Distributed Economic MPC for Vehicle Energy Management

The use of Distributed control based on Economic Model Predictive Control (MPC) for vehicle control is briefly summarized in the following. The Economic MPC and Distributed optimal control paradigms are presented. The application of these methods in complete vehicle energy management is considered.

Economic MPC

The cost-function of conventional Model Predictive Control (MPC) problems is normally defined so that closed-loop responses and sensitivity functions can be easily tuned. There are very few occasions where the cost-function has a physical significance and represents a quantity to be optimized. This is not a weakness of predictive control but is normally the case in most optimal control design problems. It is therefore unlikely to be an adequate representation for managing real-time plant or process operation with respect to the economic performance.

The effects of nonlinearities and constraints may also be significant in economic optimization problems. A positive deviation from a target may represent a profit, whilst a negative deviation from a target may represent a loss (or vice versa). For example, consider an input that supplies heat energy to a reactor (e.g., a steam jacket). Supplying more steam to the jacket than the target is more costly in terms of the energy consumption of the reactor, whilst supplying less steam consumes less energy. There are therefore problems in using linear system models and “least squares” or “quadratic cost function” control problem constructions to solve economic optimization problems.

This mismatch between standard MPC results and practical needs resulted in calls to unify process economic optimization and process control needs in a “tailored” theory. The idea of using an economic cost functions directly in an MPC scheme emerged and has led to a significant research effort. The resulting MPC scheme is called economic MPC (EMPC). EMPC minimizes an arbitrary economic cost objective directly, which does not necessarily penalize the tracking error to the optimal target, as opposed to minimizing the deviation from a set-point in some norm. Since EMPC accounts directly for process economics which is aligned with the core ideas of next-generation manufacturing (e.g., Smart Manufacturing, market-driven manufacturing, and real-time energy management) its popularity amongst researchers has significantly increased.

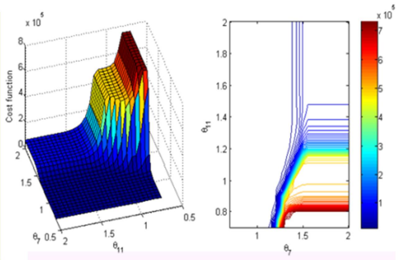
Distributed MPC

The key to the success of MPC is the inherent flexibility of the policy, which allows for complex issues such as constraints or delays to be dealt with explicitly. Despite this, the control of large-scale, interconnected or networked systems (e.g. a platoon of vehicles, or electricity network) still presents significant difficulties to MPC. For example, the organizational structure of the system and its information flows may not be conducive to a centralized control approach suggested by standard MPC. Moreover, even if it is, the MPC optimization problem for the whole system may be too large to simulate or solve on-line. In Distributed MPC (DPMC), the optimal control problem is decomposed into several smaller sub-problems that are distributed to a set of local controllers or control agents. Each controller or agent is responsible for controlling a subsystem composed of a subset of the system states and control inputs. In order to achieve system-wide stability and satisfactory closed-loop performance, the agents exchange information so that they can coordinate their decision making. Many schemes have been proposed to date, and differ according to the particularities of the scenarios in which they are applied: for example, the way in which the system is decomposed, the source of coupling, or the limits in the communication or computational capacity.

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**
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- **High-fidelity modelling of system behaviour**
- **Expert analysis of complex problems**
- **Proven project management and research skills**

Our Core Competencies

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- **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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Complete Vehicle Energy Management

The Problem

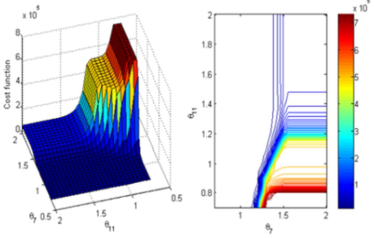
In electric vehicles, different power sources provide the energy required for powertrain and auxiliary subsystems (e.g. the climate control system and the air supply system). Because of the presence of these auxiliaries, the energy consumption cannot be managed only considering the powertrain. The role of auxiliaries is of major importance in heavy-duty vehicles, which can be equipped with special power-consuming components (e.g. a refrigerated semi-trailer). These particular auxiliaries have a potential energy buffer that can be utilized by the energy management system to schedule energy flows and thereby improve the energy efficiency. At the same time, heavy-duty vehicles are augmented with many different types of auxiliaries and this require the energy management system to be flexible and scalable, to reduce development time and costs. Moreover, as heavy-duty vehicles typically drive long distances, the energy management problem must be solved over very long horizons. These aspects define the so-called "Complete Vehicle Energy Management (CVEM) problem" for electric vehicles.

Distributed Economic MPC for Electric CVEM

Distributed Economic MPC (DEMPC) would provide a flexible framework for tackling the CVEM problem that can be formulated as an EMPC problem. This enables the performance of the complete energy system to be optimized in an electric vehicle, managing the power flow between the different subsystems, energy buffers and power sources. The limit of the EMPC approach is the strong dependency of the control system on the specific system architecture. The DMPC could be considered for extending the capability of an EMPC for CVEM, improving the scalability and flexibility of the controller. This approach is based on the use of dual decomposition methods for optimal control problems. The application of a duel decomposition method to the EMPC CEVM optimal control problem results in relatively small constrained optimization problems. Each limited size problem is related to an auxiliary subsystem involving the energy system of the vehicle. After each limited size optimization problem is solved, these solutions are combined (normally linearly) to define the solution of the original optimal EMPC problem, for controlling the vehicle energy system.

The Advantage

- Because the original CEVM is based on EMPC, it guarantees that energy losses are minimized, forcing the system to operate in the most efficient way.
- The distributed approach involves the solution of small-size problems instead of a large optimization problem. This results in a reduced computational effort to compute the control law (it is computationally less expensive to solve a number of small optimization problems rather than a big one).
- Due to the dual decomposition, the distributed control system can be adapted to include different auxiliaries by adding small sub-problems. The solution of the global optimization problem is given by the linear combination of solutions of the limited-size problems. The new DMPC problem has the same problem formulation despite the new subsystems introduced.



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

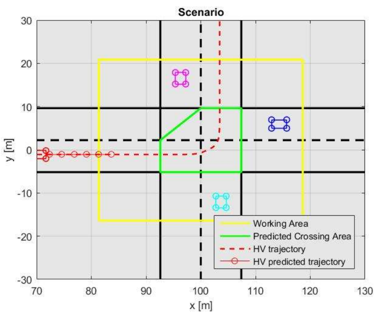
- **Ford at Dearborn annual courses between 2004-2019**
- **Cummins at Columbus, 2018**
- **Toyota at Ann Arbor 2014 & 2018**
- **Chrysler at Auburn Hills 2011-2016**
- **Freescale in Glasgow and Detroit 2008**
- **NXP in Glasgow 2018**
- **GM Detroit 2015**
- **Jaguar in Coventry and Gaydon 2006 & 2009**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

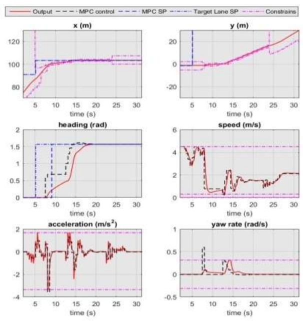
"Approaching a problem with an open mind is an important aspect of the ISC philosophy, as is using the simplest, most cost-effective solution."

ISC Expertise in Automotive Control and Optimization

ISC Ltd has been involved in the last years in different research and development projects involving both universities and automotive companies.

ISC is expert in the development of MPC and optimal control system able to optimize the control performance of any dynamic system, including cars and autonomous vehicles. For reaching this target, different advanced techniques have been considered and their potentiality exploited and customized. Nonlinear optimization, computational efficient modelling, advanced data-driven and model-based techniques have been considered and used for developing different complex and performable control system.





ISC Control of AVs by computationally efficient nonlinear MPC method

Proposed activities give a possible approach for directing possible activities involving the autonomous vehicles featured by an electric/hybrid drivetrain. Further, several bespoke solutions and studies could be evaluated for evaluating advantages and limits of this type of vehicle. Expertise of ISC on advanced control techniques and their application in the automotive field permits extend the research horizon overcoming the state-of-the-art of the technique, for matching different needing of the single customer.

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