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Fermentation Processes Monitoring and Control Using Generalized Nets

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Abstract: In this paper a generalized net model for monitoring and control of main of physics-chemical parameters, gases, as well as foam levels of fermentation processes is developed. Generalized nets are preliminary proved to be an appropriate tool for description of the logics of fermentation process modelling, including the opportunity for the biochemical variables of considered processes to be described. The proposed generalized net model for monitoring and control of fermentation processes is a combination of already developed generalized nets into a single model, that allows optimal process implementation through monitoring and control of essential process variables and parameters.

Keywords: Generalized nets, Monitoring and control, Fermentation processes.

1. Introduction

Considering fermentation processes, all bioreactors used nowadays use control strategies for three basic environmental factors: pH, temperature and dissolved oxygen (DO). Invariably, these control implementations are achieved via regulation of flow rate of acid/base, flow rate of fluid through the cooling coil, and agitation, respectively. Needless to say, these three parameters are extremely important for optimal cellular activity. But they alone do not guarantee the maximum productivity, which is the objective for most of the industrial fermentations.

A control system cannot be implemented unless the process under consideration has been understood. An efficient way of understanding the process is constructing a mathematical model. A good process model is an invaluable tool to develop a control algorithm. It is not implied that controllers are unable to control poorly understood processes; in practice, this is how they often function. However, an expensive, and time-consuming trial and error adjustment of the control algorithm is required in that case.

Automatic control systems have advanced far from their initial applications in the process industries. The conversion from local single-input single-output loops through initial application of advanced methods to current multivariable, adaptive, and neural network applications has increased plant profits. The use of Generalized Nets (GNs) [1-3] affords the opportunities for on-line control; searching of optimal process conditions; learning on the basis of experimental data; control on the basis of expert systems, etc. The facility of obtaining GN models demonstrates the flexibility and the efficiency of generalized nets as modelling tools in different fields [1-3, 12]. This fact provokes the idea of developing a GN model for fermentation processes monitoring and control.

So far, GNs have been used as a tool for modelling of various operational modes of fermentation processes, for different processes such as fed-batch fermentation of *E. coli* and *Br. flavul*, as well as for wastewater treatment processes, [12]. On the other hand, generalized nets are used for optimal control of fermentation processes [4], PID controller [11], and for monitoring and control of some physics-chemical parameters of considered processes, such as temperature [7, 9], pH [8], DO [6], carbon dioxide (CO_2) [10] and foam levels [5]. The known advantages of the generalized nets presents them as a very appropriate tool for the modelling complex processes such as fermentation processes. The generalized nets models, that have been developed so far, allow us to simulate the fermentation processes easily and quickly [12].

This paper is focused on the application of these already developed generalized nets for the fermentation processes monitoring and control. In this work a GN model is proposed that generalizes the known GNs for monitoring and control of physics-chemical parameters, gases and foam level of considered processes.

2. Monitoring and Control of Fermentation Processes

The proposed generalized net model describes a system for monitoring and control of physics-chemical parameters **(**pH, temperature), gases (DO and CO_2) and foam during a fed-batch fermentation process [13, 14]. An example of fermentation processes monitoring and control is presented on Figure 1. Parameters that must be precisely regulated are: temperature, pH and oxygenation (DO). In addition, monitoring and control of the CO_2 and foam level is needed [13, 14].

Monitoring and temperature control

Temperature is one of the most influential factors affecting the fermentation process. Temperature affects the growth and activity of all living cells. At high temperatures, organisms are destroyed, while at low temperatures their rate of activity is decreased or even suspended.

A generalized net model describing the whole system for temperature control in the bioreactor is developed [7]. The GN model permits to control the temperature at a desired value during the fermentation processes. The apparatus of generalized nets allows easy and simple in logics description of temperature control system. The GN model allows taking into account factors that affect the temperature control system, and it presents the calculation of water temperature that should be added into the double jacket of the bioreactor. This ensures the control of the temperature at the desired value during the fermentation processes.

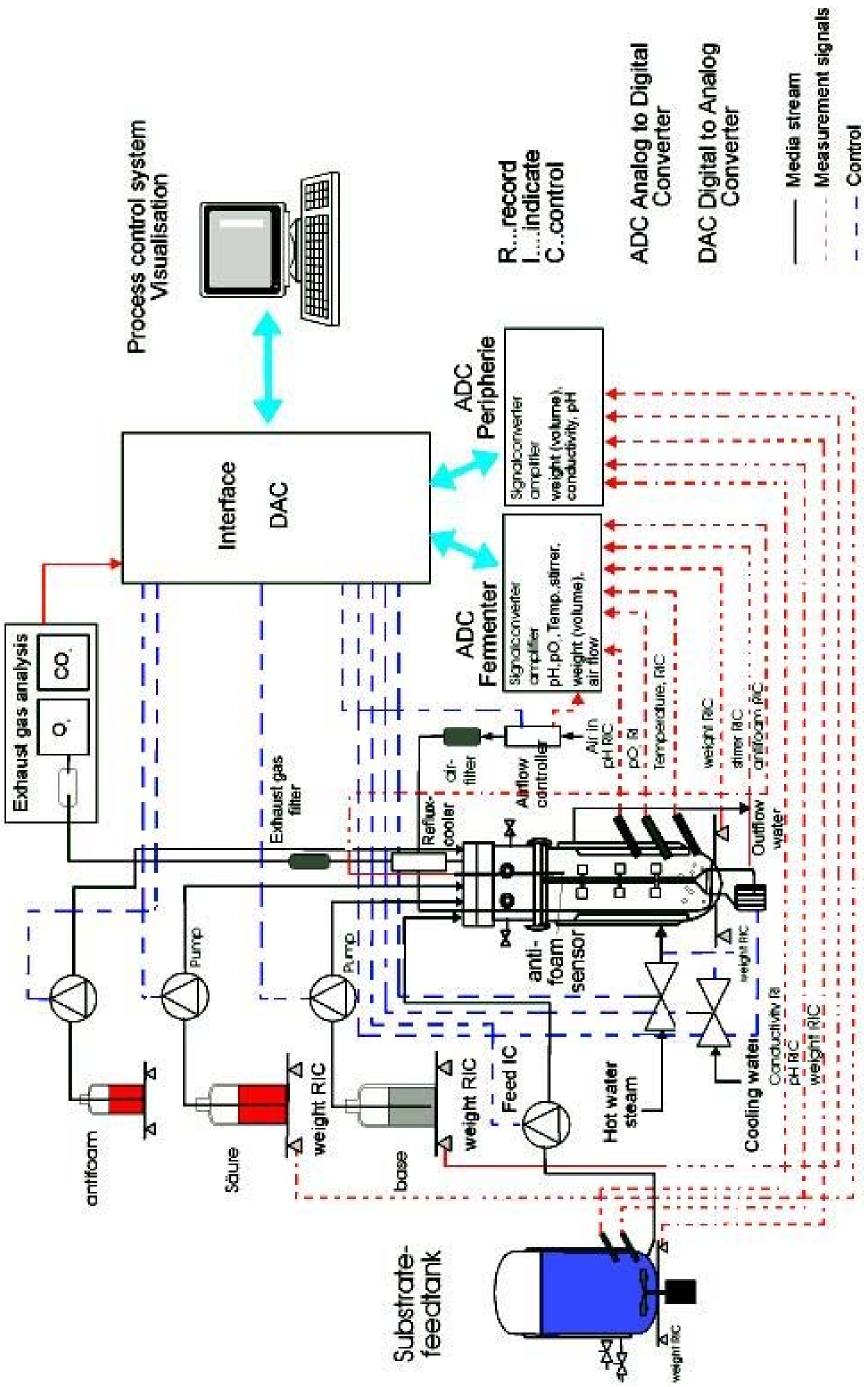

Figure 1. Fermentation processes monitoring and control

Monitoring and pH control

Control and monitoring of pH is an important aspect of many industrial biotechnological processes in order to provide the optimal conditions for microorganisms' growth. pH is one of the most important chemical environmental measurements used to indicate the course of the biotechnological process. It detects the presence of specific chemical factors that influence growth, metabolism, and final product.

A generalized net model, describing pH control system, is presented in [8]. The GN model, taking into account the value of pH in the bioreactor, determines which reagent should be added to the bioreactor. If the culture medium is acidic, then a base should be infused. Otherwise, if the culture medium is basic, then an acid should be infused. An effective and well controlled pH adjustment system will use as little reagent as possible.

Monitoring and dissolved oxygen control

The control of DO in microbial fermentations creates problems on both laboratory and pilot/production scale. This is most frequently due to:

- The increasing overall oxygen demand with increasing biomass.
- Changing mass transfer coefficient due to changes of fluid characteristics by metabolic products.
- Foaming at high aeration rates and high stirrer speed.

The control of oxygen is even more complicated if it is controlled by both airflow or oxygen concentration in the aeration gas and stirrer speed. In this case, traditional control strategies would normally employ proportional integral differential (PID) algorithms connected to a control cascade [13, 14]. As the control loop is dependent on the overall oxygen consumption, which increases dramatically with exponentially proliferating biomass, optimal tuning of the controller will be linked to oxygen uptake rate.

In [6], a generalized net model of oxygen control system in fermentation processes is presented. The presented generalized net model describes the operations in the dissolved oxygen control during the fermentation processes and allows the DO concentration to be kept within the desired interval [DO_{min}, DO_{max}]. The control could be done easily and in simple logic. The GN model, taking into account the DO concentration in the bioreactor, determines variation of rotation speed of the stirrer or variation of the aeration gas concentration added to the bioreactor.

Monitoring and carbon dioxide control

Exhaust gas monitoring is a powerful tool for process control and troubleshooting at all scales of fermentation, as fermentation activity is reflected in the O_2 consumption and CO_2 production. In conjunction with pH and dissolved oxygen, in-situ measurement of dissolved CO_2 is a critical parameter in evaluating the respiratory efficiency of microorganisms in cell culture. Any deviation from the optimal metabolism of the microorganism can be reflected in the respiratory quotient.

Using the apparatus of GNs, a net model for monitoring of CO_2 concentration during fermentation processes is proposed in [10]. Applying developed GN, optimal conditions for microbial growth process can be ensured and current process status based on the observed values of CO_2 concentration and RQ can be determined. Ensuring better monitoring and control of exhaust gases is a precondition for higher efficiency of the fermentation process.

Monitoring and foam control
Microbial fermentation requires a high amount of agitation and aeration, which often results in excessive foaming. Antifoam controllers prevent foam levels from getting too high. Excessive foam tends to emerge through ports in the headplate, open the system to contamination, and inhibit proper oxygen transfer. Many investigations show that the control of the foam level is important for optimal run of the cultivation process [13, 14].

A generalized net model of the foam monitoring control system during a cultivation process is developed in [5]. The proposed GN model permits to control the foam level in an appropriate value. The GN model, taking into account the foam level in the bioreactor and decides if a proper amount of defoaming agent should be added to the culture medium or not.

3. Generalized Net Model

The generalized net model, describing the considered system, is presented in Figure 2. The model is based on the GN model for fed-batch operational mode [12] and generalizes previously developed models for monitoring and control of the parameters temperature, pH, DO, CO_2 and foam levels. It is shown that the GN model developed for fed-batch mode can be easily transformed for batch and continuous mode, [12].

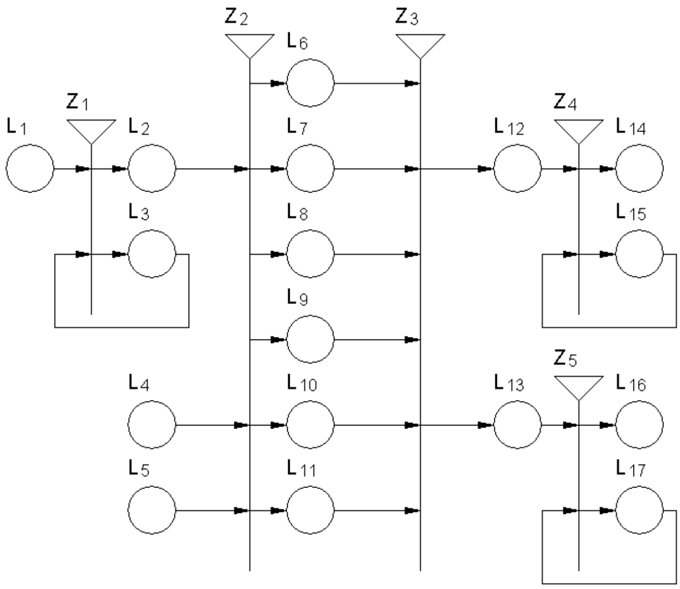

Figure 2. GN model for fermentation processes monitoring and control

The token α enters GN through place l_1 with an initial characteristic "Flow rate of the medium feed". The form of the first transition of the GN model is:

$$Z_1 = \langle \{l_1, l_3\}, \{l_2, l_3\}, \begin{array}{c|cc} & l_2 & l_3 \\ \hline l_1 & false & true \\ l_3 & W_1 & true \end{array}, \vee(l_1, l_3) \rangle,$$

where W_1 is "Need of new concentration of substrate, depending on the substrate value in place l_6". The token α obtains the characteristics "Concentration of the substrate added to the bioreactor" in place l_2, "Amount of medium feed in storage" in place l_3.

The token β enters GN in places l_4 with a characteristic "Initial concentration of process variables". As process variables are considered substrate(s), biomass, product(s) and bioreactor volume.

In place l_5 the token γ enters the GN model with a characteristic "Initial concentration of physics-chemical parameters (temperature and pH), gases (DO and CO_2) and foam level".

The form of the second transition of the GN model is:

$$Z_2 = \langle \{l_2, l_4, l_5\}, \{l_6, l_7, l_8, l_9, l_{10}, l_{11}\}, r_2, \vee(l_2, l_4, l_5) \rangle$$

$$r_2 = \begin{array}{c|cccccc} & l_6 & l_7 & l_8 & l_9 & l_{10} & l_{11} \\ \hline l_2 & true & W_3 & W_3 & W_3 & W_3 & W_3 \\ l_4 & true & W_4 & W_4 & W_4 & W_4 & W_4 \\ l_5 & W_2 & W_5 & W_5 & W_5 & W_5 & W_5 \end{array}$$

where

- W_2 is "Presence of parameter values (place l_5) in the mathematical description of process parameters dynamics";
- W_3 is "Presence of parameter values (place l_2) in the mathematical description of temperature and pH, gases (DO and CO_2) and foam level dynamics";
- W_4 is "Presence of parameter values (place l_4) in the mathematical description of temperature and pH, gases (DO and CO_2) and foam level dynamics";
- W_5 is "Presence of parameter values (place l_5) in the mathematical description of temperature and pH, gases (DO and CO_2) and foam level dynamics".

In place l_6 information about tokens α (place l_2) and β (place l_4) is combined in a new token δ that keeps the information about the concentration of the process variables (substrate(s), biomass, product(s) and bioreactor volume) in the current moment, i.e. has a characteristic "Main process information".

The token γ is split into five tokens (ρ_1, ρ_2, ρ_3, ρ_4 and ρ_5) respectively in places l_7, l_8, l_9, l_{10} and l_{11}. Through the hierarchical operator H_1 (see [1]) places l_7, l_8, l_9, l_{10} and l_{11} are substituted with the corresponding GN model for monitoring and control as follows:

- place l_7 is replaced with GN model for control of temperature, presented in [7];
- place l_8 is replaced with GN model of pH control system, presented in [8];
- place l_9 is replaced with GN model of oxygen control system, presented in [6];
- place l_{10} is replaced with GN model for carbon dioxide monitoring, presented in [10];

- place l_{11} is replaced with GN model of foam monitoring control systems presented in [5].

The form of the third transition of the GN model is:

$$Z_3 = <\{l_6, l_7, l_8, l_9, l_{10}, l_{11}\},\ \{l_{12}, l_{13}\},\ \begin{array}{c|cc} & l_{12} & l_{13} \\ \hline l_6 & true & false \\ l_7 & false & true \\ l_8 & false & true \\ l_9 & false & true \\ l_{10} & false & true \\ l_{11} & false & true \end{array},\ \wedge(l_6, l_7, l_8, l_9, l_{10}, l_{11})>,$$

In place l_{12} the token δ keeps its previous characteristic "Main process information". In place l_{13} the tokens ρ_i are combined into one token ρ whit characteristic "Information of physics-chemical parameters (temperature and pH), gases (DO and CO_2) and foam level".

The form of the fourth transition of the GN model is:

$$Z_4 = <\{l_{12}, l_{15}\}, \{l_{14}, l_{15}\},\ \begin{array}{c|cc} & l_{14} & l_{15} \\ \hline l_{12} & false & true \\ l_{15} & W_6 & W_7 \end{array},\ \vee(l_{12}, l_{15})>,$$

where W_6 is "End of the fed-batch cultivation process" and $W_7 = \neg\ W_6$. The token δ obtains the characteristics "Main process information in the end of the process" in place l_{14} and "Main process information during the process" in place l_{15}.

The form of the fifth transition of the GN model is:

$$Z_5 = <\{l_{13}, l_{17}\},\ \{l_{16}, l_{17}\},\ \begin{array}{c|cc} & l_{16} & l_{17} \\ \hline l_{13} & false & true \\ l_{17} & W_6 & W_7 \end{array},\ \vee(l_{13}, l_{17}) >.$$

The token ρ obtains the following characteristics:

- in place l_{16} – "Information of physics-chemical parameters (temperature and pH), gases (DO and CO_2) and foam level in the end of the process";
- in place l_{17} – "Information of physics-chemical parameters (temperature and pH), gases (DO and CO_2) and foam level during the process".

The resulting net model, which is a generalization of already developed GN models [5-8, 10] gives possibility for optimal process implementation through monitoring and control of essential process variables and parameters.

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