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Predictive planning of optimal velocity and state of charge trajectories for hybrid electric vehicles☆

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ABSTRACT

The combination of electric motors and internal combustion engines in hybrid electric vehicles (HEV) can considerably improve the fuel efficiency compared to conventional vehicles. In order to use its full potential, a predictive intelligent control system using information about impending driving situations has to be developed, to determine the optimal gear shifting strategy and the torque split between the combustion engine and the electric motor. To further increase fuel efficiency, the vehicle velocity can be used as an additional degree of freedom and the development of a predictive algorithm calculating good choices for all degrees of freedom over time is necessary.

In this paper, an optimization-based algorithm for combined energy management and economic driving over a limited horizon is proposed. The results are compared with results from an offline calculation, which determine the overall fuel savings potential through the use of a discrete dynamic programming algorithm.

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1. Introduction

Over the last few decades, reducing fuel consumption for vehicles has become a more and more important field of research. Reasons for this development are increasing environmental awareness accompanied by stricter regulations and rising fuel costs. One technology emerging from this research is the hybrid electric vehicle (HEV), combining electric batteries and motors with the internal combustion engine (ICE) in one powertrain. There exists a wide variety of HEVs with different structures, e.g. parallel hybrid vehicles or series hybrid vehicles, and different degrees of hybridization, e.g. micro-hybrids, which are characterized by small batteries and electric motors (EM) whose main purpose is to implement an automatic engine start/stop function. At the other end of the scale plug-in hybrid vehicles with large batteries and motors facilitate long all-electric range and the possibility to charge the battery from the power grid (Guzzella and Sciarretta, 2013).

To achieve the best fuel efficiency, an optimal energy management system (EMS) is necessary to coordinate both power sources. Since an optimal control strategy depends on the driving cycle, this poses two main challenges: firstly, the parameters of the driving cycle are not necessarily known and, secondly, finding a global, optimal solution for the resulting nonlinear optimal control problem is numerically challenging. Therefore, this is a demanding field of research. For previous work in this field, see Sciarretta and Guzzella (2007), Pisu and Rizzoni (2007), Johannesson and Egardt (2008), Bender, Kaszynski, and Sawodny (2013) and Panday and Bansal (2014).

Another approach is economic driving, i.e., using the velocity as an additional degree of freedom to reduce fuel consumption. In recent years, work for different types of vehicles, such as conventional cars and trucks (e.g. Hellström, Åslund, and Nielsen, 2010; Hooker, 1988; Kamal, Mukai, Murata, and Kawabe, 2013; Llamas, Eriksson, and Sundström, 2013; Terwen, Back, and Krebs, 2004), fuel-cell cars (Sciarretta, Guzzella, and van Baalen, 2004) and electric cars (Petit and Sciarretta, 2011) has been published.

The next step to increasing fuel efficiency is to combine both economic driving and predictive EMS. In van Keulen et al. (2009, 2010), the velocity profiles for a hybrid electric truck are optimized. Therefore, the driving cycle is partitioned into segments of constant power request and each of these segments is divided into four phases: max. power acceleration, constant velocity, coasting and max. power deceleration. The parameters of these phases are then optimized to maximize power recovery and minimize fuel consumption. In Kim, Manzie, and Sharma (2009), a model

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Nomenclature

Δd	discretization of the short horizon optimization
ΔJ_{SHO}	stage transition costs for the short horizon optimization
Δp	phase length
Δp_{max}	maximum phase length
Δp_{min}	minimum phase length
Δv_{ex}	maximum allowed velocity exceedance
Δv_{off}	offset between reference and maximum velocity
Δv_{safety}	security offset to the maximum possible curve velocity
$\Delta x_{SoC,max}$	maximum SoC change for a use case in long horizon battery planning
$\Delta x_{SoC,min}$	minimum SoC change for a use case in long horizon battery planning
$\dot{m}_f$	fuel consumption per second of the internal combustion engine
$\dot{m}_{f,save}$	fuel saved per second for a certain engine and motor operation point
γ	road grade
κ	road curvature
λ	equivalence factor of the ECMS
$\mathcal{U}$	use case in the long horizon battery planning
μ	friction coefficient between road and wheels
μ_R	rolling coefficient
ω_{EM}	speed of the electric motor
ω_{ICE}	speed of the internal combustion engine
ω_{prop}	speed of the propshaft
ω_{whl}	speed of the wheel
ς_i	weighting factors in the cost functions of the short horizon optimization
ξ_i	weighting factors in the cost functions of the long horizon battery planning
a	vehicle acceleration
b_{clt}	state of the clutch (open or closed)
b_{ICE}	engine on/off state
C_{Air}	air drag coefficient
F_{drag}	air drag resistance force
F_{grade}	grade resistance force
F_{roll}	rolling resistance force
$\boldsymbol{f}_{SHO}$	position derivative of the states $\boldsymbol{x}_{SHO}$
$\boldsymbol{f}_s$	vector of time derivatives for the vehicle states $\boldsymbol{x}_s$
$\boldsymbol{f}_t$	vector of time derivatives for the vehicle states $\boldsymbol{x}_t$
g	gravitational acceleration
h	physical constraints of the short horizon optimization problem
$I_{bat,max}$	maximum battery current
$I_{bat,min}$	minimum battery current
I_{bat}	battery current
i_G	gear transmission ratio
i_{RA}	rear axle transmission ratio
J_{eff}	effective vehicle inertia, inertias of all rotating parts
J_{EM}	inertia of the electric motor
J_G	inertia of the gear box
J_{ICE}	inertia of the internal combustion engine
J_{RA}	inertia of the rear axle
J_{whl}	inertia of the wheels
$J_{LHBP,fuel}$	cost during use cases in LHBP except recuperation
$J_{LHBP,f}$	final costs for the long horizon battery planning
$J_{LHBP,recup}$	cost during recuperation use cases in LHBP
$J_{LHBP,k}$	cost functions for the long horizon battery planning
$J_{SHO,f}$	final costs for the short horizon optimization
$k_{P,j}$	phase transition stage j
m	vehicle mass
m_{eff}	effective vehicle mass, including all inertias
N_{LHBP}	number of use cases in the long horizon battery planning
N_P	number of phases in the short horizon optimization
$N_{S,j}$	number of stages in phase j
N_S	number of stages in short horizon optimization
$\boldsymbol{p}$	parameter vector
P_{aux}	electric power consumed by the auxiliaries
P_{bat}	battery power
P_{brk}	braking power
P_{el}	power demand of power electric loads
$P_{EM,el}$	electric power of the electric motor
$P_{EM,max}$	maximum EM power
$P_{EM,min}$	minimum EM power
$P_{ICE,max}$	maximum ICE power
$P_{ICE,min}$	minimum ICE power
P_{lim}	power limits for long horizon battery planning
P_{req}	predicted power demand for long horizon battery planning
Q_{bat}	battery capacity
R_{EM}	torque derivatives of the electric motor
R_{ICE}	torque derivatives of the internal combustion engine
R_i	battery resistance
r_{whl}	wheel radius
s	position
$s_{P,j}$	starting position of phase j
s_{SBS}	battery power substitution benefit
t	time
T_{brk}	service brake torque
T_{des}	desired torque from driver model
T_{drag}	air drag resistance torque
$T_{EM,high}$	highest possible EM torque for SoC change limit calculation in LHBP
$T_{EM,low}$	lowest possible EM torque for SoC change limit calculation in LHBP
T_{EM}	electric motor torque
$T_{G,in}$	torque transmitted from the motor side to the gearbox
$T_{G,out}$	torque transmitted from the gear box to the propshaft
T_{grade}	grade resistance torque
T_{ICE}	internal combustion engine torque
$T_{loss,clt}$	torque loss in the clutch
$T_{loss,G}$	torque loss in the gear box
$T_{loss,RA}$	torque loss in the rear axle
T_{resist}	driving resistance torque
T_{roll}	rolling resistance torque
T_{whl}	accumulated torque at the wheels
$\boldsymbol{u}$	vector of model inputs
U_0	open circuit voltage of the battery
U_{bat}	battery voltage
u_{clt}	clutch open/close command
u_G	desired gear
u_{ICE}	engine on/off command
$\boldsymbol{u}_{SHO}$	input vector for short horizon optimization
v	vehicle velocity
v_{corr}	merged velocity limits
$v_{curve,max}$	curve velocity limit
v_{des}	desired velocity
v_{law}	speed limit
$v_{lim,min}$	lowest curve velocity limit
v_{max}	maximum velocity
v_{min}	minimum velocity

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