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Executive Summary

This report describes the process that was followed to produce a special issue of the *Journal of Process Control* on Hierarchical and Distributed Model Predictive Control. The special issue appears in June 2011 and contains 12 papers on the topic of the HD-MPC project, among which also a few papers written by authors outside the HD-MPC consortium as well as a joint paper on the HD-MPC four-tank benchmark. Bart De Schutter and Riccardo Scattolini have acted as guest editors for this special issue.

Chapter 1

The special issue of the Journal of Process Control on hierarchical and distributed model predictive control

1.1 Overview

The special issue of the *Journal of Process Control* on Hierarchical and Distributed Model Predictive Control appears in June 2011 (volume 21, issue 5).

We have selected *Journal of Process Control* as the target journal for the special issue on "Hierarchical and Distributed Model Predictive Control" due to its widespread diffusion, its impact factor (2.235), and its excellent match between the subject area and readership of this journal and the primary objective of the HD-MPC project, viz. developing new and efficient methods for distributed and hierarchical control of large-scale, complex, networked systems with many embedded sensors and actuators, and characterized by complex dynamics and mutual influences.

For this special issue the guest editors (and authors of the current deliverable), Bart De Schutter and Riccardo Scattolini, have invited 20 teams participating in the HD-MPC project as well in other related European projects such as WIDE ("Decentralized and Wireless Control of Large-Scale Systems"), EMBOCON ("Embedded Optimization for Resource Constrained Platforms"), and HYCON2 ("Highly-complex and networked control systems") to submit a contribution. This resulted in 14 papers being submitted. These papers were next subjected to the regular review process of the *Journal of Process Control* (JPC). In this context it is important to mention that the reviews of the papers co-authored by one of the guest editors were managed independently by JPC's regional editor for Europe, Prof. Dochain. Moreover, in order to guarantee an independent and anonymous review process, the papers co-authored by the Editor-in-Chief of JPC, Prof. Marquardt, were partly[1] handled outside the JPC on-line review system. The overall review process resulted in 12 papers being accepted, after one or more revisions. These papers are all included in the special issue.

The special issue covers four main subareas of the broad field of hierarchical and distributed Model Predictive Control (MPC), where some papers belong to more than one category: distributed control, distributed optimization, distributed estimation, and applications. More specifically, the papers on distributed control cover negotiation and coordination methods, decentralized control, and hierarchical control. The papers on distributed optimization include decomposition methods, partitioning methods,

[1] During the review period the on-line review system was revised and updated, and as a result anonymity of the reviewers could also guaranteed within the framework of the on-line review system.

and parallel algorithms. The applications considered involve chemical processes, temperature control, hydro-power plants, irrigation and water distribution networks, and a real-life quadruple-tank process.

1.2 Papers in the special issue

Below we list the papers that appear in the special issue, including a brief description of the contents of each paper.

1.2.1 "Distributed model predictive control based on agent negotiation" by J.M. Maestre, D. Muñoz de la Peña, E.F. Camacho, and T. Alamo, pp. 685–697

The authors present a distributed MPC algorithm for a class of distributed linear systems consisting of several subsystems coupled through the inputs. At each sampling time the control agents make proposals to improve an initial feasible solution based on their local cost function, state, and model. These proposals are accepted if the global cost improves the cost corresponding to the current solution. The authors also present conditions that guarantee asymptotic stability of the closed-loop system as well as an optimization-based procedure to design the controller so that these conditions are satisfied.

1.2.2 "Cooperative distributed model predictive control for nonlinear systems" by B.T. Stewart, S.J. Wright, and J.B. Rawlings, pp. 698–704

This paper presents a distributed controller that can stabilize nonlinear systems. A novel nonlinear non-convex optimizer is proposed that uses parallel optimizations and gradient projection and that converges to stationary points. A unique feature of the optimization is that no coordinating optimization is required, and hence the controller is truly distributed. Asymptotic stability is established for the controlled system, and an illustrative example is presented showing the stabilizing properties of the controller.

1.2.3 "Decentralized model predictive control of dynamically coupled linear systems" by A. Alessio, D. Barcelli, and A. Bemporad, pp. 705–714

A decentralized MPC scheme is proposed for large-scale dynamical processes subject to input constraints using the cooperation of multiple decentralized model predictive controllers. Sufficient criteria for asymptotic closed-loop stability are provided, under possible intermittent lack of communication of measurement data between controllers. The approach is also extended to asymptotic tracking of output set-points and rejection of constant measured disturbances. The effectiveness of the approach is shown on a simulation example involving decentralized temperature control.

1.2.4 "Sensitivity-based coordination in distributed model predictive control" by H. Scheu and W. Marquardt, pp. 715–728

This paper proposes a new distributed iterative MPC method for linear time-invariant systems that relies on a sensitivity-based coordination mechanism. Coordination and therefore overall optimality is achieved by means of a linear approximation of the objective functions of neighboring controllers within the objective function of each local controller. An analysis of the method with respect to its convergence properties is provided. For illustration, the proposed sensitivity-driven distributed MPC algorithm is applied to a simulated alkylation process.

1.2.5 "A distributed MPC strategy based on Benders' decomposition applied to multi-source multi-zone temperature regulation", by P.-D. Moroşan, R. Bourdais, D. Dumur, and J. Buisson, pp. 729–737

The authors propose a distributed MPC algorithm for multi-source multi-zone building temperature regulation. The MPC controller minimizes the heating energy cost subject to soft comfort constraints. Using a linear system model of the controlled process, the resulting MPC optimization problem can be solved by linear programming. To reduce the computational demand, the authors propose a distributed MPC algorithm based on Benders' decomposition and using a network of local controllers, coordinated by a master controller.

1.2.6 "Multiple shooting for distributed systems with applications in hydro electricity production" by C. Savorgnan, C. Romani, A. Kozma, and M. Diehl, pp. 738–745

This paper introduces a new method for the solution of optimal control problems for systems composed of many subsystems the dynamics of which are coupled through input-output connections. The proposed approach can be regarded as a generalization of the direct multiple shooting method and exploits the structure of the problem to achieve a highly parallelizable algorithm. The method is applied to the control of a hydro-power plant. The simulation results show that the algorithm performs well in terms of convergence while decreasing the computational load required per SQP iteration.

1.2.7 "An iterative scheme for distributed model predictive control using Fenchel's duality" by M.D. Doan, T. Keviczky, and B. De Schutter, pp. 746–755

The authors present an iterative distributed version of Han's parallel method for convex optimization that can be used for distributed MPC for dynamically coupled linear systems. The underlying decomposition technique relies on Fenchel's duality and allows subproblems to be solved using local communications only. Two distributed algorithms are investigated that aim at improving the convergence rate of the iterative approach. The proposed methods are applied to an irrigation canal network.

1.2.8 "Parallel and distributed optimization methods for estimation and control in networks", by I. Necoara, V. Nedelcu, and I. Dumitrache, pp. 756–766

The paper reviews and analyzes the optimization-theoretic concepts of parallel and distributed methods for solving coupled optimization problems and demonstrates how several estimation and control problems related to complex networked systems can be formulated in those settings. A systematic framework is developed for exploiting the potential of the decomposition structures as a way to obtain different parallel algorithms, each with a different trade-off among convergence speed, message passing amount, and distributed computation architecture.

1.2.9 "Moving horizon estimation for distributed nonlinear systems with application to cascade river reaches", by M. Farina, G. Ferrari-Trecate, C. Romani, and R. Scattolini, pp. 767–774

This paper presents a novel distributed moving horizon estimation method for discrete-time large-scale nonlinear systems that can be partitioned into a number of subsystems with non-overlapping states. In the proposed algorithm, each subsystem solves a reduced-order moving horizon estimation problem to estimate its own state based on the estimates computed by its neighbors. The convergence properties of the method are analyzed and sufficient conditions are derived. The proposed approach is applied to a cascade of three river reaches.

1.2.10 "Partitioning approach oriented to the decentralised predictive control of large-scale systems", by C. Ocampo-Martinez, S. Bovo, and V. Puig, pp. 775–786

The authors propose a graph-theory-based algorithm for the automatic partitioning of large-scale systems into subsystems intended to be applied along with a decentralized MPC strategy. The resulting partition is composed of a set of non-overlapping subgraphs such that their numbers of vertices are similar and the number of edges connecting them is minimal. The proposed approach is used to decompose a dynamical model of the Barcelona drinking water network.

1.2.11 "A hierarchical distributed model predictive control approach to irrigation canals: A risk mitigation perspective" by A. Zafra-Cabeza, J.M. Maestre, M.A. Ridao, E.F. Camacho, and L. Sánchez, pp. 787–799

This paper presents a hierarchical distributed MPC approach applied to irrigation canal planning from the point of view of risk mitigation. The objective is to optimize the operation of the system, taking into account explicitly modeled risks (including unexpected changes in demand, failures in operation, as well as maintenance costs). The proposed approach consists of two levels. At the lower level, a distributed MPC controller optimizes the operation by manipulating flows and gate openings, while the higher level implements a risk management strategy.

1.2.12 "A comparative analysis of distributed MPC techniques applied to the HD-MPC four-tank benchmark", by I. Alvarado, D. Limon, D. Muñoz de la Peña, J.M. Maestre, M.A. Ridao, H. Scheu, W. Marquardt, R.R. Negenborn, B. De Schutter, F. Valencia, and J. Espinosa, pp. 800–815

The objective of this paper is to design, implement, and compare for a real-life four-tank benchmark process eight different MPC algorithms, including centralized and decentralized MPC schemes and several distributed MPC schemes based on cooperative game theory, sensitivity-based coordination mechanisms, bargaining game theory, and serial decomposition of the centralized problem. The results reported show how distributed strategies can improve the performance of decentralized strategies by using the information shared by the controllers.