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A new adaptive controller for bio-reactors with unknown kinetics and biomass concentration: Guarantees for the boundedness and convergence properties

A. Rincón [a], D. Piarpuzán [b], F. Angulo [b,*]

[a] *Facultad de Ingeniería y Arquitectura, Universidad Católica de Manizales, Cr 23 no 60–63, Manizales, 170002, Colombia*
[b] *Universidad Nacional de Colombia - Sede Manizales - Facultad de Ingeniería y Arquitectura - Departamento de Ingeniería Eléctrica, Electrónica y Computación - Percepción y Control Inteligente - Bloque Q, Campus La Nubia, Manizales, 170003, Colombia*

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Highlights

- An adaptive controller for bioreactors is developed.
- A new method to handle the unknown time-varying control gain is proposed.
- The output tracks the desired reference with a user-defined tolerance.
- The exact values of the plant parameters are not required to be known.
- Upper or lower bounds related to the plant parameters are not required to be known.

Abstract

In this work, an adaptive controller for bioreactors, using the measurement of output gas flow rate to handle the uncertainty on biomass concentration and kinetic rate is developed. A mass–balance model based on a unique reaction pathway to represent the input–output behavior is considered. Time-varying and unknown but bounded behavior of plant parameters, including the substrate concentration at the inflow and the yield coefficients is taken into account in the controller. The Lyapunov-like function method to develop the controller is used. A new method to handle the unknown time-varying behavior of the control gain is developed; with this method it is assured that the output tracks the desired reference with a user-defined tolerance and parameter drifting is avoided. The main contributions of the scheme with respect to closely related works are: (i) the exact values of the plant parameters are not required to be known; (ii) upper or lower bound related to the plant parameters is not required to be known; (iii) the time-varying behavior of plant parameters in the control design and in the convergence analysis is considered.

Keywords: Adaptive control; Robust control; Lyapunov-like function; Bioreactor

* Corresponding author.
E-mail addresses: arincons@ucm.edu.co (A. Rincón), dpiarpuzane@unal.edu.co (D. Piarpuzán), fangulog@unal.edu.co (F. Angulo).

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1. Introduction

In recent years, the control of bioprocesses has been a practical problem of wide research [4,40,7]. The last progresses allowed the development of different control strategies with the main motivation to improve the efficiency and provide stability to this type of processes. The adaptive control has been perhaps the most important technique to control bioreactors due to its ability to compensate the parametric model uncertainties.

Nonlinear adaptive controllers to bioreactors based on finite order models by means of the orthogonal collocation method are designed in [27]. Using the exact linearization and estimation algorithms in [34], a nonlinear adaptive controller was proposed for a fed-batch bioprocess. In [38], the adaptive control for bioreactors is improved through sliding mode control. The gain-scheduling methods and adaptive control are combined in [15] to control the pH of a bioreactor in a fermentation processes. Kapadia et al. [18] designed a nonlinear robust controller for a CSTR bioreactor and Lyapunov stability theory is used to prove semi-global tracking. The adaptive control structure proposed by [28] was designed on the combination of the nonlinear model of the process a state observer and a parameter estimator. The *software-sensors* are part of the adaptive control developed for a Simultaneous Saccharification–Fermentation Process from Starch to Ethanol (SSFSE) in [26].

The fed-batch bioreactor control resolving a problem of dynamical identification of unknown characteristics (state/parameters) is considered in [19].

The algorithm control is based on the principle of auxiliary models with adaptive controls. The comparison of two robust adaptive controllers using minimal a priori process knowledge and minimal measurement information is presented in [33] for a bioreactor control in a fermentation processes. In Petre et al. [29] the two cascaded CSTR bioreactors multivariable adaptive control strategy is designed and analyzed. This control method is derived by combining a linearizing control law with a new parameter estimator.

Mass–balance models involving only one or two microorganism species can provide predictions with acceptable accuracy [23,5,3,2]. In addition, these models are suitable for adaptive and robust control of bioreactors [23,22,36], as they have a simple structure. Nevertheless, there are several difficulties for control design (cf. [36,16,1]): (i) there is lack of on-line sensors that combine reliability and low cost, so that the concentration of biomass and substrate in the inflow and in the inside of the reactor is difficult to obtain; (ii) the kinetic rates are uncertain and its parameters vary with time. In [23,22] they propose the use of the measured output gas flow rate to overcome the uncertainty on the biomass concentration. They assume unknown control gain and unknown plant parameters. Nevertheless, the developed update law requires the knowledge of upper or lower bounds of the kinetic parameters and influent concentration. In addition, the plant parameters are assumed constant.

As far as we know, the most effective method to tackle unknown time-varying control gain is the Nussbaum gain method. Indeed, if the controller is properly devised, upper or lower bounds of plant parameters are not required to be known. The main drawbacks of the Nussbaum gain method are: (i) the upper bound of the transient behavior of the tracking error is significantly modified in comparison with that of the disturbance-free case, as the value of this bound depends on the time integral of terms that comprise the Nussbaum terms, (see [33,37,9,10,14,12,11,41,8]); (ii) upper or lower bounds of the plant coefficients are required to be known to achieve asymptotic convergence of the tracking error to a residual set of user-defined size, as in [33,10,14,12,13,6,39,21]; (iii) the control or update law involves signum type signals, as in [37,9,11,41,8,32]. In addition, several assumptions on the control gain are usually required: (iv) the control gain is assumed to be the product of an unknown constant and a known function, as in [39,21]; (v) the control gain is assumed upper bounded by some unknown constant, as in [33,37,9,10,14,12,11,41,8]; (vi) the control gain is assumed upper bounded by a known function, as in [13,32]. In this paper an adaptive controller that circumvents these facts is proposed.

In this study, it is assumed that the control gain is unknown and its lower bound is unknown, it is time varying and bounded away from zero. In addition, it is assumed too (i) other plant parameters are unknown, time-varying, bounded, and upper or lower bounds involving these parameters are not required to be known; (ii) the output gas flow rate is measured. The Lyapunov-like function is used to develop the control and update laws. The gas flow rate is used to handle the unknown value of the biomass concentration. The following results are guaranteed: (i) the tracking error converges to a residual set whose size is user-defined; (ii) updated parameters are bounded, so that parameter drifting is avoided.

The work is organized as follows. In Section 2 the plant model is presented. In Section 3 it is established the goal of the control design. In Section 4 the bounded nature of the biomass concentration under non-negative dilution rate