TELEMAC : an integrated system to remote monitor and control anaerobic wastewater treatment plants through the internet

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Abstract The TELEMAC project brings new methodologies from the Information and Science Technologies field to the world of water treatment. TELEMAC offers an advanced remote management system which adapts to most of the anaerobic wastewater treatment plants that do not benefit from a local expert in wastewater treatment. The TELEMAC system takes advantage of new sensors to automatically stabilise the treatment plant, meet the depollution requirements and provide a biogas quality suitable for cogeneration. If the automatic system detects a failure which cannot be solved automatically or locally by a technician, then an expert from the TELEMAC Control Centre is contacted via the internet and manages the problem.

Keywords Anaerobic digestion, automation, control, fault detection and isolation, instrumentation, modelling, software sensors, on-line VFA sensor, remote monitoring, vinasses, winery.

Introduction

The TELEMAC project is designing a modular and reliable system to support remote telemonitoring and telecontrol of wastewater treatment units with no local expertise available to them. The project is more specifically focusing on a re-emerging technology, namely anaerobic wastewater treatment processes (WWTP). It offers very interesting advantages compared to the traditional aerobic treatment: a high capacity to degrade slowly degradable substrates at high concentrations, very low sludge production, low energy requirements and, in some cases, energy recovery through methane combustion. However, despite these advantages, there are too few industrial anaerobic treatment plants, probably because of the drawback of their efficiency: some perturbations, such as changes in the quantity or quality of the wastewater to be treated, can lead to destabilisation of the process due to accumulation of intermediate compounds, resulting in biomass elimination (Verstraete and Vandevivere, 1999; van Lier et al., 2001). A period of several weeks to several months is then necessary for the process to recover and, during this period, no biological treatment can be performed by the unit. As a consequence, the technology could so far not be run without local expertise.

Nevertheless, the advantages of the anaerobic digestion reaction scheme largely justify a wider use, even though it demands continuous and efficient supervision. It is therefore a great challenge for computer and control sciences to make these processes more reliable and usable at industrial scale.

Reducing pollution generated by a widespread network of industrial units is a major issue. This is all the more true with specific and polluting industries like wineries or distilleries since the treatment of vinasses and alcoholic wastewater is difficult. Moreover, these types of wastewater have a deep environmental impact and are produced by many users all over the world. Because of the high organic carbon concentration (for example a middle size Tequila factory produces a pollution equivalent to 125 000 inhabitants) and of the slow degradability of these alcoholic beverage effluents, anaerobic digestion is well suited. However, vinasses are often produced by small and/or isolated units (especially SMEs) which have their own treatment plant but cannot afford a human expert to monitor it. It therefore clearly appears that wineries and alcoholic beverage producers need a reliable and efficient treatment system able to work despite constant perturbations and without any local human expertise available.

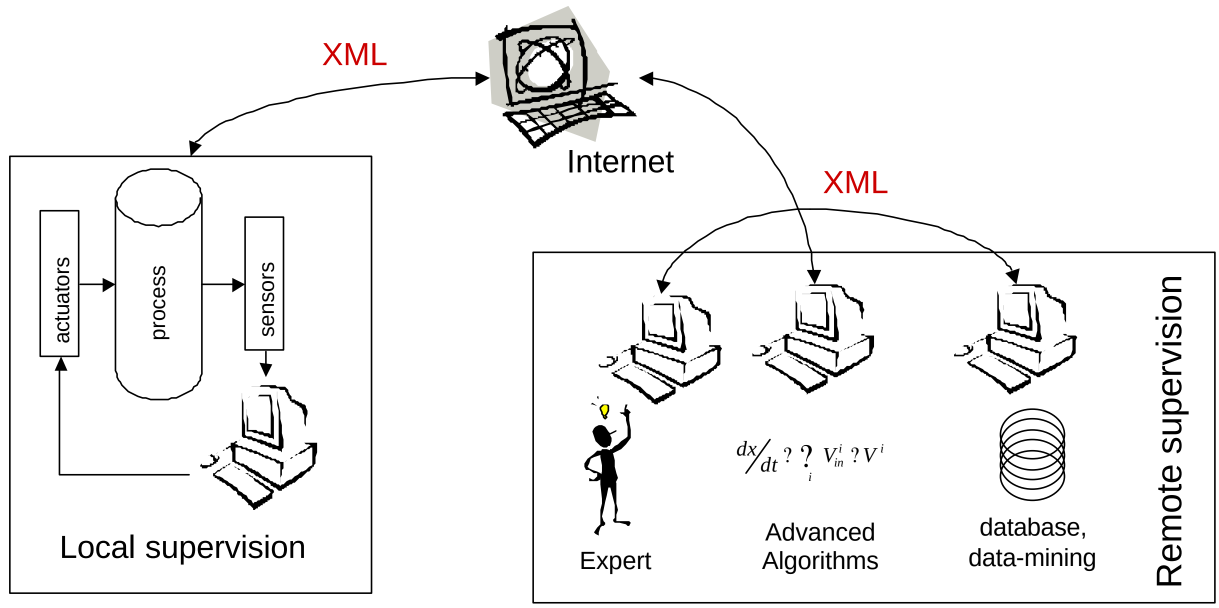

Figure 1. The overall architecture of the TELEMAC supervision system.

TELEMAC is a European project funded by the European Information Society Technologies (IST) Program (*i.e.*, IST-2000-28156 project) and coordinated by ERCIM and INRIA, with 15 partners. The project is particularly focusing on the treatment of vinasses. In order to improve this telemonitoring task, additional on-line sensors have been developed to provide information on biogas quality and quantity, volatile fatty acids, bicarbonate and alkalinity. These hardware sensors have been complemented by software sensors which take advantage of the developed models to estimate the unmeasured variables whose values have a deep impact on the process behaviour.

A key issue to improving performance and stability of anaerobic WWTP is to set up advanced control strategies. Providing a series of validated models for ordinary working conditions and also for specific failures is the basis for the development of robust controllers to achieve an optimal control strategy in normal conditions and to recover in case of failures. Advanced control strategies are supplemented by a supervision system able to detect in real-time or as early as possible any fault which can occur on any element of the process. This means that an automatic supervision system is able to perform this task for SME's which cannot afford a local expert on site, and that analysis by remote experts must be given only when it is needed. For this last point, computer communication technology provides new tools able to improve process supervision. Thanks to Internet resources, a remote centre can efficiently collect and manage data from several plants and run a database diagnosis, and a human expert can remotely reconfigure the control policy of a plant at any time and from anywhere in the world (see Figure 1).

Sensor development

The first key step to better monitor the anaerobic digestion process consists in increasing the information flow from the process by implementing new sensors. The priority for the project was the development of two sensors providing strategic information on the state of the anaerobic plant at a reduced cost.

The first sensor – intended to be cheap and robust – is based on thermal conductivity for detection of CO_2 in order to accurately measure the produced biogas. A peltier cooler and a H_2S scavenger to protect the analyser against corrosion for long-term use are implemented to ensure a long life for the sensor.

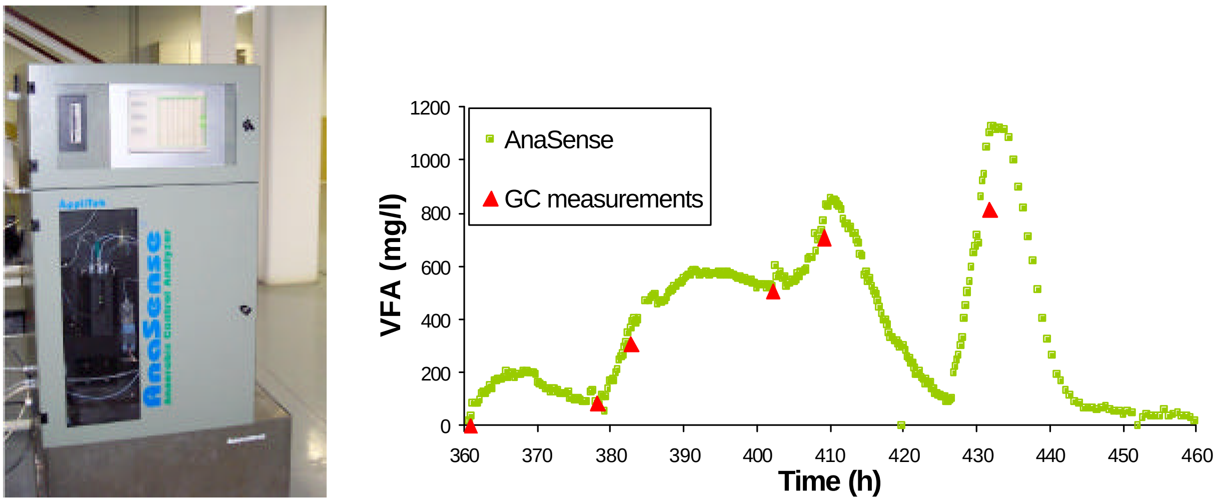

Figure 2. Validation of the AnaSense sensor dedicated to the measurement of VFA, bicarbonate, total and partial alkalinity.

The second on-line sensor measures the total volatile fatty acid (VFA) concentration, bicarbonate and alkalinity (total and partial). The method can also detect and quantify the appearance of abnormal products, provided they have an impact on the buffering system. Figure 2 presents the on-line VFA sensor (named AnaSense®) and the validation results on a pilot plant with comparison to off-line gas chromatographic (GC) measurements.

The efficiency of these hardware sensors is complemented by software sensors which combine the information from the sensor network with a process model in order to predict some concentrations (e.g. chemical oxygen demand (COD)) which are generally not available on-line. Figure 3 gives an example of such software sensor prediction for 150 days from a 2000 m^3 CSTR digester processing wine vinasses at the AGRALCO company (Chachuat *et al*, 2004).

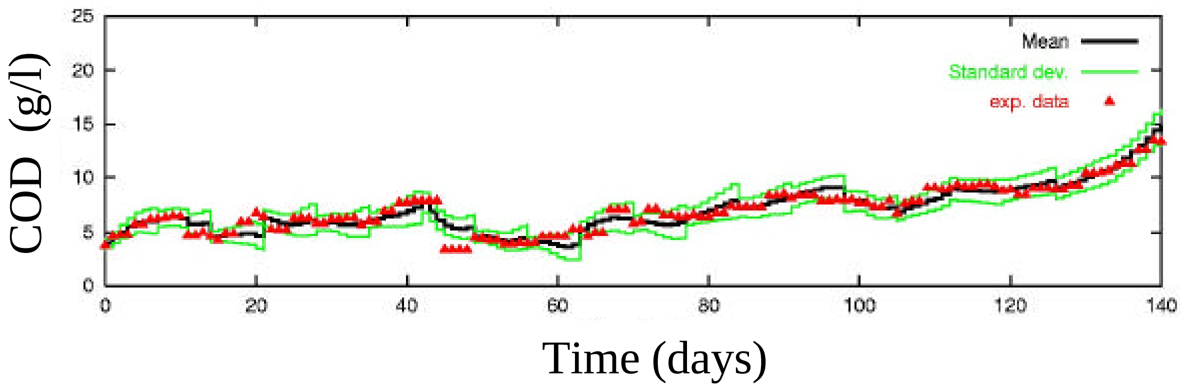

Figure 3. Software sensor validation: off-line soluble COD measurements (▲) are compared to the predictions of the software sensors (average predicted value and confidence interval).

Advanced supervision and control

Several mathematical models have been developed in order to optimize the information provided by the sensor network. These models, of increasing complexity, can predict the evolution of the anaerobic process, provided that the influent concentrations are known. They are used as a basis for optimal management strategy, design of automatic controller ensuring the process stability, and they give tools to test several feeding strategies and forecast their consequence on the process viability.

Figure 5 shows an example of the model's ability to represent abnormal working modes (model based on an improvement of Bernard *et al*. 2001), with comparison to experimental data performed at INRA on a 1 m^3 fixed bed digester processing wine vinasses (Chachuat *et al*. 2004). It is worth noting that a very large overload has been reached in this experiment (more than 9 g/l of total VFAs). They are used as a basis for optimal management strategy, design of automatic controllers ensuring the process stability,and they provide tools to test several feeding strategies and forecast their possible consequences on the process viability (Puñal *et al*. 2003, Mailleret *et al*. 2003,2004). Several automatic controllers derived from these models are integrated in the TELEMAC framework, with a variety of objectives (depollution, stability, cogeneration etc.). Finally, the more complex ADM1 model (Batstone et al., 2002) simulating in great details the anaerobic digestion process has been implemented and serves as a virtual plant in a first validation step of the developed algorithms (Zaher *et al*. 2003).

Two key requirements are of prime importance for fault detection and diagnosis of anaerobic digestion processes (Genovesi et al, 2000): uncertainty management and modularity in the design of the supervision system. This allows: (i) to handle the poor knowledge usually available on-line about the internal functioning of the process and (ii) to account for adaptivity, novelty and multiple fault identifiability requirements.

To achieve this objective, one natural way is to account for all the information available in a single diagnosis system. This is of course possible but would lead to a high complexity of the diagnosis system in cases of high dimension of the fault space (as it is the case in anaerobic digestion processes). Moreover, adding or removing one dimension (*e.g.*, one sensor) could break down the overall structure of the diagnosis system and lead to false alarms or wrong diagnosis. This is why a modular diagnosis system has been chosen: separate fault detection systems are built, each of them handling only partial information on the process. This is in fact similar to different persons analysing the same situation but with different point-of-views and/or different sources of information (Lardon *et al*, 2004). Of course, these fault detection systems are further combined within an overall system called a "state manager" that is based on evidence theory (Smets and Kennes, 1994). As shown in Figure 4, this state manager detects a fault when the set of information provided by the sensors is either incoherent (*e.g.*, sensor fault due to fouling) or shows an abnormal working mode (*e.g.*., process fault due to organic and/or hydraulic overload, presence of a toxicant). Once the diagnosis system has detected a failure, it alerts the expert centre. The supervision module can also detect the presence of a steady state (of normal or abnormal state) based on principal components analysis (PCA) data space reduction and multivariate statistical analysis (Ruiz *et al*, 2004). Moreover, the overall fault detection and diagnosis system fits most of the plants and automatically adapts to any development (new sensor, change of an actuator, etc.).

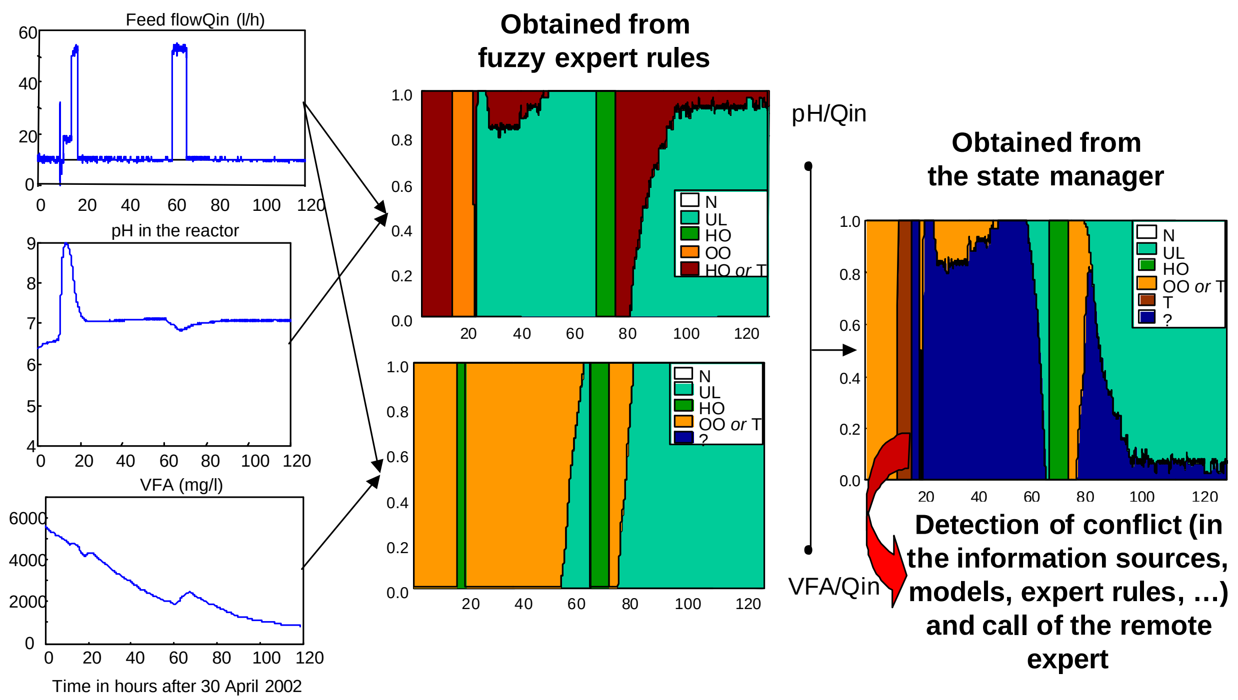

Figure 4: Illustration of the results provided by the TELEMAC fault detection and diagnosis system. N: normal, UL: Underload, HO: Hydraulic overload, OO: Organic overload, T: Toxic, ?: Unknown state.

The software developed

Three major software modules have been developed. First, local software associated with embedded boards manages the signals coming from the sensors and going to the pumps and electrovalves. It allows display of the evolution of the available measured variables and computes the advanced regulation and diagnosis. The main role of this software is to ensure the maximal autonomy of the depollution process by integrating most of the expert knowledge and thus meet the depollution requirements and guarantee a biogas quality suitable for cogeneration. The data are automatically sent to a remote database using a new XML language – called *PlantML* – specifically dedicated to wastewater treatment processes. This XML language provides a high modularity and standardisation of the communication between the various modules. Second, remote software runnable under any web browser allows a network of experts to connect to the plant or to the database to check the process state and to perform any action (change of the automatic controller, request a maintenance operation, *etc*.) . The state of the process can also be verified using WAP access from a mobile phone (see Figure 6). In case of problem the local software sends a message to request expert assistance.

Finally, a third software module has been developed in order to train a future expert to run the complex and unstable anaerobic plant despite perturbations and failures, by assessing the effect of a bacterial inhibitor in the influent, testing advanced control strategies, or even estimating the best strategy to process the wastewater to be treated in the coming months.

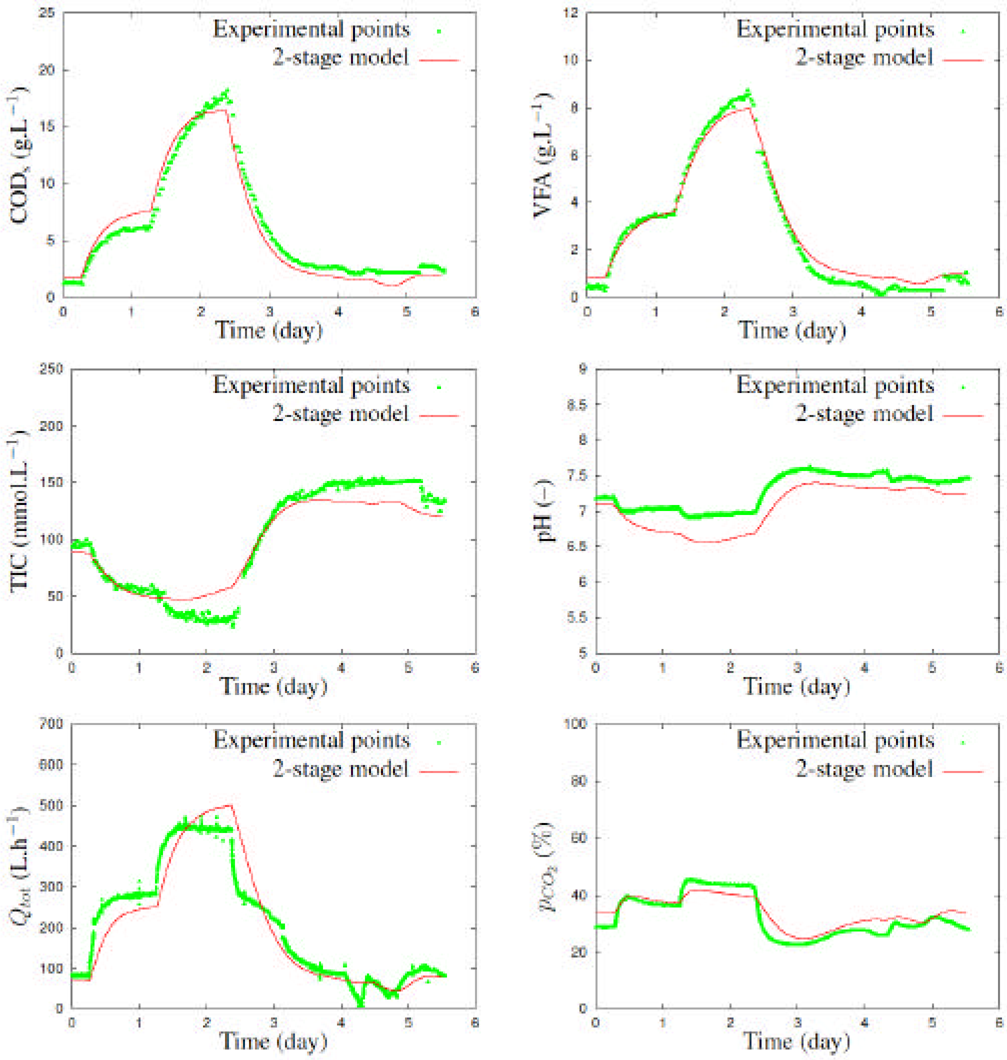

Figure 5. Experimental process overloading on a fixed bed digester processing wine vinasses. Comparison between sensor measurements and model predictions.

Experimental validation

The sensors, software and hardware, have been experimentally tested, using digester scales ranging from 5 L to 2000 m^3 with a broad variety of processes such as UASB, CSTR, Anaerobic contactor, fixed bed digesters or hybrid digesters. As shown in Figure 5, the purpose of these experiments is not only to collect data describing the standard working mode of the process but also to run experiments in extreme working mode (Ruiz *et al*. 2004; Dupla *et al*. 2004, see Figure 5). The conclusion is that the derived models have a good validity even in these degraded modes and can be used to support strategies that allow the system to recover.

A broad range of experiments were run and the data collected and stored in a database are available from the web. This database was used for model identification and algorithms development (Ruiz *et al*. 2004) and also supports data mining algorithms to take advantage of previous comparable events to analyse the latest records and ultimately use this experience to better manage a problem.

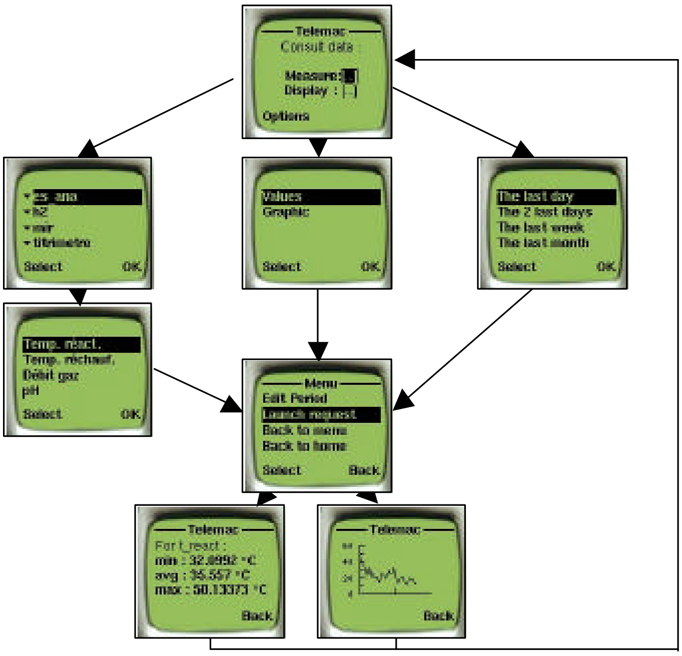

Figure 6. WAP access to the current data recorded by the plant and stored in the database.

Conclusion

TELEMAC offers an efficient, modular and reliable monitoring and management system for remotely controlling anaerobic treatment plants. After the implementation at the plant of the local software associated with a network of sensors, a remote expert centre is able to monitor the anaerobic digester. With such a system, the depollution of plants located in remote areas becomes possible and even profit earning.

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