Student competition at ECC 2015: design your optimal control to reduce CO_2 emissions

Background

In order to reduce CO_2 emissions, engines in vehicles must be used at their best. However, pushing engines to the limits can lead to problems which threaten their integrity. From a good control engineer we expect a solution which minimizes fuel consumption while avoiding dangerous situations – a classical constrained optimal control problem. In the case of gasoline engines, the dangerous situations are essentially knock (combustion takes place when it should not) and misfire (combustion does not take place even if it should).

Toyota has developed a Simulink® model as benchmark for the JSAE-SICE "near boundary control benchmark problem"[1], and a slightly modified version is available for students who wish to design their own control. This model computes the combustion, and indicates whether knock and misfire would happen under these conditions.

In the following we explain

- the procedure to participate to the contest
- the process to be controlled
- the task to be solved
- the provided software and expected deliverables

How to participate

1. Prospective participants should send an email with the subject "ECC15 student competition" to student_competition@ecc15.at, including their name and affiliation.
2. As soon as we have received your data, we will provide you with the model by email.
3. Participants are expected to document their approach and results as a regular paper with a special deadline (7.12.2014) which will be peer reviewed and, if accepted, scheduled for presentation and published in the proceedings.
4. To submit your contribution, please select the category "Student Competition paper" in the submission site for contest papers.
5. Decision on acceptance will be done at the same time as for all other papers.
6. Accepted papers will be scheduled for presentation in a dedicated session.
7. A Workshop organized by Toyota on the "bigger" problem is tentatively scheduled for Tuesday 14th of July. Participants to the contest are welcome to attend this workshop.

[1] http://cig.ees.kyushu-u.ac.jp/benchmark_JSAE_SICE/index_e.html

General problem formulation

The system to be considered is a complex nonlinear system described by its dynamics $\dot{x} = f(x,u)$, the output $y = g(x,u) \in \mathbb{R}^4$, input $u \in \mathbb{R}^3$ and a given reference $ref \in \mathbb{R}$, see Figure 1. The control task can be generally described as optimization problem in the form

$$\min_u J(y, ref) = \int_0^{t_f} \phi(\mathrm{t})\, dt$$

$$\begin{aligned} \text{s.t.} \quad & \dot{x} = f(x,u) \\ & y = g(x,u) \\ & h(x,u) < 0 \\ & u_{min} < u < u_{max} \, . \end{aligned}$$

The objective is to minimize a cost function (y, ref) , the integral of the instantaneous costs ϕ depending on the output while maintaining constraints in form of a nonlinear function $h(x,u) \in \mathbb{R}^2$ and boundaries on the input u_{min}, u_{max} . The system dynamics $f(x,u), g(x,u)$ are given as black box simulation model. The constraint function $h(x,u)$ is an additional output of the black box system and the applied restrictions ensure that the system is operated within safe conditions. ϕ is also an output of the model.

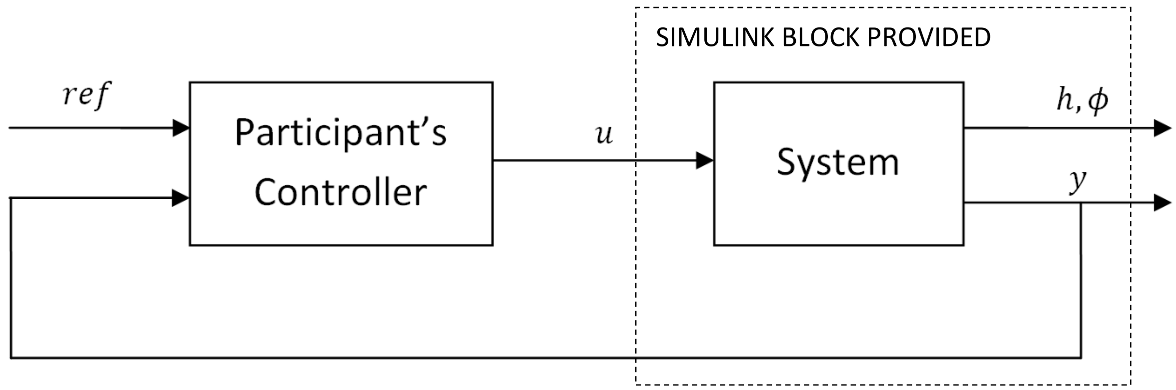

Figure 1 - Control structure

For more information on the process see the description. However, the problem can be solved also without the physical understanding (even if it is funnier if you understand what happens…)

The designed optimal control will be evaluated with a given reference scenario also described below.

More detailed process description

The physical system described in the black box model is a passenger car gasoline engine, its schematic set-up is depicted in Figure 2. The working principle of the engine is well known – a mixture of air and gasoline in a fixed ratio is led to the combustion chamber, ignited by a spark and the produced heat is partly converted into mechanical energy. The burnt gases leave the combustion chamber – the famous exhausts.

The considered inputs for engine control are throttle valve x_{TH}, EGR valve x_{EGR} and the spark advance φ_{SA}:

- The throttle valve is used to regulate the air flow (and thus the fuel) to the combustion chamber, it affects primarily the torque.
- The EGR valve is used to mix some already burnt exhaust gases to the fresh air, it affects primarily both consumption and misfire risk.
- The timing of the spark which ignites the fuel and air mixture is defined by the spark advance, so the angle before the piston has reached it maximum position, it affects mainly consumption and knock risk.

More information on the engine simulator can be found in [1] and on engine control in general in the corresponding literature, e.g. [2,3,4,5].

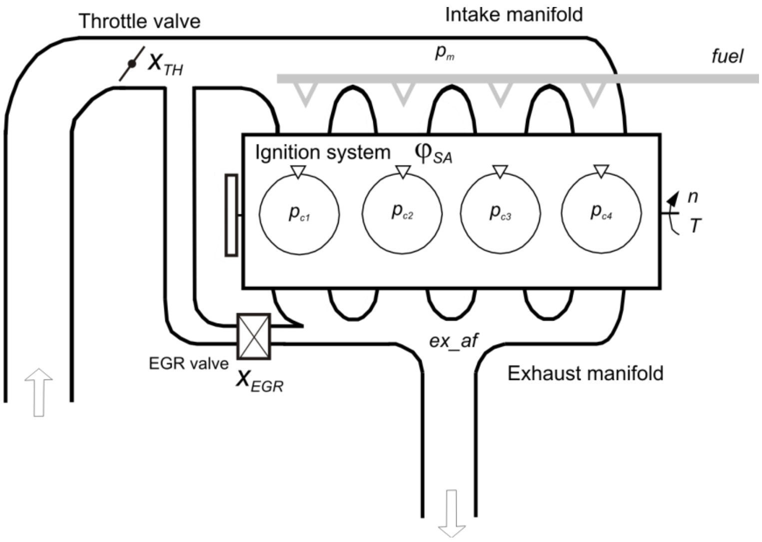

Figure 2 - Schematic description of the engine

OPTIMIZATION TASK

The aim of this benchmark competition is to minimize the overall fuel consumption while tracking a given reference, namely a desired engine torque profile T_d(t) and keeping the engine within a safe and sustainable operation, i.e. avoiding abnormal engine operating conditions such as knocking and misfiring.

This problem can be formulated as constrained optimization

$$\min_u \int_{t_0}^{t_f} c_f q_f(t) + c_t |T_d(t) - T(t)|^2 dt$$

$$\text{s.t.} \qquad h(x,u) < 0$$

$$u_{min} < u < u_{max} \,.$$

The information about misfire and knocking is obtained by the function $h(x,u)$ which depends on different factors, such as the intake manifold pressure p_m or the cylinder pressure $p_{c,i}$. Negative values of $h(.)$ indicate avoidance of knocking and misfiring whereas positive values indicate their appearance. Thus the constraints are to omit these conditions and of course to consider the possible input range.

Inputs to the system are spark advance φ_{SA} $[CAD]$ defined positive before top dead center, throttle valve position x_{TH} $[\%]$ and EGR valve position x_{EGR} $[\%]$. For both valves the minimum value corresponds to the closed position, whereas the maximum corresponds to a fully opened valve. The engine speed n $[rpm]$, is considered as measured disturbance and within this competition kept constant at $n = 1500\ rpm$. Thus, the available control inputs are

$$u = [\varphi_{SA} \quad x_{TH} \quad x_{EGR}]^T$$

with the input constraints given by

$$u_{min} = [-30 \quad 5 \quad 0]^T$$

$$u_{max} = [60 \quad 90 \quad 100]^T.$$

Measured outputs are engine torque T $[Nm]$, the function $h(.) = [h_K \quad h_M]^T$ which indicates knocking and misfiring of the engine respectively and the current fuel consumption q_f $[kg/s]$. For simplicity these quantities are further summarized in the output vector

$$y = [T \quad h \quad q_f]^T.$$

The constants c_f and c_t of the objective function are fixed and provided in the simulation dataset.

Optionally, for control development it is possible to consider other quantities which are related to the combustion process. These quantities are intake manifold pressure p_m $[kPa]$, current crank angle CA $[CAD]$, cylinder pressure $p_{c,i}$ $[kPa]$, EGR rate EGR_{RATE} $[\%]$ and exhaust air to fuel ratio ex_{af} $[1]$. All quantities are available in the competitor code block of the Simulink® model. ***Please notice that it is not mandatory or required to use these quantities for the control task.***

The performance will be evaluated under fixed conditions, precisely

- Engine speed at 1500 rpm
- Torque profile according to Figure 3

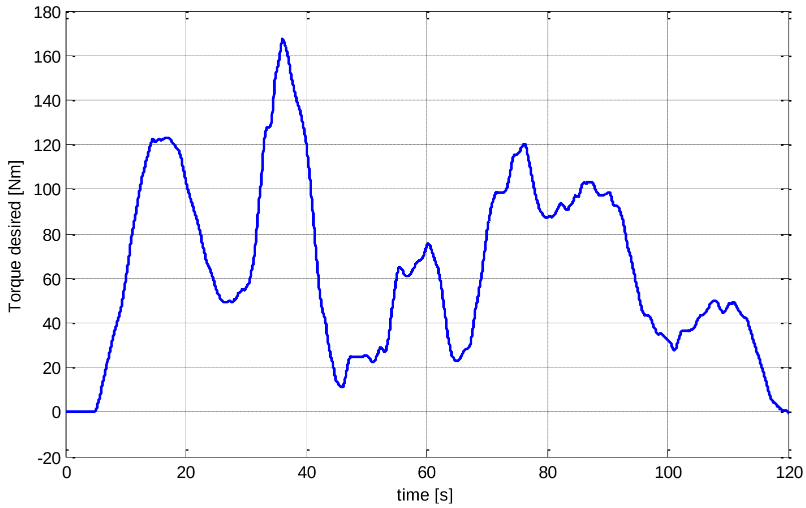

Figure 3: Desired torque profile for evaluation

Important: To neglect effects in the model during start up and initialization, the evaluation of the objective functions should be done only in a specified time range. Please use for all your evaluations $t_0 = 5s$ and $t_f = 120s$ (The evaluation blocks inside the provided model already consider this specification).

Provided software and expected deliverables

We provide two elements:

- The Simulink® engine model is depicted in Figure 4 and based on the model used in the JSAE-SICE benchmark [1]. The provided files require Matlab/Simulink® version 2012b or above.
- A file with the data for initialization of model and test cycle: “engine_data.mat”

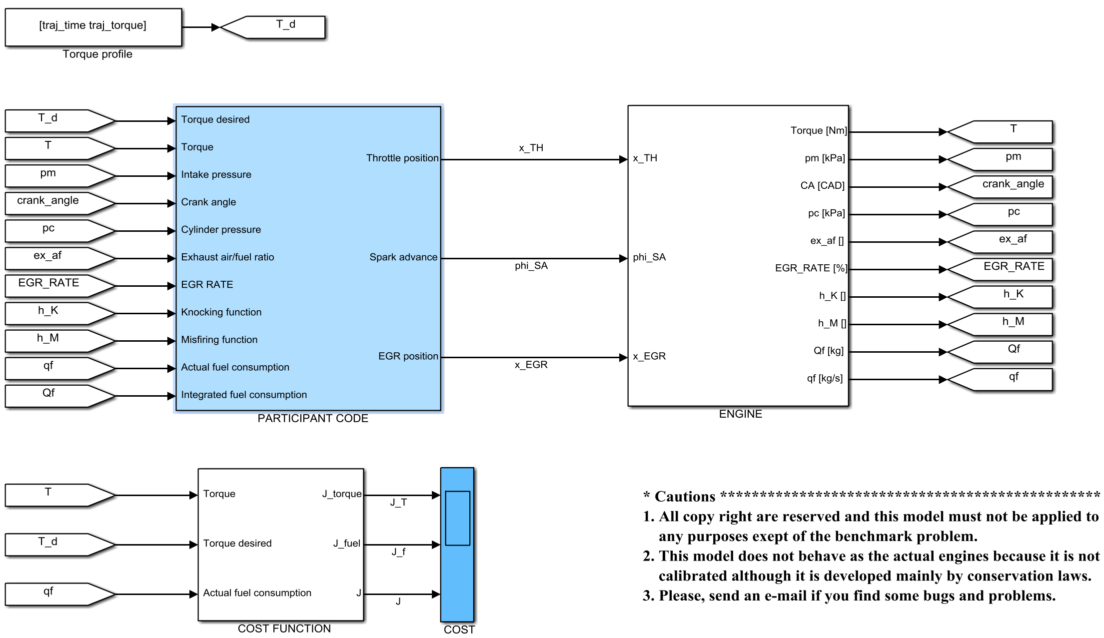

Figure 4: Simulink® model for the student competition

You should provide:

- Simulink® Control block (should run with the model as provided)
- Paper with description of the method including a table summarizing the achieved objectives for the given desired torque profile in Figure 3. Additionally figures presenting the trajectories of the controlled inputs $u = [\varphi_{SA} \quad x_{TH} \quad x_{EGR}]^T$ and the obtained output quantities $y = [T \quad h \quad q_f]^T$ need to be provided.

Objectives		
Fuel consumption	$J_{fuel} = \int_{t_0}^{t_f} c_f q_f(t)dt$	
Torque deviation	$J_T = \int_{t_0}^{t_f} c_t \lvert T_{des}(t) - T(t)\rvert^2 dt$	
Overall objective	$J = J_{fuel} + J_T$	

The proposed control should be placed within the blue block “Participant Code” in Simulink® which currently includes only a simple baseline engine controller. The baseline controller is purely based on maps in dependency of the desired torque and does not take into account any feedback information or optimization. ***The participants are free in the choice of the approach or method they apply to address the challenge.***

However, any solution must only use the provided signals for control and monitoring.

The model itself must not be changed by the competitor and additional, internal intermediate quantities from the engine model must not be used for the control.

References

[1] S. Watanabe, A. Ohata, *Benchmark Problem for Near Boundary Operation Control for Automotive Engine*, available online at http://cig.ees.kyushu-u.ac.jp/benchmark_JSAE_SICE/index_e.html

[2] J. B. Heywood, *Internal Combustion Engine Fundamentals*, McGraw Hill International Editions Automotive Technology Series, 1988.

[3] U. Kienke, L. Nielsen, *Automotive Control Systems*, 2nd edition, Springer Verlag, 2005

[4] L. Guzzella and C. Onder, *Introduction to Modeling and Control of Internal Combustion Engine Systems*, Springer Verlag, 2010.

[5] L. Eriksson, L. Nielsen, *Modeling and Control of Engines and Drivelines*, Wiley, 2014