Intelligent PI Controller for Microalgae Growth in a Closed Photobioreactor

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***Abstract*—One of the microorganisms used in the industry to generate high value products is the microalga. Due to its nonlinear dynamics and variation in time, bioprocesses that involve the use of microalgae pose challenges in modeling, controlling, and increasing their production. Normally, at the laboratory level, closed cultures of microalgae are carried out in photobioreactors. To produce biomass, the culture conditions can be controlled using a photobioreactor. This paper describes the design of an intelligent Proportional-Integral controller applied in a continuous culture of *Chlorella vulgaris* microalga, where the controlled variable is the dilution rate *D(t)*. This controller is characterized by formulating the dynamics of the system with an ultra-local model. In this ultra-local model, both the uncertainties of the system dynamics and the disturbances are handled in one unified way. The performance of the intelligent Proportional-Integral controller was tested at simulation level using Matlab Environment^{TM}. In this research, the accomplishment of the controller was contemplated against disturbances, under nominal conditions and front variation of parameters. The simulations showed that the intelligent Proportional-Integral controller ensures excellent reference tracking capability. Finally, it is important to highlight the robustness of the strategy.**

Keywords— i-PI controller, continuous culture, Chlorella vulgaris, biomass production.

I. INTRODUCTION

Microalgae are photosynthetic organisms that form their biomass by assimilating nitrogen (N), carbon dioxide (CO_2), and phosphorus (P) [1]. Additionally, they are a source of saturated and polyunsaturated fatty acids, polysaccharides, vitamins, carotenes, pigments and hydrogen [2], [3]. These diverse applications of biomass obtained from microalgae have generated an increase in the research, seeking to identify the optimal conditions of growth and increase the productivity of closed cultures [4], [5]. The closed cultures are carried out in photobioreactors (PBRs), which may operate in a continuous, semi-batch or batch mode.

Choosing a model that describes the behavior of microalgae growth is a required step to design a control strategy. In the literature, several models for continuous culture have been developed [6]–[10], these models search to predict the growth of microalgae. In this article, the model proposed by Nouals was used. This model is characterized by not including the term inhibition of the substrate, it also associates the Contois model for the restrict effect by a substrate such as Total Inorganic Carbon (TIC) and the Monod model for managing the effect of light. When this type of bioprocess is controlled, it is important to ensure that the reference signal is followed by the bioprocess, despite disturbances. With the goal of the follow up of an established trajectory, that is: the biomass $C_X(t)$, many researchers have applied different control techniques. Some control strategies are: Artificial Neural Networks–Model Predictive Control (ANN–MPC) [11], Filtered Smith Predictor (FSP) [12], Nonlinear Model Predictive Control (NMPC) [7], MPC-based reference [13], Active Disturbance Rejection Control (ADRC) [14].

In this work, the authors designed an intelligent Proportional Integral (i-PI) controller. This type of control strategy was proposed by Fliess and Join [15], [16], and it has been used in electrical, electronic, mechanical and mechatronic systems. The design of an i-PID controller is based on the framework of differential algebra, which makes parameter adjustment for highly non-linear or time-varying systems a simple task [17]. Since the chosen model is associated with a continuous culture, the only signal chosen to be controlled was the dilution rate, *D(t)*. This variable was selected, since achieving its control is useful to avoid "washing" of the crop. The operation of the i-PI controller, proposed in this work, was evaluated at the level of numerical simulations using MATLAB/Simulink^{TM}. The simulations showed that the i-PI controller ensures excellent reference tracking capability.

This paper is organized as follows: Section II encompasses both the report of system and growth model. Section III includes the controller design. Simulations are included in Section IV. Finally, in Section V, the conclusions are found.

II. SYSTEM DESCRIPTION AND BIOPROCESS MODEL

The growth model of the green *Chlorella vulgaris* microalga herein used is described in detail in references [10], [14], and [18]. This model combines the Contois model for the restriction by a substrate and the Monod model for managing the effect of light. The effective volume (9.6 L) of the PBR is assumed constant and under perfectly stirred conditions. Here, the temperature and irradiance values used were 25 °C and 90 $\mu E/m^2 \cdot s^1$ respectively, according to [18]–[20]. Equation (1) shows the density of the cell number of the culture. The

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concentration of Total Inorganic Carbon, TIC, is given in mmol·L^{-1}, is expressed by (2).

$$\frac{dC_X(t)}{dt} = \mu C_X(t) - DC_X(t) \tag{1}$$

$$\frac{d[TIC]}{dt} = \frac{-\mu C_X(t)}{Y_r} - D[TIC] + k_L a([CO_2]_e - [CO_2]) \tag{2}$$

where $C_X(t)$ (10^9·cell/L) represents the cell number of microalgae; D (h^{-1}) is the dilution ratio; μ(h^{-1}) corresponds to the specific growth rate; [TIC] is Total Inorganic Carbon (mol/L); Yr (10^9·cell/L·mol) is the carbon conversion yield; $[CO_2]_e$ (mmol/L) is the equilibrium carbon dioxide concentration; $[CO_2]$ (mmol/L) is the actual carbon dioxide concentration and $k_{L}a$ (h^{-1}) is the overall gas-liquid mass transfer coefficient of carbon dioxide.

$[H^+]$ (mol/L) represents the hydrogen ions concentration, $[CO_2]_e$ and $[CO_2]$ are given by (3), (4) and (5).

$$[CO_2]_e = \frac{P_{CO_2}}{H} \tag{3}$$

$$[H^+] = 10^{-pH} \tag{4}$$

$$[CO_2] = \frac{[TIC]}{1 + K_1/[H^+] + K_1K_2/[H^+]^2} \tag{5}$$

where H (atm·L/mmol) is Henry's constant for CO$_2$ at 25°C when Bristol 3N medium is used, PCO_2 (atm) is the partial pressure of CO$_2$; $K_1 = 6.35$ and $K_2 = 10.33$ are the dissociation constants of the chemical equilibrium at 25 °C.

While the specific growth rate ($\mu(t)$); E (µE/s·10^9/cell) is the intensity of light available per 10^9 cells; the light intensity accessible and the outgoing light intensity (I_{out}) are described by (6), (7) and (8).

$$\mu(t) = \mu_{max}\left(\frac{E}{K_E + E}\right)\left(\frac{[TIC]}{K_{CL}C_X(t) + [TIC]}\right) \tag{6}$$

$$E = \frac{(I_{in} - I_{out})A_r}{V \cdot C_X(t)} \tag{7}$$

$$I_{out} = I_{in} \cdot C_1 \cdot C_X^{C_2}(t) \tag{8}$$

where K_E (µE/s^{-1}·10^9/cell^{-1}) is the half saturation constant for E; K_{CL} (mmol·10^9/cell) is the TIC limitation constant; μ_{max} (h^{-1}) corresponds to the maximum specific growth rate; V is the PBR volume (L), I_{in} (µE/m^2·s^1) is the incident intensity of light; C_1 and C_2 are constants which determine the light absorption and A_r (m^2) is the area of the PBR that is illuminated.

Bioprocess parameters were determined at 25°C [18]. They are summarized in [14], [18].

TABLE I. *Chlorella vulgaris* PARAMETERS USED IN THE SIMULATION.

Parameter	Unit	Value
PBR geometry		
C_1		0.49
C_2		-0.92
A_r	m^2	0.31
V	L	9.6
[*TIC*] properties		
$k_{L}a$	h^{-1}	1.36
pH		6
H	atm·L·mol^{-1}	29
Operating Conditions		
I_{in}	µE·s^{-1}·m^2	90
P_{CO_2}	Atm	0.05
μ_{max}	h^{-1}	1.068
K_E	µE/s·10^9/cell	0.0817
K_{CL}	mmol·10^9/cell	0.0038
Y_r	10^9·cell·L^{-1}·mol_TIC^{-1}	4.353

III. CONTROL STRUCTURE

A. Preliminaries

The intelligent Proportional-Integral Controller (i-PI) is restricted to systems that handle a single variable of control (u) and one variable of output ($y(t)$). An ordinary differential equation of unknown finite dimension governs, approximately, the relation between input and output actions of the process, this behavior isn't essentially linear [15], [16]:

$$E\left(y, \dot{y}, \ldots, y^{(a)}, u, \dot{u}, \ldots, u^{(b)}\right) = 0 \tag{9}$$

The ultra-local model replaces the "complex" mathematical model of the process:

$$y^{(w)}(t) = F + \alpha \cdot u(t) \tag{10}$$

Here, $w \geq 1$, $\alpha \epsilon$□ is a constant parameter not necessarily physical. It should be therefore clear that $\alpha \cdot u(t)$ and $y^{(w)}(t)$ have the identical size. F includes both the various possible disturbances and the unknown parts of the model. Finally, it is important to note that equation (10) must be continuously updated because it is effective during a brief period of time [16]. Given the equation of the ultra-local model in (10), this indicates that the requirement for a model as accurate as possible is abandoned [21].

Using the intelligent proportional-integral controller (i-PI) the loop can be closed.

$$u(t) = -\frac{1}{\alpha}\left(F - y^{*(w)}(t) + k_P \cdot e(t) + k_I \int e(t)\right) \tag{11}$$

Here, $y^*(t)$ is the output desired reference path, $e(t) = y(t) - y^*(t)$ is the tracking error, k_P and k_I are the typical i-PI gains.

B. Problem statement

Since the biomass concentration $C_X(t)$ can be controlled manipulating the rate of dilution *D(t)* when the photobioreactor is operating in continuous mode. In such a way that regardless of the uncertainty in the model and the perturbations, the number of cells follows, as near as possible, the established reference. The above will guarantee a follow up error $e(t) \approx 0$.

C. Design of an intelligent Proportional-Integral Controller

Since this microalgae culture was considered as a Single-Input and Single-Output (SISO) process, the chosen control variable was *D(t)* and output variable was $C_X(t)$. The mathematical model was replaced by their ultra-local model:

$$\frac{dC_X(t)}{dt} = F + (-C_X(t)) \cdot D(t) \qquad (12)$$

where the knowing of the control variable *D(t)* and output variable $C_X(t)$, allows the estimation of *F*. Since equation (12) is first order, the control law generated was:

$$D(t) = -\frac{1}{C_x(t)}\left(-F + \dot{C}_X^*(t) + k_P \cdot e(t) + k_I \int e(t)\right) \qquad (13)$$

Here, $C_X^*(t)$ is the desired output reference trajectory, $e(t)=C_X(t)-C_X^*(t)$ is the follow up error; $k_P=25$ and $k_I=0.01$ are the tuning i-PI gains. For the application of this type of controller, it is essential to estimate the on-line amount of $C_X(t)$. Fig. 1 shows an overall scheme of the control proposal.

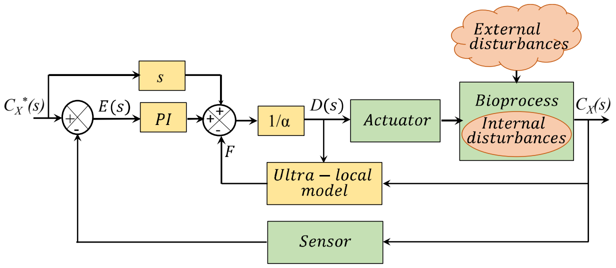

Fig. 1. Diagram of i-PI controller and signals flow.

IV. NUMERICAL SIMULATIONS

The performance of i-PI was evaluated by numerical simulations with the MATLAB/Simulink^{TM} program with a fixed-step ODE 4 solver and a sample time of 0.01; that in this case was equivalent to hours. These simulations tested the effectiveness of the proposed approach under nominal conditions and perturbations.

A. Nominal case

Figures 2 and 3 show the behavior of cell growth of microalgae $C_X(t)$ and the dilution rate *D(t)* in nominal conditions. Additionally, Figure 2, the follow-up to the reference signal is observed. While in Figure 3, the input of control *D(t)* complies with the physical restrictions that are characteristic of the bioprocess. Finally, it is possible to appreciate that when $C_X(t)$ is at 99.48% of the reference magnitude *D(t)* stabilizes, and this occurs at $t = 8.09$ h.

B. Disturbance rejection case

The proposed controller performance was tested with a disturbance step type in the control signal input at 30 h $\leq t \leq$ 35 h. The $C_X(t)$ and *D(t)* for this test are shown in Figures 4 and 5. While *D(t)* was disrupted with signals of $78.64\% \cdot |D_{MAX}(t)|$, the involvement on $C_X(t)$ was not important, $0.076\% \cdot |C_{XMAX}(t)|$. Therefore, it can be said that the i-PI controller modifies the control signal *D(t)* to compensate the effect of the disturbance and to maintain the tracking of $C^*_X(t)$ under the presence of a disturbance.

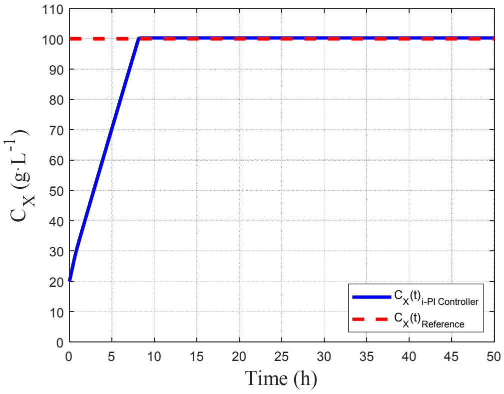

Fig. 2. Cell growth of microalgae, CX(t), under nominal conditions.

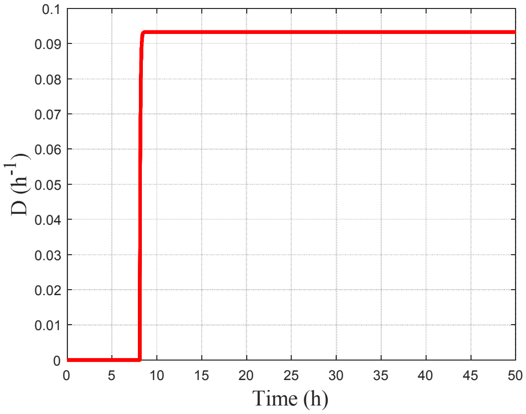

Fig. 3. Behavior of dilution rate, D(t), under nominal conditions.

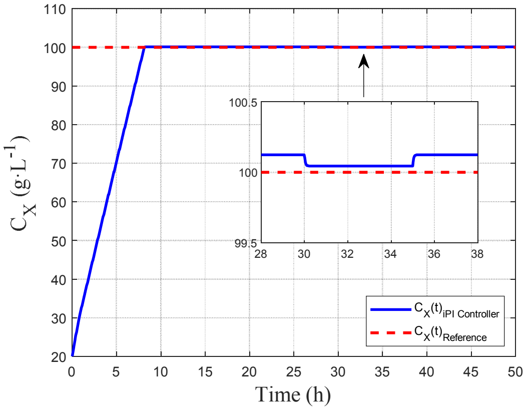

Fig. 4. Cell growth of microalgae, CX(t), against a disturbance.

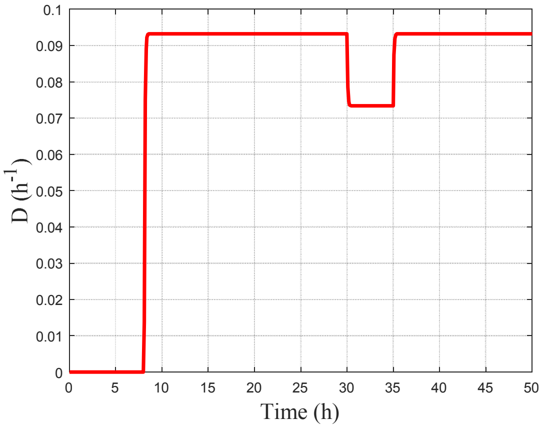

Fig. 5. Behavior of dilution rate, D(t), front to a disturbance.

C. *Variation of parameters*

The proposed controller performance was tested under variation of parameters. In this case, μ_{max} was varied at t=24 h. The behaviors of $C_X(t)$ and $D(t)$ for this test are shown in Figures 6 and 7, respectively. It was found that the i-PI controller adjusted $D(t)$ by the controller to keep $C_X(t)$ very close to the reference, according to the variation of μ_{max}. So, it can be said that the i-PI controller maintains tracking of $C^*_X(t)$ against the variation of parameters.

V. CONCLUSIONS

A successful design of an i-PI controller that can be implemented for a continuous crop of *C. vulgaris* microalga, at the simulation level, is show in this article. In this proposal, the disturbances and non-modeled dynamics were grouped in the ultra-local model. This is an advantage because bioprocesses require models with parameters that are susceptible to wide variations during operation or by the changes that can occur at the physicochemical level. Its control using i-PI shows that it is possible to build a control law that can effective to ensure the tracking reference signal, C_X^*(t), both nominal conditions and under the presence of disturbances or under non-modeled dynamics. Reference tracking was accomplished within a small error magnitude. This leads to the conclusion that to use of i-PI controllers in microalgae cultures is a promissory strategy given that you can work with "poor" models or with disturbed systems.

In future work, it is expected to implement this i-PI controller and test its performance in a continuous cultivation of microalgae.

ACKNOWLEDGMENTS

The authors to thank Universidad de La Sabana for the funding of ING-224-2019 "*Una combinación de ADRC multivariable y optimización, para ser aplicada a un cultivo continuo de microalgas*" project. The authors also thank at Universidad de La Sabana (Colombia), Universidad Panamericana (México) and Universidad Don Bosco (El Salvador) by support.

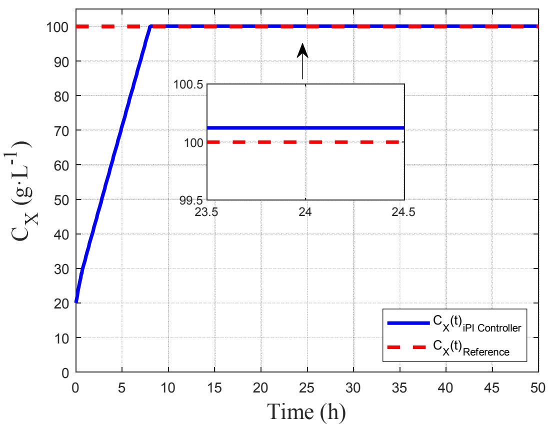

Fig. 6. Cell growth of microalgae, CX(t), front to variation of *μmax*.

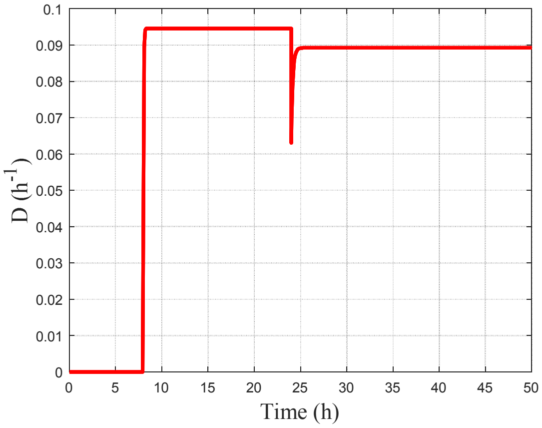

Fig. 7. Behavior of dilution rate, D(t), front to variation of *μmax*.

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