An Agent Architecture for Supervising a pilot WWTP

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Abstract:

This paper describes the development and implementation of a real-time Knowledge-Based System (KBS) for the supervision and control of a wastewater treatment pilot plant (WWTPP) with biological removal of organic matter and nutrients. The hardware architecture contains different supervision levels, including two autonomous process computers (plant control and analyzers control) and a PLC, being the KBS the top supervisory level. The KBS has been developed using the G2 expert systems shell, and it is implemented for real-time operation. The implementation of the different components of the KBS is done under the Intelligent Agents paradigm. The knowledge is organized in several distributed agents, representing the available knowledge for every sub-process of the WWTPP. In addition to these independent agents, a Supervisor Agent acts as the master of the independent agents. The implementation of the KBS in the pilot plant has supposed the transformation of a classical control system with a fixed behavior in a system adaptable to different problems that could appear in a WWTP. The main achievement of this prototype is a versatile framework able to deal with different plant configurations, based on the object-oriented paradigm and on rule-based reasoning.

Introduction

Actual trends in process control are determining an increase in complexity at each control level. Utilization of automatic analyzers, industrial controllers, PLC (Programmable Logic Controller) and industrial computers is continuously increasing. The application of computer technology to control and supervision of technological processes has lead to a spectacular increase in the information acquired by these systems. However, this increase in frequency, quality and diversification of process data has not lead to an equivalent system improvement. The amount of information is so vast that its depth study is impossible. The results of this technology are Data Acquisition Systems, with the purpose of giving a process situation overview. To improve this situation, utilization of Artificial Intelligent techniques for processing this information has been proposed (Serra et al. 1993; Serra et al. 1997; Patry and Barnett 1992).

Monitoring of the components of wastewater treatment processes is an important feature in order to assure its control, particularly when simultaneous organic matter, nitrogen and phosphorus removal are involved. The complexity of these systems, due to the number of biological processes implicated, makes necessary the development of reliable on-line instrumentation. Furthermore, a reproducible and robust sampling device is a critical fact to provide reliable data of the process. On-line and in-line measurements continuously obtained from the process, combined with a model and different control strategies implemented are capable of making wastewater treatment plants more efficient.

A Knowledge-Based System (KBS) is a possible framework where measurements, rules and models can be integrated. Barnett (Barnett et al. 1992) presents an extensive literature review on application of KBS for the activated sludge process. Most of the systems here summarized are off-line KBS mainly diagnostic and advising tools to help operators (Gall and Patry 1989; Ozgur and Stenstrom 1994). Some KBS have been designed with the main purpose of on-line supervision (Verheijen 1997) though the emphasis on real-time supervisor control is usually absent.

In the present work is shown the hardware architecture and software development of an intelligent distributed control system for supervision of a wastewater treatment pilot plant with biological removal of organic matter, nitrogen and phosphorus. This development can be defined as a knowledge distributed system. This means that all the possible knowledge at every subsystem of the process is applied, as the main tendency in the actual real-time control and supervision of processes. In this supervisory control outline, every element supervises the elements situated hierarchically under its control. This fact increases system complexity, but some important advantages are obtained. Firstly, control of process failure is increased to assure system security. With this architecture is easy to obtain a fault tolerant system. Secondly, the top-level control can be used to work in system supervision. In our case, this top-level control is occupied by a distributed Expert System built with G2 (Gensym 1995), a tool to develop real-time expert systems, using an Agent-based software engineering perspective.

As a modeling framework for complex tasks, agent architectures (Maes 1990; Jennings et al. 1997) are widely used for the implementation of distributed KBS. Some of the advantages of the Agent paradigm are the distribution of data, the distribution of control, distribution of expert knowledge and the distribution of knowledge. This characteristics fit perfectly in the problem that we want to solve with this application. In real WWTP, the global optimization of the process is usually accomplished with the local optimization of the several subsystems forming the WWTP. This is true in general situations, but when some problems appear, the local optimization is unable to accomplish legal requirements. With the Agent Technology, it is possible to build intelligent systems able to deal with both situations. The independent agents adjust every subsystem of the WWTP, while the Supervisor Agent is in charge of the coordination among agents in order to improve the overall plant situation. Theoretically, this architecture is able to obtain better results than a centralized one, although the system development and integration are more difficult tasks.

Architecture of the System

The architecture of the intelligent distributed control system is outlined in Figure 1. The whole system can be divided in five blocks: the pilot plant, its monitoring and control system, the analytical devices, the data server and the KBS.

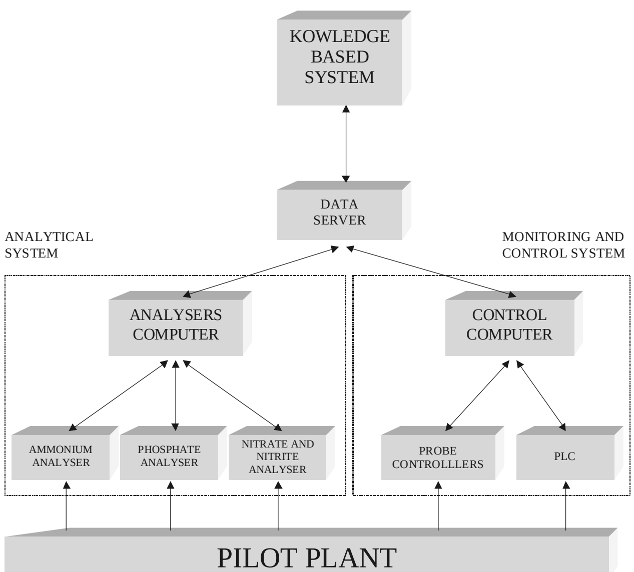

Figure 1. Outline of the architecture of the control system

In this architecture, the different control dynamics that are found in a real WWTP are reflected. The fastest dynamic is the operation of oxygen control. This parameter should be controlled in a very fast dynamic therefore the utilization of an independent controller as for example a PID (Proportional Integral Derivative) Controller can be necessary. It depends on the aeration system used, but in our plant, the necessary frequency of actuation is about 10 seconds. Other fast parameters are the different flows of the plant, the stirring speed, etc. All these parameters should be controlled directly with local control loops. In our plant, this is done through the utilization of an independent monitoring and control system.

In order to acquire more information about the process in the pilot plant, another subsystem has been designed and implemented. This is the automatic analytical system. This is independent from the monitoring and control system, and is controlled by another computer.

These two systems are physically independent, but are linked through the data server, which permits the data transmission between these computers and the agents system. The independence of every subsystem assures the security of the other subsystem if a problem appears in one of them.

The monitoring and control subsystem is able to maintain the plant performance in normal conditions, but this control acts with a set of fixed setpoints. When not normal conditions appear, this subsystem could not be able to take the plant to a good performance. Is in this moment when the need for a higher supervisory level appears. These tasks, that classical control systems are not able to manage, are the ones where KBS are a good tool.

The Pilot Plant

The process under study is a biological wastewater treatment based on A^2/O multistage configuration (EPA 1993) with nitrification - denitrification and biological excess phosphorus removal. The pilot plant is fully automated and is able to treat 500 liters per day of a synthetic influent. Figure 2 shows a schematic diagram of the pilot scale facility, which consists of an anaerobic selector (9 liters), three identical aeration tanks (28 liters) and a settler (60 liters).

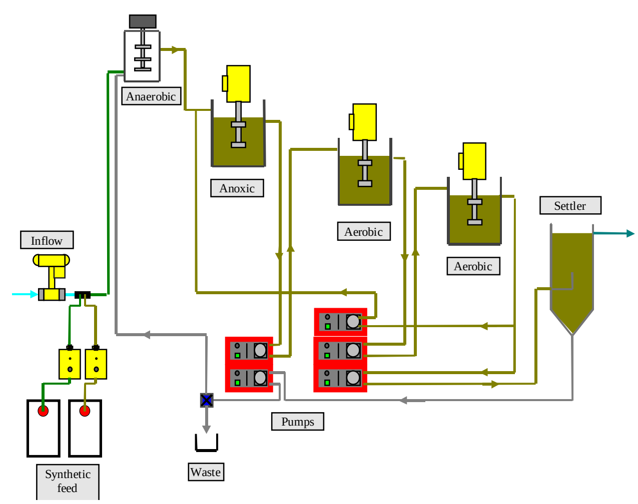

Figure 2. Scheme of the pilot plant.

The oxic state of these three tanks is easily configured from the expert system. The first tank usually is used as an anoxic reactor, but an aerobic operation mode is also possible. The presence of an anaerobic selector is due to phosphorous removal. The inlet wastewater is a synthetic influent made by mixing two concentrated complex sources of carbon and phosphorus, and nitrogen diluted with tap water. Different concentrations and flows can be automatically assigned and scheduled to simulate real situations.

Monitoring and Control System

Each mechanical unit of the plant (pumps, level detectors, nipping valves, etc) is controlled by a PLC, that allows to automate all those elements. In the PLC program, the operation failure detection and corrective actions are included. This is the first control level. Every reactor of the pilot plant has in-line sensors (dissolved oxygen, pH, ORP, temperature) connected to probe controllers.

A control and monitoring computer supervises the PLC. This computer also acquires data from the probe controllers and it controls the dissolved oxygen (DO) through the manipulation of the pneumatic control valves of every reactor. This control loop is based on a digital PID algorithm programmed in the computer.

The information provided by the sensors is sent by the agent implemented on this subsystem to the agent in charge to distribute this information to other agents. It can also receive messages communicating changes in control actions. The agent includes graphic monitoring, data backup, and control of key process parameters (flow-rates, stirring rates, etc).

Analytical System

Flow Injection Analysis (FIA) and Continuous Flow Analysis (CFA) techniques have been implemented for ammonium, nitrate, nitrite and phosphate monitoring. The analytical system developed focuses on automation, reliability and long-term stability to operate the maximum time in an unattended manner. The analyzers are an automation of standardized chemical procedures. They are controlled with a computer where all the modules of the three systems are connected.

FIA for simultaneous determination of nitrate plus nitrite (Gabriel et al. 1998) is based on the Shinn method. A copper-coated cadmium reduction column for nitrate reduction to nitrite is used. The maximum sampling rate is 180 samples per day.

FIA for phosphate determination is based on the colorimetric determination of the vanadomolybdo-phosphoric acid previously formed by addition of vanadate-molybdate reagent. This analyzer is based on the reverse-FIA technique where reagent is injected to a sample flow. The maximum sampling rate is 480 samples per day.

The CFA for ammonium is based on potentiometric determination of ammonia. The sample is continuously feed to the analyzer and mixed with a flow of sodium hydroxide to obtain quantitative ammonia. This flow passes through a gas diffusion unit where ammonia is transferred to a crosscurrent flow of ammonium chloride buffer solution. This flow passes through a cell with a flat pH electrode where the potential is read. The maximum sampling rate is 90 samples per day.

An automated sampling system was mounted to obtain a continuous biomass-free sample flow. A set of computer controlled nipping valves is used to select the sampling circuit.

The agent implemented on this subsystem includes data acquisition, graphic monitoring, data backup, and control of the sampling system. In addition, it actuates each module of the analyzers (three-way valves, injection valves and pumps). All this information is used to feed the agent managing a database.

The Data Server

The process computers are linked, using an Ethernet Network, to a Sun SPARCstation where the data server is executed. This data server allows the maintenance of a real time database with the information generated in the system. An agent manages this information and answers the data requests from other agents. It is a bi-directional communication system WWTPP ⇔ KBS: information from the WWTPP variables is sent to the data server and control actions from the KBS are sent to the WWTPP. This data server is able to receive a message of petition from any agent at any moment, and it sends the required information immediately. It is capable of maintaining several communications with different agents simultaneously to avoid any delay in the connections of the agents.

TCP/IP protocol, which is based on a client / server architecture, has been used to solve communication requirements. With the implemented system, communication between any client computer connected to Internet and the data server is possible. This system is very useful to maintain the on-line database. You can visit a web page generated by the data server (http://eq3.uab.es/depuradoras/piloto/plantatr2.html) to see some of the on-line data available in this moment.

The KBS also needs off-line data from analysis and microorganism observations to obtain more information about the WWTP situation. This analytical and microbiological data is sent to the data server using forms on web pages (http://eq3.uab.es/depuradoras/offline.htm, http://eq3.uab.es/depuradoras/microbiol.htm). These pages generate e-mail messages, which are sent to the data server, where the information is used to update the values of the corresponding variables or parameters.

Knowledge-Based System

The KBS developed in the G2 shell, running in the Sun workstation, is on the top of the system architecture. It consists in a set of agents that actuate in a supervisory setpoint control (SSC) scheme. It is also able to do other control actions not included in that kind of systems, as for example deactivating local control loops in some situations.

The knowledge stored in the KBS is based on the existing scientific background about similar processes and the practice acquired in our particular system. Main bibliographic sources used are *Wastewater Engineering* (Metcalf & Eddy Inc. 1991) and the *Manual of Nitrogen Control* (EPA 1993), although other papers related to wastewater treatment have also been used. The practical experience considered comes from interviews with the designers of the system and the plant operators. The pilot plant has been working continuously for more than four years, so an important set of heuristic rules has been found.

All this knowledge is structured trough a whole of rules and procedures for each subsystem of the pilot plant, distributed on a set of specialized agents and coordinated with a supervisory agent. The supervisory agent can have a bi-directional communication with its subordinate agents, can request data from the agent managing the data server and can control the behavior of the plant.

Architecture of the Knowledge-Based System

The KBS is based on a distributed architecture integrated by a supervisor, and is a particular application of previously defined architectures (Serra et al. 1994; Sànchez et al. 1994; Sànchez et al. 1996). The knowledge is distributed on several agents, representing the available knowledge for every sub-process of the WWTPP. The use of an Agent-based software engineering perspective has some advantages (Jennings et al. 1997), as for example obtaining modularity, reusability and extendibility of the system, or obtaining a system able to manage the increasing complexity of AI systems. All the independent agents and the supervisor agent share a common knowledge base that is used during the interchange information between them. In figure 3, a scheme of the KBS architecture is shown. The system is divided in four different levels: Local control level, Data level, Distributed knowledge level, and the Supervisory level.

Local Control Level

The WWTPP was initially built and operated with this distributed local control system. This level allows direct control of the pilot plant, with a set of pre-defined setpoints, and applying mainly numerical control. The hardware architecture with this local control permits the independence of the monitoring and control system and the KBS. This control can work without the presence of the KBS, although with a set of fixed setpoints.

This is a first important improvement of the control of WWTP, but it still has not been widely applied in real WWTP. As was said, two agents are implemented at this level, one specialized on the on line sensors and the mechanical control elements of the plant, and other on the analytical system.

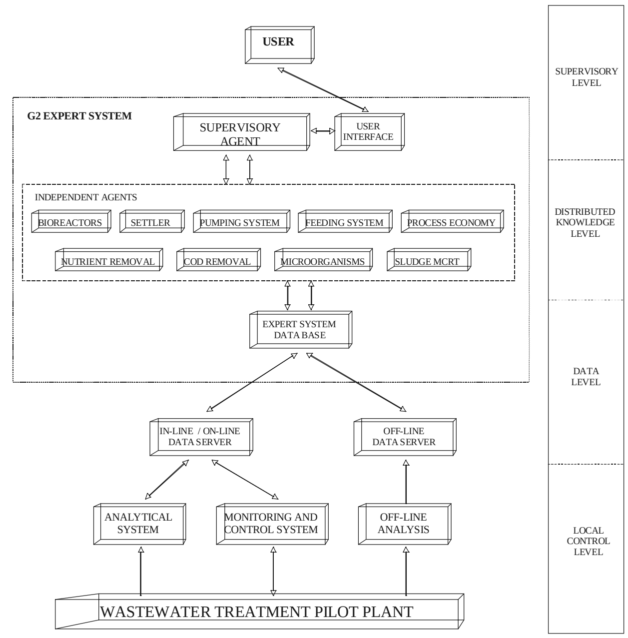

Figure 3. Scheme of the KBS architecture.

Data Level

The data level includes the bi-directional data transmission between the local control level and the KBS. It also includes the real-time database maintained by a specialized agent. This data level profits from the real-time interfaces and assures a real-time environment for the KBS. This level not only takes into account the data transmission from the pilot plant to the KBS, but also is in charge of the transmission of setpoints from the KBS to the distributed control system. The data is obtained from on line measures from the plant and off line measures provided by a plant manager.

An agent processes all this information and puts it in a database. The information inside the database has an organized structure based on the domain of each agent. The agents from the upper level can use it as knowledge base.

Distributed Knowledge Level

The implementation of this level is based on a set of independent agents that take care of simple tasks on the WWTPP and are the information source for the supervisor agent. There is defined a minimal communication language between those agents that allows the supervisor agent to request data from an agent, deactivate or activate an agent or change system parameters. This communication is based on a set of predefined tables with the plant parameters or variables. This information codified in tables is not only limited to numerical information, it can also be symbolic. Any agent can request information from these tables (coming from any other agent) or modify the variables or parameters from the tables that are in charge of the agent.

The Supervisor Agent is able to access to any table and modify any parameter, in order to control the behavior of the independent agents. These tables are physically implemented using shared memory regulated through semaphores.

The subordinate agents are controlling a simple process parameter, and solve their tasks based on numerical algorithms and rules when the situation is normal. These parameters are established using forward chaining reasoning when new data arrives to the real time database. The information arrives to the database from the monitoring and control systems. Those agents can generate messages to the control system in order to change system parameters.

The Supervisory Agent checks periodically the situation of every agent in a pre-defined sequence. When the situation of any specific agent is abnormal, the overall situation of the WWTPP is problematic or a complex parameter not controlled by a specific agent has to be calculated, the supervisor requires information to the agents and deduces the correct control action to be made. The Supervisor agent can deactivate these agents totally or partially when some problems are detected. Then, although they are independent, the supervision and control over them is guaranteed.

The actual number of agents is nine, although some additional integration is possible. The specific agents are:

Bioreactors agent. It supervises the operation in the bioreactors, specially the aeration, stirring and probes subsystems behavior. In this agent are included the possible deactivation of local control loops. For example, if the agent detects an oscillatory behavior of the oxygen control loop, it can infer that the measure provided by the oxygen probe is not correct, and it can deactivate the local loop and set a fixed aeration. It is also in charge of validating data provided by the monitoring system and the analytical system. This validation consists of checking the measures with different criteria: the value must be into a predefined interval, the rate of change should not be too fast or too low and the measures must not be in discrepancy with other related data.

Settler agent. This agent takes charge the supervision of the settler operation. This is an important element to ensure the correct performance of the activated sludge process, because the water - microorganisms separation is a general source of problems in WWTP. In order to conclude the actual situation of this process unit, the Settler Agent utilizes data flows and microorganisms concentration, which are provided by the Pumping System Agent and the Sludge MCRT Agent respectively.

Pumping system agent. It supervises the operation and maintenance schedule of the pumps used in the pilot plant. A problem with any pump produces a disturbance of the biological process because the plant has to stop. In these conditions, an early diagnostic of any possible problem is a great help for the whole process. This agent is also in charge of maintaining the desired recycling conditions. It can work with different strategies, as for example, fixed flow or fixed recycling/inlet flow ratio and it can also receive setpoints from the Supervisor Agent if any agent concludes that it is required.

Feeding system agent. This agent supervises the automatic feeding system. It integrates the total volume and concentration of compounds fed to the pilot plant. This agent estimates the volume of concentrates used, and advises the operator when the vessel of concentrate should be filled. It also estimates food / microorganisms ratio, and advises when this relation can produce problems in the plant.

Process economy agent. In all the WWTP processes, economy must be taken into consideration. In some situations, the main restrictions come from the economic point of view, therefore, it should be taken into account when necessary. This agent is mainly advisor, giving different messages to the operator with the purpose of maintaining the performance of the plant diminishing the total energy consumption.

COD removal agent. The organic matter removal is the most important task in a WWTP. This removal must satisfy legal requirements and should be supervised to ensure those requirements. Some predefined usual situations, as overload or low-load, can be detected and then the agent can apply the control actions programmed to avoid future problems.

Nutrient removal agent. Nutrient removal is a new requirement for WWTP. The processes involved are more complicated than the COD removal. The combination of COD, phosphorous and nitrogen removal produces new problems in a more complex framework. The COD removal and the nutrient removal are two very interrelated agents, so the co-operation through the supervisor agent is very important in this case.

Microorganisms agent. This agent uses the information obtained off-line with the microscopic observation to supervise the microorganisms present in the sludge. These observations are very useful to infer future problems. Taking into account these possible problems, preventive actions can be executed in order to avoid them. Here is included a great amount of symbolical information, hence the presence or absence of some microorganisms can be an indicator of some current or future problems in the plant. The data agent is in charge to receive and process this off-line information.

Sludge MCRT agent. MCRT is an important parameter of the process that determines the species of microorganisms present in the system. For its calculation, in-line and off-line data are required, therefore it is a complex key parameter. The MCRT setpoint is calculated by the supervisor agent taking into account information provided by this and other agents, such as Process economy, Nutrient removal or Microorganisms.

Supervisory Level

The Supervisor agent is the manager and master of the distributed system. It receives the information required to the independent agents and concludes if a supervisory control action is necessary. If no action is required, the agents maintain active its algorithms and rules. In addition, it controls complex operational parameters that involve information generated from several agents. The communication between the supervisor agent and the other agents is done using a minimal set of messages: request information, deactivate, partial deactivate, activate and change parameters. Each particular agent has its own parameters depending on their task.

The Supervisor agent also permits the data interchange between the user and the system, by means of a user interface. This interface includes graphical monitoring of the data acquired and an explanation module that allows the debug of the way used to arrive to a determined conclusion of the KBS. All the decisions or actions made by the agent and the messages interchanged between the agents are displayed in real time for user monitoring. An alarm system can also be activated instructing the supervisor agent to send a warning message in certain circumstances.

KBS Implementation

The system is implemented using the G2 shell, an expert system building tool. It permits the organization of a KBS in knowledge bases. A knowledge base can contain one or many workspaces. The objects upon workspaces are capable of having their own subsidiary workspaces. Thus, logical hierarchy of objects and workspaces to group and organize data can be created. In our prototype definitions, plant diagrams, graphical monitoring, and agents are considered as main workspaces. The agents are subdivided in several workspaces, maintaining an organized structure.

Knowledge representation in G2 is maintained and extended through classes. G2 maintains class attributes within attribute tables. Main classes considered include process units (14 object definitions), instrumentation (38 object definitions), connections (27 object definitions), sludge and microorganisms (84 object definitions), and computers (4 object definitions). Every object is an instance of a class, which is defined through an object definition. Figure 4 presents the KBS shell with several workspaces, objects with their icons, and connection stubs.

The KBS is fed with in-line data (pH, T, DO, ORP, aeration and flows) and on-line data (NO_3^-, NO_2^-, NH_4^+ and PO_4^{3-}) generated by the plant using the data server. Qualitative data (odors, colors, microbiological observations data) and discrete data from off-line analyses (COD, TSS, VSS, TKN, and SVI) are sent to the KBS. Each specialized human operator can send specific data from any computer using a form page through a WWW server. HTML code generates an e-mail message that is send to the appropriate agent. The data and the supervisor agent are able to read these messages, and to use this symbolic and numeric knowledge to update information in the database or its own knowledge base.

Using rules based on the available data and the operator confirmation in problematic situations, the agent system continuously decides the optimum operation. Finally, control actions are transmitted to the process computer that acts on the required plant elements.

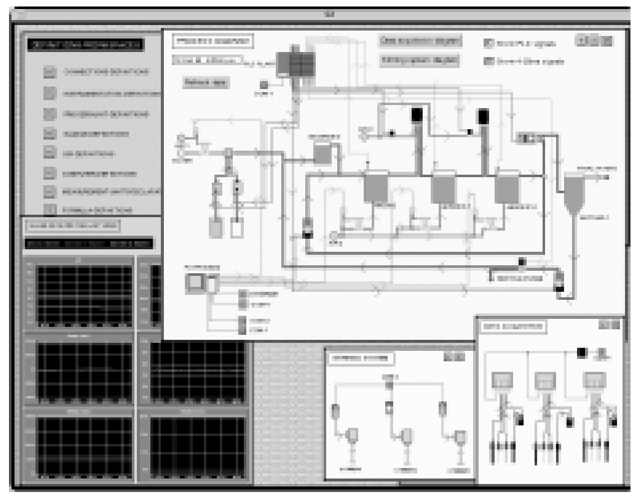

Figure 4. The Expert System shell.

Application

KBS implementation makes possible to control the overall performance of the process through the relation among different parameters. As an example about the applied Agent Technology, two different situations usually found in our system are explained.

In the first situation, if an organic overload in the influent is detected, the Feeding System Agent sends a corrective action to the Supervisor Agent. The corrective action implemented in our case is to increase the external recycling flow to maintain the food/microorganisms relation (F/M) in a predefined set point. The Supervisor Agent, taking into account the detected situation and the actual flows provided by the Pumping System Agent, concludes that the corrective action has to be performed. Then the required orders are sent to the Pumping System Agent who modifies the set point of the external recycling pump. Classical control based on local control loops is not able to deal efficiently with situations that imply the relation among different information generated by the plant.

A detailed practical example of how the overall supervisory system works is shown, focusing on the control of the Mean Cellular Residence Time (MCRT):

The operator realizes a routine analysis and then introduces the analytical results in the Web Page using a standard browser. This produces an e-mail, with the data codified, which is sent to the data agent. The data agent checks periodically if a new e-mail message has arrived. When detected a new e-mail, the data included is read. This data is used to update the corresponding attributes of the defined objects. The changes of the value of the attribute 'suspended volatile solids' in the reactors produce a new value of the MCRT. If this value is different to the previous one, the agent 'Sludge MCRT' is automatically activated. This agent checks if the new value was into the predefined band. This band is determined by the Supervisor agent with an optimization procedure, taking into account the information provided by several agents, as the 'Nutrient Removal', the 'Microorganisms' or the 'Economical Restrictions' agents. If a difference between the required MCRT and its actual value is detected, a procedure that calculates the purge parameters to obtain the required MCRT is activated.

These parameters are sent to the data agent, who is in charge of transmitting them to the monitoring and control computer. The control computer, with the new setpoints obtained from the data agent, sends to the PLC new setpoints, corresponding to the opening time of the purge electrovalve. The PLC uses the new setpoints to open and close the purge electrovalve in the prefixed intervals. The position of this electrovalve determines if the sludge recycling flow is directed to the anaerobic reactor or to the vessel where the purge of the system is accumulated. The change in the recycling flow derived to the vessel determines a new value of MCRT.

The above facts sequence is started when a new off-line analysis data is sent. The same sequence can be originated when on-line data is received. A change in the plant conditions, for example if the external recycling flow is modified by another rule, can produce new values for the parameters of the system involved in the MCRT calculation. These news values are detected by the KBS, which will activate the necessary agents to conclude new control parameters if necessary, as has been shown before.

Conclusions

The implementation of the KBS in the pilot plant has supposed the transformation of a classical control system with a fixed behavior in a system adaptable to different problems that could appear in a WWTP. The capacity to deal with these problems is useful to control abnormal situations and to maintain legal restrictions in the effluent. In addition, it is able to avoid the appearance of some situations that could cause long term problems. These situations are, for example, imbalance growth of some microorganisms that can induce long term bulking problems in the plant. Consequently, difficulties to accomplish effluent restrictions in some parameters appear. The corrective actions made by the expert control are not implementable in a classical control system, therefore this is a great improvement respect to classical control. Furthermore, it is possible to implement all the classical algorithms for numerical control. Therefore, there is a net gain of possibilities to deal with the different problems of the WWTP.

With respect to the distributed multi-agent architecture, our system has shown some characteristics that improve previous developments with monolithic KBS. This agent-based architecture permits the development of independent and reusable agents. These agents can be made by different developers, taking into account some established requirements for the communication with the Supervisor Agent. After the construction, the agent can be integrated with the rest of the system. This task has been done for example with the Microorganisms Agent, where different experts have co-operated in its construction. This also means that the developed agents can be re-used in other expert systems, they can be adapted with minimum changes. Another important characteristic is a better maintainability with respect to the previous versions. The tasks made independently by different agents are easily validable because they are independent, so this task is simplified. In contrast, the integration with the Supervisor Agent must be inspected with detail to avoid errors in the co-ordination. The difficulty of its integration can be the fact that the developer has to decide between a monolithic expert and a multi-agent system.

The main achievement of this prototype is a versatile framework able to deal with different plant configurations, based on the object-oriented paradigm and on rule-based reasoning. The on-line feature is an important innovation of this system, particularly for data monitoring and supervisor control. Recently, some papers with good results have appeared showing the promising potential for implementing on-line monitoring and control (Balslev et al. 1996; Nielsen and Önnetrh 1996), though their knowledge integration is not as formal and versatile as KBS would require. In our system, different control strategies can be implemented for activated sludge control of carbon, nitrogen, and phosphorus removal with different plant configurations. In addition, the developed KBS can be adapted to a new plant in a short time because of object-oriented design.

Finally, this system has been running continuously for 700 days. In this period the operational objectives of the pilot plant were changing periodically (nitrogen removal, phosphorus removal, etc.). The supervisory expert system has shown an excellent performance to manage the WWTPP. The system developed detects and controls all the wrong and special operations, for example pump failure, feeding problems, probes malfunction, equipment maintenance, analyzers control and maintenance.

References

Balslev, P.; Lynggaard-Jensen, A.; Nickelsen, C. 1996. Nutrient sensor based real-time on-line process control of a wastewater treatment plant using recirculation. *Wat. Sci. Tech.* 33(1): 183-192.

Barnett, M.W.; Patry, G.G.; Hiraoka, M. 1992. Knowledge-based (expert) systems for the activated sludge process. *Dynamics and Control of the Activated Sludge Process*, Technomic Publ. Co., Lancaster, pp. 231-243. Andrews, J.F. Editor. Lancaster, USA

EPA. 1993. *Manual Nitrogen Control.* EPA, Washington, DC, USA.

Gabriel, D.; Baeza, J.; Valero, F.; Lafuente, J. 1998. A novel FIA configuration for the simultaneous determination of nitrate and nitrite and its use for monitoring an urban waste water treatment plant based on N/D criteria. *Analytica Chimica Acta*, 359: 173-183.

Gall, R.A.B.; Patry G.G. 1989. Knowledge-based system for the diagnosis of an activated sludge plant. *Dynamic Modeling and Expert Systems in Wastewater Engineering*, Lewis Publ., Chelsea, 193-240. Patry, G.G., Chapman, D. Editors. Lewis Publishers, Inc., Chelsea, MI.

Gensym 1995. Gensym Corporation. *Gensym G2 Reference Manual Version 4.0.* Gensym Corporation. Cambridge, Massachusetts.

Jennings, N. R.; Wooldridge, M. J. (eds) 1997. *Agent Technology: Foundations, Applications and Markets*. Springer Verlag.

Maes, P. (ed). 1990. *Designing Autonomous Agents.* Cambridge, MA. MIT Press.

Metcalf & Eddy Inc. 1991. *Wastewater Engineering: Treatment/Disposal/Reuse*, 3rd edn. McGraw-Hill, New York.

Nielsen, M.K.; Önnerth, T.B. 1996. Strategies for handling of on-line information for optimising nutrient removal. *Wat. Sci. Tech.* 33(1): 211-222.

Ozgur, N.H.; Stenstrom, M.K. 1994. KBES for process control of nitrification in activated sludge process. *J. of Environ. Eng*. 120(1): 87-107.

Patry, G.G.; Barnett, M.W. 1992. Innovative computing techniques for development of an integrated computer control system. *Wat. Sci. Tech.* 26(5-6): 1365-1374.

Sànchez, M.; R-Roda, I.; Poch, M.; Cortés, U.; Lafuente, J. 1994. DAI-DEPUR architecture: Distributed agents for real-time WWTP supervision and control. In *Proc. Of IFAC/IFIP/IMACS Symp. on Artificial Intelligence in Real Time Control (AIRTC'94), València (Spain)*, 147-152. Servei de Publicacions de la Universitat Politècnica de València (UPV), València, Spain

Sànchez, M.; Cortés, U.; Lafuente, J.; R-Roda, I.; Poch, M. 1996. DAI-DEPUR: an integrated and distributed architecture for wastewater treatment plants supervision. *Artificial Intelligence in Engineering* 1: 275-285.

Serra, P.; Lafuente, J.; Moreno, R.; De Prada, C.; Poch, M. 1993. Development of a real time expert system for wastewater treatment plants control. *Control Eng. Practice.* 1(2): 329-335.

Serra, P.; Sànchez, M.; Lafuente, J.; Cortés, U.; Poch, M. 1994. DEPUR: a knowledge-based tool for wastewater treatment plants. *Engng. Applic. Artif Intell.* 7(1): 23-30.

Serra, P.; Sanchez, M.; Lafuente, J.; Cortes, U.; Poch, M. 1997. ISCWAP: A knowledge-based system for supervising activated sludge processes. *Computers Chem. Engng.* 21(2): 211-221.

Verheijen, L.; Uchiakawa, I.; Kobayashi, T.; Endo, I. 1997. IMCS (Intelligent Monitoring and Control System) for wastewater-treatment. *Book of Abstracts of 8th European Congress on Biotechnology*, Budapest, pp. 299. Publisher: Hungarian Biochemical Society, Budapest.