Contract Number ICA4-CT-2002-10012
Efficient Operation of Urban Wastewater Treatment Plants

Hardware sensor networks
Deliverable D8.2

Deliverable type: Report
Number: D8.2

Date of delivery: 1st September 2005
Task: WP8.2

Responsible:

Paolo Ratini
SPES scpa
Via Broganelli 84
60044 Fabriano (AN)
Italy
Email: paolo.ratini@spesonline.com

Other contributors:

Nicola Fiocchi
D.I.I.A.R. Sezione Ambientale
Politecnico di Milano
Piazza Leonardo da Vinci, 32
20133 MILANO
Italy
Email: nicola.fiocchi@polimi.it

Elena Ficara
D.I.I.A.R. Sezione Ambientale
Politecnico di Milano
Piazza Leonardo da Vinci, 32
20133 MILANO
Italy
Email: elena.ficara@polimi.it

Abstract

This report summarizes the work done during the project in several steps and phases, regarding the selection and integration of several probes and of the two new hardware sensors, developed in WP3, for the data set generation at lab and pilot scale plants, mainly for the validation of the modules generated by other partners and WPs.
Data are generated in five reactors: two lab scale SBR reactor at UU, a pilot scale SBR reactor at INRA, a pilot scale SBR reactor at ENEA, and a full scale SBR reactor expressly built up by IbTech in Mexico.
Two sensor configurations are delivered for the implementation of the monitoring and control tasks.
The experimental data sets obtained are stored and managed using the database designed and implemented in this WP8 for the integrated system architecture.

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Introduction

The purpose of this deliverable is to present and to record the fundamental decisions that have been taken concerning with the selection of the signals to acquire for the implementation of an automated supervision and control of a SBR reactor and the definition of two specific sensor configurations, based on the use of both common electrode probes and the new two hardware sensors developed inside the project.

The main goal of the EOLI project is the control of a wastewater treatment plant (or multiple plants) both locally and from a remote centre. The key issues dealing with the data acquisition and management can be summarised as below:

- characterization of the information framework needed to manage the process in terms of software modules that have run feeding with data and producing control actions;
- selection of the most suited signals for on line acquisition to extract this information from the process;
- revision of existing probes and sensors looking for the appropriate tools to acquire directly these signals, where possible, or to provide information with known and reliable correlation with them to be used as estimations;
- integrate these probes and sensors in the system architecture;
- design and implementation of a database to store and to represent this information under a formal approach in terms of relations between the data.

The structure of the deliverable follows the sequence set out above.

The planned delivery date for this deliverable was T0+28. It was decide to postpone this date till now to fully verify the correctness of the decision taken on the basis of the feedback from the integration and validation activity at the two pilot plants and not only on the basis of the data from the lab plants.

Selection for specific sensors' configuration

Wastewater treatment plants, similar to natural ecosystems, are open and dynamic systems. Therefore conventional steady-state system design and operation usually lead toward poor performances. For this reason real-time monitoring and control systems have been developed to solve this problem in the operation of wastewater treatment plants with the introduction of automatic adaptivity. The effectiveness of these real-time control systems depend first of all on the reliability of the on-line sensors, the suitability of the monitored parameters and the applicability of the control strategy.

A lot of results obtained from fixed-time control study indicate that the ORP pattern and profile can represent with enough accuracy dynamic characteristics of batch systems, in particular of SBR process; the pH and DO profile can also indicate some of those characteristics. The tracks of these process variables during batch operation present some typical patterns that can be used to detect the terminations of the biodegradations processes. Therefore these patterns have a great potential for on-line control: in the operation of a SBR they can be used to detect the completion of the nitrification and denitrification processes in the aerobic and anoxis phases of the batch cycle.

ORP is highly sensitive and instantaneous: it reflects the amount of materials such as dissolved oxygen, organic substrate, activity of organisms and some toxic compounds. It also indicates some operation conditions such as overloading, under-loading, over-aerating and under-aerating. Also some special variations (break-point and knee) in the ORP profile can provide information to determine and identify bacterial activity. Moreover, relations arise between ORP and nitrate concentration in the anoxic zone.

The pH too can provide significant and more stable data than ORP in the aerobic/anoxic sludge digestion batch systems as far as different biological reactions including nitrification and denitrification.

Ar far as the latter two biological processes, they are known to be the critical ones for those SBR which purpose is, besides the removal of organic matter, the nitrogen removal. Nitrogen removal is desirable, since nitrogen is known to cause eutrophication of the receiving water body, while some nitrogen compounds (typically ammonia and nitrite) show a relevant environmental toxicity. It is well known that, when both nitrogen and carbon removal, are to be achieved, the first is the limiting step, while carbon removal is automatically guaranteed. Conventional nitrogen removal is achieved by oxidising the nitrogen content to nitrite and the latter to nitrate (nitrification) and by reducing nitrates to nitrogen gas (denitrification), which is then released in the atmosphere.

Nitrification is brought about by autotrophic bacteria known to be slowly growing and sensitive to a variety of chemicals. Therefore, nitrification failures are often experienced in full scale continuous as well as fed batch systems. Denitrification is due to facultative heterotrophic bacteria which are able, in the absence of dissolved oxygen, to oxidize organic molecules by using nitrate/nitrite as final electron acceptors.

Denitrification failures are normally caused by insufficient carbon availability, which causes the build up of the effluent nitrate content. Nitrites build up may also be an issue, since they are intermediate products of both nitrification and denitrification.

In the literature, monitoring methods for both nitrification and denitrification have been suggested, simply based on the patterns of DO, pH and ORP signals.

As for the **denitrification process** the end-point of the reaction can be detected by:

1) the “nitrate knee” in the ORP profile

2) the “nitrate-apex” (i.e. the maximum), in the pH profile.

As for the **nitrification process,** the end-point can be detected by observing:

1) the “ammonia valley” in the pH profile (Chang and Hao, 1996),

2) the bending point in the ORP profile (Plisson-Saune et al., 1996);

3) the "DO flex" or "break-point" (Plisson-Saune et al., 1996; Andreottola et al., 2001), that is the typical change in the slope of the DO profile.

In Figure 1 and 2, ORP, pH and DO profiles, together with the above described relevant points can be observed; these data were collected from the lab-scale POLIMI-SBR during a “standard condition” cycle (more details can be found in POLIMI-WP1Technical Annex). It can be observed that both ANOXIC (from time 0 to 150 min) and AEROBIC REACT (from time 150 to 360 min) phases were overlasting, since the relevant biological process, i.e. the denitrification reaction in the anoxic phase and the nitrification reaction in the aerobic phase, ended well in advance with respect to relating phase. This example suggests that pH, DO and ORP profiles can be used to shorten the REACT duration leading to energy saving and to the enhancement of the treatment capacity of the SBR. On the contrary, in the presence of a toxic compound in the influent, one of more of the above listed notable points may not be detected, thus indicating that a process malfunction is possibly affecting the treatment efficacy. As an example, profiles collected during a nitrification inhibited cycle (allylthiourea – ATU -, a well known nitrification inhibitor was added to the standard SBR influent) in reported in Figure 3 and 4. No nitrification end point can be observed on signal patterns. Moreover, no denitrification end point was detected in neither the ORP nor in the pH trend. As verified by analytical nitrate and COD determinations, this was due to the insufficient COD/N ratio in the SBR feed.

In the EOLI project a combination of different signals has been proposed for possible use in the on-line monitoring and control of the biodegradation processes (for more details refer to the WP5): two different specific configurations for the sensor's network have been delivered.

The first configuration is dedicated to a SBR with poor instrumentation, that is with only a dissolved oxygen (DO) probe and/or with redox potential (ORP) and pH probes. This configuration is though and suited having in mind the basics application of monitoring and control tasks to a classical industrial scale SBR plant. For the anoxic phase termination time, the ORP signal is used, while the end time of the aerobic phase is detected with the help of the DO and pH signals.

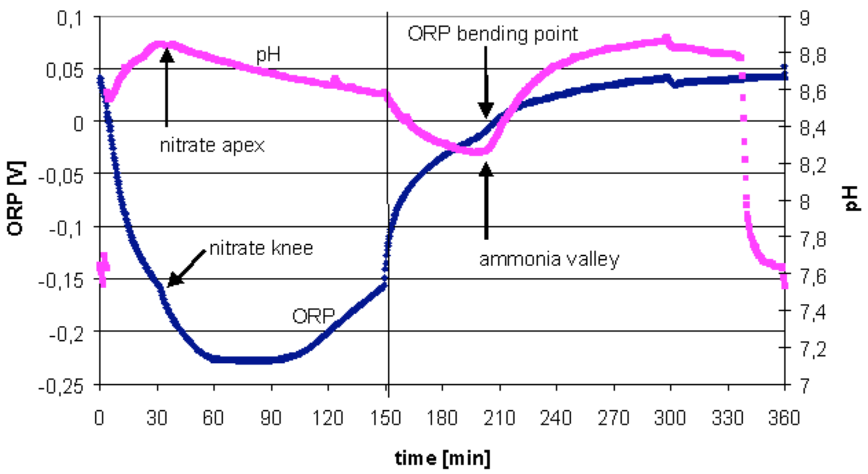

Figure 1: ORP and pH profiles during an SBR "standard conditions" cycle.

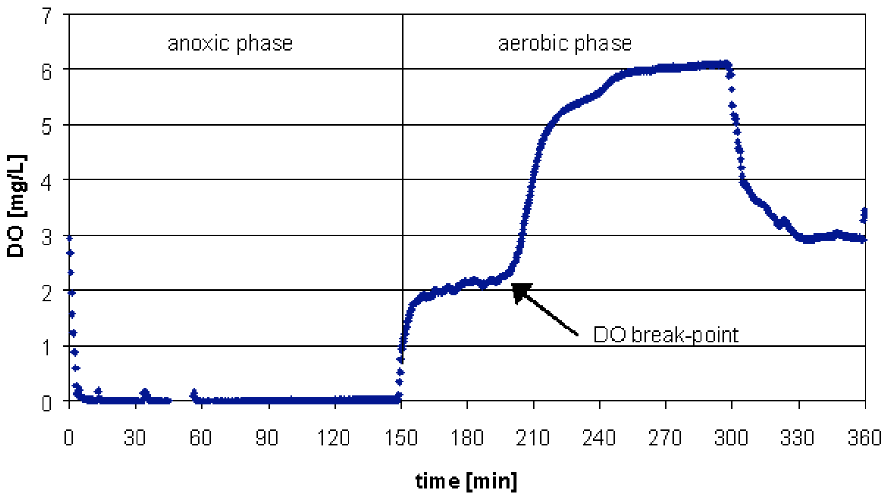

Figure 2: DO profile during an SBR "standard conditions".

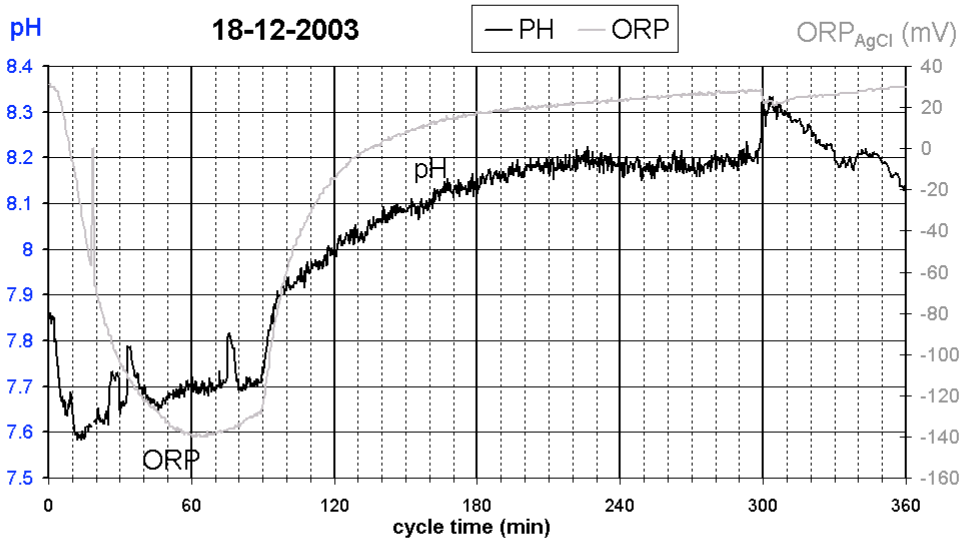

Figure 3: ORP and pH trends in the presence of a nitrification inhibitor (ATU) and of an insufficient COD/N influent ratio.

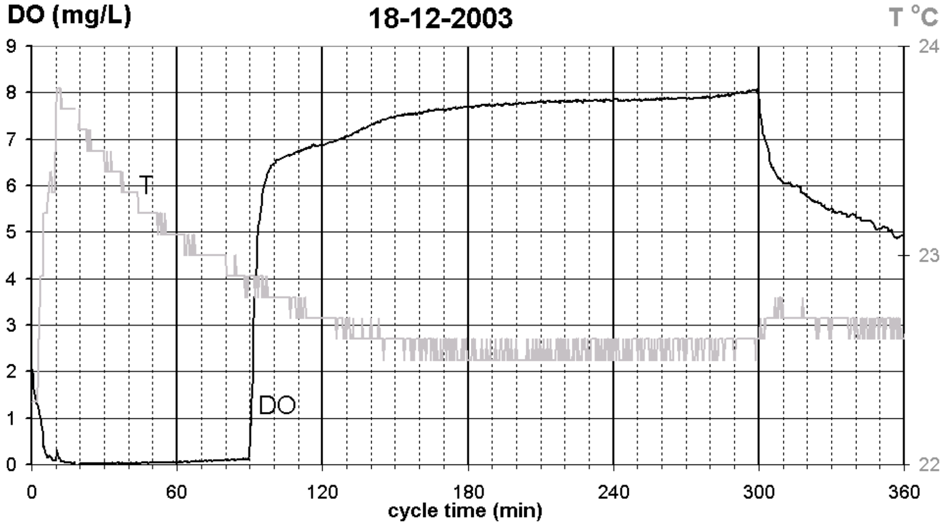

Figure 4: DO and temperature trends in the presence of a nitrification inhibitor (ATU) and of an insufficient COD/N influent ratio.

The second configuration is related to an advanced monitoring and control of the SBR plant, proposed within the EOLI (see WP5 and WP7 reports and deliverables) to get insight about the nitrogen removal rates and toxicants, and it is implemented when the UV and/or TITAAN hardware sensors (see WP3 reports and deliverables for details) are present together with the classical probes (pH, DO and ORP). In particular, the added information provided by the UV sensor is concerning with the monitoring of some organic pollutants (chlorophenol) and compounds (nitrite and nitrate), while the TITAAN can be used to detect toxicant in real time and to evaluate on-line estimations of the bacterial activity.

The UV sensor was used at the INRA to monitor the evolution of nitrates, nitrites and soluble COD in the SBR reactor. For technical details and development of this sensor please refer to Gradient report of the WP3. In order to evaluate the instruments on the LBE-INRA SBR, firstly a series of experiment were done during May-July 2005 to calibrate the sensor with Narbonne effluent and perform a robust COD, nitrites and nitrates estimation. In Figure 5 a comparison between the data obtained by the UV sensor (Y-axis) and data obtained by laboratory measurement (X-axis) are given. From left to right the variables are NO3, NO2, COD. In Table 1 are reported the regression coefficient, the maximum error and the range of the measurement for each variable.

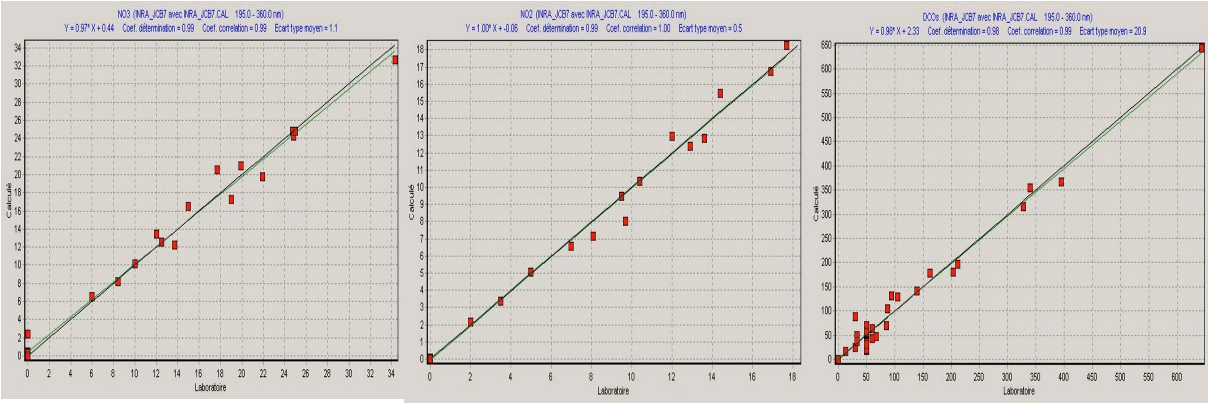

Figure 5 - UV sensor calibration

Table 1 : Calibration of the UV sensor

	NO_3	**NO_2**	**COD**
Regression coeficient	**0.99**	**1**	**0.98**
Maximum error	**1.1 mg/l**	**0.5 mg/l**	**20.9 mg/l**
Range	**0-35 mg/l**	**0-35 mg/l**	**0-600 mg/l**

In Figure 6 it's reported the validation of the measurements: analysis performed with UV sensor (blue square) are compared with laboratory data analysed with the chromatographic Dionex (black triangle). The figures from left to right match with NO3, NO2 and COD. The data correspond to one SBR cycle that starts at the point 'a' with a quick filling followed by denitrification phase until point 'b', where the nitrification starts.

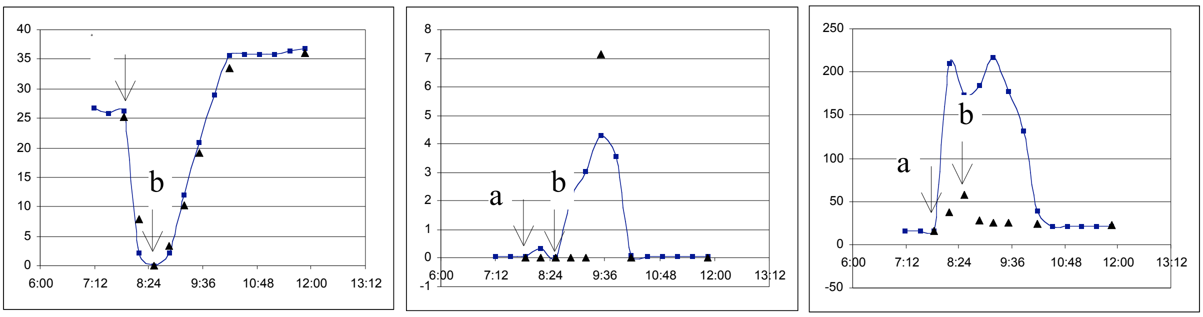

Figure 6 : Validation for one SBR cycle

On line NO3 and NO2 measurements fitted well with the off line measurements while the sensor present some problems to measure the COD which is not easy to detect with accuracy even with laboratory analysis. For NO2 the values less then 2 mg/l are not detectable with the Dionex.

The UV sensor is in use at the LBE-INRA reactor to monitor the evolution of the nitrogen oxidized forms and of the soluble organic matter; anyhow a periodic calibration of the instrument is needed to assure good quality estimations.

The TITAAN instrument is described in details in the Deliverable 3.2. It is an on-line set-point titrator which allows the plant operator to perform pH-stat and/or DO-stat titration tests on sludge samples on on sludge+influent samples automatically collected by the system at definite times synchronised with the SBR cycle time.

The implemented set-point techniques is well known in the literature for its potentiality in nitrification and denitrification monitoring capacity. A comprehensive literature review on this subject can be found in Deliverable 3.1. Based on literature data and on the experience gathered on the use of an off-line titrator (the MARTINA instrument developed by SPES) by POLIMI for the monitoring of the lab-scale POLIMI-SBR and of the pilot-scale ENEA-SBR, five titrimetric procedures were proposed (referred to as MODEs) for evaluating parameters of great interest for the monitoring of SBRs for nitrogen removal. These Modes are hereafter summarised (more details can be found in the Deliverable 3.2):

- Mode 1: detection of acute toxicity of the SBR influent on nitrifying biomass;
- Mode 2: estimation of the nitrifiable nitrogen content of the SBR influent;
- Mode 3: measurement of the nitrification capacity of the SBR, assessed in terms of oxidation rates of both ammonium to nitrite and of nitrite to nitrate, allowing to predict nitrite build up;
- Mode 4: monitoring of the ammonia oxidation process during the aerobic phase in a SBR reactor;
- Mode 5: estimate NO_x^- concentration at the end of the aeration phase in the SBR tank.

Data collected during the titration tests are automatically elaborated by the master computer linked with TITAAN and results are stored in a permanent memory.

It has to be stressed that TITAAN is a powerful tool in the hands of plant operators, who can efficiently use the results obtained by the titrator in order to prevent faults in the biological processes. Examples of possible usage of TITAAN results to implement correct operational strategies can be listed as follows:

– Mode (1) can give an early warning that allows the operator to divert part of the influent flow to a provisional storage tank (e.g. a rainwater tank) and/or to operate other countermeasures (e.g.: addition of powdered activated carbon).

– Mode (2) can alert the operator to increase air blower velocity and valve openings, well before the detection of low-DO conditions during the aeration phase (which can be too late); also, the duration of the aerobic phase can be increased if necessary.

– Modes (3) and (4) can check whether both autotrophic populations (AOB and NOB) are working at their optimal rates; for example, this test can detect if the rate of nitrite oxidation is slowing down, leading to possible nitrite build-up. By looking at historical data of the measured rates the operator can check whether the trend is decreasing and, consequently, can take adequate countermeasures (i.e.: increasing the duration of the aeration phase and/or inoculate fresh fully nitrifying sludge.

– Historical data collected from Mode (5) can point out trends of increasing nitrate concentration (both at the end of the anoxic phase and in the effluent), so that, again, adequate countermeasures can be taken by the operator, such as dosing easily biodegradable organic carbon during the fill or the anoxic phase or increasing the duration of the anoxic phase. Moreover, Mode 5 allows the operator to measure on follow the evolution of the the maximum denitrifiation rate of the SBR sludge.

Sensors' integration

As far as the on site implementation at the plants of the two configurations discussed above in terms of a sensor network, the focus point is the hardware and software integration of the several probes and hardware sensors as system components into the EOLI supervision system architecture.

The hardware integration migrates form the EOLI approach for the development of a WWTP digital platform. Each probe and sensor is equipped with an embedded electronic slave board that has the task to acquire and perform a first conditioning of the signal and, if required, to carry out periodical operation of diagnosis, such as detection of faults, and auto-calibration.

The information from the slave boards are gathered for storing or logging by the main board exclusively on a digital support (viz. digital media). The communications between the main and the slave boards are made via serial RS485 link or by RF wireless link. The embedded electronic main board of the platform is equipped with an integrated PSTN modem, with an Ethernet card and with serial RS232/RS485 interfaces to exchange data and commands with a PC and possibly a PLC.

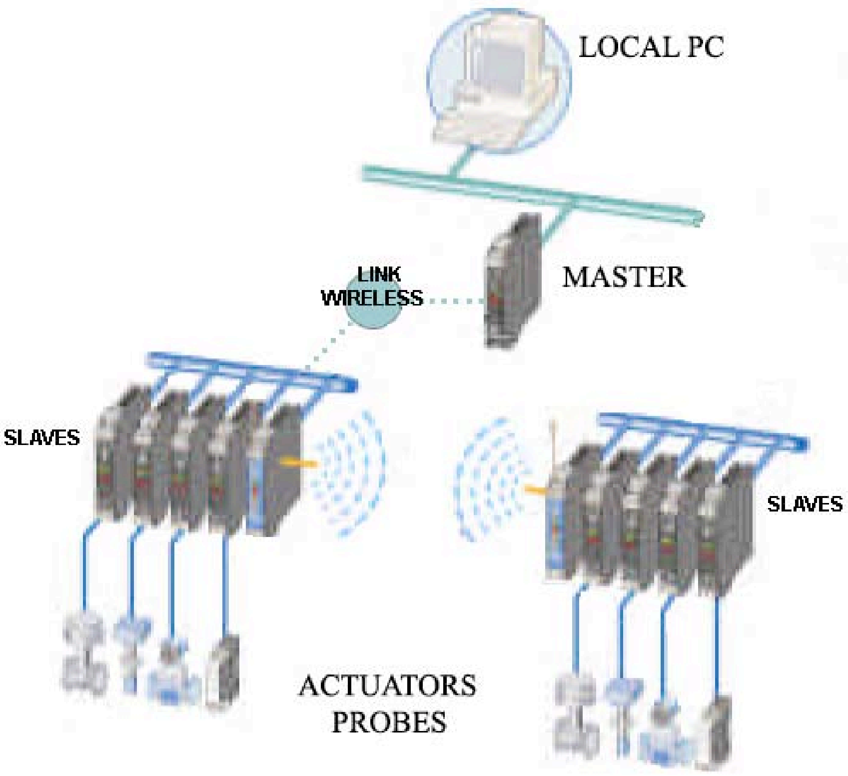

Figure 7: EOLI integration architecture

For the EOLI set of sensors we have only one kind of wiring (RF or RS485) with only one protocol to manage. From the communication point of view, the PC is the master for the main board of the plant: at fixed time interval the EOLI local software (see deliverables D8.3 and D8.4 for more details) requires data, via RS232 serial port, from the board. In this way the PC will only implement one communication protocol and will interface only one hardware board (Figure 7).

The EOLI software architecture is based on the client/server technology in which different modules implemented for different purposes, can share the same resources using a relational database management system (DBMS) that is introduced to replace the limitations of the file sharing architecture.

In this communication system the Remote Procedure Calls (RPCs) or standard query language (SQL) statements are typically used to communicate between the client and server.

The modules can be developed in any programming language that is able to open a socket towards the database server and this assumes a wide number of possible developments.

The core, both at remote control centre and at the local plant, is a database implemented in MySQL technology and is used to store all the data gathered (measurements), generated (commands), transferred and managed by the EOLI system.

At the local plant level, the main frame software is organized in modules. Software modules can be enrolled into the system to implement features and functionalities.
The general schema for the integration of the several modules in the software main frame is focused on how MySQL queries are used to implement a powerful method for the on-site integration of the EOLI system.
The co-operation between different modules is really effective – even if they are resident on different machines and in different places – because they would interact in the same way they would do if they were implemented at the same site: by the way of the MySQL server database.

As far as the on site implementation of the two EOLI sensor configurations established in the previous section it is possible to split the problem in two following steps:

- the connection of the pH, DO and ORP probes;
- the connection of the two hardware sensors, The UV one and the titration biosensor TITAAN, developed within the EOLI.

The first step is attended with the physical connection of the probes to one or more slave boards according with their location at the plant. The procedure for the enrolment of the probes into the EOLI system using the tool provided by the local software (see deliverable D8.4) creates the table into the MySQL database for the storage of the measurements of each variable.
The second step enables the second end more complex sensor configuration.
The UV sensor is managed by a devoted PC: the EOLI system interact with this alien PC using a software module as media. As a consequence the integration of this hardware sensor is reduced to the enrolment of both the related software module and the variables to manage the measurements produced into the EOLI local software, actions that automatically imply the update of the database tables.
The titration biosensor TITAAN is managed by the main board in the same way of a slave board, connected by a RF link or a serial link – the TITAAN is provided with the same kind of links as it is a slave board. So its integration is attended simply enrolling into the EOLI local software the variables needed for the management of the measurements produced, and this automatically imply the update of the database tables.

The solution assumed for sensor's network integration is really modular: any new sensor can be added connecting it to the system by the way of a slave board or a software module and assigning it a code (the address) for the enrolment into the EOLI software. The increase of complexity so remains a priori defined as the same enrolment procedure applies to any kind of sensor. It is a real plug and play solution because the only installation requirement is that the slave boards have to be connected to the sensors and the main board to the PC via RS232 (or by the other links) or a software module has to be enrolled into the local software. Then the enrolment of the sensors is performed into the EOLI software, with no need to modify or to interact with the PC operating system or to run set-up or installation software packages.

Conclusions

Two different configuration for the sensor network were defined and investigated in the experimental and validation activity during the life of the project.

They are thought to be applied under different working conditions and to match the requirements of different on site installation at industrial poor instrumented plants (the first configuration) and at advanced instrumented plants – big size plants and pilot plants for research and development (the second configuration).

The formal definition of the hardware and software architecture of the EOLI system and its implementation takes into account the issues for the integration of the sensor network.

A well assessed and reliable procedure was implemented for the integration in the EOLI system of the several probes and sensors involved as components of the sensor network and GUI's for the operators were provided into the EOLI local software.

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