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PROJECT PERIODIC REPORT

Grant Agreement number: 223854

Project acronym: HD-MPC

Project title: Hierarchical and Distributed Model Predictive Control of Large-Scale Systems

Funding Scheme: STREP

Date of latest version of Annex I against which the assessment will be made: 07/03/08 (approved by commission on 08/03/08)

Periodic report: 1st ☑ 2nd ☐ 3rd ☐ 4th ☐

Period covered: from 01/09/08 to 31/08/09

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the grant agreement

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm ; logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

Declaration by the scientific representative of the project coordinator1

I, as scientific representative of the coordinator1 of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (tick as appropriate):

  ☑ has fully achieved its objectives and technical goals for the period;

  ☐ has achieved most of its objectives and technical goals for the period with relatively minor deviations[3];

  ☐ has failed to achieve critical objectives and/or is not at all on schedule[4].

- The public website is up to date, if applicable.
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 6) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 5 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator1: Bart De Schutter

Date: 23 / 10 / 2009

Signature of scientific representative of the Coordinator1: ....

3 If either of these boxes is ticked, the report should reflect these and any remedial actions taken.

4 If either of these boxes is ticked, the report should reflect these and any remedial actions taken.

1. Publishable summary

Project at a Glance: HD-MPC

Hierarchical and distributed model predictive control of large-scale systems

HD–MPC

Objective:
HD-MPC focuses on the development of new and efficient methods for distributed and hierarchical model-based predictive control of large-scale complex networked systems.

Partners:
Delft University of Technology (*The Netherlands),* Electricité de France SA (*France*), Katholieke Universiteit Leuven (*Belgium*), Politecnico di Milano (*Italy*), Rheinisch-Westfälische Technische Hochschule Aachen (*Germany*), Universidad de Sevilla (*Spain*), Universidad Nacional de Colombia (*Colombia*), Ecole Supérieure d'Electricité (*France*), Inocsa Ingeniería S.L. (*Spain*)

Cooperation partner: University of Wisconsin-Madison (*USA*)

Project web site: http://www.ict-hd-mpc.eu

Project coordinator: Bart De Schutter (*Delft University of Technology*)
Duration: 36 months
Start: September 1, 2008
Total Cost: € 2768861
EC Contribution: € 2000000
Contract Number: INFSO-ICT-223854

Summary: HD-MPC

HD-MPC: Hierarchical and Distributed Model Predictive Control of Large-Scale Systems

Abstract: In this project we develop new and efficient methods for distributed and hierarchical control of large-scale, complex, networked systems with many embedded sensors and actuators, and characterised by complex dynamics and mutual influences.

Keywords: control of complex large-scale systems, hierarchical and distributed control, networked and embedded systems, model-based control

Main Objectives
Manufacturing systems, traffic networks, process plants, electricity networks are often composed of multiple subsystems, characterised by complex dynamics and mutual influences such that local

control decisions may have long-range effects throughout the system. This results in a huge number of problems that must be tackled for the design of an overall control system. Improper control and insufficient coordination of these large-scale systems could result in a hugely suboptimal performance or in serious malfunctions or disasters. Current centralised control design methods cannot deal with large-scale systems due to the tremendous computational complexity of the centralised control task and due to scalability issues and communication bandwidth limitations, all of which make on-line, real-time centralised control infeasible.

The main objective of this proposal is therefore to develop new and efficient methods and algorithms for distributed and hierarchical model-based predictive control of large-scale, complex, networked systems with embedded controllers, and to validate them in several significant applications. We will design these methods to be much more robust than existing methods in the presence of large disturbances, and component, subsystem, or network failures, with a performance approaching that of a fully centralised methodology. The resulting control methods can be applied in a wide range of application fields such as power generation and transmission networks, chemical process plants, manufacturing systems, road networks, railway networks, flood and water management systems, and large-scale logistic systems.

Technical Approach

The new structured and tractable control design methods for large-scale systems we will develop will be based on a hierarchical, distributed model-based control approach in which a multi-level model of the system is used to determine optimal control signals, and in which the controllers operate along several time scales and at different control levels (see figure below). We will develop both the necessary new theory and the corresponding control design methods for using a combination and integration of techniques from computer science, operations research, optimisation, and control engineering. This will result in systematic approaches that outperform existing control strategies, which are often case-dependent and based on heuristics and simplifications.

In order to adapt to dynamic changes in the demands, the structure of the system, and the environment, adaptive on-line control is required. Therefore, we will use a model-based approach, which will allow the controller to predict the effects of future control actions on the system, and to take external inputs and demands into account.

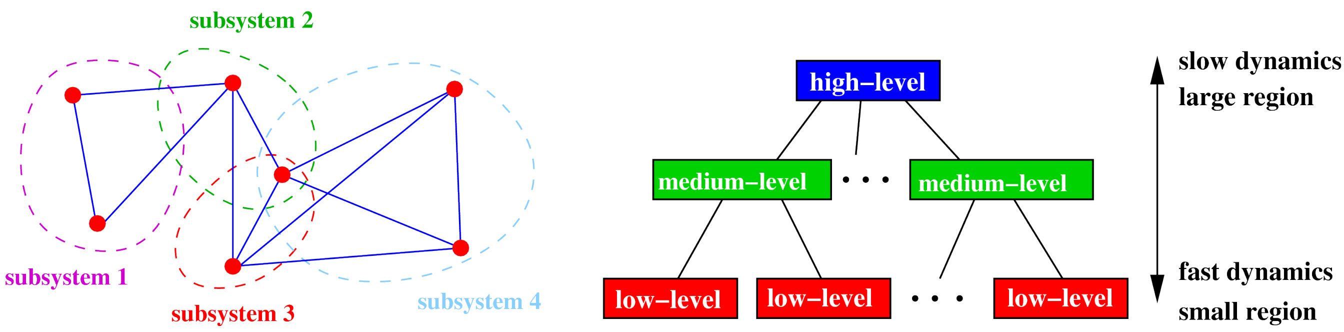

Figure: Illustration of the spatially distributed (left) and hierarchical control (right).

We will also take various aspects of large-scale complex systems into account that are often not considered in current control methods such as their hybrid nature, the variety of – often conflicting – objectives and constraints that play a role, and the interactions between the different time scales of the system dynamics and the control actions. This implies that we need a multi-level, multi-objective, distributed control approach.

Other important aspects of our approach are communication of information between subsystems, and cooperation between their controllers towards a common goal.

In addition to performing fundamental research on hierarchical and distributed control of large-scale systems we also concentrate on applications, in particular on combined cycle plants (CCP), hydro-power valley operations, and water capture systems.

Key Issues

The key challenges that will have to be addressed are:

- developing new, efficient, robust, and scalable methods for on-line, real-time hierarchical and distributed control of large-scale systems,
- appropriately dealing with the computational complexity issues, various types of uncertainty, and coordination and cooperation between the controllers both within and across the control levels,
- integrating the methods within currently deployed embedded sensor and controller structures, so as to allow practical implementation and smooth adoption of the new methods by industry.

In order to address these challenges and to achieve the objectives the research team gathers fundamental and technical core expertise in various fields such as systems and control, chemical engineering, mechanical engineering, electrical engineering, optimisation, operations research, and computer science.

Expected Impact

Due to the use of massive parallel computation and newly developed advanced optimisation and coordination approaches the new MPC methods for large-scale networked systems developed in this project will result in efficient and scalable control methods that – at a fraction of today's effort – can deal with systems that are one or more orders of magnitude larger than what current methods can handle. The new methods will also result in much higher dependability and availability, and significantly reduce maintenance times and costs.

Organization of the Project

In order to carry out the research objectives detailed above, the following work packages have been established:

WP1: Management and coordination
WP2: Definition of the hierarchical architecture for control design
WP3: Development of hierarchical and distributed MPC methods
WP4: Optimization methods for hierarchical and distributed MPC
WP5: Distributed state estimation algorithms
WP6: Hardware and software implementation, and benchmarking
WP7: Validation and applications on simulated plants
WP8: Dissemination

Highlights for Period 1 (01/09/2008-31/08/2009)

In the first year of the project we have accomplished the following results:

- We have compiled a definition and classification of the problems where a distributed or hierarchical control structure is useful. This has resulted in a general formulation of hierarchical MPC.
- We have continued the development of new hierarchical and distributed MPC methods, which has resulted in a nonlinear distributed dynamic optimization method with promising convergence properties. This method has also been successfully applied to a nonlinear process model.
- Several optimization algorithms for linear and nonlinear distributed MPC have been proposed.

- We have started the development of distributed moving horizon state estimation algorithms for sensor networks and for partitioned systems.
- Four benchmark cases have been prepared (including a complete description, models, and related papers): four-tank system, chemical plant, electric network, and heat system.
- For the three industrial case studies, viz., the combined cycle start-up, the hydro-power valley, and the water capture system we have defined the control specification and initiated the development of the prediction models required for the application of hierarchical and distributed control.
- Special sessions on hierarchical and distributed model prediction control have been organized for the 14th Belgian-French-German Conference on Optimization (BFG'09) and the 2010 American Control Conference (ACC'10).

In addition, three joint progress meetings were held in Leuven, Milan, and Rennes, and the cooperation between work packages and partners was further intensified by more dedicated technical meetings, mutual, and exchanges of researchers.

2. Project objectives for the period

According to the Description of Work the following tasks should have been started and/or carried out during the reporting period[5] (M indicates the month counted from the start of the project):

- WP1: Management and coordination
  - Task 1.1: Management (M1-36)
  - Task 1.2: Monitoring and reporting (M1-36)
  - Task 1.3: Knowledge management (M1-36)
  - Task 1.4: Design and implementation of a Virtual Portal (VP) (M1-6)
- WP2: Definition of the hierarchical architecture for control design
  - Task 2.1: Survey (M1-3)
  - Task 2.2: Definition of the control architecture (M4-9)
  - Task 2.3: Extension of the control architecture (M10-15)
  - Task 2.4: Multi-level models (M4-15)
- WP3: Development of hierarchical and distributed MPC methods
  - Task 3.1: Hierarchical and distributed nonlinear MPC (M4-36)
  - Task 3.2: Hierarchical and distributed robust nonlinear MPC (M7-36)
  - Task 3.3: Coordination mechanisms (M7-30)
- WP4: Optimisation methods for hierarchical and distributed MPC
  - Task 4.1: On-line optimisation methods for hierarchical and distributed MPC (M1-36)
  - Task 4.2: Optimisation of uncertain large-scale systems (M1-36)
  - Task 4.3: Optimisation methods for robust distributed MPC (M4-33)
- WP5: Distributed state estimation algorithms
  - Task 5.1: State estimation (M16-33)[6]
- WP6: Hardware and software implementation, and benchmarking
  - Task 6.1: Analysis of hardware and software (M4-24)
  - Task 6.2: Development and implementation of a benchmark model guide (M4-6)
  - Task 6.3: Preparation of benchmarking cases (M7-9)
  - Task 6.4: Implementation of benchmark exercises (M9-18)
  - Task 6.5: Maintenance of the benchmarking service (M19-36)
  - Task 6.6: Dissemination of benchmarking and results (M10-36)
- WP7: Validation and applications on simulated plants
  - Task 7.1: Application to the start-up of a combined cycle plant (M4-36)
  - Task 7.2: Application to the operation of a hydro power valley (M4-36)
  - Task 7.3: Short-term and long-term control of a large-scale water capture system (M4-36)
- WP8: Dissemination
  - Task 8.1: Setting up a web site (M4-6)
  - Task 8.2: Organizing special sessions at conferences or special issues of journals (M10-15, M25-30)

[5] See pages 21-24 of the Description of Work for a complete overview.
[6] Although this task should only start in month 16, it is listed here also as work on this task has already been started.

- Task 8.4: Industrial short courses (M19-24, M28-33)[7]

The tasks listed above can be detailed as follows according to the Description of Work (pages 28-54):

WP1: Management and coordination

- *Task 1.1: Management (M1-36):*
  This includes the establishment of a steering committee (with one member per participant), the organisation of the kick-off meeting, the annual project meetings, and the regular work package meetings (at least twice a year).
- *Task 1.2: Monitoring and reporting (M1-36):*
  This includes regular monitoring of the progress within the work packages, managing the annual report, etc.
- *Task 1.3: Knowledge management (M1-36):*
  This includes putting information on the project's (intranet) web site (see also Task 1.4) with a list of available equipment, software, and set-ups, so as to facilitate integration of resources, establishing links with potential users of results developed in project and other interested parties, solving IPR issues, etc.
- *Task 1.4: Design and implementation of a Virtual Portal (VP) (M1-6):*
  The VP has to permit the communication among partners and the integration of remote experiences in a unique virtual space. This task will state the requirements of this environment and will design and implement the software infrastructure to support it. The development will be based on open source tools.

WP2: Definition of the hierarchical architecture for control design

- *Task 2.1: Survey (M1-3):*
  We will start with a survey of the state-of-the-art with focus on hierarchical and distributed control architectures that could be used for MPC. We will perform a qualitative assessment of strong and weak points of existing architectures, and identify options for improvement.
- *Task 2.2: Definition of the control architecture (M4-9):*
  This includes the definition of a hierarchical control architecture that integrates sequential decisions in the global MPC scheme, and the definition of a hierarchical control architecture that integrates at each level various optimisation criteria (quadratic, linear, etc.) and control schemes (MPC, classical PID, etc.)
- *Task 2.3: Extension of the control architecture (M10-15):*
  We will adapt the architecture and control schemes to improve the availability in response to changes in the subsystems. Moreover, we will adapt global control to take in account the availability of distributed controllers and of the communication network as well as other network constraints for distributed subsystems that could arise in practical applications.
- *Task 2.4: Multi-level models (M4-15):*
  In this task we will explore ways to define and to construct models that are consistent with the hierarchical level of each controller. This includes multi-level, multi-resolution models, i.e., models with various levels of spatial and temporal aggregation. We will also investigate and assess

[7] Although this task should only start in month 19, it is listed here also as work on this task has already been started.

existing reduction and aggregation methods to obtain such models, and select those that are most suited for hierarchical and distributed MPC.

WP3: Development of hierarchical and distributed MPC methods

- *Task 3.1: Hierarchical and distributed nonlinear MPC (M4-36):*
  This task has the following subtasks:
  - Task 3.1.1: Literature review: In order to assess the strong and weak points of existing methods and to identify the most suitable methods that can serve as a starting point for the hierarchical and distributed nonlinear MPC we first review relevant literature from the 60s and 70s. Main ideas and concepts are summarised. Recent literature will be reviewed as well. Existing approaches are analysed, evaluated, and compared. This comparison will reveal the relationship between the approaches. A common framework will be established comprising all concepts. Based on this, a focus is put on nonlinear approaches.
  - Task 3.1.2: Method development: Based on the literature review, new ideas on extending concepts from linear distributed MPC to the nonlinear case are further developed based on the results of WP2. Step by step, complexity is increased starting from linear, stationary, and unconstrained problems up to nonlinear, dynamic, and constrained control problems. It is very likely that there is a balance between speed of convergence of the approaches and the amount of information that needs to be shared among the agents and/or the higher-level coordinators. Hence, variants of the methods are developed which differ in the amount of required information. This is also closely related to the coordination mechanisms that are examined and developed in Task 3.3. Appropriate methods are finalised that are tailored to the amount of possible sharing in real-life processes
  - Task 3.1.3: Implementation: The proposed methods as well as selected approaches from literature are implemented in a suitable programming environment as, e.g., Matlab or Octave, such that the methods can easily be shared among the partners.
  - Task 3.1.4: Evaluation: All developed approaches are evaluated using case studies of varying complexity. Benefits and drawbacks are highlighted. The expected impact and economical potential are evaluated and documented. Suggestions for application to real life processes are given (see also WP7 (Validation and applications on simulated plants)).

- *Task 3.2: Hierarchical and distributed robust nonlinear MPC (M7-36):*
  This task has the following subtasks:
  - Task 3.2.1: Literature review: In order to assess the strong and weak points of existing methods and to identify the most suitable methods that can serve as a starting point for the development of our own methods, the literature for optimisation methods of uncertain and disturbed systems in general with a focus on centralised robust MPC is reviewed. Recent articles on distributed robust and fault-tolerant MPC are also reviewed and compared.
  - Task 3.2.2: Method development: Interaction of single controlled subsystems has to be taken into account by hierarchical and distributed robust MPC schemes, additionally to model uncertainties and external disturbances, which are also common to centralised robust MPC approaches. The influence of control actions and state trajectories of one subsystem on other subsystems are treated as additional disturbances. Methods for hierarchical and distributed robust MPC are developed starting from our own robust optimisation approaches. Initially, investigations focus on strategies for distributed robust steady-state optimisation. Complexity is gradually increased, ultimately resulting in a method to solve hierarchical and distributed robust and fault-tolerant nonlinear dynamic problems. These robust approaches have to guarantee that process constraints are not violated despite uncertainties, disturbances and interactions between subsystems. Generally, more conservative results are obtained for larger

uncertainties. Therefore, the developed methods also allow to quantify the economic impact of robustness and to assess the potential gain of increased information sharing.

- Task 3.2.3: Implementation and applications: The developed robust optimisation methods are implemented in a suitable programming environment such as Matlab or Octave to enable easy sharing of methods and code among the partners (this task is closely related to Task 4.3 of work package WP4 (Optimisation methods for hierarchical and distributed MPC)).
- Task 3.2.4: Evaluation: All developed approaches are evaluated using case studies of increasing complexity, and benefits and drawbacks are highlighted. The impact on the economics and on safe operability of distributed processes is evaluated.

Note that Task 3.2 is closely related to Task 4.3 (Optimisation methods for robust distributed MPC). Both tasks will interact and cooperate, where Task 3.2 mainly focuses on problem formulation and method development for robust distributed MPC and where Task 4.3 deals with the development (stochastic) optimisation algorithms for robust distributed MPC.

- *Task 3.3: Coordination mechanisms (M7-30):*

Two features required for achieving high performance in hierarchical and distributed control systems are communication between and cooperation among the subsystems. Using MPC for the low-level or local subsystem controllers provides rich capabilities for both communication and cooperation. MPC allows communication not only of the current control moves, but also the full horizon of planned control moves. The availability of each subsystem's future plans enables a high degree of coordination between the many interconnected systems. A goal of this research is to design the communication protocols between these subsystems.

For strongly interacting subsystems, it is generally insufficient to achieve only closed-loop stability by damping the behaviour of strongly interacting subsystems. However, the performance loss is large in these cases. By instead changing the objective functions to achieve cooperation and coordination, closed-loop performance near that of centralised control is achievable while maintaining the modularity of separate subsystems. A specific goal of this task is to design the protocols to modify the local agents' objective functions to ensure cooperation and coordination between strongly interacting subsystems. Naturally a further consideration in this design is to achieve these goals while minimising the overhead in communication and cooperation imposed on the subsystems. All this is closely related to Task 3.1, in which methods for hierarchical and distributed MPC are developed. The strong interaction between the participants of both tasks will yield high mutual benefits and integrated solutions.

WP4: Optimisation methods for hierarchical and distributed MPC

- *Task 4.1: On-line optimisation methods for hierarchical and distributed MPC (M1-36):*

The first goal of this task is to provide all partners with a collection of existing state-of the-art MPC optimisation algorithms, and to apply these algorithms to the hierarchical and distributed MPC and estimation formulations developed in the other work packages. Second, in addition to the stability questions of distributed MPC formulations that is investigated in other work packages, the suboptimality of existing distributed MPC formulations will be assessed and new distributed optimisation methods shall be developed that provably converge to the optimal solution of the centralised optimization problem. For these newly developed algorithms we will also provide an analysis of the convergence speed towards the centrally optimal solution. Finally, efficient optimization algorithms and hot-starting techniques will be developed that exploit the specific structures of the distributed MPC formulations for fast real-time optimisation. The newly developed algorithms will be documented, shared with the partners and in a later phase made public as open-source software.

- *Task 4.2: Optimisation of uncertain large-scale systems (M1-36):*

Decision making under uncertainty, both on medium-term and long-term basis, requires a redefinition of the criteria and methodologies used in current static optimisation methods. Criteria such as mini-max, risk avoidance, multi-goal and probabilistic issues play an important role. The uncertainty level in the process model parameters must also be taken into account. This task involves the following steps:

- Problem analysis and choice of most appropriate approaches that can serve as the starting point for newly developed methods
- Redefinition of optimality criteria
- Generation of optimal solutions
- Sensitivity analysis with respect to parameters
- Analysis of scalability of solutions and computing cost.

Task 4.2 will closely interact with Task 3.2 (Hierarchical and distributed robust nonlinear MPC), where Task 3.2 mainly focuses on problem formulation and method development for robust distributed MPC and where Task 4.3 deals with the development of (stochastic) optimisation algorithms for robust distributed MPC.

- *Task 4.3: Optimisation methods for robust distributed MPC (M4-33):*

The design of hierarchical control systems presents several opportunities for the use of optimization techniques that are the focus of extensive current research. They also present several challenges.

Simplified models of subsystems at the lower levels, or cooperating subsystems on thesame level, will inevitably be inexact. Moreover, the measurements that are made inthe process of evaluating functions will contain noise and possibly other, more systematic errors. The function and gradient evaluations that are occurring in the optimisation/control process running on an individual subsystem will thus contain errors of different kinds. How can we ensure that the decisions produced by these optimization processes are robust in the presence of these errors? Can we quantify the suboptimality of the decisions, as a function of model and measurement error, and thus understand which of these errors has the biggest impact on the quality of the control decisions? How can we propagate the random error distributions (see also the discussion of variance estimation in WP5) through the model into the objective, and thus into the control decisions?

The rapidly developing field of robust optimisation (to which researchers in control have already contributed a great deal) may be able to contribute to resolving these issues. Cross-fertilisation with formulation and solution techniques from stochastic optimisation, along with recent applications to financial problems, have yielded results that should be investigated in the setting of control problems, including distributed control. Among topics that may be applicable are chance constraints (guaranteeing satisfaction of constraints to a specified level of probability) and value-at-risk objectives (in which the underlying objective is recognised as being a distribution, rather than a single objective, and we will optimise some function of the "tail" of this distribution, that is, its performance in the worst cases).

WP5: Distributed state estimation algorithms

- *Task 5.1: State estimation (M16-33)[8]:*

Consider the discrete-time, possibly nonlinear system subject to random disturbances in the state evolution and measurement: $x(k+1) = F(x(k),u(k)) + Gw(k)$, $y(k) = H(x(k)) + v(k)$, in which w, v are zero-mean, normally distributed random variables. The state estimation problem can be compactly summarised as finding the maximum of the conditional probability $p(x(k)|y(0),\ y(1),$

[8] Although this task should only start in month 16, it is listed here also as work on this task has already been started.

…,$y(k)$), written as $p(x(k)|Y(k))$. This close link between state estimation and optimisation allows us to formulate and solve many distributed state estimation problems in the same fashion that we formulate and solve distributed regulation and control problems in the other working packages. The two problems of regulation and state estimation are similar, but not identical, however, and we focus here on their differences and the special requirements for state estimation that are unnecessary for distributed regulation.

The first important difference is the disturbance model used in the state estimation problem. In order to remove steady offset in selected outputs (which may be states or functions of states), the system model above is augmented with integrating disturbance models. The augmented model then takes the form $x(k+1) = F(x(k),u(k),d(k))+Gw(k)$, $d(k+1) = d(k)+\xi(k)$, $y(k) = H(x(k),d(k))+v(k)$, and the state estimation problem is now to find the maximum of the state, disturbance pair conditioned on the measurements $p(x(k),d(k))|Y(k))$. So a significant design issue for the distributed system is to choose the number and location of the integrating disturbances. The goals of this disturbance design are (i) to remove offset in the outputs of interest, and (ii) to create a detectable system so each subsystem's measurements are adequate to estimate the subsystem's state and disturbance pair.

WP6: Hardware and software implementation, and benchmarking

- *Task 6.1: Analysis of hardware and software (M4-24):*
  - Hardware: Distributed systems require a network of sensing devices as well as local actuators to enhance the effectivity of decisions.
  - Software: Analysis of operating systems, middleware incorporation with high-level communication capabilities, visualisation components of the system state.
- *Task 6.2: Development and implementation of a benchmark model guide (M4-6):*
  This task consists of developing a model guide to help partners to develop benchmark exercises and will take the shape of a web-based computer tool.
- *Task 6.3: Preparation of benchmarking cases (M7-9):*
  A collection of real and simulated benchmark cases will be prepared using the tool developed in the previous subtask. For each test case, an exhaustive description of its main technological and operational data as well as of the main performance criteria will be provided. Also, best existing solutions and their performance values will also be included. The test cases will be provided by partners and they will consist of processes and research infrastructure, simulation models, and other tools already existing in the labs of the partners (see also WP7).
- *Task 6.4: Implementation of benchmark exercises (M9-18):*
  This task will start with the collection and selection of proposals and will go on with the implementation of the experiments. It also includes the preparation of test reports, the analysis of benchmark tests, and adoption of best practises.
- *Task 6.5: Maintenance of the benchmarking service (M19-36):*
  This is a key task because benchmarking is, above all, a practical and heuristic tool which is constantly evolving in the light of ever increasing experience. This task consists of maintaining alive the benchmark library by the introduction of new test results on existing experiments, deletion of obsolete test cases, introduction of new test cases, and modification of existing test cases.
- *Task 6.6: Dissemination of benchmarking and results (M10-36):*

The main objective of this task is to disseminate the benchmark library and knowledge acquired from the benchmarking exercises inside and outside the project (see also Tasks 1.3 and 1.4 of work package WP1).

WP7: Validation and applications on simulated plants

- *Task 7.1: Application to the start-up of a combined cycle plant (M4-36):*
  Power plants are complex systems that are usually hierarchically controlled. The global control structure and the coordination between local controllers are in general determined using heuristics and experience, and the question remains open whether the chosen solution is optimal. The project proposes a new scientific approach to find a global optimal solution. In this task we will study the applicability of the control design methods for hierarchical and distributed MPC to power plant applications. First, we will build a model of a combined cycle plant. The plant model will be decomposed in several interconnected submodels. A distributed and hierarchical control system will also be simulated in order to implement the global distributed MPC scheme. In order to validate the applicability of the approach and its robustness, some loops of the lower level will be controlled by classical PID controllers. This task will consist of the following subtasks or stages:
  - Stage 7.1.1: Control specification,
  - Stage 7.1.2: Modelling of the plant,
  - Stage 7.1.3: HD-MPC design validation.
- *Task 7.2: Application to the operation of a hydro power valley (M4-36):*
  In this application the control will be hierarchical with several local controllers regulating a dam (water level and turbine power) and a global controller that coordinates the sum of the productions. We will build a model of a valley and will test the distributed MPC. This task will consist of the similar subtasks as for Task 7.1:
  - Subtask 7.2.1: Control specification,
  - Subtask 7.2.2: Modelling of the plant,
  - Subtask 7.2.3: HD-MPC design validation.
- *Task 7.3: Short-term and long-term control of a large-scale water capture system (M4-36):*
  This application involves a water capture system consisting of rivers, reservoirs and watering channels. The objective is to design short-term and long-term control systems for the water reception in the different sources: rivers, reservoirs, channels, etc., so that flows requested are guaranteed for the different types of users while also guaranteeing the ecological minimum flows. At the same time the control systems will keep in mind the meteorological forecasts with the objective to predict possible periods of rain/dryness that can affect the available storage notably. This task will consist of two subtasks:
  - Subtask 7.3.1: Modelling for hierarchical and distributed MPC,
  - Subtask 7.3.2: Predictive management of water resources.

WP8: Dissemination

- *Task 8.1: Setting up a web site (M4-6):*
  We will set up a dedicated web site for the project that will be used to disseminate the project results (including press releases, downloads of reports, presentations, videos, open-source software, and a database of benchmark problems). To reach a broad audience we will provide interfaces for the developed software with Matlab and/or Octave. The web site will also contain two restricted access entry points, one for the Commission, and one for the reviewers, so that they can also access deliverables and other documents that are not available to the general public.

- *Task 8.2: Organizing special sessions at conferences or special issues of journals (M10-15, M25-30):*
  We will organise invited sessions at leading international control conferences (IEEE CDC, IFAC, ECC, ACC, etc.), or a special issue or a special section of international control journals (Automatica, IEEE Transactions on Automatic Control, International Journal of Control, European Journal of Control, ...).
- *Task 8.4: Industrial short courses (M19-24, M28-33)[9]:*
  We will offer industrial short courses on the topics of the project to transfer the developed methods to industry. The goal of these industrial short courses is to present the state-of-the-art and the new methods for hierarchical and distributed control of large-scale networked systems to industry, consultancy and engineering firms, and other interested parties, to give them insight in the applicability of the methods in a broad range of fields (including, but not limited to, the benchmarks considered in WP6 and the case studies of WP7), and to give them a hands-on experience via case studies and assignments in which the tools developed in this project will also be used.

The following milestones should have been reached during the reporting period (see also Section 4):

- M1.1.1: Kick-off meeting of the project (M1)
- M1.1.2: Installation of the steering committee (M1)
- M1.1.3: First annual meeting (M12)
- M1.4.1: Definition of the requirements for the virtual portal (M3)
- M1.4.2: Implementation and opening of the virtual portal (M6)
- M2.1: Analysis of the available methods for system decomposition (M3)
- M2.2: Definition of decomposition procedures for distributed estimation and control (M9)
- M3.1.1: Analysis of existing methods for hierarchical and distributed nonlinear MPC, and simple own methods implemented and shared with partners (M12)
- M3.2.1[10]: Analysis of existing (optimisation) methods for robust distributed MPC (M12)
- M4.1.1: Analysis of suboptimality of existing algorithms (M9)
- M4.2.1: Choice of appropriate tools for optimisation of uncertain large-scale systems, and redefinition of the optimality criteria (M12)
- M6.2.1: Distribution of the model guide and opening of the web-tool (M9)
- M7.1.1/M7.2.1: Control specification for the combined cycle start-up and for the hydro-power valley available (M12)
- M7.3.1: Meteorological forecasting model (M12)
- M8.1.1: Opening of a web site including downloads of reports, presentations, open-source software and a database of benchmark problems (M6)

In addition the following deliverables should be produced during the reporting period (see also Section 4); these deliverables document how the milestones listed above have been realized and reached:

- D1.2.1: First annual progress report (M12)
- D1.4.1: Report on the requirements for the virtual portal (M3)

[9] Although this task should only start in month 19, it is listed here also as work on this task has already been started.
[10] This milestone is a joint milestone of WP3 (Task 3.2) and WP4 (Task 4.3).

- D2.1: Report on literature survey and preliminary definition of the selected methods for the definition of system decomposition and hierarchical control architectures (M6)
- D2.2: Report on the final assessment of the methods for the definition of the control architecture and preliminary report on extended algorithms coping with structural constraints, changes, and multi-level models (M12)
- D3.1.1: Report on literature survey on hierarchical and distributed nonlinear MPC, including analysis and comparison, and description of the resulting methodological framework (M12)
- D3.1.2: Report on readily available methods for simple toy problems (M12)
- D3.2.1[11]: Report on literature survey and analysis of (optimisation) methods for robust distributed MPC (M12)
- D4.1.1: Report of literature survey, analysis, and comparison of on-line optimisation methods for hierarchical and distributed MPC (M6)
- D4.1.2: Overview, toolbox and tutorial manual of existing state-of-the-art distributed optimisation algorithms (M12)
- D4.2.1: Report of literature survey and analysis of optimisation methods for MPC of uncertain large-scale systems (M9)
- D6.2.1: Model guide and web-based computer tool for benchmarking (M9)
- D6.3.1: Documentation for benchmark cases (M12)
- D7.1.1: Report that defines the control specification for the combined cycle start-up (M12)
- D7.2.1: Report that defines the control specification for the hydro-power valley (M12)
- D7.3.1: Report on meteorological forecasting models (M12)
- D8.1.1: Report on the set-up of a web site including downloads of reports, presentations, open-source software and a database of benchmark problems (M3)

Moreover, a *draft* of the following deliverables (for month 15) has been promised:

- D3.3.1: Report on assessment of existing coordination mechanisms for simple case studies, and on possible options for improving and extending these coordination mechanisms (M15)

[11] This deliverable is a joint deliverable of WP3 (Task 3.2) and WP4 (Task 4.3).

3. Work progress and achievements during the period

WP1: Management and coordination

Please note that – as requested in the guidelines for producing this report – Tasks 1.1 (Management) and 1.2 (Monitoring and reporting) of this work package will be reported upon in Section 5.

Objectives

The goal of this WP is to coordinate, to monitor, and to supervise the progress of the project as a whole, and to coordinate the interactions between the work packages and participating groups. Related activities are the coordination of the dissemination package that is associated with the periodic and the concertation with other FP6 and FP7 ICT projects working in the area (see also WP8).

Progress and achievements

All tasks within this work package are progressing as required. The intranet web site (Task 1.3) and the Virtual Portal (Task 1.4) have been set up and are now fully operational.

The intranet web site is currently tied to the main public web site and the participants area can be accessed through the HD-MPC main web page or directly at http://www.ict-hd-mpc.eu/participants. On the intranet web site there are now three password-protected regions: one for the participants, one for the reviewers, and one for the commission. Likewise, the Virtual Portal also offers (personalized) password-protected access to all participants, and password-protected for the reviewers and the commission. The intranet provides the participants (as well as the reviewers and the commission) access to information about the upcoming and past HD-MPC meetings (agenda, minutes, presentations), the HD-MPC logo (in various formats) as well as a dedicated HD-MPC style for presentations (in Powerpoint and LaTeX formats), cover page for HD-MPC deliverables (in Word and LaTeX), pdf files of papers published by other participants within the framework of the project, and presentations by other participants within the framework of the project.

The objective of the Virtual Portal is to permit the communication among HD-MPC partners and to share experiences, documentation, and software in a virtual space. Also it must serve as a document repository and distribution tool among all project participants and ensure the privacy requirements of contents. In the reporting period we have implemented the Virtual Portal using a Content Management System based on open-source tools. The Virtual portal has been implemented at a server located at USE and can be reached at http://www.nyquist.us.es/hdmproject.
The guidelines and requirements of the Virtual Portal have been established and documented in Deliverable D1.4.1. The Virtual Portal now gives access to deliverables (including sources), and information about HD-MPC events and technical meetings. The Virtual Portal also has dedicated areas for each individual work package, and it features a forum and a directory.
Ongoing activities include the maintenance of the Virtual Portal: creating new users if required, making back-ups, adding new content, adding new main areas, etc.

Due to the rather high overlap between the intranet and the Virtual Portal, we plan to integrate them in the near future and merge the current intranet into the Virtual Portal.

Resources

Resources for this work package have been used as planned in the description of work.

WP2: Definition of the hierarchical architecture for control design

Objectives

The objective of this work package is to define and to establish appropriate *control architectures* for distributed and hierarchical control. This will serve as a basis for the other work packages.

Progress and achievements

Task 2.1: Survey

In the first phase, a survey on the most promising results and open problems in Model Predictive Control (MPC) for linear and nonlinear systems has been performed (Magni and Scattolini, 2009). Then, the literature on hierarchical and distributed control has been reviewed, paying particular attention to the algorithms based on the MPC approach (Scattolini, 2009). This phase has allowed us to classify the approaches adopted so far as follows:

- Decentralized control schemes, where the plant inputs and outputs are partitioned into disjoint sets and local regulators are designed to achieve both performance and overall closed-loop stability. Although this approach is very popular in industrial applications, strong results based on MPC synthesis are still lacking and effort must be paid to develop new and efficient methods, with particular attention to output feedback laws.
- Distributed control schemes, where local regulators can exchange information to compensate for mutual interactions. Many methods already proposed are based on a dynamic game approach, where any local control unit is viewed as a player which can cooperate or not with its neighbourhoods. Also in this case, most of the algorithms assume that the plant state is known and rely on linear models. The extension to nonlinear models and output feedback schemes is mandatory to cope with the majority of industrial control problems.
- Hierarchical control systems, where the adopted multilevel structure can be used for: (a) coordination of local regulators; (b) design of control laws operating at different time scales for systems characterized by a significantly different dynamic behaviour; (c) design of multilayer control structures based on different abstract models of the plant to cope with high level objectives, typically minimizing an economic criterion, and with specific dynamic control problems. Although many methods have been proposed so far, still MPC methods with stability and robustness properties are missing.
- Coordinated schemes, where the goal is to control a number of dynamically decoupled systems which must contribute to the fulfilment of a common objective. Although this problem is not central in the HD-MPC project, still it must be considered to include cases such as the coordination of autonomous vehicles.

Details on the results obtained have been thoroughly described in Deliverable D2.1 and in (Magni and Scattolini, 2009) and (Scattolini, 2009), while an additional state-of-the-art analysis on hierarchical and distributed architectures in control (especially on MPC) showing their main advantages and disadvantages has also been reported in (Valencia and Espinosa, 2009).
This task can be considered as completed and all the objectives have been achieved.

Task 2.2: Definition of the control architecture

The final outcome of Task 2.1 is that a unifying framework for the design of hierarchical control schemes with MPC is still largely missing. For this reason, the research activity has focused on the development of a mathematical formulation of the problem by considering a three layers structure and different time scales. The adopted approach can be used to characterize the following cases:

- *Case 1*: Plants under control composed by many process units, so that it is advisable to design a high level regulator optimizing the overall performance and coordinating the underlying units. The overall controller is organized into a cascade structure where the high level regulator computes the reference signals for the systems at the lower level, which are endowed with local controllers and provide the higher level with the required (control) actions. Additional information may be transmitted from the lower level to the upper one to guarantee the feasibility of the provided references.
- *Case 2*: Systems characterized by significantly different dynamic behaviour, often called singularly perturbed. In this case, the control action is due to two main contributions: a regulator working at low frequency and accounting for the slow dynamics produces both the value of the control variables with a long term effect and the references for another regulator working at a higher frequency. In turn, the latter regulator computes the values of the manipulated variables with a short term effect, so as to obtain a tighter control action and to reject disturbances.
- *Case 3*: Hierarchical control schemes for plant-wide control, where different models of the system under control are used to design regulators working at slow and high frequencies. At the higher level of the hierarchy a simplified model is used to compute the reference values for the lower level by minimizing a cost function usually based on economic considerations. At the lower level a dynamic model is used for the synthesis of a regulator (typically designed with MPC) guaranteeing the proper effective control action.
- *Case 4*. Another version of the scheme described in case 3, consisting of a top layer with a static model of the system used to fix the set-point for the lower level controllers. Such a model, in this case, may also be quite detailed.

For any layer, starting from the highest one which corresponds to the representation of the system in the slowest time scale, an MPC problem is formulated and its solution is transmitted to the lower layer until the procedure is completed. More specifically, at any layer the corresponding MPC algorithm computes both its own control variables and the reference values for the lower layer. The performance index to be minimized at any layer is very general, so as to include different specifications and goals. Notably, at the lowers level of the hierarchy, standard industrial regulators can be used, so as to simplify the design procedure and to consider the majority of industrial control solutions, where the actuators' regulators are PID.

The mathematical formulation of the MPC problem for the hierarchical structures corresponding to the cases discussed above has been extensively described in Deliverable D2.2 and in (Picasso et al., 2009).

A hierarchical structure of the control system fitting with Case 3 has also been considered in (Negenborn, Leirens, et al., 2009), where the design of a higher-layer controller using MPC is considered. The higher-layer controller uses MPC to determine set-points for controllers in a lower control layer.

Formal proofs of stability for the proposed hierarchical structure are still under development, and will be the object of an in-depth analysis in the framework of Work Package 3. Further extensions will concern the development of output feedback methods based on the use of state estimators working at the different layers of the hierarchical structure.

The research activity related to Tasks 2.1 and 2.2 has been used for the definition of a control architecture for the case studies of the Hydro Power Valley and the Combined Cycle application (WP7). In particular, for the Hydro Power Valley, a 2-level control structure has been envisaged, that consists of:

- local controllers that optimize the compromise between the power production and the level regulation;

- a global optimiser that send signals to each power plants to coordinate them. This architecture is described in detail in the report D7.2.1, where four means to achieve the coordination have been considered: the price decomposition, the quantity decomposition, the Interaction Prediction Principle and the cascade decomposition.

Concerning the Combined Cycle application, the definition of the control architecture is still under development, and will be extensively described in Deliverable D7.1.1.

Another significant application of a hierarchical control architecture has been discussed in (Negenborn, van Overloop, et al. 2009b), where irrigation canals have been considered. These are large-scale systems, covering vast geographical areas, and consisting of many interconnected canal reaches that interact with control structures such as pumps and gates. The control of such irrigation canals is usually done in a manual way, in which a human operator travels along the irrigation canal to adjust the settings of the gates and pumps in order to obtain a desired water level. In the paper it has been discussed how distributed MPC can be applied to determine autonomously what the settings of these control structures should be. In particular, the application of a distributed MPC scheme for control of the West-M irrigation canal in Arizona has been proposed. A linearised model representing the dynamics of the canal has been derived, and a distributed MPC scheme has been developed, that uses this model as a prediction model. The performance of the scheme has been tested in simulation studies on a nonlinear simulation model of the canal.

In view of the results achieved, the Task 2.2 can be considered as completed and all the initial goals have been achieved. Further details on the results obtained are described in Deliverable D2.2.

Task 2.3: Extension of the control architecture

With reference to the hierarchical architecture developed in Task 2.2, the communication protocol regulating the information exchange among the layers has been considered, so as to coordinate the control actions computed at the different levels. First, the basic communication rules have been established, and next two alternative protocols have been proposed.

The basic communication rules are

1. Let k_f be the discrete time index related to the base fast time scale associated to the dynamics of the lowest level of the hierarchical structure, k_m (multiple of k_f) the discrete time index related to the medium time scale associated to the intermediate level and k_s (multiple of k_m) the discrete time index related to the slow time scale associated to the highest level. At every instant k_f, each level is supposed to know the current value of its state and control.
2. At any long sampling time (k_s), the high level communicates to the middle level its current control value and the computed reference values for the state and the control variables of the middle level.
3. At any long sampling time (k_s), the middle level communicates to the low level the control value associated (and received) to the high level. At any intermediate sampling time (k_m) the middle level communicates to the low level its current control value the computed reference values for the state and the control variables of the lower level.

The knowledge of the state of the higher level is needed by the MPC controller at the middle level and the availability of the states at both the high and medium levels is needed by the MPC controller at the low level. Then more information must be exchanged between the layers. To this regard, two communication protocols are proposed. These protocols are extensively described in Deliverable D2.2, while only their main characteristics are summarized here.

In Protocol 1 there is an exact pyramidal structure of the information on the system: any level has no information concerned with the lower levels and the lowest level knows everything on the system.

In Protocol 2, the amount of information exchanged is much larger than that in Protocol 1. On the other hand, Protocol 2 allows one to reduce the information transmitted by the high level (i.e., the top level of the hierarchy is less pressed with information requests). However, such a reduction is to be counterbalanced by a large amount of information to be transmitted by the low level. As a consequence, there is an information redundancy at the middle level; in fact the whole information on the system is available.
In both Protocols 1 and 2, tolerance to unmodelled disturbances affecting the system can be gained if the information transmission from the middle level to the low level is more frequent: e.g., if at any intermediate sampling time (km) the middle level communicates to the low level the value of the state at the high level (which has received by the high level, in case of Protocol 1, or which has reconstructed, in case of Protocol 2) and its current state.
In view of the results achieved, the analysis of the problems related to the communication network and of the communication protocols can be considered as almost completed and all the details on the results obtained are described in Deliverable D2.2 and in (Picasso et al., 2009).
A further analysis of the communication protocols and limitations could concern the presence of transmission delays and/or loss of information. However, it is believed that this particular aspect must be analyzed in the framework of WP3 (Task 3.4) since the possible solutions are strictly dependent on the specific control algorithms adopted.

Further work has to be done within this task to cope with the requirement to adapt the proposed hierarchical architecture to varying conditions. To this regard, at any layer it is possible consider the possibility that the subsystems at the lower layers, which can be viewed as the equivalent of actuators, can be in use or not depending on the specific control tasks to be completed. In the context of MPC, this can be trivially done by including in the problem formulation a number of binary variables, one for each subsystem, taking the value 1 (switch on) or 0 (switch off) depending on the configuration adopted. These additional logical control variables must be optimized on-line together with the "continuous" input variables computed and applied at any layer of the structure. In so doing, it is possible to include in the problem formulation also a "plug-and-play" procedure allowing one to optimize the control configuration. On the other hand, the resulting optimization problem turns out to be of a mixed-integer nature, so that the computational effort required is higher. Furthermore, additional logical conditions must be considered as well, through explicit or implicit (soft) constraints, to avoid unrealistic switch on/off of the subsystems (actuators). The problems related to time varying control architectures will be further analyzed in the final part of the work package and, mainly, in WP3.

Task 2.4: Multi-level models

A number of approaches have been analyzed and reported in Deliverable D2.1 for the solution of the following problems for linear systems:

1. decomposition of a dynamical system into a number of weakly interacting subsystems;
2. representation of a dynamical system at different levels of abstraction for the design of decentralized/distributed or hierarchical control systems.

These problems can be solved according to different rules and goals:

1. A functional/spatial decomposition aimed at minimizing the control system complexity while still guaranteeing a given level of performance. In this context, it is necessary to choose the proper controlled outputs; to select the inputs to manipulate; to partition the system into weakly interacting subsystems, to define the control structure, to synthesize the control law.
2. A temporal decomposition where different dynamic behaviours (fast/slow) of the system must be recognized so as to facilitate the synthesis of controllers working at different time

scales. Another important problem concerns the representation of the system at different levels of abstraction where the higher levels describe the slow system dynamics. This representation naturally leads to the design of hierarchical control systems where the top control level defines the system operating conditions usually according to economic criteria, while the lower levels are more related to the control of the plant units.

The research activity concerned with Task 2.4 was aimed at surveying the available methods already proposed in the literature, which can be classified as follows (see Deliverable 2.1):

a) methods based on the Relative Gain Array (RGA) for the "optimal" grouping of inputs and outputs into disjoint sets and for the subsequent design of decentralized and distributed controllers
b) decomposition approaches based on the analysis of the controllability and observability gramians, again for spatial and functional decomposition;
c) model reduction techniques for temporal decomposition of the system under control and for the design of hierarchical control structures as defined in Tasks 2.1.and 2.2. Specifically, these approaches are based on the analysis of the system's singular values and can be used both to define the structure of singularly perturbed systems, characterized by significantly different dynamic behaviours, and to derive different abstract representations of the overall system for real-time optimization. A further temporal decomposition approach based on the analysis of the system's eigenvalues has been examined (see Calderon, 2009).

A different classification has been described in (Calderon and Espinosa, 2009), where five categories to decompose a system hierarchically have been proposed. The five categories are: decomposition by abstraction levels, decomposition by complexity levels, decomposition by functional levels, decomposition by temporal levels and decomposition by decision-making levels. Placing a system in one of these categories directly impacts on the structure of the control system to be designed.

The considered methods have been tested on a couple of benchmarks specifically developed for this scope. The first one is the nonlinear model of a chemical plant, composed by three distillation columns and three chemical reactors, see also WP6. In the adopted representation, the overall model is constituted by 183 state variables, 6 input and 6 output variables, although it can be easily reparametrised to obtain a more detailed representation of the phenomena involved or to consider additional input and output variables. The developed simulator has been distributed to all the partners of the project. The second benchmark is a simulator of the New England electric power system. It uses a combination of centralized MPC formulation with the traditional speed and voltage controllers. The results achieved are reported in (Calderon, 2009), (Valencia and Espinosa, 2009b).

Multi-level models have also been considered for the application of hierarchical control of intelligent vehicle highway systems. Advanced technologies from the field of control engineering, communication, and information technology are currently being combined with the existing transportation infrastructure and equipment. This results in integrated traffic management and control systems that incorporate intelligence in both the roadside infrastructure and in the vehicles, and that are called Intelligent Vehicle Highway Systems (IVHS). Such systems consist of interacting intelligent vehicles and intelligent roadside controllers. The vehicles are organized in platoons with short intraplatoon distances, and larger distances between platoons. All vehicles are fully automated, i.e., throttle, braking, and steering commands are determined by an automated on-board controller. In order to obtain a tractable control approach for such systems it has been developed a multi-level hierarchical control framework with several levels: vehicle control, platoon control, roadside control, area control, regional control, and supraregional control. In the lower control level (vehicle control), which is present inside each vehicle, detailed models of the car are used. The platoon controller are responsible for control and coordination of each vehicle inside the platoon and use a more simplified

model that mainly involves distance keeping and speed adaption within the platoon. The roadside controllers control stretches of highways and they determine appropriate speeds, lane allocations, on-ramp release times for platoons. For tractability these roadside controllers it is possible to consider each platoon in the highway network as a single entity (described by a "big" vehicle with a speed-dependent length. The area controllers are mainly concerned with routing the (stream of) platoons through the network, and they consider a more aggregate model based on flows of platoons. The framework and the various models used are described in (Baskar, De Schutter, et al., 2008a,b) and (Baskar, De Schutter, et al., 2009).
The work already developed has covered much of the initial objectives and the planned activity has been mostly performed. The final part of the research activity will concern the development of new partitioning methods specifically tailored to the MPC approach. These methods will consider both the problems related to the definition of MPC state-feedback control laws and the problems inherent to distributed estimation schemes. To this regard, tight relations with the developments of the tasks in WP3 and WP5 are required, as witnessed by some preliminary results achieved in the initial part of task 5.1. No specific corrective actions are required.

Resources

Resources for this work package have been used as planned in the description of work.

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WP3: Development of hierarchical and distributed MPC methods

Objectives

The objectives of this work package are

- to develop methods for determining appropriate spatial and temporal divisions,
- to develop coordination mechanisms,
- to define communication and computational algorithms for MPC based on the hierarchical control architecture defined in WP2, taking into account linear as well as nonlinear models of the local agents,
- to analyze the control methods and algorithms with respect to their properties (stability, robustness and fault tolerance, local/global convergence, (sub)optimality, ...) using the results from WP4 and WP5, and
- to apply the results to selected simulation case studies.

Progress and achievements

An intensive literature review on hierarchical and distributed MPC, including nonlinear and robust MPC methods, has been accomplished. Based on these results first results on new MPC methods, including new coordination mechanisms, for both linear and nonlinear systems have been developed. As the MPC methods cannot be considered without the context of optimization, many of the results are closely related to distributed optimization methods (see WP4). In fact the optimization methods are the basis for further progress in hierarchical and distributed MPC.

The newly developed MPC methods within WP3 have successfully been applied to case studies. Note however that, due to the lack of common benchmarks at the time of performing the research, these benchmarks still differ among the partners. In the future, these and newly developed methods will be applied to the common benchmarks that are being developed in WP6. The methods are so far mainly analyzed with respect to their convergence properties.

The progress and achievements for the various tasks within this work package is detailed next.

Task 3.1: Hierarchical and distributed nonlinear MPC

Literature review:

As a basis for further research an intensive literature review on hierarchical and distributed control methods with a focus on hierarchical and distributed model-predictive control methods has been accomplished. On the one hand literature from the beginning of research for large-scale optimization, large-scale systems control and control of hierarchical and distributed systems has been reviewed. Some of those ideas of the 1960s and 1970s are still present in today's research, such as Dantzig-Wolfe decomposition (Dantzig and Wolfe, 1960), Dual Decomposition (Lasdon, 1968) or Interaction Balance and Prediction principles (Mesarovic et al., 1970). However, many ideas of that period of time have not been explored in subsequent research. Hence, there exist many ideas, which could be used to be implemented in future HD-MPC methods.

On the other hand also present literature has been reviewed: Main focus in today's research is on methods for linear time-invariant systems in discrete-time. Results for continuous time systems and nonlinear systems are quite rare. Most of the related results are related to special classes of systems.

Furthermore it is unclear, to what extend the existing methods for linear systems can be applied for nonlinear systems. As a result, for the method development (Task 3.1.2) for nonlinear systems, it seems that new approaches will be necessary.

Results of the literature review have been gathered in a report (D3.1.1: Report on literature survey on hierarchical and distributed nonlinear MPC, including analysis and comparison, and description of the resulting methodological framework)

The analysis performed in the framework of Work Package 2, and in particular Task 2.1 (survey of the state-of-the-art on hierarchical and distributed control architectures) also allowed to review the main algorithms proposed in the literature for distributed and hierarchical control with MPC. This has been partially described in a paper (Scattolini 2009).

Method development, implementation, and evaluation:
Based on some ideas of the 1970s (Mesarovic et al.) a new optimization method for nonlinear (spatially) distributed dynamic systems has been proposed, which is a basis for a future nonlinear distributed model predictive control. The method, which will be referred to as Gradient-Based Distributed Dynamic Optimization (GBDDO), can be implemented for systems that interact via the input variables as well as the state variables. There may be constraints on the input and state variables of the local subsystems. However, inequality constraints for the overall process are not considered yet.
The method is based on coordination via first order sensitivities. These first order sensitivities are used to modify objective functions of the infimal objective functions of the local subprocesses in order to achieve optimality for the overall process. Thus, a main challenge within the method is the calculation of first order sensitivities in a decentralized way. A main result is that these calculations can be performed in a decentralized manner. However, due to a necessary discretisation of continuous variables for continuous-time systems, the resulting sensitivities are an approximation. The method revealed promising properties for further research: In first optimization studies very fast convergence of the method could be observed.
The method has at first been implemented in Matlab using a standard nonlinear constrained optimization solver (fmincon), in order to have some sharable software among the partners. Then, the method has been evaluated for a simple nonlinear system and also been compared to the well-known Dual Optimization method, as well as to fully decentralized and fully centralized methods.
The results of this research have been summarized in conference paper and submitted for ACC'2010 (Scheu et al., 2010).

As standard Matlab solvers do not provide acceptable performance for nonlinear optimization, especially for large-scale and dynamic optimization, existing dynamic optimization software (DyOS) has been extended in order to evaluate the results of GBDDO for mid-scale and large-scale problems in future. DyOS integrates highly efficient solvers to calculate sensitivities as well as highly efficient nonlinear programming solvers. Furthermore, it uses multiple CPUs for a speedup of optimizations.

A new methodology for the design of two level hierarchical control systems has been developed. The higher level corresponds to a system with slow dynamics and whose control inputs must be provided by the subsystems (actuators) with faster dynamics and placed at the lower level. MPC control laws are synthesized for both the levels and overall convergence properties are established. The use of different control configurations is also considered by allowing the switching on/off of the subsystems at the lower level. In so doing, it is possible to consider overactuated plants, often built up for physical redundancy purposes to tackle damage events or to meet secondary objectives. The problem of distributing the control effort among a number of actuators is usually called control allocation and is of paramount importance in applications ranging from the automotive to the aerospace, aircraft, robotics, marine, power of wireless nodes, demands in free market fields, and so on.
In the development of the hierarchical control synthesis algorithm, a robust control approach has been undertaken to obtain a convergence result for the overall system. This approach stems from

considering the discrepancy between the ideal control actions, requested by the high level controller, and those actually achieved by the actuators as a disturbance term to be rejected in the design phase of the high level controller.
The results achieved are extensively described in a technical report (Picasso et al., 2009).

The algorithm developed has been extended to consider the case where the system at the higher level is described by a nonlinear Wiener model, i.e., a model with linear dynamics followed by a block with nonlinear static characteristics, while the subsystems at the lower level are described by linear or nonlinear models. In this case, an MPC regulator is designed at a slow time scale to guarantee robust steady-state zero error regulation for constant reference signals by including a suitable integral action in the control law. Also the actuators are controlled with the MPC approach, so that it is possible to cope with control and/or state constraints.
The results of this research activity have been published in (Picasso, Romani and Scattolini, 2009)

In (Negenborn, Leirens, et al., 2009) we consider the design of a higher-layer controller using MPC. The higher-layer controller uses MPC to determine set-points for controllers in a lower control layer. We use of an object-oriented model of the system for making predictions is proposed. When employing such an object-oriented prediction model the MPC problem is a nonlinear, non-smooth optimization problem, with an objective function that is expensive to evaluate. Multi-start pattern search is proposed as approach to solving this problem, since it deals effectively with the local minima and the non-smoothness of the problem, and does not require expensive estimation of derivatives. Experiments in an emergency voltage control problem on a 9-bus dynamic power network show the superior performance of the proposed multi-start pattern search approach when compared to a gradient-based approach.

We have also considered several specific applications, in particular hierarchical and distributed control of intelligent vehicle highway systems, combined electricity and natural gas systems, and baggage handling systems.

Intelligent vehicle highway systems consist of interacting intelligent vehicles and intelligent roadside controllers. The vehicles are organized in platoons with short intraplatoon distances, and larger distances between platoons. All vehicles are fully automated, i.e., throttle, braking, and steering commands are determined by an automated on-board controller. In order to obtain a tractable control approach for such systems we have developed a multi-level hierarchical control framework with several levels: vehicle control, platoon control, roadside control, area control, regional control, and supraregional control. Within WP3 we have mainly focused on the roadside control and the area control. The roadside controllers control stretches of highways and they determine appropriate speeds, lane allocations, on-ramp release times for platoons. The area controllers are mainly concerned with routing the (stream of) platoons through the network. In (Baskar, De Schutter, et al., 2008a,b; Baskar, De Schutter, et al., 2009) we consider both dynamic speed limit control for the platoons in the IVHS and access control at the on-ramps using ramp metering based on MPC.

Related work for conventional traffic networks is described in (van Katwijk, De Schutter, et al., 2008) and (van den Berg, De Schutter, et al. 2009a).

In (Arnold, Negenborn, et al. 2008) and (Arnold, Negenborn, et al. 2009a,b) the optimization of combined electricity and natural gas systems is addressed. The two networks are connected via energy hubs. Using the energy hub concept, the interactions between the different infrastructures can be analyzed. A system consisting of several interconnected hubs forms a distributed power generation structure where each hub is controlled by its respective control agent. Recently, a distributed control method has been applied to such a system, in which the overall optimization problem including the entire system is decomposed into subproblems according to the control agents. In this paper, a parallel and serial version of that method is discussed. Simulation results are obtained through experiments on a three-hub benchmark system.

Additional review of concepts of MPC was based on the paper of Qin and Badgwell published in 2001. They present a good compilation of industrial MPC algorithms since 60's with the work of Kalman. Other concepts on linear and nonlinear MPC and large scale MPC have been reviewed in different papers and books. Until now, an integration of the information collected has not been done completely but there is a clearly identified problem, the optimization algorithms for efficient performance of nonlinear MPC.

Approximations using literature proposals such as temporal decomposition are being developed for our necessities in order to find problems. These implementations are being done using Matlab-Simulink. Figure 1 below shows a schematic representation of the controller that is being implemented now in (Calderon, 2009).

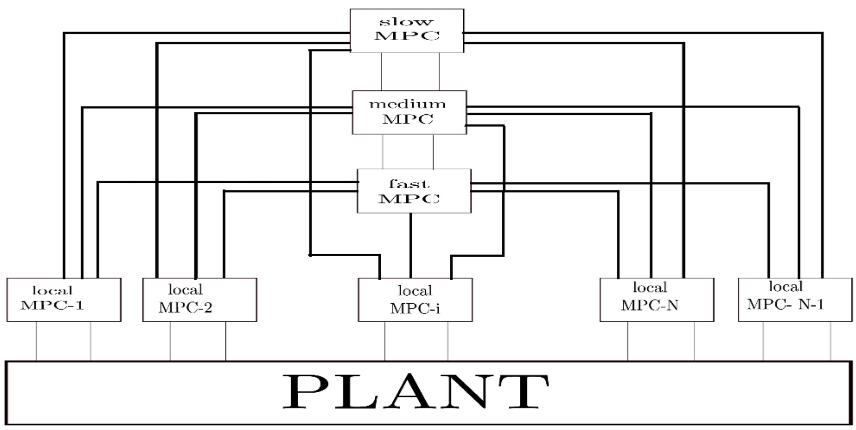

Figure 1: Hierarchical Temporal Controller

Additionally a basis for nonlinear HD-MPC has been prepared:

- The identification of main ideas and concepts about distributed model predictive control;
- the identification of tools that may possible the implementation of non-linear distributed model predictive control architectures;
- a formulation of multi-model linear coordinated model predictive controller;
- the implementation of model predictive controllers in Matlab/Simulink software; and
- selection and implementation of a case study in Matlab/Simulink software (New England Electric Power System).

Task 3.2: Hierarchical and distributed robust nonlinear MPC

The basis for robust hierarchical and distributed nonlinear MPC is not as good as the basis for methods that do not take into account robustness. The robustness property seems to be much more challenging to be achieved within the project. However some progress has been achieved as described below.

Literature review:
An extensive search of the existing papers on hierarchical and distributed MPC has been carried out. This search has been aimed to the study of the stability and robustness of the proposed controllers.

This point is interesting since a number of distributed and hierarchical predictive controllers have been proposed without an explicit study of the closed loop stability or constraint satisfaction. Once the papers fulfilling such properties have been gathered, these have been studied and compared. This study has been reported in a survey document (deliverable D3.2.1).

Method development, implementation, and evaluation:
Hierarchical robust nonlinear MPC: Based on the experience of the group in this topic, robust predictive control techniques based on guaranteed estimation have been reviewed. The problem of the robust design of predictive controller has two main issues: the robust stability problem and the robust constraint satisfaction. The former is typically achieved by means of the decreasing property of the optimal cost function. Depending on how the performance index is defined different stability property is achieved. In worst-case approaches, practical stability can be ensured. In mean value or nominal value, input-to-state stability (ISS) can be guaranteed. In the case of min-max, specialized formulations can be used to obtain ISS. The robust constraint satisfaction is a weak point of robust nonlinear MPC and solutions based on guaranteed estimation has been proposed by the group. In this year we have been formulating the problem for a hierarchical MPC in which each subsystem is assumed to be locally controlled by a suitable unconstrained control law. The upper level MPC is capable to calculate the inputs to each subsystem ensuring the robust constraint satisfaction of each subsystem. This is based on polyhedral methods to calculate the range of a certain function. These can be derived from interval natural extension of the model function, the zonotope algebra or DC programming. We are currently working on a suite of functions to execute such algorithms. Besides a chapter on a Lecture Notes on Control Information Sciences has been published (Limon et al., 2009).

Hierarchical steady state optimization: Most of the predictive controllers ensure stability and constraint satisfaction by adding a terminal cost function together with an additional constraint on the terminal constraint. The stabilizing design conditions make these ingredients valid for a certain operation point. If this changes, these might be not valid and the stabilizing properties might be lost. Besides, the constraint on the terminal state may produce a loss of feasibility. In order to overcome this problem, a novel MPC has been recently proposed for the case of linear systems. This is based on the addition of virtual references as decision variables of the controller and using a suitable cost function and terminal constraint to ensure convergence and recursive feasibility. During this year this controller has been extended to a hierarchical nonlinear MPC. Firstly it is assumed that each subsystem is controlled by an unconstrained control law capable to steer the system to the range of steady states where the system will be operated. The MPC is capable to send the inputs to each controller ensuring constraint satisfaction under any change of the operation point within the specified range. The robustness of such constraint has also been analyzed and techniques to compensate the possible steady offset have been also studied. Currently we are working on the extension of these control techniques to the case of decentralized control structure. As a result of this research, a paper has been submitted and accepted in the next IEEE Conference on Decision and Control 2009.

Robust Distributed MPC: We have studied the problem of controlling two linear systems coupled through the inputs. This class of systems considered arises naturally in multi-input multi-output processes in which a transfer function model is obtained using standard identification techniques. For this class of problems, a novel distributed model predictive control method based on game theory has been proposed. This control law is based on two different agents that share some information in order to find a cooperative solution to the centralized control problem. We assume that each agent only has partial information of the model and the state of the system. The performance and the robustness of the proposed control scheme with respect to data losses in the communications have been analyzed. The proposed controller has been illustrated by extensive simulations and compared with other existing results. As a result of this research, a couple of papers have been submitted and accepted in the next IEEE Conference on Decision and Control 2009 (Maestre et al., 2009).

Task 3.3: Coordination mechanisms

As already indicated in the Description of Work (i.e., Annex I), this task is strongly related to Task 3.1. Any of the methods presented above, rely on some coordination mechanism. Therefore, only a short overview is given here.

A possible objective function for distributed subsystems has been formulated, which takes into account cooperation among subsystems in a strongly interconnected system (Valencia and Espinosa, 2009). Then, the well known Dual Optimization method has been examined, e.g. in (Scheu et al., 2010). This method belongs to the class of price coordination mechanisms and is an implementation of the Interaction Balance Principle.
The proposed GBDDO (Scheu et al., 2010) method achieves overall optimality by an implementation of goal-coordination, as the goal, i.e. the objective function, is adapted in order to achieve optimality for the overall system.
A totally different type of coordination has been achieved by game-theory methods (Maestre et al., 2009).
While the coordination methods, which have been mentioned so far, are applicable for spatially decomposed systems, also coordination has been considered for temporal decomposition (Picasso et al., 2009).

Resources:

Resources for this work package have been used as planned in the description of work.

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WP4: Optimisation methods for hierarchical and distributed MPC

Objectives

In this work package we will develop well-founded optimisation formulations and algorithms for the newly developed methods in the other work packages (in particular, WP3 and WP5). Apart from the classical three optimisation problems occurring in all MPC applications — model and parameter identification, on-line moving horizon state estimation, and on-line MPC optimisation on the prediction horizon — where the groups participating in this WP have long standing experience, in this work package we will develop new on-line optimisation methods for distributed MPC in the case of control systems with limited mutual information.

Progress and achievements

The aim of WP4 is to develop the optimization formulations and algorithms for the methods developed in the other work packages. The activities during the first year of the project have mainly focused on the survey and analysis of the methods already available in the literature and on the development of new algorithms especially in the case of systems without uncertainties.

Task 4.1: On-line optimisation methods for hierarchical and distributed MPC

As pointed out in survey in Deliverable D4.1.1, the literature on distributed optimization is extensive since this subject has been investigated for decades. However, it seems that most of the methodologies developed so far have not been conceived for the on-line deployment required by MPC applications. This fact motivates the investigation of new optimization methods, specially tailored for HD-MPC.

In the first year of the HD-MPC project, the research activities related to Task 4.1 have explored several research directions.

- The study of distributed MPC for dynamically coupled linear systems has so far typically focused on situations where coupling constraints between subsystems are absent. In order to address the presence of convex coupling constraints, in Doan et al. (2009a,b) a distributed version of Han's parallel algorithm for a class of convex programs has been developed. The distributed algorithm relies on local iterative updates only, instead of system-wide information exchange as in Han's parallel algorithm. The new algorithm then provides the basis for a distributed MPC method that is applicable to sparsely coupled linear dynamical systems with coupled linear constraints. The approach is illustrated using a system consisting of coupled oscillators. Convergence to the global optimum, recursive feasibility, and stability are established using only local communications between the subsystems.
- In (Maestre et al., 2009a) a new distributed MPC method has been developed based on a cooperative game. This method only needs two communication steps in order to obtain a cooperative solution to the centralized optimization problem. Each agent solves an optimization problem that only depends on its local model and partial state information. After sharing information about the local cost, the agents choose the solution that yields the best global performance among a set of suboptimal possibilities. The options are suboptimal because each agent has an incomplete view of the system and they propose the best solutions from their point of view. The proposed algorithm has low communication and computational burdens and provides a feasible solution to the centralized problem. Sufficient conditions that guarantee practical stability of the closed-loop system as well as an optimization based procedure to design the controller so that these conditions are satisfied have been developed. In (Maestre et al., 2009b) the method developed in (Maestre et al., 2009a) has been analyzed and compared with other method in the literature using the MIT beer game as a benchmark.

- In (Necoara et al., 2009) a distributed optimization method for non-linear optimal control has been developed. The first step to achieve a distributed algorithm is using sequential convex programming. This technique solves iteratively a convex local approximation of the general non-convex problem. The convex subproblems to be solved at every iteration are decomposed using smoothing techniques and Nesterov's optimal first order method.
- Development of a MPC suite for PC104 platforms: A first step for the development of distributed MPC is the implementation of the local controllers. While the centralized solution is based on the execution of the predictive controller on a high performance computer platform, distributed, hierarchical, or decentralized predictive controllers require the implementation of the predictive controllers on lower performance embedded platforms interconnected between them. Among the existing vendor solutions, the PC104 platform is one of the most used. During this period, the group has been working on the development of predictive control techniques for a PC104. This has been mounted on an existing plant in order to test the developed code. The aim is to develop a suite of functions to implement predictive controllers for linear systems and nonlinear systems described as Volterra models. These basically are devoted to prepare offline the optimization problem, to prepare on-line the optimization problem and to solve the optimization problem. Once this is finished, the suite will be tested on the real plant. The next step is to extend the suite to implement different decentralized predictive controllers.

Task 4.2: Optimisation of uncertain large-scale systems

As emerged in Deliverable D4.2.1, the results in the literature on optimization methods for MPC of uncertain large-scale systems are limited. This is due to the complexity of the problem and the difficulty to prove closed loop properties of the obtained control schemes. Most of the available methods present advantages and drawbacks and there is no method which is a clear winner among the others.

An outcome of the research regarding Task 4.2 is report in the paper by Bernardini et al. (2009), in which the problem of combining optimal control with efficient information gathering in an uncertain environment has been tackled. In the problem considered it is assumed that the decision maker has the ability to choose among a discrete set of sources of information, where the outcome of each source is stochastic. Different sources and outcomes determine a reduction of uncertainty, expressed in terms of constraints on system variables and set-points, in different directions. The paper proposes an optimization based decision making algorithm that simultaneously determines the best source to query and the optimal sequence of control moves, according to the minimization of the expected value of an index that weights both dynamic performance and the cost of querying. The problem is formulated using stochastic programming ideas with decision-dependent scenario trees, and a solution based on mixed-integer linear programming is presented.

Task 4.3: Optimisation methods for robust distributed MPC

As planned, the research activities concerning Task 4.3 have been limited during the first year of the project. This is due to the fact that the development of optimization methods for robust distributed MPC can be seen as a second step after considering distributed MPC problems that do not require robustness. The main outcome of the activities regarding Task 4.3 is Deliverable D3.2.1, which is a joint work with WP3. In this deliverable, which surveys and analyses the literature on robust distributed MPC, it is pointed out how the research in this particular field has been limited so far and that few results can be found. On the other hand, also the generic literature on robust distributed optimization is very limited, thus showing that robust distributed MPC deserves a lot of attention in the proceedings of the HD-MPC project. Deliverable D3.2.1 points out also another important fact: if we manage to characterize how the uncertainty propagates into the system, the optimization methods designed for distributed MPC without uncertainties can be easily extended to the robust case using tube based MPC. This can bring the development of new methods which do not require a big online computational burden at the cost of finding only a suboptimal controller.

Resources

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WP5: Distributed state estimation algorithms

Objectives

In this work package we will develop new on-line optimisation methods for distributed state and variance estimation.

Progress and achievements

Although the tasks for this work package are scheduled to start from month 16 only, we have already started to work on this work package, in particular on the first task, viz., state estimation.

Task 5.1: State estimation

This task has been anticipated with respect to the planned activity due to the need to consider also the state estimation problem in the definition of the system partitioning (see WP2 and in particular Task 2.4) for the design of distributed and hierarchical control systems. This allowed us to define new partitioning criteria based on the observability properties that any subsystem must possess (see the following description of the proposed PMHE algorithms), or the local, regional and global observability properties required by sensor networks for distributed control (see the following description of the proposed DMHE algorithm)

First, the available methods and strategies for estimating the whole state in a large-scale system with Moving Horizon Estimators (MHE) have been reviewed, see (Garcia and Espinosa, 2009a and 2009b). Moreover, the most relevant Kalman-based observers (KF) have been considered in order to highlight their differences with MHE.

The computational issues related to these centralized and distributed algorithms have been studied to verify their applicability in industrial problems. To this regard, the performance of a set of distributed KFs has been tested in a benchmark case, see (Garcia and Espinosa, 2009c), to analyze their computational burden, communication requirements and complexity as more variables are considered. The main idea is reconciliate the common variables of the distributed KF using a methodology suggested by the physical phenomena involved in the process. Once the advantages of this distributed estimation scheme will be proven over a centralized one, the next step will be the design of a MHE and compare it with the results previously achieved.

Then the research activity has focused on the development of MHE distributed estimation algorithms for linear discrete-time systems subject to noise. Specifically, some significant cases have been treated:

- We have developed a novel distributed estimation algorithm (DMHE) for sensor networks made by a set of electronic devices, with sensing and computational capabilities, which coordinate their activity through a communication network. Any sensor of the network measures some variables, computes a local estimate of the overall state of the system under monitoring, and transmits to its neighbours both the measured values and the computed state estimation. The main challenge is to provide a methodology which guarantees that all the sensors asymptotically reach a common reliable estimate of the state variables, i.e. the local estimates reach a consensus. This goal is achieved by the proposed algorithm even if the measurements performed by any sensor are not sufficient to guarantee observability of the process state (namely, local observability), provided that all the sensors, if put together, guarantee such property (namely, collective observability). The transmission of measurements and of estimates among the sensors leads to the twofold advantage of enhancing the property of observability of the sensors and of reducing the uncertainty of state estimates computed by each node. The proposed distributed algorithm is based on the concept of Moving Horizon Estimation (MHE). This approach has many advantages; first of all, the observer is optimal in a sense, since a suitable minimization problem must be solved on-line at each time instant. Furthermore, it has been proven that, under weak observability conditions, convergence of the state estimate is guaranteed in a deterministic framework. Finally, constraints on the noise and on the state are taken into account, as it is common in receding horizon approaches in control and estimation. Preliminary results on the developed DMHE schemes have been described in (Farina et al., 2009a and 2009b).

- We have also started the development of novel state estimation methods for large-scale discrete-time constrained linear systems that are partitioned, i.e. represented by coupled subsystems with non-overlapping states, see (Farina et al., 2009c). Also in this case, focus is placed on Moving Horizon Estimation (MHE) schemes due to their capability of exploiting physical constraints on states and noise in the estimation process. The computational burden of MHE hampers the applicability of centralized solutions. Therefore three different Partition-based MHE (PMHE) algorithms have been proposed, where each subsystem solves reduced-order MHE problems to estimate its own state. More specifically, the first scheme (PMHE1) is totally decentralized in the sense that subsystems exploit a communication network where links are present only if subsystem dynamics are coupled. Algorithms PMHE2 and PMHE3 assume an all-to-all communication but a reduced amount of information is transmitted over each communication channel. Compared to PMHE2, PMHE3 has lower computational complexity at the price of a loss in noise filtering performance. In all cases it has been shown how to compute suitable penalties on the states at the beginning of the estimation horizon in order to guarantee convergence of the estimation error to zero. Moreover, it has been shown how the system partitioning influences the achievable results, so that explicit criteria for partitioning can be stated (see the objectives of Task 2.4).
- A procedure based on the decomposition of a linear process model into a cascade of simpler subsystems and the use of a Kalman filter to individually estimate the states of these subsystems has been described in (Lendek, Babuška, et al., 2008). Both a theoretical comparison and simulation examples have been considered. The theoretical results show that the distributed observers, except for special cases, do not minimize the overall error covariance, and the distributed observer system is therefore suboptimal. However, in practice, the performance achieved by the cascaded observers is comparable and in certain cases even better than the performance of the centralized observer. A distributed observer system also leads to increased modularity, reduced complexity, and lower computational costs.
- The analysis of a special class of nonlinear dynamic systems that can be decomposed into cascaded subsystems, represented as Takagi-Sugeno (TS) fuzzy models has been performed. In (Lendek, Babuška, et al., 2009) it has been studied the stability of the overall TS system based on the stability of the subsystems, and it has been proven that the stability of the subsystems implies the stability of the overall system. The main benefit of this approach is that it relaxes the conditions imposed when the system is globally analyzed, thereby solving some of the feasibility problems. Another benefit is that by using this approach, the dimension of the associated linear matrix inequality (LMI) problem can be reduced. For naturally distributed applications, such as multi-agent systems, the construction and tuning of a centralized observer may not be feasible. Therefore, the cascaded approach has been extended also to observer design, and the use of fuzzy observers to individually estimate the states of these subsystems has been proposed. A theoretical proof of stability and simulation examples are presented. The results show that the distributed observer achieves the same performance as the centralized one, while leading to increased modularity, reduced complexity, lower computational costs, and easier tuning. Applications of such cascaded systems include multi-agent systems, distributed process control, and hierarchical large-scale systems.

The results already achieved in this task are significant, since no MHE estimation algorithms for constrained distributed and partitioned systems were available in the literature so far. However, the task is in its early stage. Future work will consider the inclusion in the already developed algorithms of integrating disturbances as well as the definition of suitable state estimation algorithms for other classes of hierarchical systems (singularly perturbed systems, or systems made by interconnected subsystems with different dynamics).

Resources

Due to the anticipation of the start of the work package some of the resources for this work package envisioned for the 2nd and 3rd year of the project have been moved to the reporting period also.

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WP6: Hardware and software implementation, and benchmarking

Objectives

The objective of this work package is to analyse hardware and software implementation issues and to use benchmarking as a means for testing the methods developed within the project.
From the point of view of the hardware and software implementation, the work package is also devoted to analyse the advantages and drawbacks of the off-the-shelf solutions, proposing the best choices for implementation.

Progress and achievements

The main achievement of this work package in the reporting period is the preparation (including a complete description, models, and related papers) of four benchmark cases: four-tank system, chemical plant, electric network, and heat system.
The progress for each of the tasks of WP6 is detailed next.

Task 6.1: Analysis of hardware and software

The work on this task has started by collecting information on the most promising or extended hardware and software platforms for distributed control systems. Specifically, operating systems such as TinyOS, Nano-RK, Contiki, BTnut, and AmbientRT will be considered. The open standard IEC 61499 and its function block engineering paradigm will also be considered. The proprietary wireless networking technology ZigBee is under study, as well as the open standard protocol WirelessHART. On the other hand, the different hardware aspects such as processors and radio systems as well as existing hardware platforms like ESB/2, BTnode, uNode, Tmote Sky, and EYES IFXv2. Finally, hardware accessories like power sources, wireless actuators, etc. will also be considered. This work has been done mainly by USE.
Also INOCSA, that is focused on the third application in WP7 (water channels, built to transport water from wet areas to dry zones) is analysing which sensors and actuators are needed in the control of large-scale systems related to watering channels.
This task is in progress and it will be finished at month 18.

Task 6.2: Development and implementation of a benchmark model guide

The main objective of the Benchmark Model-Guide is to help HD-MPC partners to develop benchmark exercises. The Model-Guide facilitates the proposal and preparation of benchmark exercises and also, it will provide a common format for the description and use of benchmarks.
For each benchmark case, an exhaustive description of its main technological and operational data as well as of the main performance criteria must be provided. Moreover, best solutions to date and their performance values will also be included.
The benchmarks consist of processes and research infrastructure, simulation models and other tools already existing in the labs of the member. The preparation of the benchmarks will consist of both the preparation of the system (real or simulated) and the preparation of the documentation.
The following tools have been developed for this purpose:

- Benchmark Questionnaire: The benchmark developer will be guided with the help of a questionnaire, including an ordered detailed explanation of the elements to be described in the proposal. It will cover both simulated and real benchmark cases. A detailed description of this tool can be found in Deliverable D6.2.1 and available in HD-MPC Virtual Portal.

- Benchmark Web-based tool: The web-based tool has been integrated in the HD-MPC Virtual Portal (Task 1.4). (http://www.nyquist.us.es/hdmpcproject/). Benchmark proposers and users find in the virtual-portal all the documentation related to the benchmarking task, including the Questionnaire format, Benchmark Cases Documentation, Database of Benchmark Cases, Database of Benchmark Exercises, and Results.

Task 6.2 has been finished, the objectives have been achieved, and Deliverable D6.2.1 is available.

Task 6.3: Preparation of benchmarking cases:

The objective of this task is the preparation of a collection of real and simulated benchmark cases using the tools developed in the previous subtask.
The consortium decided to prepare four main benchmark cases to be used in the first round of exercises during the first 18 months, one real plant and three simulated systems. These benchmark cases are:

- Four-Tank System (prepared by USE): It is a real plant in USE labs. The process is a hydraulic system of four tank interconnected. The four tank process is designed as an experimental benchmark for testing control techniques, either centralized, hierarchical or distributed controllers. The main property of this system is that it is highly configurable in a simple way. Thus, a great number of experiments can be thought and easily implemented. The overall target is to maintain the level of the tanks in a given range of admissible values.
- Electric Network (prepared by UNC): electric power system is composed by 10-machines 39-buses, interconnected among them by transmission lines. This power system has been widely used in open literature as a study case mainly to prove new optimal power dispatch schemes, or new decentralized control schemes. In the cases of optimal power dispatch, the main objective is to minimize active and reactive power losses in transmission lines while quality of service is guaranteed (voltage magnitude and frequency inside the region bounded by the regulation constraints). In the cases of control schemes, New England power system has been used to demonstrate the performance of control schemes based on local information in networked systems.
- Heat System (prepared by UNC): Heat conduction and convection at three elements (a rod, a plate and a cube) is considered in this benchmark case. The objective is focussed on guarantee a temperature profile across the solid element using heaters.
- Chemical plant (prepared by UNC and POLIMI): The benchmark is a chemical plant of six generic compounds. The aim is to transform the raw material into a final product at the lowest operational cost. The process is composed of three chemical reactor type CSTR and three non-reactive binary distillation columns.

The documentation of these four benchmarks has been prepared, including a complete description of the process and exercises, models, bibliography, etc. All the documentation is available for the interested partners in the HD-MPC virtual portal.

Besides these four main benchmark cases, some partners have been working in the preparation of new benchmark cases. These new systems can be added to the four main systems or used as benchmark cases in the second round of benchmark during the last 18 months of the project. The next paragraphs describe briefly these new systems.

INOCSA is preparing a benchmarking case consisting of 6 km of channel. The scenario of this benchmarking case is a real area of Spain (channel of Campo de Cartagena, belonging to the Post-trasvase Tajo Segura). The nodes (gates, pumping stations, etc), sensors and actuators are identified, and also the geometry of the system has been studied. The controlled and manipulated variables are identified. There are 4 data-acquisition points in the channel that supply real time data. This data will be used for the validation of results.

RWTH has established a nonlinear differential-algebraic simple-toy benchmark. The system consists of 4 tanks for liquid fluids. The system can be interpreted as a system consisting of two subsystems with two tanks for each subsystem. The tanks are connected in a variable way. Thus the strength of the coupling between the subsystems can be varied. The system is implemented in Matlab, including Jacobi matrices of the system equations, as well as in gProms. The system was implemented in order to validate nonlinear HD-MPC methods of WP3 on the different platforms. A full description of the system will presumably be available in (Scheu et al, 2010).

Finally, TUD has been working in some systems, obtaining the results summarized as follows. In (Negenborn and De Schutter, 2008; Negenborn, van Overloop, et al., 2009a) we consider irrigation canal networks operated by local decentralized controllers which receive set-points from human operators. We discuss how communication among the local controllers can be included and in particular propose the use of distributed MPC for enabling the local controllers to determine set-points autonomously using communication and coordination. A simulation study on a 7-reach irrigation canal illustrates the potential of the proposed approach. In (Negenborn, van Overloop, et al. 2009b) we discuss how distributed MPC can be applied to determine autonomously what the settings of these control structures should be. In particular, we propose the application of a distributed MPC scheme for control of the West-M irrigation canal in Arizona. We present a linearized model representing the dynamics of the canal, we propose a distributed MPC scheme that uses this model as a prediction model, and we illustrate the performance of the scheme in simulation studies on a nonlinear simulation model of the canal.

In (Tarău, De Schutter, et al., 2008) and (Tarău, De Schutter, et al., 2009a,b) we consider baggage handling systems at airports. Currently, the fastest way to transport the luggage is to use destination coded vehicles (DCVs). These vehicles transport the bags at high speed on a mini railway network, but their route has to be controlled in order to ensure the system optimum. In this paper we determine an event-based model of a DCV-based baggage handling system and we compare centralized and decentralized approaches for routing the DCVs through the network. The proposed centralized control methods are optimal control and MPC. Due to the large computation effort required, we also analyze a fully decentralized control approach. In this case, each junction has its own local controller for positioning the switch into the junction or out of it, routing the DCVs through the network. The local controllers do not communicate their actions. The considered control methods are compared for several scenarios. Results indicate that optimal control becomes intractable when a large stream of bags has to be handled, while MPC can still be used to suboptimally solve the problem. However, the decentralized control method usually gives worse results to the ones obtained when using MPC, but with very low computation time. In (Tarău, De Schutter, et al., 2009d) we extend this work and we consider centralized, decentralized, and distributed MPC. To assess the performance of the proposed control approaches, we consider a simple benchmark case study, in which the methods are compared for several scenarios. The results indicate that the best performance of the system is obtained when using centralized MPC. However, centralized MPC becomes intractable when the number of junctions is large due to the high computational effort this method requires. Decentralized and distributed MPC offer a balanced trade-off between computation time and optimality.

Similar work, but then related to postal automation and automated flats sorting machines is reported in (Tarău, De Schutter, et al., 2009c).

Another application involves MPC for residential energy resources. In (Negenborn, Houwing, et al., 2009) we propose MPC is using the mixed-logical dynamic model to control the energy flows inside the household. The context is that with the increase in the number of distributed energy resources and the amount of intelligence in electricity infrastructures, the possibilities for minimizing costs of household energy consumption increase. Household systems are hybrid systems, in the sense that they exhibit both continuous and discrete dynamics. We use the mixed-logical dynamic framework to construct a dynamic model of a household system equipped with distributed energy resources and the corresponding MPC controller. In simulation studies we assess the performance of the proposed controller, and we illustrate how additional profits can be obtained by increasing the decision freedom of the controller. Related work is presented in (Houwing, Negenborn, et al., 2009) and (Bajracharya, Koltunowicz, et al., 2009).

Resources

Resources for this work package have been used as planned in the description of work.

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WP7: Validation and applications on simulated plants

Objectives

The goal of this work package is to apply and to demonstrate the methods and algorithms developed in the other work packages on three applications:

- the start-up of a combined cycle plant,
- the operations of a hydro power valley,
- short-term and long-term control of a large-scale water capture system.

Progress and achievements

The main results obtained within WP7 in the reporting period are also described in the control specification reports (Deliverables D.7.1.1 and D7.2.1) and the report on meteorological forecast models (Deliverable D.7.3.1). In particular, Deliverable D.7.1.1 presents the process and the main control objective. It proposes a decomposition according to the main water and steam circuits. An upper-level control that coordinates the subsystems is introduced. Deliverable D.7.2.1 presents the case study and the information needed to build a HD-MPC solution. Coordination mechanisms are proposed for the following. Deliverable D.7.3.1 presents a state of the art of meteorological models and particularly the HIRLAM (High resolution Limited Area Model) used by AEMet (the Spanish meteorological agency). It presents the integration platform that will be developed by the consortium.
The progress for each of the three tasks and applications is detailed next.

Task 7.1: Application to the start-up of combined cycle

Power plants are complex systems that are usually hierarchically controlled. The global control structure and the coordination between local controllers are in general determined using heuristics and experience, and the question remains open whether the chosen solution is optimal. The project proposes a new scientific approach to find a global optimal solution. In this task we will study the applicability of the control design methods for hierarchical and distributed MPC to power plant applications. A model of a combined cycle plant will be built. The plant model will be decomposed in several interconnected sub models. A distributed and hierarchical control system will also be simulated in order to implement the global distributed MPC scheme. In order to validate the applicability of the approach and its robustness, some loops of the lower level will be controlled by classical PID controllers.

Subtask 7.1.1: Control specification for the combined cycle start-up

During this first year, the Combined Cycle Power Plant start-up has been analyzed. In order to specify the problem, a physical structuring of the plant has been proposed by SUPELEC and validated by EDF the industrial partner. From this first structure, a set of physical, operating and safety constraints has been defined and the set of pertinent control actuators and sensor signals has been set-up. On another hand, a start-up procedure has been studied and linked with the structural decomposition and the set of constraints. From this study, the set of constraints has been structured and for each stage of the start-up the main constraints have been defined.
A first analyze of a control architecture has been performed. This is based on the physical structure of the plant and will be refined according the simulation first results and the results of the work packages on distributed control design.
The results of this work have been included in the deliverable D7.1.1. The control specification will be completed with precise numerical values for the constraints and the initial state when model simulations will be performed.

Subtask 7.1.2: Modeling of the combined cycle start-up

To give numerical specification values for the various constraints with precise ideas of the plant and its physical characteristics and in order to define consistent sets, a model of the plant using the Dymola software and the Modelica language has been started using previous development.

The plant model of a Combined Cycle power plant has been provided by the research unit at the Politecnico di Milano to all the project partners. The simulation model is written in Modelica and is based on the ThermoPower library developed at the Politecnico. It has been parameterized with design and operating data from a typical unit, and validated by replicating a real start-up transient. Specifically, the plant under investigation is composed by a 250 MWe gas turbine unit (GT), coupled to a heat recovery steam generator (HRSG) with 3 levels of pressure, driving a 130 MWe steam turbine (ST) group.

The model can be used to test faster start-up manoeuvres, with the objective of either reducing the plant life-time consumption at equal start-up times, or reducing the start-up time at the same level of plant life-time consumption.

For this system, the limiting factors to a reduction of the start-up time are:

- the maximum load change rate of the gas turbine;
- the thermal stress in thick components (in particular, the steam turbine shafts);
- the ability of the control system to keep their controlled variables within the allowable limits.

SUPELEC has started to adapt the components of the ThermoPower library to the hierarchical structure that was defined in the control specification task. Each component must be analyzed and its consistency with the start-up problem has to be checked. At the moment the work is focused on a simple model with one level of pressure. The objective of this first model is to be able to cope with modelling difficulties and specially the problem of setting initial conditions for the start-up sequence and assess the possibility to be used for optimization. For the next months, the objective is to build a non linear model that will be used for the validation but also maybe simpler model that will be integrated in the optimization scheme.

Subtask 7.1.3: Validation of method for hierarchical and distributed MPC for the combined cycle start-up

A simple model has been used to optimise the start-up trajectories for a combined cycle. The model developed in Matlab contains only one pressure level. The optimisation minimizes the start-up time under the constraints on superheater and drum temperature (Faille, 2009).

Another development that is not related to start-up but applies to the commitment has been undertaken by USE. USE has actually been working in the definition of control specifications for Combined-Cycle Plants (CCP) from an innovative point of view: the consideration of risk management techniques. Higher fuel and electricity prices open up opportunities for further use of on-site generation (cogeneration) since it saves large amounts of primary energy inputs. The industrial self generation action is determined by the effects of the price of purchased electricity, the derived demand for electricity and the marginal cost of self-generation. CCP performance is greatly affected by the market and the technical actions of the centralised power plant. The consideration of these uncertainties in CCP system scheduling (both long- and short-term) is necessary. For that, we are introducing in the application of the CCP, risk management techniques in order to get scheduling and results more suitable. In the last decade, risk management has been extended to the fields of project management and financial policies, in which it is arousing a growing interest. Methods and disciplines that address risk management are becoming more accepted by companies. The main innovative point is the consideration of mitigation actions to reduce the exposure of the identified risks. Model predictive control can be used to select the strategic plan to execute according to an index performance.

Task 7.2: Application to the operation of a hydro power valley

Hydro Power Valleys can also be controlled hierarchically. Each plant is then equipped with local controllers and the coordination is done by the operator who imposes flow or level set-points. In this task we investigate the use of HD-MPC methods to optimally coordinate the power plants of one valley.

Subtask 7.2.1 Control specification

EDF has selected a case study that contains high head and cascade run of river power plants. The system consists of 9 subsystems that are interconnected. Three objectives functions have been defined so far that correspond to different goals (maximisation of the power produced, minimization of the power regulation error, distributed regulation problem). The constraints on the actuator and on the state have been defined as well as the tests to check the robustness of the solution. A method to coordinate the global and local optimization has been defined.

Subtask 7.2.2: Modeling of the hydro power valley

Two kinds of model are wanted for the case study. First we need a simple model that will be embedded in the regulation. The level of details of model will be adjusted to the capabilities of the optimisation and the precision required. The choice of the model will be done in the next months.
In parallel non linear model based on the Saint-Venant equations will be developed to be used as a virtual plant for the validation of the HD-MPC schemes. Some reaches have been connected within the open-source software tool Scilab and the model must be developed in the next months. This non linear-model will be used to build simpler models more suited for HD-MPC algorithms.

Subtask 7.2.3: Validation of method for hierarchical and distributed MPC for hydro power valley

Unconstrained coordinated MPC solutions have been developed for simple models and are tested on simple models. This work has been presented at the BFG'09 conference (Zárate Flórez et al., 2009).

Task 7.3: Short-term and long-term control of a large-scale water capture system

Subtask 7.3.1: Modeling for Hierarchical and Distributed MPC

After studying the problem of water distribution systems in Spain, the decision of focusing the third application on watering channels, built to transport water from wet areas to dry zones has been made by INOCSA. The target is managing the water in channels in order to guarantee flows requested by different types of users (mainly irrigation).
INOCSA decided to use the software platform FEWS (Flood early warning system) that provides a state of the art of water forecasting and warning system. FEWS integrates all the necessary modules for managing water distribution and shows the results. These modules will be:

- meteorological forecast
- radar data (rainfall)
- hydraulic model
- controller (the model predictive control software), and

- real time series obtained for telemetry systems like observed water, flow, level of water, …

This platform provides the consortium with an operative and friendly management of all the information over only one interface which facilitates research, test and application.
The standard interchange format (FEWS with Hydraulic model and with Controller) will be XML files. HEC-RAS is the hydraulic model chosen for the simulation of water progress in the water distribution system. HEC-RAS is a public-domain software to perform one-dimensional hydraulic calculations for a network of channels. INOCSA has already implemented a module for the importation of data to FEWS.
For meteorological forecasting, the numerical model HIRLAM from AEMet (State Meteorological Agency of Spain) will be used (see Deliverable D7.3.1)

The activities of USE in the Water Capture System applications have been focused on the evaluation of canal irrigation simulation tools to be integrated with the software to implement the controller. Also, USE has worked in the development of linear control models and the implementation of preliminary controllers.
Two simulation tools have been tested and analyzed how to integrate controllers and prediction tools, as weather forecast.
SIC software (Simulation of Irrigation Canals) is a commercial package developed by Cemagref. The advantage of this tool is the easy integration with Matlab, then the controller can be developed using this tool. On the other hand, the integration with FEWS, the package to integrate weather forecast, is complex. Preliminary results on control model identification and MPC controllers have been obtained. The integration of HEC-RAS with MATLAB is more complicated than in the previous software. The adopted solution has been to use FEWS as integration platform also for the controller tools. USE has been working with INOCSA in the integration of HEC-RAS and MATLAB with FEWS platform.

Resources

Resources for this work package have been used as planned in the description of work.

References

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WP8: Dissemination

Objectives

The goal of this work package is to publicise the results of the project towards a broad audience including academia, industry, and other interested parties. This will be done via various channels, including press releases, a web site, papers and special issues in international journal papers, papers and special sessions at international conferences, scientific presentations, demonstrations, open-source software releases, technical reports, a publicly available database of benchmark problems, and the organisation of an international workshop.

The project undertakes to establish a web site supported by the project partners, to provide a unified view of the project; a copy thereof will be included in the Dissemination Package.

The project will also actively participate in the concertation activities organised at ICT Programme level relating to the area of Wireless Sensor Networks and Cooperating Objects, involving ongoing FP6 and FP7 projects in this area, with the objective of providing input towards common activities and receiving feedback, contributing advice and guidance and receiving information relating to ICT programme implementation, standards, policy and regulatory activities, national or international initiatives, etc.

Progress and achievements

The main achievements of this work package for the reporting period are the creation of a project web site and the organization of activities aimed at the divulgation of the results in the scientific community, in particular invited sessions at international conferences.

Task 8.1: Setting up a web site

A web site has been set up for the project by Bart De Schutter and Moritz Diehl. The web site, which can be found at the address http://www.ict-hd-mpc.eu, contains several sections to illustrate the project and the results achieved. A private Intranet for HD-MPC participants only has also been created (see http://www.ict-hd-mpc.eu/participants).

In addition to the project web site, a Virtual Portal has been set up by Miguel Ridao (see the activities reported for WP1), which can be found at http://www.nyquist.us.es/hdmpcproject/. As indicated in the report for WP1 we plan to merge the contents of the Intranet into the Virtual Portal in the near future.

Task 8.2: Organising special sessions at conferences or special issues of journals

Two invited sessions have been organized in international conferences:

- Tamás Keviczky and Rudy Negenborn have organised an invited session on "Optimization Methods for Hierarchical and Distributed Model Predictive Control" at the 14th Belgian-French-German Conference on Optimization, Leuven, Belgium, September 14-18, 2009.
- Bart De Schutter, Rudy Negenborn, and Moritz Diehl are organizing invited sessions on "Hierarchical and Distributed Model Predictive Control" and on "Distributed Model-Based Control" at the 2010 American Control Conference (ACC 2010), Baltimore, Maryland, USA, June 30-July 2, 2010.

Task 8.4: Industrial short courses

Tamás Keviczky has co-organized (in cooperation with Siep Weiland and Mircea Lazar from Eindhoven University of Technology, Eindhoven, The Netherlands) the DISC Summer school on "Distributed Control and Estimation", Noordwijkerhout, The Netherlands, June 2-5, 2009. This summer school was aimed at research students and staff members of DISC, as well as other researchers and engineers (including people from industry) engaged in the systems and control area.

Resources

Resources for this work package have been used as planned in the description of work.

4. Deliverables and milestones tables

Deliverables (excluding the periodic and final reports)

Please list all the deliverables due in this reporting period, as indicated in Annex I of the Grant Agreement.
Deliverables that are of a nature other than written "reports", such as "prototypes", "demonstrators" or "others", should also be accompanied by a short report, so that the European Commission has a record of their existence.
If a deliverable has been cancelled or regrouped with another one, please indicate this in the column "Comments".
If a new deliverable is proposed, please indicate this in the column "Comments".

This table is cumulative, that is, it should always show all deliverables from the beginning of the project.

TABLE 1. DELIVERABLES[12]

Del. no.	Deliverable name	WP no.	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I (proj month)	Delivered Yes/No	Actual / Forecast delivery date	Comments
1.1	Report on the requirements for the virtual portal (D1.4.1)	1	TUD	R	PP	3	Yes	01-03-2009	
8.1	Report on the set-up of a web site including downloads of reports, presentations, open-source software and a database of benchmark problems (D8.1.1)	8	KUL	R	PU	3	Yes	01-03-2009	
2.1	Report on literature	2	POLIMI	R	PP	6	Yes	01-04-2009	

[12] For Security Projects the template for the deliverables list in Annex A1 has to be used.

	survey and preliminary definition of the selected methods for the definition of system decomposition and hierarchical control architectures (D2.1)								
4.1	Report of literature survey, analysis, and comparison of on-line optimisation methods for hierarchical and distributed MPC (D4.1.1)	4	KUL	R	PU	6	Yes	28-08-2009	
4.2	Report of literature survey and analysis of optimisation methods for MPC of uncertain large-scale systems (D4.2.1)	4	KUL	R	PU	9	Yes	21-09-2009	
6.1	Model guide and web-based computer tool for benchmarking (D6.2.1)	6	USE	R,O	PU	9	Yes	05-06-2009	
1.2	First annual progress report (D1.2.1)	1	TUD	R	RE	12	Yes	04-10-2009	
2.2	Report on the final assessment of the methods for the definition of the control architecture and preliminary report on extended algorithms coping	2	POLIMI	R	PP	12	Yes	31-08-2009	

	with structural constraints, changes, and multi-level models (D2.2)								
3.1	Report on literature survey on hierarchical and distributed nonlinear MPC, including analysis and comparison, and description of the resulting methodological framework (D3.1.1)	3	RWTH	R	PU	12	Yes	29-09-2009	
3.2	Report on readily available methods for simple toy problems (D3.1.2)	3	RWTH	R	PU	12	Yes	01-10-2009	
3.3	Report on literature survey and analysis of (optimisation) methods for robust distributed MPC (D3.2.1)	3&4	RWTH	R	PU	12	Yes	28-08-2009	
4.3	Overview, toolbox and tutorial manual of existing state-of-the-art distributed optimisation algorithms (D4.1.2)	4	KUL	R	PU	12	Yes	01-08-2009	
6.2	Documentation for benchmark cases (D6.3.1)	6	USE	R	PU	12	Yes	24-09-2009	This deliverable consists of 2 parts. Part I describes the four tank system and Part II describes the other three benchmark cases, viz., the chemical benchmark case, the electric power system, and the

									heat system.
7.1a	Report that defines the control specification for the combined cycle start-up (D7.1.1)	7	EDF	R	PU	12	Yes	03-09-2009	
7.1b	Report that defines the control specification for the hydro-power valley(D7.2.1)	7	EDF	R	PU	12	Yes	03-09-2009	
7.2	Report on meteorological forecasting models (D7.3.1)	7	EDF	R	PU	12	Yes	03-09-2009	

3.4	Report on assessment of existing coordination mechanisms for simple case studies, and on possible options for improving and extending these coordination mechanisms (D3.3.1)	3	RWTH	R	PU	**15**	Draft[13]	01-12-2009	

[13] As promised in the Description of Work we have also prepared a draft of the deliverables that are due within the next 3 months after the review meeting.

Milestones

Please complete this table if milestones are specified in Annex I of the Grant Agreement.
Milestones will be assessed against the specific criteria and performance indicators as defined in Annex I.

TABLE 2. MILESTONES							
Milestone no.	**Milestone name**	**Work package no**	**Lead beneficiary**	**Delivery date from Annex I**	**Achieved Yes/No**	**Actual / Forecast achievement date**	**Comments**
M1.1.1	Kick-off meeting of the project	1	TUD	1	Yes	03-09-2009	See minutes of the kick-off meeting
M1.1.2	Installation of the steering committee	1	TUD	1	Yes	03-09-2009	See minutes of the kick-off meeting
M1.1.3	First annual meeting	1	TUD	12	Yes	09-09-2009	See minutes of the meeting
M1.4.1	Definition of the requirements for the virtual portal	1	TUD	3	Yes	01-03-2009	See Deliverable D1.4.1
M1.4.2	Implementation and opening of the virtual portal	1	TUD	6	Yes	01-05-2009	See Virtual Portal at http://www.nyquist.us.es/hdmpcproject/

M2.1	Analysis of the available methods for system decomposition	2	POLIMI	3	Yes	01-03-2009	See Deliverable D2.1
M2.2	Definition of decomposition procedures for distributed estimation and control	2	POLIMI	9	Yes	01-06-2009	See Deliverable 2.2
M3.1.1	Analysis of existing methods for hierarchical and distributed nonlinear MPC, and simple own methods implemented and shared with partners	3	RWTH	12	Yes	01-09-2009	See Deliverable D3.1.1 and D3.1.2
M3.2.1	Analysis of existing (optimisation) methods for robust distributed MPC	3 & 4	RWTH	12	Yes	01-09-2009	See Deliverable D3.2.1
M4.1.1	Analysis of suboptimality of existing algorithms	4	KUL	9	Yes	01-06-2009	See Deliverable D4.1.1

M4.2.1	Choice of appropriate tools for optimisation of uncertain large-scale systems, and redefinition of the optimality criteria	4	KUL	12	Yes	01-09-2009	See Deliverable D4.2.1
M6.2.1	Distribution of the model guide and opening of the web-tool	6	USE	9	Yes	01-06-2009	See Deliverable D6.2.1
M7.1.1/M7.2.1	Control specification for the combined cycle start-up and for the hydro-power valley available	7	EDF	12	Yes	01-08-2009	See Deliverables D7.1.1 and D7.2.1
M7.3.1	Meteorological forecasting model	7	EDF	12	Yes	01-08-2009	See Deliverable D7.3.1
M8.1.1	Opening of a web site including downloads of reports, presentations, open-source software and a database of benchmark problems	8	TUD	6	Yes	01-04-2009	See the HD-MPC web site at http://www.ict-hd-mpc.eu

5. Project management

Consortium management tasks and achievements

The management of the HD-MPC consortium is the subject of Task 1.1 (Management) and Task 1.2 (Monitoring and reporting) of WP1. More specifically, Task 1.1 (Management) includes the establishment of a steering committee (with one member per participant), the organisation of the kick-off meeting, the annual project meetings, and the regular work package meetings (at least twice a year). Task 1.2 (Monitoring and reporting) includes regular monitoring of the progress within the work packages, managing the annual report, etc.

During the kick-off meeting of the project on September 3, 2008 in Leuven, Belgium the steering committee has been installation with the following members:

- Bart De Schutter (TUD),
- Wolfgang Marquardt (RWTH),
- Riccardo Scattolini (POLIMI),
- Miguel Ridao (USE),
- Javier Arbáizar (INOCSA),
- Jairo Espinosa (UNC),
- Damien Faille (EDF),
- Hervé Guéguen (SUPELEC),
- Moritz Diehl (KUL).

In the mean time Arbáizar has left INOCSA. His role within the steering committee has been taken over by Laura Sánchez Mora (INOCSA).

The progress of the project and the work packages were further monitored during the HD-MPC meetings in Milan, Italy (March 5-6, 2009) and Rennes, France (September 9-10, 2009).

In view of the fact that most HD-MPC participants are involved in almost all work packages and in order to actively stimulate coordination and cross-fertilization between work packages, we have opted to let the work package meetings coincide and to organize joint HD-MPC-wide meetings, instead of organizing separate work package meetings. We aim at organizing at least two of these joint meetings per year. We have already organized such a meeting in Milan in March 2009 and Rennes in September 2009, and three more are already planned for 2010, viz. Aachen (February 11-12, 2010), Seville (June 3-4, 2010) en Delft (September 2-3, 2010). In addition, for some dedicated, specialized topics, separate work package meetings are of course still possible. An example of the latter is the WP7 meeting on models for modelling, simulation, and control of water systems that took place in Chatou, France (May 29, 2010).

In order to allow for additional interaction between the HD-MPC participants outside the meetings and visits, the Virtual Portal and the Intranet provide a place to exchange published and submitted papers as well as reports on the latest research. The Virtual Portal now also features a forum function. Related to this, each HD-MPC participant has a personalized account on the Virtual Forum. Moreover, two mailing lists have been installed to allow for an easy and fast communication within the consortium and within the steering committee.

Problems which have occurred and how they were solved or envisaged solutions;

Although the project is running smoothly and all the deliverables scheduled for the first reporting period have been delivered by the time of the first review meeting, we have encountered two problems.

The first problem involved the timely hiring of researchers. In particular, there has been some delay in the activities of WP4 during the first year, to the fact that the KUL team had some problems with the recruitment of a suitable person working on the project. Since September 2009 the KUL team has a Ph.D. student who will work full time on the project and therefore we expect no further problems of this kind in the future. The development of the web site has also suffered from the unexpected leaving of the web site designer at KUL, making it more difficult to add new items and sections to the web site. Therefore, we have decided to switch to an open-source content management system (CMS Made Simple[14]), which allows for easy editing and addition of sections and items.
A second problem we noted was that some of the deliverables projected to be delivered at months 3, 6, and 9, were not produced by the time indicated in the Description of Work (this delay was around 3 months at most (except for the WP4 deliverables, see above), but note that now all these deliverables have been completed). A possible cause for the delay is that originally we had envisioned that WP leaders would take the main lead in the monitoring, coordination, and editing of all the deliverables for their work package. To streamline the process of producing the deliverables, we have now opted – also along the lines of the topic of this project, viz. hierarchical and distributed control – to explicitly appoint one partner for each deliverable to take care of the editing and coordination of that deliverable. This should result in a more timely delivery of the deliverables (as already evidenced by the deliverables scheduled to be completed at month 12). The WP leaders (and the coordinator) will continue to monitor the deadlines for the deliverables.

Changes in the consortium, if any;
No changes took place in the composition of the consortium

List of project meetings, dates and venues;
The following joint meetings involving several partners have taken place (the reports of these meetings can be found on the Intranet and the Virtual Portal):
- September 3, 2008: Kick-off meeting in Leuven, Belgium
- March 5-6, 2009: HD-MPC meeting in Milano, Italy
- May 29, 2009: WP7 meeting on Modelling and Control of Water Systems, Chatou, France
- September 9-10, 2009: HD-MPC meeting in Rennes, France

In addition, USE and INOCSA have also met frequently:
- November 20, 2008: Joint meeting USE-INOCSA on modelling software for water canals, Madrid, Spain
- April 7, 2009: Joint meeting USE-INOCSA to prepare the WP7 meeting in Chatou (May 29, 2009), Seville, Spain
- May 13, 2009: Joint meeting USE-INOCSA on WP7, Madrid, Spain
- June 30, 2009: Joint meeting USE-INOCSA on WP7, Madrid, Spain

Project planning and status;
The project is running according to the schedule and all the deliverables and milestones planned for the reporting period have been realised (albeit for some delay for the deliverables planned for months 1-9; but note that now all these deliverables have been completed). In addition, the work on two of the future tasks, viz. Task 5.1 (planned to start in month 16) and Task 8.4 (planned to start in month 19), has even already been started.

[14] See also http://www.cmsmadesimple.org/

We plan to continue the project as described in the original Description of Work except for the continued anticipation of Task 5.1 of WP5.
Moreover, as emerged during HD-MPC meeting in Rennes in September 2009, during the first year of the HD-MPC project most of the research efforts considered optimization method for spatially distributed MPC problems. As a consequence, little attention has been devoted to optimization methods for hierarchical MPC schemes. The project participants will increase their focus on these practically relevant schemes in their future work.
The following joint HD-MPC meetings have been planned:
- February 11-12, 2010: HD-MPC meeting in Aachen, Germany
- June 3-4, 2010: HD-MPC meeting in Seville, Spain
- September 2-3, 2010: HD-MPC meeting in Delft, The Netherlands

Impact of possible deviations from the planned milestones and deliverables, if any;
All the deliverables and milestones planned for the reporting period have been realised (albeit for some delay for the deliverables planned for months 1-9, but this delay has been addressed and does not have any impact on the current status and future progress of the work package).

Any changes to the legal status of any of the beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs;
There have not been any changes in the legal status of the participants.

Development of the Project web site, if applicable;
A web site has been set up for the project. The web site can be found at the address http://www.ict-hd-mpc.eu, and it contains several sections to illustrate the project and the results achieved. Originally the web site was custom-made (see Deliverable 8.1.1), making it rather difficult to maintain after the web master left, but during the course of the reporting period the web site has been converted to an open-source Content Management System: CMS Made Simple, making it much more manageable.
A private Intranet for HD-MPC participants only has also been created (see http://www.ict-hd-mpc.eu/participants). In addition to the project web site, a Virtual Portal has been set up (see http://www.nyquist.us.es/hdmpcproject/). The work on the Intranet website and the Virtual Portal is described in the progress report for WP1 (see Section 3 above).

Use of foreground and dissemination activities during this period (if applicable).
The work performed within HD-MPC has been published[15] in the following international journal and conference papers (all of these explicitly mention HD-MPC as funding source):
- M. Arnold, R.R. Negenborn, G. Andersson, and B. De Schutter, "Distributed control applied to combined electricity and natural gas infrastructures," *Proceedings of the International Conference on Infrastructure Systems 2008: Building Networks for a Brighter Future*, Rotterdam, The Netherlands, Nov. 2008. Paper 172.
- M. Arnold, R.R. Negenborn, G. Andersson, and B. De Schutter, "Model-based predictive control applied to multi-carrier energy systems," *Proceedings of the 2009 IEEE PES General Meeting*, Calgary, Canada, July 2009. Paper 09GM1452.

[15] We only list published papers here. In addition, some submitted and accepted papers are listed in the WP progress descriptions in Section 3 above.

- M. Arnold, R.R. Negenborn, G. Andersson, and B. De Schutter, "Multi-area predictive control for combined electricity and natural gas systems," *Proceedings of the European Control Conference 2009*, Budapest, Hungary, pp. 1408-1413, Aug. 2009.
- G. Bajracharya, T. Koltunowicz, R.R. Negenborn, Z. Papp, D. Djairam, B. De Schutter, and J.J. Smit, "Optimization of maintenance for power system equipment using a predictive health model," *Proceedings of the 2009 IEEE Bucharest Power Tech Conference*, Bucharest, Romania, June-July 2009. Paper 563.
- L.D. Baskar, B. De Schutter, and H. Hellendoorn, "Dynamic speed limits and on-ramp metering for IVHS using model predictive control," *Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems (ITSC 2008)*, Beijing, China, pp. 821-826, Oct. 2008.
- L.D. Baskar, B. De Schutter, J. Hellendoorn, and A. Tarău, "Traffic management for intelligent vehicle highway systems using model-based predictive control," *Proceedings of the 88th Annual Meeting of the Transportation Research Board*, Washington, DC, Jan. 2009. Paper 09-2107.
- D. Faille and F. Davelaar, "Model Based Start-up Optimization of a Combined Cycle Power Plant", in *Proceedings of the IFAC Symposium on Power Plants and Power Systems Control (IFAC PP&PSC 2009*, Tampere Hall, Finland, July 2009
- M. Farina, G. Ferrari Trecate, R. Scattolini: "Distributed moving horizon estimation for sensor Networks", *Proceedings of the IFAC Workshop on Estimation and Control of Networked Systems (NecSys'09)*, pp. 126-131, Venice, Italy, 2009.
- M. Houwing, R.R. Negenborn, M.D. Ilič, and B. De Schutter, "Model predictive control of fuel cell micro cogeneration systems," *Proceedings of the 2009 IEEE International Conference on Networking, Sensing and Control*, Okayama, Japan, pp. 708-713, Mar. 2009.
- R.R. Negenborn and B. De Schutter, "A distributed model predictive control approach for the control of irrigation canals," *Proceedings of the International Conference on Infrastructure Systems 2008: Building Networks for a Brighter Future*, Rotterdam, The Netherlands, Nov. 2008. Paper 152.
- R.R. Negenborn, M. Houwing, B. De Schutter, and J. Hellendoorn, "Model predictive control for residential energy resources using a mixed-logical dynamic model," *Proceedings of the 2009 IEEE International Conference on Networking, Sensing and Control*, Okayama, Japan, pp. 702-707, Mar. 2009.
- R.R. Negenborn, S. Leirens, B. De Schutter, and J. Hellendoorn, "Supervisory nonlinear MPC for emergency voltage control using pattern search," *Control Engineering Practice*, vol. 7, no. 7, pp. 841-848, July 2009.
- R.R. Negenborn, P.-J. van Overloop, T. Keviczky, and B. De Schutter, "Distributed model predictive control of irrigation canals," *Networks and Heterogeneous Media*, vol. 4, no. 2, pp. 359-380, June 2009.
- R.R. Negenborn, P.-J. van Overloop, and B. De Schutter, "Coordinated distributed model predictive reach control of irrigation canals," *Proceedings of the European Control Conference 2009*, Budapest, Hungary, pp. 1420-1425, Aug. 2009.
- B. Picasso, C. Romani, R. Scattolini: "Hierarchical model predictive control of Wiener Models", *Nonlinear Model Predictive Control* (L. Magni, D.M. Raimondo, F. Allgower eds.), Vol. 384 in *Lecture Notes in Control and Information Sciences*, pp. 139-152, Springer, 2009.
- B. Picasso, C. Romani, R. Scattolini: "On the design of hierarchical control systems with MPC", *Proceedings of the European Control Conference 2009*, Budapest, Hungary, 2009.
- R. Scattolini: "Architectures for distributed and hierarchical model predictive control – a review", *Journal of Process Control*, Vol. 19, pp. 723-731, 2009, doi:10.1016/j.jprocont.2009.02.003.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Route choice control of automated baggage handling systems," *Proceedings of the 88th Annual Meeting of the Transportation Research Board*, Washington, DC, Jan. 2009. Paper 09-0432.

- A. Tarău, B. De Schutter, and H. Hellendoorn, "Centralized versus decentralized route choice control in DCV-based baggage handling systems," *Proceedings of the 2009 IEEE International Conference on Networking, Sensing and Control*, Okayama, Japan, pp. 334-339, Mar. 2009.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Model-based control for throughput optimization of automated flats sorting machines," *Control Engineering Practice*, vol. 17, no. 6, pp. 733-739, June 2009
- A.N. Tarău, B. De Schutter, and H. Hellendoorn, "Receding horizon approaches for route choice control of automated baggage handling systems," *Proceedings of the European Control Conference 2009*, Budapest, Hungary, pp. 2978-2983, Aug. 2009.
- M. van den Berg, B. De Schutter, A. Hegyi, and H. Hellendoorn, "Day-to-day route choice control in traffic networks with time-varying demand profiles," *Proceedings of the European Control Conference 2009*, Budapest, Hungary, pp. 1776-1781, Aug. 2009.
- R.T. van Katwijk, B. De Schutter, and J. Hellendoorn, "Multi-agent coordination of traffic-control instruments," *Proceedings of the International Conference on Infrastructure Systems 2008: Building Networks for a Brighter Future*, Rotterdam, The Netherlands, Nov. 2008. Paper 141.

In addition, the work performed within the HD-MPC project has been presented at several conferences and workshops:
- Riccardo Scattolini has attended the workshop on "Automotive Model Predictive Control: Models, Methods and Applications", held in Linz on February 2009, with the scope to find potential applications of hierarchical and distributed MPC in the automotive field. He also gave the invited talk: “An overview of Nonlinear Model Predictive Control”.
- Riccardo Scattolini attended the workshop on "Optimization Based Control and State Estimation for Decentralized and Networked Systems", University of Magdeburg, June 1-2, 2009, where he gave the invited talk: “Distributed State Estimation with Moving Horizon Observers”
- Riccardo Scattolini attended the European Control Conference, Budapest, August 23-26, 2009, where he presented the paper "On the design of hierarchical control systems with MPC ".
- Jenifer Zaráte Flóres gave a presentation on “Hydro power valley control: Decomposition/Coordination methods” at the 14th Belgian-French-German Conference on Optimization, Leuven, Belgium, September 14-18, 2009
- Marcello Farina attended the IFAC Workshop on Estimation and Control of Networked Systems, Venice, September 2009, where he presented the paper “Distributed moving horizon estimation for sensor Networks”.

In order to connect with other ongoing FP6 and FP7 projects, we have presented HD-MPC at several Concertation Meetings organized on behalf of the European Commission and at the HYCON final workshop:
- Bart De Schutter has given a presentation on HD-MPC at the Concertation Meeting on Control of Large-Scale Systems (CLaSS), Brussels, Belgium, October 20, 2008
- Bart De Schutter gave a presentation on “Distributed Control for Power Networks” at the Concertation Meeting on Monitoring and Control for Energy Efficiency, Brussels, Belgium, October 21, 2008.
- Bart De Schutter gave a talk in “Distributed control of power networks” at the Final Workshop of the Network of Excellence HYCON, Brussels, Belgium, March 3, 2009

There have also been some visits and exchanges of researchers between the participating groups:
- Jairo Espinosa (UNC) has visited the KUL team on September 4, 2008.
- Jairo Espinosa (UNC) has visited the group at RWTH on March 9, 2009 and the KUL group on March 10, 2009.

- Brett Stewart (UWM) has visited TU Delft for a 3-month period in May-June 2009. While at TU Delft he worked on the topic "Distributed cooperative model predictive control". On June 17 he gave a presentation on "Cooperative, Distributed Model Predictive Control for Systems with Coupled Input Constraints".
- Jim Rawlings (UWM) and Brett Stewart (UWM) have visited KUL in June 2009.
- Brett Stewart (UWM) has visited RWTH Aachen on June 15, 2009. This visits included a lively and intense discussion on Distributed MPC.
- Jim Rawlings (UWM) has visited TU Delft on .June 22, 2009. He also gave a presentation on the past, present, and future of MPC entitled "Optimal dynamic operation of chemical processes: assessment of the last 20 years and current research opportunities".
- In the week June 22-26, 2009, Marcello Farina visited the research groups in Louvain and Delft, giving the seminar: "Distributed State Estimation with Moving Horizon Observers**".**
- Jairo Espinosa (UNC) has visited the KUL team on September 11, 14, and 15, 2009.
- A four-month visit of the MSc student Daniele Balzaretti (POLIMI) to Delft is planned for the period October 2009-January 2010 to develop and test distributed estimation and control algorithms.

6. Explanation of the use of the resources

See the financial part of this report.

7. Financial statements – Form C and Summary financial report

See the financial part of this report.

8. Certificates

See the financial part of this report.