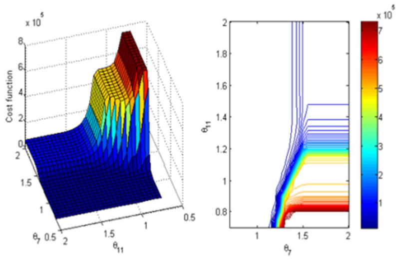

Battery State of Charge Estimation

This document briefly reviews the problem and the estimation approach representing the state of the art for developing algorithms to determine the state of charge (SoC) of the battery used in electric vehicle applications. Industrial Systems and Control (ISC) Ltd., has expertise in advanced control systems, developing sophisticated algorithms able to observe and optimize the performance of a system, including modern hybrid/electric vehicles and related subsystems, e.g. batteries.

Battery SoC Estimation Problem

Electric vehicles (EVs) are one of the most promising technologies, owing to their remarkable energy saving capabilities and potential interactions with a renewable power grid. Traction battery packs are currently the most common electric energy carrier onboard and thus play an important role in the performance, economy, and acceptance of EVs. To make costly batteries safe, efficient, and durable in a complex vehicle environment, meticulous monitoring and control of internal battery states, e.g., State-of-Charge (SoC) is required. Accurate SoC estimations have always been a critical and important concern in the design of a Battery Management System (BMS) in EVs. The BMS in EVs consists of different types of sensors, actuators, and controllers. A BMS performs the following main tasks: *i)* protects the battery, *ii)* operates the battery with a safe limit of current, voltage and temperature, and *iii)* measures and estimates the battery states precisely. The uncertainty of states may thwart vehicle energy routing and exacerbate battery safety/durability problems. Limited sensing and actuation, nevertheless, constitute a daunting technological challenge holding back accurate SoC tracking.

Classical SoC Estimation Methods

Different solutions have been proposed for solving the battery SoC estimation problem by considering classical paradigms:

- **Direct measurement** SoC estimation methods can be classified into electromotive force methods (EMF, requiring significant time to model OCV relaxation after current disruption), impedance spectroscopy methods (IS, featured by low accuracy because large variations of the SoC have low impact on the change in resistance), internal resistance methods (IR, having good results for identical charging and discharging currents , and therefore it is unsuitable for EVs), and open circuit voltage methods (OCV, it cannot be implemented for online estimations).
- **Book-Keeping methods** are essentially Coulomb Counting methods based purely on the battery charging or discharging current. This method integrates the battery charging or discharging current over time to find SoC. The implementation is quite simple with very low computational complexity. The initial unknown SoC and the sensor error are main concern on the accuracy of the SoC estimation. It works efficiently if the SoC needs to be estimated for the short period and the initial SoC is known. Several factors, such as an unknown initial SoC, aging, temperature, self-discharging, coulomb efficiency and device precision, affect its accuracy.
- **Model-based SoC estimation** methods overcome the deficiencies of the conventional methods by using battery parameters to deploy a model and then estimate its SoC using advanced algorithms. Previous methods have issues relating to their efficiency and estimation accuracy in real time. Advanced methods include **Adaptive Filters** (H_∞, Kalman and Recursive Least-Square filters) and **Observed-based estimators** (Nonlinear, Sliding Mode, Proportional Integral and Luenberger observers).

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 find practical and innovative solutions without compromising performance.**
- **Imparting understanding and empowering clients to drive improvements themselves.**

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Artificial Intelligence SoC Estimation Methods

Classical techniques have several limits, reducing estimation capabilities and related performance. In recent years, Artificial Intelligence (AI) and Machine Learning (ML) techniques have captured the attention and the interest of operators belonging to different fields, included EVs and BMS design. Different AI-based solutions can be considered, by using modern ML techniques for estimating the battery SoC in EV applications:

- **Meta-heuristic optimization techniques**. These techniques provide a nonlinear optimization framework permitting to solve complex optimization problems by limiting the magnitude of the sub-optimality provided due to effects of local minima.
- **Fuzzy logic**. It is a method to identify the unknown parameters of a highly complex and nonlinear system, such as a EV battery. It does not require a mathematical model but only uses the input data and the fuzzy rule base.
- **Neural Networks**. The neural network (NN) is basically inspired by the human brain and is a framework of many different machine learning algorithms to perform different tasks. The NN has self-adaptability and learning abilities to establish a highly complicated and non-linear system, such as a battery.
- **Support Vector Machines.** Support vector machine (SVM) techniques have attracted considerable attention becoming a powerful tool to solve regression problems in nonlinear systems by using different kernel functions and regression algorithms to transmute a nonlinear model into a linear model.

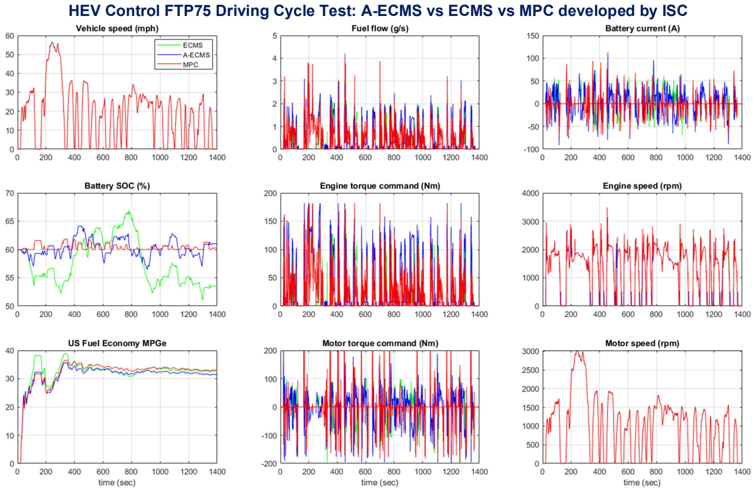
Each ML algorithm provides different performance with respect to the problem considered, boundary conditions and specifications limiting the algorithm design (e.g., computational burden or data storage). Because of this, a priori it is not possible to select a ML algorithm for battery estimation purpose.

In their standard formulation, AI techniques are affected to limits and disadvantages related to their structure and original purpose, rather different to the control and estimation of a dynamic system target. Considering particular problems affecting ML techniques involved in battery SoC estimation, they can be treated individually by developing ad-hoc solutions based on recent innovative algorithms (e.g. SVM Low-Rank Approximation). The introduction of those techniques can address the different problems affecting AI and ML algorithms.

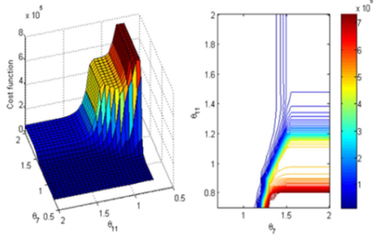
ISC Expertise in Automotive Control and Optimization

Over the last 2 decades ISC has been involved in several research and development projects with both universities and companies. The development of physical models and advanced control systems represents the main service provided by ISC to study and design ad-hoc solutions for optimizing the behavior of a system.

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



The collaboration between ISC and automotive field companies has been consolidated by a multitude of projects, activities and training courses, establishing a partnership with many international companies over the last 20 years. ISC expertise covers strong knowledge on techniques for modelling and controlling automotive systems and sub-systems, considering vehicle's dynamics control and the development of models/controllers for different types of vehicle subsystem, e.g., engines, autonomous vehicles, and HEV/EV controls.



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 the ISC philosophy, as is using the simplest, most cost-effective solution."

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