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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 01/09/09 to 31/08/10

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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 coordinator[1]

I, as scientific representative of the coordinator[1] 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 Coordinator[1]: Bart De Schutter

Date: 01 / 09 / 2010

Signature of scientific representative of the Coordinator[1]: Bart De Schutter

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[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***

**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.

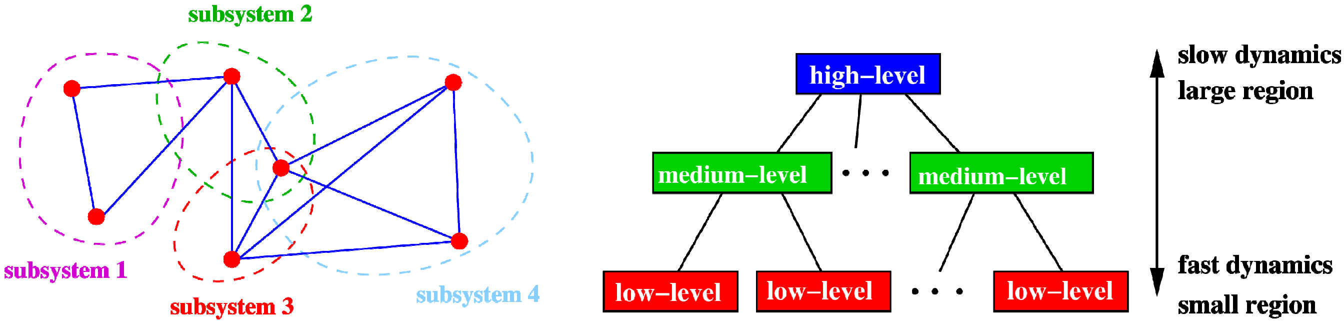

Figure: Illustration of the spatially distributed (left) and hierarchical control (right).

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 2 (01/09/2009-31/08/2010)**

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

- A hierarchical control structure with reconfiguration capabilities has been proposed to emphasize the performance of predictive controllers in response to changes in the subsystems.
  Multi-level models have been used to derive hierarchical control systems for cases where a global approach is not suitable due to the complexity of the underlying optimization problem. More specifically, hierarchical controllers have been designed for Intelligent Vehicle Highway Systems (IVHS) and baggage handling systems, while a multi-level model has been derived to describe a non-isothermal tubular reactor.
- We have continued the development of new hierarchical and distributed MPC methods. Among these, we have proposed a new design method for control systems with a two-layer hierarchical structure, where the high layer corresponds to a system characterized by slower dynamics, whose control inputs are provided by subsystems with faster dynamics and placed at the low layer. A convergence result for the overall system has been obtained by resorting to a robust MPC approach, where the discrepancy between the ideal control actions, requested by the high level controller, and those actually achieved by the actuators has been considered as a disturbance term to be rejected.
- We have also developed new methods for nonlinear optimal control of large-scale systems. In particular, the GDBBD algorithm allows separate subsystems to optimize independently, while taking the influence of their actions on the neighbouring subsystems in form of a gradient correction into account. This algorithm is shown to be able to converge to the true nonlinear minimum despite distributed computations. Moreover, the distributed Multiple Shooting approach allows to decouple multiple subsystems by adding their coupling input and output variables as degrees of freedom into the optimization problem. In this way, each subsystem can simulate and linearize its own response independently, while only a large-scale quadratic program needs to be solved in a coordinated way. These algorithms have been applied to the hydro-power valley case study, resulting in considerable speed-ups in computing the exact solution, compared to a centralized algorithm.
- A nonlinear Distributed Moving Horizon Estimation (DMHE) algorithm with convergence properties has been developed for systems characterized by a nonlinear dynamics and assuming that any sensor of the network measures some variables, computes a local estimate of the overall state of the system, and transmits to its neighbours both the measured values and the computed state estimation. In addition, three Partition-based MHE (PMHE) algorithms have been proposed for linear and nonlinear systems that can partitioned into a number of interconnected but non-overlapping subsystems.
- Different distributed algorithms have been tested on the defined benchmark cases. A paper with a comparative study of different distributed controllers developed by HD-MPC partners applied to the four-tank system has been prepared to be submitted to the Journal of Process Control. Moreover, two new benchmark cases related to the WP7 applications (viz. the hydro-power valley and irrigation channels) have been prepared.
- For the three industrial case studies, viz., the combined cycle start-up, the hydro-power valley, and the water capture system we have developed prediction models required for the application of hierarchical and distributed control. The models have been implemented using various software tools, and the integration of the modelling software with the control software to be used in the next stage of the project has been addressed.
- Special sessions on hierarchical and distributed model prediction control have been organized for the 2010 American Control Conference (ACC'10) and the IFAC World Congress 2011, and a special issue on HD-MPC of the *Journal of Process Control* is currently being prepared.

In addition, three joint progress meetings were held in Rennes, Aachen and Seville, and the cooperation between work packages and partners was further intensified by more dedicated technical meetings, mutual visits, 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], i.e. M13-24 (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)
- WP2: Definition of the hierarchical architecture for control design
  - 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)
  - Task 3.4: Timing and delay issues (M13-27)
- 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)
  - Task 5.2: Variance estimation (M19-36)
- WP6: Hardware and software implementation, and benchmarking
  - Task 6.1: Analysis of hardware and software (M4-24)
  - 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 8.2: Organizing special sessions at conferences or special issues of journals (M10-15, M25-30)
  - Task 8.4: Industrial short courses (M19-24, M28-33)

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[5] See pp. 21-24 of the Description of Work for a complete overview.

The tasks listed above can be detailed as follows according to the Description of Work (pp. 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.

## WP2: Definition of the hierarchical architecture for control design

- *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 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**.**

- *Task 3.4: Timing and delay issues (M13-27):*
  The main objectives are to reduce the performance degradation due to delays and timing issues, and to provide tools for control design for integrated networks. Large-scale systems, and especially distributed and flow involved systems (such as water networks) present delays in the measured and action signals. These delays strongly affect the control performance. Approaches to take into account the delays as well as asynchronous timing should be developed.

## 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 the same level, will inevitably be inexact. Moreover, the measurements that are made in the 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, has 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):*
  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 $p(x(k)|y(0), y(1),\ldots,y(k))$, 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.

- *Task 5.2: Variance estimation (M19-36):*
  In order to design state estimators, we require the statistics of the random disturbances ($w$,$v$,$\xi$) in addition to the deterministic system models ($F$,$G$,$H$). Because of the central limit theorem, we almost universally represent the random disturbances as zero-mean, normally distributed random variables. So the problem reduces to estimating the variances (covariances) of the noises. In the distributed context, this problem becomes more challenging. In the distributed case, we restrict correlations to be nonzero only between driving noises and states and outputs in selected subsystems. One goal of this research therefore is to develop methods to estimate from data the noise variances restricted to obey the supplied structure of nonzero correlations. But a second goal is to develop modelling methods to provide the nonzero correlation structure itself for a large, interconnected system. There will be interaction between these two issues, and an iterative design procedure will be required. We may also require a monitoring system that can flag changes in plant operation in which the currently chosen correlation structure is no longer adequate to describe the actual $u(t)$, $y(t)$ behaviour that is being observed.

**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 6.4: 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 8.2: 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):*
  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):

- M1.1.4: Second annual meeting (M12)
- M2.3: New algorithms for the definition of multi-level models and architectures suitable for hierarchical and distributed MPC (M15)
- M3.1.2: Methods developed for hierarchical and distributed MPC for complex control problems (M24)

- M3.3.1: Newly developed coordination mechanisms for hierarchical and distributed MPC (M24)
- M3.4.1: Assessment of existing methods to deal with timing and delay issues, and identification of most appropriate methods including options and ways to extend them (M18)
- M5.1: Analysis of the available methods for distributed state and variance estimation (M21)
- M6.1.1: Selection of the best choices for hardware and software (M18)
- M6.4.1: Selection of the benchmark proposals (M15)
- M7.1.2/M7.2.2: Model and open-loop simulation results for the combined cycle start-up and for the hydro-power valley available (M24)
- M7.3.2: Predictive model of hydraulic transport systems (M24)
- M8.2.1: Organisation of special session at an international conference (M15)
- M8.4.1: Communication of the project results to industry by organising industrial short courses (M24)

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:

- D1.2.2: Second annual progress report (M24)
- D1.3.1: Report on knowledge management, links with potential users of results, and future perspectives (M24)
- D2.3: Final report on the results regarding multi-level models and architectures for hierarchical and distributed MPC (M18)
- D3.1.3: Report on new methods for complex control problems (nonlinear, dynamic, constrained) (M24)
- D3.2.2: Report on newly developed methods for hierarchical and distributed robust nonlinear dynamic MPC (M24)
- 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)
- D3.3.2: Report on newly developed coordination mechanisms for hierarchical and distributed MPC (M24)
- D3.4.1: Report of literature survey and analysis regarding timing and delay issues (M18)
- D4.2.2: Report on redefinition of optimality criteria and generation of optimal solutions, and on analysis of sensitivity, scalability of solutions and computing cost (M24)
- D5.1: Report on the state of the art in distributed state and variance estimation, and on preliminary results on disturbance modelling for distributed systems (M24)
- D6.1.1: Report on results of hardware and software analysis (M18)
- D6.4.1: Report on implementation for selected benchmarks (M18)
- D7.1.2/D7.2.2: Report that presents the model and open-loop simulation results for the combined cycle start-up and for the hydro-power valley (M24)
- D7.3.2: Report on models of hydraulic transport systems (M24)
- D8.2.1: Report on or proceedings of special session at an international conference (M18)
- D8.4.1: Report on the organisation of an industrial short course (M24)

Moreover, a *draft* of the following deliverables (for month 27) has been promised to be available by the time of the review meeting in October 2010:

- D3.4.2: Report on implementation of timing and delay related approaches to simple case studies (M27)

## 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 project's public web site can be found at http://www.ict-hd-mpc.eu, while the intranet web site/Virtual Portal can be found at http://www.nyquist.us.es/hdmproject (this intranet/Virtual portal is password-protected and only accessible for HD-MPC participants, reviewers, and the commission).

In the current reporting period we have further maintained and updated the public web site and added information on the publications produced within the project, links to software, links to related STREP projects and events, as well as the pdf files of the public deliverables.

In the previous reporting period we had set up a separate intranet web site (tied to the main public web site) and the Virtual Portal with the URL given above. In the current reporting period the intranet web site had been merged into the Virtual Portal so as to get increased efficiency and a more clear way of accessing the internal information for the HD-MPC participants. The intranet/Virtual Portal now 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, the cover page for HD-MPC deliverables, 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, as well as dedicated areas for the work packages, where in particular the WP6 area contains all the required information (description, models, software, …) on the benchmarks. In the current reporting period the Virtual Portal has also been further maintained and extended with new sections and articles.

In conjunction with WP8 we have also further publicized the results of the HD-MPC project towards the academic community and potential users through our website, publications, presentations, special sessions at conferences, seminars, visits, and joint projects/proposals. This is described in more detail in deliverable D1.3.1 ("Report on knowledge management, links with potential users of results, and future perspectives").

#### 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*

According to the timing of the project, the main activity of this work package has been performed in the first year of the HD-MPC project. This work package was organized in four tasks, the first (Task 2.1: Survey (M1-3)) and the second (Task 2.2: Definition of the control architecture (M4-9)) have been completed in the first year of the project, while the third and the fourth task have been completed in the period reported here. The main results achieved during this reporting period are summarized in the following.

## *Task 2.3: Extension of the control architecture*

The final results on this topic, extensively described in deliverable D2.3 and in the conference paper [1], concern the design of a reconfigurable two layer hierarchical controller for cascade systems. Along the lines already described in [2] and further developed in [3] for non reconfigurable hierarchical control systems (see also the scientific report for the first year of the project and the achievements regarding WP3), the high layer provides for a slow dynamics regulator, computing the reference signals the plant would ideally need to be suitably controlled. In turn, at the low layer, a number of faster actuation control loops are in charge of tracking such references as accurately as they can, in accordance to their dynamics, which for simplicity is supposed here to be first order. Because of several inaccuracies, stemming from the real behaviour of the actuation equipment, a discrepancy between the ideal control actions determined at the high level and those effectively afforded to the plant arises, leading to a robustness problem for the overall control system. To tackle this problem, the upper level controller is designed by resorting to a robust MPC approach based on small gain results. In so doing, a convergence property for the overall closed-loop system is derived. The structure here considered can be viewed as a particular case (cascade systems) of the more general structure for hierarchical control previously described in deliverable D2.2. In order to deal with the problems considered in WP2 and to emphasize the reconfiguration capabilities of optimization-based predictive controllers in response to changes in the subsystems (actuators), in the activity here reported it has been shown how the proposed MPC algorithm may be readily extended to cope with the self reconfiguration of the controller, owing to an actuator replacement/addition. The proposed approach can take a significant role within the “Plug and Play” research community, which studies how to modify the control strategies as soon as a new device, in general a sensor or actuator, is plugged/substituted into an already functioning control system (see the very recent works [4, 5, 6]). In fact, when many actuators are present in the plant, a complete re-design of the controller further to the addition/replacement of only one actuator may often be undesirable for various reasons. Hence, an on-line reconfiguration is advisable in order to guarantee an incrementally self updatable control apparatus still ensuring desired stability and performance properties.

## *Task 2.4: Multi-level models*

The literature review on multi-model structures in model predictive control and model reduction, already partially performed in the first year, has been completed (see deliverable D2.3). Specifically, three decomposition approaches are analyzed, namely functional, temporal and spatial decomposition, for the design of multi-level, multi-resolution MPC regulators. For each one of them, the main contributions proposed in the technical literature have been reported and critically examined.

As a second activity, multi-level models have been used to derive hierarchical control systems for a couple of significant examples where a global approach is not suitable due to the complexity of the underlying optimization problem, viz. Intelligent Vehicle Highway Systems (IVHS) and baggage handling systems. In both cases, it has been shown how an efficient hierarchical control structure can be designed with the MPC approach applied to models with different levels of aggregation at the various levels of the control hierarchy. In the development of multi-resolution models for hierarchical control for IVHS, several levels have been used to model the system and to design the controller, depending on the temporal scale and spatial scale at which the given controller operates. First, the structure and the main features of Intelligent Vehicle Highway Systems (IVHS) have been reviewed and the hierarchical traffic management and control framework of [7] has been analyzed. Then, vehicle and traffic models have been developed and an MPC method for the roadside controllers to determine optimal speeds, lane allocations, and on-ramp release times for the platoons has been proposed. Next, focus has been placed on the route guidance tasks of the area controllers and a simplified flow model together with the corresponding optimal route guidance has been studied. Both the static (constant demands) and the dynamic case (time-varying demands) have been considered. In general, the dynamic case leads to a nonlinear non-convex optimization problem, but it has been show that this problem can be approximated using mixed integer linear programming (MILP). The problem and the results achieved have been extensively described in [8]-[13] and in deliverable D2.3.

In second application example considered, a hierarchical control framework for state-of-the-art baggage handling systems is presented. The luggage is transported by fast destination coded vehicles (DCVs). In this control framework switch controllers provide position instructions for each switch in the network. A collection of switch controllers is then supervised by a network controller that mainly takes care of the route choice instructions for DCVs. In general, the route choice control problem is a nonlinear, mixed integer optimization problem, with high computational requirements, which makes it intractable in practice. Therefore, an alternative approach for reducing the complexity of the computations is developed by approximating the nonlinear optimization problem and rewriting it as a mixed integer linear programming (MILP) problem for which solvers are available that allow one to efficiently compute the global optimal solution. The solution of the MILP problem is then used in computing optimal switch control actions. For a benchmark case study the hierarchical control is compared with centralized switch control. The results indicate that the proposed hierarchical control offers a balanced trade-off between optimality and computational efficiency. In the proposed approach two different types of models are used, depending on the time scale involved. For simulations and for the lower control levels, a fast event-based model is used, while for the higher level controller a model based on queues and flows is used, that can ultimately be recast into a mixed-integer linear programming description.

As a third activity, multi level models were derived for a non-isothermal tubular reactor. The models were obtained using the technique of Proper Orthogonal Decomposition (POD), making a significant order reduction from a discretized partial differential equation. In order to test the quality of the reduction the model was used to design an infinite horizon model predictive controller for the temperature and concentration [14].

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## *Resources*

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

## *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*

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

## *Task 3.1: Hierarchical and distributed nonlinear MPC*

The research in Task 3.1 is divided into research for distributed and for hierarchical model predictive control. The research activity on the design of control systems with a two-layer hierarchical structure, already started in the first year, has been further developed. In the considered structure, the high layer corresponds to a system characterized by slower dynamics, whose control inputs are provided by subsystems with faster dynamics and placed at the low layer. The control allocation problem has also been considered by allowing to switch on/off on-line some subsystems. Many examples where this design problem is significant can be mentioned. In process control, the slower system can describe a production unit (distillation columns, reactors, heat exchangers, etc.), while the faster subsystems are the available actuators. In plantwide control, at the high level dynamic optimization and control of the overall plant is made, while at the low level the control of the process units is performed. In production planning, the high level system can represent a large company, whose long-term behaviour is controlled by assigning given targets to its divisions. In the automotive field, a significant example concerns traction control and optimal power management of a hybrid vehicle, with slow mechanical dynamics, equipped with faster actuators, such as an internal combustion engine, an electric motor and a battery. The considered problem fits also a large number of engineering and economic problems, in which some demand must be shared by distinct sources with limited capabilities. Finally, the control effort distribution issue for overactuated systems allows one to meet secondary objectives, such as fault tolerance and reconfiguration ability requirements.

Multi-layer control structures are extensively used to control large scale systems where, typically, the design of a single centralized control unit is not a viable approach. For this reason they have received great attention for many years. Hierarchical control is also useful to deal with multi-time scale systems characterized by clearly separable slow and fast dynamics, or to coordinate a number of local controllers. As for the control allocation problem, it is of importance in a wide number of application fields, such as automotive, aerospace, robotics, marine. Finally, switching among different control configurations, designed with MPC, has been considered to improve the robustness and fault tolerance properties of the control scheme.

In spite of the widespread application of hierarchical control systems, synthesis procedures guaranteeing stability properties are still largely missing. Hence, the research efforts have been focused on the design of a stabilizing two-layer control system. Specifically, a cascade control structure has been considered: the regulator at the high layer selects the switching on/off policy (i.e., the configuration of active subsystems) and computes the desired control actions, which are the reference signals for the local regulators controlling the low layer subsystems. The design at the two layers is made with MPC in view of its capability to explicitly consider state and control constraints and to its wide popularity in the process industry. Contrary to the common practice in the design of cascade controllers, perfect reference tracking of the control loops at the lower layer has not been assumed. A convergence result for the overall system has been obtained by resorting to a robust MPC approach, where the discrepancy between the ideal control actions, requested by the high level controller, and those actually achieved by the actuators has been considered as a disturbance term to be rejected. The adoption of a robust control paradigm allows one to largely decouple the design at the two layers of the hierarchical structure.
The main results achieved in this research have been reported in the paper [10], where the effectiveness of the proposed design approach has also been tested in a significant simulation example. This example has shown the need to resort to a robust design approach for hierarchical control.

Then, we studied hierarchical model-based predictive controllers for an integrated public transport system. In this research, the major objective is to analyze how to combine a traditional public transport service on trunk corridors (big buses operating with established stops along the route) with a more flexible system (reroutable vans or big cars), transferring passengers between systems at specific transfer stations. This type of scheme could be attractive to people who presently prefer the automobile to traditional transit systems for their regular trips. A hierarchical model predictive control strategy with two levels is considered. The first level is the control algorithm for the public transit system exclusively. This level keep the headways of the buses as regular as possible and the effect of the dial-a-ride system will not be considered as a high demand of passengers for the use of the transit system is assumed. In the second level the control algorithm of the dial-a-ride selects the best vehicle to serve each request, using information that comes from the first level (headways/schedules) whenever a user requires the service. The relations between systems are the waiting times of users in the transfer points. With a better coordination and synchronization of transfer operations, the level of service of users can be increased; however, the trade-offs with the total operational costs should be considered.
So far, a hierarchical model predictive controller was proposed. In the formulation, the relations between both sub-systems are the transfer points. Considering that, a regular passenger will have several options to travel from origin to destination, depending on the location of such points (close or far from a trunk bus route), and on the passenger willingness to pay higher fares for a more personalized service as well. The proposed operational scheme was designed in order to minimize the total operational costs and to optimize the level of service of users, the latter by means of the minimization of travel and waiting times as well as number of transfers. The entire optimization scheme relies on the availability of computer and communication technology in order to allow real-time optimization and coordination/synchronization between subsystems. Fixed route services in transit without near-the-door pickup and delivery are not very attractive to certain users with poor accessibility to the bus route from their origin or destination, or both; however, fixed route services are recommended in case of some very high-density demand corridors. That is the major reason to propose more flexible alternatives to the user, taking advantages of fixed route services (with high capacity vehicles) on high-demand corridors, in combination with local dial-a-ride systems for low demand portions of the trip.

In addition, as the model predictive control optimization problem for the integrated dynamic public transport system is huge at every instant time, as further research it is proposed to study local optimization versus global optimization schemes, under a multi-objective optimization predictive control framework. Specific algorithms will be developed in order to propose real-time optimization of the whole system, properly defining the system cost functions considering the necessity of coordination at transfer points but also considering the operator cost. The implementation of this type of flexible systems shall be investigated, which can be incrementally phased or contracted out for private fleet operators. Potential zoning method and heuristics for reducing computational time should be also analyzed. The results have been published in several papers [17], [18] and [19].

Among the existing distributed model predictive controllers for constrained linear systems, one of the most interesting is the one proposed by Rawlings [1] and Venkat [2]. In this case each agent calculates the subsystem's input from the measured state of the whole plant by predicting the trajectories using the model of the whole plant. The distributed optimization method is an iterative algorithm such that the solution of each agent at each iteration is transmitted to the rest of agents. This controller ensures stability and constraint satisfaction of the plant, and global optimality if the constraints are uncoupled. However, this controller may lose the feasibility under changes in the operation point.

In [3] and [4] an MPC for tracking of constrained linear systems is proposed, which is able to lead the system to any admissible set point in an admissible way. The main characteristics of this controller are: an artificial steady state considered as a decision variable, a cost that penalizes the error with the artificial steady state, an additional term that penalizes the deviation between the artificial steady state and the target steady state added to the cost function (the offset cost function) and an invariant set for tracking considered as extended terminal constraint. This controller ensures that under any change of the target steady state, the closed loop system maintains the feasibility of the controller and ensures the convergence to the target if admissible. Based on this, a cooperative distributed model predictive control for tracking of constrained linear systems is presented. Each agent, besides optimizing the corresponding subsystem input, calculates the best artificial state of the whole plant according to a global offset cost function added in the cost function. These variables, however, are not required to be transmitted to each agent and then this technique does not incur in a larger transmission load. The derived controller inherits the properties of Venkat's controller, while ensures feasibility and stability under any change of the optimization problem.

In [21] we have studied the advantages and drawbacks of two hierarchical controllers applied to a toy problem. The problems with the centralized MPC control structure and decentralized control structure are already known for a long time. The lack of scalability, the lack of efficient algorithms for applications in real time for complex systems and the lack of information are the main addressed issues. The hierarchical structure based on spatial decomposition improves in the behaviour of the overall system, as simulation results show. This structure can be scaled in an efficient way since the model can reduce, significantly, its complexity as one goes up in the levels of the control hierarchy. It can be coupled easily to the control systems currently implemented in the most industries (decentralized control). At the same time it is considered as a robust control structure since failures in any local controller can be considered as perturbations in higher levels and corrective actions can be taken in time. The hierarchical structure based on temporal decomposition showed the best behaviour of the hierarchical structures, better than decentralized. In our simulations the performance of the system using temporal decomposition structure is very similar to the centralized strategy. The advantage is that the temporal decomposition splits the optimization problem in as many as temporal levels as can be achieved. The problem is that the highest MPC in the temporal decomposition has the same number of decision variables as the initial problem had. This shows a possible lack of scalability. In [20] we discuss a temporal decomposition using eigenvalues. An approach suggested in the literature is applied with some modifications to deal with large-scale systems. Theoretical foundations are briefly depicted and the application to a chemical benchmark case is proposed in order to develop a hierarchical control system based on temporal decomposition.

Finally, we continued research on dual-decomposition-based distributed MPC, and demonstrated its application on canal systems: We tackled interconnected systems with coupled dynamics and coupled constraints. In [14], we present a distributed version of Han's parallel algorithm for a class of convex programs, in order to address the presence of convex coupling constraints. The distributed algorithm relies on local iterative updates only, instead of system-wide information exchange as in Han's parallel algorithm. Convergence to the global optimum, recursive feasibility, and stability are established using only local communications between the subsystems. In [15], we present the distributed version of Han's parallel algorithm and the distributed MPC method. The new algorithm is then applied to an example of coupled spring-mass system with coupled linear constraints. The simulation results demonstrate the convergence and stability properties of the algorithm. In [16], we propose an improved version of the distributed MPC method based on Han's parallel algorithm, and apply it to a canal system. The simulation results show that the modifications lead to faster convergence of the method, thus making it more practical in control of water networks.

## *Task 3.2: Hierarchical and distributed robust nonlinear MPC*

The research in hierarchical control with MPC described in the previous paragraph has witnessed the necessity to resort to control design algorithms guaranteeing some robustness properties. There are nowadays many ways to formulate stabilizing MPC methods in nominal conditions. However, it is also well known that nominal MPC can be non-robust with respect to even arbitrarily small disturbances. Moreover, discontinuity of the closed-loop dynamics, and of the Lyapunov functions for the nominal system, can emphasize such a lack of robustness. This issue is crucial in MPC, where both the resulting feedback law and the available Lyapunov function (which is typically the value function associated to the optimal control problem defining MPC) can be discontinuous.

For this reason, in the last years, attention has been focused on the development of MPC algorithms robust with respect to specific classes of disturbances. This activity has lead to the development of two broad classes of robust MPC algorithms. The first one is based on a min-max formulation of the underlying optimization problem; the second class of algorithms is based on the a-priori evaluation of the effect of the disturbance over the prediction horizon and on the use of tighter and tighter constraints to be imposed in the optimization problem to the predicted state trajectories.
In any case, robust MPC methods are much more complex than those developed for nominal conditions, requiring either a heavy on-line computational burden, or a long off-line design phase. For this reason, it is still of interest to move back to the problem of analyzing under which conditions nominal MPC can guarantee robustness in the face of specific classes of disturbances. This is exactly the goal of the research activity described here and based on the notions of Input-to-State Stability (ISS) and Input-to-State practical Stability (ISpS). The main results of the research concern the characterization of stability properties in perturbed conditions which can be deduced by the properties of a Lyapunov function for the nominal system. More specifically, it has been shown that a function $\Psi$ can be constructed in terms of standard $K\infty$-functions used to bound the Lyapunov function $V$ and its variation along trajectories. The robustness analysis is then easily derived by the analysis of the behaviour of such a function $\Psi$, which thus represents a kind of robustness energy measure. The analysis includes the critical case of systems with a discontinuous dynamic equation and discontinuous Lyapunov functions. A classical example, already considered in the literature, has been revisited in view of the results achieved. Moreover, the analysis and results have been

specialized to linear systems. Finally, the achieved results have been applied to closed-loop dynamics resulting by an MPC stabilizing the nominal system. In particular, it has been proven that, under mild and easily testable assumptions, robustness properties can be enforced by properly selecting the free tuning parameters of an MPC algorithm designed for the nominal model.
The results of this research activity have been extensively described in [11].

Distributed MPC algorithms can be developed (i) assuming that there exists exchange of information between the subsystems, or (ii) considering that there does not exist any information exchange yielding to a fully decentralized control structure. The proposed controller considers the second case, that is, fully decentralized MPC. In this case, the possible interactions between subsystems are considered as unknown disturbances that the controller must accomplish. The design of a fully decentralized MPC can be done relying on a robust design of each predictive controller [5].
In other words, to design a robust predictive controller for a subsystem, the uncertainty model must be considered in the controller calculation in order to provide robust stability and robust constraint satisfaction. In this case particularly interesting are those approaches that provide robustness based on the solution of a nominal optimization problem. Input-to-state stability appears as a suitable framework for the robust stability analysis while constraint satisfaction can be ensured by means of approximations of the reachable sets. See [7] and the references there in for a survey on this topic.

In [5] a decentralized min-max MPC is proposed. Stability of the whole plant is achieved relying on the ISS property of each single min-max MPC controller and assuming certain bounds on the coupling terms. In this work we extend this result to the case of nominal MPC, which avoids the computational complexity of the solution of the min-max optimization problem. The methodology to design the nominal MPC for each subsystem has also proposed. Under a certain design, which generalizes [6], the nominal MPC can ensure ISS of the system with a less conservative stability margin. The uncertainty is modelled as a parametric uncertain signal, not as an additive disturbance. Assuming that the model function is uniformly continuous, enhanced design of the robust controller is achieved: in the calculation of the constraints of the optimization problem and in the stabilizing conditions. The obtained stabilizing design of the controller turns out to be particularly interesting to relax the terminal conditions for a certain class of model functions, yielding a less conservative control law [8].

## *Task 3.3: Coordination mechanisms*

The recent literature on multi-agent systems has witnessed an increasing interest in consensus-related problems. Examples are given by contributions on the performance of coordinated tasks or by formation control and obstacle avoidance. A field of particular interest is represented by distributed sensing, and in particular by the definition of strategies for the efficient deployment of sensors over regions to be measured. This problem seems technically compelling, especially in the case the field to be sensed has a stochastic description. On the other side, the number of applications of distributed sensing is very broad, ranging from surveillance of areas to environmental monitoring. Another emerging field of research is related to the use of hierarchical control structures, i.e., leader-following control strategies, in order to ensure the fulfilment of geometrical constraints on the agents' motion. A relevant example is given by the so-called containment problem, in which the leader agents are required to define a (possibly time-variant) geometrical shape in the space, consisting in their convex hull, while the followers are forced to move confined in it.
The research activity within the project aimed to merge the two problems discussed above in order to face a potentially interesting application: a mixed containment-sensing problem. The idea is to

exploit a hierarchical control structure in order to perform a complex measuring task. A group of sensing units, represented as followers, have to be driven to zones of interest to be sensed within a region. Leaders are used in order to coordinate the sensing task at a higher level, while guaranteeing suitable containment properties. The described control problem is addressed in presence of agents subject to single-integrator dynamics and with possibly saturated inputs by means of a combination of Model Predictive Control (MPC) schemes. Such tools have been formally proven to fulfil the following set of requirements: the containment property, i.e., the ability of the control scheme to drive the followers back to the leaders' convex hull in the event they get outside; the liveness of the hybrid strategy; the convergence of the system, i.e., the complete fulfilment of the task. The results achieved partially rely on the properties of optimal state paths available in the literature.
This research activity has been described in the conference paper [12].

We have also produced the deliverable 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"), in which we provide a compact literature review on existing coordination mechanisms and summarize results of the assessment of different coordination mechanisms. For this purpose we introduce the problem of coordination, on the hand by some practical motivation and on the other hand by some mathematical problem description. Coordination mechanisms are a crucial part of hierarchical and distributed model predictive control methods. The literature review provides an overview of the existing coordination methods: Many of them are closely related to each other and based on some price-driven coordination. Then we provide some short compact results of our own assessments. The results are analyzed regarding properties such as optimality and performance. Finally we give an overview of the results and discuss possible alternative coordination approaches.

We have noticed a lack of distributed model predictive control methods for nonlinear systems. Most existing methods are related to linear systems. In addition, many of them rely on dual decomposition based coordination mechanisms. Due to these facts, we concentrated on a new coordination mechanism for distributed model predictive control, with the goal to derive nonlinear DMPC methods. We have derived a new coordination mechanism, where each controller contains linear information of neighbouring systems, i.e. the controllers objective function is modified such that it contains linear information of the whole interconnected process. By means of this adaption, each controllers gains knowledge of the total process and thus overall optimality. Compared to the inclusion of the full objective function as proposed by Venkat [2], the linear information can be easily derived for each subsystem and spread among the distributed controllers, in particular for nonlinear systems. In the conference paper [13] we have provided a first introduction to sensitivity-based coordination methods with a small nonlinear application. There, the method shows promising properties, such as easy implementation and fast convergence in offline optimization. The current work concentrates on the mathematical analysis of this method and the application to a large-scale system, in order to verify the new method.

We have also considered the formulation of a distributed model predictive control scheme as a decision problem in which the decisions of each subsystem affect the decisions of the other subsystems and the whole system performance. This decision problem is formulated as a bargaining game. This formulation allows each subsystem to decide whether to cooperate or not depending on the benefits that the subsystem can gain from the cooperation. In this work, based on the Nash theories about the bargaining problem and two-person cooperative games distributed model predictive control is analyzed as a game. Properties like convexity, feasibility, and stability of the proposed control scheme are being analyzed. The proposed control scheme has been tested through simulations using a chain of two reactors followed by a non-adiabatic flash, and using the four-tank system benchmark. In the first case, by applying the proposed control scheme the subsystems cooperate in order to jointly select the best control actions in the sense of local performance without decreasing the entire system performance. With the purpose of determining the effect of the measurement noise in the performance of the proposed control scheme, a measurement noise was added to the controlled variables. Despite of the presence of the noise, by applying the proposed control the subsystems manage to maintain the value of the controlled variables close to their reference values. In the second case, similar results were obtained: the controllers in a cooperative way select the best control actions in the sense of the local performance without decreasing the entire system performance. Furthermore, this second experiment was also implemented on a real plant [22].

## *Task 3.4: Timing and delay issues*

During this period, the deliverable D3.4.1 ("Report of literature survey and analysis regarding timing and delay issues") has been compiled. This report describes the results of a literature survey regarding timing and delay issues and delay present in the distributed predictive issues in the context of hierarchical and distributed MPC. More specifically, the following topics are considered:

When a control system is implemented in a distributed fashion, with multiple processors communicating over a network, both the communication delays associated with the network and the computation delays associated with the processing time can degrade the systems performance. In this case, the performance of the system may depend not only on the performance of the individual components but also on their interaction and cooperation. Therefore, the deliverable discusses modelling and control of time-delay systems, including stability and robustness.

Next, we focus on communication and computational delay in MPC in the context of networked control systems. We characterize the issues related to communication delays and dropped network packets. Afterwards, we discuss model-based compensation of the dynamic effects of the network, and efficient schemes for on-line optimal control and MPC in networked control systems.

The subsequent topic is robust MPC for delayed systems, where we consider in particular stability and prediction.

Furthermore, we have been working on the design of predictive controllers aimed to reduce the effect of the delay induced by transmissions. Using time-stamped methods, a tight estimation of the delay can be obtained. Then, an open-loop predictor is typically used to estimate the future state and compensate the effect of the delay. Under absence of uncertainty this technique provides good results, but in the case that the prediction model differs from the real plant or the estimation of the delay is not accurate, the controller may exhibit a loss of performance or even of stability. To overcome this problem we have proposed predictive controllers that takes the uncertainty (modelled as additive) explicitly into account in the design. Particularly, the problem of explicit delay compensation in robust tube based MPC strategies has been addressed. The underlying idea is to robustly control a constrained process with dead-time by considering a prediction model without dead-time. As consequence, the prediction model order does not depend on dead-time length. Moreover, the effect of the uncertainty on the predicted state and the real state are studied and based on this, it has been proposed a slight different output tighter constraint in order to ensure robust constraint satisfaction. The proposed controller enjoys the input to state stability property and has demonstrated to provide robust controllers less sensible to the uncertainty in the model and in the estimated delay [9].

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### ***Resources***

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

## *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. During the reporting period new advancements have been made in the research directions already explored in the first year of the project and new algorithms have been devised.

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

The first line of research with Task 4.1 involves a distributed version of Han's parallel algorithm for a class of convex programs with convex coupling constraints [2,3]. The distributed algorithm relies on local iterative updates only, instead of system-wide information exchange as in Han's parallel algorithm. Convergence to the global optimum, recursive feasibility, and stability are established using only local communications between the subsystems. In [3] the new algorithm is then applied to an example of coupled spring-mass system with coupled linear constraints. The simulation results demonstrate the convergence and stability properties of the algorithm. In [4] an improved version of the distributed MPC method based on Han's parallel algorithm is proposed and applied to a canal system. The simulation results show that the modifications lead to faster convergence of the method, thus making it more practical in control of water networks.

In [8] a cooperative distributed linear model predictive control strategy applicable to any finite number of subsystems satisfying a stabilizability condition is presented. The control strategy has the following features: hard input constraints are satisfied; terminating the iteration of the distributed controllers prior to convergence retains closed-loop stability; in the limit of iterating to convergence, the control feedback is plantwide Pareto optimal and equivalent to the centralized control solution; no coordination layer is employed. In [9] a hierarchical distributed MPC scheme is presented. This iterative method aims at reducing the communication between the subsystems. Data is exchanged at each iteration between the neighbouring subsystems, while only slower asynchronous communication is required between non-neighbouring subsystems. This method is plantwide stabilizing and does not require iterating until convergence is achieved.

In order to achieve a practical implementation of distributed predictive controllers, routines to be executed in industrial platforms such as PLC, PC-104 based PACs or DSP have been developed at USE. On the PLC platforms, a suite that allows in a user-friendly way to implement explicit predictive control law using standard tools for MATLAB has been developed. A library of functional blocks to implement predictive controllers solving the optimization problem on-line is currently under development. A first predictive controller in absence of constraints has been successfully implemented. The constrained case is in progress. For the PC-104 and DSP platform, a QNX environment has been installed. Efficient quadratic programming solvers based on interior-point methods are under development. These are programmed in ANSI C-Language to ensure the portability between the different platforms. The derived predictive controller for tracking based on the developed QP-solver has been successfully tested in simulation. Specialized algorithms to speed up the control action calculation are currently under investigation.

In addition to these results other research directions are under investigation:

- The group at TUD is developing a subgradient scheme for solving convex optimization problems. The virtue of the new method is the ability to guarantee feasibility within a finite number of iterations. This subgradient method will enable implementing a distributed MPC that guarantees recursive feasibility and stability.
- The group at KUL is developing optimization methods which can be applied to the direct multiple shooting for large-scale distributed systems. These methods rely on the structure of the optimal control problems inherent in distributed systems. Inexact sequential quadratic programming is deployed to reduce the computations required.
- The solution of convex optimization problems based on interior point methods requires the solution of a set of linear equations that can be efficiently solved using well-known methods as Cholesky decomposition based algorithms. In the case of the optimization problems to be solved for large scale systems, algorithms that do not exploit the structure of the problem may exhibit poor results. In this regard, USE is studying methods which can detect on-line the dominant couplings between the subsystems in order to split the large scale problem into smaller tasks.

### *Task 4.2: Optimisation of uncertain large-scale systems*

As a first step towards optimisation of uncertain large-scale systems we have developed a line of research whose major objective is to systematize the use of the well-known multi-objective optimization tools, in dynamic environments [5,6,7]. In this context, a multi-objective model-based predictive control approach was developed for solving a dial-a-ride problem, which is inherently a hierarchical system. The dynamic objective function of the logistic part of this problem considers two components that are usually aimed at opposite goals: user and operator costs. When a new call asking for service is received (which is an uncertain process that cannot be predicted well in advance), the method first solves a multi-objective optimization problem, based on a predictive model of the process, providing the Pareto optimal set. Note that from this set just one solution has to be applied to the system. Then, the dispatcher participates in the dynamic routing decisions by expressing his/her preferences in a progressively interactive way, seeking the best trade-off solution at each instant among the Pareto optimal set. The idea of this method is to provide to the dispatcher a more transparent tool for the decisions. Several criteria, emulating different dispatchers, are proposed in order to systematize different ways to use the information provided by the dynamic optimal Pareto front.

We have proposed different criteria to obtain control actions over real-time routing using the dynamic Pareto front. The criteria allow giving priority to a service policy for users, ensuring a minimization of operational costs under each proposed policy. We have evaluated multi-objective model-based predictive control based on a weighted-sum criterion, a goal achievement method, and a fuzzy expert criterion. The service policies were verified approximately on the average of the replications. Under the implemented on-line system it is easier and more transparent for the operator to follow service policies under a multi-objective approach instead of tuning weighting parameters dynamically.

## *Task 4.3: Optimisation methods for robust distributed MPC*

In the context of optimisation methods for robust distributed MPC we are continuing previous research on the use of mixed-integer linear programming [1], with load scheduling for large-scale irrigation channels as benchmark application.

In large-scale irrigation networks, water is often distributed via open water channels under the power of gravity (i.e. there is no pumping). In practice, channel capacity is limited. This forces farmers to take water by placing orders. Moreover, the time-delay for water to travel from the upstream end to the downstream end of the pool limits the closed-loop bandwidth, which dampens the performance. Hence, the starting and ending of off-takes induce transients (i.e. the water-level drops and rises from set-point). Such a transient response propagates to upstream pools as regulators take corrective actions. In load scheduling, a set of off-takes (requested by farmers) is organized, which ensures that the water level constraints are satisfied, in the face of transients associated with load changes. Moreover, from a farmer's perspective, a preferable solution would involve the smallest possible delay between the requested starting time and the time the load is scheduled. As a result, the scheduling can be expressed as an optimisation problem involving minimising the delay of water delivery subject to constraints. Indeed, the load scheduling sits on the higher level of a two-level control hierarchy. On the lower-level, controllers are designed to ensure stability, robustness, good set-point tracking, and disturbance rejection.

In this research, the problem of load scheduling for large-scale irrigation channels is considered. Based on the analysis of the special structure of open water channels under decentralised control, a decomposition of the scheduling problem is discussed. The solution could be suboptimal compared to an optimal solution, if it exists, to the scheduling problem initially formulated in [1], without considering the structure of the irrigation system. However, such a decomposition scheme avoids computational issues, including memory requirements and computing time, which is significant for large-scale system.

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## *Resources*

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

## *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*

As already reported in the HD-MPC annual for Period 1 (M1-12), although the tasks for this work package were scheduled to start from month M16 in the project planning, the research on this work package (in particular on the first task, viz., state estimation) started earlier, during the first year of the project, to allow for the availability of distributed state estimation schemes to be used in conjunction with the distributed state-feedback control laws to be designed in WP3 and WP4.

## *Task 5.1: State estimation*

During the first year of the project, the following main results were obtained, as reported in the first scientific report:

- Preliminary analysis of the existing literature concerning distributed state estimation with Kalman Filters (KF) and Moving Horizon Estimators (MHE) and testing of distributed KF algorithms in a benchmark case;
- Definition of new observability criteria, i.e. local, regional, and global observability properties required by sensor networks for distributed control;
- Development of 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;
- Definition of 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;

During the second year of the project, the literature review has been completed, including the problem of disturbance modelling in Model Predictive Control, see deliverable D5.1 ("Report on the state of the art in distributed state and variance estimation, and on preliminary results on disturbance modelling for distributed systems") and [1]. In fact, it is well known that in MPC, the use of augmented models including (even fictitious) disturbance dynamics is widely used to guarantee tracking properties to the closed-loop system. This reflects in the state estimation problem, which must be solved for the extended system. So the significant design issue for the distributed system which consists in extending to the case of distributed control systems the previous considerations has been addressed, see again deliverable D5.1.

The Distributed Moving Horizon Estimation (DMHE) algorithms developed in the first year of the project have been further developed in many ways. First, we recall that the problem of distributed state estimation for sensor networks can be described as follows: assume that 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. Then, 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 must be achieved 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 must lead 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. Consensus algorithms for distributed state estimation based on Kalman filters have been recently described in the literature and rely on consensus on the measurements and/on the estimates to reduce the uncertainty when Kalman filters are applied by each agent. With respect to the solutions available in the literature, the proposed DMHE 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, we have proven that, under weak observability conditions, convergence of the state estimate is guaranteed in a deterministic framework. Finally, constraints on the noise are taken into account, as it is common in receding horizon approaches in control and estimation.

With respect to the initial developments reported in the scientific report of the first year, in the second year we have highlighted how the performance of the state estimation scheme depends upon various observability properties of the system; we have extended the main results in case different communication protocols are employed, we have analyzed how the parameters of the communication protocols can be properly tuned, so as to enhance the performance of the estimation scheme. A further significant development concerns the generalization of our previous results to the nonlinear setting with the goal of providing a Nonlinear DMHE (NDMHE) scheme enjoying stability properties. In order to characterize states that can and cannot be recovered by each sensor without communication we have exploited the notion of MHE detectability. Moreover we have used a consensus-on-estimates penalty term in local MHE problems to let each sensor learn locally MHE-undetectable parts of the state from other sensors. The results of this research activity have been extensively described in [2]-[5].

A second research line has concerned the further development of MHE algorithms for large-scale discrete-time constrained linear partitioned systems, i.e. represented by coupled subsystems with non-overlapping states. The properties of the three Partition-based MHE (PMHE) algorithms proposed have been further examined in terms of convergence and requirement (“all-to-all” or neighbour-to neighbour” communication protocols, computational burden, amount of information to be transmitted). The extension of this approach to nonlinear systems is currently underway. The algorithms which are now under development will be applied to the hydro-power valley benchmark (see WP7). The results of this research activity have been extensively described in [6,7].

Finally, for macroscopic traffic flow models several estimation methods have been investigated, including extended and unscented Kalman filters and particle filters. In particular, in [8] a fuzzy observer has been proposed for the continuous time version of the macroscopic traffic flow model METANET. In order to design the observer, a dynamic Takagi-Sugeno fuzzy model that exactly represents the traffic model of a segment of a highway stretch has been developed. The fuzzy observer is designed based on the fuzzy model and applied to the traffic model with promising results.

### *Task 5.2: Variance estimation*

In the first phase of this task (months 18-24), the currently available techniques for the estimation of the noise covariances have been reviewed, focusing attention on the algorithms which appear to be the most reliable and efficient solutions to the considered problem.

The estimation of the covariances from open-loop data has long been a subject in the field of adaptive filtering, and can be divided into four general categories: Bayesian [9,10], maximum likelihood [11,12], covariance matching [13], and correlation techniques. Bayesian and maximum likelihood methods have fallen out of favour because of their sometimes excessive computation times. They may be well suited to a multi-model approach as in [14]. Covariance matching is the computation of the covariances from the residuals of the state estimation problem. Covariance matching techniques have been shown to give biased estimates of the true covariances. The fourth category is correlation techniques, largely pioneered by Mehra [15,16] and Carew and Belanger [17,18]. In [19] an alternative method to the one presented in [15,16] has been described, and necessary and sufficient conditions for uniqueness of the estimated covariances have been given. In [20] and [21] simple necessary and sufficient conditions for the existence of the covariance estimates provided by the method proposed in [19] are given, and a modification of such method is proposed, to estimate the number of independent stochastic disturbances affecting the states. The two main contributions to the field, i.e. those reported in [15] and [19] have been extensively analyzed and compared in deliverable D5.1.

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### *Resources*

As indicated in the annual report for Period 1 (M1-12) we have anticipated of the start of this work package (i.e., although work on this work package and in particular Task 5.1 was only scheduled to start in M15, we have already started working on it during the first year to allow for the availability of distributed state estimation schemes to be used in conjunction with the distributed state-feedback control laws to be designed in WP3 and WP4.). Taking this into account (i.e., looking at the entire 2-year period covering Period 1 and Period 2 (M1-24)), the resources for this work package have been used as planned in the description of work.

## *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. In addition, two new benchmarks related to WP7 (viz. the hydro-power valley and irrigation channels) have been defined. The progress for each of the tasks of WP6 is detailed next.

### *Task 6.1: Analysis of hardware and software*

The objective of this task is the analysis on hardware and software for hierarchical and distributed model predictive control. The software and hardware needed to implement HD-MPC in industrial systems is almost the same of any industrial Distributed Control System (DCS). This task has been focused on the requirements, software and hardware needed for industrial HD-MPC applications and also in those required in HDMPC based on sensor networks.

On the industrial applications side, a number of commercial industrial control solutions have been considered: Invensys, Honeywell, ABB, Schneider-Telemecanique, Siemens, and Telvent, which constitute a good sample of the whole offer. These systems are reviewed from the point of view of the requirements of a truly distributed control system. Thus, general, visualization and communications requirements and how each system can fulfil them are discussed. Concerning the communications requirements, the special redundant network topologies used in industrial DCS are reviewed and also the possibility of having different communication systems for those remote locations in which no other means of connecting to the net is available.

Another alternative to implement distributed MPC schemes is based on wireless sensor networks. Wireless sensors (often called motes) can have enough computing power to implement predictive control algorithms for typical industrial processes and also have very good networking capabilities. The advantages and challenges of designing wireless sensor networks for industrial applications are reviewed together with the main standards and operating systems used in those networks. Some hardware platforms are also reviewed.

Also, different long distance communication systems has been analysed in the task. It is important for the HD-MPC Project to consider this type of communication system because some of the project application cases, such as the water capture system, the irrigation system or the hydropower valley, need long-distance communications.

The task finished in month M18 and the deliverable D6.1.1: “Report on results of hardware and software analysis” has been produced.

## *Task 6.4: Implementation of benchmark exercises*

The objective of this task is the implementation of the experiments on the benchmark cases defined in Task 6.3.

The consortium decided the use of 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 were prepared in the first year of the project in Task 6.3. 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.
- **Electric network** (prepared by UNC): electric power system is composed by 10-machines 39-buses, interconnected among them by transmission lines.
- **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.
- **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.

### Four-tank system

The proposed benchmark exercise tested and analyzed different control approaches (centralized, decentralized and distributed) when four reference changes on the levels of lower tanks (tanks 1 and 2) are performed. Experiments are tested on simulation and also on the real plant. These are the analyzed controllers:

- Tracking Control. Control that allows changes in the reference.
    - Centralized control for tracking: The algorithm developed in [5] has been implemented.
    - Decentralized control for tracking. Two MPC for tracking are used, the same as in the previous case, but applied to each subsystem. The pairing procedure between the inputs is done based on the Relative Gain Array. Two examples are done, one with the correct pairing, and the second with the wrong one.
- Regulation controller. To perform the reference changes, one controller for each reference is designed.
    - Centralized control.
    - Distributed control. Distributed MPC based on a cooperative game [6].

A complete description of the algorithms and results can be found in Deliverable D6.4.1 (Chapter 3)

### Heat system

The two-dimensional heat system benchmark has been used to compare various centralized, decentralized and distributed Kalman filters (See deliverable D6.4.1 (Chapter 1) for a detailed description). The methods that are compared are:

1. CKF - Centralized Kalman filter [3],
2. PIF - Parallel information filter [10],
3. DIF - Decentralized information filter [9],
4. DHKF - Decoupled hierarchical Kalman filter [2],
5. DFFWA - Distributed Kalman filter with weighted averaging [1],
6. DKFCF - Distributed Kalman filter with consensus filters [8],
7. DKFBFG - Distributed Kalman filter with bipartite fusion graphs [4].

The obtained results show that, in general, the DKFCF and the DHKF give the smallest errors. Of these two, the DHKF yields more variation than the DKFCF.

A one-dimensional heat system has been used to test another distributed state estimation scheme, DDKF-Distributed and Decentralized Kalman Filter [7]. The observer performance under additive and structural disturbance is also studied. Finally, a combined DDKF and MPC formulation is tested on the same benchmark. (See Deliverable D6.4.1, Chapters 2 and 3 for further information).

### Electric power system

A centralized MPC is formulated for the control of generation units of an electric power network. Due to the different time scales of the machines' dynamics, a two levels time-response-based hierarchical structure is proposed. The proposed control structure involves the interaction among the centralized MPC and classical voltage and speed regulators.

## *Task 6.5: Maintenance of the benchmark service*

This task consists of maintaining the HD-MPC benchmark system by the introduction of new experiments on defined benchmark cases and the definition of new cases.

The four benchmark cases defined in Task 6.3 and two new benchmarks related to the WP7 applications (viz. the hydro-power valley and irrigation channels) are the cases that are being used in this task.

The work on this task during the second year consisted of the performance of new experiments on the four-tank real plant, using the distributed controllers developed in HD-MPC project, and the comparison with centralised and decentralised approaches. Also, the model guide of an irrigation channel case has been developed.

**New experiments on the four-tank system**

A comparison of some of the main controllers developed in the HD-MPC Project has been performed in this task. This activity adds new controllers to the ones tested in Task 6.4 and also evaluated all of them with a complete set of performance indexes, including qualitative to evaluate the controllers and quantitative to evaluate the experiments:

- Knowledge and modeling requirements.
- Controller objectives (Functional, constraints, stabilizing design, ...)
- Estimated design time.
- Tests required on the plant.
- Auxiliary software needed
- Performance index $J$.
- Constraint violations
- Computation time needed
- Communication needs

The compared algorithms are:

- Centralized MPC for Tracking (USE)
- Decentralized MPC for Tracking (USE)
- MPC based on nonlinear dynamic optimization methods (RWTH)
- Feasible-Cooperation Distributed Model Predictive Controller Based on Bargaining Game Theory Concepts (UNC)
- Distributed MPC based on cooperative and coalitional games (USE)
- Distributed MPC (TUD)

A paper with the results has been submitted to Journal of Process Control.

**New benchmarks: Irrigation Channels**

INOCSA and USE have designed the model guide of an irrigation channel benchmark. The proposed benchmark is a section of the "postrasvase Tajo-Segura" in the South-East of Spain. The "postrasvase Tajo-Segura" is a set of canals which distribute water coming from the Tajo River in the basin of the Segura River. The selected section is a Y-shaped canal (see Figure 1 on the next page), a main canal that splits into two canals with a gate placed at the input of each one of them.

- "Canal de la Pedrera", 6.68 km long.
- "Canal de Cartagena", with a length of 7.44 km

The total length of the canals is approximately of 24 km and there are 7 main gates and 17 off-take gates in the section selected. At the end of the whole "Canal de Cartagena" there is a reservoir with limited capacity.

The main target is to control the management of water in canals in order to guarantee flows requested by users. The controlled variables are the upstream levels beside the gates, and the manipulated variables are the flow at the head of the canal and the position of the gates. There is a constraint on the flow at the head: The total amount of water over a determined time period is limited.

Figure 1: Irrigation channel benchmark

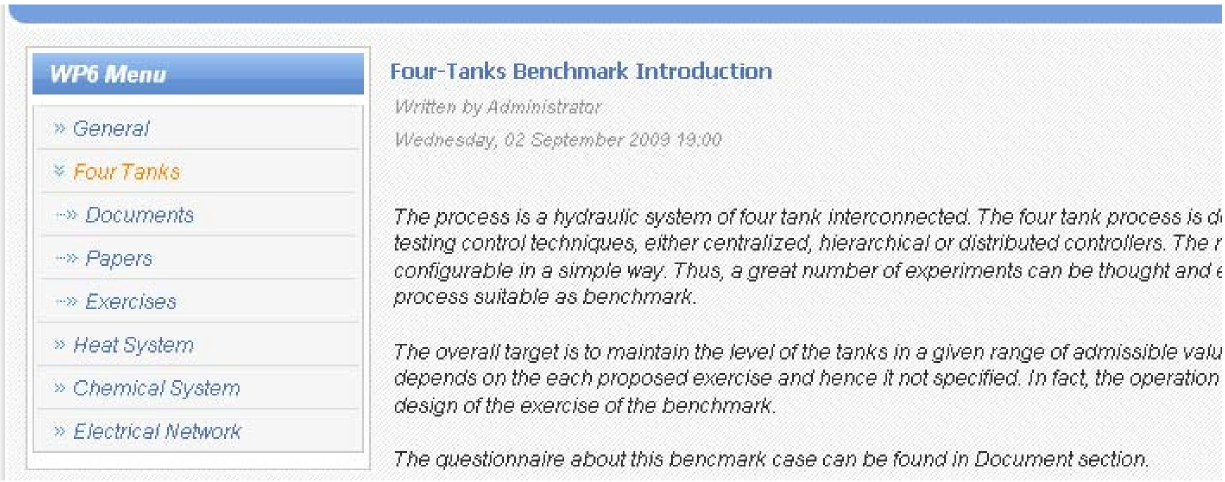
Also, we have created a model library in gPROMS to model distributed water systems, such as the irrigation channels or the hydro-power valley. The library is highly modular, such that it can be adapted to different benchmarks in that field. The library contains full nonlinear models for relevant parts of the distributed water systems and can be used to be embedded in nonlinear controllers. A detailed description of the library can be found in Deliverable D7.2.2.

## *Task 6.6: Dissemination of benchmarking and results*

The objective of this task is to disseminate the benchmarking activity inside and outside the project.

**Inside the HD-MPC project**

A section on “benchmarking” has been included in the HD-MPC Virtual Portal. This section includes all the available documentation on the active benchmark cases: model guide, available models, papers and results of the experiments.



Four-Tanks Benchmark Introduction

*Written by Administrator*

*Wednesday, 02 September 2009 19:00*

*The process is a hydraulic system of four tank interconnected. The four tank process is d*
*testing control techniques, either centralized, hierarchical or distributed controllers. The r*
*configurable in a simple way. Thus, a great number of experiments can be thought and e*
*process suitable as benchmark.*

*The overall target is to maintain the level of the tanks in a given range of admissible valu*
*depends on the each proposed exercise and hence it not specified. In fact, the operation*
*design of the exercise of the benchmark.*

*The questionnaire about this bencmark case can be found in Document section.*

### Outside the HD-MPC project

The consortium plans to send the main results of the benchmarking task to Journals and Conferences. A paper entitled “Comparative analysis of distributed predictive controllers to the four-tank plant” has been submitted to the special issue on HD-MPC of *Journal of Process Control*.

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## *Resources*

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

## *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*

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

Combined Cycle Power Plant (CCPP) control systems are hierarchical and distributed and consist mainly of logic controls and PID loops. The aim of Task 7.1 is to propose HD-MPC solutions to optimize the start-up transients of the combined cycle units that can be integrated in the existing hierarchical control.

The task is decomposed in 3 subtasks: (i) control specification, (ii) modelling, and (iii) validation of HD-MPC solutions in simulation.

The control specification that defines the control problem (i.e., Task 7.1.1) has been done during the first year. The modelling that has been developed during the second year (i.e., Task 7.1.2) is described in the present report. The last sub on validation of method for hierarchical and distributed MPC for combined cycle start-up (i.e., Task 7.1.3) has not started yet: this task will be performed in the next period. Specific HD-MPC control method will then be developed on the base of the available models.

### *Task 7.1.2: Modelling of the combined cycle start-up*

SUPELEC has developed a model of a single pressure CCPP with the Modelica Thermopower library provided by POLIMI. The model implemented in Dymola can be downloaded from the project's Virtual Portal by every partner. A presentation of this model was made during a specific web-meeting organized at the end of 2009. The model will be used for the validation of HD-MPC controller in the last year of the project.

Despite the simplification of the circuits (one pressure instead of three), the Modelica model remained to complex to be directly used for optimization and control purpose. Two approaches have been adopted:

- the first approach envisaged by SUPELEC is to withdraw all the elements that make the optimization difficult (switching conditions, discontinuities, …). A new Modelica library has been developed and used to build a Modelica smooth model of CCPP. The Modelica smooth model and the Modelica initial model responses have been compared. In spite of some small errors, the Modelica smooth model is considered to be sufficient and will be used in the next stage. For the Modelica smooth model, J-Modelica and DyOs will be used for the optimization in Task 7.1.3.
- the second approach adopted by POLIMI is to develop a non linear transfer function model of CCPP. First, local linear models are identified at different Gas Turbine load with step responses simulated on the Modelica model. Then, the linear models are interpolated with membership functions depending on the Gas Turbine load. The non-linear transfer function

and the Modelica model have been compared on small and big transients. The transfer function is considered to be sufficiently precise and will be used in the next stage.

The HD-MPC deliverable D7.1.2 presents the model of a single pressure level CCPP in Modelica. Simulations were made with this model and simplified models easier to use for the optimization were developed too.

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

Hydro-Power Valleys (HPVs) are hierarchically controlled. Each plant is equipped with local controllers and the coordination is done by the operator who imposes flow, power or level set-points. In this task we investigate the use of HD-MPC methods to optimally coordinate the power plants of one valley. As for CCPP, the task is divided in 3 subtasks: (i) control specification, (ii) modelling, and (iii) validation of HD-MPC solutions. During the first year a case study that corresponds to an industrial application has been selected and the main control objectives have been defined. During the second year models for the case study have been developed (this corresponds to Task 7.2.2).

### *Task 7.2.2: Modeling of the hydro-power valley*

EDF developed a model of the HPV case study within the public software SciCos and Mascaret. The model considers Saint-Venant PDE equations for simulation of the river reaches and simpler dynamical or algebraic equations for the other components of the HPV (reservoir, turbine, …). The SciCos/Mascaret model will be used to test and validate the HD-MPC solutions that will be proposed. EDF developed OPC communication modules to facilitate the connection of the SciCos/Mascaret model and the controllers that will be developed by the partners. In particular, Matlab and gPROMS have already OPC communication possibilities that will also be used for the connection.

Three types of model have been developed for the control:

- A Simulink model of the case study has been developed by POLIMI. The parameters have been tuned to fit the SciCos/Mascaret model as much as possible. The reach models are derived from the Saint-Venant equations with a spatial discretization.
- A gPROMS library has been developed by RWTH. This library contains also a river reach model based on Saint-Venant equations. Optimization for small scale system has been successful as well as simulation of large scale system. This library will be used to develop the case study.
- A model of a cascaded river reach described by Saint-Venant equations has been developed in ACADO by KUL and POLIMI. ACADO is a free software developed by KUL to simulate and optimize dynamical systems.

Optimization tests have already been done with ACADO and gPROMS during the second year. In the next year within Task 7.2.3 ("Validation of method for hierarchical and distributed MPC for hydro power valley) HD-MPC solutions will be developed using the Simulink, gPROMS and ACADO control models.
The HD-MPC deliverable D7.2.2 presents the HPV case study model developed with SciCos and Mascaret software as well as the other models (Simulink, ACADO, gPROMS) that will be used for the optimization. OPC communication between the SciCos Model and OPC server has been developed too, which will make the connection of the controller and the simulator easier.

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

During the reporting period the work within Task 7.3 focused on modelling (Task 7.3.1) and predictive control (Task 7.3.2) of large-scale water capture systems.

### *Task 7.3.1: Modelling for hierarchical and distributed MPC*

During the second year of the project, the following actions have been performed jointly by INOCSA and USE:

1. Detailed study of the management that is being performed, the current control techniques and the elements which constitute the "Canales del Bajo Guadalquivir" (South of Spain) and the "Canales del Postrasvase Tajo-Segura" (South- East of Spain).
2. Formulation of the general HD-MPC problem applied to these kinds of canals and the related constraints.
3. Development of a simulation platform to test distributed controllers in the field of Water Capture System applications. This work is closely related to the Irrigation Canals Benchmark of WP6. Two approaches have been considered:
    a. Integration of HEC-RAS and MATLAB with the FEWS platform: The work consists in the development of adaptation software to convert input/output data from one application to another. The most difficult task is the conversion between FEWS and HEC-RAS data, because of the important quantity of data managed by HEC-RAS and the lack of information about input/output data of this software package. The conversion is between XML files generated or read by FEWS and HEC-DSS format, the HEC-RAS database system. The communication between the controller (MATLAB) and FEWS is quite simpler. Some functions written in MATLAB read XML and produce an output in that format.
    b. SIC and MATLAB: Due to some difficulties with HEC-RAS, another alternative has been considered. SIC software (Simulation of Irrigation Canals) is a commercial package developed by Cemagref. The advantage of this tool is an easier integration with MATLAB, then the controller can be developed using this tool. The adaptation needs to integrate MATLAB and SIC (task already performed), and current work is related to produce a SIC model of the Postrasvase Tajo-Segura.

### *Task 7.3.2: Predictive management of water resources*

During the second year of the project, the following action has been performed jointly by INOCSA and USE: Design and development of a hierarchical distributed model predictive control approach applied to irrigation canals planning from the point of view of risk mitigation.

The approach considers two levels. At the lower level, a distributed model predictive controller optimizes the operation by manipulating flows and gate openings in order to follow the water level set-points. The upper level modifies the water level set points and executes mitigation actions if risk occurrences are expected. Risk factors have been identified for that problem, (i.e. changes in demand and operating and maintenance costs). These factors are considered in the optimization. The decision variables include the mitigation actions which reduce the risk impacts that may affect the system.

The HD-MPC deliverable D.7.3.2 presents the different tools that will be used to simulate the irrigation channel.

Besides the work done by INOCSA and USE, TUD has addressed the problem of irrigation and developed a "Decomposition of a Fixed-Profile Load Scheduling Method for Large-Scale Irrigation Channels" (see also the description given in the section on work package WP4 for Task 4.3: Optimisation methods for robust distributed MPC).
The problem of load scheduling for large-scale irrigation network is considered. Based on the analysis of the special structure of a channel under decentralized control, a decomposition strategy of the scheduling problem is provided. The decomposition prevents the forbidding requirement on storage capacity in building the predictive model of the controlled plant and solving the formulated optimization problem.

The main results achieved so far are the following. In large-scale irrigation networks, water is often distributed via open water channels under the power of gravity (i.e. there is no pumping). In practice, channel capacity is limited. This forces farmers to take water by placing orders. Moreover, the time-delay for water to travel from the upstream end to the downstream end of the pool limits the closed-loop bandwidth, which dampens the performance. Hence, the starting and ending of off-takes induce transients (i.e. the water-level drops and rises from set-point). Such a transient response propagates to upstream pools as regulators take corrective actions. In load scheduling, a set of off-takes (requested by farmers) is organized, which ensures the water level constraints are satisfied, in the face of transients associated with load changes. Moreover, from a farmer's perspective, a preferable solution would involve the smallest possible delay between the requested starting time and the time the load is scheduled. As a result, the scheduling can be expressed as an optimization problem involving minimizing the delay of water delivery subject to constraints. Indeed, the load scheduling sits on the higher level of a two-level control hierarchy. On the lower level, controllers are designed to ensure stability, robustness, good set-point tracking, and disturbance rejection. In this research, the problem of load scheduling for large-scale irrigation channels is considered. Based on the analysis of the special structure of open water channels under decentralized control, a decomposition of the scheduling problem is discussed. The solution could be sub-optimal compared to an optimal solution, if it exists, to the scheduling problem initially formulated in [1], without considering the structure of the irrigation system. However, such a decomposition scheme avoids computational issues, including memory requirements and computing time, which is significant for large-scale system.

#### References

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### *Resources*

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

## *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 achievement of this work package for the reporting period is the organization of activities aimed at the divulgation of the results in the scientific community, in particular invited sessions at international conferences, the preparation of a special issue of the *Journal of Process Control*, and the preparation of an industrial short course.

In addition, the website (http://www.ict-hd-mpc.eu) set up as part of Task 8.1 has been updated and is being maintained. Moreover, the contents of the Intranet web site linked to the main website (http://www.ict-hd-mpc.eu/participants) have now been merged in the HD-MPC Virtual Portal (http://www.nyquist.us.es/hdmpcproject/). This Virtual Portal contains all the data related to the work packages and other tools to improve the communication between the partners.

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

Bart De Schutter and Riccardo Scattolini are organising as guest editors a special issue of the *Journal of Process* Control on “Hierarchical and Distributed Model Predictive Control”. The submitted papers are currently under review. The publication of the special issue is expected by the first semester of 2011.

In addition, during the reporting period two invited sessions in international conferences have taken place:

- Tamás Keviczky and Rudy Negenborn have organized 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 have organized an invited session on “Hierarchical and Distributed Model Predictive Control” at the 2010 American Control Conference (ACC 2010), Baltimore, Maryland, USA, June 30-July 2, 2010.

For more details on these invited sessions we refer to HD-MPC deliverable D8.2.1 (“Report on or proceedings of a special session at an international conference”).

Moreover, Alfredo Núñez and Bart De Schutter are in the process of preparing two invited sessions on hierarchical and distributed model predictive control for the IFAC World Congress 2011.

### *Task 8.4: Industrial short courses*

Moritz Diehl, Boris Houska, and Hans Joachim Ferreau will organise an industrial course on “Embedded Optimization for Nonlinear Model Predictive Control” on February 10-11, 2011 in Leuven, Belgium. The course will cover several aspects of MPC for its application to real world scenarios.

During the reporting period, Bart De Schutter also gave a 1-hour lecture on “Advanced traffic control: Model-based predictive control” on September 30, 2009 in Delft, The Netherlands. This lecture was part of the course on ”Dynamic traffic management” organised by the Stichting Postacademisch Onderwijs (PAO), which was explicitly aimed at practitioners and participants from industry.

### *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**[6]

| 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 | |

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

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|---|---|---|---|---|---|---|---|---|---|
| | 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 with structural | 2 | POLIMI | R | PP | 12 | Yes | 31-08-2009 | |

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|---|---|---|---|---|---|---|---|---|---|
| | 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. |

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|---|---|---|---|---|---|---|---|---|---|
| 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 | Yes | 01-12-2009 | |
| 2.3 | Final report on the results regarding multi-level models and architectures for hierarchical and distributed MPC (D2.3) | 2 | POLIMI | R | PU | 18 | Yes | 28-02-2010 | |
| 3.5 | Report of literature survey and analysis regarding timing and delay issues (D3.4.1) | 3 | RWTH | R | PU | 18 | Yes | 01-03-2010 | |
| 6.3 | Report on results of hardware and | 6 | USE | R | PU | 18 | Yes | 01-03-2010 | |

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|---|---|---|---|---|---|---|---|---|---|
|  | software analysis (D6.1.1) |  |  |  |  |  |  |  |  |
| 6.4 | Report on implementation for selected benchmarks (D6.4.1) | 6 | USE | R | PU | 18 | Yes | 01-03-2010 |  |
| 8.2 | Report on or proceedings of special session at an international conference (D8.2.1) | 8 | KUL | R | PU | 18 | Yes | 20-02-2010 |  |
| 1.3 | Second annual progress report (D1.2.2) | 1 | TUD | R | RE | 24 | Yes | 01-09-2010 (scientific part) | The scientific part was delivered on 01-09-2010 |
| 1.4 | Report on knowledge management, links with potential users of results, and future perspectives (D1.3.1) | 1 | TUD | R | RE | 24 | Yes | 27-08-2010 |  |
| 3.6 | Report on new methods for complex control problems (nonlinear, dynamic, constrained) (D3.1.3) | 3 | RWTH | R | PU | 24 | Yes | 27-08-2010 |  |
| 3.7 | Report on newly developed methods for hierarchical and distributed robust nonlinear dynamic MPC (D3.2.2) | 3 | RWTH | R | PU | 24 | Yes | 27-08-2010 |  |
| 3.8 | Report on newly developed coordination mechanisms for hierarchical and distributed MPC (D3.3.2) | 3 | RWTH | R | PU | 24 | Yes | 27-08-2010 |  |

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| 4.4 | Report on redefinition of optimality criteria and generation of optimal solutions, and on analysis of sensitivity, scalability of solutions and computing cost (D4.2.2) | 4 | KUL | R | PU | 24 | Yes | 26-08-2010 | |
| 5.1 | Report on the state of the art in distributed state and variance estimation, and on preliminary results on disturbance modelling for distributed systems (D5.1) | 5 | POLIMI | R | PU | 24 | Yes | 26-08-2010 | |
| 7.3a | Report that presents the model and open-loop simulation results for the combined cycle start-up (D7.1.2) | 7 | EDF | R | PU | 24 | Yes | 28-08-2010 | |
| 7.3b | Report that presents the model and open-loop simulation results for the hydro-power valley (D7.2.2) | 7 | EDF | R | PU | 24 | Yes | 28-08-2010 | |
| 7.4 | Report on models of hydraulic transport systems (D7.3.2) | 7 | EDF | R | PU | 24 | Yes | 01-09-2010 | |
| 8.3 | Report on the organisation of an industrial short | 8 | KUL | R | PU | 24 | Yes | 26-08-2010 | |

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|---|---|---|---|---|---|---|---|---|---|
| | course (D8.4.1) | | | | | | | | |
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## 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.*

***Note: Milestones for the current reporting period (M13-24) are indicated in bold italics.***

| **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 |
| ***M1.1.4*** | ***Second annual meeting*** | ***1*** | ***TUD*** | ***18*** | ***Yes*** | ***03-09-2010*** | ***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 |

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|---|---|---|---|---|---|---|---|
| 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 |
| ***M2.3*** | ***New algorithms for the definition of multi-level models and architectures suitable for hierarchical and distributed MPC*** | ***2*** | ***POLIMI*** | ***15*** | ***Yes*** | ***01-12-2009*** | ***See Deliverable 2.3*** |
| 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 |

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|---|---|---|---|---|---|---|---|
| ***M3.1.2*** | ***Methods developed for hierarchical and distributed MPC for complex control problems*** | ***3*** | ***RWTH*** | ***24*** | ***Yes*** | ***01-08-2010*** | ***See Deliverable D3.1.3*** |
| 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 |
| ***M3.3.1*** | ***Newly developed coordination mechanisms for hierarchical and distributed MPC*** | ***3*** | ***RWTH*** | ***24*** | ***Yes*** | ***01-08-2010*** | ***See Deliverable D3.3.1*** |
| ***M3.4.1*** | ***Assessment of existing methods to deal with timing and delay issues, and identification of most appropriate methods including options and ways to extend them*** | ***3*** | ***RWTH*** | ***18*** | ***Yes*** | ***01-03-2010*** | ***See Deliverable D3.4.1*** |

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|---|---|---|---|---|---|---|---|
| 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 |
| ***M5.1*** | ***Analysis of the available methods for distributed state and variance estimation*** | ***5*** | ***POLIMI*** | ***21*** | ***Yes*** | ***01-06-2010*** | ***See Deliverable D5.1*** |
| ***M6.1.1*** | ***Selection of the best choices for hardware and software*** | ***6*** | ***USE*** | ***18*** | ***Yes*** | ***01-03-2010*** | ***See Deliverable D6.1.1*** |
| 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 |
| ***M6.4.1*** | ***Selection of the benchmark proposals*** | ***6*** | ***USE*** | ***15*** | ***Yes*** | ***1-12-2009*** | ***See HD-MPC Virtual Portal and Deliverable 6.4.1*** |

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|---|---|---|---|---|---|---|---|
| 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 |
| ***M7.1.2/M7.2.2*** | ***Model and open-loop simulation results for the combined cycle start-up and for the hydro-power valley available*** | ***7*** | ***EDF*** | ***24*** | ***Yes*** | ***01-08-2010*** | ***See Deliverables D7.1.2 and D7.2.2*** |
| M7.3.1 | Meteorological forecasting model | 7 | EDF | 12 | Yes | 01-08-2009 | See Deliverable D7.3.1 |
| ***M7.3.2*** | ***Predictive model of hydraulic transport systems*** | ***7*** | ***EDF*** | ***24*** | ***Yes*** | ***01-08-2010*** | ***See Deliverable D7.3.2*** |
| M8.1.1 | Opening of a web site including downloads of reports, presentations, open-source software and a database of benchmark problems | 8 | KUL | 6 | Yes | 01-04-2009 | See the HD-MPC web site at http://www.ict-hd-mpc.eu |

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|---|---|---|---|---|---|---|---|
| ***M8.2.1*** | ***Organisation of special session at an international conference*** | ***8*** | ***KUL*** | ***15*** | ***Yes*** | ***01-12-2009*** | ***See Deliverable D8.2.1 and the on-line program of the BFG'09 conference at www.cs.kuleuven.be/conference/bfg09/ as well as the on-line program of the ACC 2010 conference at https://css.paperplaza.net/conferences/conferences/2010ACC/program/*** |
| ***M8.4.1*** | ***Communication of the project results to industry by organising industrial short courses*** | ***8*** | ***KUL*** | ***24*** | ***Yes*** | ***01-09-2010 (for the DISC Summer School and the PAO lecture as well as the preparation of the Leuven course, which will actually take place in February 2011)*** | ***See Deliverable D8.4.1*** |

## 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).

During the reporting period the progress of the project and the work packages were monitored during the HD-MPC meetings in Rennes, France (September 9-10, 2009), Aachen, Germany (February 11-12, 2010), and Seville, Spain (June 1-2, 2010). In addition, the second annual meeting of the project will take place on September 2-3, 2010 in Delft, The Netherlands.

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; with the annual meetings included, we had 2 such meetings in the first reporting period (in Milan and Rennes) and 3 in the current reporting period (in Aachen, Seville, and Delft), and three more are already planned for 2011, viz. Chatou (February 3-4, 2011), Leuven (June 2-3, 2010) en Milan (September 2011). In addition, for some dedicated, specialized topics, separate work package meetings are of course still possible. An example of the latter is the WP7 web meeting on modelling and optimization of the combined cycle start-up that took place on December 14, 2009, and the meeting on models that took place in Aachen on February 10, 2010. The minutes of all these meetings can be found on the HD-MPC Virtual Portal.

In order to allow for additional interaction between the HD-MPC participants outside the meetings and visits, the Virtual Portal provides a place to exchange published and submitted papers as well as reports on the latest research, models, and software. 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;*

In the current reporting period the project has been running smoothly and we have not encountered any problems.

At the end of the first reporting period we had reported two problems: one was related to the timely hiring of the researchers, in particular for the KUL team. Since September 2009 the KUL team has a Ph.D. student who works full-time on the project, which has addressed the hiring problem and which has also allowed us to execute the research program of the project as scheduled. The second problem was related to the timely delivery of the deliverables for months 3, 6, and 9. For month 12 all deliverables were approximately delivered on time. To streamline the process of producing the deliverables, we have since month 12 of the project opted to explicitly appoint one partner for each deliverable to take care of the editing and coordination of that deliverable. This has resulted in a timely delivery of all the deliverables for the current reporting period. The WP leaders (and the coordinator) will continue to monitor the deadlines for the deliverables.

During the review meeting in October 2009 and in the subsequent review report the reviewers identified the following main issues:

- the communication and interaction between the groups should be improved,
- the interaction with other related STREP projects could be increased,
- the quality of some deliverables should have been better,
- more focus is required,
- how about the continuation of the work beyond the current project.

We have addressed these issues as follows:

- To increase the level of communication and interaction between the HD-MPC groups we have stimulated more joint activities (including joint deliverables, joint posters, joint papers, …) as well as more exchanges of researchers and students. We have also taken more time for discussions at the HD-MPC meetings and we have set up two dedicated meetings on WP7 topics (the web meeting in December 2009 and the model meeting in Aachen in February 2010). In the current reporting period also much more joint work has been performed for the deliverables. In addition, for the special issue of the *Journal of Process Control* we have written a joint paper with several groups in which the theoretical methods developed by those groups were applied to the real-life four-tank set-up at the University of Seville.
- In order to establish stronger links with related EU projects we have invited them for the special sessions we have organized for ACC 2010 and for the IFAC World Congress 2010, as well as for the special issue on HD-MPC of *Journal of Process Control*. For these special sessions and for the special issue about 40% of the contributions are now coming from other STREPs and other EU projects including WIDE, FeedNetBack, EMBOCON, HYCON, and HYCON2.
- The process for producing deliverables of high quality has been streamlined with explicit responsibles assigned for each deliverable as well as one or two HD-MPC reviewers (different from the authors), where the first final draft of each deliverable should be available for internal review well ahead of the deadline (at least one month) so that there is enough time for a proper review and for adequately taking the comments and suggestions of the reviewer into account.
- To increase the focus within the project we have decided to primarily consider the following joint case studies within the more fundamental work packages WP3–5:
    - water networks (hydro-power valley and irrigation network),
    - combined cycle plants.

  These would be simplified versions of the WP7 applications and they will be included as such within WP6.

- To ensure the continuation of the research program beyond the current project we have started some local/national projects, including cooperation with companies on HD-MPC related work (see deliverable D1.3.1: “Report on knowledge management, links with potential users of results, and future perspectives”). Moreover, we also intend to apply for two or more follow-up STREP projects for HD-MPC. Initial steps towards this have already been undertaken during the HD-MPC meetings in Seville and Delft.

### *Changes in the consortium, if any;*

No changes took place in the composition of the consortium

### *List of project meetings, dates and venues;*

During the reporting period the following joint meetings involving several partners have taken place (the minutes of these meetings can be found on the Virtual Portal):

- September 9-10, 2009: HD-MPC meeting in Rennes, France
- December 14, 2009: web meeting the combined cycle start-up
- February 10, 2010: meeting on models in Aachen, Germany
- February 11-12, 2010: HD-MPC meeting in Aachen, Germany
- June 1-2, 2010: HD-MPC meeting in Seville, Spain
- September 2-3, 2010: HD-MPC meeting in Delft, The Netherlands

In addition, there were also some meetings with a smaller number of participants:

- March 18, 2010: meeting of INOCSA and USE with the managers of the 'Canales del Bajo Guadalquivir' about the HD-MPC project; including a visit to the 'Canales del Bajo Guadalquivir' (WP7), and definition of the control and management of the 'Canales del Bajo Guadalquivir'
- April 6, 8, and 28, 2010: meeting between USE and INOCSA in Seville about the irrigation canal benchmark (WP6) and WP7.
- May 4, 2010: meeting between USE and INOCSA in Madrid on the irrigation canal benchmark
- May 26-27, 2010: meeting between USE-INOCSA in Seville to work on the irrigation canal benchmark
- August 19, 2010: meeting between EDF and KUL on the connection between the controller and the HPV simulator

In addition, the teams of SUPELEC and EDF also regularly met each other about the power plant model. There were also some exchanges of the SUPELEC team with Holger Scheu (RWTH) about smooth models for optimisation

### *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 in time.

We plan to continue the project as described in the original Description of Work.

The following joint HD-MPC meetings have been planned:

- September 2-3, 2010: HD-MPC meeting in Delft, The Netherlands
- February 3-4, 2011: HD-MPC meeting in Chatou, France
- June 2-3, 2011: HD-MPC meeting in Leuven, Belgium
- September 2011: Final HD-MPC Workshop in Milano, Italy (in parallel with the IFAC World Congress 2011)

### *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.

### *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 public 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 to publicize the results we have achieved.

A password-protected private Intranet/Virtual Port for HD-MPC participants only has also been set up at http://www.nyquist.us.es/hdmpcproject/. This Virtual Portal is also accessible to the reviewers and the commission.

More details on the web site and the Virtual Portal can be found in the section above that reports on WP1 as well as in the deliverables D1.4.1 and D8.1.1.

### *Use of foreground and dissemination activities during this period (if applicable).*

The work performed within HD-MPC has been published[7] in the following international journal papers and book chapters (all of these explicitly mention HD-MPC as funding source):

- D. Doan, T. Keviczky, I. Necoara, M. Diehl, and B. De Schutter, "A distributed version of Han's method for DMPC using local communications only," *Journal of Control Engineering and Applied Informatics*, vol. 11, no. 3, pp. 6-15, 2009.
- M. Farina, G. Ferrari-Trecate, and R. Scattolini: "Moving horizon state estimation of large-scale constrained partitioned systems," *Automatica*, vol. 46, no. 5, pp. 910-918, 2010.
- J. Garcia and J.J. Espinosa. "Moving horizon estimators for large-scale systems," *Journal of Control Engineering and Applied Informatics*, vol. 11, no. 3, pp. 49-56, Sept. 2009.
- D. Limon , I. Alvarado, T. Alamo, and E.F. Camacho, "Robust tube-based MPC for tracking of constrained linear systems with additive disturbances," *Journal of Process Control*, vol. 20, pp. 248–260, 2010.
- Z. Lukszo, M.P.C. Weijnen, R.R. Negenborn, and B. De Schutter, "Tackling challenges in infrastructure operation and control: Cross-sectoral learning for process and infrastructure engineers," *International Journal of Critical Infrastructures*, vol. 5, no. 4, pp. 308-322, 2009.
- J.M. Maestre, D. Muñoz de la Peña, and E.F. Camacho. "Distributed MPC based on a cooperative game," *Optimal Control Applications and Methods*, 2010.
- B. Picasso, D. De Vito, R. Scattolini, and P. Colaneri: "An MPC approach to the design of two-layer hierarchical control systems," *Automatica*, vol. 46, no. 5, pp. 823-831, 2010.
- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Route choice control of automated baggage handling systems," *Transportation Research Record*, no. 2106, pp. 76-82, 2009.

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

- A.N. Tarău, B. De Schutter, and J. Hellendoorn, "Centralized, decentralized, and distributed model predictive control for route choice in automated baggage handling systems," *Journal of Control Engineering and Applied Informatics*, vol. 11, no. 3, pp. 24-31, 2009.
- A.N. Tarău, B. De Schutter, and H. Hellendoorn, "Model-based control for route choice in automated baggage handling systems," *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, vol. 40, no. 3, pp. 341-351, May 2010.

- M. Arnold, R.R. Negenborn, G. Andersson, and B. De Schutter, "Distributed predictive control for energy hub coordination in coupled electricity and gas networks," Chapter 10 in *Intelligent Infrastructures* (R.R. Negenborn, Z. Lukszo, and H. Hellendoorn, eds.), vol. 42 of *Intelligent Systems, Control and Automation: Science and Engineering*, Springer, pp. 235-273, 2010.
- B. De Schutter, H. Hellendoorn, A. Hegyi, M. van den Berg, and S.K. Zegeye, "Model-based control of intelligent traffic networks," Chapter 11 in *Intelligent Infrastructures* (R.R. Negenborn, Z. Lukszo, and H. Hellendoorn, Eds.), vol. 42 of *Intelligent Systems, Control and Automation: Science and Engineering*, Springer, pp. 277-310, 2010.
- D. Limon, A. Ferramosca, I. Alvarado, T. Alamo, and E.F. Camacho. "MPC for tracking of constrained nonlinear systems," in *Nonlinear Model Predictive Control. Towards New Challenging Applications* (L. Magni, D.M. Raimondo, and F. Allgöwer, Eds.), vol. 384 of *Lecture Notes in Control and Information Sciences*, 2009.
- L. Magni and R. Scattolini: "An overview of nonlinear Model Predictive Control," in *Automotive Model Predictive Control: Models, Methods and Applications* (L. Del Re, F. Allgower, L. Glielmo, C. Guardiona, and I. Kolmanvski, Eds.), vol. 402 of *Lecture Notes in Control and Information Science*, Springer, pp. 107-117, 2010.
- P.-J. van Overloop, R.R. Negenborn, B. De Schutter, and N.C. van de Giesen, "Predictive control for national water flow optimization in The Netherlands," Chapter 17 in *Intelligent Infrastructures* (R.R. Negenborn, Z. Lukszo, and H. Hellendoorn, eds.), vol. 42 of *Intelligent Systems, Control and Automation: Science and Engineering*, Springer, pp. 439-461, 2010.

Moreover, the work performed within HD-MPC has been published[7] in the following international conference papers (all of these also explicitly mention HD-MPC as funding source):

- L.D. Baskar, B. De Schutter, and H. Hellendoorn, "Optimal routing for intelligent vehicle highway systems using mixed integer linear programming," *Proceedings of the 12th IFAC Symposium on Transportation Systems*, Redondo Beach, California, pp. 569-575, Sept. 2009.
- L.D. Baskar, B. De Schutter, and J. Hellendoorn, "Optimal routing for intelligent vehicle highway systems using a macroscopic traffic flow model," *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems (ITSC 2009)*, St. Louis, Missouri, pp. 576-581, Oct. 2009.
- A. Cabañas, L. Sánchez, M.A. Ridao and L. Garrote, "Plataforma para el control y similación en la gestión de sistemas de canales," *XXXI Jornadas de Automática*, Jaén, Spain, Sept. 2010.
- D. De Vito, B. Picasso, and R. Scattolini: "On the design of reconfigurable two-layer hierarchical control systems with MPC," *IEEE American Control Conference*, Baltimore, 2010.
- D. Doan, T. Keviczky, I. Necoara, M. Diehl, and B. De Schutter, "A distributed version of Han's method for DMPC of dynamically coupled systems with coupled constraints," *Proceedings of the 1st IFAC Workshop on Estimation and Control of Networked Systems (NecSys 2009)*, Venice, Italy, pp. 240-245, Sept. 2009.
- M.D. Doan, T. Keviczky, and B. De Schutter, "An improved distributed version of Han's method for DMPC of canal systems," *Proceedings of the 12th IFAC Symposium on Large Scale Systems: Theory and Applications*, Villeneuve d'Ascq, France, 6 pp., July 2010.

- M. Farina, G. Ferrari Trecate, and R. Scattolini: “Distributed moving horizon estimation for sensor Networks,” *IFAC Workshop on Estimation and Control of Networked Systems*, pp. 126-131, Venice, Italy, 2009.
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- R.T. van Katwijk, B. De Schutter, and J. Hellendoorn, "Multi-agent control of traffic networks: Algorithm and case study," *Proceedings of the 12th International IEEE Conference on Intelligent Transportation Systems (ITSC 2009)*, St. Louis, Missouri, pp. 316-321, Oct. 2009.

In addition to the above conferences, the work performed within the HD-MPC project has been presented at the following symposia, workshops, and seminars:

- B. De Schutter and R.R. Negenborn, "Distributed model predictive control for water infrastructures", *LCCC Workshop on Multi-agent Coordination and Estimation*, Lund, Sweden, February 5-6, 2010.
- M. Diehl, "Inexact SCP methods for hierarchical optimization of decomposable systems." Presentation at the *LCCC Workshop on Distributed Model Predictive Control and Supply Chains,* Lund University, Lund, Sweden, May 19-21, 2010.
- C. Savorgnan, "Distributed nonlinear MPC with applications in hydroelectricity production." Seminar at the Lund University, Lund, Sweden, May 25, 2010.
- A. Tica, H. Guéguen, D. Dumur, "Design optimisation and validation of start-up sequences for power plants," IETR doctoral student workshop, Université de Rennes, Rennes, France, June 16, 2010 (poster in French).

Several HD-MPC researchers participated in the LCCC Workshops on Multi-agent Coordination and Estimation and on Distributed Model Predictive Control and Supply Chains organized by Prof. A. Rantzer of Lund University. At these workshops also several researchers from other ongoing EU projects were present (including WIDE, FeedNetBack, EMBOCON, HYCON, and HYCON2), with whom we have interacted intensively during these workshops.

In order to connect with other ongoing FP7 projects, we have also (re)presented HD-MPC at several events organized by or on behalf of the European Commission:

- Bart De Schutter gave a presentation on "Multi-agent control of traffic networks" at the ESF Exploratory Workshop on Foundations of Autonomic Computing for Traffic Management Systems, Durham, UK, April 14-16, 2010.
- At the special session on EU projects organized by dr. Pereira at CPS Week, April 12-16, 2010 in Stockholm, Sweden, the HD-MPC project was present with three posters:
    - general overview poster of the HD-MPC project,
    - poster on the fundamental results obtained within HD-MPC, in particular robust hierarchical MPC, distributed optimization, and a new coordination method,

    - poster on the application to the start-up of the combined cycle power plant.
- Riccardo Scattolini and Bart De Schutter participated in the EU Workshop on Monitoring and Control for Full Water-Cycle Management co-organized with HD-MPC and EUCLID, Brussels, Belgium, June 18, 2010. There, Bart De Schutter gave a presentation on “Distributed model predictive control for water systems”.

There have also been some visits and exchanges of researchers between the participating groups:

- Antonio Ferramosca (USE) has visited the UWM team for a 6-month period from August 2009 to February 2010.
- Jairo Espinosa (UNC) has visited the KUL team on September 11, 14, and 15, 2009.
- Carlo Romani (POLIMI) visited the KUL team from September 11, 2009 to February 14, 2010. He followed the optimization course taught by Moritz Diehl and worked on modelling and distributed control of a hydro-power valley.
- Daniele Balzaretti (MSc student at POLIMI) visited TUD from November 2009 to May 2010 to develop his MSc Thesis on distributed state estimation.
- Francesco Petrone (MSc student at POLIMI) visited EDF from February 1, 2010 to March 26, 2010 and from June 1, 2010 to June 30, 2010 to develop his MSc thesis on modelling and control of a hydro-power valley.
- Fabio Righetti (MSc student at POLIMI) visited EDF from March 1, 2010 to March 31, 2010 and from June 1, 2010 to June 30, 2010) to develop his MSc Thesis on modelling and control of a combined cycle power plant.
- Dang Doan (TUD) has visited the partner group at KUL on March 16, 2010 to discuss about his research and to meet with prof. Stephen Boyd (Stanford, USA).
- Felipe Valencia Arroyave (UNC) has visited TUD from March 22, 2010 to August 31, 2010 to work on a feasible-cooperation distributed model predictive control scheme based on game theory.
- During April and June 2010 the team at SUPELEC had several exchanges with Fabio Righetti (POLIMI) about the power plant model simulation.
- Rudy Negenborn (TUD) and Yu Ping (TUD) have visited the INOCSA and USE teams in the week of May 10-14, 2010.

## 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.*