EOLI

Efficient Operation of Urban Wastewater Treatment Plants

Work Packages 6 & 7
Mid-Term Report

J. Harmand & C. Verde
Participants
D Wimberger
J Mina
J Cuellar
D. Mazouni
L. Lardon
F. Ciappelloni

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Content

1. Introduction

The WP6 is dedicated to the automatic detection and identification of faults, (FDI) which produces unpermitted deviations of the characteristic properties or parameters of the SBR process from the standard conditions [1]. The general framework of the FDI system attempts to extract sensors, actuators and plant faults information from measurement data considering the normal operation of the global process. This fact demands available measurements and a complete characterization of the normal process conditions. Common characterizations of the normal conditions are rules, equations, patterns, parameters intervals. In order to tackle the FDI problem is common to search a decomposition of the system.

The WP7 is dedicated to the design of an on-line decision support system which integrates all the available information, coming from the FDI and Control systems, and takes appropriate actions to maintain the operation of the SBR. It can be considered as a continue support for the operator of the process [5] and its called supervision system (SUS).

On the other hand, taking into account that

- **the EOLI objective is to design a modular and reliable monitoring system for WWTP,**
- **the supervision, monitoring and FDI tasks are strong correlated, and**
- **the impossibility to handle all the FDI cases for the EOLI process in the global traditional framework,**

Leaders of WP6 and WP7 decided to merge part of the activities of both packages reorganizing the activities into a common framework and suggest the joint development of the above mentioned tasks in the internal report. Therefore, this document reports the methodologies, activities, results and future works of both packages in an integrated way. For the annual reports, as it has been suggested at UCL, each work package report must be written separately with the common technical information given in annexes.

2. Methodology

To specify the functionality of the FDI and SUS considering practical situations, as first step we captured the information about the faults of the EOLI experiments made during the first year. The Annex A shows the questionnaire sent to the four laboratories, POLIMI, UU, LBE-INRA and UNAM, to capture the real faults of the installations. The sensors, actuators have a common template and the abnormal condition of the process has a free format.

On the base of this poll, we analyze the more important and critical faults to be considered by the FDI system and SUS. Taking into account the reported faults, the available models, data, and computer requirements we propose to tackle the faults for actuators and sensors separate from those of the process [2]. The faults in sensors and

actuators are generic and independent of the process; and the faults associated with a particular SBR of EOLI demand specific descriptions of the process behavior with strong interrelation between variables and usually access historical data. The selection of faults to be tackled in EOLI has been carrying out and the final selection was discussed during the fourth EOLI meeting at UCL. As result, the specifications of the FDI diagnosis system are determined achieving the first milestone of WP6. Base on this specification the work of the tasks for the future has been organized in a discussion with the participants of the WP6 and WP7.

For the design of the SUS a hierarchical and modular architecture is proposed that allows different implementations.

At this moment the architecture has been distributed between the participants involved in WP6 and WP7 for discussion and its final version must be confirmed at the meeting at UCL. It is planned that the complete SPES implementation will be validated in the SBR at the LBE-INRA and the SBR of UNAM and IBtech will be used for partial validations of the UNAM SUS implementation.

3. Activities

The activities of the first semester were carried out within the selection of interesting components of the global system with their associated faults. For the particular case of actuators and following devices were considered: servo-valve, pump, air blower, mixer, mass flow controller and for sensors the variables: PH, dissolved oxygen, temperature, level and flow rate. In particular we started to work with the case of fault detection in the dissolved oxygen sensor at the UNAM. For the case of FDI in the process we are working in the classification of the reactions phases and a detection proposition have been tested with the model EM2 of the LBE-INRA. For the particular SBR at the UNAM we started to find an interpretation of the activity of the biomass in term of the measurement data.

Regards WP7 the definition of the hierarchical architecture of the SUS was proposed and two implementations have been foreseen (LBE-INRA, UNAM). With this work the deliverable D7.1 *Definition of the hierarchical structure of the supervision system* has been achieved.

3.1 Specifications for Sensors and Actuators

Table 1 and 2 of the Annex A summarized the results of the questionnaire for sensors and actuators faults. Fig. 1 shows the results for the more critical sensors of the SBR process in which the Device Vulnerability Index is defined as follows. According to the severity of a fault, *j*, and the abnormal states of a device (*fuzzy, confuse or blind*) reported by the participant, *i*, the *Weight*, W_{ij}, quantifies the level of the fault *j*

$$W_{ij} = \begin{cases} 33.33 & \text{, for Fuzzy state} \\ 66.66 & \text{, for Confuse state} \\ 100 & \text{, for Blind state} \end{cases}$$

Then, considering

***n*=** **number of participants (4) and**

F_{ij}= **frequency of the fault *j* reported by the participant *i*, normalized to 6 months**

The Fault Vulnerability Index (FVI_j) can be quantified by

$$FVI_j = \frac{1}{n}\sum_{i=1}^{n}\left(F_{ij}W_{ij}\right)$$

and the global Device Vulnerability Index (*DVI*) can be evaluated by

$$DVI = \frac{1}{m}\sum_{j=1}^{m}\left(FVI_j\right)$$

where *m* corresponds to the number of reported faults. It means, the DVI represents the average of the faults states by the frequency of the events during 6 months for the 4 reactors.

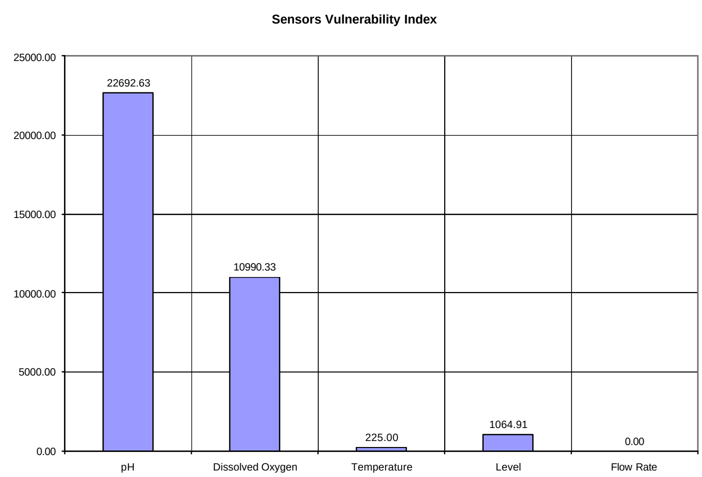

Fig. 1 Vulnerability Index

From the set of sensors faults and the characteristics of the SBR process shown in Fig 1, one can conclude that the detection of faults on both PH and Dissolved Oxygen sensors must be a high priority of the FDI system. Both abrupt as well as incipient faults are important to detect.

The vulnerability index for the common actuators, defined as above for the sensor case, is given Fig. 2. One can see from them that they have a low vulnerability index in comparison with the sensors, however because of hazardous effects of a fault in the hydraulic system, one suggests to include in the FDI specifications pump, valve as important cases. To study the effect of the failure air blower system some experiments were required at the WP1 using the UNAM SBR. At this moment the analysis of the data is carried out.

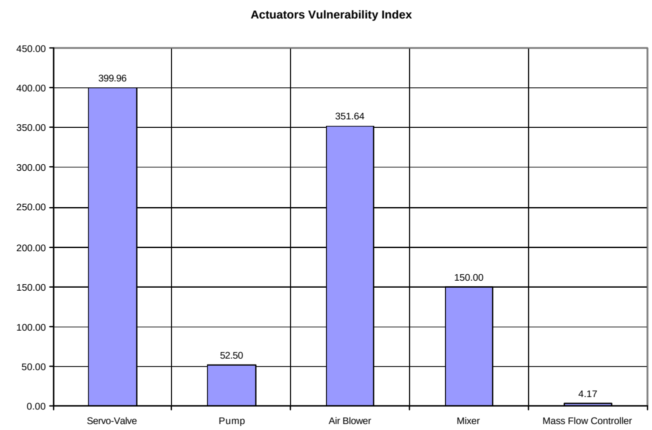

Fig. 2 Vulnerability Index

3.2 Specifications for Process Faults

The abnormal conditions reported by experts of EOLI and interesting cases in the four SBR process are summarized in the following paragraphs. The complete answers are given in the Annex A.

SBR pilot plant at UNAM modeled by EM1. The main concerns at the UNAM laboratory are human errors and inadequate maintenance which for example leads to lack of feeding or a leak in the peristaltic pump tubing.

Additionally the process and its model (EM1) have been investigated from the point of view of FDI routines that guarantee the protection of the biomass. Experiments were carried out by the WP1 UNAM to obtain data for characterization of process usual conditions and to verify biomass behavior under extended anaerobic conditions (i.e. interruption of the air supply system). Moreover, it has been required to WP4 for the design of a SS for the state variable associated to the biomass. The idea is to use the estimator for detection of slowly normal conditions deterioration.

SBR pilot plant at LBE-INRA modeled by EM2. The main concerns of the plant #2 are the problems associated to the sludge settlement and the classification of the reactions phases of the SBR. In particular the goal is to detect a problem in the sludge settlement capacity earlier than an expert would do and it is expected that a data-based system could solve the problem. A number of experiments will be dedicated to test the sludge level device which is already installed on the pilot plant of partner 2.

SBR pilot plant at UU modeled by EM2. The concern of the experts in Uruguay is concentrated on the vulnerability of the process to temperature deviation and its correlation with the recycling flow rate. In particular some unknown event (process fault or weather condition) produces an increase in the temperature and the recycling flow rate allows to compensate the effect. Therefore a regulator system can reduce the frequency of the event and a simple alarm can be used for monitoring.

SBR pilot plant at POLIMI modeled by EM2. The main concerns of the process at Milano are reduced nitratation capacity and the growth of gazing organisms. The

latter is supposed to be related to the acclimation of the biomass to reactor and influent conditions, and a natural adaptation is expected to take place. The reduced nitratation capacity could be detectable by MARTINA (assessment of the nitrification capacity) or related to a similar problem that is being investigated at LBE-INRA.

It is to remark that the participants of the meeting at UCL discussed possible reasons which deteriorate the nitratation capacity of the reactor. They agree to consider this as the main PF problem.

Considering:

- **the above given information which includes experience of the EOLI participants with their processes,**
- **the inaccuracy of models EM1 and EM2; EM1 deals with the reactor of UNAM and IBTech, while the EM2 is related to the other three laboratories (UU, LBE-INRA and POLIMI)**
- **the available scientific literature,**
- **the measurements variables,**
- **the reported specific faults, and**
- **the lack of on-line data,**

One can conclude that the detection and isolation of some of the reported faults will be impossible in the SBR at this moment. However, subset of faults and specific cycles of the process can be considered achieving a considerable improvement of the reliability of the SBR. This less ambitious task requires characterizations of subsystems of the SBR process to generate faults indicators (residual) which will be integrated by the monitoring system to determine the conditions of the process. This means the fault detection and isolation task must be spread in all the system. In particular, we propose to tackle the FDI problems using a distributed scheme in which diverse faults and cycles of the process are considered independently giving modularity to the diagnosis [3]. In this case the properties of a batch process can be exploited to solve some FDI problems.

3.3 Distributed FDI Scheme

To tackle the fault detection problem with a distributed structure, a change in the traditional scheme is proposed. Fig. 3 shows the novel structure detecting separately the sensors and actuators faults from the process at the first level [4].

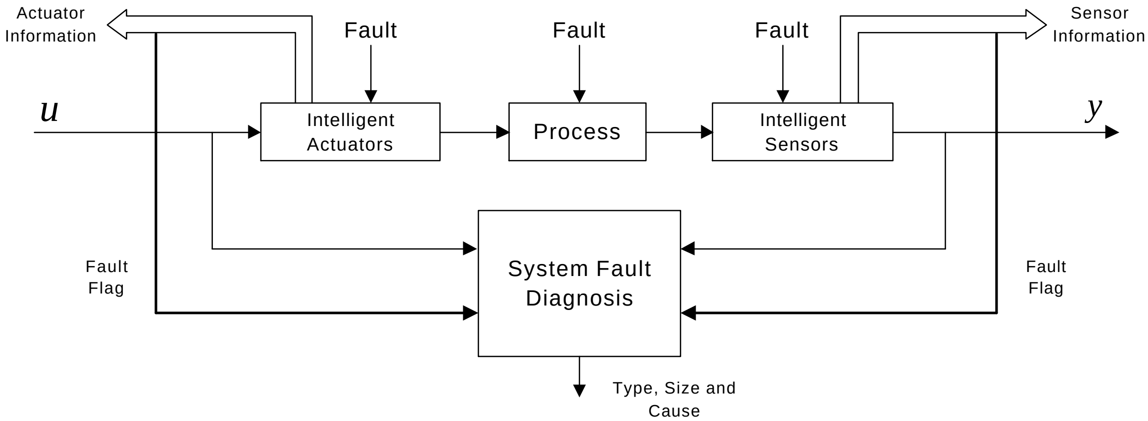

Fig. 3 Separation of the Fault Detection Tasks

This idea called distributed FDI scheme is shown in Fig. 4 for sensors and actuators and captures in an abstract structure, the faults diagnosis functions as they are implemented in practical cases.

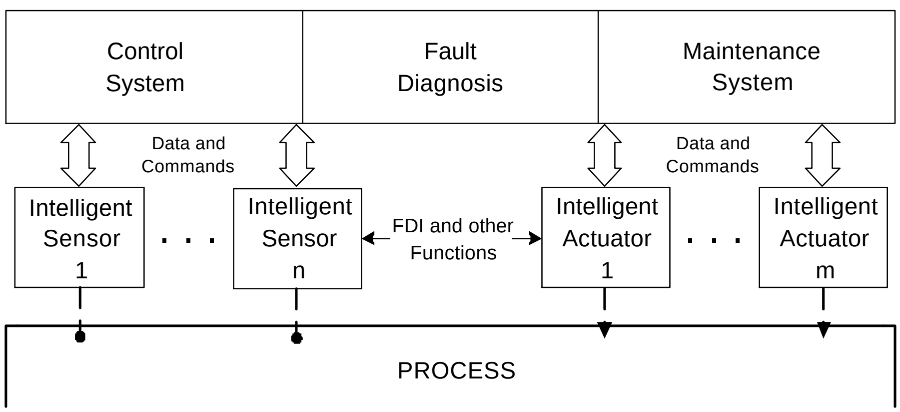

Fig. 4 Distributed FDI Scheme

This scheme requires the design of specific tests for each device but the same detection algorithm can be used in identical sensors without regard to the process. An advantage of this FDI structure is its modularity, since new fault cases can be integrated without requiring redesign of the system,. i. e. each indicator works independently of the others at the field level and therefore reliability of the system can be improved. More details of this contribution are given in the paper included in the Annex B.

3.3.1 Fault Detection for the Dissolved Oxygen Sensor

Since from the measurements of the dissolved oxygen (DO) critical information of the reactor conditions are obtained, and its vulnerability index is very high, there is a necessity to test frequently the conditions of the DO sensor; in particular we considered a dirty membrane which is the more sensitive part of the device. In this case the fact that the data of DO is not critical during the sedimentation cycle is exploited to test automatically deviations of the diffusion transfer time by an

estimation algorithm. The procedure is based on the step response of the current from the measurement Clark electrode given by

$$i(t) = i_{\infty}\left(1 + 2\sum_{n=1}^{\infty} exp(-\frac{(np)^2 D_m t}{b^2})\right)$$

Where: i_{∞} is the steady state current, D_m is the diffusivity of membrane and b is the thickness of the membrane. Fig. 5 shows the behavior of the estimator of $t = D_m / b^2$ with clean and dirty membrane and when the electrode current is interrupted during *60s* at *420s*. In normal conditions the estimation yields the nominal transfer time, *60s*, and with a dirty membrane a deviation of the values is detected. Deviations of *10%* and *20%* of *b* produce increments of *12s* and *30s* in the transfer time. At this moment we analyze the sensitivity of the detector to determine its viability in practical cases. This result is part of the master thesis of J. Cuellar at UNAM and will be integrated to the deliverable D6.1. The implementation requires extra efforts due to the lack of an extra sensor and electronic equipments to test the methodology.

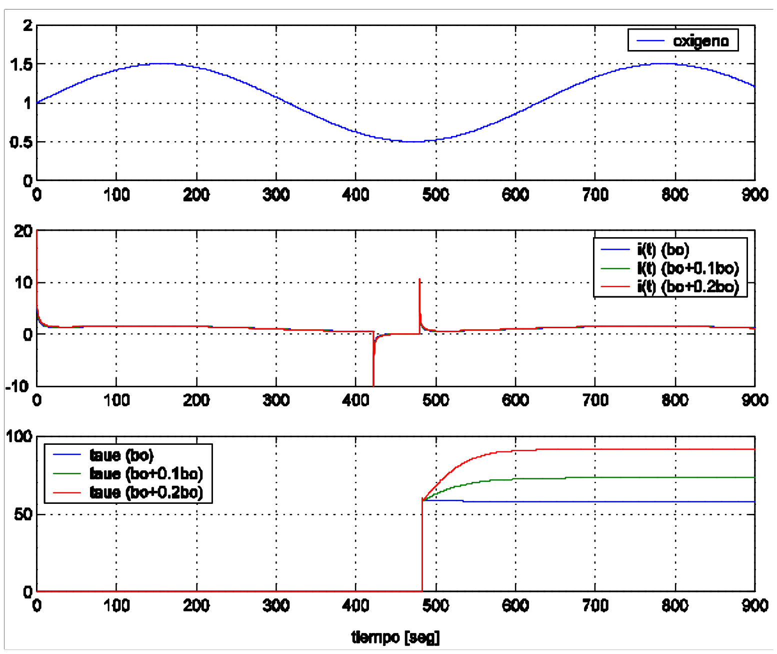

Fig. 5 Detection of the diffusion transfer time

3.4 Architecture of the Supervision System, SUS

To achieve a successful incorporation of the process control and the fault diagnosis in the supervision system, integration is a crucial factor: a completely integrated system allows a more complete access to subsystems as well as to combine various methods (hybrid approach) and thus leverage their varying capabilities with regard to a control task or detection and isolation problems.

This fact motivated the participants of WP7 to create an abstraction and patterns that allow the assembly of a reliable and adaptable complex control system, that incorporates fault detection and isolation elements of process, sensors and actuators, as well as supervision and decision support. Emphasis is put on properties like modularity and extensibility, with the final objective of creating a "design for change".

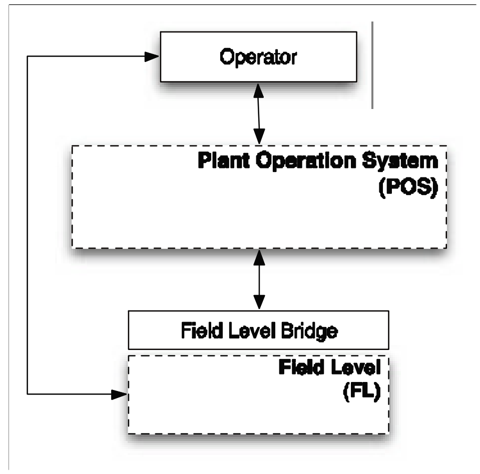

Fig. 6 General Supervision Architecture

The general architecture for SUS with its main subsystems is given in Fig. 6. The field level shown in Fig.7 includes process, actuators and sensors and it is communicated with the rest of the system using the bridge.

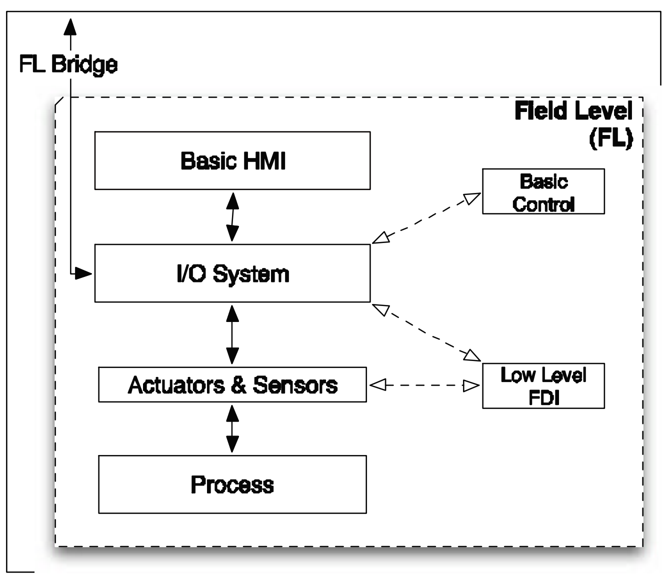

Fig. 7 Interaction of Field Level Components

The field level bridge provides a bidirectional link between the FL and the POS in a modular way. The idea behind the design is to achieve decoupling and to create patterns for reusable elements. The high level subsystem called Plant Operation System shown in Fig. 8 includes control, decision algorithms, data base, and human machine interface.

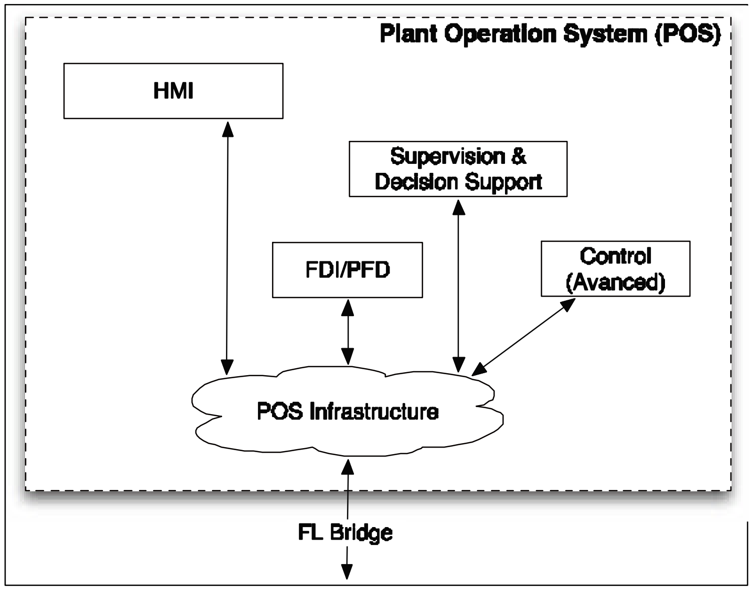

Fig. 8 POS Structure

The abstract architecture in detail is given in Annex B and has been distributed to the participants of WP6 and WP7. The report includes possible mapping of the SPES implementation is included there. This contribution is in preparation for submission to a conference.

3.5 FDI example at the POS level

Taking into account the SUS architecture one can see that a FDI algorithm can be located at two levels of the architecture. The field level refers to the cases in which the detection can be achieved in an independent way without communication of components and huge amount historical data. The high level fault diagnosis included in the POS block FDI/PFD requires measurements of diverse variables and couplings of residuals (indicators) to isolate faults and in most of the cases use a data base for historical process data included in the SUS.

Regarding the structure of the supervision system, we recall that again the objectives are rather different with respect to each SBR pilot plant. However, a common methodology can be suggested keeping in mind that the most important source of information is the history of the process, and then the system to be developed must include a data base to be accessed whenever needed for each element of the POS. In this case, statistical methods can be used allowing the classification of the actual state of the system with respect to previously identified conditions.

As example, the LBE-INRA, Narbonne proposed an algorithm which will be part of the POS to maintain the SBR working under high loading rate conditions while the settlement capacity of the sludge is maintained high. Therefore, the aim associated to WP6 and WP7 in this case is:

- **to detect organic or nitrogen overloads,**

- **to detect problems in ecosystem equilibrium (autotrophs vs heterotrophs),**
- **to detect problems in the aeration of the process,**
- **to detect a degradation of the sludge settlement capacity early enough to propose appropriate corrective actions other than a re-inoculation of the SBR.**

In each of these situations, the PFD element will propose a number of corrective actions to the user. Details of the contribution are given in the full work included in the Annex B.

At the UNAM the process and its model (EM1) are being studied from the point of view of FDI routines that guarantee the protection of the biomass. It is vital to encounter a valid description for the activity of the biomass that is backed by biological and biochemical knowledge. According to literature activity is strongly correlated with the respiration rate, a parameter that has been widely accepted as tool for model calibration and process control [6, 7]. Experiments have been carried out by WP1 UNAM with the objective to obtain an idea of the usual process conditions as well as to verify biomass behavior when exposed to extended anaerobic periods (6 hours). Latter does not seem to have any fatal impact on the biomass activity in subsequent cycles.

4. Results

During this semester four contributions have been made. The first one associated with the first milestone of WP6 *specifications of a diagnostic system for SBR considering practical situations*; final details of this milestone was discussed at UCL. As conclusion, the reduced nitratation capacity for reactors with model EM2 and the damage in the DO sensor are the main FDI problems for the EOLI reactos. The second one introduces a novel distributed scheme for FDI in a SBR process, in which two possible levels for the FDI are proposed, this work has be presented at the Congress XI CLCA04, La Habana, May, 2004. As particular case a FDI for the DO sensor has been validated by simulation and introduced in this publication. The third contribution introduces a new method to detect critical points during the reaction cycle of a SBR using DO and PH measurements and part of this work is submitted to Watermatex 2004. These results are part of the tasks associated to milestone of WP6 *A set of validated FDI routines which guaranties the protection of the biomass in the SBR*. The last result is related with the definition of the architecture for the supervision in which as particular case the SPES and UNAM implementation can be described. With this contribution the deliverable D7.1 *Definition of the hierarchical structure of the supervision system* is partial achieved.

Results & Task Objectives	Progress towards achieving objectives
WP6.1 Specifications of the FDI system	• **By a poll the most frequent and critical faults of the reactor during the filling and reaction phases was analyzed. The final version of the list of specifications for the diagnosis system was discussed at UCL.** • **For the PFI the reduced nitratation capacity is the main case to be investigated. In the sensors case the PH and DO are the most important and vulnerable devices.** • **A distributed FDI scheme is proposed to tackle the abnormal conditions**
WP6.2 FDI System Design	• **Since the biomass is not measured on line, it has been required to WP4 the design of a SS for the biomass (model EM1 at the UNAM).** • **A residual generator for faults in the DO membrane has been tested by simulations.**
WP7.1 Specifications of the supervision system	• **Since the system is to be implemented in Narbonne's SBR pilot plant, the identification of all information sources is the same than that of the Narbonne's SBR** • **In connection with WP6 and WP8 leader, the specifications for the SUS has been sent to WP8 leader** • **A general SUS architecture has been proposed which will be implemented at the UNAM reactor.**

WP7.2 Specifications system design	• **Development of a hierarchical structure of FDI and supervision and installation of a database under a TES/MSCP/MATLAB local platform (work detailed available in the Annex)** • **Installation of the TELEMAC database solution: the data are automatically sent to a database under the proposed PlantXML format** • **To be realized soon: implementation and tests of the SPES hardware and software solution**

5. Future Work

As result of the discussion at the meeting in UCL and taking into account the index of vulnerability for each device, a new poll will be required to finish the tasks associated to milestones M6.1. The leader of WP6 will ask the partners to weight the more important devices for the particular control and monitoring of each reactor.

The study about the implementation and validation of the algorithm for the DO membrane will be concluded at the UNAM.

Taking into account the models developed in WP2 and the measurement data the reduced nitratation capacity problem of model EM2 will be studied.

Taking into account the performance and assumption of the SS for the biomass developed in WP4 for the model EM1 at the UNAM, the development of the set of FDI routines for biomass protection will continue.

Related with WP7, the implementation of the SUS for the UNAM reactor will be started. In particular the software platform to dialog with I/O of the control and FDI algorithms (bridge implementation) will be started. This task requires a strong integration and collaboration of WP5 and WP7 as, it was mentioned at UCL.

Adaptation of the SUS architechture proposed in LLN for the monitoring of the sludge settlement capacity (at least the ability to early detect a problem in the settling velocity)

Implementation of the SPES system on the LBE pilot plant and evaluation of the system

6. References

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Annex A
EOLI-Questionnaire Sensors and Actuators

Please provide a table for each equipment installed in your reactor. We did not include a table for the hardware sensors developed in WP3, but may be André and Nicola can help us to define some abnormal conditions with the new equipments which can be considered in the WP6 and WP7 (Development of the Fault Diagnosis and Isolation System and Supervision system development).

We classified 3 fault levels for each equipment and the rate indicates the number of occurrences of the fault during the reactor operation hours (#fault/hr).

The levels are:

1) ***"Fuzzy"*** **means that the behavior is abnormal but still reasonable (noisy or spectrum out of shape)**
2) ***"Confuse"*** **(creasy) means that it is evident that the behavior is substantially abnormal, but the duration of this condition is to short to diagnostic the fault or the fault is intermittent.**
3) ***"Blind"*** **means the signal has not relation with any expected value and this effect persists during a long time.**

The working months means the number of total months which the equipment has been used without maintenance or replacement.

The rows of the tables indicate the most common faults for each equipment, but if an important case is missing, please don't hesitate to add a row that describes the condition. If you think we missed important cases or you don't understand what we want, please give us a comment about it.

1. Faults in Sensors and Transmitters

1.1. PH, type of sensor ________________ Manufacturer ______________
installed in ___________________

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Lost power				
Transmitter disconnected				
Lost temperature compensation				
Dirty membrane				
Cracked membrane				
Broken Electrode				
Drift				
Human				
Worn-out				
Unknown				
Others/describe ____				
General remarks ____				

1.2. Dissolved Oxygen, type of sensor______________ Manufacturer __________ installed in ________________________

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Lost power				
Disconnected transmitter				
Lost temperature compensation				
Dirty membrane				
Cracked Membrane				
Broken Electrode				
Drift				
Human				
Worn-out				
Unknown				
Reading out of the normal conditions				
Others/describe ____				
General remarks ____				

1.3. Temperature, type of sensor______________ Manufacturer ________________ installed in_____________

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Lost power				
Disconnected transmitter				
Open circuit in the transducer				
Leak of the thermal fluid (thermocouple)				
Thermal well dirty or debris filled (thermocouple)				
Drift				
Human				
Worn-out				
Unknown				
Others/describe ____				
General remarks ____				

1.4. Level, type of sensor ____________ Manufacturer _____________________
installed in ________________________________

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Lost power				
Disconnected transmitter				
Lost temperature compensation (sonic or ultrasonic)				
Receptor dirty (sonic or ultrasonic)				
Plates dirty (capacitor sensor)				
Inappropriate tank ground (capacitor sensor)				
Sewage flow out of the reactor				
Sewage reach erroneous level				
Human				
Worn-out				
Unknown				
Drift				
Others/describe ____				
General remarks ____				

1.5. Flow rate meter, type of sensor _____________ installed in______________

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Lost power				
Drift				
Human				
Worn-out				
Unknown				
Others/describe ____				
General remarks ____				

1.6. Light intensity, type of sensor Optic installed in_____________ (LBE)

Effect or Fault	Fuzzy rate	Confuse Rate	Blind Rate
Dirty			
Worn-out			
Human			
Unknown			

2. Faults in Actuators

2.1. Servo-valve, type of actuator_________________ Manufacturer ____________ installed in______________________

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Signal conversion stage failed				
Modulator system disconnected or failed				
Valve Not moving				
Not closing fully				
Not opening fully				
Movement sluggish				
Human				
Worn-out				
Unknown				
Others/describe ____				
General remarks ____				

2.2 Pump, type of actuator_______________ Manufacturer _____________________ installed in ______________________

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Lost power				
Inlet or outlet valve blocked (positive displacement pump)				
Piston blocked (positive displacement pump)				
Rising vibration				
Human				
Worn-out				
Unknown				
Others/describe ____				
General remarks ____				

2.3 Air blower, type of actuator_______________ Manufacturer ________________ installed in _______________________________

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Lost power				
System blocked				
Human				
Worn-out				
Unknown				
Not moving				
Others/describe ____				
General remarks ____				

2.4 Mixer, type of actuator_______________ installed in

Effect or Fault	Fuzzy Rate	Confused Rate	Blind Rate	Working months
Lost power				
Decreasing power in the motor				
Eccentric rotation or rising vibration				
Human				
Worn-out				
Unknown				
Others/describe ____				
General remarks ____				

3. Abnormal Process Conditions

In the following, you can find the questionnaire that we have put together for abnormal process conditions that you think might occur and/or have occurred in the SBR. Abnormal conditions are to be understood as process conditions that are not considered by control and that you consider to be outside of the normal operating conditions of your process.

Please provide one filled in questionnaire for each case of abnormal condition.

Questionnaire (Template for each specific case)

Abnormal Condition: (Name, short name)
1. Description
2. Description of observations or reasoning indicating the abnormal condition
3. Description of actual or possible operator action
4. Occurred or expected to occur in your EOLI dedicated reactor? (Yes/no/don't know)
5. Frequency or expected frequency of occurrence (low, medium, high)
6. Importance/criticality you would assign to this abnormal condition (1=low-5=high)
7. References or literature that you consider to be related to this abnormal condition

Fault Occurrence Statistics for Device

Fault	**Sensors**	Uruguay	Italia	México	Francia					
Fault	pH	Type	Type	Type	Type	Fault Frequency Normalization				Fau
		Electrode	InLab 412[2]	720A[2]		times / 6 months				F=33.33 ,
		P - 6m	P – 6m	P - 0.5m		Uruguay	Italia	México	Francia	Uruguay
1	Lost Power		B- 1 t/m			0	6	0	0	0
2	Transmitter Disconnected			F- 2 t/m		0	0	12	0	0
3	Broken Transmitter			B- 2 t/m		0	0	12	0	0
4	Dirty Membrane			F- 4 t/m		0	0	24	0	0
5	Drift	F- 2 t/w				48	0	0	0	33.33
6	Worn-Out		F- 1 t/6m	F- 1 t/5y		0	1	0.1	0	0
7	Human		C- 1 t/w			0	24	0	0	0
8	Unknown		F- 5 t/h			0	21600	0	0	0

Fault	Dissolved Oxygen	Type	Type	Type	Type	Fault Frequency Normalization				Fau
		Electrode	COS 3s[2]	COS4 COM 223[2,4]		times / 6 months				F=33.33 ,
		P - 6m	P – 6m	P - 10m		Uruguay	Italia	México	Francia	Uruguay
1	Lost Power		B- 1 t/m			0	6	0	0	0
2	Dirty Membrane	F- 2 t/d	C- 1 t/h	F- 1 t/w		360	4320	24	0	33.33
3	Cracked Membrane	F- 1 t/3m		B- 1 t/10m		2	0	0.6	0	33.33
4	Drift			F- 1 t/w		0	0	24	0	0
5	Worn-Out		F- 1 t/6m			0	1	0	0	0
6	Human		C- 3 t/w			0	72	0	0	0
7	Unknown		B- 1 t/m			0	6	0	0	0

Fault	Temperature	Type	Type	Type	Type	Fault Frequency Normalization				Fau
		Electrode	Pt100[2]	Inc. in DOx Sensor		times / 6 months				F=33.33 ,
		P - 6m	P – 6m			Uruguay	Italia	México	Francia	Uruguay
1	Lost Power		B- 1 t/m			0	6	0	0	0
2	Dirty Electrical Connection		B- 1 a 2 t/m			0	12	0	0	0

Fault	Level	Type	Type	Type	Type	Fault Frequency Normalization				Fa
		3 Metal Elect.		Level Switch[2]		times / 6 months				F=33.33 ,
		P - 6m				Uruguay	Italia	México	Francia	Uruguay
1	Transmitter Disconnected	B- 1 t/w				24	0	0	0	100
2	Inappropriate Tank Ground	B- 1 t/6m				1	0	0	0	100
3	Sewage Flow Out of Reactor	C- 1 t/2d				90	0	0	0	66.66
4	Sewage Reach Err. Level	C- 1 t/d ~10%				180	0	0	0	66.66
5	Dirty Electrodes	?- 1 t/w				24	0	0	0	33.33

Fault	Flow Rate	Type	Type	Type	Type	Fault Frequency Normalization				Fa
		Rotameter				times / 6 months				F=33.33 ,
		P - 6m				Uruguay	Italia	México	Francia	Uruguay
0	No Fault					0	0	0	0	0

Actuators

Fault	Servo-Valve	Type	Type	Type	Type	Fault Frequency Normalization				Fa
		Solenoid[1]				times / 6 months				F=33.33 ,
		P - 6m				Uruguay	Italia	México	Francia	Uruguay
1	Not Closing Fully	C- 1 t/w				24	0	0	0	66.66
2	Not Opening Fully	C- 1 t/w				24	0	0	0	66.66

Fault	Pump	Type	Type	Type	Type	Fault Frequency Normalization				Fa
		Peristaltic	Peristaltic[3]	Peristaltic[5]		times / 6 months				F=33.33 ,
		P - 6m	P – 6m	P - 10m		Uruguay	Italia	México	Francia	Uruguay
1	Lost Power		B- 1 t/m			0	6	0	0	0
2	Line Clogging	?- 1 t/6m				1	0	0	0	33.33
3	Worn-Out		B- 1 t/6m			0	1	0	0	0
4	Human	C- 1 t/6m		F- 1 t/4m		1	0	1.5	0	66.66
5	Unknown			F- 1 t/m		0	0	6	0	0

Fau lt	Air Blower	Type	Type	Type	Type	Fault Frequency Normalization	Fa

		Rec. Air Comp.	Mem. Air Comp.	Air Compressor		times / 6 months				F=33.33 ,
		P - 6m	P – 6m	P - 10m		Uruguay	Italia	México	Francia	Uruguay
1	Lost Power	B- 1 t/6m	B- 1 t/m			1	6	0	0	100
2	Blocked Diffuser	F- 1 t/d				180	0	0	0	33.33
3	Broken Air Line	?- 1 t/6m				1	0	0	0	33.33
4	Worn-Out		B- 1 t/6m			0	1	0	0	0
5	Unknown			F- 1 t/m		0	0	6	0	0

Fault	Mixer	Type	Type	Type	Type	Fault Frequency Normalization				Fau
		Helix Impeller	Mec. Var-Speed			times / 6 months				F=33.33 ,
		P - 6m	P – 6m			Uruguay	Italia	México	Francia	Uruguay
1	Lost Power		B- 1 t/m			0	6	0	0	0

Fault	Mass Flow Controller	Type	Type	Type	Type	Fault Frequency Normalization				Fau
				GFC37[6]		times / 6 months				F=33.33 ,
				P - 4y		Uruguay	Italia	México	Francia	Uruguay
1	Worn-Out			B- 1 t/3y		0	0	0.1666	0	0

General Remarks:

1. There are 6 solenoid valves operating in each reactor. One of them, in each reactor, fails 1 t/w.
2. This sensor is cleaned and calibrated 1 t/w.
3. Pipes cleaning 1 t/m.
4. Drift appears when the membrane is dirty. Membrane change is done 1 t/10m of operation.
5. The piping tube must be replaced in average 1 t/15d. When the tubing is changed the pump must be recalibrated.
6. One week before the failure, the valve do not closed fully and a small leak of air was observed during decantation.

Notation:

P; Indicates the period during the equipment has been used.

t; Times (occurrence).

d, w, m, y; Respectively means, Days, Weeks, Moths and Years.

F, C, B, ?; Respectively means, Fuzzy, Confuse, Blind and Not Indicated.

Annex B Contributions

Submitted:
Watermatex 2004 Conference: F. Ciappelloni, D. Mazouni, L. Lardon, J. Harmand On-line Supervision and Control of an Aerobic SBR Process

Presented:
IX Congreso Latinoamericano de Control Automático, 10-15 May, 2004, La Habana, Cuba. C. Verde, J. Cuellar, J. Mina. Arquitectura distribuida para la detección autónoma de fallas en sensores.

Preparation:
D. Wiemberger. Enabling FDI and Supervision: An integrated system for the operation of a Process/Plant.

On-line Supervision and Control of an Aerobic SBR Process *(submitted to watermatex 2004)*

F. Ciappelloni, D. Mazouni, L. Lardon, J. Harmand[*]

Laboratoire de Biotechnologie de l'Environnement, INRA-LBE, Avenue des étangs, 11100 Narbonne, France. Telephone +33 468 425 161, Fax +33 468 425 160

Abstract: This paper presents a new software developed in MATLAB for analyzing on-line data of an aerobic SBR, detecting faults and, in this case, proposing the most probable causes of fault. Process diagnosis is achieved using a statistical method divided in two main phases: off-line model building and on-line data diagnosis. The off-line model identifies the correct working conditions of the system (standard operative conditions). It includes the characterization of the deviation of the system from these standard conditions in the case of changing in the biomass properties or carbon and nitrogen load characteristics. The on-line diagnosis aims at collecting and analyzing all the available data available through industrial sensors, and at classifying the behavior of each treatment cycle. The diagnosis performance of the proposed method is tested using a data set of an aerobic SBR pilot plant.

Keywords: monitoring, Sequencing Batch Reactor (SBR), Fault Detection and Isolation (FDI), Principal Component Analysis (PCA), Decision Support System (DSS).

INTRODUCTION

Safety in industrial processes is becoming more and more an important requirement and the ability to early detect and isolate possible causes of process faults is a primary need. In wastewater biological treatment processes, and in particular when dealing with batch processes, the on-line diagnosis is a very important requirement because of the high sensitivity of the whole system to a wide variety of external inputs and internal changing conditions. The operating efficiency can significantly vary over the time and is not easy, even for operators or experts to understand the observed changes. It is proved that the application of an efficient diagnosis system may help operators and engineers to manage in the best way the treatment process to maintain it as close as possible to the optimal conditions before the integrity of the process is affected.

A fault is any unexpected change in a system, due to malfunctions or variation of operating conditions. The aim of an advanced diagnosis system is not only to detect and isolate a fault, but also to propose the operator, as soon as the problem is detected, the most probable causes of fault to intervene quickly and to solve the problem in the fastest way and restore the optimal conditions. The need for an efficient supervisory system able to control bioprocesses in real time is important. Maintaining the efficiency and the quality of the sludge in the reactor is the first requirement. However, it is highly influenced by external inputs. Furthermore, the settleability of the sludge can be durably altered by changes in environment conditions. Too often, the only way to restore the process is to re-start up the process with fresh biomass leading to an important waste of time.

[*] **Corresponding author**

In the present study, an aerobic SBR pilot plant has been chosen as an illustrative example of biological WWTP. In aerobic conditions a series of biological processes take place in presence of oxygen provided by diffusers to the mix of organic matter and biomass. The first step in organic degradation is the consumption of COD (Chemical Oxygen Demand), the second is the transformation of NH4 (ammonium produced by the ammonification of organic nitrogen present in the input) into NO2, while the third and last step is the transformation of NO2 into NO3 that will be discharged at the end of the settling phase. In this treatment process, the most critical phase is clearly the aeration period during which the most influent parameters are Kla (oxygen transfer coefficient in liquid phase), COD and TKN loading rates and the concentrations of biomasses (heterotrophic and autotrophic) in the reactor.

The supervision system analyzes on-line data provided by the acquisition system of the plant comparing each treatment cycle to the "ideal cycle" and to the others obtained by varying some operating conditions; if the real cycle is near to the best cycle, it will be classified as a good cycle, else it will be considered similar to the nearest simulated cycles and so its operating conditions.

The paper is organized as follows. First, the description of the aerobic SBR pilot plant and of its instrumentation is given. Then, the methodology used to analyze and classify on-line data as well as the model implemented to generate the optimal condition and the possible causes of fault are presented. Finally, the application of PCA to compare simulated and real cycles and so to suggest the most probable cause of fault is reported. Finally examples of experiments and results of the application are presented and discussed.

MATERIAL AND METHODS

The SBR pilot Plant

The experiments were performed using an aerobic SBR pilot plant at the "Laboratoire de Biotechnologie de l'Environnement" of INRA in Narbonne, France.

Activated sludge

The sludge used in the SBR comes from the urban wastewater treatment plant (WWTP) of Coursan, France. This plant was chosen because both carbon and nitrogen are removed biologically. The 200 liter tank was filled with about 100 liters of this sludge and operated under aerobic conditions for the first two months. A low organic loading rate (<0.7 kg COD/m3/day) was applied. Then, the anoxic phase was added and after a total start up period of three months, a good purification rate of 98% was obtained while high sludge settleability was observed. The actual average sludge concentration is 12 g/l.

Influent wastewater

Semi-synthetic dairy wastewater is used as influent. This feed is prepared by dilution of concentrated whey collected in a cheese dairy. The characteristics of the raw whey is as follows : 70 g/l COD and 2 g/L TKN. To simulate possible changes in the C/N ratio of the whey, organic nitrogen as Urea (CH4N2O) is used. Regarding these characteristics and given that the process is operated under low loading rate, in "standard conditions", the volume treated is 50 l/day. Its average properties are : 5 g/l COD, 250 mg/l N-TKN, TSS>10 g/l and pH = 6.23.

Pilot plant

The reactor tank is a 47 cm (diameter) times 130 cm (height) cylinder of a total volume of 255 liters. It is equipped with a variable input flow rate pump to fill in the reactor and a controlled valve to withdraw the effluent by gravitation and, when necessary, the sludge in

excess. Air is used for aeration and mixing. Its flow is controlled by a gas flow meter. The plant is operated as follows. Filling period 1 (25 liters) : 5 mn, Anoxic period 1 : 2 h, Aerobic period 1 : 8 h 50, Filling period 2 (25 liters) : 5 mn, Anoxic period 2 : 2 h, Aerobic period 2 : 8 h 50, Settling and draw period : 2 h 05.

Measurements

The following sensors are installed : pH, Temperature, Dissolved Oxygen, Redox, CO2 and O2 content of the output gas and sludge level. All sensors and actuators are connected to a PC and the functioning of the process is completely automatized. The on line measurements are acquired through a home made software called MSPC and automatically stored in a data base using a data format defined by *PlantML*, a language of management of information fluxes via XML for biological processes developed within the framework of the European Project TELEMAC (Cf. Neveu *et al.*, 2003).

The diagnosis system : classification of reaction phases

The developed system aims at computing a "distance" of a given cycle (one anoxic + one aerobic period) from a reference called "standard". In particular, the objective is to detect and isolate a COD or TKN overload, a problem in the oxygen transfer rate (Kla) or related to the heterotrophic or autotrophic bacteria. The fact that the detection is realized a posteriori (once the cycle is finished) is not a problem because the consequences of an overloading or of a problem on the oxygen transfer or on the biomasses are rather long term consequences rather than short terms ones. For instance, a "durable" COD overload will lead in problems on sludge settleability several cycles after this overload has began. The most probable cause of the identified problem is then displayed to the operator who can adjust the time of the subsequent reaction phases or take any other appropriate decision (calibration, withdrawingt of the sludge, etc).

Regarding the objectives of the study, the aerobic phase is the most important period to investigate the process performance. In fact, during this phase, significative information can be extracted from the dissolved oxygen, pH and Redox curves. In particular, using either the pH or the curve (as shown in figure 1), it is possible to detect when each substrate is completely degraded. The first point corresponds to the end of the COD consumption, the second corresponds to the end of the nitritation while the last one corresponds to the end of the nitratation. Based on this information, notice that an interesting optimization strategy is to switch to the next phase (settle in this case) as soon as the COD and NH4 are degraded.

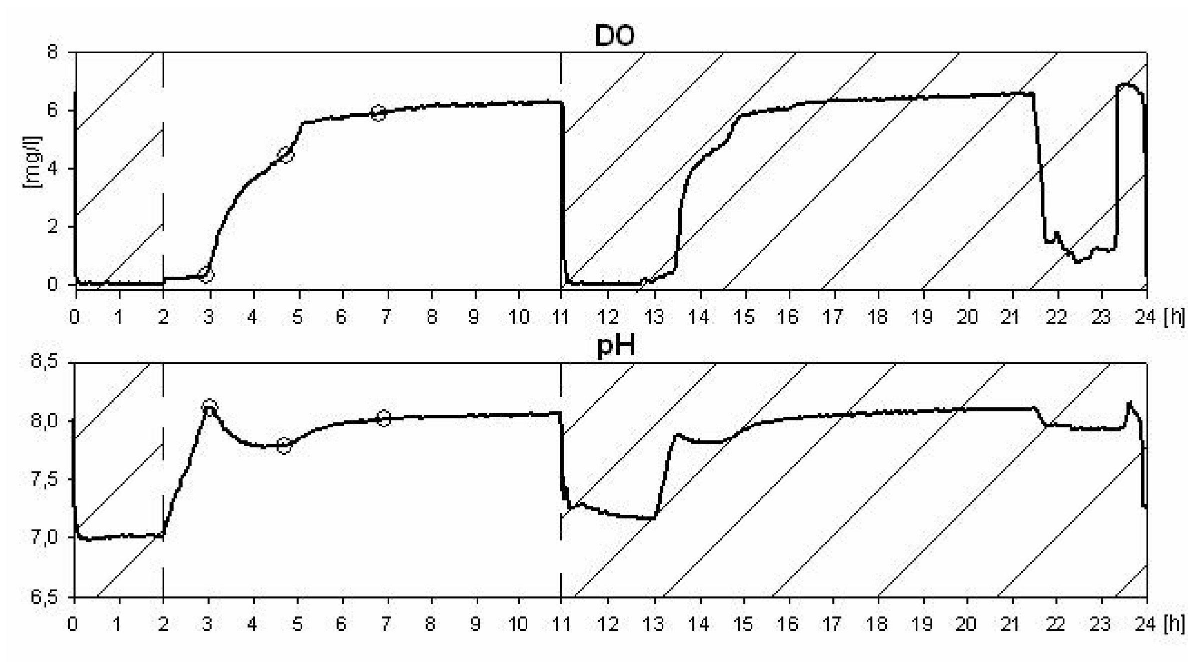

Figure 1 : pH and Dissolved oxygen curves (25/01/04)

The detection of the critical points defined hereabove in figure 1 is very useful for classifying a given cycle. These points define three distinct periods : the first one comprised between the beginning of the aerobic period and T1, the ending time of the COD removal (between 2 and 3 hours in figure 1), the second comprised between T1 and T2 defining the end of the nitritation (between 3 and 5 hours in figure 1) and the third one comprised between T2 and T3 defined as the end of the nitration (between 5 and 7 hours in figure 1). In particular, using the temperature to compute the oxygen saturation, notice that it is possible to determine the quantity of oxygen respectively needed in each of these periods (noted H1, H2 and H3). While the Ti parameters give us immediate information about the degradation rates, the Hi parameters are proportional to pollutant quantity. Of course, these values are not exact values since biological reactions evolve simultaneously (for instance both the COD removal and the nitrification begin when the dissolved oxygen differs from zero), however, the oxygen consumption rates significantly differ between the different phases in order this uncertainty to be neglected.

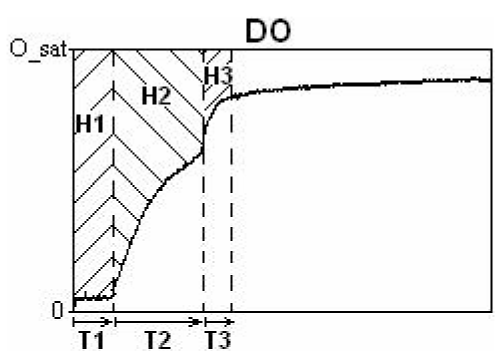

Figure 2 : Definition of parameters Ti and Hi

The Ti and Hi parameters are then used as descriptors in the framework of a Principal Component Analysis (PCA) approach. In the proposed software, two different approaches are

proposed. The first one is a model-based approach where the projection basis for the PCA procedure is calculated using data generated by a mathematical model of the SBR plant. This approach is particularly interesting because it allows to simulate - in an acceptable time - a large number of simulations corresponding to a large spectrum of environmental conditions (different C/N ratios, different oxygen transfer rates, heterotrophic and autotrophic biomass concentrations, etc). However, it also means that a validated model of the plant is available : such a model is usually difficult to obtain and its validation is time consuming. The other available approach makes use of a limited number of real cycles for which the functioning conditions are well known provided that the available data have been obtained in a large range of functioning conditions. This approach has the advantage of being rather more robust than the model based approach because it does not use any model of the process but only the available on line measurements.

MODEL BASED APPROACH

The model used for the simulations is a modified ASM1 in which the nitritation step has been added. The data to be used in the PCA procedure are generated using this model. A large number of simulations are then run around a standard cycle defined by the following operating parameters : Kla in aerobic and in anoxic conditions, concentrations of COD and NH4 in the input, concentrations of biomass (XH and XA) in the tank, volume of the input and initial volume of the tank, duration of anoxic and aerobic periods, duration and frequency of air pulses during the anoxic phase, parameters Ti imposed as "optimal", parameters successively used to vary the conditions of the simulations (Kla, CODin, NH4in, XH, XA), ranges of parameters variation.

In order to be as open and as generic as possible, the software leaves the possibility to automatically adapt the values of the maximum growth rates model parameters. To do so, it is assumed that the operator is able to enter into the software the theoretical values (defined as "optimal") of the duration of each cycle for the standard conditions. In the previous list, the first seven parameters are used to identify the μ_{maxH}, μ_{maxNS}, μ_{maxNB} (maximum growth rates for heterotrophic, nitrifiant and nitratant biomasses). The last two parameters are needed to compute the operating parameters for each simulation. Usually the most important process faults to detect are related to the Kla, the CODin and/or the NH4in. The operator can define the range of variations of these parameters from their standard value. The possible variations of a parameter are:

- << : very low (e.g. -50% of nominal value);
- < : low (e.g. -25% of nominal value);
- > : high (e.g. +25% of nominal value);
- >> : very high (e.g. +50% of nominal value).

After the compilation and the execution of all the simulations, a database is created and will be used for the next step : the application of a PCA to reduce the space of analysis from six parameters to less.

PCA STUDY

From now, the procedure is the same for the model-based approach and for the data-based approach. The Principal Component Analysis (PCA) is one of the most popular methods for extracting information from data, and has found application in a wide range of disciplines : data rectification in chemical process operation and control (Kramer and Mah, 1994), disturbance detection and isolation (Ku et al., 1995), statistical process monitoring (Kresta et al., 1991; Wise et al., 1990), and fault diagnosis (MacGregor et al., 1994; Dunia et al., 1996). PCA transforms the data matrix in a statistically optimal manner by diagonalizing the

covariance matrix and by extracting the cross correlation or relationship between the variables in the data matrix. If the measured variables are linearly related and are contaminated by errors, the first few components capture the relationship between the variables, and the remaining components are comprised only of the errors. Thus, eliminating the less important components reduces the contribution of errors in the measured data and represents it in a compact manner. The popularity of PCA relies on its high ability to reduce the dimension of any data matrix while capturing the underlying variations and relationships between the related variables.

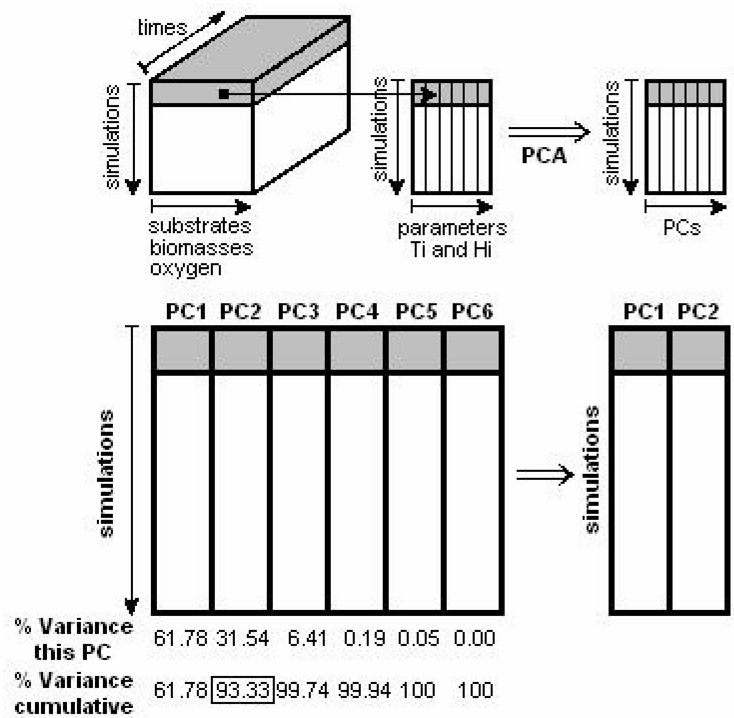

Figure 3 : Reduction of the data matrix by a PCA

In our particular case, the data matrix includes the Ti and Hi of all the available experiments (for the data based approach) or simulations (for the model based approach). Once the projection basis has been computed, the original matrix (six parameters for each considered cycle) is transformed into another matrix in which the columns are the principal components. In our case (in both the model based approach and in the data based approach), it was noticed that more than 90 % of the data can be explained in only looking at what happens in the first two principal components. In other words, most of the time, it will be possible to discriminate two different cycles in projecting its six associated descriptors Ti and Hi into on a plan.

THE DECISION TABLE FOR THE DIAGNOSIS

Once the characteristics of a cycle have been projected onto the discriminating plan P via the PCA, the next step is to identify a possible fault affecting the process. It is clear that if two cycles are very similar (similar Ti, Hi), then their parameters projected onto P will be very close one from each other. Then, once projected, the underlying idea is to search for the closest points. Since this plan has precisely been designed in order to discriminate different data, it is expected that two points that are close reflect the same process behavior. Assuming experiments or simulations used for computing the Principal Components (coordinates that are used to project any new parameters extracted from a given cycle) have covered a range

sufficiently large of functioning conditions, it becomes possible to associate the state of a specific point to the state of the closest point.

At this step, a number of decision algorithms can be used. One of the most popular procedure is the k-closest neighbors that consists in associating the actual point to the majority class of its k-closest neighbors. If this algorithm is particularly attracting in a supervised context (all points have been associated to a fixed number of predefined known number of classes), its use is less obvious in the present case. Indeed, only the point corresponding to standard conditions can be classified in a "normal class". The other points correspond to specific conditions that differ from the standard conditions by several parameters. The way we have proceeded is as follows. A parameter x is first defined. If there is a point defined as "normal" (corresponding to the standard conditions) in the vicinity x of the point p, then the point p is assigned to be itself in this set. If it is not the case, a decision table (such as the one pictured in figure 4) is built. In each column, the sum of the inverse of the squared distances to all classified points of the plan are specified. The explanation corresponding to the point p corresponds to the case of the table with the greatest value. This procedure is a kind of weighted explanation table.

It should be noticed here that the developed tool is very generic and not only valid for decisions in a plan. It seems that when the process faults the user is interested in is sufficiently small – as in our case where we are only interested in identifying overloads and problems in the oxygen transfer rate - two dimensions in the discriminating space are sufficient. However, the number of PCs to be finally retained remains under the responsibility of the user : providing that a large number of experiments covering a large range of functioning conditions (including possible simultaneous combination of explanation variables) are available (or a large number of simulations can be run in the model based approach), it would be possible to identify any problem as long as its "signature" in the discriminating plan is known.

Table 1 : Table for fault causes definition

	Kla	COD_{in}	$NH4_{in}$	X_H	X_A
<<	0	0	0	0	0
<	0	0	0	0	0
>	0	0	0	0	0
>>	0	0	0	0	0

RESULTS AND DISCUSSIONS

To validate the approach, it was decided to proceed to a number of experiments. The different conditions tested are reported in the table 2. Both approaches (model based and data based) were investigated. For the model based approach, in order to be as close as possible from experiments, the simulation corresponding to the standard conditions were realized using the average values of the parameters obtained experimentally.

Table 2 : Experiments time table

DATE	*TEST*	*T1 [min]*	*T2 [min]*	*T3 [min]*	*H1 [mg/l*h]*	*H2 [mg/l*h]*	*H3 [mg/l*h]*	*PC1 sim.*	*PC2 sim.*	*problems found*	*PC1 real*	*PC2 real*
simul.	standard	75	121	130	11.6	11.9	7.4	0.38	-0.16			
15/01/04	standard	82	120	162	12.8	12.2	6.7	0.05	-0.40	OK or COD<	1.03	-0.10
16/01/04	CODin +30%	130	56	96	19.5	7.8	6.4	1.21	2.16	NH4< or COD>	0.66	1.76
17/01/04	standard	78	96	148	11.9	8.3	4.6	1.05	-0.08	OK or COD>	0.92	-0.43
20/01/04	standard	58	158	130	9.3	12.9	6.3	0.20	-0.88	OK or COD<	0.52	-1.02
21/01/04	standard	76	144	126	12.0	14.2	6.9	0.01	-0.29	OK or COD>	0.48	-0.26
22/01/04	CODin +50%	154	92	132	23.0	11.8	9.5	-0.48	1.87	COD> or Kla<	1.00	2.82
23/01/04	standard	96	90	126	14.5	10.4	7.9	0.59	0.64	OK or COD>	1.06	0.55
24/01/04	standard	82	102	130	12.5	11.0	7.8	0.55	0.16	OK or COD>	1.06	0.02

25/01/04	standard	64	110	138	9.9	11.1	8.1	0.57	-0.42	OK or COD<	1.25	-0.63
26/01/04	Kla +50%	38	110	172	5.2	6.7	5.4	1.24	-1.49	COD< or Kla>	1.58	-2.00
27/01/04	NH4 +50%	110	382	16	16.8	33.1	0.7	-2.87	-0.41	NH4> or Kla<	-4.30	0.30
28/01/04	COD -50%	34	318	38	5.5	21.0	1.4	-0.54	-1.77	NH4> or COD<	-2.43	-2.43
29/01/04	Kla -30%	134	274	46	20.3	26.7	2.4	-1.9	0.78	Kla< or COD>	-2.86	1.43
30/01/04	standard	76	136	138	12.2	13.5	7.0	0.03	-0.36	OK or COD<	0.69	-0.25
31/01/04	standard	81	154	126	13.7	17.9	7.9	-0.59	-0.23	OK or NH4>	0.31	0.12
01/02/04	standard	89	110	114	14.7	14.7	8.2	0.15	0.51	OK or COD>	0.63	0.49

Up to this date, only a few cycles are available for validation. Thus, the presented results may rather be considered as a demonstration instead of a the validation of an operational tool. Nevertheless, both for the model based and for the data based approaches, the results are given in Figure 4. In both of the figures, the x axis is PC1 and the y axis is PC2. The red triangles indicate the direction of each of the six parameters (the descriptors) in the space : for example if a cycle has a large T1, its projection will be near the corresponding triangle and so on. It is clear that highly correlated parameters, as T1 and H1, give the same direction. In the left figure, the stars represent all the simulations realized with different conditions automatically generated by the software. The green zone defines the class of "standard cycles". The blue diamonds correspond to the experiments reported in Table 2 used to demonstrate the capabilities of the system to detect and isolate process faults. All 10 standard cycles were correctly classified in the green zone. For the six remaining ones, three were correctly identified while the problems corresponding to the three others were given as the second possible explanation instead of the first one :

cycle 16/01 : the most probable problem detected is NH4< instead of COD> because T1 is large but T2 is very small ;

cycle 26/01 : the most probable problem detected is COD< instead of Kla> because T1 is small but T2 and T3 are similar to values of standard cycles ;

cycle 28/01 : the most probable problem detected is NH4> instead of COD< because T1 is small but T2 is very large.

The most probable explanation of this phenomenon is the particular composition used to artificially increase the nitrogen content of the input : while the input COD is only due to the raw whey, in standard conditions half of the nitrogen content comes from the whey and half of it comes from added Urea. The difference between these two forms of nitrogen is that nitrogen in the whey is probably easily degradable while urea need to be ammonified before the nitrification can take place.

In the right graph, only the real cycles reported in the previous table are represented. To illustrate the data based approach approach, only seven of the standard cycles were used in the learning phase while three were kept for the validation. The colored circles near the origin are the first seven standard cycles while the colored stars are the tests corresponding to functioning conditions differing from the standard ones. The black stars are the last three standard cycles. Their projections onto the plan are all located very close to the origin. In other words, they were correctly identified as standard cycles.

CONCLUSIONS

In this paper a new software for analyzing the state of aerobic SBR has been presented. The classification of on-line data acquired from the plant is realized using a standard PCA procedure together with a decision algorithm. Depending on the available knowledge and data, two distinct approaches (a model based and a data based) were proposed. Using a set of real experiments, both approaches have been validated. Both were able to detect and isolate overload problems. It is also shown that the application of this method of analysis can support

in an determinant way the decisions of the operator in the case a process fault occurs in the treatment cycle. In this case, the most probable causes are provided to the user in order for him to rapidly take adequate preventing or correcting actions to restore standard conditions.

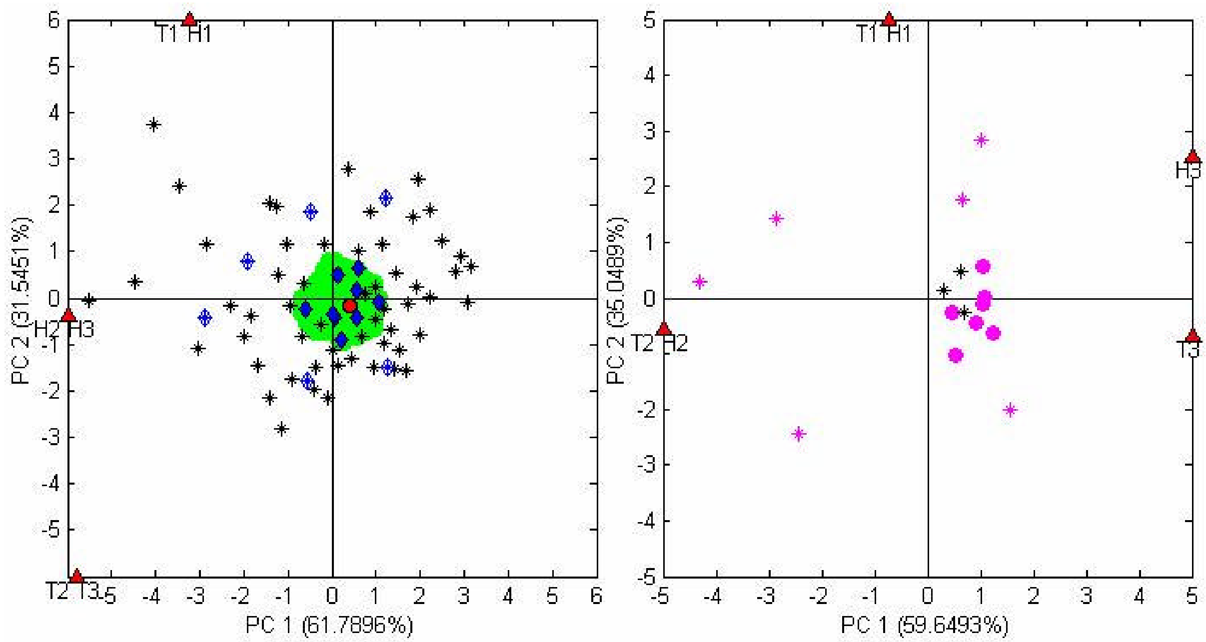

Figure 4 : Model based and data based approaches

ACKOWLEDGEMENTS

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ARQUITECTURA DISTRIBUIDA PARA LA DETECCIÓN AUTÓNOMA DE FALLAS EN SENSORES

C. Verde, J. Cuellar, J. Mina

Instituto de Ingeniería, UNAM
Apdo. Postal 70-472
04510 DF, México
verde@servidor.unam.mx
Fax: (52)-55-56228130

Resumen:
A pesar de la tendencia actual de incluir en los transductores de los sensores dispositivos digitales que compensan incertidumbres y sesgos, pocos de ellos están dotados con capacidad para suministrar información adicional sobre la confiabilidad y validación de las mediciones que se realizan. Por otro lado pocas veces se cuenta con suficiente redundancia para detectar y aislar fallas en todos los sensores de un proceso. Estos hechos motivaron la idea de explotar el hardware de los transductores y acondicionadores y aumentar sus capacidades para mejorar las tareas de supervisión de procesos dinámicos. Así se propone en este trabajo dotar a los transductores de los sensores con capacidades individuales para el suministro de información sobre la confiabilidad de las mediciones en tiempo real. Esta filosofía para mejorar la supervisión de un proceso deja en un segundo nivel la integración de las tareas de toma de decisiones y reconfiguración del proceso. En particular como ejemplo se presenta una plataforma para la detección de fallas en la membrana de un medidor de oxígeno disuelto tipo Clark en donde de manera periódica se verifican las características dinámicas de la membrana, la cual depende de su espesor, la constante de difusión y la temperatura.

1. INTRODUCCIÓN

Una tarea fundamental de los sistemas de supervisión automática de procesos industriales es el diagnóstico de fallas en los diferentes componentes de la planta. El marco teórico de referencia para los sistemas de diagnóstico involucrando tanto la detección como la localización de fallas en procesos, es presentado por la mayoría de los expertos de manera integrada considerando las fallas en sensores, actuadores y proceso, ver (Patton *et al.*, 2001). Sin embargo, esta conceptualización tan general provoca en sistemas complejos resultados conservadores sobre todo en la etapa del aislamiento de las fallas y en las condiciones de existencia de soluciones. Casos de referencia como el sistema hidráulico de tres tanques (Astrom *et al.*, 2001) deben ser tomados como ejemplos académicos, y no como procedimientos generales para atacar un problema de diagnóstico de fallas y control tolerante a fallas en aplicaciones industriales reales. Adicionalmente a esta problemática la comunidad de deteccción y aislamiento de fallas (FDI por sus siglas en inglés) ha reconocido que la robustificación de los sistemas de diagnóstico complejos se logra usando diferentes enfoques y

[1] Este trabajo incluye resultados del proyecto EOLI apoyado por la Comunidad Europea bajo el programa ICO con contrato ICA4-CT-2002-10012 y el contenido es responsabilidad de los autores. Este trabajo cuenta además con el apoyo de los programas de becas de la UNAM y el CONACYT-México

metodología en la parte de detección y aislamiento y dejando a un segundo nivel la toma de decisiones y reconfiguración (B. Koeppen-Seliger, June,2003).

Por otro lado, las tareas de calibración y compensaciones de los transductores en los sensores tienden a explotar las capacidades computacionales del hardware actual (Tortora *et al.*, 2003). Esta tendencia puede ser explotada ya que provee las condiciones para diseñar subsistemas llamados supervisores distribuidos de manera análoga al caso de los sistemas distribuidos de control. Este tipo de subsistemas autónomos incluyen tareas o funciones como: diagnóstico, información sobre la confiabilidad y tendencias de la medición, validación, etc. Este enfoque es el que se aborda en esta presentación. En particular, aquí se analizan las ventajas de un sistema distribuido de supervisión diseñado como parte del proyecto (EOLI, 2004) patrocinado por la Comunidad Europea. Para ejemplificar la potencialidad de la propuesta se toma como dispositivo con auto-evaluación el caso de un medidor de oxígeno disuelto.

El presente trabajo está organizado de la siguiente forma: en la sección 2 se propone una plataforma distribuida de supervisión de los sensores de un proceso. En la sección 3 se describe el comportamiento del medidor de oxígeno disuelto, así como el modelo considerado para diagnosticar fallas y en la sección 4 se propone el mecanismo de auto-evaluación de las condiciones del estado de la membrana del sensor. Finalmente en la sección 5 se presentan las conclusiones del trabajo y algunas de la actividades previstas para la integración del sistema distribuido de supervisión.

2. ARQUITECTURA DISTRIBUIDA PARA FDI

En los años setenta los dispositivos electrónicos y sensores conectados a los procesos eran pasivos, sin embargo, a principio de los 80's se inicio una evolución para hacerlos activos e inteligentes. La distinción de inteligente se debe a las funcionalidades que permite el procesamiento de datos a través de tecnología digital asociada a los dispositivos. La asignación de cierta inteligencia entre todos los componentes del sistema permite transformar los sistemas centralizados de supervisión en Sistemas Distribuidos Inteligentes. En (Panetto *et al.*, 1993) y (Bayar and Staroswiecki, 1992) se proponen algunas funciones en los dispositivos de campo inteligentes.

Este tipo de sistemas de monitoreo y supervisión los cuales llegan a incluir tareas de reconfiguración de un proceso, son fuertemente demandados en aplicaciones industriales. Específicamante el pre-

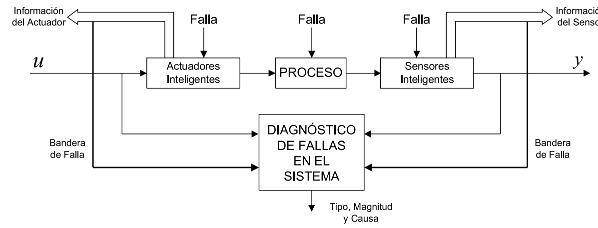

Fig. 1. Estructura del Sistema Distribuido de Diagnóstico

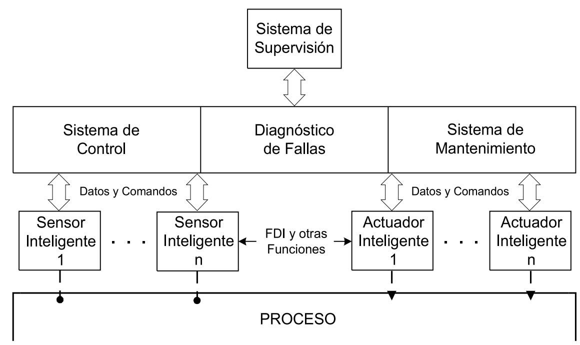

Fig. 2. Comunicación entre los dispositivos y niveles superiores

sente trabajo se enfoca a las funciones de supervisión distribuida de fallas en donde cada subsistema debe contar con un mecanismo de auto-evaluación que suministre indicadores de fallas a partir del diagnóstico. La validación apoyada por los resultados obtenidos en el diagnóstico consistirá en suministrar la medición o acción de control nominal directamente en ausencia de fallas y en caso contrario corregir el dato o acción a través de un ajuste.

La figura 1 muestra la estructura propuesta en donde se genera información sobre la confiabilidad de las mediciones y de las acciones de control, así como indicadores del desempeño de los sensores y actuadores de un proceso.

En esta arquitectura, las fallas del proceso se tratan de manera independiente en otro nivel, es decir, una falla en el proceso será detectada usando información del proceso junto con los reportes individuales de las funciones de FDI en los sensores y actuadores.

Con este esquema si bien es cierto que se requiere un gran esfuerzo inicial en el diseño de cada subsistema de supervisión, esto se compensa con los beneficios obtenidos en cuanto a modularidad, transportabilidad e intercambio de información con otros niveles jerárquicos en la estructura de control del proceso, véase la figura 2.

Por lo que respecta al indicador de fallas en los sensores se propone tener tres niveles.

- Borroso (*Fuzzy)*: significa que el comportamiento es anormal pero está dentro de los límites razonables (ruido y forma).
- Confuso (*Confuse)*: significa que hay evidencias de un comportamiento anormal, pero la duración de la condición es pequeña para diagnosticar una falla permanente.
- Ciego *(Blind*): significa que la señal no tiene relación con los valores esperados y este efecto se mantiene a lo largo del tiempo.

La información adicional que suministran los sensores permite entonces, no solo localizar fallas, sino ayudar a la toma de decisiones en la reconfiguración o suspensión parcial de un proceso.

3. MODELO DEL SENSOR DE OXÍGENO DISUELTO *DO*

La concentración del oxígeno disuelto DO es una medida de la capacidad para mantener vivos a los microorganismos en un líquido. Así que los sensores de DO tienen múltiples aplicaciones en el monitoreo de procesos biológicos. En particular, la estrategia de control de un reactor SBR para plantas de tratamiento de aguas está fundamentada en el estado del oxígeno disuelto siendo los sensores de DO dispositivos muy sensibles y fáciles de dañar.

El DO se mide normalmente en unidades de presión parcial p_{o_2} (atmósferas) o de concentración (partes por millón o mgl^{-1} $[O_2]$), y estas unidades son intercambiables vía Ley de Henry $[O_2] = H\ p_{o_2}$.

Para un medidor del tipo celda de Clark la relación existente entre la corriente y el nivel de DO se deriva vía la Ley de Faraday. La carga total Q de especies electroquímicas electrolizadas en un electrodo después de un intervalo de tiempo t en que circula la corriente i, está dada por

$$Q = \int_0^t idt = mnF \tag{1}$$

con m = cantidad de moles de oxígeno ($mole$ = 16grs), n = número de electrones requeridos para electrolizar una molécula de oxígeno, F = constante de Faraday. A partir de (1) se tiene entonces

$$i = nF\frac{dm}{dt} \tag{2}$$

en donde la razón de flujo de masa $\frac{dm}{dt}$ está relacionada vía la Primer Ley de Fick de Difusión con el flujo molar $\frac{1}{A}\frac{dm}{dt}$, el gradiente de concentración $\frac{dC}{dy}$ en la dirección de la difusión y el coeficiente de difusión D; es decir

$$J = D\frac{dC}{dy} = \frac{1}{A}\frac{dm}{dt} \tag{3}$$

donde, A es el área del electrodo, J es la densidad de flujo molar de oxígeno en la superficie del electrodo. Así que la corriente i se puede expresar como

$$i = nFAD\frac{dC}{dy}\ |_{y=0} \tag{4}$$

Si se asume que la difusión del flujo de oxígeno es total, el flujo de salida J de la membrana está dado por la primer Ley de Fick

$$J = D_m H_m \frac{\partial p}{\partial y} \tag{5}$$

donde D_m es la difusividad de la membrana, H_m es el coeficiente de la ley de Henry para el material de la membrana y p es la presión parcial.

En la mayoría de las celdas Clark, el flujo J en la superficie del electrodo depende del flujo a través de la membrana y no es fácil de caracterizar su comportamiento en todas las direcciones. Sin embargo, se puede asumir que el flujo de salida de la membrana es uniforme y alcanza al electrodo instantáneamente, para obtener un modelo de una dimensión. Bajo estas condiciones el gradiente de la concentración puede ser aproximada por

$$\frac{dC}{dy} = \frac{[O_2]}{b} \tag{6}$$

donde b es el espesor de la membrana. Así la corriente en estado permanente puede escribirse como

$$i_{ss} = \frac{nAFD_m H_m p_w}{b} = \frac{nAFD_m H_m}{bH_w}\,[O_2]_w \tag{7}$$

en donde los subíndices m, w refieren a la membrana y al fluído externo (agua) respectivamente. Por tanto, la corriente está linealmente relacionada con las partes por millón de oxígeno disuelto en el fluído, y es inversamente proporcional al espesor b de la membrana. Así el oxígeno en estado permenete se reduce a

$$[O_2] = \frac{b}{nFAkD_m} i_{ss} = G_0 G(T) i_{ss} \tag{8}$$

donde $k = \frac{H_m}{H_w}$, siendo H_m y H_w las constantes de proporcionalidad de las leyes de Henry en la membrana y en el agua, respectivamente, $G(T)$ refleja las variaciones con respecto a la temperatura de calibración, y finalmente la constante de calibración G_0 está definida como

$$G_0 = \frac{[O_2]_0}{i_{ss0} G(T_0)} \tag{9}$$

donde $[O_2]_0$, i_{ss0} y $G(T_0)$ son valores en el punto de calibración.

Así que la corriente i_{ss} varía por efectos de la temperatura, el espesor b de la membrana y el propio oxígeno disuelto y se requiere de información complementaria para determinar la causa de una variación Δi_{ss}. Para ello se emplea el comportamiento transitorio de la corriente.

La idea básica consiste en energizar los electrodos del sistema una vez que se haya alcanzado un

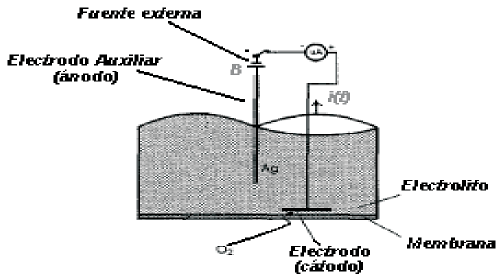

Fig. 3. Circuito del sensor de DO

equilibrio en la presión parcial de la membrana, es decir, cuando la presión en los extremos y dentro de la membrana es igual.

Al energizar los electrodos, las moléculas de oxígeno existentes en el electrolito son rápidamente removidas ocasionando una gran corriente inicial, la cual desciende hasta alcanzar el equilibrio con una difusión permanente a través de la membrana.

La Fig. 3 muestra el esquema básico usado para la medición de DO, con una fuente externa B, la cual se propone usar para generar un comportamiento transitorio en la corriente.

Considerando la segunda ley de Fick de difusión

$$\frac{\partial p}{\partial t} = D_m \frac{\partial^2 p}{\partial y^2} \tag{10}$$

con las condiciones de frontera

$$p(0,t) = 0; \quad p(b,t) = p_w \tag{11}$$

y la condición inicial

$$p(y,0) = p_w \tag{12}$$

se puede obtener

$$p(y,t) = v(y) + \sum_{n=1}^{\infty} c_n \exp\left(-\frac{n^2\pi^2 D_m t}{b^2}\right) \sin\frac{n\pi y}{b} \tag{13}$$

donde

$$c_n = \frac{2}{b}\int_0^b (p_w - v(y)) \sin\frac{n\pi y}{b} dy \tag{14}$$

$$v(y) = p_w \frac{y}{b} \tag{15}$$

y simplificando se tiene

$$\frac{p(y,t)}{p_w} = \frac{y}{b} + \sum_{n=1}^{\infty} \frac{2}{n\pi} \exp\left(-\frac{n^2\pi^2 D_m t}{b^2}\right) \sin\frac{n\pi y}{b} \tag{16}$$

Finalmente, considerando el intercambio de unida des vía la Ley de Henry ($[O_2] = Hp_{o_2}$) y la ec. (4), se tiene la expresión de la corriente dada una distribución de oxígeno uniforme a través del sensor

$$i(t) = i_{ss}\left(1 + 2\sum_{n=1}^{\infty} \exp\left(-\frac{n^2\pi^2 D_m t}{b^2}\right)\right) \tag{17}$$

en donde la corriente en $t = 0^+$ tiende al infinito y los términos en la sumatoria determinan la parte transitoria, los cuales dependen solamente de la difusión D_m y del espesor b de la membrana. Por tanto identificando ambos parámetros es posible detectar el deterioro de la membrana.

Para ello, se propone integrar la corriente ec. (17) a partir de un instante $h > 0$ durante una ventana de tiempo $h = 2h - h$ obteniendo

$$\frac{I}{i_{ss}} = h - \frac{2\tau}{\pi^2}\sum_{1}^{\infty}\frac{1}{n^2}\left(e^{-2n^2\pi^2 h/\tau} - e^{-n^2\pi^2 h/\tau}\right) \tag{18}$$

con $I = \int_h^{2h} i(t)dt$ y $\tau = \frac{b^2}{D_m}$.

Así, a través de la relación entre el valor de la corriente en estado permanente y de su integral durante el transitorio en un ventana de tiempo es posible estimar la constante τ y detectar las variaciones con respecto a la constante nominal $\tau_o = b_0^2/Dm_o$, obtenida al calibrar el instrumento.

4. AUTO-EVALUACIÓN DEL ELECTRODO

Los principales problemas que afectan la medición del sensor de DO de una celda tipo Clark, además de las variaciones en la temperatura, son los daños en la membrana por envejecimiento, ruptura y suciedad de la superficie de la membrana por sustancias externas.

Las condiciones mencionadas en el parrafo anterior producen una variación en la constante de tiempo de difusión $\tau = \frac{b^2}{D_m}$y en el valor de i_{ss}. Debido a la gran sensibilidad del proceso electroquímico del sensor con respecto a la temperatura, es común medir ésta y compensar sus efectos por software. Fraher (Fraher and Clarke, 1998) compensa la incertidumbre en la medición ΔO debido a la temperatura y al deterioro de la membrana (b, D_m) usando un análisis de sensibilidad e incluyendo una membrana extra de comparación; es decir usando una membrana redundante (hardware) para diagnosticar variaciones de la corriente producidas por partículas adheridas a la membrana o desgaste de ésta. Sin embargo, esta redundancia no puede incluirse en los dispositivos ya existentes. Por el contrario, aquí se propone un procedimiento para detectar el deterioro en la membrana aprovechando las secuencias de un reactor SBR aerobio sin necesidad de duplicar el hardware.

La propuesta se basa en el hecho de tener un proceso en tanda de 4 fases con dinámicas muy lentas (Fibrianto and Dochain, 2003) en donde en la fase de vaciado y decantado permite interrumpir la circulación de corriente en la sonda del medidor de DO, Fig. (3) durante un intervalo de tiempo mayor a $\Delta\Gamma$, de tal manera que cuando se cierre nuevamente el circuito cátodo ánodo en la etapa de llenado se tenga una respuesta transitoria en la corriente de la forma de (17) y de ahí pueda identificarse la constante de tiempo τ.

Si el circuito del sensor (cátodo-ánodo) involucra un potencial externo B de ajuste como el de la Fig. 3, se puede interrumpir el voltaje de manera periódica para excitar al sistema y generar un transitorio en la corriente con lo cual se emula la condición obtenida en (17).

Así el coeficiente τ/τ_o es un indicador del estado de la membrana de la sonda que puede ser suministrado por intervalos de tiempo al sistema de supervisión junto con la medición del oxígeno disuelto actual.

Actualmente se encuentra en construcción el dispositivo y el sistema de adquisición de datos que permitirá validar la propuesta.

5. CONCLUSIONES

Se presenta una estructura distribuida para el monitoreo y supervisión de fallas de procesos complejos en donde se dota a cada sensor de un mecanismo de auto-evaluación y de comunicación para entregar junto con la medición un indicador de falla. Esta propuesta permite integrar la tarea de supervisión y diagnóstico de procesos complejos con niveles distintos de detección. En particular, el contar con sensores inteligentes que validen sus propias mediciones en tiempo real reduce la carga de trabajo de los supervisores de mayor jerarquía. Como ejemplo se presenta un procedimiento para autoevaluar las condiciones de la membrana de un sensor de oxígeno disuelto.

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Enabling FDI and Supervision:

An Integrated System for the Operation of a Process/Plant

Cristina Verde Rodarte
Dieter Wimberger

11th March 2004

1 Introduction

The successful design and implementation of intelligent complex control systems is a grand challenge problem for process control engineers, especially with regard to the incorporation of process fault diagnosis (PFD) [VEN03c]. Industry and academic research alike are seeking patterns and designs that allow the creation of reliable and extensible complex control and supervision systems [HWV03, SAN00]. For the industry, these systems tend to consist more and more of software elements (60-80%) and requirements are:

- Interoperability and Integration
- Adaptability (e.g. cope with changes in the future)
- Ease of deployment

In academic research these requirements are seldom addressed, which sometimes leads to abandonment of successfully implemented prototypes for specific tasks [VEN03c]. Especially with regard to successful incorporation of process fault diagnosis and supervision, the integration of a system is a crucial factor: a completely integrated system allows a more complete access to the system as well as to combine various methods (hybrid approach) and thus leverage their varying capabilities with regard to detection and isolation of problems [VEN03a, VEN03b, VEN03c, DAS00].

The motivation of this work is to create an abstraction and patterns that allow the assembly of a reliable and adaptable complex control system, that incorporates PFD and FDI elements as well as supervision and decision support. Emphasis is put on properties like modularity and extensibility, with the final objective of creating a ”design for change” [SAN00].

The rest of the document is organized as follows: Section 2 presents the system design and describes it’s elements. Section 3 presents a possible mapping of the SPES implementation for the EOLI project to the formerly presented abstract architecture. A glossary is appended to explain terms used throughout the document.

2 System Design and Elements

Figure 1 presents an abstract scheme of the complete system architecture.

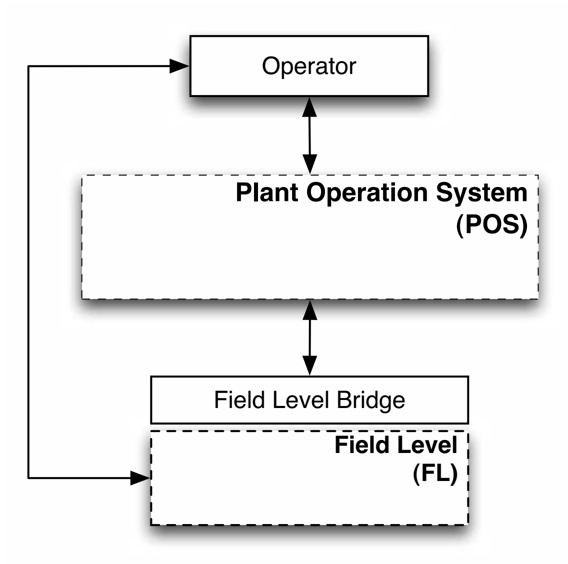

Figure 1: System Structure

The basic division is between the field level (FL) and the plant operation system (POS), which has been introduced because of following reasons:

- Avoid dependencies on a specific field level implementation
- Separation of concerns
- Provide a pattern that can be repeated and re-utilized

2.1 Field Level (FL)

The basic motivation for the design of the field level is to achieve total confidence that the process can be controlled at any time. It is expected that the implementation will make use of automatization hardware providing hard realtime[1], although for certain implementations this might not be a requirement. The design should be flexible enough to allow different choices regarding the requirements of the actual realization.

Figure 2 presents the structure of the field level design, which consists of:

- Basic Human-Machine Interface (HMI):
  see Glossary

[1] a failure in the latency of the system consequently leads to a failure of the system.

- I/O System:
  Input/Output system capable of communicating with sensors and actuators. Examples are Distributed I/O, PLC with I/O Modules etc.

- Actuators and Sensors:
  Sensors provide the online data of the process state and actuators allow to control the process by commanding actions.

- Basic Control:
  This element includes basic control loops and logic blocks that are required to maintain operation even if the communication with the higher level is interrupted.

- Low-Level FDI:
  This element includes FDI blocks for sensors, actuators as well as the low level control system. Nowadays sensor and transmitters are implemented with microprocessors enabling the design of intelligent or smart devices. An FDI block for a sensor should realize a diagnosis of the sensor state and it's measurements, providing information complementary to the actual measurement (data quality, abnormal sensor conditions) to a higher decision level. In case of actuators an FDI block should try to identify abnormal instrument conditions based on inherent characteristics and convey them as well to the higher decision level. Additionally low-level control FDI blocks could realize the evaluation of basic system alarms.

Certain building blocks might be omitted, in case they are not required for a specific implementation.

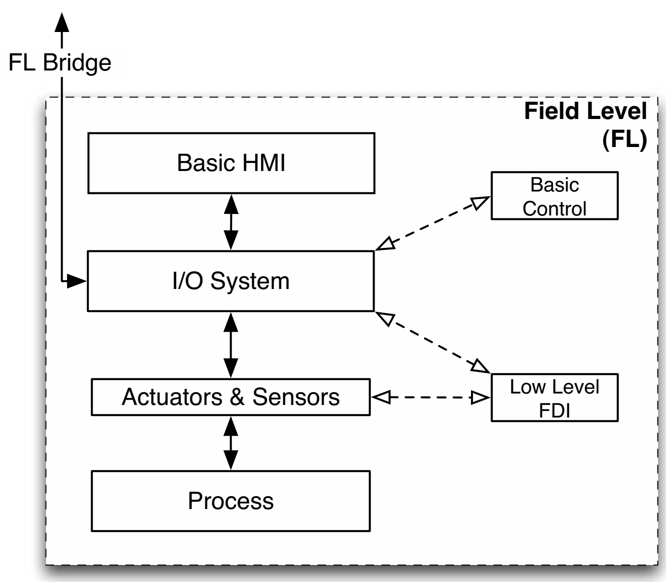

Figure 2: Field Level Structure

An industrial standard implementation of the FL design is demonstrated in Figure 3 (left). The core is a PLC with I/O modules interfacing with the basic HMI as well as the plant. The basic control is realized as a program on the PLC, the low-level FDI could as well be a PLC program or directly coupled with a sensor or actuator, providing extra inputs describing the state of a particular sensor or actuator.

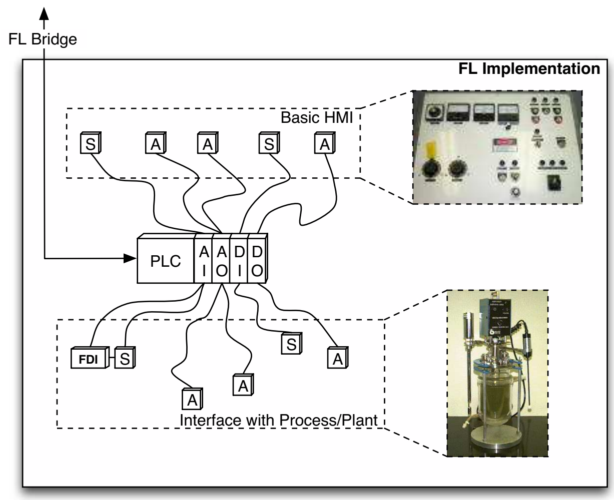

Figure 3: Field Level Implementation Example

2.2 Field Level Bridge

The field level bridge provides a bidirectional link between the field level and the POS in a modular way. The idea behind the design (see Figure 4) is to achieve decoupling and to create patterns for reusable bridge elements. Basically the bridge will be composed of three elements:

1. POS Infrastructure Communication:
   This element of the bridge is a POS infrastructure specific implementation, utilizing the infrastructure's mechanisms for communication with other POS elements.

2. Field Level Model:
   This element of the bridge should represent an abstract model of the field level environment instead of relying on raw data channels for sensors and actuators. An example would be a model of a tank with aeration that can be turned on or off, rather then just having a digital channel DO 04 which is "somehow" mapped to the aerator. Similarly the model should provide the temperature of the bulk media content, instead of having to work with an analog channel AI 01 that provides an integer value representing 12.3 mA and by transformation the actual temperature.

3. Field Level Communication:
   This element of the bridge provides a field level specific implementation of the communication with the I/O System. An example could be the implementation of a serial communication protocol over a RS232 cable (see 3), as well as Modbus or any other type of field bus communication protocol (which might even require special hardware). Well done, the

abstraction should shield from low level details, so that the implementations for different protocols might easily be reused.

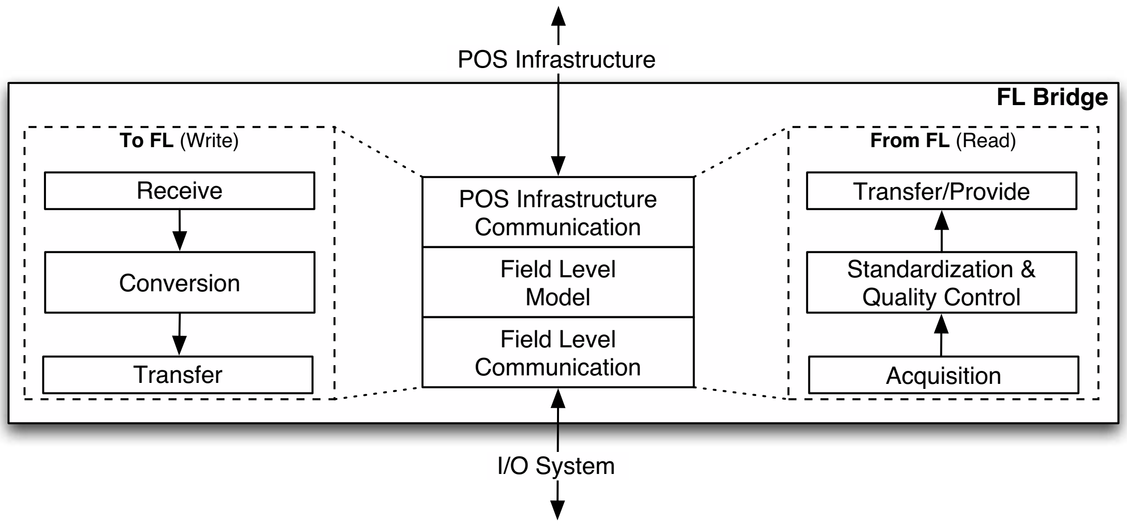

Figure 4: Bridge Structure

A possible implementation of this bridge could be realized on a small embedded system node (distributed system implementation), as well as it could be directly integrated into a single node.

2.3 Plant Operation System (POS)

The basic operation of a plant/process is a principal requirement, but today it is much desired to have an automatic system that:

- tries to maintain the process within conditions defined by design specifications
- tries to detect and identify failures (i.e. when the process is no longer within design conditions)
- tries to help the operator to correct an abnormal condition or to correct it automatically through reconfiguration
- provides data and information (actual as well as historical) about the process to the operator

The elements that provide this functionality are basically the different functional aspects of a complex control system:

1. Human-Machine Interface:
   see Glossary

2. Supervision and Decision Support:
   This element should use the information available from a fault diagnosis system to check and monitor the process under regulatory process control, with the objective of assisting a human operator to manage the process [VEN03c] on a time-frame smaller than planning. The idea is to enable the system to cope with natural variability in processes (due to raw material variability and unsteady environmental condition), that often make the closed world assumption for regulatory control strategies invalid.

3. Advanced Control:
   This element includes control blocks that are leveraging resource intensive methods (heuristic and/or capable of adaptation or learning).

4. Fault Detection and Isolation (FDI) and Process Fault Diagnosis (PFD):
   This element should provide a diagnosis of the process from a higher level perspective. It's task is to evaluate when the process leaves the conditions defined by design specifications and provide the Supervision and Decision Support with information that identifies and describes an abnormal condition.

The basic motivation for the design of the POS architecture is to achieve integration between all these elements in a way that allows the system to evolve over time ("design for change" [SAN00]). Basic design goals are thus modularity and extensibility. Although it is not required or necessary to implement the POS as a distributed system, it would probably be the best solution to ensure the flexibility for future changes. No assumption is made about the system latency, basically it will depend on the specific realization (e.g. hard or soft realtime, as well as "best effort"). Figure 5 presents the structure of the POS design.

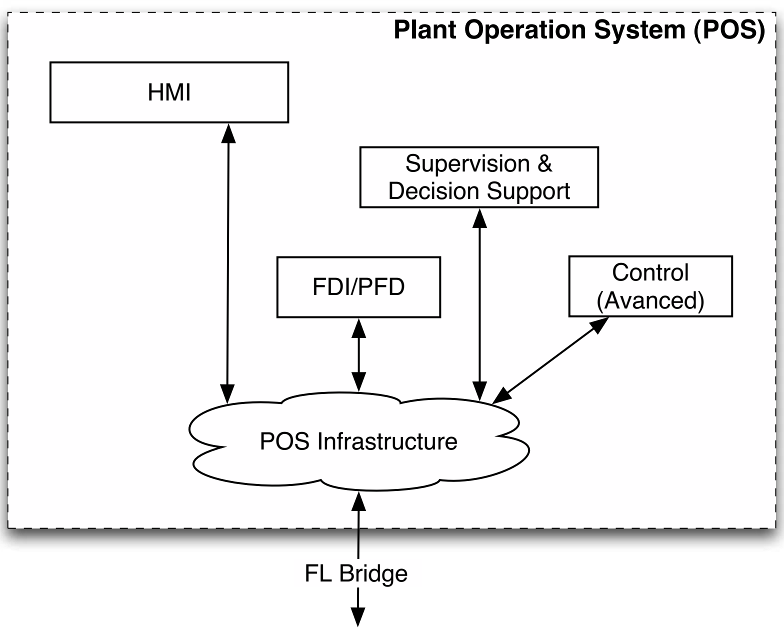

Figure 5: POS Structure

The POS infrastructure is the part of the POS that provides:

- Communication between elements:
  The details of network or interprocess communication should be hidden from the actual component implementation and interoperability between heterogeneous components and platforms should be possible.
- Dynamic reconfiguration and extensibility mechanisms
- Basic services like for example data storage

3 Example: SPES Implementation for the EOLI Project

3.1 Field Level and Bridge

Figure 6 (right) shows how the SPES proposal for the EOLI project maps to the field level abstraction. The I/O System is realized as embedded master board with RF links to actuators and sensors (each with it's own slave board). A simple PLC connected via an RS232 serial link provides basic control.

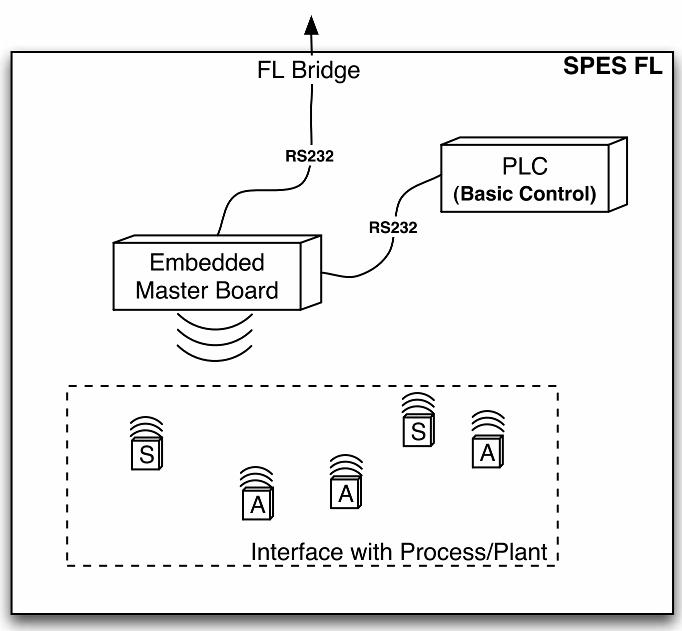

Figure 6: SPES Field Level

Field level communication is realized via another RS232 serial link between the host PC and the embedded master board using a proprietary protocol. Some software component running on the PC has to provide the FL bridge functionality. Although a model has not yet been proposed, it is very likely that there will be some kind of mapping or interface that helps the various components to read from/write to specific field level sensors and actuators.

3.2 POS

The SPES implementation can also be mapped to the POS abstraction, although everything will be running on a single node. This means that the system has certain natural limitations with regards to the proposed ”design for change” (i.e. properties like extensibility and dynamic reconfiguration). However, the POS infrastructure is reflected by the following elements:

1. Communication between components:
   Windows Messages and global variables

2. Data Storage:
   Database interface and a MySQL RDBMS

Control, FDI and Supervision are to be realized as compiled Matlab modules running within a VC++ host application, that will provide the HMI (GUI) and FL bridge at the same time.

A Glossary

Bus-Coupler Processing unit of a modular Distributed I/O system, capable of handling the communication with various I/O modules as well as with the other nodes on the network.

Distributed-I/O An I/O system capable of communicating with sensors and actors, as well as with other nodes on a network, allowing them to remotely read inputs or write outputs.

HMI The human-machine interface (HMI) is where people and technology meet. In can be as simple as a button on a control board, or nowadays as complex as an operator console application. However, in any case it should be well designed and fit the user’s mental map of the task he or she wishes to carry out. [IEC03]

I/O Input/Output

I/O-System Input/Output system capable of communicating with sensors and actuators. Examples are Distributed I/O, PLC with I/O Modules etc.

PLC Programmable Logic Control

Remote-I/O see Distributed I/O

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