PROJECT FINAL REPORT

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4.1 Final publishable summary report

4.1.1 Executive summary

Increased global competition and an urgent need to address sustainability and resource-efficiency of operations force European industries and large-scale infrastructure operators to look for efficient real-time decision-making systems that allow them to react rapidly, consistently and effectively to a continually changing economical and environmental landscape. By exploiting advances in distributed optimization tools and the emergence of new highly pervasive, cheap, and reconfigurable wireless sensing technologies, the WIDE project has developed a rigorous framework for distributed control of truly large-scale processes to maximize an overall economical/ environmental performance measure under operational constraints, and for designing very flexible feedback control systems based on wireless sensor feedback.

The WIDE project has developed a unified, distributed, and multilayer modelling and goal/constraint specification framework that ensures cross-layer and inter-layer compatibility, responsiveness to structural changes in the process, consistency with measured data. Based on such a modelling framework, within WIDE several new techniques were developed for designing and coordinating a network of model predictive controllers (MPCs) to achieve the best performance of the system and robustness under uncertainty and possible physical and topological constraints, including decentralized MPC schemes, fully distributed or partially supervised MPC schemes ensuring global optimality, and hierarchical MPC schemes.
WIDE has proposed original methods for cooperating wireless sensor networks and advanced process control. New results on transmission scheduling for WirelessHART networks are based on novel theoretical work on ultra-reliable communication for short-range wireless networks, also providing bounds on the achievable performance for convergecast operations; the theoretical results on maximum reliable routing lead efficient routing and scheduling protocols for real-time traffic.

Network-aware closed-loop analysis and controller synthesis methods were investigated in WIDE to cope with the presence of a communication network in the control loop and with its many induced imperfections, such as varying transmission delays, varying sampling/transmission intervals, packet loss. New synthesis methods for MPC and Kalman filters that are aware of communication and power-consumption aspects of the network ensure an optimized controller/wireless-sensor operation.

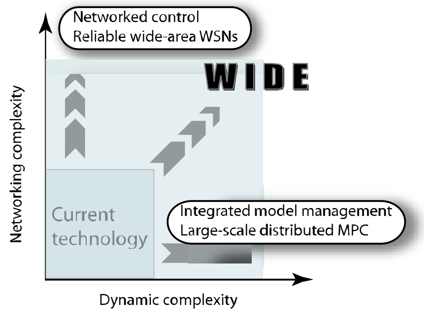
The innovative concepts developed within WIDE were tested in the Barcelona water network problem. Production-ready software implementing distributed MPC algorithms was interfaced at the AGBAR Control Center with the existing SCADA system and validated against a realistic simulator of the network.

Various analysis and control methodologies developed within WIDE were validated experimentally at a pumping station located on the water network for controlling valves based on wireless feedback from pressure and flow sensors, demonstrating the practical feasibility of the advanced wireless automation solutions developed within the WIDE project.

The analysis and design methodologies developed within the project are collected inside the WIDE Toolbox for MATLAB, available for download on the project web site. The Toolbox offers several features for control of large-scale and networked systems, including tools for decentralized MPC, hierarchical MPC, energy-aware MPC, distributed MPC, network-aware Kalman filtering, a wireless control loop simulation environment in Simulink, data acquisition in MATLAB from real sensor nodes, tools for modelling large-scale systems, and various tools for networked control system analysis.

4.1.2 Summary description of project context and objectives

The WIDE project aimed at developing a rigorous framework for advanced control and real-time optimization of truly large-scale and spatially distributed processes, based on the integrated use of distributed model predictive control and wireless sensor feedback.



WIDE was aimed at addressing the question of how to operate a wide-area physical system to maximize an overall economical/environmental performance measure under operational constraints, drawing from a broad range of information sources. There are three clear issues that obstruct this approach in practice: *computational* issues (centralized solutions are not viable because of problem size), *communication* issues (restrictions in communication and sensor technologies prevent that all information is gathered at all times in a central location), and *control* issues (robustness to process uncertainty and instrumentation failures, scalability, re-tuning of control design). By taking advantage of recent advances in optimization and communication technologies, WIDE has proposed to address the computational, communication, and control issues by developing novel *distributed* and cooperative optimization-based *model predictive control* (MPC) algorithms that exploit information from *wireless sensor networks* (WSNs) to enhance their coordination for the best global performance.

In current hierarchical control schemes, units at the same level have a rather limited and indirect dialogue; moreover, in most cases the layers above advanced process control (APC) only address steady states. WIDE has proposed a novel approach to interlayer cooperation:

- *(i)* Both MPC and *real-time optimization* (RTO) are based on models and optimization, albeit at different level of abstraction and time scales. A strategy for **managing dynamical models and optimization specifications and uncertainties** guarantees consistency at all levels of decision-making.
- *(ii)* RTO will provide optimization-based target trajectories and dynamic target allocations instead of steady state ones. Optimization of additional integer/logical-valued variables (e.g., decisions on starting up/shutting down some units) will be considered, as well as integrating fault detection and isolation features. Associated robustness issues will be fully taken into account.
- *(iii)* To achieve plant-wide performance objectives **cooperative MPC devices** share sub-models and performance sub-objectives and exchange local decisions with the surrounding units.
- *(iv)* MPC agents also acquire additional information from other, spatially adjacent, subsystems that have an influence on or are influenced by the underlying controlled subsystem. Due to the dynamically changing nature of interactions among subsystems, **wireless sensor networks** are advocated as the most suitable technology. This is because of their flexibility, ease of deployment and of spatial reconfiguration, and low cost. Moreover, current latency and jitter issues in the sub-second range are not critical to WIDE, since wireless sensors will be primarily used within "Class 2 - Closed-loop supervisory control" of the taxonomy in the ISA-SP100 standard[1], where information availability is often not safety-critical.

The WIDE project had four main objectives to achieve in order to develop a novel rigorous and integrated framework for advanced control and real-time optimization of large-scale and spatially distributed processes that exploits wireless sensor networks as a pervasive and highly reconfigurable information gathering system, and at validating the approach on a real city water distribution system.

[1] ISA-SP100.14 – Wireless Networks Optimized for Industrial Monitoring, 14 July 2006, http://www.isa.org/filestore/ISASP100_14_CFP_14Jul06_Final(2).pdf

Objective 1

The first objective of WIDE was to develop a unified, distributed, and multilayer modelling and goals/constraints specification framework that ensures (*i*) cross-layer and inter-layer compatibility, (*ii*) responsiveness to structural changes in the process, (*iii*) consistency with measured data. This facilitates scalability and reconfigurability of the developed distributed control and estimation procedures, and guarantees timely reaction and adaptation to a changing environment. Achieving this objective requires a methodology, theoretical results and algorithms that enable control engineers to configure a hierarchy of models consistent with the hierarchy of control and optimization tasks. More in detail, it is requested a model management tool for plant/enterprise-wide control and optimization that maintains the consistency of models, operation constraints and performance goals for all levels of the hierarchy, and a set of techniques/methodologies for system identification and experiment design that are suitable for the modelling framework and methods of distributed control developed in the project.

Objective 2

The second objective of WIDE was to develop new techniques for designing and coordinating a network of MPCs to achieve the best performance of the system and robustness under uncertainty and possible physical and topological constraints. The technologies and methodologies investigated in WIDE have the ambition of being applicable to truly large-scale systems spanning over whole processing plants (e.g., a refinery including utilities) and beyond – whole supply chains and/or distribution networks (such as water networks, electrical grids, gas distribution, traffic networks). For systems of that scale, it is not feasible to realize the lower and intermediate layers by a single and centralized controller/optimizer: the control or optimization task has to be distributed among several units in order to manage vast computational loads and also to achieve the required flexibility. The problem associated with distributed control is to divide the original problem into sub-problems and coordinate their solution in order to achieve performance as close as possible to the global optimum. The decomposition should minimize interactions among the different controllers/optimizers. This problem arises particularly at the advanced process control layer. WIDE has focused on MPC due to this technique's ability to handle constraints, and because it provides a systematic design flow, independent on the number of inputs and outputs of the model and on the prescribed performance/constraint specifications.

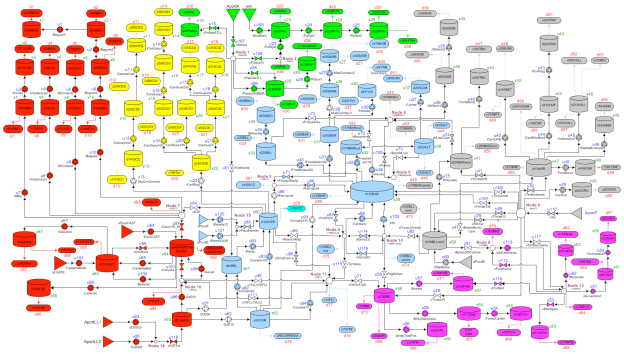
The methodology requested to achieve this objective must enable the control engineer to easily and smoothly recast the model of the complete process into a collection of submodels, to map global control objectives and constraints into several MPC designs (one for each submodel), and to assess the overall performance of the closed-loop process.

Objective 3

The third objective of WIDE was to exploit wireless sensor networks for establishing a flexible, reliable and cost-effective communications infrastructure. One of the driving objectives for wireless sensing in automation is to reduce the cost of cablings, and avoid associated failures due to wear and tear. Another advantage is the possibility to rapidly reconfigure the communications infrastructure in case of failures or addition of system components. In addition, wireless sensing allows measuring quantities that were previously inaccessible. At the same time, there are associated disadvantages such as unreliable communications and cumbersome management (e.g., replacement of batteries). The WIDE project has analysed and demonstrated the advantages of wireless sensing while trying to reduce and eventually eliminate the currently present barriers towards wireless control of large-scale infrastructures by mainly two lines, on the *networking side* by developing specific protocols tailored to wireless automation applications, and on the *application side* by developing control algorithms that are robust to communications imperfections, based on models of network characteristics, including model predictive control methodologies tailored to tackle unreliable communication and aware of power-consumption aspects of the network, therefore ensuring an optimized controller/wireless-sensor operation.

Objective 4

The WIDE project a fourth objective, namely to verify concretely the effectiveness of the developed approaches and measure their performance in real life applications. In particular WIDE has focused on two demonstrations based on the water network of the city of Barcelona, a network supplying water to ~3 Mio consumers, distributed in 23 municipalities in a 424 km^2 area. The complete water transport network model includes 67 storage tanks, 10 water sources, 111 pumps/valves, 15 complex nodes and 88 points of water consumption.



The first demonstration was aimed at testing the innovative distributed model predictive control concepts developed within WIDE on controlling the entire water network, based on production-ready software implementing the control algorithms interfaced with the existing SCADA system and validated against a realistic simulator of the network.

A second demonstration was aimed at validating experimentally various networked control systems methodologies developed within WIDE at a pumping station located on the water network, where the problem consists of controlling valves based on wireless feedback from pressure and flow sensors, therefore demonstrating the practical feasibility of the advanced wireless automation solutions developed within the WIDE project.

WIDE Toolbox for MATLAB

An horizontal objective of WIDE was to collect the analysis and design methodologies developed within the project are collected inside a MATLAB toolbox and make it available for download on the project web site, for maximum impact on industry and academia. The Toolbox offers several features for control of large-scale and networked systems, including tools for decentralized MPC, hierarchical MPC, energy-aware MPC, distributed MPC, network-aware Kalman filtering, a wireless control loop simulation environment in Simulink, data acquisition in MATLAB from real sensor nodes, tools for modelling large-scale systems, and various tools for networked control system analysis.

4.1.3 Description of the main S&T results/foregrounds

SUMMARY OF RESULTS

The WIDE project has developed a unified, distributed, and multilayer modelling and goal/constraint specification framework that ensures cross-layer and inter-layer compatibility, responsiveness to structural changes in the process, consistency with measured data. Based on such a **modelling framework**, within WIDE several new techniques were developed for designing and coordinating a network of **model predictive controllers** (MPCs) to achieve the best performance of the system and robustness under uncertainty and possible physical and topological constraints, including **decentralized MPC** schemes, fully distributed or partially supervised MPC schemes ensuring global optimality, and **hierarchical MPC** schemes.

WIDE has proposed original methods for cooperating wireless sensor networks and advanced process control. New results on transmission scheduling for **WirelessHART** networks are based on novel theoretical work on ultra-reliable communication for **short-range wireless networks**, also providing bounds on the achievable performance for convergecast operations; the theoretical results on maximum reliable routing lead efficient routing and scheduling protocols for real-time traffic.

Network-aware closed-loop analysis and controller synthesis methods were investigated in WIDE to cope with the presence of a communication network in the control loop and with its many induced imperfections, such as varying transmission delays, varying sampling/transmission intervals, packet loss. New synthesis methods for MPC and Kalman filters that are aware of communication and power-consumption aspects of the network ensure an optimized controller/wireless-sensor operation.

The innovative concepts developed within WIDE were tested in two control problems related to the water network of the city of Barcelona. A first demonstration involved the development of production-ready software implementing distributed MPC algorithms that was interfaced at the AGBAR Control Center with the existing SCADA system and validated against a realistic simulator of the entire network. A second demonstration involved testing various analysis and control methodologies developed within WIDE experimentally at a pumping station located on the water network, for controlling valves based on wireless feedback from pressure and flow sensors, demonstrating the practical feasibility of the advanced **wireless automation** solutions developed within the WIDE project.

The most significant analysis and design methodologies developed within the project were collected inside a MATLAB toolbox, the WIDE Toolbox for MATLAB, which is available for download on the project web site.

In the following sections, we detail the main S&T results and foregrounds of the project within the four different directions summarized above.

MODEL MANAGEMENT

Most of the effort in model management was focused towards supporting other project tasks in acquiring process models necessary for control and optimization of large-scale systems in multiple layers. However, several original results were obtained that are of general interest and of importance beyond mere support of other tasks. Main results were obtained in the following directions: (*i*) consistent modeling and self-maintaining models, (*ii*) input signal design; (*iii*) system identification for large-scale systems.

The support for building relatively detailed models of large-scale systems from component-based libraries or system identification is becoming increasingly reliable and easy-to-use. However, the resulting models might have a huge number of states and are not always easy to use for analysis and control design. It is therefore important to develop techniques for reducing the complexity of these models while maintaining the underlying problem structure (e.g., the interconnection structure) and keeping track of a bound on the guaranteed performance difference between the original complex model and the easier to use low-order model. In the area of consistent modeling/self-maintaining models, two results were achieved [34]: First, merging models of different quality, and second, structure-respecting identification and order reduction. Regarding the former topic, a methodology was developed for merging several models of different quality for the same system considering FIR and/or ARX models. The proposed approach uses merging models in the time domain, using the concept of equivalent data. Addressing the second topic, a methodology was proposed for consistent combination of arbitrarily interconnected sub-models with uncertainty into a complex, large-scale model. The interconnected models were assumed to be FIR and/or ARX models with parameters given by the mean and variance. The main result is obtaining a global ARX/FIR model with statistically correct mean and variance. Another novel solution achieved in this subtask is a method for closed-loop order reduction of parallel models with application to parallel boilers [37]. It is an application of earlier results on structured order reduction, specialized to parallel interconnection of subsystems. Preservation of the interconnection structure in the reduction in this case significantly simplifies integration in standard Model Predictive Control (MPC) software [40]. Honeywell has filed a patent on work that was inspired by this activity.

In another line of research in system modeling, WIDE addressed problems related to input signal design for identification. The optimal experiment design is a non-convex and hence non-tractable problem. Therefore a suboptimal, yet simple and tractable, method was proposed for designing an input that can improve the overall model quality, while minimizing abruptions to identified system [36]. Input design strategies were also developed for system identification of models targeted towards model-predictive control [48,49,50,51,52,53]. Since its introduction, model predictive control has grown very popular and become widely used in industry. Because MPC relies on good process models, system identification for MPC has become an increasingly important object of study. A major accomplishment has been the development of experimental procedures for efficient estimation of models that give good closed-loop performance of MPC loops.

Regarding identification of large-scale systems, algorithms able to incorporate basic types of prior information (e.g., gains, time constants) to subspace identification methods were developed [33]. Incorporating prior knowledge improves the posedness of the identification problem, which may be poor in cases of low input excitation. This is often the case of large-scale interconnected systems. In an additional development, a modification of the subspace identification for large-scale systems was proposed which uses better internal data representation and dramatically reduces memory requirements. Hence, the modified algorithm improves scalability of subspace identification methods. Another approach for grey-box identification was developed in [35], based on numerical optimization of mixed prediction and simulation error based criterion.

A methodology to analyze the structure of the large-scale and identify the different partitions (subsystems) and the interacting variables using tools coming from graph theory was also proposed. Two novel partitioning algorithms were developed that allow obtaining an optimal division of the interconnected model into subsystems suitable for decentralized control design. The first partitioning approach [46] is based on identifying clusters of elements that are weakly interconnected by analyzing the interconnection matrix of the system [47]. The second approach translates the system model into a graph representation. Once the equivalent graph is obtained, the problem of graph partitioning is then solved. The resultant partition consists in a set of non-overlapping subgraphs whose number of vertices is as similar as possible and the number of interconnecting edges between them is minimal. To achieve this goal, the proposed algorithm applies a set of procedures based on identifying the highly-connected subgraphs with balanced number of internal and external connections.

DISTRIBUTED/DECENTRALIZED AND HIERARCHICAL MODEL PREDICTIVE CONTROL AND ESTIMATION

The main efforts in decentralized and distributed MPC control and estimation resulted in development of new methods for:

- decentralized MPC based on model decomposition
- hierarchical and multi-rate MPC
- distributed MPC with price coordination based on distributed coordinator and consensus;
- distributed Kalman filtering with limited radius of communication.

Regarding WIDE activities in *decentralized* model predictive control (DMPC), a novel scheme for large-scale dynamical processes subject to input constraints was investigated in [1,2]. The main idea of the approach is to approximate the global model of the process as the decomposition of several (possibly overlapping) smaller models used for local predictions. The degree of decoupling among submodels represents a tuning knob of the approach: the less coupled are the submodels, the lighter the computational burden and the load for transmission of information among the decentralized MPC controllers; but the smaller is the degree of cooperativeness of the decentralized controllers and the overall performance of the control system. A methodology was provided for synthesizing decentralized MPC closed-loop systems and sufficient criteria for analyzing their asymptotic stability, also extending the approach to asymptotic tracking of output set-points and rejection of constant measured disturbances. The effectiveness of the approach was tested on the WIDE simulation benchmark related to decentralized temperature control in a railcar [3]. A complete survey of existing DMPC approaches is reported in [2].

Original ideas for hierarchical multi-rate control were developed in [4] for multi-layer control of large-scale systems. The approach takes into account constraints on both input and state variables. In the proposed two-layer control structure, at the lower level a linear controller stabilizes the open-loop process without considering the constraints. A higher-level controller commands reference signals at a lower sampling frequency so as to enforce linear constraints on the variables of the process. By optimally constraining the magnitude and the rate of variation of the reference signals applied to the lower control layer, quantitative criteria are provided for selecting the ratio between the sampling rates of the upper and lower layers to preserve closed-loop stability without violating the prescribed constraints. A decentralized extension of the approach that treats submodel interactions as disturbances was proposed in [5] and demonstrated on a dynamically coupled multi-mass system, which is now one of the demos of the WIDE Toolbox for MATLAB.

Hierarchical and decentralized MPC ideas were also applied to autonomous navigation of a formation of unmanned aerial vehicles (UAVs) under obstacle and collision avoidance constraints [6,7,8]. At the lower level, a linear MPC controller takes care of vehicle stabilization. Each vehicle is stabilized around a desired reference attitude, generated at a slower sampling rate by a hybrid MPC controller per vehicle at the upper control layer. Such a hybrid MPC controller is based on a hybrid dynamical model of the UAV and of its surrounding environment (i.e., the other UAVs and obstacles). The resulting decentralized scheme controls the formation based on a leader-follower approach. The performance of the hierarchical control scheme is assessed through simulations and comparisons with other path planning strategies, showing the ability of linear MPC to handle the strong couplings among the dynamical variables of each UAV under motor voltage and angle/position constraints, and the flexibility of the decentralized hybrid MPC scheme in planning the desired paths on-line.

The approach to *distributed* model predictive control is based on the price coordination method of the underlying optimization problem. Various coordination strategies were explored; in particular, there can be a centralized coordination (as is standard in the literature on price coordination methods) or, the coordinator can be distributed and integrated into local controllers. The latter option results in more iterations and hence larger computational and communicational load but in a more flexible solution where the network topology can be changed on-line. Further, local controllers were used either to elementary subsystems (as are tanks in the water network) or to groups of subsystems obtained by partitioning of large-scale system by graph-theoretical methods. The approach was tested on the full-scale model of the transport layer of the Barcelona water network. It was found that the all decentralized approaches outperform (in terms of computational time) the central MPC, while the solutions obtained were essentially the same (communication times were neglected in the study). On the other hand, distributed and coordinated algorithms are perfectly scaleable. A summary of these methods applied to water networks was published in [44].

Regarding distributed *estimation* schemes, a distributed Kalman filter was proposed for interconnected systems having the same topology as the observed process. State-spaces of local estimators were augmented by the estimates of the interconnection input deviations. These additional states represent the only overlap in state spaces of the filters and hence, the state space handled by local estimators is comparatively small. The proposed solution is based on iterative filtering process, converging to an equilibrium that is sub-optimal in general and optimal in particular cases. Uncertainties of the form of state covariance are propagated throughout the network. A drawback of the proposed approach is the communication load – the filters need to share a significant amount of information, which is passed from one neighbor to another; these data are processed upon receiving, there is no need to idle till all information is available. Further, the local agents need the global model knowledge, which is also a restrictive requirement. In order to reduce the need for internal data / model knowledge sharing, an approach was proposed to restrict the communication to a pre-specified network neighborhood. Hence, on the expense of certain performance loss and increased local computational load, we have reduced the overall communication and increased the flexibility. Essentially, instead of using process models and internal data beyond the selected network radius, local agents increase their internal uncertainties. The extensions resulting in lower computational load are in [39].

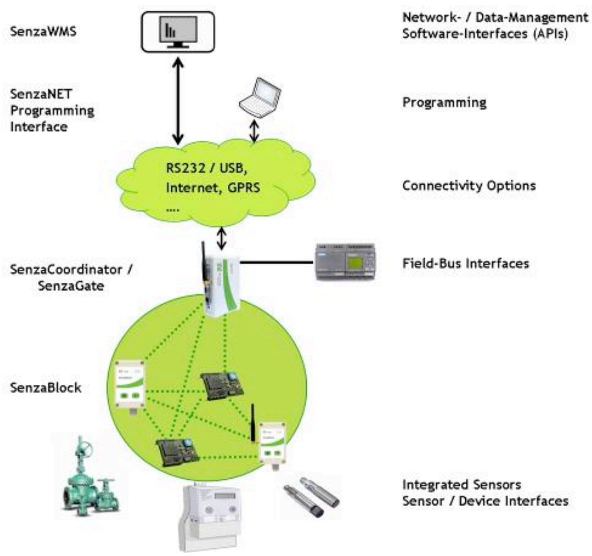
A natural extension of the advanced process control is *real-time optimization,* which represents an additional layer, one level higher in the decision-making hierarchy. This layer was traditionally a static one, optimizing steady-states of the process; only recently, dynamical real-time optimizers have been used. These optimization units span over multiple processing units, in many cases, this layer spans process-wide or plant-wide. Then, it is natural to consider dynamic optimization of decentralized MPC controllers developed in WIDE. While working on this task, a highly innovative approach to coordinating local MPC controllers by means of parametric coordination was developed. This proposed method uses the same basic idea as the price-coordinated MPC. However, exploiting geometric properties of the distributed optimization problem lead to a parametric-programming formulation of the coordination problem, resulting in a significant increase of computational efficiency. The main improvement is in the fact that the local units can send to the coordinator not only a solution at a point, but a parameterized solution with a region of validity for this solution. The global coordinator than can form not only a gradient, but also a Hessian of the dual cost function and its region of validity. Then, a Newton-like method can be used for the coordination problem that requires far less iterations than the gradient one. Unlike the hierarchical MPC described above, this coordination proceeds on the same sampling rates as the lower-layer MPC's; in addition, it requires iterative data exchange between local controllers and the coordinator within control period. On the other hand, it provides a globally optimal solution. It is further suitable also for systems with strong interconnections. This method can accommodate changes in the problem topology and respond to failures. Therefore, this method was found suitable for controlling and optimizing water networks, which was confirmed by simulations on the full scale network model. This method was implemented on a control platform as the key part of the WIDE demonstration case showing highly satisfactory results [45]. These results were used in an European patent application.

Another line of work has considered distributed optimization of large-scale systems [62,63,64]. In this area, we have developed novel optimization techniques for distributed coordination of multiple subsystems that are constrained to cooperate and exchange data with only a subset of other subsystems. These techniques rely on combinations of gradient descent and consensus algorithms and, in some cases, on randomized incremental gradient techniques. A recent effort has been devoted to acceleration of networked optimization techniques using fast gradient methods. We have developed algorithmic refinements of existing techniques, optimal parameter settings, and robustness bounds on the convergence rate when the underlying optimization parameters are unknown. An intensive course on distributed optimization [65] was arranged with around 100 participants from all over Europe (some of which come from industry). The book chapter [66] in the WIDE book on Networked Control Systems summarizes the topics covered in the intensive course.

A multi-rate/multi-layer architecture within the framework of the hierarchical-based DMPC has been proposed [46]. The approach aims at optimizing the system performance considering different time scales. The implementation of the multi-rate approach requires two control levels. The first control level is denoted as Supervisory (Global) Control Level, establishing the set-points at the Regulatory (Local) Control Level. Regulatory controllers are of PID type, while the controllers of the supervisory control level are of MPC type. The Supervisory Control Level of the hierarchical structure is, in turn, divided in two control layers, which are characterized by different models and time scales. First, a daily CMPC is used considering a daily-time scale to coordinate the subsystems (to fulfill the global objective), and a hourly-DMPC controller is designed for each subsystem at hourly-time scale in order to achieve local objectives. The effectiveness of the control strategy and the topology was assessed in the demonstration case on the Barcelona water transport network through comparison with the CMPC using several days of operation.

WIRELESS NETWORKS FOR CONTROL

In the area of wireless sensor networking for control, a focus has been on energy-efficient real-time protocols [56,57,58,59,60,61]. WIDE has considered the problem of joint routing and scheduling for maximizing the probability of meeting a hard deadline-constraint on packet transmissions. This work allowed, for the first time, to characterize the theoretically optimal relation between the latency and reliability of packet transmissions in these networks. This work was later extended this work to also account for energy consumption, and been able to derive the Pareto-optimal latency-loss-energy consumption surface. Interestingly, initial reliability improvements come at a low energy cost, while there is a sharp reliability threshold that is very costly (in terms of transmission energy) to exceed. We have complemented this work with the development of distributed networking protocol that have good latency-energy-reliability performance, but do not rely on centralized network management (as *Wireless*HART does). Examples of these protocols is an enhanced version of the contention resolution protocol StrawMAN, and a novel solution to opportunistic forwarding in wireless sensor networks. The latter two protocols have been backed up by extensive performance evaluations in large-scale testbed deployments.

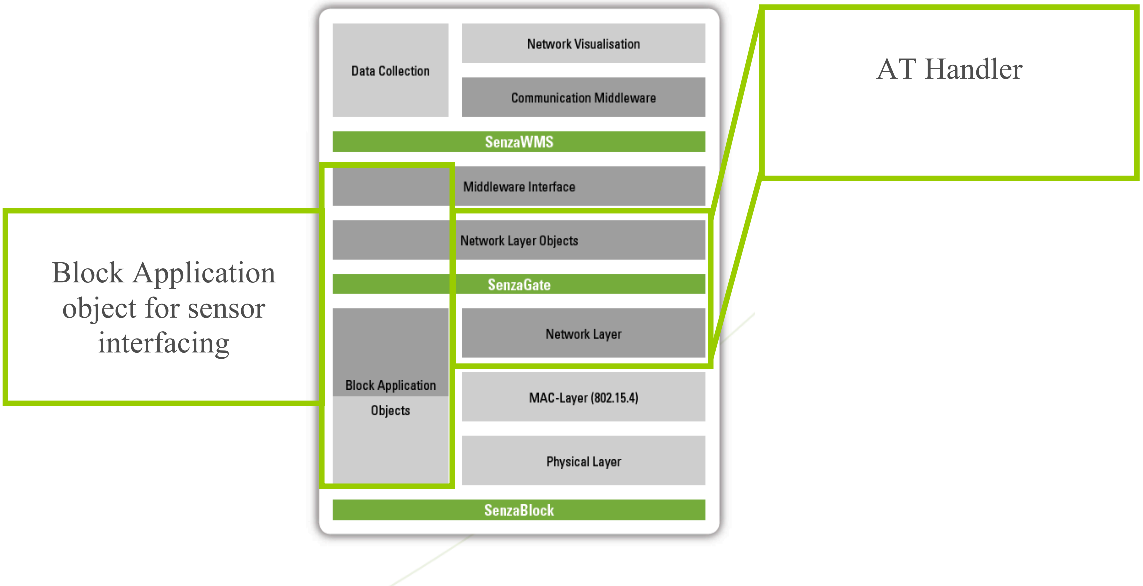


Within the WIDE project, E-Senza Technologies has improved its proprietary SenzaNET technology, a unique wireless networking protocol, which enables sensors and actuators to communicate through a self-organizing wireless mesh network while at the same time it allows for controlled, pre-determined network latency, which is essential for control applications. Network management is much simplified when compared to existing industrial wireless technologies, e.g., WirelessHART, especially when multiple patches of sensor networks are combined into a larger, wide-area system. For every network patch, the gateway is the network master, responsible for all communication to/from the wireless network. Hence, all communication to any network node is done through the gateway. This is possible through the SenzaNET programming interface or through Field-Bus interfaces. Network elements of SenzaNET include *SenzaBlock* (the basic component of SenzaNET with mesh networking capabilities that enables sensor and actuator devices to be controlled wirelessly and exchange data through a self-organizing wireless mesh network with ultra-low power consumption), *Gateway* (that supports integration of the wireless network with existing systems and, at the same time, is the network master, with the following industrial interfaces used within WIDE: RS232, Ethernet, and GPRS), and *SenzaWMS* (a middleware providing a user-interface for a comfortable administration of the individual wireless network patches and status monitoring for each individual node, with comprehensive software-APIs and data-export options allow seamless integration into existing IT-infrastructures).

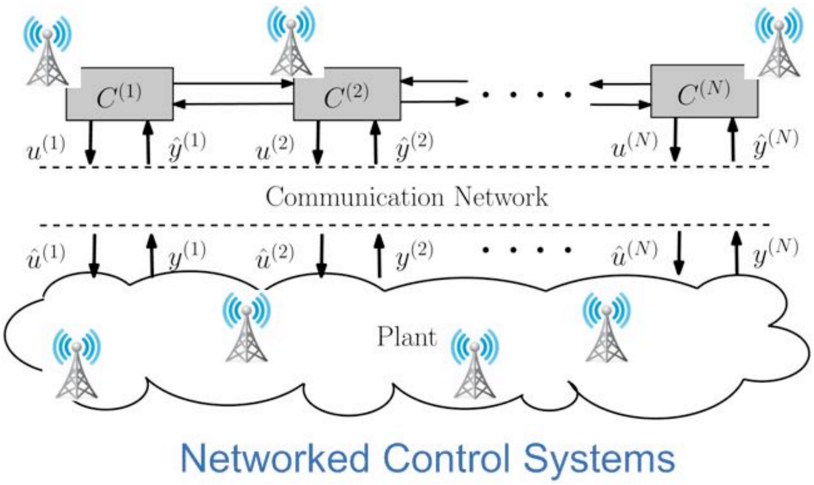
To simplify network management, in SenzaNET decisions on slot allocation and routing are taken locally and the network is divided into so-called "branches", which can be considered subnetworks managed independently to a certain extent: The gateway manages all global parameters like the network time and communication channels to be used. All the wireless devices have a dedicated slot of to send their own data over several hops to the gateway. In other slots they support communication of other nodes. Directly connected nodes are nodes which are connected to one gateway directly on the first level. These nodes then can form a branch, other nodes connecting to the network can either connect to them or also directly to the coordinator.

SenzaNET consists of two separate application objects:

- The AT Handler object which provides a command-set for integration with the WIDE toolbox
- The Block Application object for device interfacing and management, which supports sensor and device integration
  - Sensor Readout
  - Sensor Data sampling & storage
  - Circular buffer for data readings
  - Data Sampling & Upload cycles
  - Sensor – power management software



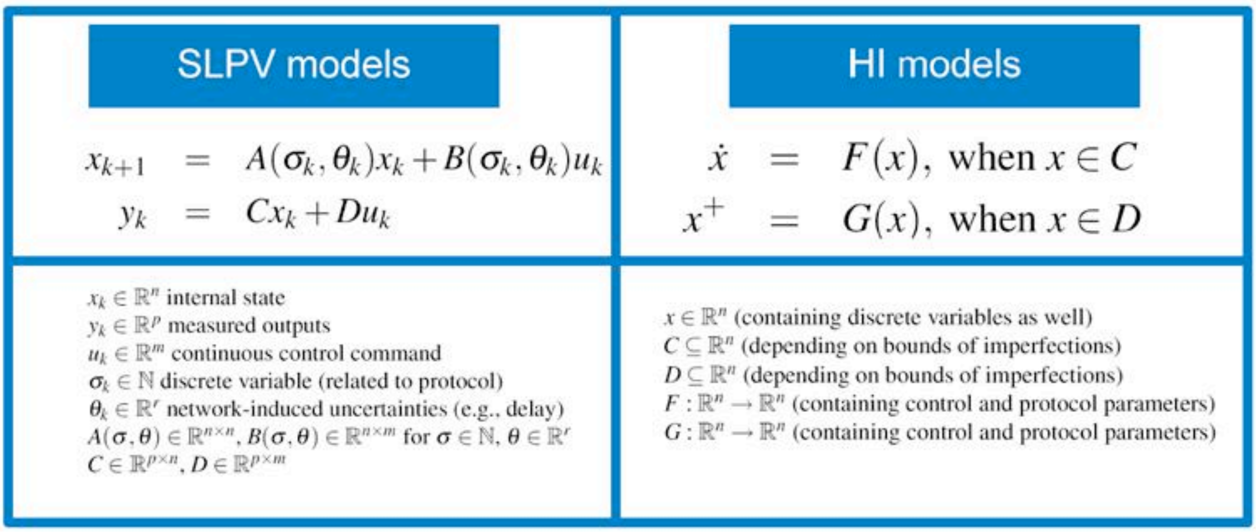
NETWORKED CONTROL



Networked communication provides many challenges when used for control purposes. In fact, wireless communication undermines basic assumptions on which feedback control systems rely. Consequently, a reconsideration of the fundamentals of control is needed in this new context. Indeed, the presence of a communication network in a control loop induces many imperfections such as varying transmission delays, asynchronous sampling instants, packet loss, and quantization effects, which can degrade the control performance significantly and can even lead to instability. In addition, the communication medium is typically a resource that is shared between many sensors, controllers and actuators, and often accessed in a mutually exclusive manner by one of the communication nodes. This requires network protocols that efficiently schedule how nodes communicate, and new techniques to optimally use the network resources and only grant access to a node when really needed from a stability or performance point of view. As a consequence, an important sub-goal of WIDE was to develop methods that effectively use the limited network resources and realize excellent robust stability and performance properties of the controlled systems.

The WIDE consortium has taken up this challenge and provided important contributions in the area of networked control systems.

Starting from an overview of existing techniques in the area of networked control systems (NCSs), which was published as a chapter [15] in the WIDE book, major open problems in the area were identified. Based on these open issues two general *analysis* frameworks for the analysis of control systems operating over shared communication networks, including wireless media as a special case were developed. The frameworks are based on switched linear parameter-varying (SLPV) systems and Hybrid impulsive (HI) systems.



The discrete-time linear parameter-varying (LPV) or SLPV models in the first framework are obtained when studying NCSs exhibiting time-varying sampling intervals, packet dropouts and time-varying delays. By discretizing the continuous-time plant models, discrete-time LPV models are obtained where the parameter-dependence is due to the uncertain nature of the delays and the sampling interval. Unfortunately, the parameter-dependence of these models is of a nonlinear kind, which is uncommon in the LPV literature. Therefore, special techniques were developed in WIDE leading to so-called polytopic overapproximations, which make the models amendable for stability analysis. In [16] overapproximation methods were proposed based on the real Jordan form, in [17] based on the Cayley-Hamilton theorem, and in [18] based on a gridding and interpolation approach. Using these overapproximated models, efficient LMI-based conditions guaranteeing the robust stability of the NCS subject to hard bounds on the delays, sampling intervals and maximum number of subsequent dropouts were derived. In [19], the ideas in [17] were further extended to incorporate delays that are larger than the sampling interval. Furthermore, in [19] it was shown that the developed setup outperforms the classical approach in the literature based on discrete-time Lyapunov-Krasovskii functions.

To compare the mentioned overapproximation and stability analysis methods based on LPV models, the advantages and disadvantages of the various methods are analyzed in a qualitative and quantitative study in [20] showing that the gridding and interpolation technique of [18] has the most favorable properties in terms of the numerical complexity of the resulting LMIs and the (limited) conservatism of the resulting stability analysis. The research reported in [20] was performed in close cooperation with the researchers that conceived the particular methods, which had a good impact on the visibility and dissemination of the WIDE results. In another comparison [21], various methods on how to "optimally" model packet dropouts in NCSs were compared both qualitatively and by the use of numerical examples.

After setting up the discrete-time LPV modeling and analysis framework for NCSs encompassing varying delays, varying sampling times, and packet loss, extensions were made in the direction of inclusion of communication protocols in [18]. This required an extension of LPV models to switched LPV (SLPV) models in order to describe the switching added to the problem due to the fact that only one of the sensor, controller or actuator nodes is allowed to transmit at a transmission time. Effective LMI-based stability analysis techniques for periodic and quadratic scheduling protocols were derived. Recently, also the effect of quantization was included in this framework showing that the SLPV framework is capable of analyzing NCS incorporating five networked-induced imperfections (delays, varying sampling intervals, dropouts, protocols and quantization). A paper describing these results is submitted for publication [22].

Next to the deterministic approaches mentioned above that provide stability guarantees of NCSs assuming hard bounds on e.g. the delays, varying sampling intervals and number of subsequent dropouts, there appeared to be a lack of results for analyzing NCSs with stochastic model information on these imperfections. A cooperation between WIDE partners led to a stochastic analysis approach for the stability problem of NCSs that are subject to time-varying transmission intervals, time-varying transmission delays, packet-dropouts and communication constraints [31]. In fact, in this stochastic framework also stochastic protocols can be analyzed.

The aforementioned results apply to linear plants and linear controllers, as this allows exact discretization of the dynamics leading to exact discrete-time models. Because of the success of this line of research, we also made a start with using the discrete-time modeling and analysis approach for nonlinear plants and controllers, see [26], which was recently accepted for publication.

A second framework based on hybrid impulsive (HI) systems was developed, which is based on continuous-time models incorporating jumps (resets) and flows (according to differential equations). Novel techniques were provided in [23] that can analyze NCSs with varying delays, varying sampling intervals, dropouts and scheduling protocols. In [23], it was also shown how performance analysis in terms of Lp gains from disturbances to important performance variables can be obtained. In [24] a unification step was made towards studying quantized systems and networked control systems simultaneously demonstrating that also the HI framework can analyze NCSs encompassing all of the five mentioned types of imperfections, although further improvements and extensions are still needed. An enormous benefit of the HI framework compared to the SLPV framework is that it allows considering general nonlinear plants and controllers, and general classes of protocols, while the SLPV framework is mainly tailored towards linear plants/controllers. For the linear case the SLPV framework is however more effective and less conservative than the HI framework.

The stability and performance analysis in [23,24] relied on a modular analytical approach in which the Lyapunov function for the overall system was assembled from a Lyapunov function for the network-free system and a Lyapunov function for the protocol. Essentially, this leads to structured Lyapunov functions and the construction can be linked to small-gain type of arguments, which are known to be conservative in certain situations. Therefore, also a computational approach was developed based on sum of squares (SOS) techniques that aims at directly synthesizing polynomial Lyapunov functions for the overall system, which turned out to be less conservative in many cases. However, this SOS-based technique only applies to polynomial systems and piecewise polynomial protocols, still including the well-known periodic protocols and quadratic protocols having the Round-Robin and Try-Once-Discard/Maximum-Error-First protocols as special cases. This work is described in detail in [25].

Other results were achieved in the area of *synthesis* methods for control systems operating over wireless networks using LMI-based and MPC-based synthesis techniques, including synthesis methods for decentralized control strategies for large-scale networked control systems. Building upon the SLPV and HI analysis framework, investigations were made of automatic synthesis of controllers that operate desirably when communication takes place via an uncertain network connection. Using the SLPV framework, in [16,19] two versions of static state-feedback control laws were synthesized in the case without (MAC) protocols. Conditions for the synthesis of a state-feedback based on a `lifted' state variable including both the sampled state of the plant and the old control input, and a `genuine' state-feedback based only on the sampled state of the plant, were derived. The latter problem is more involved as it leads to a structured synthesis problem [19], but it was still possible to obtain a LMI-based design methodology.

As in many situations not all states of the plants are measured and available for feedback, , in [27] general observer-based controllers for large-scale linear plants were analyzed and synthesized in the presence of communication constraints requiring scheduling protocols. In addition to rendering the controllers output-based, they were also considered to be decentralized in order for them to be implemented for large-scale systems. Due to the communication constraints, only one sensor/controller/actuator node is allowed to transmit its data. As a consequence, it turned out to be fruitful to adopt a switched observer structure that switches based on the transmitted information. By taking a discrete-time switched linear system perspective, a general model is derived that captures all these aspects and provides insight into how they influence each other. Focusing on the class of so-called 'periodic protocols' (of which the well-known Round-Robin protocol is a special case), a method to assess robust stability using a polytopic overapproximation and LMI-based stability conditions in line with the SLPV framework are presented. Although the design problem is in general non-convex, a procedure to find stabilizing control laws by simplifying the control problem is presented. The design of the controller exploits the periodicity of protocols and ignores the global coupling between subsystems of the plant and variation of the sampling intervals. To assess the robust stability of the resulting closed-loop system including the ignored effects, an a posteriori stability analysis can be conducted based on the results discussed earlier. Important further progress was made regarding this highly challenging problem that is central to the objective of WIDE. New ideas were conceived that significantly improved the earlier ideas in [27]. These results are submitted for publication: [28] treats the case of static decentralized output feedback case, while [29] treats the full observer-based decentralized control problem over communication networks and leads to LMI-based synthesis conditions.

Next to the above synthesis methods exploiting LMI-based techniques, alternative design techniques were explored as well. In particular, using the SLPV framework for NCSs including varying delays and varying sampling intervals, which are modelled by random variables and given by probability distributions [31], a stochastic MPC approach was developed in [32], which turned out to be an effective control strategy for NCSs. The approach is based on the general stochastic MPC ideas developed in [12,13].

Another important achievement of WIDE was related to the problem of synthesis of *decentralized linear controllers* that need to operate over unreliable network links. A new approach was proposed based on linear matrix inequalities for discrete-time linear systems subject to input and state constraints [9]. Measurements and command signals are exchanged over a sensor/actuator network, in which some links are subject to packet dropout. The resulting closed-loop system is guaranteed to asymptotically reach the origin, even if every local actuator can exploit only a subset of state measurements. Two strategies were developed, addressing the problem form a conservative and a stochastic viewpoints, respectively. The first strategy do not assumes a model for losses, thus retain stability for any occurrence of measurement reception even though exploits the information available at the current instant. In the second strategy, packet dropout is modeled by means of a finite-state Markov chain that allows one to exploit available knowledge about the stochastic nature of the network. For such model, a set of decentralized switching linear controllers is synthesized that guarantees mean-square stability of the overall controlled process under packet dropout and soft input and state constraints.

The *decentralized MPC* approach based on model decomposition described earlier for large-scale systems was also extended to take into account possible loss of information packets [3], providing sufficient criteria for asymptotic tracking of output set-points and rejection of constant measured disturbances under possible intermittent lack of communication of measurement data between controllers. The effectiveness of the approach was shown on the WIDE simulation benchmark (distributed temperature control in the passenger area of the railcar) under packet loss.

For the HI framework, design of controllers is typically carried out from the perspective of emulation meaning that, in principle, the controller is designed assuming a network-free context in a first stage, and in a second stage it is investigated using the developed tools [23,24] how small the delays / transmission intervals should be in order to guarantee certain stability and performance properties. Interestingly, the HI framework [23,24] discussed above provides directions for how to design the network-free controller in the first stage in order that it indeed performs well once the controller is implemented using the communication network.

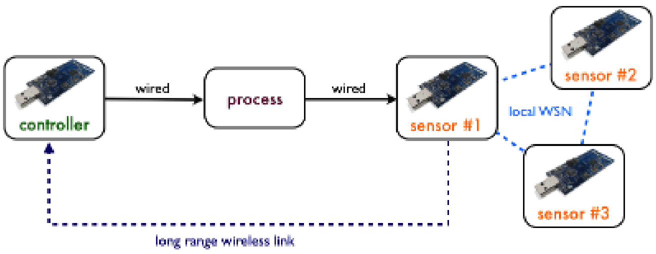
In the area of control and *estimation over wireless networks*, WIDE focused on network-aware Kalman filtering. Kalman filter provides a stochastically optimal estimate of process state under standard assumptions (linear process model, Gaussian noise). This state estimate is typically used in advanced control algorithms, e.g., MPC. The fact that the networked communication from the sensors to the estimator is not perfectly reliable – the data may be delayed or lost – increases further the importance of state estimation. A suitable extension of Kalman filter is able to provide an optimal state estimate even in the case when data arrive with a delay, even out-of-sequence. The only condition is that the filter knows the delay, e.g. from the time stamp marking the time of acquiring the particular data from the sensor. Optimal Kalman filter may be obtained as a standard time-varying Kalman filter where the model of the plant is augmented by a chain of delays at process output. This solution is, however, computationally highly extensive and prohibitive in case of fast processes. HPL worked on computationally effective algorithms of optimal and sub-optimal Kalman filters that can be possibly integrated in base control layer. The result was obtaining a novel algorithm of the optimal Kalman filter for single-output systems with communication delay [41]. The algorithm exploits the particular structure of the problem, uses some gains pre-computed off-line to achieve computationally efficient implementation relative to the standard square root implementation, but equally robust. Further, a highly efficient sub-optimal algorithm was proposed, extending an existing idea that under the assumption that all data arrive to the filter within a given maximum delay, the optimal filter can be implemented as a switched linear system, when Kalman gain depends entirely on the combination of missing samples. There are a finite number of Kalman gains that can be pre-computed off-line. Thus, the optimal filter is of the structure similar to the steady-state Kalman filter; the only difference being that Kalman gain is switched; the right gain is chosen from the pre-computed set based on the state of the input data buffer. The necessary off-line computational requirement is thus very low. The down side is, that the number of pre-computed gains may be very high, growing exponentially with the maximum communication delay, making the algorithm intractable in cases when this delay is high. The proposed sub-optimal solution is made on the assumption that long delays are infrequent. The algorithm thus can behave optimally for small delays; if delay of a particular measurement exceeds a threshold, the filter pretends that it was received, replacing its value by its own estimate; this is, of course, a non-optimal way of handling this situation. Nevertheless, when the missing sample finally arrives, it is fused correctly, correcting the previously made wrong update. If there are currently no more long-delayed samples, optimality of the estimate is restored. The number of long-time missing samples is restricted; the maximum number of these samples is a filter parameter determining the number of pre-computed gains. If the maximum number of long-time missing samples is exceeded, then some of the data arriving with long delays cannot be used for improving the estimate and are considered lost, which may decrease the filter performance. This suboptimal filter is almost equally fast as the switched optimal filter; the set of gains that needs to be pre-computed and stored is highly reduced. Compared to the optimal switched filter, some additional missed sample tracking needs to be implemented, but the number of numerical operations needed for a one step update of the filter is still low. This method is thus suitable for the use in distributed control systems (DCS) and thus may contribute to the integration of DCS and WCN. Algorithms of network-aware Kalman filters were implemented as Simulink S-functions and made available as a part of WIDE Toolbox. The included demo models include also alternative ways of handling delays (e.g., Smith predictors) as well as network-unaware approaches. It was established, that these filters, when correctly applied, contribute to better performance and stability of the closed loop in the base control layer (including a PID controller).

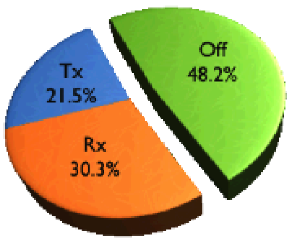
In the area of networked control, a focus has been also on exploiting the results on wireless real-time communication and to develop co-design procedures for networked control systems [67]. It is since long known that control loops are sensitive to both latency and information loss. Previous work in low-power real-time wireless showed that both cannot be made small at the same time: increased reliability requires longer deadlines (and hence, more opportunities for retransmissions). A major accomplishment in WIDE was the development of a framework for jointly optimal control design and network operation. In contrast to previous work in this area, our framework separates the networking and control design tasks into two modular subproblems, parameterized by the sampling time of the control loop. We could then demonstrate that a one-dimensional search over the sampling time, followed by the solution of the optimal network forwarding and control design task, allows one to find the jointly optimal solution in terms of closed-loop control performance

Event-triggered control (ETC) strategies were also developed within WIDE to save communication resources and battery power for the wireless devices. At present, most control systems execute the control tasks periodically, since this allows the closed-loop system to be analyzed and the controller to be designed using the well-developed theory on sampled-data systems. Although periodic sampling is preferred from an analysis and design point of view, it is less preferable from a resource utilization point of view. Namely, executing the control task at times when no disturbances are acting on the system and the system is operating desirably is clearly a waste of the system's resources. In particular, in case the measured outputs and/or the actuator signals have to be transmitted over a shared (and possibly wireless) network, unnecessary utilization of the network (or power consumption of the wireless radios) is introduced. To mitigate this unnecessary waste of computation and communication resources, it is of interest to abandon the conventional periodic sampled-data control schemes. Therefore, WIDE considered an alternative control paradigm, namely event-triggered control (ETC). ETC is a control strategy in which the control task is executed after the occurrence of an event, generated by some well-designed event-triggering condition, rather than the elapse of a certain fixed period of time, as in conventional periodic sampled-data control. In this way, ETC is capable of significantly reducing the network usage, while retaining a satisfactory closed-loop performance.

In particular, in WIDE major advances were obtained in the direction of *output-based decentralized* event-triggered controllers in [30]. This paper is one of the first works in the area of ETC considering output-based controllers, as almost all existing results assumed that the full state was available for feedback, which is rarely the case in practice. In addition, the paper unifies and generalizes several existing event-triggered control algorithms in one framework, and the framework allows for making tradeoffs between closed-loop performance on the one hand and resource usage expressed in the number of required events on the other. Interestingly, a new analysis and design method exploiting tools from hybrid systems leads to improved designs of event-triggering laws with larger inter-event times and thus less utilization of computation, communication and energy resources. The hybrid system tools adopted in the context of ETC are related to the HI framework mentioned above. As such, a fruitful connection was established between the robust analysis/design approach for NCSs and ETC.

Also between the areas of ETC and MPC interesting connections were realized withinWIDE wleading to a novel model predictive control approach for wireless automation schemes as in the figure on the right, that are *aware of the energy-constrained nature* of WSNs. In particular the discharge of batteries of sensor nodes, which is mainly due to radio communications. A novel transmission strategy for communication between controller and sensors was developed that takes into account radio usage [10,11,12]. The strategy minimizes the data exchanged over the wireless channel. Moreover, an energy-aware control technique for constrained linear systems based on explicit Model Predictive Control (MPC), providing closed-loop stability in the presence of disturbances, was developed. The presented control schemes were tested and compared to traditional MPC techniques. Results showed the effectiveness of the proposed energy-aware approach, with battery savings in the order of 50%, which achieves a profitable trade-off between energy savings and closed-loop performance, as shown in the table for an example involving three sensor nodes.





Controller	Performance	Tx Rate
Standard Robust MPC	2.5025	100%
Energy-Aware Robust MPC	2.5514	51.8%

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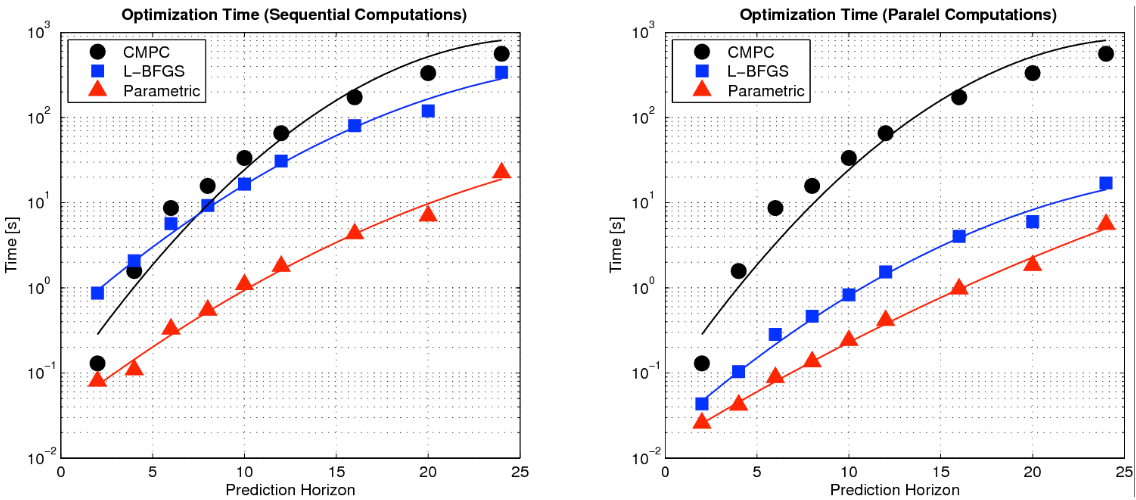
DEMONSTRATION

The effectiveness of the most relevant control approaches described in the previous paragraphs was tested in two real-life demonstrations based on the water network of the city of Barcelona.

The first demonstration was aimed at testing the innovative distributed model predictive control concepts developed within WIDE on controlling the entire water network, based on production-ready software implementing the control algorithms interfaced with the existing SCADA system and validated against a realistic simulator of the network. A decentralized/coordinated MPC control and subsystem decomposition for water networks have been developed providing satisfactory results compared with the existing legacy or centralized solutions. The proposed algorithms represent an improvement with respect the current centralized solutions already in place in some water networks.

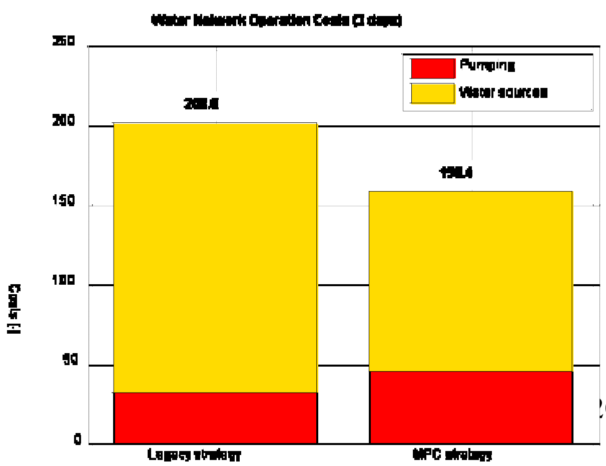
The key contributions in this first demonstration are: (*i*) an integrated multilayer decentralized control and optimization framework based on the results of MPC for large-scale systems described above to water network control; (*ii*) an infrastructure for connecting the distributed hierarchical control algorithms implemented on an industrial control platform with the virtual network testing environment in Simulink; (*iii*) adopting existing components in the industrial platform for advanced process control for predictive controllers to work as local controllers in distributed/coordinated MPC and development of a new component for the coordinator; (*iv*) the demonstration of coordinated MPC control on a part of the Barcelona water network model divided into three subsystems by a distributed controller implemented on an industrial platform.

The original method of coordinated MPC control described earlier was used for *control design of the full scale model* of the transportation layer of Barcelona water network. This solution was found particularly suitable for this application; in particular, it recovers the optimality of the centralized solution, and, because of a relatively long sampling interval, several iteration steps can be made within one sampling period involving data exchange between local controllers and the coordinator. It was found that this solution is scaleable; while the centralized MPC is computationally infeasible in MATLAB for longer prediction horizons using standard QP solvers, the distributed and coordinated solutions can easily be computed. In the settings when the centralized solution can be applied, it is far slower than the coordinated solution, even if the local control tasks are performed sequentially on one PC. In fact, the newly proposed method outperforms the L-BFGS (limited-memory Broyden–Fletcher–Goldfarb–Shanno) method, as shown in the figure below.

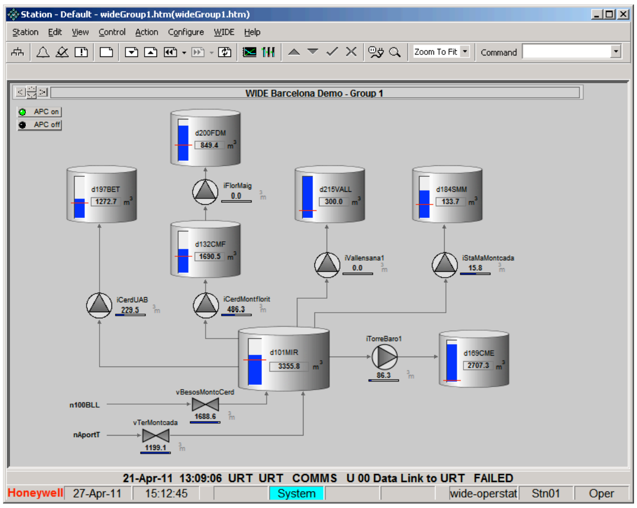


Performance tests of controllers on the full-scale Barcelona water network model: Centralized MPC (standard active-set method-based QP solver) compared to distributed MPC based on L-BFGS method and the original coordinated MPC with parametric coordination. Left: sequential solution of local tasks; right: parallel execution.

An *off-line evaluation tool* was developed in MATLAB for the water network model to assess benefits of various control strategies. This tool allows building the network topology, setting process limits and prices, import historic data (with reconciliation), performing optimization, comparing flow and tank level trajectories (computed versus historical values) and evaluating benefits. A considerable cost-decrease was found for the optimal centralized / distributed / coordinated MPC solution relative to the legacy solution (represented by archived process data), as shown in the figure on the right. Important indirect benefits of the advanced solution are smoother operations of manipulated variables resulting in lower

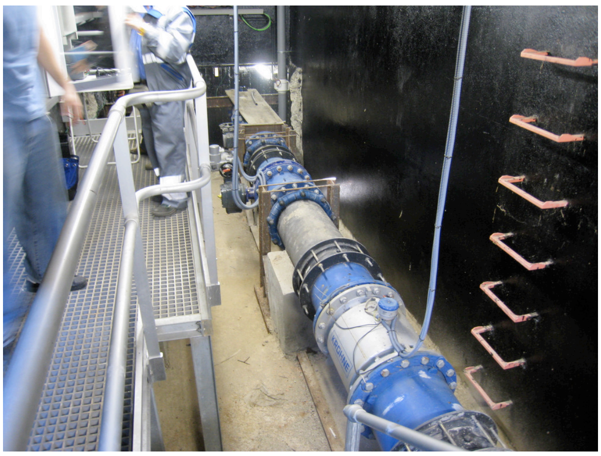


pressure surges (leakage prevention) and reduced equipment wear & tear.



The essential part of the demonstration was *implementing the solution on an industrial control platform* for advanced control and optimization, specifically, the URT (Unified Real-Time) platform of Honeywell. In order to connect controllers built on this platform to the Simulink model of the network, an interface has to be made. Advanced controllers programmed in URT are never connected directly to the process; they communicate with the base control layer (DCS, PLC, SCADA) using the OPC protocol. Hence, an interface layer between the water network model in Simulink and an industrial control platform for URT was developed. This layer consists of a model of the base control layer in Simulink. A library of standard DCS blocks was developed including standard functionalities (wind-up handling, mode handling –auto/manual/cascade with bumpless switching, propagation of initialization signal, ranges and limits propagation). Further, Simulink provides OPC Client only, while URT assumes OPC server at the base control layer; therefore, an OPC bridge was developed as an interface. This guarantees that the virtual testing environment behaves as a real application with a base control layer (DCS or SCADA) and allows implementing back-up control strategies if, for some reason, the advanced control layer fails. This is an essential safety feature necessary for any APC project (an operator GUI for the network area is shown in the figure above).

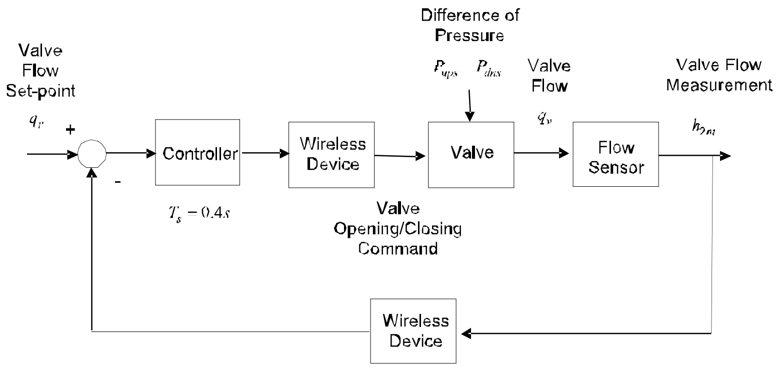
To develop a prototype of the coordinated MPC, the existing component for MPC with state-space model in URT was adapted so that it can serve as a local unit. The coordinator block was implemented in URT in C++ together with communications with local MPC blocks in URT, in order to build a distributed, coordinated MPC. For the demonstration of viability of the solution, distributed MPC was built for a segment of a network, divided into 3 subsystems, each controlled by a local MPC. These local controllers run as different applications, running on separate virtual machines. They communicate with both base-layer control, and the higher layer coordinator, via OPC. The local controllers handle the flows from the uncontrolled part of the network as disturbances. Furthermore, the controllers can be switched on/off sequentially, without disturbing the overall process. Also, in the case of failure, base-control layer switches to a back-up strategy. To monitor the state of the controlled model, a standard operator Graphical User Interfaces were programmed in a standard environment (HMIWeb of Honeywell). This interface shows, in different tabs, the status of the network / areas (subsystems) / elements (tanks, pumps, valves, nodes). In this extensive validation setup, various scenarios were tested and the solution validated.



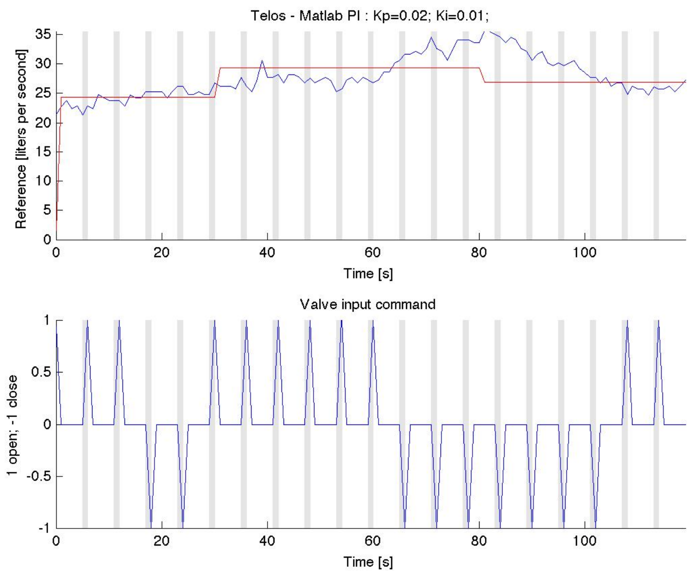
A second demonstration involved design and *experiments of wireless control* of a valve at a pumping station in Barcelona, based on wireless feedback from pressure and flow sensors, therefore demonstrating the practical feasibility of the advanced wireless automation solutions developed within the WIDE project.

The existing legacy control system involves regulatory controllers operating with a sampling time of 0.4s responsible of the control in pumps and valves. The regulatory layer was selected in the WIDE project for illustrating the wireless control concept. In particular the closed-loop control of valve located in Ronda

Litoral was used. The controller can control some of the following variables using the available instrumentation: flow and pressure downstream or difference of pressure. The aim of the demonstration was to replace the current wired regulatory controller by a wireless controller, see block diagram below.



For the demonstration, both E-Senza's SenzaNET nodes and Moteiv's Telos nodes were used. A linear controller for the wireless control loop was designed and analysed using WIDE's networked control approaches and the MATLAB data acquisition toolset available in the WIDE Toolbox. An example of tracking results in shown in the figure below.



WIDE TOOLBOX FOR MATLAB

The main analysis and design methodologies described in the previous paragraphs have been collected inside the WIDE Toolbox for MATLAB, to favour their use by other academic and industrial researchers in a user-friendly manner. This is the best way to transfer the most successful scientific developments into real industrial practice. The Toolbox offers several features for control of large-scale and networked systems, including tools for:

- modelling of large-scale systems
- analysis of networked control systems
- distributed MPC
- decentralized MPC
- hierarchical MPC
- energy-aware MPC

- network-aware Kalman filtering
- wireless control loop simulation in Simulink (based on TrueTime)
- data acquisition in MATLAB from real sensor nodes.

The toolbox is available for download on the project web site at http://ist-wide.dii.unisi.it/index.php?p=toolboxsp.

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4.1.4 Potential impact, dissemination, and exploitation of the results

The presence of industrial players like Honeywell, E-Senza, and AGBAR in the consortium consent the exploitation of several outputs of the project, some of them already with patents pending, enhancing European competitiveness in the monitoring and control market. The novel algorithms for optimal management of the water network will bring substantial savings of important resources like water, energy, and money, contributing to a richer and cleaner world. Similar benefits are foreseeable in other domains like gas/oil distribution, sewer networks, smart energy grids, urban and extra-urban traffic.

Decentralized/coordinated MPC control strategies for water networks have been developed providing satisfactory results compared with the existing legacy or centralized solutions. According to the AGBAR evaluation, the developed decentralized/coordinated MPC control strategies could be easily integrated in a real operational system relying on a SCADA since they have been implemented using industrial products and standards. As a result of such integration, the management utility company will benefit from the decentralized/coordinated MPC strategies regarding the incremental implementation/deployment of the control or the capability of mixing subsystems being controlled with the current legacy control with other controlled using MPC. In case that AGBAR goes to upgrade the current control strategy based on a centralized solution will consider seriously implementing on-line some of the decentralized/coordinated MPC control strategies developed in the WIDE project.

In order to disseminate WIDE results in industrial communities and to get a possible feedback for project execution and possible further exploitation, an End-User panel was established in early 2010. The activities of the panel were planned from the beginning as virtual teleconference meetings, where members of WIDE consortium presented project objectives and its results to the industrial members of the panel, following a discussion, and collecting feedback forms which were distributed among the participants. The industrial members of the panel were 11 distinguished researchers from a range of industries, including steel processing, automotive, wind power and data security. These people were given an overview information of WIDE research plan and to the date achievements prior to the first teleconference meeting, which took place on June 23, 2010. This teleconference was hosted and moderated by Honeywell in Prague, using Genesys infrastructure for audio and desktop applications. A general WIDE overview and a fairly detailed description of all workpackages was given by the representatives of the WIDE Consortium. The feedback from the panel participants confirmed that WIDE approaches and results are of interest and innovative. The particular interest of the participants differ according to the industry: *Processing industry* representative was interested mainly in distributed modeling and control of large-scale systems, while the people of the *automotive industry* showed an interest in wireless solutions, mainly with the intention for the applications involving vehicle-to-vehicle vehicle-to-infrastructure communication. The second teleconference meeting of the End-User Panel took place on June 8, 2010. The participants were given an overview of the achievements of WIDE at the end of the project, including the demonstration case – distributed control of Barcelona Water Network, including the prototype of the industrial solution. The prevailing opinion was that WIDE results are exploitable, but in a longer term, on a step-by-step basis, requiring further follow-up development. Details on the panel meetings can be obtained at the public area of WIDE web site, http://ist-wide.dii.unisi.it/index.php?p=virtualmeeting2010 and http://ist-wide.dii.unisi.it/index.php?p=industrialmeeting2011.

Honeywell Prague Laboratories (HPL) was active in presenting WIDE results within its parent organization, Honeywell International. In particular, there was a participation in poster sessions of Honeywell Technology Symposia in 2010 and 2011 to the company technology and marketing management; the presented topics where results on model management, distributed MPC, net-aware Kalman filtering and water network control.

Towards the end of WIDE, HPL increased its efforts towards possible exploitation of project results within Honeywell. Several presentations to marketing and technical leaders of other divisions were given; in particular, the representatives of HBS (Home and Building Solutions) were given details on coordinated MPC control of water networks. A successful presentation of a prototype solution on the URT platform drew an interest – as prior to finishing this prototype, WIDE solutions were received coldly when presented as concepts, the attitude changed after demonstrating a validated solution on a raw prototype. A description was given to marketing staff that will present it to their customers and search for possible project. A promising situation is that the solution is not limited to water networks – it can be readily used to any media distribution networks as wastewater, gas and oil. At this moment, no particular timetable for productization has been specified.

Another intersection of WIDE results and Honeywell business interest is control over wireless networks. The solution of net-aware Kalman filters was introduced technology leaders of the wireless team as a solution integrator between wireless sensor networks and distributed control systems.

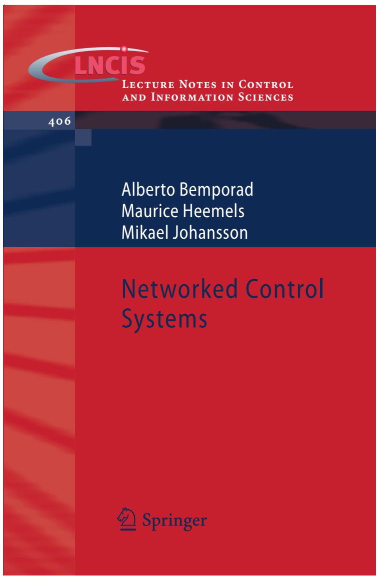
WIDE results in model-management – structured order reduction – is a subject of a follow-up development at HPL. In particular, its integration into a computational environment for hosting control algorithms that is being developed in an EU FP7 Project IMC-AESOP (Grant agreement no: 258682). The goal is obtain a variable topology model usable in advanced process control application. The process may involve a number of parallel units, part of which may be shut down. The overall model for APC depends on the particular configuration. It is not feasible to do identification experiment on all combinations of the process configuration. There may be a large number of these combinations and every test may take several hours, during which the process may be significantly disturbed, effecting on the plant operation; step testing is the most expensive part of an advanced control commissioning. The logical alternative is to identify the subsystems, build the global model by interconnecting and subsequently, reduce order of this global model. This, however, must be done in a correct way, respecting the interactions among the subsystem. The core technology was developed in WIDE. Current effort in AESOP is focused towards obtaining a model component for newly developed service-oriented control architecture. This model component will provide a reduced-order model of required accuracy on-line, in response to a changed process configuration, to predictive controllers as well as to Kalman filters. The intended application area for this new application is industrial energy.

The interest of Honeywell in particular WIDE results and their future exploitation follows from their patent protection Four patent applications listed below were filed at the European patent office. This filing was done after consulting WIDE consortium and sub-sequent approval, as required by the consortium agreement.

1. EU Patent Application entitled *A System for Modelling Parallel Working Units for Advanced Process Control,* Application No.: 11152627.3, Filing Date: January 28, 2011, Inventor: P. Trnka
2. EU Patent Application entitled *Optimization Problem Solving*, Application No.: 11157244.2, Filing Date: March 7, 2011, Inventors: P. Trnka, J. Pekar
3. EU Patent Application entitled *Distributed Kalman Filter Tolerant to Communication Failures*, Application No.: 11167187.1 , Filing Date: May 23, 2011, Inventor: L. Baramov
4. EU Patent Application entitled *Controller that Estimates Delayed Manipulated Variables*, Application No.: 11182649.1, Filing Date: September 23, 2011, Inventor: L. Baramov

The results developed by the TU Eindhoven in WIDE are already being fruitfully applied in the scope of other application-oriented projects, such as the Dutch HTAS project ‘Connect & Drive’. Within this project, the problem of the velocity control of vehicles on highways is considered in order to increase traffic flow (avoid traffic jams), and to improve fuel efficiency and safety. This goal is achieved by so-called cooperative adaptive cruise control, which heavily relies on wireless communication between vehicles. The techniques developed in WIDE are currently being used to assess the robustness of cooperative adaptive cruise control in the presence of impairments induced by the wireless communication, where such robustness is crucial in such a safety-critical application. These techniques form a crucial enabling tool for tackling this multi-disciplinary design problem involving vehicle dynamics, controller design and network design. This is just one example of how the results in WIDE can and will be used in future technological advancements with high societal impact.

Scientific dissemination was also quite intense in WIDE. The 3rd WIDE PhD School on Networked Control Systems took place on July 7-9, 2009 in Siena, Italy (http://www.wide.dii.unisi.it/school09). The program included three days of lectures, seven hours of 45min each day, covering several aspects of networked control systems: fundamental issues, distributed estimation and consensus, cooperative control, distributed optimization, decentralized and hybrid model predictive control, simulation, stability, feedback over limited capacity channels, event-triggered and self-triggered control. Leading researchers in these domains were invited to lecture on these topics, included researchers from the WIDE Consortium.



The lectures of the school were converted into a Networked Control Systems handbook, edited by leading WIDE Consortium members and published in early 2011 by Springer Verlag in the Lecture Notes in Control and Information Sciences series.

The WIDE Consortium also organized several invited sessions at major control conferences including CDC/ECC11, ACC10 and ECC09. At ECC09 one of these sessions was together with the EU-FP7 project FEEDNETBACK. In addition to these invited sessions and the presentations at major international conferences, many members of the Consortium disseminated WIDE knowledge broadly through various *invited talks* at different universities, research institutes, and conferences. In addition, TU Eindhoven and KTH Stockholm developed a *new PhD course* (4 times 120 min) on Networked Control Systems based on the knowledge developed within WIDE. The course was given in Utrecht, the Netherlands, within the framework of the Dutch Institute for Systems and Control (DISC) and attended by 25 PhD students in control theory/engineering from different universities in the Netherlands. Also Prof. Mikael Johansson (KTH) and Prof. Maurice Heemels (TU/e) lectured together for 8 hours at the 2nd PhD School of the DFG-Priority Program 1305 Control Theory of Digitally Networked Dynamical Systems, Rodt, Germany, thereby disseminating the WIDE knowledge to around 40 PhD students active in the area.

4.1.5 Project web site and contact details

The website of the WIDE project is **http://ist-wide.dii.unisi.it**

Contact details: Prof. Alberto Bemporad, IMT Institute for Advanced Studies Lucca, P.zza San Ponziano 6, 55100 Lucca, Italy, Tel: +39 0583 4326600, Fax: +39 02 700 543345, email: bemporad@imtlucca.it.

4.2 Use and dissemination of foreground

Contributions to standards and to policy development

In order to have a large industrial impact on control and operations of large-scale systems and infrastructures, it is important to disseminate project results to academia and industry, and to make sure that relevant standards support the unique requirements of such systems. With two partners (E-Senza and Honeywell) contributing to the emerging standards on industrial wireless, WIDE is committed to feeding back its experiences to the ISA100 standardization committees.

WIDE will also have a wider societal impact, not only via employment, education and research, but also through reduced environmental strain. Research and education in WIDE will reinforce Europe's competitiveness in automation, and secure and enlarge employment in Europe that depends on automation technologies. A better and faster information flow, coupled with effective system-wide resource optimization, saves energy and resources, and helps to protect the environment.

Dissemination plan

The technologies and methodologies developed in WIDE are highly innovative and culturally new in the context of management and optimization of processing plants and distribution infrastructures. An effective and well-managed dissemination plan is thus vital to explain and promote our results in the industrial and scientific communities. This plan will target knowledge transfer and results dissemination during the entire project, and will be tightly coordinated through an exploitation strategy plan and the Intellectual Property Rights (IPR) management. The dissemination plan will define specific steps for

- Dissemination of results in the academic community;
- Dissemination within the industry;
- Collecting feedback to research teams.

Dissemination of results within the academic community.
WIDE's scientific achievements have been reported at well-established top-ranked international conferences and published in high-impact journals, creating project visibility and interest of other parties in contributing to the relevant theories and transfer results to other sectors. WIDE has organized invited sessions at conferences with a worldwide audience from both the industry and the academia, subject to the acceptance from program committees.

The project web-site http://ist-wide.dii.unisi.it will serve an important point of access to project results. The web-site is linked from the research sections of the beneficiaries' web-pages, and in some of the scientific publications, to ensure maximum visibility.

The project has also created liaisons to major research initiatives in other countries, including other ICT projects on "control of large-scale systems" funded in FP7 and the networks of excellence HYCON2. Another channel of results disseminations will be via distributing free software, in particular the WIDE Toolbox for MATLAB.

Dissemination within the industry.
To enable effective industrial dissemination, WIDE has created a panel of representatives of potential end-users and researchers from a range of industries. Two teleconference meetings of the panel were organized; in the first one, representatives of WIDE consortium presented the objectives of WIDE the research plan and to the date results, while in the second one, the major achievements of the project were overviewed. Possibilities of future exploitation of the results were addressed. Feedback was collected

through discussions, e-mail correspondence and feedback forms. Several ideas coming from the panel were useful for the project execution and were taken into account. The participants found the project results innovative and of interest; exploitation in their respective organizations would require a follow-up development.

Exploitation plan

Apart from dissemination, the exploitation plan includes monitoring research, charting its potential applications and studying market prospects. The intense participation of three industrial partners representing the full value chain of control and optimization of large-scale processes exploiting wireless communication infrastructures already indicates the relevance and potential of WIDE in their respective markets. A particular effort will be devoted to spreading research results that do not fall under IPR protection of the participants to all parties interested in the developed technology, in particular, small and medium scale enterprises (SMEs). In order to reach this aim, participants intend to showcase the research results at brokerage events, workshops and company missions.

Efforts were made throughout WIDE for preparing results that are industrially exploitable after standard follow-up development. This was facilitated by having developed: a unified framework for modelling and design so that all pieces fit well together; the WIDE Toolbox prototyping algorithms in the MATLAB/SIMULINK™ environment, and subsequent tests using simulations with model-in-the loop; documentation of algorithms and prototype code. These algorithms and documentation were made public and disseminated according to the strategy outlined in the above paragraph.

The successful implementation of the demonstration cases, in particular, distributed MPC control of the water network is highly important for future exploitation. In particular, it demonstrates that MPC, which is a standard in the advanced process control, can be implemented in a distributed way, applied to processes that are of truly large scale and geographically distributed. Furthermore, it was shown that it can be implemented in an industrial platform for advanced control, it can communicate with any standard industrial infrastructure for base-layer control, and can guarantee operational safety. Also, it can be implemented on a sub-set of the network, respond to failures and changes of topology. Hence, it addresses the issues the process managers have regarding advanced control technology. In addition, a reduction of overall costs was demonstrated, and further, intangible benefits were achieved, as is a smoother operation. This successful demonstration opens the door for possible future exploitations in water/sewage networks, oil and gas distributions and others. It needs to be noted that the solution in the demo is a hardened prototype. To become a marketable product it will require routine development that is beyond the scope of WIDE, e.g. professional visualization and configuration tools.

We would like to emphasize that the commercialization of WIDE results has not be done within the project. Process industries and infrastructure operators are conservative in acquiring new disruptive technologies and project negotiations may take a some time before the contract is agreed (budget planning cycle of the end-user is a significant constraint here). Therefore, we do not expect the WIDE results to be exploited commercially immediately after the project completion in significant numbers. However, successful applications have accelerating effects and this can be started by the demonstration case. To support and speed up the process, the WIDE consortium will continue advertising its results among the process industry and infrastructure operators, tailored to the specific needs of selected user-groups. Our continuous promotion effort will contribute to improving the acceptance of these novel technologies among the plant and infrastructure management.

We expect that significant opportunities for exploitation will appear, in particular because of the synergy of advanced control and wireless communication, which is a synergy largely unexploited to this date. A strategy for cooperation on a commercial follow-up development within WIDE participants after project completion is under consideration. Indeed, the industrial members of the WIDE consortium will integrate some of the results, after the necessary follow-up development, in their products. We describe their exploitation plans here below.

AGBAR

In complex water supply networks, where management and optimization become risky and time-consuming, the decentralized control turns out to be an option to consider in detail for further extensions of the control itself, aiming to gain robustness and increase flexibility. The results of WIDE project show the benefits of decentralized/coordinated MPC. The incremental implementation/deployment of the control considering the capability of mixing subsystems being controlled with the current legacy control together with other controlled by means of MPC has been tested off-line. For this reason, AGBAR will for sure take into account the decentralized/coordinated control as a feasible architecture option. Nonetheless, before getting ready for the real application, some practical issues should be addressed. Among them: how flow set-points computed by MPC are translated to pressure set-points or how discrete on-off actions in pump stations will be handled. Therefore, next steps would lead to dedicate efforts on overcoming the aforementioned issues. Regarding the wireless technology, AGBAR thinks that, for the moment, it is not a mature technology to be used in water facilities with communications underground, where wired connections offer reliability in critical communications. In any case, AGBAR will keep its eye close to the market to see the improvements of this technology in order to analyze any potential application of wireless technology in its network and other facilities, especially when dealing with long distance communications and when it is sure that no disturbances could arise and make the communications fail.

HONEYWELL

HPL widely promoted the achievements of WIDE within its parent organization, Honeywell. In particular, WIDE results were presented at company-wide Technology Symposia, attended by marketing and technology management in 2010 and 2011. A presentation is also planned for 2012.

The following three results were identified by HPL as best aligned with Honeywell activities and further exploitation is likely

- Distributed MPC control of distribution networks.
- Structured order reduction of parallel combinations of processing units.
- Network-aware Kalman filter.

These results are being presented to technology and marketing leaders within the company. Most interest was attracted by the distributed solution for water networks: first, it is supported by the availability of hardened prototype demonstrated on the WIDE demo case. Second, it complements the current Honeywell portfolio. Presently, a customer is sought for a pilot project.

Structured order reduction of parallel combinations of processing units is a result of collaboration of HPL and KTH in model management during WIDE. It is needed for variable topology models in advanced process control; in many cases, controlled process may involve a number of processing units working in parallel; of those, several may be out of operation for maintenance, or due to reduced load. The global model involving full order model of each unit would be overly complex; identifying an acceptable complexity model for any combination of units would require long experiments with the plant, resulting in high commissioning costs. In the case of more than a few units it is infeasible. The structured order reduction for parallel units would offer a suitable tool for handling this problem resulting in decreased off-line commissioning effort. Currently, a follow-up development takes place in HPL, where SW component is being prepared within Project AESOP of FP7 Programme.

Network-aware Kalman filter developed in WP4 is of interest to Honeywell, as it opens the possibility of integrating distributed control systems (DCS) and wireless control network – areas where Honeywell has strong portfolios. The exploitation requires the ability of WSN to transmit time stamps marking the time of acquisition by the sensors that needs to be implemented. This need was also stressed in the document on WIDE recommendations to standardizations of WSN, deliverable D6.5. Currently, discussions on this subject with the wireless team take place.

ESENZA

Considering the slow adaption of wireless technologies for monitoring applications and due to the fact that control applications will be only the next step in leveraging wireless after monitoring, it is quite obvious that a direct exploitation of the developments made within the framework of WIDE will be possible only in the long term. This is somewhat unexpected, because back in 2006 market reports indicated a multi-billion dollar market for wireless sensor networking, which would have been the ideal breeding ground for taking the next step into wireless control.

Market participants have become extremely cautious about investments into the low power wireless networking space and technology standardization has not yet reached the level required for a mass market. Although standards are defined on paper to a fairly sophisticated level, implementation lacks behind significantly and it will take several years until the large-scale adoption anticipated at project start will actually take place. The customer business case, however, is still intact, both for monitoring and control applications.

Exploitation, therefore, is still limited to monitoring. As a consequence, fast control loops are out of scope for the time being and related networking protocols for very low-latency applications cannot be exploited in the near term. On the hardware side, the device interfaces developed for interfacing with industrial sensors (flow sensor) and actuators (valves) share that fate: Since wireless industrial control is not going to be a significant market anytime soon, exploitation will take longer.

Time-synchronized low-power wireless protocols as well as related RF-hardware, wireless gateways and application middleware could easily be adopted for monitoring applications and that is where the results of WIDE are partly translated into products. Essentially, SenzaBlocks have been modified such that, instead of industrial interfaces connecting to flow sensors or valves are replaced by digital sensors for e.g. temperature, humidity and pressure as well as for collecting metering data. SenzaGates remain largely unchanged and the SenzaWMS middleware is applied for collection of data only.

As such, SenzaNET products are mainly used for three application segments:

1. Temperature Monitoring in Cold Chains and for energy efficiency applications in buildings
2. Data Center optimization using wireless nodes for mapping the temperature patterns under dynamic load variations and for verification as well as energy optimization of the cooling systems.
3. Metering applications, mostly for collection electricity consumption data, also for collection of water and gas consumption data.

ACADEMIC PARTNERS

Academic partners do not plan to exploit the results of the project commercially, and no patenting of any of their algorithms is foreseen. They will however continue researching and developing new methods along the various research fields tackled within the project, with funding coming from other national and European projects, and from industries. The WIDE Toolbox will be further maintained within the HYCON2 Network of Excellence, in which IMTL, UNITN, KTH, TUE are actively involved.

4.2.1 Section A (public)

A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
1	*Networked Control Systems*	*A. Bemporad, M. Heemels, M. Johansson*	*Lecture Notes in Control and Information Sciences*	*No 406*	*Springer*	*Heidelberg, Germany*	*2010*			
2	*Optimal Routing and Scheduling of Deadline-Constrained Traffic Over Lossy Networks*	*P. Soldati, H. Zhang, Z. Zou, M. Johansson*	*Proceedings of the IEEE Global Telecommunications Conference*			*Miami FL, USA*	*Dec. 2010*			
3	*Delay-Constrained Maximum Reliability Routing Over Lossy Links, Dec 2010.*	*Z. Zou, P. Soldati, H. Zhang and M. Johansson*	*Proceedings of the 49th IEEE Conference on Decision and Control*			*Atlanta, GA, USA,*	*Dec 2010*			
4	*System identification of complex and structured systems"*	*H. Hjalmarsson*	*European Journal of Control*	*Vol 15*		*Budapest, Hungary*	*2009*	*pp. 275-310*		
5	*On subspace identification of cascade structured systems*	*P. Hagg, B. Wahlberg, and H. Sandberg*	*Proceedings of the 49th IEEE Conference on Decision and Control*			*Atlanta, GA, USA*	*2010*			
6	*Model reduction of interconnected linear systems*	*H. Sandberg, R. M. Murray*	*Optimal Control, Applications and Methods*	*Vol 30, Issue 3*	*John Wiley & Sons, Ltd*		*2009*	*pp. 225-245*		

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

7	*Understanding the energy-reliability tradeoff in deadline-constrained packet transmission over lossy links*	*Z. Zou, P. Soldati and M. Johansson*	*First Workshop on Real-Time Wireless for Industrial Applications, part of CPS Week*			*Chicago, IL*	*April 2011.*			
8	*Hidden terminal-aware contention resolution with an optimal distribution*	*E. Ghadimi, P. Soldati, F. Österlind, H. Zhang and M. Johansson*	*IEEE MASS*			*Valencia, Spain*	*October 2011*			
9	*Accelerated gradient methods for networked optimization*	*E. Ghadimi, M. Johansson and I. Shames*	*American Control Conference*			*San Francisco, CA, USA*	*June 2011*			
10	*Modular Co-Design of Controllers and Transmission Schedules in WirelessHART*	*B. Demirel, Z. Zou, P. Soldati and M. Johansson*	*IEEE CDC*			*Orlando, FL*	*December 2011*			
11	*Controller synthesis for networked control systems*	*M.B.G. Cloosterman, L. Hetel, N. van de Wouw, W.P.M.H. Heemels, J. Daafouz, H. Nijmeijer*	*Automatica*	*Vol 46, No 10*	*Elsevier Ltd*		*2010*	*pp. 1584-1594*		
12	*Comparison of overapproximation methods for stability analysis of networked control systems*	*W. P.M.H. Heemels, N. van de Wouw, R. H. Gielen, M. C. Donkers, L. Hetel, S. Olaru, M. Lazar, J. Daafouz, and S. Niculescu*	*Proceedings of the 13th ACM international conference on Hybrid systems: computation and control*			*New York, NY, USA*	*2010*	*pp. 181–190*		
13	*Networked Control Systems With Communication Constraints: Tradeoffs Between Transmission Intervals, Delays and Performance*	*W.P.M.H. Heemels, A. R. Teel, N. van de Wouw, D. Nesic*	*IEEE Transactions on Automatic Control*	*Vol 55, No 8*			*2010*	*pp. 1781-1796*		
14	*Stability analysis of networked control systems using a switched linear systems approach*	*M. Donkers, W.P.M.H. Heemels, N. van de Wouw, L. Hetel, and M. Steinbuch*	*IEEE Transactions on Automatic Control*	*Vol 56, No 9*			*2011*	*pp. 2101-2115*		

15	*Hierarchical multi-rate control design for constrained linear systems*	*D. Barcelli, A. Bemporad, G. Ripaccioli*	*Proceedings of the 49th IEEE Conference on Decision and Control*			*Atlanta, GA, USA*	*2010*	*pp. 5216-5221*		
16	*Decentralized model predictive control of dynamically-coupled linear systems: Tracking under packet loss*	*D. Barcelli and A. Bemporad*	*1st IFAC Workshop on Estimation and Control of Networked Systems*			*Venice, Italy*	*2009*	*pp. 204-209*		
17	*Synthesis of networked switching linear decentralized controllers*	*D. Barcelli, D. Bernardini, and A. Bemporad*	*Proceedings of the 49th IEEE Conference on Decision and Control*			*Atlanta, GA, USA*	*2010*	*pp. 2480-2485*		
18	*Decentralized hierarchical multi-rate control of constrained linear systems*	*D. Barcelli, A. Bemporad, and G. Ripaccioli*	*Proc. 18th IFAC World Congress*			*Milano, Italy*	*2011*	*pp. 277–283*		
19	*Decentralized hybrid model predictive control of a formation of unmanned aerial vehicles*	*A. Bemporad and C. Rocchi*	*Proc. 18th IFAC World Congress*			*Milano, Italy*	*2011*	*pp. 11900–11906*		
20	*Decentralized linear time-varying model predictive control of a formation of unmanned aerial vehicles*	*A. Bemporad and C. Rocchi*	*Proc. 50th IEEE Conf. on Decision and Control and European Control Conf.*			*Orlando, FL*	*2011*			
21	*Stabilizing model predictive control of stochastic constrained linear systems*	*D. Bernardini and A. Bemporad*	*IEEE Trans. Automatic Control*				*2011*			
22	*Energy-aware robust model predictive control based on noisy wireless sensors*	*D. Bernardini and A. Bemporad*	*Automatica*				*2011*			
23	*Stability analysis of stochastic networked control systems*	*M.C.F. Donkers, W.P.M.H. Heemels, D. Bernadini, A. Bemporad, and V. Shneer*	*Automatica*				*2010*			
24	*Output- Based Event-Triggered Control with Guaranteed L_\infty-gain and Improved and Decentralised Event- Triggering*	*M.C.F. Donkers and W.P.M.H. Heemels*	*IEEE Transactions on Automatic Control*				*To appear*			

25	A Discrete-time Framework for Stability Analysis of Nonlinear Networked Control Systems	N. van de Wouw, D. Nesic, W.P.M.H.Heemels	Automatica				2011			
26	An upper Riemann-Stieltjes approach to stochastic design problems	M. Heemels and A. Bemporad	Proc. 50th IEEE Conf. on Decision and Control and European Control Conf.			Orlando, FL	2011			
27	Stability Analysis of Networked Control Systems: A Sum of Squares Approach	N.W. Bauer, P. Maas and W.P.M.H. Heemels	49th IEEE Conference on Decision and Control				2010			
28	Periodic Event-Triggered Control based on State Feedback	W.P.M.H. Heemels, M.C.F. Donkers, and A.R. Teel	Proc. 50th IEEE Conf. on Decision and Control and European Control Conf.			Orlando, FL, USA	2011			
29	On the Minimum Attention and the Anytime Attention Control Problems for Linear Systems: A Linear Programming Approach	M.C.F. Donkers, P. Tabuada, and W.P.M.H. Heemels	Proc. 50th IEEE Conf. on Decision and Control and European Control Conf.			Orlando, FL, USA	2011			
30	Stability Analysis for Nonlinear Networked Control Systems: A Discrete-time Approach	N. Van De Wouw, D. Nesic and W.P.M.H. Heemels	49th IEEE Conference on Decision and Control				2010			
31	An Approach to Observer-Based Decentralized Control under Periodic Protocols	N.W. Bauer, M.C.F. Donkers, W.P.M.H. Heemels, N. van De Wouw	American Control Conference 2010			Baltimore, USA	2010	pp. 2125-2131		
32	Decentralized model predictive control of dynamically-coupled linear systems	A. Alessio, D. Barcelli, and A. Bemporad,	Journal of Process Control	Vol 21, No 5	Elsevier		June 2011	pp. 705-714		
33	Overlapping models merging for large-scale model management	P. Trnka and V. Havlena	IEEE Multi-Conference on Systems and Contro			Yokohama, Japan	2010			
34	Kalman filter for system with communication delay	L. Baramov, D. Pachner, V. Havlena	Proceedings of 1st IFAC Workshop on Network Estimation			Venice, Italy	Sept 2009			

			and Control NeCSys09							
35	*Suboptimal State Estimation under Communication Delays*	*D. Pachner, L. Baramov, and B. Havlena*	*IFAC Workshop on Time Delay Systems*			*Prague, Czech Republic*	*2010*			
36	*Closed-loop model reduction of parallel models*	*C. Sturk, P. Trnka, H. Sandberg, V. Havlena, and J. Rehor*	*Proc. 18th IFAC World Congress*			*Milan, Italy*	*2011*			
37	*Structured Model Order Reduction of Boiler-Header Models*	*C. Sturk and H. Sandberg and P. Trnka and V. Havlena and J. Rehor*	*Proc. 18th IFAC World Congress*			*Milan, Italy*	*2011*			
38	*Grey-box model identification - control relevant approach*	*J. !eho" and V. Havlena*	*IFAC Workshop on Adaptation and Learning in Control and Signal Processing*			*Antalya, Turkey*	*2010*			
39	*Application of Distributed MPC to Barcelona Water Distribution Network*	*P. Trnka and J. Pekar and V. Havlena*	*Proc. 18th IFAC World Congress*			*Milan, Italy*	*2011*			
40	*Decentralised MPC based on a Graph Partitioning Approach applied to the Barcelona Drinking Water Network*	*C. Ocampo-Martinez, V. Puig and S. Bovo*	*Proc. 18th IFAC World Congress*			*Milan, Italy*	*2011*			
41	*Tuning of Predictive Controllers for Drinking Water Networked Systems*	*R. Toro, C. Ocampo-Martinez, F. Logist, J. Van Impe and V. Puig*	*Proc. 18th IFAC World Congress*			*Milan, Italy*	*2011*			
42	*Operational Predictive Optimal Control of Barcelona Water Transport Network*	*J. Pascual, J. Romera, V. Puig, R. Creus, M. Minoves*	*Proc. 18th IFAC World Congress*			*Milan, Italy*	*2011*			
43	*Multi-Rate Decentralized MPC Strategy for Drinking Water Networks: Application to the Barcelona Case Study*	*C. Ocampo-Martinez, V. Puig and S. Montes de Oca*	*10th International Conference on Hydroinformatics*			*Hamburg, Germany*	*2012*			
44	*Model Predictive Control of Drinking Water Networks: A*	*C. Ocampo-Martínez, V.*	*Proceedings of American Control*			*Baltimore, USA*	*2010*			

	Hierarchical and Decentralized Approach	*Fambrini, D. Barcelli, V. Puig*	*Conference*							
45	*Cooperation and Learning in Distributed MPC of Large Scale Systems: the MAMPC Architecture*	*V. Javalera, B. Morcego, V. Puig*	*Proceedings of American Control Conference*			*Baltimore, USA*	*2010*			
46	*A Multi-Agent MPC Architecture for Distributed Large Scale Systems*	*V. Javalera, B. Morcego, V. Puig*	*Proceedings of International Conference on Agents and Artificial Intelligence*			*Valencia, Spain*	*2010*			
47	*Decentralized Model Predictive Control of Drinking Water Networks using an Automatic Subsystem Decomposition Approach*	*D. Barcelli, C. Ocampo-Martínez, V. Puig, A. Bemporad*	*Proceedings of IFAC Large Scale Systems Conference*			*Lille, France*	*2010*			
48	*Distributed MPC for Large Scale Systems using Agent-based Reinforcement Learning*	*V. Javalera, B. Morcego, V. Puig*	*Proceedings of IFAC Large Scale Systems Conference*			*Lille, France*	*2010*			
49	*Partitioning Approach oriented to the Decentralized Predictive Control of Large-Scale Systems*	*Ocampo-Martínez, C., Bovo, S., Puig, V.*	*Journal of Process Control*		*Elsevier*		*In press*			
50	*Hierarchical and Decentralised Model Predictive Control of Drinking Water Networks: Application to the Barcelona Case Study*	*C. Ocampo-Martinez, D. Barcelli, V. Puig and A. Bemporad*	*IET Control Theory & Applications*				*In press*			
51	*Approach oriented to the Decentralised Predictive Control of Large-Scale Systems.*	*C. Ocampo-Martinez, S. Bovo and V. Puig*	*Journal of Process Control*	*Vol 21, No 5*			*2011*	*pp. 775-786*		
52	*Scenario-based model predictive control of stochastic constrained linear systems*	*D. Bernardini and A. Bemporad*	*Proc. 48th IEEE Conf. on Decision and Control*				*2009*	*pp. 6333-6338*		

A2: LIST OF DISSEMINATION ACTIVITIES								
NO.	Type of activities[4]	Main leader	Title	Date	Place	Type of audience[5]	Size of audience	Countries addressed
1	*PhD school*	*UNISI*	*WIDE PhD School on Networked Control Systems*	*July 7-9, 2009*	*Department of Information Engineering, University of Siena*	*PhD students*	*53*	
2	*Two invited sessions at the joint Conference on Decision and Control and European Control Conference 2011*	*TUE, KTH*	*Recent Advances in Event-Triggered Control*	*2011*	*Orlando, Fl, USA*	*Scientific Community*		
3	*Invited session at the American Control Conference 2010*	*TUE,*	*Stability and Stabilisation of Networked Control Systems*	*2010*	*Baltimore, USA*	*Scientific Community*		
4	*Invited session at the European Control Conference 2009*	*KTH, TUE*	*Wireless control systems,*	*2009*	*Budapest, Hungary*	*Scientific Community*		
5	*Invited session at the European Control Conference 2009*	*TUE, KTH*	*Event-Triggered Sampling and Control*	*2009*	*Budapest, Hungary*	*Scientific Community*		
6	*Teleconference*	*HPL*	*End-user panel meeting*	*June 23, 1010*		*WIDE Consortium, Industrial panel*	*13*	

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.
[5] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias ('multiple choices' is possible.

7	*Teleconference*	*HPL*	*End-user panel meeting*	*June 8, 2011*		*WIDE Consortium, Industrial panel*	*12*	
8	*Workshop at the 18th IFAC World Conference*	*IMTL, UNITN*	*WIDE Final Workshop*	*August 27, 2011*	*Milan, Italy*	*Scientific Community*		