Realtime MPC for multivariable engine control

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Introduction

This CDIO project was performed during the fall of 2020 in a collaboration between students at Linköping University and Volvo Cars Corporation. The goal was to implement a model predictive controller (MPC) for an internal combustion engine to achieve two different drive modes, one with high fuel efficiency and one with high performance. The controller together with a simulation environment was successfully created in MATLAB and Simulink.

Models

The two actuators to be controlled were the throttle and Variable Valve Time (VVT). Models for these were implemented both in the MPC controller and in the simulation environment.

Throttle and Intake manifold

The throttle model controls the air mass flow into the engine using the throttle angle α_{th}, and is described by the following equation:

$$\dot{m}_{at} = \frac{p_{bef,th}}{\sqrt{RT_{bef,th}}} A_{eff}(\alpha_{th})\Psi(\Pi)$$

Here, A_{eff} represents the effective area for the air flow to pass through, dependent on the throttle angle α_{th}. Ψ is a function that describes the flow velocity through the throttle, and Π represents the pressure ratio, i.e. the pressure after the throttle divided by the pressure before the throttle.

The pressure and temperature in the intake manifold are modeled with the following differential equations:

$$\frac{dp_{im}}{dt} = \frac{RT_{im}}{V_{im}}(\dot{m}_{at} - \dot{m}_{ac})$$

$$\frac{dT_{im}}{dt} = \frac{RT_{im}}{p_{im}V_{im}c_v}[\dot{m}_{at}c_v(T_{bef,th} - T_{im}) + R(T_{bef,th}\dot{m}_{at} - T_{im}\dot{m}_{ac}) - \dot{Q}]$$

Variable valve time

The model that was used for the VVT is a black-box, which means that the model is not based on physical formulas. Based on measurement data from a Volvo engine, functions were made that convert the input signals, the intake manifold pressure and the crankshaft angle, to the desired output which is the air mass flow into the cylinders.

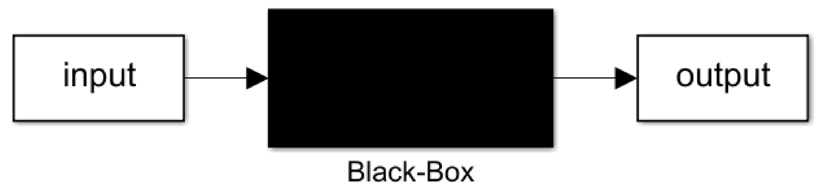


Figure 1: The black-box model for VVT

MPC Controller

The investigated real time model predictive controller (MPC) controls the non linear system of the actuators through linearizing and discretizing the system signals. Two alternative methods for linearization are presented and used: current state linearization using Taylor expansion and trajectory prediction the linearization using Taylor expansion with Euler's step method to predict the trajectory. The signals are then discretized with Euler's forward method.

Working Point:

$\bar{x}_k = \bar{x}_0, \bar{u}_k = \bar{u}_0$

$\Delta x_{k+1} = F_0\Delta x_k + G_0\Delta u_k + D_0$

Trajectory:

$\bar{x}_{k+1} = \bar{x}_k + TsK_k,$

$\Delta x_{k+1} = F_k\Delta x_k + G_k\Delta u_k$

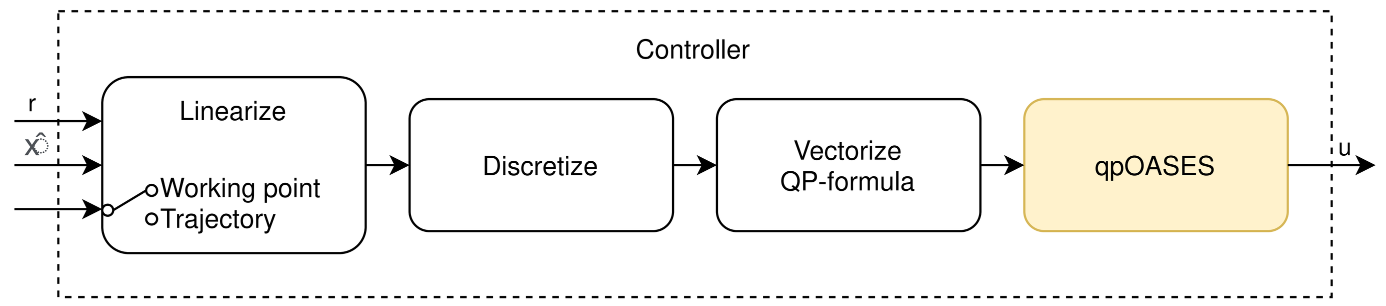


Figure 2: Description of the MPC structure

The system handles four states (x) and two control signals (u).

States:

$x = [p_{im},\ \alpha_{th},\ \theta_{ivo},\ T_{im},\ I_e]$

Control signals:

$u = [\alpha_{th,ref},\ \theta_{ivo,ref}]$

For the controller to find an optimal solution the open source QP-solver qpOASES, which supports real time code generation to the engine-test-cell, is used for solving the cost function. The cost function (minimizing u) optimized in the solver is described as follows.

Cost function:

$$\min \tfrac{1}{2}U^T M^T Q_1 M G + Q_2(G^T M^T Q_1(\tilde{M}(\bar{x}_k, \bar{u}_k,) - R))^T U$$

Constraints:

$\alpha_{th,ref} \in [0,1], \quad \theta_{ivo,ref} \in [0,50]$

The control system is created with two settings for engine optimization: Performance and Efficiency, using two different goal functions. Performance is defined as prioritizing cylinder mass flow, and efficiency considers both mass flow and pump losses.

Performance:

$$\tilde{M}(\bar{x}_k\bar{u}_k) = [\dot{m}_{ac}(\bar{x}_k, \bar{u}_k)]$$

Efficiency:

$$\tilde{M}(\bar{x}_k\bar{u}_k) = \begin{bmatrix}\dot{m}_{ac}(\bar{x}_k, \bar{u}_k) \\ p_{im} - p_{em}\end{bmatrix}$$

To handle the noise and disturbance to the signals from the engine the system is using an Extended Kalman filter.

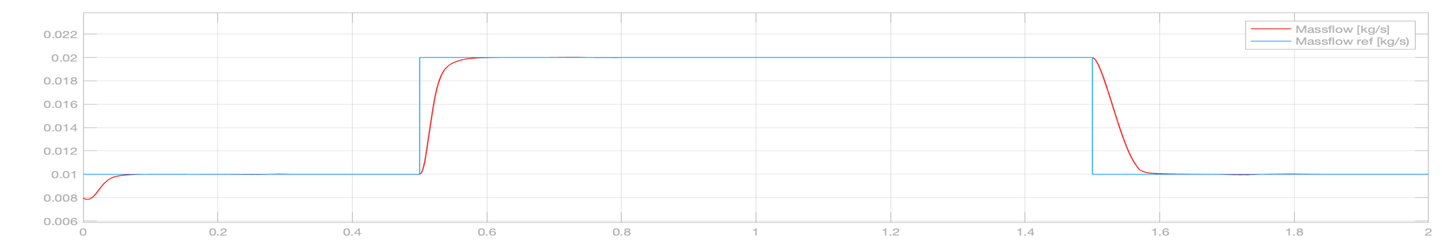
Simulation environment

The Simulation Environment contains models for the throttle, intake manifold and VVT, with the addition of optional added noise and steady state error. Using the signals (u) from the controller and engine parameters, the engine response is simulated.

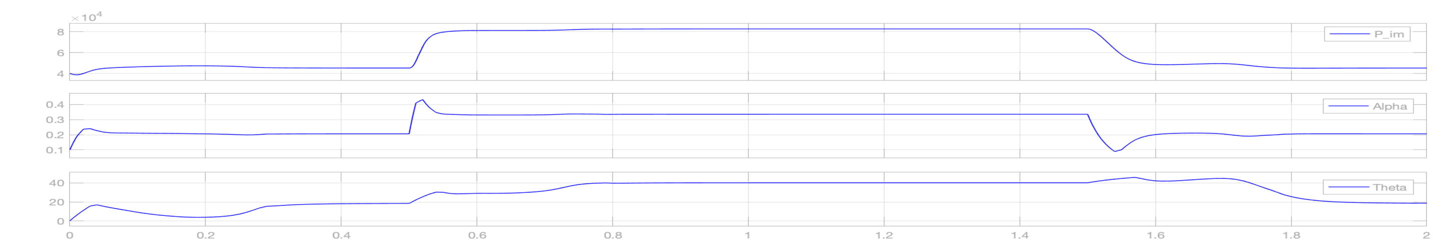
Results and Conclusion

The project resulted in an real-time MPC that was successfully implemented and run in the Simulation environment. Simulation examples are shown below (without disturbances):

Mass flow for the performance setting:



State behavior for the performance setting:



The mass flow graph shows the expected dynamic behavior in the steps. The states (p_{im}, α, θ) are also acting as expected to create the mass flow according to the cost functions.

Acknowledgements

The student group would like to thank the mentor Robin Holmbom for invaluable guidance and great commitment throughout the project. Thanks are also directed to Lars Eriksson and Volvo Cars for their help and enthusiasm.

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