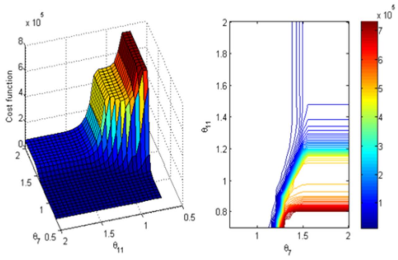
- modelling and simulation
- control design
- system troubleshooting
- technology transfer and training
- energy efficiency investigation
- software tools

industrial systems and control



Hybrid Electric Powertrain Control

Electric vehicles (EVs) and Hybrid Electric vehicles (HEVs) have received tremendous attention over the past decade as one of the promising methods of addressing greenhouse gasses. In this document classical and modern Energy Management Strategies (EMSs) for HEVs are reported, according to the experience of Industrial Systems and Control Ltd. (ISC) in automotive.

Hybrid Electric Powertrain

A HEV consists of the fuel converter (internal combustion engine), the inverter, the battery, and the electric machines (motor and generator). Depending on the driving mode, e.g., accelerating or decelerating, either a positive or a negative torque is demanded from the powertrain. The power from the electric machine is regulated by changing the torque such that it can be either positive or negative depending on the operating mode. In the motor mode, the electric machine contributes power to the driveline by drawing electrical energy from the battery. In the generator mode, the electric machine absorbs power from the driveline and charges the battery. The generator absorbs the maximum possible amount as determined by the system's physical constraints when braking.

Classical Hybrid Electric Powertrain Control

Power management policies for HEVs have been developed according to Dynamic Programming (DP), Equivalent Consumption Minimization Strategies (ECMS) and Adaptive ECMS. The DP approach has been widely employed as the principal method for the analysis of sequential decision-making problems, e.g., deterministic, and stochastic optimization and control problems, Markov decision problems, min-max problems, and sequential games. While the nature of these problems may vary widely, their underlying structure is similar and has two principal features: an underlying, discrete-time dynamic system whose state evolves according to given transition probabilities that depend on a decision at each time instant, and a cost-function that is additive over time. DP for HEVs control can yield a global optimal solution in closed loop form but the associated computational requirements are excessive and computing a solution by DP is impossible in real time, since it requires future knowledge. It therefore only provides a useful benchmark to assess other physically realizable designs.

ECMS, and the equivalent Pontryagin's Minimum Principle (PMP), are the principal procedures in solving the HEVs optimization problem by deriving a set of necessary conditions that must be satisfied by any optimal solution. Power management control algorithms, based on these techniques, usually consist of an instantaneous optimization problem that accounts for battery State-Of-Charge (SOC) variation through the equivalent fuel consumption (EFC) factor. The fuel consumption is then minimized by selecting optimal combinations of control variables.

Adaptive ECMS reduces the sub-optimality of the solution computed by ECMS (with respect to DP) by adapting the EFC factor according to a defined policy, e.g., introducing a feedback control policy for stabilizing the battery SOC to a prescribed value. Model Predictive Control (MPC) based systems now offer greater benefits particularly for reducing battery degradation.

Industrial Systems and Control Ltd.

ISC Ltd. works across industrial sectors and has gained wide experience in a range of applications. It is this peripheral vision which is valuable for automotive companies, which have a complete understanding of current advances in the automotive industry. ISC Ltd. has particular expertise and experience on the following areas and methodologies:

- Physical system modelling and simulation, including training simulators.
- Developing tailored optimal or predictive control solutions for real-world applications.
- Production of bespoke estimation and filtering algorithms for nonlinear control.
- Use of stochastic or robust controls for different industries like wind energy and marine.
- Design of Machine Learning algorithms for industrial and embedded domains.
- Training courses mostly for the automotive industry based in the US.

Our Expertise

- **In-depth understanding of control technologies**
- **Extensive experience in diverse industrial applications**
- **High-fidelity modelling of system behaviour**
- **Expert analysis of complex problems**
- **Proven project management and research skills**

Our Core Competencies

- **Dynamic modelling & simulation**
- **Control strategy design and implementation**
- **Optimization**
- **Algorithm development**
- **Benefits analysis and technology review**
- **Research & Development**
- **Troubleshooting**
- **Training**

Our Philosophy

- **Approaching problems with an open mind**
- **Dedicated to identifying practical and innovative solutions without compromising performance.**
- **Imparting understanding and empowering clients to drive improvements themselves.**

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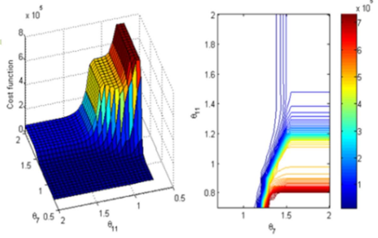


Advanced Hybrid Electric Powertrain Control

Among the different modern control policies suitable for controlling a hybrid electric powertrain, and more in general for the different automotive control problems, in the recent year the companies in the automotive field have definitely moved towards the use of model-based techniques. In particular, model-based predictive control (MPC) attracted the interest of such companies, due to the different advantages provided by this paradigm. MPC predictive control would be able to effectively replace classical ECMS-based methods in HEV control.

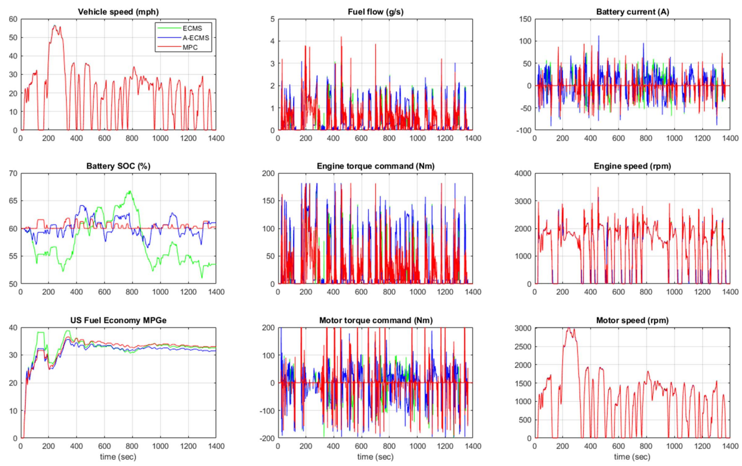
MPC offers a predictive scheme such that future cycle information can be incorporated into various EMSs. The algorithm performance relies on model quality, sampling step, and prediction horizon length. The horizon length has to be tuned accordingly to the control strategy used, computational effort, model accuracy, and external conditions and disturbances. MPC can be combined with GPS information, improving the prediction results by means of past, present, and future driving conditions. ECMS would benefit from additional drive cycle information through predictive algorithms such as MPC. It can be used to tune the parameters systematically, which will be less dependent on the drive cycle. Furthermore, MPC does not require full information of the drive cycle, as it happens with Differential Dynamic Programming (DDP). A MPC has a limited prediction horizon and if a Linear Parameter Varying (LPV) model may be used a fast algorithm may be produced using quadratic programming (QP). The algorithm may then be used for real-time control.

The availability of future driving information is a prerequisite for advanced power management policies. It is therefore necessary to review the prediction methods used in the literature to develop an effective optimal EMS. Different solutions have been proposed for integrating and exploiting the predicted behaviour of the future vehicle dynamics into the controller design. Because of the performance required and the control specifications, the MPC framework appears to be the more suitable for the selected application, permitting the integration with Artificial Intelligence algorithms, Telematics information or predicted patterns affecting the powertrain performance.

ISC Expertise in Automotive Control and Optimization

Over the last 2 decades ISC Ltd has been involved in a number of research and development projects with both universities and companies. The development of advanced control systems represents the main services provided by ISC able to study and design ad-hoc solutions for optimizing the behavior of any system to be controller.

The collaboration between ISC and automotive field companies has been consolidated by a multitude of projects, activities and training courses, permitting to establish partnership during last 20 years. ISC expertise covers strong knowledge on techniques for modelling and controlling automotive systems and sub-parts, considering vehicle's dynamics control and the development of models/controllers for any type of vehicle subsystem, e.g. engines.



HEV Control FTP75 Driving Cycle Test: A-ECMS vs ECMS vs MPC developed by ISC

ISC has large expertise in the development of MPC and other optimal control systems for a variety of applications and industries, including autonomous and non-autonomous vehicles. Various advanced modelling and control techniques have been considered and their potential exploited and customized – these include nonlinear optimization methods, computationally efficient modelling, advanced data-driven and model-based control techniques.

Clients Include

- **Torotrak: variable transmission system.**
- **Visteon: applying LabVIEW to automotive power control.**
- **General Motors: SI engine control.**
- **General Motors: SCR system identification.**
- **General Motors: Control model calibration.**
- **Toyota: Diesel engine control.**
- **Cummins: Diesel engine design methods assessment.**
- **Ford: Autonomous vehicle control.**
- **FCA: Training Activity via Electronic throttle design study.**
- **NXP: Hybrid Electric powertrain control.**

Recent Automotive Training Courses

- **Ford at Dearborn annual courses between 2004-2019**
- **Cummins at Columbus, 2018**
- **Toyota at Ann Arbor 2014 & 2018**
- **Chrysler at Auburn Hills 2011-2016**
- **Freescale in Glasgow and Detroit 2008**
- **NXP in Glasgow 2018**
- **GM Detroit 2015**
- **Jaguar in Coventry and Gaydon 2006 & 2009**
- **Riccardo in Leamington and Shoreham 2006 & 2009**
- **Visteon in Detroit 2004**

"Approaching a problem with an open mind is an important aspect of ISC philosophy, as is using the simplest, most cost effective solution"

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