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Hierarchical control for microalgae biomass production in photobiorreactors ☆

I. Fernández [a], M. Berenguel [a], J.L. Guzmán [a,*], F.G. Acién [b], G.A. de Andrade [c], D.J. Pagano [c]

[a] Dpt. Informatics, University of Almería, CIESOL-ceiA3, Carretera Sacramento s/n, E04120 Almería, Spain
[b] Dpt. Chemical Eng, University of Almería, CIESOL-ceiA3, E04120 Almería, Spain
[c] Dpt. Systems and Automation, Federal University of Santa Catarina, 88040-900 Florianópolis, SC, Brazil

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ABSTRACT

This paper addresses the development of a hierarchical control strategy for microalgal production in a tubular photobioreactor. The proposed control scheme is composed of two layers. On one hand, a lower layer is in charge of tracking a pH set-point by a PI controller plus feedforward compensator, which was used due to its recognized efficiency in industrial control processes. On the other hand, the upper layer calculates optimal pH set-points based on an economic model predictive control approach. The main aim of this control scheme is to maximize profits, computed as the difference between the incomes obtained from the final production sale and the associated production costs (including the environmental impact of the exhausted CO_2 losses). For this purpose, two types of models have been used depending on the requirements of each layer. Simulated and experimental results of the proposed hierarchical control architecture are presented, as well as a comparison with a single-layer architecture with constant reference implemented by the controller used in the lower layer of the hierarchical structure.

1. Introduction

The impact of dynamic modelling and automatic control in biological processes is increasing nowadays (Bastin & Dochain, 2013; Bernard, 2011; Bernard, Mairet, & Chachuat, 2016; Dochain, 2008; Picó, Vignoni, Picó-Marco, & Boada, 2015), offering many challenges and opportunities. The control on microalgae cultivation is one of the most promising fields due to the potential widespread use in pharmacy, medicine, chemistry, food, cosmetic and fuel industries. Microalgae can be cultivated into reactors under controlled circumstances, where its high growth rate allows us to obtain large productivity (Pulz, 2001). The carbon fixed by microalgae is incorporated into proteins, carbohydrates, lipids, etc., in such a way that a wide range of chemical products can be obtained from the microalgae biomass.

Microalgal cultures have been traditionally cultivated in open photobioreactors ("open raceway"), due to its simplicity, easiness and low cost (Richmond, 2008; Ugwu, Aoyagi, & Uchiyama, 2008). Unfortunately, this type of photobioreactor presents a low control of the operating conditions and it is prone to contamination. When it is desired to produce high-value algal products from strains that cannot be maintained in open ponds, it is necessary to employ closed photobioreactors such as tubular ones, which facilitate conditions of reproducible culture, operating control, and the absence of culture pollution (Pulz, 2001). pH control in tubular photobioreactors, which is one of the most critical variables to be controlled, is performed by means of pure carbon dioxide injection, accounting for 30% of the production cost (Benemann, Tillett, & Weissman, 1987). Furthermore, carbon losses are higher than 75%, although they can be reduced below 30% through proper design and operation of photobioreactors (Camacho, Acién, Sánchez, García, & Molina, 1999). However, to reduce them even further, it is necessary to design advanced control strategies that take into account the mixing and mass transfer phenomena that take place in the system (García et al., 2003). As an example, a Model Predictive Control (MPC) strategy based on a grey-box dynamical model was designed in Berenguel, Rodríguez, Acién, and García (2004) allowing to reduce the carbon losses to less than 5%. These promising results fostered the development of new control strategies to improve the operating mode, and to reduce CO_2 losses and costs especially at large and industrial scale (e.g. Andrade, Berenguel, Guzmán, Pagano, & Acién, 2016; Barbu, Ifrim, Ceanga,

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☆ A preliminary version of this paper (Hierarchical Non-linear Control of a Tubular Photobioreactor) without including real tests was presented by the same authors at the 5th IFAC Conference on Nonlinear Model Predictive Control NMPC'15, Seville, Spain, 2015.

* Corresponding author.
E-mail addresses: ifernandez@ual.es (I. Fernández), beren@ual.es (M. Berenguel), joseluis.guzman@ual.es (J.L. Guzmán), facien@ual.es (F.G. Acién), gandrade@das.ufsc.br (G.A. de Andrade), daniel@das.ufsc.br (D.J. Pagano).

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& Caraman, 2015; Ifrim, Barbu, Ceanga, & Caraman, 2015; Johnsson, Sahlin, Linde, Lidén, & Hägglund, 2015; Pawlowski et al., 2014).

Other control approaches deal with biomass production and productivity optimization, most of them at simulation level. In Becerra-Celis, Hafidi, Tebbani, Dumur, and Isambert (2008) and Becerra-Celis, Tebbani, Joannis-Cassan, Isambert, and Siguerdidjane (2008), both nonlinear predictive control (NMPC) and PID with feedback linearization are applied to operate a photobioreactor in a constant biomass density mode, in order to maintain the culture at the optimal population density and sustain high biomass production levels. This objective is achieved by regulating the biomass density while tracking a reference culture medium feeding profile determined off-line. These results were extended to a state feedback linearizing control law plus PI control (including on-line estimation of biomass concentration in a photobioreactor) and demonstrated by experiments in Tebbani, Lopes, Filali, Dumur, and Pareau (2014a, 2014b) and Tebbani, Lopes, and Becerra-Celis (2015). The same authors recently proposed both robust NMPC and hierarchical approaches (Benattia, Tebbani, & Dumur, 2014, 2015a, 2015b, 2015c; Benattia, Tebbani, Dumur, & Selisteanu, 2014) to regulate biomass concentration by simulation. In Abdollahi and Dubljevic (2012) interior point optimization and moving horizon estimator MPC are used to maximize lipid production in a fed-batch heterotrophic microalgae cultivation. In Khaksar-Toroghi, Goffaux, and Perrier (2013) a passivity-based control is designed using the dilution rate as control input and biomass concentration as controlled state. In Ifrim et al. (2013) a nonlinear multivariable controller based on the exact feedback linearization technique is applied to stabilize the photoautotrophic microalgae growth in photobioreactor regardless of the operation point or the transient trajectory. The selected measurable outputs were the biomass concentration and the pH, whose simultaneous control was realized by manipulating the dilution rate and the injected carbon dioxide gas flowrate. In Grognard, Akhmetzhanov, and Bernard (2014), a simple bioreactor model is used to obtain a control law that optimizes productivity over a single day through the application of Pontryagin's maximum principle. The dilution rate is the main control, the input concentration being only used as the secondary control to maintain the substrate concentration high.

In the photobioreactor treated in this paper, also biomass production optimization has been carried out by acting on the culture medium injection of the system to optimize the biomass production over the period of one day (Andrade, Pagano, et al., 2016).

The approach in this paper is different to the previous ones, as it deals with the application of a hierarchical economic-based control strategy for microalgal growth control, where two hierarchical levels are considered and characterized by the existence of different dynamical time scales. In this control architecture, the bottom level (fast time scale – seconds/minutes) corresponds to the control of pH value of the culture, that in this work is controlled using a PI controller plus feedforward compensator to improve the performance on the pH reference tracking. On the other hand, the upper level considers an economic optimization problem on the profits of the system (difference between incomes associated to biomass production and costs related to CO_2 injection and losses), where time scales are governed by physiological processes and can vary between hours and days. The existence of different time scales allows us to decouple the pH dynamics from the biomass growth, in such a way that this layer calculates the pH set-points that are established in the lower layer, usually by using static versions of a microalgal production model or a simplified dynamic model helping to obtain these set-points in a reasonable time. In this paper, pH set-points are obtained based on economic criteria according to economic data, weather forecasts, and a lumped parameter microalgal model developed by the authors in Fernández et al. (2012) and Fernández, Acién, Berenguel, and Guzmán (2014). A dynamic distributed parameters first principles model formulated by Partial Differential Equations (PDEs), reported in Fernández et al. (2014), has been used as simulator to evaluate the performance of the proposed strategy before applying it to the real system. Once the pH set-point is obtained, it can be used by the pH control layer. The pH controller implemented uses CO_2 injection as control input variable, being necessary to implement a Pulse Width Modulation (PWM) technique to deal with the discontinuous characteristics of the valve. Once the structure was evaluated and its parameters adjusted by simulated tests, it was implemented in a real system obtaining promising results.

2. Tubular photobioreactor

The microalgal production facility used in this work is located at “Estación Experimental Las Palmerillas”, property of Fundación CAJAMAR (Almería, Spain). The facility consists of ten tubular fence-type photobioreactors, which main features can be found in Acién, Fernández, Sánchez, Molina, and Chisti (2001) and Molina, Fernández, Acién, and Chisti (2001). Fig. 1 shows a scheme of one of the tubular photobioreactors. The system is composed of a vertical external-loop airlift pump that drives the culture fluid through the vertical tubular solar receiver and a bubble column. The solar receiver is made of transparent tubes joined into a loop configuration to obtain a total horizontal length of 400 m and 0.09 m diameter. Total culture volume in the photobioreactor is 2600 L, it has 19.0 m length and 0.7 m width. The loop is optimally

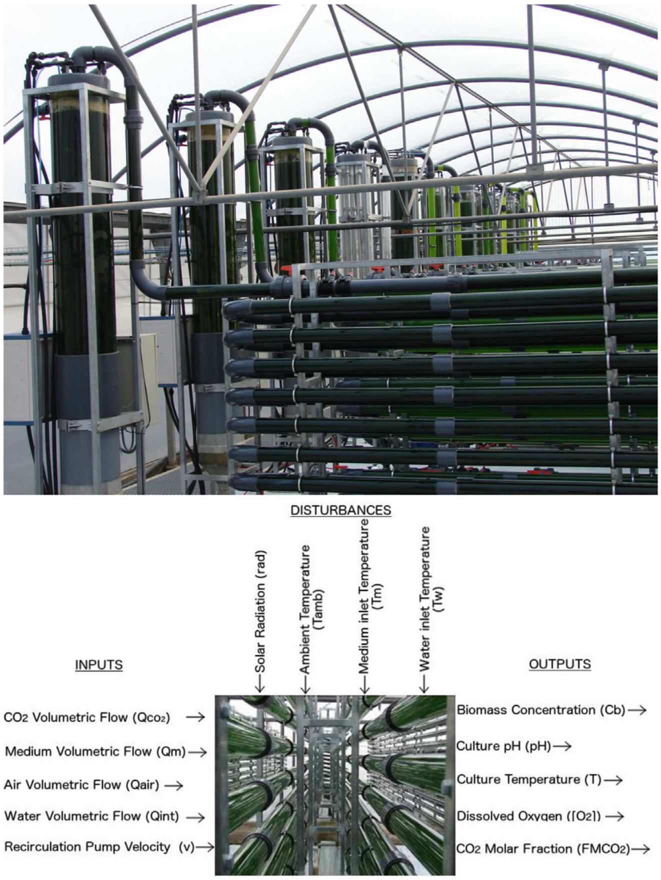

Fig. 1. Real view and scheme with inputs, outputs and disturbances of a tubular photobioreactor at the experimental facility.