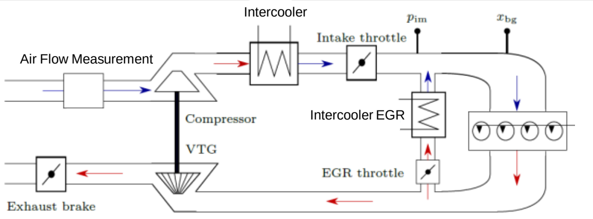

Fig. 1: Generic engine airpath layout for compression ignition engines.

Modern Diesel engines feature a turbocharger and an exhaust gas recirculation (EGR). For highly transient operation, turbines with variable geometry (VTG) are used, which allow for the control of the turbocharger speed and the exhaust manifold pressure. With the addition of a throttle for exhaust gas recirculation, different mixtures of exhaust gas and fresh air can be fed into the cylinders, influencing the combustion process in terms of efficiency and engine-out pollutant emissions. For more stationary applications, for example heavy-duty engines, no VTG turbine are present. However other airpath actuators are present, for example an exhaust brake. The goal of an airpath controller is to track the pressure (p_{im}) and the ratio of recirculated burnt gas (x_{bg}) in the intake manifold. Depending on the system, different actuators can be used to reach the desired target values.

System Analysis

Figure 2 shows the steady-state characteristics of a 2 litre Diesel engine at a fixed speed and fixed fuel mass flow. The engine features an EGR-throttle and a VTG-turbine. Clearly, a strong relation between burnt gas mass ratio x_{bg} and engine-out NO_x-emissions is present. This relation can be explained that with increased x_{bg} the in-cylinder peak temperature and oxygen availability is reduced during combustion. Both quantities are important for NO_x formation. The iso-surfaces of the pressure p_{im} and burnt gas mass ratio x_{bg} of the intake manifold clearly show the cross-coupling between the inputs u_{egr} and u_{vtg}. Therefore, using SISO controllers clearly limits the choice of reachable system configurations. Furthermore, strong non-linearities are present, which could be addressed using gain-scheduled controllers. However, this requires an extensive measurement campaign, which would greatly increase development costs.

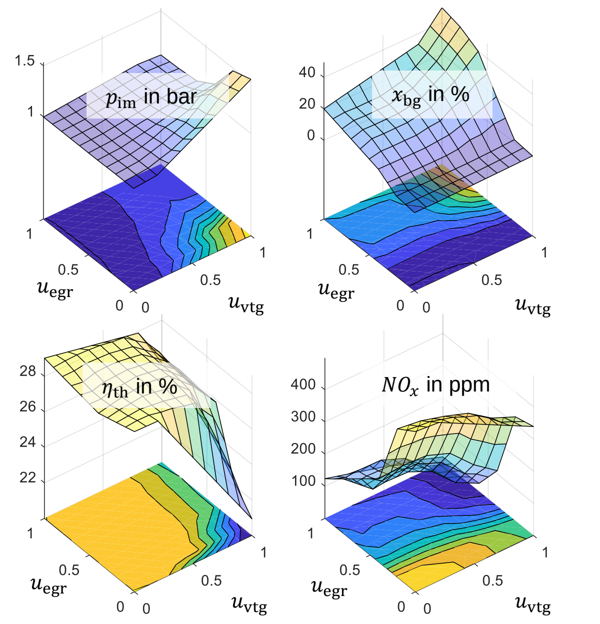

Fig. 2: Steady-state measurements for a 2 litre Diesel engine. The variable η_{th} denotes the thermal efficiency.

Nonlinear Model Predictive Control

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\begin{aligned}
\min_{x(\cdot|k),\,u(\cdot|k)} \quad & J(x(\cdot|k), u(\cdot|k)) \\
\text{s.t.} \quad & x(k+i+1|k) = f_{\mathrm{ROM}}(x(k+i|k), u(k+i|k)) \\
& 0 \le u_{\mathrm{vtg}}(\cdot|k) \le 1 \\
& 0 \le u_{\mathrm{egr}}(\cdot|k) \le 1 \\
& x_0 = x(k|k)
\end{aligned}
$$

Eq. 1: Formulation for the Optimal Control Problem [1].

In model predictive control, a state trajectory $x(\cdot|k)$ of a system is predicted using a reduced order model $f_{\mathrm{ROM}}(x(k), u(k))$ in dependence of its initial state x_0 and input trajectory $u(\cdot|k)$. The control inputs are found by minimizing a cost function $J(x(\cdot|k), u(\cdot|k))$, in this case being the weighted sum of a tracking error and input penalization. Since the engine exhibits large nonlinearities, a nonlinear model predictive control (NMPC) framework is used. NMPC has already been used for various applications. However, for engine control tasks, time scales are more challenging compared to usual applications. Real-time feasibility is key in enabling NMPC for engine control tasks [2]. Improving turnaround time of processors with tailored numerics and innovative algorithms is still a hot topic of research.

Results

Since the airpath layout for different Diesel engines is similar, a modular NMPC controller has been investigated in a student thesis. To use the same problem formulation as described in Eq. 1 for different engines, the plant model f_{ROM} and the selected inputs $\boldsymbol{u}$ have to adapted. The modular NMPC controller has been tested on two different engines. The first engine is a 2 litre passenger car engine featuring an EGR throttle u_{egr} and a VTG turbine u_{vtg}. The second engine is a 7 litre engine for heavy-duty applications featuring EGR throttle u_{egr} and an exhaust brake u_{eb}. The modular NMPC controller shows good tracking behavior for both engines and clearly outperforms a linear control approach.

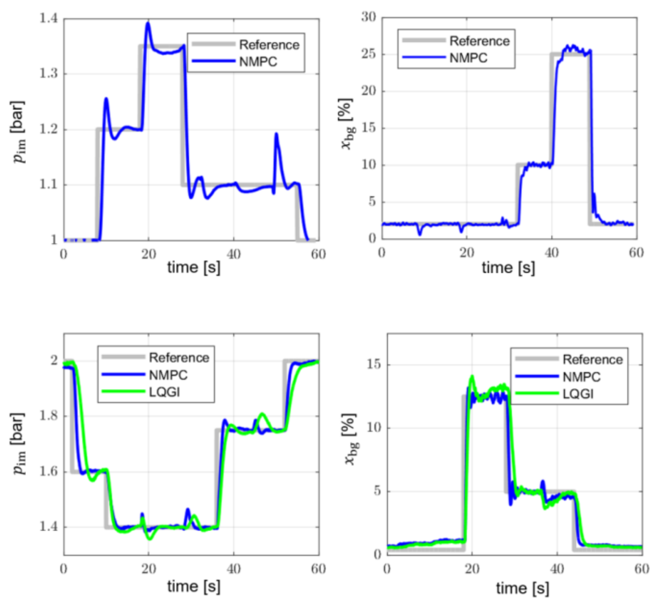

Fig. 3: Performance of the modular NMPC controller. Top figures show the reference tracking for the 2 litre engine, bottom figures the reference tracking for the 7 litre engine.

Expected Impact

The feasibility of the modular NMPC controller shows, that NMPC is a promising technology that helps in improving the calibration effort for ICEs. Furthermore, the NMPC control allows for a precise tracking of intake pressure and burnt gas mass. This is important to further improve engine efficiency as well engine-out pollutant emissions.

References

[1] Model Predictive Engine Control – Lecture Notes ETH Zurich
[2] FOR2401 Antrag – Optimierungsbasierte Multiskalenregelung motrischer Niedertemperatur-Brennverfahren

Partners

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich
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