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REAL-TIME MONITORING AND CONTROL FOR EFFICIENT MANAGEMENT OF DRINKING WATER NETWORKS: THE BARCELONA CASE STUDY

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INTRODUCTION

Drinking water utilities in urban areas are facing new challenges in their real-time operation: limited water resources, intensive energy requirements, a growing population, a costly and ageing infrastructure, increasingly stringent regulations, and increased attention towards the environmental impact of water use. The efficient use of resources is becoming a priority for water managers and the recent advances in ICT technologies can provide solutions to this end.
Real-time management in water networks may be considered as a process comprising two different levels:

- Monitoring, which is concerned with the observation and estimation of the current state of a system and the detection/diagnosis of abnormal situations. It is achieved through sensors and communications technology, together with mathematical models
- Control, related to computing and applying the best admissible control strategies for network actuators. Optimal control seeks to optimize a given set of operational goals related to the network performance, such as efficiency in resource use, environmental impact, etc.

Real-time monitoring and control techniques can significantly improve the use of water and energy resources in water networks. This paper addresses the developments of the European project EFFINET[a], which proposes a novel integrated water resource management system based on advanced ICT technologies of automation and telecommunications for improving the efficiency of drinking water networks in terms of water use, energy consumption, water loss minimization, and water quality guarantees by addressing the real-time monitoring and control levels.

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[a]EFFINET: Efficient Integrated Real-time Monitoring and Control of Drinking Water Networks (FP7-ICT2011-8-318556)

Two real-life pilot demonstrations in Barcelona (Spain) and Lemesos (Cyprus) are considered in the project, to prove the general applicability of the proposed integrated ICT solution and its effectiveness in the management of drinking water networks, with considerable savings of electricity costs and reduced water loss while ensuring the high European standards of water quality to citizens. This paper is concerned with the Barcelona demonstration case.

REAL-TIME MONITORING FOR LEAK DETECTION

Real-time monitoring of water networks is based on the use of sensor data from telemetry and mathematical models to detect and diagnose possible abnormal situations, such as leaks or water quality deterioration events. It links the real sensor data gathered from the network to the decision making procedure, by detecting possible faults as well as their probable location within the network. The main idea behind real-time monitoring, both for water balance and for water quality problems, is to use real-time sensor data and to compare them with those generated by a well-calibrated hydraulic model of the network in absence of faults. By analyzing the difference between these two sets of data, a detection of abnormal events can be performed.

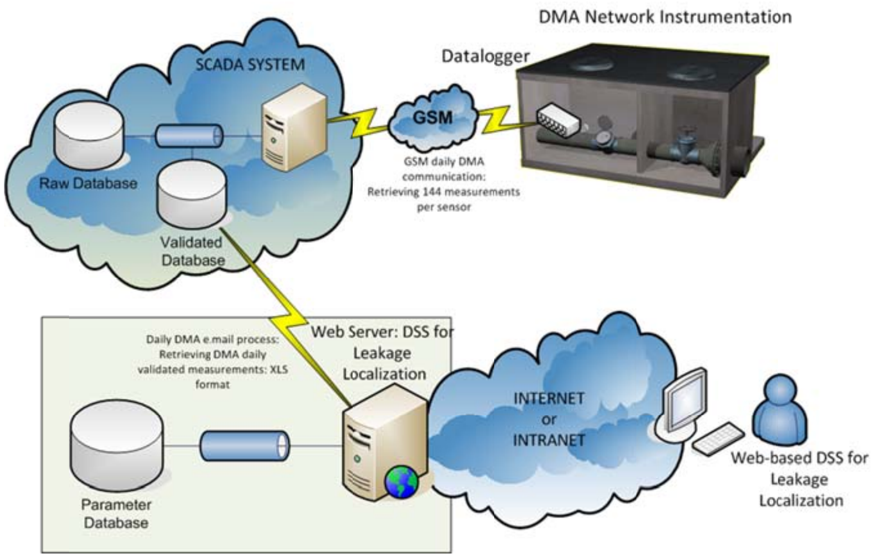

Figure 1 Conceptual scheme of the DSS prototype for water network monitoring

Real-time Monitoring Methodology

The EFFINET project proposes the use of a model-based methodology for leakage detection and localisation in DMAs of water distribution networks, based on the use of pressure sensors and a well-calibrated hydraulic model, as in Casillas et al. (2014). This methodology is based on the principles of model-based diagnosis of Blanke et al. (2006).
The process of searching the zone with highest probability of containing a leakage can be summarized in the following steps:

- Simulation of possible faults in the different nodes of the network using a hydraulic simulation (for instance, EPANET)
- Generation of the residual sensitivity-to-leak matrix containing the theoretical Fault Signature Matrix (FSM), i.e. the effects all potential leaks on the pressure at the sensor locations.
- Collecting pressure measurements from the sensors installed in the network.
- Generation of the residuals comparing the pressure measurements with the estimations provided by the hydraulic simulator considering a model without leaks.
- Comparison of the residuals with the FSM contained in the residual sensitivity-to-leak matrix using the correlation function.
- Results aggregation and representation

The Castelldefels Demonstrator

The monitoring demonstration in Barcelona will be carried out in two district metered areas of the Castelldfels area, covering approx. 50km of pipes, with approx. 10000 contracts and 30 to 50% of automatic meter reading (AMR).

Figure 2 shows a scheme of the hydraulic model of the Castelldefels DMA demonstrator

Figure 2 Castelledefels DMA demostrator

The objective of the ongoing work in EFFINET is to apply the leak detection and location methodology to the demonstration network:

a) In simulation, by the inclusion of leaks as additional demand in nodes of the hydraulic simulation model
b) In a real scenario, by creating an artificial leak (see Figure 3)

The most recent developments on real-time monitoring carried out by the project teams at IRI and CETaqua involve optimal sensor placement placement (Casillas et al., 2013) and multiple-leak scenario detection.

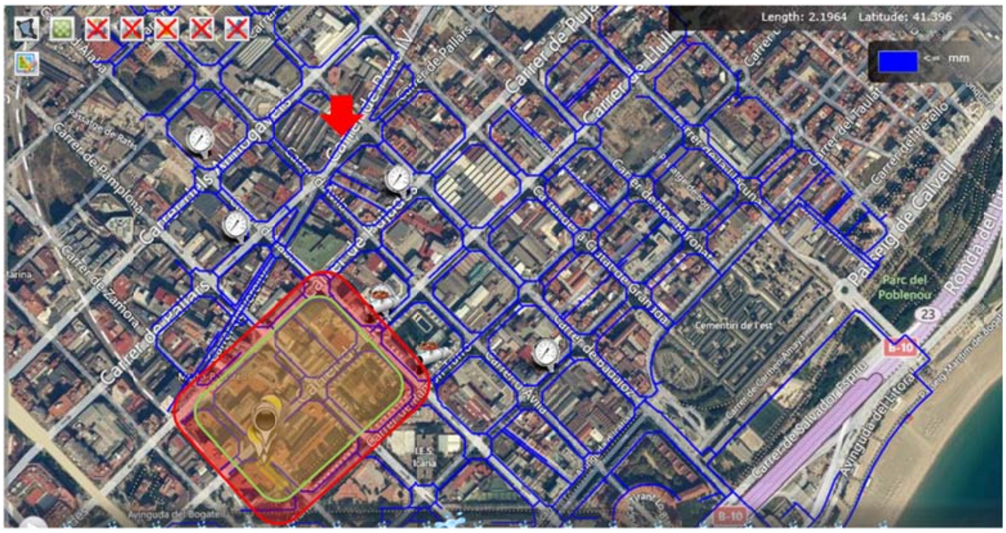

Figure 3 Leak isolation demostrator

OPERATIONAL CONTROL

The real-time **operational control** of a water network by means of a SCADA system involves planning strategic operations of pumping stations and flow- or pressure regulation valves over a 24-hour horizon, in order to meet consumer demand at all times, with the appropriate levels of pressure and quality. This is generally achieved using intermediate water tanks, booster pumping, and pressure reduction valves. Optimal model predictive control (MPC) techniques are the best candidate to perform operational control, as they compute, ahead of time, the best admissible control strategies for valves, pumps, or other control elements in a network to achieve minimum energy consumption, cost minimization, environmental protection, and other operational goals, that ensure current and future satisfaction of water demand, as shown e.g. in (*Cembrano et al. 2011*, *Pascual et al. 2013)*.

The control of the network is very sensitive to faults affecting sensors (flowmeters, pressure sensors, etc.) and actuators (pumps, valves, etc.). A diagnosis of faulty situations must be ensured, so that the control system does not derive in anomalous performance of the network. One way of achieving fault-tolerance is to employ an on-line Fault Detection and Isolation (FDI) scheme at the monitoring stage that is integrated with the real-time control system, so that when a fault is detected and isolated, the FDI module will trigger the controller to activate in some accommodation actions. MPC algorithms have the very nice feature of being easily and automatically to reconfigure, so as to immediately provide the best control action after a structural change due to a fault.

Model Predictive Control in Water Networks

The management of the UWS must be carried out predictively. Control actions must be computed ahead of time, with an appropriate time horizon, based on real measurements and on-state estimation, as well as predictions of the stochastic variables involved in the models such as consumer demands. For water distribution networks, the prediction horizon is usually of 24 h.

A water transport and distribution system generally contains a number of telecontrolled flow- or pressure-control elements, such as valves and pumping stations. A convenient description of the dynamic model of a water network is obtained by considering the set of flows through these n_u control elements (valves and pumps) as the vector of control variables $u \in \mathbb{R}^{n_u}$.

The set of n_x tank volumes monitored through a telemetry system is considered a vector of state variables $x \in \mathbb{R}^{n_x}$. Water demand at consumer nodes $d \in \mathbb{R}^{n_d}$ may be considered a is a vector of stochastic disturbances containing the values of the demands at the n_d consumer nodes in the network. Since the model is used for predictive control, d will generally be a vector of demand forecasts, obtained through appropriate demand prediction models.

The dynamic model of the network may then be written, in discrete time, as:

$$x(k+1) = f(x(k), u(k), d(k), \theta(k)) \tag{1}$$

This expression describes the effect on the network, at time *k+1*, produced by a certain control action *u(k)*, at time *k*, when the network state was described by *x(k)*. Function f represents the mass and energy balance in the water network and *k* denotes the instantaneous values at sampling time *k*, *d(k)* is the demand prediction at time *k* and $\theta(k)$ are the parameters of the network at time *k*.

Other constraints of the problem are related to:

- Mass balance relationships at the network nodes (relations between manipulated inputs and, in some cases, measured disturbances). These equalities are written as
- Bounds on system states and on control actions

The system performance is expressed in a cost function and model predictive control proceeds by solving a sequence of optimization problems to minimize the cost function in a 24h horizon, taking into account the system dynamics and its constraints. The methodology works with a receding horizon, so that at each time step, a 24-hour problem is solved, but only the controller setpoint for the first hour are used.

Predictive Control in the Barcelona Water Transport Network

The EFFINET project will develop innovative energy-aware water network control algorithms based on MPC techniques for the operational management of urban water networks, controlling pumping and valve actuation in real-time to cope with varying energy-prices and water demand in an economically profitable and risk-averse way

(Ocampo-Martínez et al., 2013). In the Barcelona demonstrator, EFFINET will address the problem of operational control of the complete transport network. A representation of the network is show in Figure 4.

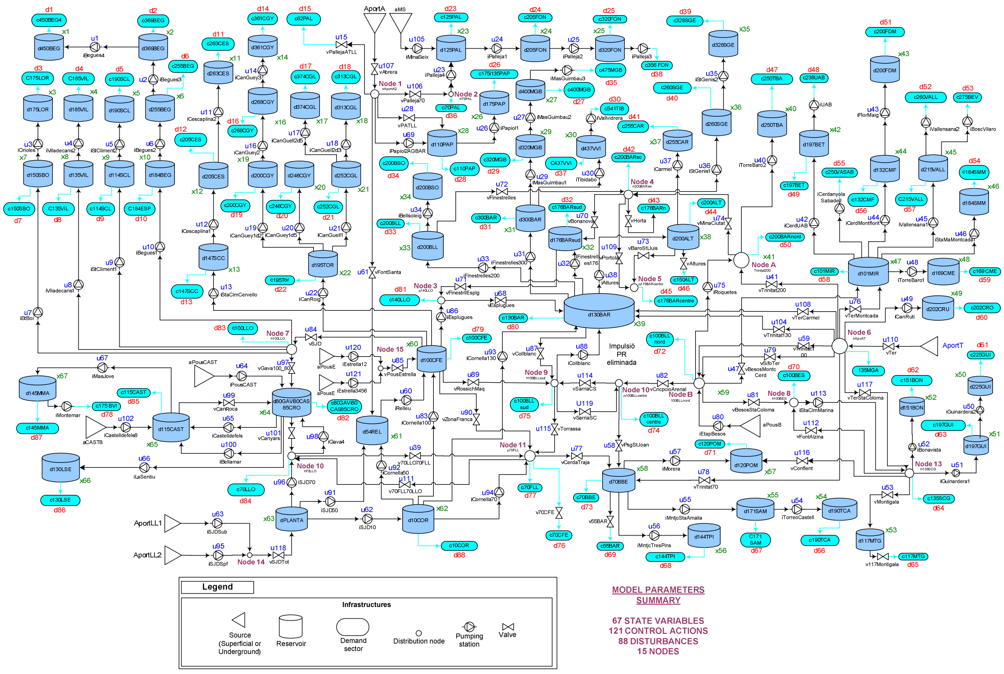

Figure 4 Conceptual representation of the Barcelona transport network

While previous work had solved MPC problems of this type using flow-only models, the focus of the EFFINET demonstrator is to derive 24-hour ahead MPC strategies for this network, taking into account both flow and pressure balance equations. Similarly, EFFINET seeks to produce discrete pumping stations set-points, while previous work had used a continuous-variable assumption for all the control actions.

The demonstration setup will contain a detailed hydraulic simulator of the transport network developed in EPANET (see Figure 5), which will be used as a virtual reality to test the effect of the MPC control actions.

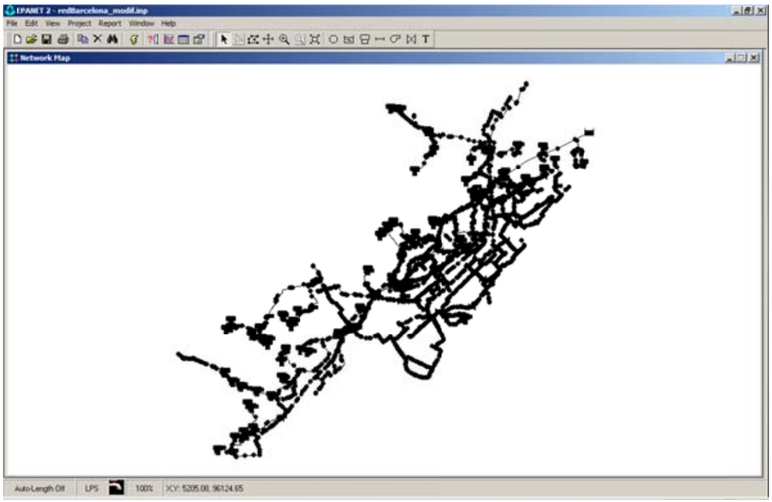

Figure 5 Hydraulic simulation of the Barcelona transport network in EPANET

CONCLUSIONS

This paper contains an overview of the developments of the European project EFFINET in the Barcelona site, on the specific subject of real-time monitoring and control. The EFFINET project has a broader scope; it envisages the development of an integrated real-time water resource management system based on advanced ICT technologies of automation and telecommunications for improving the efficiency of drinking water networks in terms of water use, energy consumption, water loss minimization, and water quality guarantees. The proposed water management system, which is linked to SCADA and GIS systems, integrates the following three main modules: (i) a decision-support module for real-time optimal control of the water transport network, operating the main flow and pressure actuators (pumping stations, pressure regulation valves) and intermediate storage tanks to meet demand using the most sustainable sources and minimizing electricity costs, thanks to the use of stochastic model predictive control algorithms that explicitly take into account the uncertainty associated with energy prices and actual demand; (ii) a module monitoring water balance and quality of the distribution network in real-time via fault detection and diagnosis techniques, using information from hundreds of flow, pressure, and water quality sensors, and hydraulic and quality-parameter evolution models, to detect and locate leaks in the network, possible breach in water quality, and sensor/actuator failures; (iii) a module for the management of consumer demand, based on smart metering techniques, producing a detailed analysis and forecasting of consumption patterns and providing a service of communication to consumers, together with economic measures to promote a more efficient use of water at the household level. Two real-life pilot demonstrations in Barcelona (Spain) and Lemesos (Cyprus), respectively, will prove the general applicability of the proposed integrated ICT solution and its effectiveness in the management of drinking water networks, with considerable savings of electricity costs and reduced water loss while ensuring the high European standards of water quality to citizens.

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