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Review

Fuzzy logic control and soft sensing applications in food and beverage processes

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ABSTRACT

Biotechnological processes – particularly fermentation processes - play a very important technological an economical role for the production steps in the food and beverage sector. In order to ensure constantly high product quality combined with efficient manufacturing, intelligent control systems and strategies are required. However, biosystems contain living organisms and therefore underlie particular process dynamics such as nonlinear and time-varying behavior. Furthermore, initial process conditions cannot be kept constant and therefore precise process reproducibility hardly can be achieved. On that account these multivariate systems put high requirements to the practical on-line observation, control, monitoring and prediction of significant process key parameters whose acquirement is of crucial importance for a comprehensive understanding and control of the process. During the last decades great efforts have been undertaken to cope with those challenges by means of intelligent soft computing and reveal great opportunities to integrate human expertise and learning procedures for improved process control strategies of biological systems. Particularly fuzzy logic based control systems show high potential to manage the complex production processes and to deal with fragmental process information. This review critically presents the chances as well as the limitations of fuzzy and hybrid expert system approaches in food and beverage process control from a theoretical and application based point of view.

Contents

1. Introduction

Due to their inherent complexity and abundance of uncertainty factors biotechnological systems, especially fermentation processes, are very difficult to describe. The quality of the product is decisively determined by its taste which is extremely difficult to

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model or sense as it is highly influenced by cultural and personal perceptions. Additionally, there is a big difference in the process objective itself, comparing manufacturing of foods to other biotechnological production steps. In proceedings like the penicillin production the focus is on the exploitation of a single component of the final product and the main concern is a yield as high and efficient as possible. The residual composition of the product is mostly of lower interest. In contrary to this, instead of subcomponents, the food as a whole is in the focus of the (fermentation) process. Regarding fermentations, the most important process sequences are directly or indirectly related to living organisms by what the realized biochemical turnovers are based on complex biological and biochemical processes whose comprehensive description would need a high number of state variables. However, due to the fact of intra- and extracellular metabolic side products, flavor substances and various cell states there exist hundreds of state variables. For setting up an appropriate process model at reasonable cost from the abundance of available state variables those have to be selected that significantly describe the process behavior. On the basis of the previously mentioned biological and biochemical processes the dynamic performance of those systems can be characterized as nonlinear and time-variant. Whilst continuous or fed-batch processes are commonly run at a fixed operating point, this is not possible for a batch operation (Chmiel, 2006). Hereby the process undergoes a wide range of nonlinear behavior (Trelea, Trystram, & Courtois, 1997). An example would be the oxygen concentration of wort which decreases from saturation to zero during the fermentation and maturation of beer and forces the yeast to shift from the aerobic to the anaerobic metabolism. Therefore, the process model cannot be linearized or limited to a fixed operating point, but rather to a combined biochemical trend to follow. Thus, the classical methods of control engineering and system theory that assume linearity and time-invariance can be applied only in a very limited way or under permanent personal control and continuous manual interventions.

The implementation of new strategic directions in the field of process control like the PAT (Process Analytical Technologies) initiative opens new gates for better process understanding (Administration, 2004; Dünnebier & Tups, 2007; Junker & Wang, 2006). By launching the PAT initiative in 2004, the FDA (Food and Drug Administration) developed a system for the design, analysis and control of production processes via defined and timed measurements of critical quality and performance parameters of raw and process parameters as well as of the contemplated methods with the objective of ensured product quality and therefore presents an innovative tool for an optimal design of process control. In contradiction to the practical established product release and validation by costly laboratory analysis that is inevitably connected to time-delayed reactions on process changes, a shift to a process-oriented validation and release of process sequences in real-time in respect to the aspect of “Quality by Design” (QbD) is intended. This indicates the demand for a quality assessment which has to take place simultaneously to the manufacturing process and requires a comprehensive understanding of the process. However, the prompt on-line detection of crucial key parameters such as biomass or substrate concentrations is still difficult to achieve and often lacks the required accuracy. For this reason, in the field of biotechnological process control, numerous approaches have been undertaken to develop corresponding indirect measuring methods that are capable to cope with the complex behavior bioprocesses. An overview of these software sensors is given in (de Assis & Filho, 2000; Becker & Krause, 2010; Shioya, Shimizu, & Yoshida, 1999). The strategy of soft-sensing hereby offers various attractive properties (Fortuna, Graziani, Rizzo, & Xibilia, 2007):

- they can represent a low-cost alternative to expensive hardware devices, allowing the realization of more comprehensive monitoring networks
- they can work in parallel with hardware sensors, supplying useful information for fault detection tasks and thus allowing the realization of more reliable processes
- they can easily be implemented on existing hardware and retuned if system parameters change
- they allow real-time estimation of data, overcoming the time delays of slow hardware sensors (e.g. gas chromatographs) and therefore improve the performance of the control strategies

In order to obtain the needed process information as a premise for process control the basic demand is to combine innovative sensor arrays (soft and hard sensing) with intelligent control operations based on comprehensive process and product knowledge. Therefore, the second part of this paper gives a short introduction to the theory of fuzzy logic as a powerful tool to implement a priori knowledge into process control actions and to handle uncertainty or vagueness by linguistic system formulation. The third section treats various food and beverage applications of fuzzy based reasoning, sensing and control approaches. The last part presents the opportunities offered through hybrid systems outlined by a comprehensive study of applications.

2. Theory of fuzzy logic and fuzzy-based expert systems

The control of food and beverage manufacturing processes in common practice is predominantly carried out discontinuously and receipt based. This way of process control is accompanied by permanent manual interactions and demands perpetual sample taking, lab analysis and process surveillance by the operator what is directly connected to higher economical efforts, incomplete process information and uncertainties. On that account sophisticated methods of soft computing could offer an alternative way to overcome the discrepancy of cost efficient process control and perpetuating claimed quality objectives. Knowledge-based expert systems are programs able to deal with uncertain and vague process information and mimic human expert-like reasoning and decision-making within a certain domain of expertise (Patterson, 1990, p. 496). The historical development of fuzzy reasoning and expert systems in food industry is given by Linko (1998). Since the implementation of fuzzy logic by Zadeh (1965), this technique has established as a fixed part for the control of biotechnological and food processes (Besli, Türker, & Gul, 1995; Davidson & Smith, 1995; Filev, 1991; Filev, Kishimoto, & Sengupta, 1985; Herrera, 2007; Nyttle & Chidambaram, 1993; Venkateswarlu & Naidu, 2000). The theory of fuzzy logic is an extension to the classical crisp set theory and allows the transition from the classical, bivalent notion of truth to a gradual, multivalued concept of truth. Characteristic for fuzzy systems is that they enable to present a complex system behavior by simple linguistic formulations. In contradiction to a quantitative, mathematical description of the systems transfer behavior, the system behavior is expressed by linguistic variables and algorithms that can be written as follows (Jantzen, 2007):