Desalination and Water Treatment
www.deswater.com

10 (2009) 192–199

1944-3994 / 1944-3986

Optimal systems engineering and control co-design for water and energy production: A European project

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Received 1 September 2008; Accepted in revised form 21 September 2009

ABSTRACT

Fresh water and energy are essential resources, which have become expensive and scarce. Moreover, their production requires nowadays high technologies and multidisciplinary advanced research. In order to combat this problem, the European Commission supports cooperative research activities in the mentioned areas by means of research grants. Open Gain is a cooperation project financed by the European Commission, whose main objective is to develop optimal systems engineering methods with embedded automation for reverse osmosis desalination plants powered by renewable energies. Thus, the present paper describes objectives, the consortium, work packages and dissemination plan of Open Gain as an example of narrow cooperation between Europe and the Mediterranean Partner Countries (MPC).

Keywords: Reverse osmosis; Alternative energies; Open Gain; European Commission

1. Introduction

In order to combat the water scarcity intensive desalination and water-reuse activities are being carried out particularly in the Mediterranean countries, where remote arid regions are suffering the desertification process. Desertification has to be understood here as the degradation of land in arid and semi-arid regions and not as the expansion of existing deserts. It is very important to remark that the United Nations Convention to Combat Desertification estimates that the arable land available worldwide will significantly be reduced by 2025 ([1]).

On the other hand, desalination requires intensive energy consumption. Depletion of non-renewable resources is considerably increasing and therefore traditional energy resources will become very expensive, even though the time for complete depletion is expected to be still very long. Thus, the water production must be drastically increased as well as the abovementioned energy consumption on the one hand and, on the other hand, energy is becoming more expensive and limited.

In this context, very large desalination plants at coast seems to be inadequate for remote areas because of an expensive infrastructure, a high energy consumption based on non renewable resources, high distribution costs and important pipe losses. In conclusion, this approach leads to the waste not only of energy but also of fresh water, i.e. the resources, which have to be careful administrated and saved.

In order to undertaken the contradiction described above, reverse osmosis (RO) emerges as a feasible desalination technology, renewable energy sources as a necessary complement and decentralized water-electricity supplies as a solution for each particular problem. The study presented in [2] has confirmed the convenience of

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Presented at EuroMed 2008, Desalination for Clean Water and Energy Cooperation among Mediterranean Countries of Europe and the MENA Region, 9–13 November 2008, King Hussein Bin Talal Convention Center, Dead Sea, Jordan.

this combination, where it was shown that RO desalination properly integrated with a renewable energy production system reduced considerably the environmental loads and the airborne emissions associated with desalination and power production.

Finally, cost reduction and energy saving have been reached until now almost exclusively from the point of view of technological improvement of the most important components of the plant (i.e. membranes, filters and high-pressure pumps). Although plants are getting more and more complex, they have not been considered as complete integrated systems at the design stage. Moreover, the automation is not considered as a relevant issue. This lack of system design and full control are found not only in the desalination industry but also in research (see e.g. [3]) as it was partially pointed out in [4]. However, it is well known that component approaches lead to oversized plants because an optimal system is normally less than the simple sum of the parts, and very often, the misconception "the best system is made from the best components" is used as design approach ([5]). In the future, technological advances in the plant's components should be accompanied by a sophisticated system design, for what design tools should be developed.

All these facts are the motivation for OPEN GAIN, a cooperation European project whose global objective can be stated as:

To develop a new model-based optimal system design approach to economically improve the overall performance, dependability, reliability and availability of co-generating water-electricity plants powered by renewable energy for remote arid areas using a high level of automation to meet specific cost requirements.

In this paper, the general concept of OPEN GAIN and its most important activities are described. Work packages, the consortium, the management and dissemination plan are explained.

2. Approach and project contributions

The use of renewable energy sources to power reverse osmosis desalination (RO) plants is not new. Already in the 80's several reports about reverse osmosis desalination combined with renewable energies can be found in the literature (see e.g. [6–8]). A review is given in [9]. Small RO projects, which were powered by photovoltaic solar energy (PV), can also be found in [10–13]. More recently, many applications in this field have been reported (some of these are [14–17]. In [18], an approach is presented, which does not need batteries.

Pioneer works on RO plants powered by wind energy are [8,19–23]. More recent works are for example [24–27]. A plant without batteries was presented by [28]. A complete control system for a combined plant (RO, PV and wind) was first proposed by [29] in a simulation environment. Such RO systems are getting more and more complex such that current system engineering design methods will become very limited and insufficient. Therefore, a system engineering design scheme based on a combination of dynamical modelling, mathematical simulations and multi-objective optimization procedures is proposed so that the selection of an optimal solution can be supported using the computer. Thus, the implementation of a library of components based on validated first-principles models for plant components as well as model-based algorithms for control, supervision and optimization is crucial for the implementation of the concept. Notice that the plant operation has also to be simulated in order to obtain a complete integrated design.

Multi-objective optimization is necessary because the design has to fit not only one objective (such as maximization of the profit) but also max-min problems like maximum production with minimum energy consumption, dependability issues, acceptable costs and operation constraints. The control system design also will require multi-objective parametric optimization [30] when multi-loop control systems and multiple controllers [31] are used and control objectives are contradictory. Technical performance and quality issues have to be taken into account because the most important plant specifications like a safe operation under all conditions has to be guaranteed. Game theory will allow considering together the different interests of all involved components. The iterative design cycle is schematically illustrated in Fig. 1.

Complex systems like desalination plants powered by renewable energies in remote arid regions have still not been studied from either an integrated fault-tolerant control system co-design or the optimal systems engineering point of view (in the sense of [32]), although these aspects are very important in order to improve the plant operation for reliability, availability and economy. This fact and the integrated approach of addressing all required aspects together make this project compelling and outstanding, and constitute the most important motivation to dedicate efforts to the project undertaking. The technical work proposed in this project will advance the state of the art and make important contributions in several directions, as it can be seen in the overview summarized in Table 1.

3. Project description

The scope of the project comprises de-central co-generation of electricity and water close to the point of consumption in remote arid MPC regions. It is planned to obtain capacities up to few hundred kW power and up to five hundred m^3 water per day from brackish water, where hybrid energy supply from fossil (gas-oil, natural gas) and renewable (solar and wind) sources are combined. The plant has to be a safety source under all circumstances and therefore, high technology of control

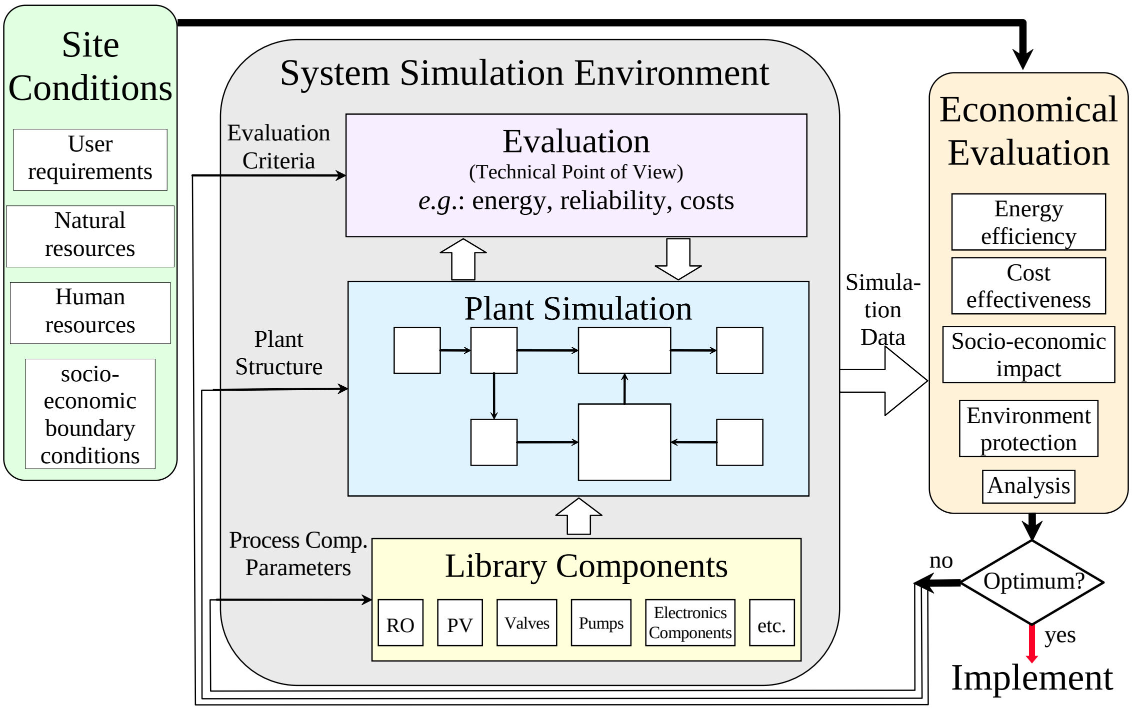

Fig. 1. Iterative design cycle.

Table 1
Summary of contributions of the project

Current state of the art	After Open Gain
Standard plant design based on combination of components.	Design based on optimal system engineering. Components are obtained according to system necessities
Performance improvement based only on technological improvement of the components	Additional performance improvement by using high level of automation and system design
Only low-level control of essential variables	Several control levels including supervision, adaptation and remote monitoring of variables
Standard control (e.g. PID).	Advanced model based control (e.g. MBPC).
Dynamic models are not used	A dynamic model of the whole plant will be developed and used for control and simulation
Reliability and availability only based on regular plant shutdown and maintenance.	Reliability and availability improved by controller adaptation in case of system degradation and system reconfiguration
Unpredictable system breakdown without availability of technical personal.	Predictable system breakdown due to remote monitoring and remote reconfiguration.
No dependability considerations are taken into account.	Design of a dependable system based on fault tolerant control ([33]).

and supervision shall be introduced. The construction of a small prototype (25 m^3/d) is included in the project.

3.1. The consortium

For the carrying out of the project, a highly qualified consortium complemented by experienced subcontracting companies was established. All participants of the project do complement one another very well: For every work package (WP) there is, besides the WP leader, one other participant with knowledge and experience in the field, who also makes a noticeable contribution to it. Thus, for every WP the experience and the brainpower of many people will be incorporated. In addition, participants have been chosen complementary to each other. Participants are summarized in Table 2.

3.2. Project management

Project management activities span the project's lifetime. They aim towards the control of the project, i.e. ensure that the project will meet the technical and business goals as set out in the objectives, and to deliver this information to the European Commission as required. An additional goal is the effective coordination of the work during all phases of the project, including the supervision of the contents and the quality of the deliverables, as well as the compliance with the project's timetable. Project management consists of the management, organization and technical monitoring of the project in accordance with well-established procedures. In addition, financial management and control of the project's resources are included.

The efficiency of the project management will be assured by clearly assigned obligations as well as by a simple, sound organizational structure, designed to minimize overheads, which is depicted in Fig. 2. Three distinct organizational levels can be identified: Level 1 (project management), level 2 (work package leaders) and level 3 (work package teams).

3.3. Work plan

The significant work that has to be carried out during this project can be classified in the following form, according to three large blocks: (1) studies, simulation and software development, (2) plant design and construction, and (3) prototype integration, start-up and real-time control implementation. This large subdivision

Table 2
OPEN GAIN consortium

Participants	Short name	Country
University of Heidelberg (Coordinator) (Automation Laboratory)	UHEI	Germany
National Technical University of Athens (School of Chem. Eng., Department II: Process Analysis & Plant Design)	NTUA	Greece
University of Valladolid (The Department of Systems Engineering and Automatic Control)	UVA	Spain
Centre de Recherches et Technologies de l'Energie (Photovoltaic and Semi-Conductors Laboratory)	C.R.T.En	Tunisia
American University of Beirut (Department of Electrical and Computer Engineering)	AUB	Libanon
National Energy Research Centre Jordan (Photovoltaic Division)	NERC	Jordan
Centre de Développement des Energies Renouvelable (Solar, Thermal & Geothermal Division)	CDER	Algeria

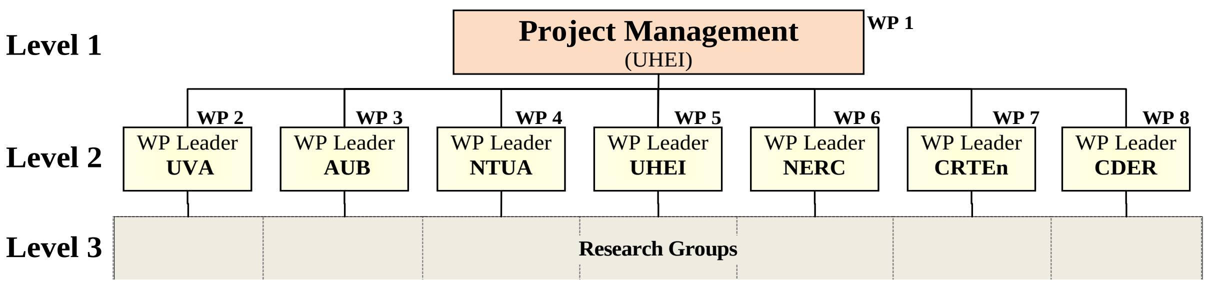

Fig. 2. Project organization.

also corresponds to the three-year time horizon, such that blocks are scheduled to the first, second and third year, respectively. Moreover, dissemination and co-ordination efforts are distributed along the entire period.

Independently of the subdivision described before, the work plan has also been designed so that on the one hand, it is possible to continue with research issues in a logically planed sequence and on the other hand, to exploit already delivered partial results as products that can be used by other companies and institutions. This is a very important aspect, because this is a unique approach that allows to activate continuously dissemination activities as well as to help other groups (companies and research groups) in the implementation of the new technologies. Thus, three sets of results are expected in-between: (1) Resources, conditions and potentials assessment, market analysis and data collection, (2) Dynamic models and decision support system, and (3) Control algorithms and prototype plans. This idea is presented in Fig. 3, where the logical work sequence is supplemented by the involved work packages and the partial results that were just described before.

The work packages are organized in such a way that at least two packages as well as partner groups are always complementary, where the most thematically specialized partner assumes the leadership of the corresponding work package and its management activities. Both groups together with other interested groups assume equitably the support activities. The principal contents of the work packages are centered around the main tasks of technology review; analysis, selection and application of system engineering techniques for optimal system design including software development; dynamic mathematical modeling and system simulation; exemplary prototype construction, laboratory and MPC field testing; implementation of real-time fault-tolerant control system including tele-diagnosis, and dissemination and exploitation in MPC and MENA countries.

The work plan is broken down into eight work packages (see Table 3). Fig. 4 shows a block diagram of the physical decomposition of the plant and the localization of the work packages.

3.4. Dissemination plan

Because the highest impact of the project is expected to lie in the Mediterranean countries, it is natural to think that dissemination activities should meanly be carried out

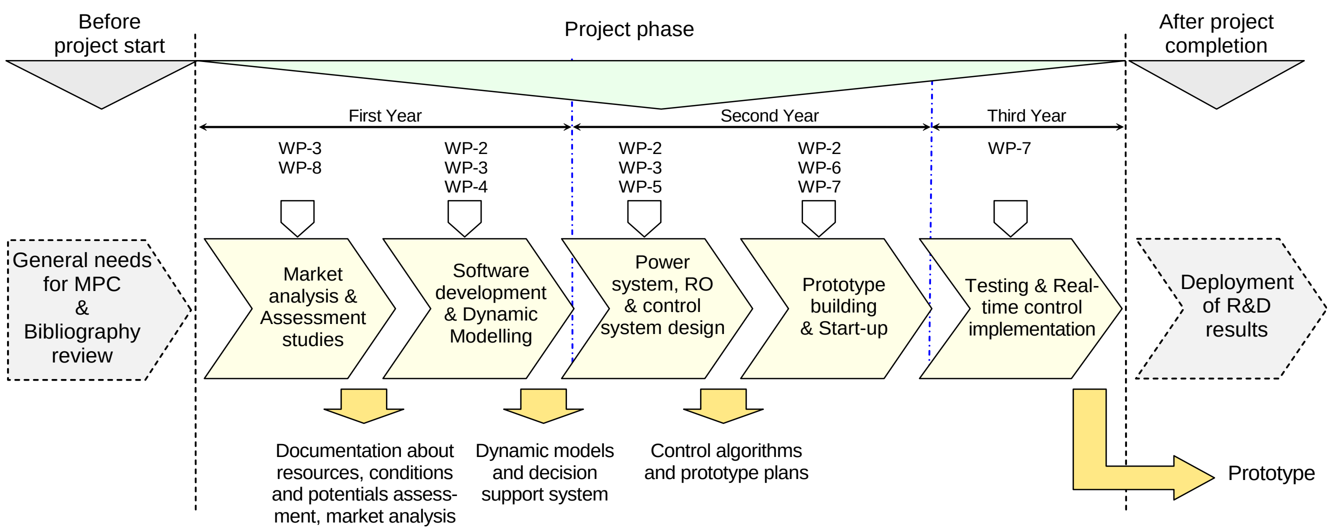

Fig. 3. Scheme of the work plan.

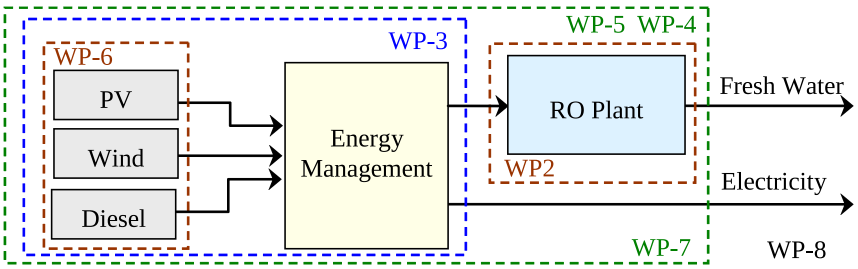

Fig. 4. Physical decomposition of the plant and localization of the work packages.

Table 3
OPEN GAIN work packages

Work package	Subject	WP- leader
WP-1	Project management	UHEI
WP-2	Modelling, simulation and construction of the RO plant	UVA
WP-3	Integrated energy management	AUB
WP-4	Systems engineering and decision support	NTUA
WP-5	Integrated dynamical modelling, simulation and control	UHEI
WP-6	Power supply subsystem	NERC
WP-7	Integrated Implementation and control system design of a prototype	CRTEn
WP-8	Dissemination of scientific work	CDER

in these countries. Therefore, all participants from MPC were chosen for dissemination activities. They are familiar with the languages and the culture of the region of interest and they know best how to avoid pitfalls, which will result in a more effective and wider spread of the results. The project's partners from Mediterranean countries are renowned institutions with international prestige and a vast experience in the area of dissemination.

Because the knowledge gained by means of the project is also important for European desalination companies, dissemination in the member states should not be underestimated. The information and knowledge transmission in the member states will be carried out for example by the *Desalination Directory* and the *European Desalination Society*, who are continuously developing intense activities in the Mediterranean countries as well as in Europe. They organize courses and workshops for the industry. Members of the consortium can take part into such activities offering teaching and consulting services.

In order to guarantee a successfully transmission of knowledge obtained during the project execution, a rich dissemination plan will be implemented. Its major objective is

to spread acquired knowledge, scientific research results and gained experience, which are obtained during the execution of the project, to the scientific community, industry and public entities, and to the public in general.

The knowledge dissemination can be planned in three wide areas: Dissemination for the scientific community, dissemination for the industry and public entities, like *water authorities* and *governmental bodies* and finally for the public in general. For each group, different dissemination activities are required as it is described below. A summary is given in Fig. 5.

3.4.1. Dissemination within the scientific community

Three mainly scientific communities are represented in the project, namely the *renewable energies community*, the *control engineering community* and the *desalination community*. They are habituated to present their scientific work

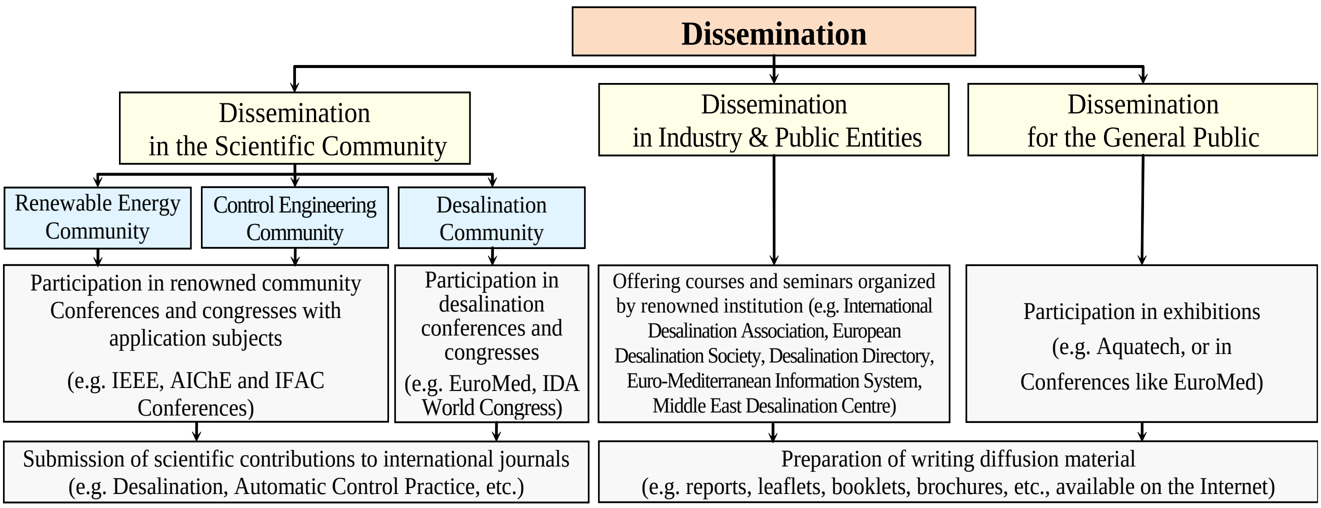

Fig. 5. Dissemination plan.

in specialized conferences, congresses and symposia. People from renewable energies and control engineering communities can present their work in the field of applied research. Presence of researchers involved in the project are expected in conferences organized by the Institute of Electrical and Electronic Engineers (IEEE), Institute of Electrical Engineers (IEE), International Federation on Automatic Control (IFAC), International Desalination Association (IDA), European Desalination Society (EDS), etc. Moreover, the submission of high quality papers to well renowned international journals is also expected. At the end of the project, a workshop will be organized by the consortium.

3.4.2. Dissemination for industry and public bodies

This is the most important ambit for the dissemination. Research knowledge has to be transferred for development and finally reflected in a product in order to be useful. This is a mission for the industry under the legal and financial support from the public entities. The implementation of dissemination in this field will be carried out by means of courses and seminars. Several institutions as the Desalination Directory ([34]), the Middle East Desalination Centre and the European Desalination Society are internationally recognized and specialized in the organization of courses and seminars. In the framework of their activities, the consortium can offer teaching and consulting services for industry and public entities. In this case, an agreement with these institutions is necessary. Thus, dissemination activities can be self-financed. Moreover, writing material as assessment reports and feasibility reports will be provided.

3.4.3. Dissemination to the general public

Public in general (i.e. taxpayers) has the right to be informed about research results. For this reason, the consortium will actively take part in exhibitions like Aquatech and EuroMed. Diffusion material, e.g. leaflets, booklets and brochures will be prepared and offered. All information materials will be made available on a continuously updated Internet server. Moreover, public presentations at schools and open days of universities, particularly in MPCs, will complete the dissemination plan at this level. Finally, mass media will continuously be informed about the progress of the project and relevant results.

4. Some preliminary results

At the current time some preliminary results have been obtained and published in international conferences. For example, modelling efforts have been concluded (see for example [35–37]) and a simulation library by using the software package EcoSimPro [38] has been implemented [39]. Parameter identification for the real plant is a task to be done because the plant is still not operative. Studies from the control point of view have been presented in [40] and [41] for a simulation model and in [42] and [43] for the real-time control of a small laboratory plant. Moreover, three diploma theses have been concluded in the framework of the project [44–46].

Finally, components for the prototype have been ordered as well as purchased and montage work has begun. This is a task, which is delayed in the project because of administrative as well as customs difficulties. Therefore, the project was prolonged one year more.

5. Conclusions

Open Gain is an innovative project whose main idea is to develop a reverse osmosis desalination plant powered by renewable energies based on the principle of integrated system engineering design. The distributed control system is co-designed and it has to be fault tolerant. The project is running since January 2007 and it has been prolonged until the end of 2010. After some project meetings, which were organized in different countries, a strong interdisciplinary cooperation research group has finally been consolidated. Assessment studies and modelling activities have already been completed. At the present time, the activities are concentrated on the design of the prototype as well as of the fault-tolerant control system. Thus, it is expected that at the end of the project an excellent example of integrated system engineering design including the distributed control system is completed and it will be able to be transferred for industrial development.

Acknowledgement

This work has been supported by the European Commission by means of the project Open Gain under contract No. 032535.

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