1 Publishable summary

General Project Description and Objectives

Advances in electronics, sensors, communications and embedded systems permit the *easy, cost-efficient and rapid installation of Large-Scale Control Systems (LSCSs)* in a wide variety of applications ranging from transport, power, communication and irrigation networks of several hundred nodes to biomedical and micro- and nano-engineering applications involving thousands of sensing and actuation elements. However, despite the existence of powerful technological solutions that permit the easy and cost-efficient installation of LSCSs, existing LSCS design methodologies require *that significant amount of effort, time and consequently cost, be devoted for deployment of the LSCS. D*espite intensive efforts by control engineers to optimize (calibrate) LSCS operations, the vast majority of LSCSs operate far from their optimal level, being – in many cases – unable to efficiently cope with system variations, stochastic user behavior and changing environmental conditions; even worse, there are many reported cases where the LSCSs totally fail or collapse in case of major faults or incidents: predominant examples of such cases being energy blackouts (e.g. 14th of August 2004 in the U.S and Canada and 23rd of July 2007 in Barcelona, Spain), severe grid-locks that frequently occur in most controlled urban traffic networks and severe floods or water waste problems in irrigation and sewage network systems that occurred due to failure of the respective LSCS to efficiently manage water levels at different points on the network.

These shortcomings of existing LSCS designs not only lead to *a costly operation of LSCSs* – as in most cases the respective authorities and operators are forced to employ large teams of engineers to monitor, calibrate and, quite often, bypass the LSCS decisions in their attempt to improve their efficiency and avoid unsafe or catastrophic situations, – but perhaps most importantly, *prevent the wide deployment and operation of LSCSs in areas and applications where they could potentially have a tremendous effect* in improving system efficiency and Quality of Services (QoS), reducing energy consumption and emissions, and improving the day-to-day quality of life. Examples of such application areas include, but are not limited to: traffic control systems that in their vast majority employ fixed-time (non-feedback) strategies; irrigation and sewage networks as well as sensor and communication networks where only a small fraction of existing systems use advanced feedback control systems to optimize their operations; energy consumption control systems at the building- and neighborhood-level that employ primitive control logic; and last, but not least, mobile-agent/sensor systems that still have a long way to go before challenging control tasks such as surveillance coverage and exploration of unknown environments can be effectively addressed.

The inability of existing LSCS designs to enjoy a broad applicability in real-life large-scale applications and, in essence, to convince large-scale system authorities and operators to adopt them is, as already mentioned, not due to the lack of technological tools for the implementation of LSCS' infrastructure. The limited adoption of LSCS is due to their inability to provide convincing solutions *essentially due to the lack of theoretical and practical designs and tools to efficiently deal with large-scale applications involving*:

- highly nonlinear phenomena,
- system uncertainties and variations,
- faults, atypical system behavior or need for major changes in the large-scale system's performance, as well as,
- constraints related to performance, safety, QoS, Resource Use (Re-Use), computational and communication requirements, etc.

Even worse, there is a lack of theoretical and practical designs that are able to provide *rapid and modular* LSCS design: major faults and incidents, frequent changes in the performance requirements, addition/removal of control nodes, etc, frequently call for major re-design (re-configuration) of the LSCS;

such a re-design has to be accomplished, in most cases, in a rapid manner in order not to allow for unstable, unsafe or even catastrophic system behavior while the LSCS is being re-configured.

Developing theoretical and practical designs that address the issues described in the previous paragraph (i.e. capable of providing efficient, rapid and modular LSCS design) is a necessary but not sufficient condition for these designs to accept a wide and rapid deployment: such designs must be additionally easily "transferable" into existing SCADA (Supervisory Control And Data Acquisition) and DCS (Distributed Control Systems) systems to allow for their implementation within today's control infrastructure technology. Additionally, these designs – appropriately embedded within SCADA/DCS – must be able to provide the LSCS' operators and users with "easy-to-understand" and "easy-to-operate" tools that are capable of "translating" complex, high-dimensional attributes describing the large-scale system state, constraints and evolution into quantities and play-buttons that are easy to be comprehended and tuned by the system operators and users. Even if theoretical and practical LSCS designs are developed that successfully address the issues mentioned in the previous paragraph, it is most likely that these designs will remain a useful tool only to their investors if they are not easily transferable to today's SCADA/DCSs and they do not provide the LSCS operators and users with user-friendly tools where they could easily enter and test a variety of constraints and requirements, monitor the large-scale system status, and easily and quickly re-design and re-configure the LSCS.

Based on a variety of methodologies (ingredients) developed, analyzed and evaluated by the AGILE partners recently, AGILE attempts to provide a *holistic and integrated LSCS methodology and design* that successfully addresses the open challenges, described in the previous two paragraphs. These open challenges (categorized as Key Issues 1, 2 and 3 in Table 1 below) along with the current-state-of-the-art, the AGILE ingredients and the proposed approach to be adopted within AGILE are briefly described in Table 1. As already mentioned, the AGILE S&T endeavor will build upon existing tools and methodologies recently developed in the past by the AGILE partners. These tools and methodologies will be appropriately extended, enhanced, and integrated within AGILE in the aim of developing, testing and evaluating a generic LSCS design system (delivered in software form similar to linear control toolboxes along with appropriate interfaces for embedding it into SCADA/DCSs) that will be capable of providing scalable and modular, rapidly self-tuning and self-reconfiguring, proactive and arbitrarily-close-to-optimal LSCS design for large-scale nonlinear systems of arbitrary scale, heterogeneity and complexity.

Table 1. Fundamental key issues required to be addressed towards the wide and rapid deployment of LSCSs

Key Issue 1: Given

- the nominal model of the large-scale system dynamics,
- the physical, performance, safety, QoS, Re-Use, computational and communication requirements and constraints,
- possible faults and incidents that are currently present
- as well as future predictions of the exogenous factors affecting the system;

provide a scalable control design that proactively schedules the LSCS actions so that its performance is – as close as desired to – the optimal LSCS.

State-of-the-art

Key issue 1 has been successfully addressed only in the case the large scale system admits linear or linear-like (e.g. feedback linearizable) dynamics and no state or control constraints are present. The presence of nonlinearities and/or state or control constraints typically results in control designs that are either sub-optimal or infeasible to be realized in real-time due to heavy computational requirements (NP-complete realizations).

AGILE Existing Ingredients

ConvCD (Convex Control Design), an approach proposed by AGILE partners, transforms (approximately) the problem of optimal LSCS design – for general nonlinear systems that are subjected to various physical, performance, safety, QoS, Re-Use, etc requirements and constraints – into a convex optimization problem (quadratic optimization function subject to linear and convex semi definite constraints). The performance of the resulting LSCS can be made arbitrarily close to that of the optimal LSCS by implementing scalable LSCSs (e.g. LSCSs comprising smoothly switching linear controllers).

Progress beyond the state-of-the-art required

- Despite the fact that ConvCD provides a convex optimization approach for the design of LSCS, the use of available optimization tools for ConvCD results in control designs whose completion requires a significant portion of computational time. Special optimization methodologies and software techniques have to be developed that quickly complete ConvCD-based LSCS designs. This requirement is crucial in order to enrich ConvCD-based designs with self-tuning, fault-recovery and re-configuration capabilities using the methodologies described under Key Issue 2 below.

- ConvCD is based on state-space optimal control formulation: its basic philosophy is to “convert” appropriately defined nonlinear optimal control problems into static convex optimization ones. As a result, it is not able to incorporate requirements and constraints (e.g. controller bandwidth, robust margins, disturbance rejection, presence of system delays, etc) that can be successfully handled using linear designs (e.g. H_∞ or μ-tools). Theoretical and practical tools need to be developed in order to incorporate such requirements and constraints within ConvCD; this will be made possible by appropriately marrying ConvCD with the MMACM (Multi-Mode Adaptive Control with Mixing), an approach proposed and analyzed by AGILE partners, which – although highly nonlinear – is capable of incorporating requirements and constraints handled by linear designs.

- ConvCD, at its present form, cannot incorporate future predictions of the exogenous factors affecting the large-scale system dynamics – a prerequisite for efficient proactive LSCS performance. Appropriate mechanisms for incorporating such future predictions within ConvCD should be developed and evaluated.

Key Issue 2: Assuming that Key Issue 1 has been successfully addressed, provide a computationally efficient methodology that:

- quickly detects and identifies variations and changes in the nominal system dynamics and exogenous factors as well as
- faults and atypical system behavior and
- rapidly, safely and efficiently re-designs (or even re-configures) the LSCS to effectively achieve its mission.

State-of-the-art

A variety of designs based on system identification, robust parameter adaptive estimation and/or computational intelligence tools have been developed in the past that can efficiently and quickly detect and identify system variations and uncertainties as well as faults and atypical system behavior. However, when these designs are incorporated within the control-loop (i.e. when they are used in real-time for the re-design of the LSCS) they possess two severe drawbacks that prohibit their applicability in real-life large-scale applications:

- they may lead to poor transient performance of the closed-loop large-scale system;
- most importantly, they may face the so-called “loss-of-stabilizability” problem - see section 1.2 (subsection: Embedding LSCS with …) for a brief description of this problem - in which case the large-scale system may enter an unstable, unsafe or even catastrophic behavior.

AGILE Existing Ingredients

AdaptST (Adaptive, automated, safe, Self-Tuning), an approach proposed by AGILE partners, has managed to overcome the problems of poor transient performance and loss-of-stabilizability mentioned above. AdaptST – combined with ConvCD – provides a self-tuning and self-reconfiguring LSCS design that efficiently, safely and rapidly takes care of system uncertainties and variations as well as faults, atypical system performance or call for major changes in the large-scale system performance requirements. The approach is applicable to large-scale systems of arbitrary complexity, scale and heterogeneity and guarantees that the large-scale system will preserve no poor transients or unsafe/unstable performance while self-tuning or self-reconfiguration are active.

Progress beyond the state-of-the-art required

- AdaptST requires that the convex optimization problem involved in ConvCD is solved at each controller time-step, a requirement that renders the implementation of AdaptST prohibitive in most large-scale applications. To overcome this problem, AGILE will develop a hybrid self-tuning, self-reconfiguring scheme: MMACM (which employs standard robust parameter adaptive estimation algorithms) is employed at each controller-time step; as MMACM may face poor transient or loss-of-stabilizability problems, AdaptST is being activated only and whenever MMACM faces such problems. Such a hybrid scheme is expected to overcome the heavy computational requirements involved when AdaptST is employed as a standalone system, while preserving efficient, safe and rapid self-tuning and self-configuring performance.
- AdaptST, in its current form, does not incorporate mechanisms for fault-detection and recovery. Combination of the above-mentioned hybrid adaptive scheme with standard identification-based fault-detection and recovery methodology will be developed in this project for embedding within the AGILE system fault-detection and recovery capabilities.
- AdaptST (even as part of the hybrid scheme mentioned above) requires the employment of high-bandwidth controllers. Appropriate enhancements of AdaptST need to be developed within AGILE, in order to come up with modified AdaptST schemes that meet the controller bandwidth requirements imposed at most of real-life large-scale applications.

<u>Key Issue 3</u>: For LSCS designs addressing Key Issues 1 and 2, provide appropriate tools & interfaces that allow

- the straightforward deployment of these LSCS designs into today's SCADA/DCSs and
- the users and operators of LSCSs to easily incorporate, modify and experiment with a variety of performance requirements and constraints as well as monitor the LSCS performance.

State-of-the-art

Today's open architecture SCADA/DCSs provide powerful tools for the design, deployment and operation of LSCSs of arbitrary scale, complexity and geometry while providing the users and operators with user-friendly tools and interfaces for the design and monitoring of LSCSs. However, with the exception of <u>application-specific</u> SCADA/DCS, the majority of existing SCADA/DCSs embed linear-based or simplified rule-based control design logics, being incapable of incorporating complicated control designs to successfully address Key Issues 1 and 2 (unless, special application-specific interfaces are developed which, however, require a considerable amount of time and effort to be completed). Moreover, the aforementioned SCADA/DCSs are not able to incorporate many significant performance requirements and constraints, due to the inability of the control designs embedded in them to deal with such requirements and constraints.

AGILE Existing Ingredients

Most of AGILE partners have had a rich experience in the development of SCADA/DCSs for application-specific LSCSs (i.e. traffic and transport control systems, sewer and irrigation network control systems, energy and power distribution control systems) or generic LSCSs (e.g. the SCADA and DCSs developed by SICE and SIE).

Progress beyond the state-of-the-art required

Combine the experience of AGILE partners in the development of SCADA/DCSs for LSCSs towards the development of all necessary software tools and interfaces to:

- allow a straightforward implementation of the AGILE system within most of today's open-architecture SCADA/DCSs, and
- facilitate – in an "easy-to-use" and "easy-to-understand" manner – the users and operators of SCADA/DCSs in incorporating a rich variety of performance requirements and constraints. These requirements and constraints will include – but will not be limited to – QoS and Re-Use performance requirements and constraints, steady state, worst-case and settling time performance requirements, bandwidth and robust margins requirements, communication and decentralization constraints, real-time requirements, state and control constraints, etc.

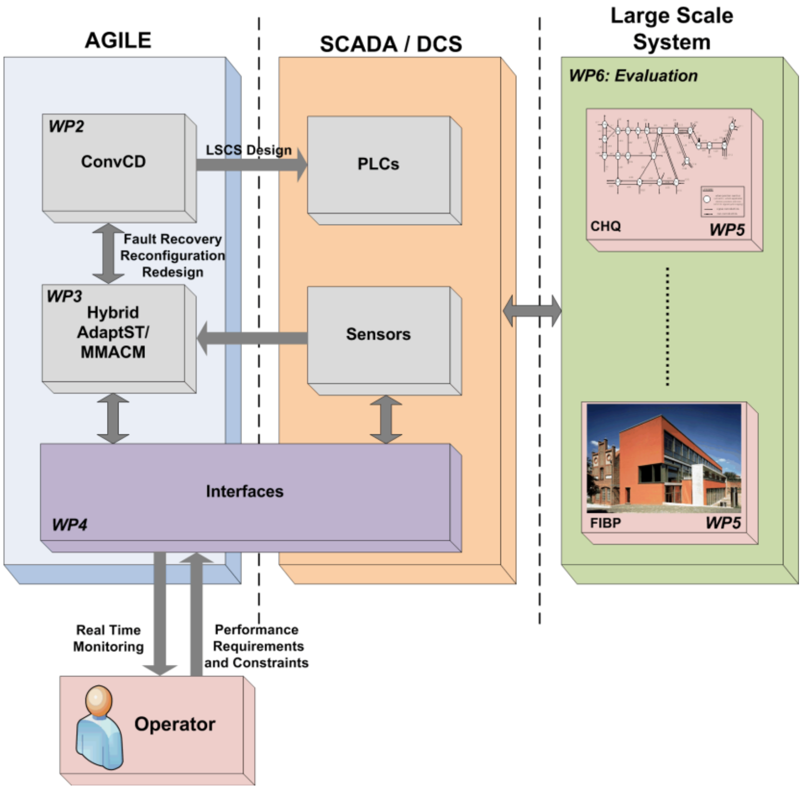


Figure 1. *The AGILE System.*

Apparently, all the advances mentioned above require several steps before they are fully developed into a generic system that can be broadly employed in real-life nonlinear large-scale control applications. First of all, all necessary theoretical tools have to be developed and their efficiency and other required properties (arbitrarily-close-to-optimal performance, robustness, self-tuning and self-reconfiguring capabilities, etc) have to be analyzed and justified using strict and rigorous mathematical tools. Moreover, extensive simulation experiments on particularly challenging nonlinear large-scale systems have to be performed leading, if necessary, to modifications of the original theoretical designs.

However, real-life large-scale systems include a number of partly unpredictable phenomena, such as sensor/communication/controller failures, peculiar demand and environmental changes, atypical operation phases and, most-importantly, end-user stochastic behavior that are likely to challenge the developed approach as to ensure a reliable and efficient operation under all practical conditions. Furthermore, the developments pursued can only enjoy broad employment and utilization, if they have been successfully applied *under real conditions*. These remaining challenges call for a combined effort at a European level that comprises advanced methodological developments, generic software tools and interfaces, real-life large-scale systems and common evaluation procedures. If project developments can be *tested and verified under real-world conditions*, the outcome of this effort would be the development of a generic methodology applicable to a broad variety of nonlinear large-scale systems. The generality of the proposed methodology affords a universality that transcends regional, behavioral, environmental or other variations. For this reason, the AGILE system will be demonstrated and evaluated in two different real-life nonlinear large-scale systems possessing a rich variety of design and performance characteristics, extremely complex nonlinear dynamics, highly stochastic effects, uncertainties and modeling errors, as well as reconfiguration and modular design requirements. More precisely, the AGILE system will be implemented, tested and evaluated at the following two real-life systems:

1. **Urban traffic control** (City of Chania urban network. Location: Chania, Greece): The first AGILE test case is related to the design, testing and evaluation of AGILE LSCS for controlling – in real-time – the

traffic light signal settings of the urban traffic network of the city of Chania, Greece. The particular large-scale system comprises 23 junctions, more than 100 control inputs (traffic light signal settings), around 200 sensor measurements (measuring traffic flow and occupancy at the network's links) and is subject to highly nonlinear and discontinuous dynamics (mostly due to the on-off behavior of the traffic lights) as well as stochastic traffic demand patterns. *Re-configurability, fault-recoverability, self-tuneability* in conjunction with *scalable and pro-active, nearly-optimal design for highly nonlinear and discontinuous dynamics* are they key issues that AGILE will have to face in *this particular application* in order to come up with an efficient LSCS design that will be able to provide *substantial reductions in congestion levels, travel times, fuel consumption and pollutants emission.*

2. **Control of an Energy-Positive Building** (The Centre for Sustainable Building. Location: Kassel, Germany). The second AGILE test case will address the recently introduced problem of controlling Energy-Positive Buildings (EPBs), a quite challenging from a controls-point of view problem. As typical in EPBs, the particular building is equipped with a variety of renewable self-generation energy systems (solar arrays, wind turbines and geo-thermal soil collector) and a variety of different control elements (HVACs, automatically-controlled shading devices and natural-ventilation systems, floor heating and cooling systems) at each of the building's rooms. *Scalable and highly-reconfigurable and modular over a variety of heterogeneous control and generation elements, pro-active over long time-periods (>10 hours), nearly-optimal design for highly nonlinear dynamics involving strict constraints and large variations of exogenous factors (e.g. weather, occupants' behaviour) are they key issues that AGILE will have to face in this particular application* in order to come up with an efficient LSCS design that will be able to provide *substantial reductions in non-renewable energy consumption while maintaining user safety, satisfaction and comfort*.

It has to be emphasized that for both AGILE's test cases, the overall control infrastructure has already been installed and thus no budgetary requirements exist for the installation of additional or new control-related infrastructures.

For each of the component development activities undertaken on Y1 of the Project the main objectives and results are presented below:

Proactive, Arbitrarily-Close-to-Optimal, Scalable LSCS Design (WP2)

WP Objectives

The objective of this work package is to develop all the necessary theoretical and software tools that will enable the ConvCD-based proactive, nearly-optimal, scalable LSCS design for general large-scale systems.

Description of the Work Performed Since the Beginning of the Project

As the basis for the development of proactive, arbitrarily-close-to-optimal and scalable LSCS design, the ConvCD (Convex Control Design) approach developed by CERTH in the past, has been used. Contrary to the other existing approaches, the ConvCD methodology does not require a time-consuming off-line design: *ConvCD converts the problem of constructing an Approximately Optimal Controller (AOC) into a convex optimization problem* and as a result it allows for the employment of computationally efficient methodologies for providing AOC designs. Such a "conversion" is made possible by combining approximation tools, Semi-Definite Programming (SDP) optimization principles and the concept of Control Lyapunov Function (CLF). Moreover, the ConvCD approach *allows for its straightforward interconnection with self-tuning/adaptation tools employed to compensate for internal/external system variations and uncertainties*. The convex nature of ConvCD guarantees that such an interconnection can be performed without getting trapped into local minima situations. Moreover, the overall adaptation can be done by avoiding singularities (loss-of-controllability problems) and therefore computational and instability issues.

Within WP2, the ConvCD approach has been revised in several ways towards the development of a generic and practically implementable tool that can be used for the LSCS design of general nonlinear and uncertain large-scale nonlinear systems.

- Firstly, the ConvCD approach has been revised so that it can ***incorporate a variety of physically-imposed constraints*** such as limited control constraints as well as any type of constraint that takes the form of a nonlinear function of the system states or outputs and controls (please note that the later type of constraints include as a special case "if-then-else" rule-based constraints which are usually met in the majority of practical control applications).
- Furthermore, the ConvCD approach has been revised so that it is able to cope with the case of ***output feedback control***, i.e., the case where the system states are not available for measurement but a lower dimensional and possibly nonlinear mapping of the system states.
- Most importantly, the **ConvCD approach has been updated so that it employs Multi-Model Control with Mixing (MMCM),** i.e., *a controller that comprises of linear or nonlinear smoothly-switching elements*. This is contrast to the original ConvCD approach which was employing polynomial control elements. There are several advantages when employing MMCM instead of controllers comprising polynomial elements:
    - First of all by employing MMCM the overall LSCS scheme is **scalable** (its computational requirements are about the same as those of a linear controller), without sacrificing efficiency.
    - Moreover and as ConvCD employs SemiDefinite Programming (SDP) optimization tools, **the size of the SDP-related matrices remains at the same order as the system dimension** (total dimension of system states and controls). This is in contrast to the original version of ConvCD (polynomial-based ConvCD), where the size of the SDP-related matrices is increasing exponentially with the system dimension. It is worth noticing that the size of the SDP-related matrices dominates the computational complexity of the problem: the computational speed of existing SDP solvers depends mostly on the size of these matrices and, moreover, most of these solvers cannot handle SDP-related matrices with sizes larger than 2000-3000 (unless they are

sparse or of some other special-type structure). As a result, using the approach proposed here for an LSCS design requiring 2nd-order polynomial control elements, the maximum size for the system dimension is around 40-50, whereas using the polynomial-based ConvCD approach, it can grow up to 2000-3000.

- Also, the use of MMCM oversimplifies the use of self-tuning/adaptation tools employed to accommodate system uncertainties and variations. Due to the use of MMCM within convCD, these tools **share a similar complexity (and properties) as those of standard adaptive tools for linear systems**.
- Finally, the ConvCD approach has been revised so that it can handle the case where exogenous but predictable factors (such as daily weather, occupants' activity and traffic demand for the AGILE Test Cases) affect the system dynamics by incorporating **predictive models** of the exogenous factors within the ConvCD approach.

Apart from the above-mentioned theoretical advances, a **fully-operational software module** tool was developed and tested in various different applications of small- and medium-scale. Using such a software module

1. The user defines the
   a. Large-control system dynamics that assume a PieceWise Linear (PWL) or PieceWise NonLinear (PWNL) form. It has to be emphasized at this point that PWL or PWNL forms can approximate the actual system dynamics to any degree of accuracy.
   b. The objective function to be minimized that assumes a PieceWise Quadratic (PWQ) or PieceWise Sum-Of-Squares (PW-SOS) form. It has to be emphasized at this point that PWQ or PW-SOS forms can approximate any given objective to any degree of accuracy.
   c. Limited control constraints as well as any type of constraint that take the form of a nonlinear function of the system states or outputs and controls.
   d. ConvCD design parameters.
2. The software returns an MMCM controller (i.e., a PWL or PWNL controller) along with an estimate of the performance of the closed-loop system at different operating conditions (states). Such an estimate is provided in terms of the time-derivative of the Optimal-Cost-to-Go function as well as in terms on the accuracy achieved in approximately solving the HJB.

The results of this WP are described in Deliverables D2.1 (1st version) and D2.2 (final version).

Description of the Main Results Achieved

A theoretical as well as a software tool that can provide proactive, scalable, arbitrarily-close-to-optimal control design for <u>known</u> systems of arbitrary scale, heterogeneity and complexity and for a large class of requirements, constraints and objectives.

Expected final result and the potential impact and use

A tool addressing Key Issue 1 of AGILE i.e., given

- the nominal model of the large-scale system dynamics,
- the physical, performance, safety, QoS, Re-Use, computational and communication requirements and constraints,
- possible faults and incidents that are currently present
- as well as future predictions of the exogenous factors affecting the system;

this tool provides a scalable control design that proactively schedules the LSCS actions so that its performance is – as close as desired to – the optimal LSCS.

Embedding LSCS with Self-Tuning, Fault-Recovery and Re-Configuration Capabilities (WP3)

WP Objectives

The objective of this work package is to enhance the LSCS design tool of WP2 by embedding to it self-tuning, fault-recovery and re-configuration attributes.

Description of the Work Performed Since the Beginning of the Project

The work of this WP is to be finished within Y2. Within Y1, the following work has been performed as part of this WP:

- An overview of **existing fault-detection methodologies** and selection of the candidate methodologies to be used within the AGILE system.

  The findings of this work are summarized in Technical Note WP3_TN_FD.

- A system identification (system id) software tool is being developed and tested **for extracting (approximately) the system dynamics in PWL or PWNL form required by ConvCD**. The development of this system id tool is based on standard least-squares optimization and automatically calculates the optimal mixing signals (switching boundaries of PWL or PWNL approximations) as well as the optimal matrices of the PWL or PWNL approximations, given input-output data (that can correspond to either real-life data or be generated using an available simulation model of the large-scale system). This system id tool replaces the use of symbolic description of the system dynamics originally planned. The reasons for employing a system id tool instead of a tool involving symbolic manipulations are many:
  - First of all, describing large-scale system dynamics using symbolic tools is very cumbersome and in many cases is not feasible.
  - Moreover, processing the symbolic definitions of the system dynamics becomes prohibitive for systems of large-scale (unless supercomputer or other special processing equipment is employed).
  - Finally and more importantly, for most of the large-scale systems, reliable and quite elaborate and validated simulation models or, even, real-life measurement data are available. The generation of the ConvCD-compatible system description (using PWL or PWNL forms) can be straightforwardly extracted by the system id tool using these simulation models or real-life measurements.

  The details of the system id tool are described in Appendix A of Deliverable D2.2.

- The original idea of AGILE for developing an LSCS design tool with self-tuning, fault-recovery and re-configuration capabilities was by combining the convCD tool of WP2 with a hybrid scheme involving AdaptST (Adaptive Self-Tuning) with Multi-Model Adaptive Control with Mixing (MMACM). However, due to the new form and developments of ConvCD in WP2, a new scheme is being developed that
  - is capable of providing a computationally efficient LSCS design with self-tuning, fault-recovery and re-configuration capabilities and, moreover,
  - overcomes the main disadvantage of the originally proposed hybrid scheme, which is that it requires on-line ConvCD re-design.

  By exploiting the new ConvCD developments of WP2 **it was made possible to render the problem of LSCS design for systems involving system uncertainties, variations, faults and incidents and, in general, requirements for minor or major re-design or re-configuration as an optimal control problem involving adaptive estimators for estimating the system variations, faults, etc (adaptive optimal control problem), which in turn, can be solved using ConvCD.** In other words, the problem of designing an efficient and scalable control for large-scale systems involving uncertainties, variations, faults and incidents, etc can be rendered into a ConvCD-compatible format.

The details of this new scheme – in its current form – are described in section 6 of Deliverable D2.2. Please note that this scheme is still under development and will be finalized in Y2.

Description of the Main Results Achieved

- An overview of existing fault-detection methodologies and selection of the candidate methodologies to be used within the AGILE system.
- A software tool (still under development) for extracting (approximately) the system dynamics in the form required by ConvCD.
- A theoretical and software tool (still under development) for embedding the AGILE LCSC design with self-tuning, fault-recovery and re-configuration capabilities.

Expected final result and the potential impact and use

A tool addressing Key Issues 1 and 2 of AGILE i.e., given

- A large-scale system of arbitrary scale, heterogeneity and complexity
- the physical, performance, safety, QoS, Re-Use, computational and communication requirements and constraints,
- possible faults and incidents that are currently present
- system small-, medium- and long-term variations
- as well as future predictions of the exogenous factors affecting the system;

this tool provides a scalable control design that proactively schedules the LSCS actions so that its performance is – as close as desired to – the optimal LSCS and, moreover, provides with a computationally efficient methodology that:

- quickly detects and identifies variations and changes in the nominal system dynamics and exogenous factors as well as
- faults and atypical system behavior and
- rapidly, safely and efficiently re-designs (or even re-configures) – when needed – the LSCS to effectively achieve its mission.

Interfaces & Integration (WP4)

WP Objectives

The objectives of this WP are

- To specify in detail and develop the building blocks and interfaces that will render the AGILE system straightforwardly implementable within existing open-architecture SCADA/DCSs.
- To integrate within the two Test Cases SCADA/DCSs the AGILE system.

Description of the Work Performed Since the Beginning of the Project

The work of this WP is to be finished within Y2. Within Y1, the following work has been performed as part of this WP:

- The **"Performance requirements and constraints met in a variety of LSCS applications"** (M3) as well as **"the SCADA/DCS requirements"** from a variety of different LSCS applications have been identified and described.
- The **functional requirements** for interfacing the integrated AGILE system with SCAD/DCSs have been identified and described.
- Types of **performance requirements and constraints – which AGILE can efficiently and automatically address but – the existing LSCS designs embedded in SCADA/DCSs are not able to automatically or efficiently handle** have been identified and described.

The above requirements are described in Deliverable D.4.1.0.

- A methodology has been developed **for transforming performance requirements and constraints that are typically met in the majority of SCADA/DCS into a format that is compatible to the AGILE ConvCD (WP2)**. More precisely, this methodology – which uses elements from the theory of fuzzy systems – transforms linguistic and similar requirements, constraints and rules (typically met in real-life SCADA/DCS implementations as they are "easily" understood and handled by the operators) into optimization state/output/control constraints that can be straightforwardly embedded within ConvCD.

The findings of this work are summarized in section 5 of Deliverable D.4.1.0.

- The **implementation plan** for both Test Cases has been finalized.

The findings of this work are summarized in Technical Note WP4_TN_IP.

- An **external group** has been formed and their inputs were used for defining SCADA/DCS requirements (M9) as well as the definition of "Performance requirements and constraints met in a variety of LSCS applications". This external group will be enlarged as soon as the integrated AGILE system (along with simulation results evaluating its performance) is ready (within Y2).

The findings of this work are summarized in section 6 of Deliverable D.4.1.0

- Based on the above, the detailed specification and the development of all the building blocks and software modules that are required for interfacing the integrated AGILE system with existing open-architecture SCADA/DCSs is taking place and will be delivered in Y2 of the project. Please note that it is not AGILE's ambition to render the AGILE system directly interface-able to each and every of the existing SCADA/DCS but, by employing open-source principles, to make sure that the interfaces to be developed will allow the incorporation of AGILE's system in existing SCAD/DCSs at a minimum effort.

Description of the Main Results Achieved

All the necessary elements for interfacing AGILE with existing open-architecture SCADA/DCSs involving real-life LSCS implementations have been identified and described. Within Y2 of the project the detailed specification and the development of all the building blocks and software modules that are required for interfacing the integrated AGILE system with existing open-architecture SCADA/DCSs will be finalized and delivered.

Expected final result and the potential impact and use

A tool addressing Key Issues 1- 3 of AGILE i.e., given

- A large-scale system of arbitrary scale, heterogeneity and complexity
- the physical, performance, safety, QoS, Re-Use, computational and communication requirements and constraints,
- possible faults and incidents that are currently present
- system small-, medium- and long-term variations
- as well as future predictions of the exogenous factors affecting the system;

this tool provides a scalable control design that proactively schedules the LSCS actions so that its performance is – as close as desired to – the optimal LSCS and, moreover, provides with a computationally efficient methodology that:

- quickly detects and identifies variations and changes in the nominal system dynamics and exogenous factors as well as
- faults and atypical system behavior and
- rapidly, safely and efficiently re-designs (or even re-configures) – when needed – the LSCS to effectively achieve its mission.

and, moreover, provides the appropriate tools & interfaces that allow

- the straightforward deployment of the AGILE LSCS design into today's SCADA/DCSs and
- the users and operators of LSCSs to easily incorporate, modify and experiment with a variety of performance requirements and constraints as well as monitor the LSCS performance.

Test Cases (WP5)

WP Objectives

The objectives of this WP are:

1. to identify the functional and performance requirements and constraints for each of the AGILE's Test Cases;
2. to test via simulations the fully-functional real-time AGILE system for the two Test Cases;
3. the integration and validation of the overall AGILE system in the two Test Cases, and
4. to successfully implement the AGILE system at the two Test Cases using a monitoring procedure.

Description of the Work Performed Since the Beginning of the Project

Most of the work of this WP will be performed in Y2 and Y3 of the project. Within Y1, the following work has been performed as part of this WP:

- The **functional as well as performance requirements and constraints** imposed in the implementation of the AGILE system in the two Test Cases has been defined in a clear and detailed manner.

The findings of this work are summarized in Deliverable D.5.1

- The **SCADA system of Test Case 1** is a proprietary system not allowing the implementation of generic LSCS designs. For this purpose a software/hardware interface has to be developed that by-passes the existing proprietary SCADA system and allows the implementation of generic LSCS designs. The details of this interface have been finalized and the development and implementation of this interface will be finalized within Y2.
- The **SCADA system of Test Case 2** is currently under development – as part of the FP7 project PEBBLE – and will be delivered within Y2 of the project. Here, the complete control and monitoring system based on Sauter technologies is changed to a new system based on Saja technologies, which allows the implementation of the AGILE system without major revisions.

Description of the Main Results Achieved

- Definition of functional and performance requirements and constraints for the two Test Cases.
- Development and installation of the interfaces for implementing AGILE in the two Test Cases (to be delivered in Y2).

Expected final result and the potential impact and use

To successfully implement the AGILE system at the two Test Cases using a monitoring procedure in order to demonstrate the efficiency and applicability of AGILE to general LSCS applications

Evaluation/Impact (WP6)

WP Objectives

The objective of this WP is to evaluate the AGILE system regarding energetic, GHG emission, economic and comfort performance.

Description of the Work Performed Since the Beginning of the Project

- A **draft evaluation plan** has been developed and communicated to the partners. The objective of this draft evaluation plan is to define the basic procedures of the evaluation, the evaluation indicators to be used as well as the sensor measurements and other data that will be required for calculating and assessing these indicators. Regarding this work plan, the tasks during the first year of the project are focusing on the evaluation planning with respect to the demonstration building as well as the traffic system. For this, the building as well as the traffic system are described with specifications and technologies installed. With respect to the buildings, relevant norms and procedures are described to evaluate the energy and comfort performance, while, with respect to the traffic control system, norms and procedures are described to evaluate the effect of the new control system to travel times and fuel consumption. In addition, a procedure has to be developed to identify the improvement potential of the new control strategy developed in this project.

The findings of this work are summarized in Technical Note WP6_TN_EP

Description of the Main Results Achieved

- Delivery and communication of a Draft Evaluation Plan
- Agreement on the basic principles of the evaluation for the Two Test Cases

Expected final result and the potential impact and use

To evaluate the AGILE system regarding energetic, GHG emission, economic and comfort performance as well as its transferability to general LSCS applications.

Dissemintation and Exploitation (WP7)

WP Objectives

The objectives of this WP are

- To broadly disseminate the project results
- To successfully prepare the exploitation of new products.

Description of the Work Performed Since the Beginning of the Project

This work package consists of dissemination and exploitation activities. The objective of the dissemination activities is to:

- ensure a maximum awareness and visibility of the achievement and results of the project,
- make known new methodologies and technologies that could be obtained as a part of the project results and to encourage their use, and to
- promote use of the AGILE system.

The objective of the exploitation activities is to promote the advertisement and commercial valorization and use of the outcomes of the project, thus to successfully prepare the exploitation of the results.

Within this Work Package, the following 2 tasks have been planned:

Task 7.1: Dissemination Activities

In the following the tasks, which have been completed or improved, towards the objectives will be described. Those tasks have been setting up the deliverable "D7.2 – Initial Dissemination and Use Plan," the website, and the leaflet and are described in more detail, below.

Initial Dissemination and Use Plan

This deliverable describes the plans and strategies for the dissemination, promotion and exploitation of the results for the AGILE project. The market for the AGILE product is assumed to include developers and providers of all types of in-building sensors, control systems and interfaces as well as renewable energy systems for buildings for the two test cases.

First the dissemination plan, including a project logo, an internet presence, publications and participations at conferences is described. The exploitation activities are described next. They include activities "during" and "after the completion" of the AGILE project in regard to different market and use opportunities. A use plan is presented under consideration of different exploitation opportunities. (For further information, please refer to the deliverable "D7.2 – Initial Dissemination and Use Plan".

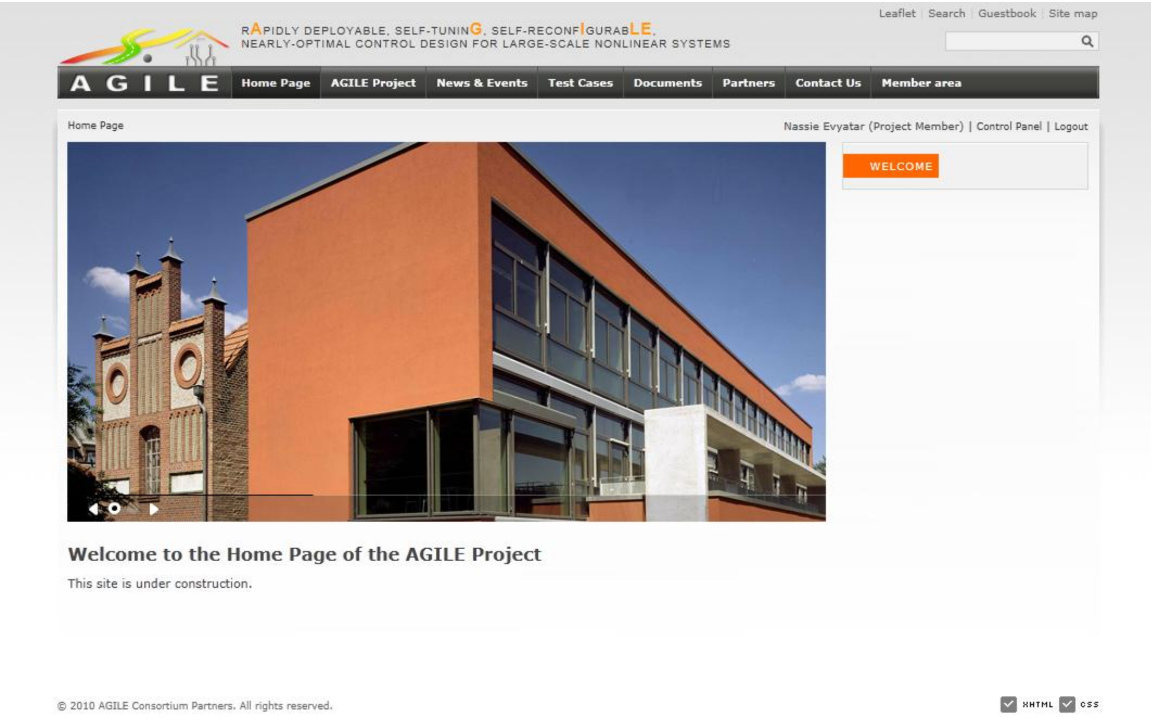
Project web site

The AGILE website is available under http://www.AGILE-fp7.eu (see Figure 2. AGILE public website).

The website consists of several sections which are briefly summarized below:

Home Page – which contain the two test case's pictures and:

- AGILE Project
    - Summary
    - Impact
    - Technical Approach
    - Work Packages
    - Project Info
- News & Events
    - News
    - Events
- Test Cases
    - Traffic Signal Control
    - Control of an Energy-Positive Building
- Documents
    - Leaflet
    - Deliverable
    - Scientific Papers
    - Conference Publications
    - Dissemination Materials
    - Other
- Partners
    - CERTH
    - UCY
    - PSU
    - AFCON
    - SICE
    - SIMENCE
    - FIBP
    - TCD – City of Chania
- Contact Us
- Member Area
    - File Manager
    - Forum
    - My Meetings
    - My Feeds
    - AGILE mailing list
    - Guestbook
    - User Control Panel
    - Logout



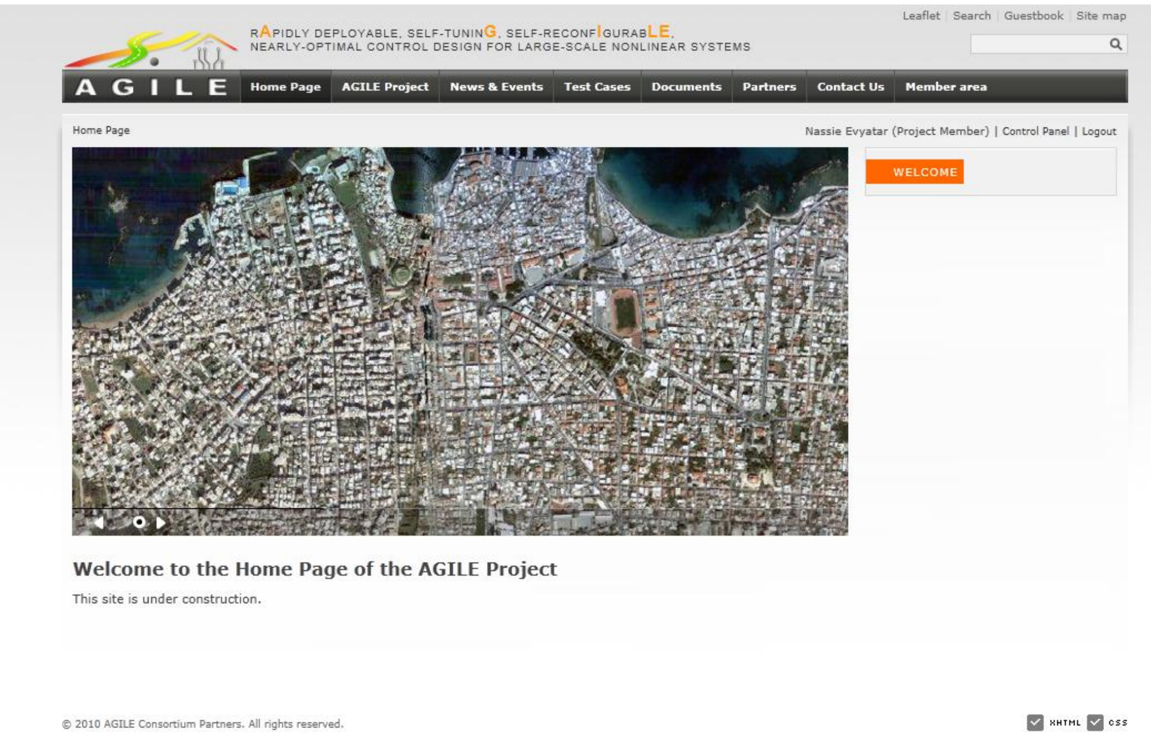


Figure 2. AGILE public website

By using the website, the public is able to get a broad insight into the AGILE project, including technical issues, the project consortium as well as information about the two test cases. The leaflet is downloadable. Actual news and events will announce by CSS technology. Moreover the member's area gives the possibility of interaction to the consortium – deliverables, forum, feedback etc.

Today, the site is still in construction, thus, some changes will take place in the future.

Beside the AGILE Information Leaflet (see Figure 3. AGILE Information Leaflet) can be downloaded.

Leaflet

As seen in Figure 3. AGILE Information Leaflet covers the most important point of the project. It can be used for advertisement activities and can serve as a giveaway at open house fair.

Networked Embedded and Control Systems

RESEARCH PROJECTS

AGILE

RApidly-deployable, self-tuninG, self-reconfIgurabLE nearly-optimal control design for large-scale nonline: systems

To develop and demonstrate an automated tool that: (a) provides self-tunable, se reconfigurable, modular, scalable and nearly-optimal control design for gene nonlinear systems of arbitrary scale, heterogeneity and complexity (b) straightforward to implement in existing open-architecture SCADA/DC infrastructures.

At A Glance: AGILE

RApidly-deployable, self-tuninG, self-reconfIgurabLE, nearly-optimal control design for large-scale nonlinear systems

Project Coordinator
Name: Elias Kosmatopoulos
Institution: Center for Research and Technology - Hellas
Email: kosmatop@iti.gr

Project Website:
http://www.agile-fp7.eu/

Partners:
Centre for Research and Technology–Hellas (GR)
University of Cyprus (CY)
The Pennsylvania State University (USA)
AFCON Software and Electronics Ltd (IL)
Sociedad Iberica de Contsrucciones Electricas SA (ES)
Siemens AE Electrotechnical Projects & Products (GR)
Fraunhofer Institute for Building Physics (DE)
Traffic Control Department – Chania (GR)

Duration: *36 months*
Start: *2010.09.01*
Total Cost: € *1.878.163*
EC Contribution: € *1.299.094*
Contract Number: INFSO-ICT-257806

Main Objectives

1. Provide the control designer with a systematic a automated tool capable of designing efficient Large-Sca Control Systems (LSCS) for *general nonlinear large-sca systems of arbitrary scale, heterogeneity and complex* The AGILE system will allow the control designer incorporate a *rich variety of physical and performan requirements and constraints.*
2. Provide a scalable/modular LSCS design. This will made possible by focusing on LSCS comprising smoot switching linear controller which possess minimu computational requirements. Moreover, given t performance requirements, constraints and objectives provided by the control designer, the AGILE tool will prov de the control designer with a scalable LSCS design that can be made as close as desired to the optimal LSCS without sacri-ficing scalability and efficiency.

AGILE aims at providing a scalable, self-tunable/reconfigurable design for complex Large-Scale Control Systems that achieves nearly-optimal performance

3. The AGILE design will be enhanced with automat self-tuning properties rendering it capable to rapid robustly and safely operate under uncertainties a modeling errors in the nominal large-scale syste dynamics as well as medium and long-term syste variations. The very same properties will embed within t AGILE design rapid fault-recovery and se reconfigurability attributes whenever significant chang and faults call for a major reconfiguration of the LS design.
4. Provide all necessary tools and interfaces that will all the straightforward implementation of the AGI system within most of today's open-architect SCADA/DCSs, and facilitate the users and operators these systems in incorporating a rich variety performance requirements and constraints.
5. Implement and evaluate the developed system in t real-life large-scale applications (test cases) duri their ordinary, everyday operation: Urban Traffic Cont (UTC) in the network of Chania, Greece and Control of Energy-Positive Building (EPB) in Kassel, Germany.

Key Issues

The following three Key Issues have been identified by the AGILE consortium as essential and crucial towards the successful accomplishment of the AGILE objectives:
Key Issue 1: Given
- The nominal model of the large-scale system;
- The physical, performance, safety, QoS, Re-Use, communication, etc, requirements/constraints;
- Possible faults and incidents currently present;
- Future predictions of exogenous factors;

provide a scalable control design that proactively schedules the LSCS actions so that they are – as close as desired to – the optimal (nearly-optimal).
Key Issue 2: Assuming that Key Issue 1 has been successfully addressed, to provide a computationally efficient methodology that:
- Quickly detects and identifies system variations, faults and atypical behavior and
- Rapidly and safely re-designs (or even re-configures) the LSCS in a nearly-optimal fashion.

Key Issue 3: For LSCS designs addressing Key Issues 1 and 2, to provide appropriate tools & interfaces that allow
- the straightforward deployment of these LSCS designs into today's open-architecture SCADA/DCSs and
- the operators of LSCSs to easily incorporate a variety of performance requirements and constraints.

Technical Approach – Ingredients

AGILE's approach to address the 3 Key Issues is based on appropriately combining, extending and integrating the following AGILE's "ingredients":
1. *ConvCD (Convex Control Design)* that transforms the problem of nearly-optimal LSCS design – for general nonlinear systems that are subjected to various requirements and constraints – into a convex optimization problem. The performance of the resulting LSCS can be made arbitrarily close to the optimal LSCS by implementing scalable LSCSs.
2. *AdaptST (Adaptive, automated, safe, Self-Tuning)* that has managed to overcome the problems of poor transient performance and loss-of-stabilizability that are present in the majority of adaptive, self-tuning and re-configurable LSCS designs. AdaptST is applicable to large-scale systems of arbitrary complexity, scale and heterogeneity. AdaptST requires that the convex optimization problem involved in ConvCD is solved at each controller time-step, a requirement that renders the implementation of AdaptST prohibitive in most large-scale applications. To overcome this problem, AGILE will develop a hybrid self-tuning, self-reconfiguring scheme that combines AdaptST with *MMACM (Multi-Mode Adaptive Control with Mixing).*
3. The rich experience of AGILE partners in developing SCADA/DCSs for LSCSs together with the fact that the previous 2 AGILE ingredients allow for the easy incorporation of a wide variety of complicated performance requirements and constraints, will allow for the development of interfaces that are easily connected with existing open-architecture SCADA/DCSs; moreover, all appropriate actions will be taken within AGILE so that performance requirements, rules and settings that are embedded within already operating SCADA/DCS are "extracted" to the AGILE system and are converted into AGILE-compatible performance requirements and constraints.

Expected Impact

A successful outcome of AGILE will lead to a next generation meta-system capable of *"automagically"* creating, deploying and fine-tuning SCADA/DCS controllers for a wide variety of large-scale applications. The 2 AGILE test cases will serve to illustrate the benefits of such a next-generation meta-system. The *1st test case*, (UTC), is an archetypal example of a large-scale system. Directly expected impacts are lower-travel times and consequently lower fuel consumption and emissions, and overall better QoS for that particular application. The stochasticity of the weather along with the unpredictable behavior of users in *the 2nd test case (EPB)* pose a very challenging problem in that the controller actions should be extremely proactive if (nearly-)optimal performance is required. A successful demonstration of the AGILE system in that test case will directly lead to improved EPB operation and efficiency and, consequently, to reduced energy intensity for EU economies, along with the obvious environmental benefits. These 2 totally distinct cases will strengthen the conviction that AGILE is truly applicable in a variety of application areas, involving extremely complex dynamics and stochasticity and attest to the fact that with minimal effort the AGILE system can be adapted and efficiently utilized in other large-scale applications. Once the AGILE system is developed the deployment costs are expected to be minimal: as there are no costs involved with the installation of new hardware or modification to existing installations, it is expected that the AGILE payback period will be markedly small. In addition by reducing the need for operators and engineers to fine-tune and calibrate the system the operational costs will also be reduced.

COOPERATION

Figure 3. AGILE Information Leaflet

Conferences

Six conference's publications were established in the Y1, most of them by CERTH and UCY (D7.2 chapter 3.3). More papers are expected to be published in the Y2 and Y3.

Scientific Papers

Four scientific papers were published in Y1, as defined in D7.2 (chapter 3.1) by the partners. More papers are expected to be published in the Y2 and Y3.

Poster

No project poster was designed and built.

Dissemination status:

Scientific papers: 4

Conference publications: 6

Workshop presentations: 0

Press releases: 4

Other Publications (Local Media, Newsletters, etc): 3

Deliverable: D7.2 - Initial Dissemination and Use Plan completed

Website completed and continuously improved

Leaflet completed

Factsheet completed

CD ROM and VIDEO not scheduled yet (no budget was allocated to this activity)

<u>Task 7.2: Exploitation Activities</u>

Exploitation status:

Products: 0

Business plans: 0

Identified external users/mailing list members: 0

Expected final result and the potential impact and use

The market for the AGILE system that is most closely linked to the implementations within the AGILE project will be the developers and providers of all types of sensors, control systems and interfaces for traffic/transport systems and buildings. But, furthermore, since the AGILE system is generic, a much wider market will consist of developers and providers of LSCSs covering all ERTI (Energy and Resource management, Transport and Industry) sectors.

As we described in D4.1.0 document, we intend to use the AGILE algorithm in a different areas projects.

To maximize the AGILE project's exploitation potential, the AGILE Dissemination and Use Plan will ensure that the products developed are advertised and commercialized according to each ERTI market's characteristics and exploitation potentials. Furthermore, the dissemination activities will reach out to the customers and developers of LSCSs and beyond.

As a most basic AGILE exploitation, the AGILE's industrial partners as well as the actively participating implementation sites (Test Cases) are committed to use the AGILE system in their Systems and Test Cases (assuming that efficiency and cost-effectiveness is successfully demonstrated). They would then furthermore be keen to deploy the AGILE system within other systems they are responsible for as well as promoting it among their colleagues in other authorities. Such examples can be found in D4.1.0.

The industry partners (ASEL and SICE) will create business opportunities in the traditional markets already addressed by them, like building automation, infrastructure automation for water, electricity and district cooling networks, energy and environmental management and control as well as industrial automation. It may also open new fields of applicability for their products such as control of barely accessible locations. Since AGILE will reduce the time, effort and cost required for deploying the automation system, it will enable formerly economically non-viable applications. In addition, this will enforce the competitiveness of ASEL and SICE solutions, since it will help maintaining their position offer as lowest Life Cycle Costs, availability, flexibility and evolution.

For further information regarding the AGILE Project:

Please visit the AGILE web site: http://www.agile-fp7.eu