Metaheuristic Multivariable PI Controller Design for an Ethanol Production Continuous Fermenter

Nikolaos D. Kouvakas and Fotis N. Koumboulis
Department of Digital Industry Technologies
School of Science
National and Kapodistrian University of Athens
Psahna Evias, Greece
nkouvak@dind.uoa.gr, fkoumboulis@dind.uoa.gr

Dimitrios G. Fragkoulis and Tatiana Chrysoula Drosou
Core Department
National and Kapodistrian University of Athens
Psahna Evias, Greece
dfragkoulis@uoa.gr, tadrosou@uoa.gr

***Abstract*— PI controllers are favorable for implementation in most industrial computer controller platforms as well as integrated circuit platforms. In the present paper a multivariable Proportional plus Integral (PI) controller is designed for the regulation of ethanol concentration in a continuous fermenter, being a reactor with several industrial and biomedical applications. Based upon the nonlinear model of the fermentation process, a linear approximant of the process is analytically derived. The range of accuracy of the linear approximant is determined using a mixed norm criterion. Based upon the linear approximant and a metaheuristic algorithm, a multivariable PI controller is designed in order to satisfy stability for the closed loop system, asymptotic command following for the ethanol concentration and model following of the respective closed loop linear approximant system. Performance of the proposed control scheme when applied to the original nonlinear model is satisfactory, even for large external commands.**

Keywords — bioreactors, PI controllers, metaheuristic algorithms

I. INTRODUCTION

The interest for industrial fermentation processes in the production of chemicals, pharmaceuticals and other related products is increasing. Of particular importance is the use of fermentation for biomedical related applications (indicatively see [1]-[4]) where they are used for the production of anti-viral drugs, therapeutic recombinant proteins and DNA, monoclonal antibodies as well as alcoholic compounds.

Towards controlling ethanol fermentation in bioreactors, several approaches have been proposed. Indicatively, see [5]-[6] and the references therein. Of particular interest are continuous fermentation processes, upon which three term type of controllers are applied. Indicatively, in [7], the mathematical model of a continuous ethanol fermentation process with delayed inhibition is presented. Using as a sole actuatable input the dilution rate, a PI controller is designed to stabilize the process for any process delay. Furthermore, the problem of noisy measurements is addressed through an appropriate filter. In [8], a nonlinear model predictive controller is designed for the control of a bioethanol production process. The controller considers three different controlled variables (ethanol concentration, productivity, and inverse of the productivity) and the results are compared to those derived using a standard PI controller. In [9], an inferential control scheme based on adaptive linear neural network soft sensors together with PID controllers, is designed for the regulation of an ethanol fermentation process. In [10], the problem of the dumping of oscillatory phenomena in a continuous bioethanol production process is studied using P and PI types of controllers and it was shown that the presence of the integral term significantly improves the performance of the control scheme. In [11], a decentralized PI controller tunning algorithm for the control of a bioethanol production process is proposed. In [12], a decoupled input–output linearizing controller has been designed for controlling an ethanol production bioprocess and its performance was compared to that of a proportional–integral–derivative (PID) controller. In [13], the development and implementation of regulatory PI type control structures in the operation of a Simultaneous Saccharification and Co-Fermentation process for bioethanol production is proposed. In [14], a linear MIMO PI controller has been designed for the control of a bioreactor used in ethanol production. The controller parameters have been tunned using the robust performance number methodology. It is important to mention that PI as well as P and PID controllers are offered for implementation in most industrial computer platforms, like PLCs, μCs, and DSPs, as well as integrated circuit platforms (indicatively see [15] to [17] as well as the references therein). Considering network connectivity capabilities of PLCs, PI controllers are easily implementable as part of remote supervisors (see [18] and the references therein).

In the present paper, a multivariable PI type of controller is designed for the regulation of ethanol concentration in a continuous fermenter. First, the model of the process is presented in the form of a nonlinear state space description. Based upon the nonlinear model of the process, its nominal values are evaluated, and a linear approximant of the nonlinear model is produced. The range of accuracy of the linear approximant, as compared to the original nonlinear model, is quantitatively determined through series of computational experiments and using a mixed norm criterion. Based upon the linear approximant, a multivariable linear PI controller is designed to satisfy the following goals: a) stability of the closed loop system, b) asymptotic command following for the performance output of the system and c) model following of the closed loop linear approximant system. The above goals are satisfied by tuning the controller parameters via a metaheuristic algorithm. Through series of computational experiments, it is shown that the application of the linear PI controller to the original nonlinear model performs satisfactorily, even for large external commands.

979-8-3503-9958-5/22/$31.00 ©2022 IEEE

II. Dynamics of a Continuous Ethanol Fermenter

A. Nonlinear Model

The nonlinear model of a continuous ethanol fermenter will be presented. Assuming that the volume of the fermenter is constant and that it is perfectly mixed, the model describing the fermentation process is of the form (see [19]):

$$\dot{x}(t) = f(x,u),\; y(t) = Cx(t), \tag{1a,b}$$

where t is the time variable, while $x(t)$, $u(t)$ and $y(t)$ are the state, input and performance output vectors, i.e.,

$$x(t) = \begin{bmatrix} x_1(t) & x_2(t) & x_3(t) \end{bmatrix}^T = \begin{bmatrix} X(t) & S(t) & P(t) \end{bmatrix}^T,$$

$$u(t) = \begin{bmatrix} u_1(t) & u_2(t) \end{bmatrix}^T = \begin{bmatrix} D(t) & S_f(t) \end{bmatrix}^T,\; y(t) = P(t).$$

The state variables X, S and P are the yeast, glucose and ethanol concentrations, respectively. The input variables D and S_f are the dilution rate and the feed substrate concentration, respectively. The system vector $f(x,u) = [f_i(x,u)] \in \mathbb{R}^{3\times 1}$ is described in terms of the state variables, the actuatable inputs and the model parameters as follows:

$$f_1(x,u) = -u_1x_1 + \mu_m x_1x_2(1-P_m^{-1}x_3)(K_m + x_2 + K_i^{-1}x_2^2)^{-1}$$

$$f_2(x,u) = u_1(u_2 - x_2) - \mu_m x_1x_2(1 - x_3P_m^{-1})Y_{XS}^{-1}(K_m + x_2 + K_i^{-1}x_2^2)^{-1}$$

$$f_3(x,u) = bx_1 - u_1x_3 + \mu_m a x_1x_2(1-P_m^{-1}x_3)(K_m + x_2 + K_i^{-1}x_2^2)^{-1},$$

where μ_m is the maximum specific growth rate, K_m is the substrate saturation constant, K_i is the substrate inhibition constant, P_m is the product saturation constant, Y_{XS} is the cell-mass yield and a and b are yield parameters for the product. The performance output matrix is $C = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \in \mathbb{R}^{1\times 3}$.

B. Linear Approximant

The linear approximant of the nonlinear model (1) will be derived around appropriate nominal points corresponding to constant operating conditions for all system variables. Let $\bar{u}_1$, $\bar{u}_2$, $\bar{x}_i$ ($i = 1,2,3$) and $\bar{y}$ be the nominal points of u_1, u_2, x_i ($i = 1,2,3$) and y respectively. The respective vectors of the nominal values for the actuatable inputs and the state variables are denoted by $\bar{u}$ and $\bar{x}$ respectively. Using (1), the nominal points can be expressed in terms of the nominal values of the actuatable inputs as

$$\bar{x}_1 = 0.5Y_{XS}\left[P_m\bar{u}_1^2 - K_iY_{XS}\mu_m(b + a\bar{u}_1)\right]^{-1}$$
$$\left\{P_m\bar{u}_1\left[K_i(\bar{u}_1 - \mu_m) + 2\bar{u}_1\bar{u}_2\right] + \sqrt{\Delta} - K_iY_{XS}\mu_m(b + a\bar{u}_1)\bar{u}_2\right\},$$

$$\bar{x}_2 = \frac{K_i\left[P_m\bar{u}_1(\bar{u}_1 - \mu_m) + Y_{XS}\mu_m(b + a\bar{u}_1)\bar{u}_2\right] + \sqrt{\Delta}}{2\left[K_iY_{XS}\mu_m(b + a\bar{u}_1) - P_m\bar{u}_1^2\right]},$$

$$\bar{x}_3 = \frac{Y_{XS}(b + a\bar{u}_1)}{2P_m\bar{u}_1^3 - 2K_iY_{XS}\mu_m\bar{u}_1(b + a\bar{u}_1)} \times$$
$$\left\{2P_m\bar{u}_1^2\bar{u}_2 + K_i\left[P_m\bar{u}_1(\bar{u}_1 - \mu_m) - Y_{XS}\mu_m(b + a\bar{u}_1)\bar{u}_2\right] + \sqrt{\Delta}\right\},$$

$$\Delta = 4K_iK_mP_m\bar{u}_1^2\left[K_iY_{XS}\mu_m(b + a\bar{u}_1) - P_m\bar{u}_1^2\right] +$$
$$+K_i^2\left[P_m\bar{u}_1(\bar{u}_1 - \mu_m) + Y_{XS}\mu_m(b + a\bar{u}_1)\bar{u}_2\right]^2.$$

The linear approximant of the model (1) is of the form

$$\delta\dot{x}(t) = A\delta x(t) + B\delta u(t),\; \delta y(t) = C\delta x(t) \tag{2a,b}$$

where $\delta u(t) = \Delta u(t) = u(t) - \bar{u}$, while $\delta x(t)$ and $\delta y(t)$ are the responses of (2) and approximate $\Delta x(t) = x(t) - \bar{x}$ and $\Delta y(t) = y(t) - \bar{y}$, respectively. The approximation is accurate around an operating point $o(t) = \bar{o}$; $o(t) = (u(t), x(t), y(t))$, $\bar{o} = (\bar{u}, \bar{x}, \bar{y})$. The system matrices in (2a) and (2b) are $A = \partial f(x,u)/\partial x|_{o=\bar{o}}$ and $B = \partial f(x,u)/\partial u|_{o=\bar{o}}$. The nonzero elements of the system matrices $A = [a_{i,j}] \in \mathbb{R}^{3\times 3}$ and $B = [b_{i,j}] \in \mathbb{R}^{3\times 2}$ are computed to be: $b_{1,1} = -\bar{x}_1$, $b_{2,1} = \bar{u}_2 - \bar{x}_2$, $b_{2,2} = \bar{u}_1$, $b_{3,1} = -\bar{x}_3$ and

$$a_{1,1} = K_i\mu_m\bar{x}_2(P_m - \bar{x}_3)\left\{P_m\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]\right\}^{-1} - \bar{u}_1,$$

$$a_{1,2} = P_m^{-1}K_i\mu_m\bar{x}_1(K_iK_m - \bar{x}_2^2)(P_m - \bar{x}_3)\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]^{-2},$$

$$a_{1,3} = -P_m^{-1}K_i\mu_m\bar{x}_1\bar{x}_2\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]^{-1},$$

$$a_{2,1} = P_m^{-1}Y_{XS}^{-1}K_i\mu_m\bar{x}_2(\bar{x}_3 - P_m)\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]^{-1},$$

$$a_{2,2} = -\bar{u}_1 - P_m^{-1}Y_{XS}^{-1}K_i\mu_m\bar{x}_1(K_iK_m - \bar{x}_2^2)(P_m - \bar{x}_3)/\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]^2\; a_{2,3} = P_m^{-1}Y_{XS}^{-1}K_i\mu_m\bar{x}_1\bar{x}_2\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]^{-1},$$

$$a_{3,1} = b + aP_m^{-1}K_i\mu_m\bar{x}_2(P_m - \bar{x}_3)\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]^{-1},$$

$$a_{3,2} = aP_m^{-1}K_i\mu_m\bar{x}_1(K_iK_m - \bar{x}_2^2)(P_m - \bar{x}_3)\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]^{-2},$$

$$a_{3,3} = -\bar{u}_1 - aP_m^{-1}K_i\mu_m\bar{x}_1\bar{x}_2\left[\bar{x}_2^2 + K_i(K_m + \bar{x}_2)\right]^{-1}.$$

C. Accuracy of the Linear Approximant

To examine the accuracy of the linear approximant (2), as compared to the nonlinear model (1), a test approach similar to that presented in [20] will be applied. Assume that both nonlinear and linear approximant systems operate at the nominal points presented in the previous subsection. Let the actuatable inputs be of the form

$$u_j(t) = \bar{u}_j(1 + p_ju_s(t))\;(j = 1,2) \tag{3}$$

where $u_s(t)$ is the unit step signal and p_j ($j = 1,2$) is the percentile change of the input signals from the respective nominal value. Note that p_j can be either negative or positive. Given p_j, a set of nonlinear and linear approximant responses for the state variables is generated, let $x_i(t)$ and $\delta x_i(t)$ ($i = 1,2,3$) respectively. To quantitatively examine the accuracy of the linear approximant, define the following metrics

$$J_\infty = \frac{\max_{i=1,2,3}\left\{\left\|x_i(t) - \delta x_i(t) - \bar{x}_i\right\|_\infty\right\}}{\max_{i=1,2,3}\left\{\left\|\delta x_i(t)\right\|_\infty\right\}} \times 100\%, \tag{4a}$$

$$J_2 = \left\{\frac{\sum_{i=1}^{3}\left\|x_i(t) - \delta x_i(t) - \bar{x}_i\right\|_2^2}{\sum_{i=1}^{3}\left\|\delta x_i(t)\right\|_2^2}\right\}^{0.5} \times 100\%, \tag{4b}$$

$$J_1 = \left\{\frac{\sum_{i=1}^{3}\left[\lim_{t\to+\infty}\left|x_i(t) - \delta x_i(t) - \bar{x}_i\right|\right]^2}{\sum_{i=1}^{3}\left[\lim_{t\to+\infty}\left|\delta x_i(t)\right|\right]^2}\right\}^{0.5} \times 100\%, \tag{4c}$$

where $\|h(t)\|_2^2 = \int_{0-}^{T_{\max}} h(t)^2\,dt$ and $\|h(t)\|_\infty = \sup_{t\in[0,T_{\max}]} |h(t)|$, where $h(t)$ is a real function of time and $T_{\max}$ is a time parameter selected by the designer. In what follows, $T_{\max}$ will be selected being equal to the maximum settling time of the step responses (from all inputs to all state variables) of the linear approximant system (2) for unit step input signals.

Define the composite metric

$$\tilde{J} = (1-\mu)J_\infty + \mu J_2 \tag{5}$$

where $\mu \in [0,1]$ is a weighting factor selected by the designer. In order to declare the linear approximant being accurate, the following constraints must be satisfied

$$J_1 < e_1,\ \tilde{J} < \tilde{e} \tag{6a,b}$$

where e_1 and $\tilde{e}$ are appropriate positive bounds set by the designer. Let $\mu_m = 0.48[\mathrm{h}^{-1}]$, $K_m = 1.2[\mathrm{g/l}]$, $K_i = 22[\mathrm{g/l}]$, $P_m = 50[\mathrm{g/l}]$, $Y_{XS} = 0.4[\mathrm{g/g}]$, $a = 2.2[\mathrm{g/g}]$ and $b = 0.2[\mathrm{g/g}]$. Assuming that $\overline{u}_1 = 0.15[\mathrm{h}^{-1}]$ and $\overline{u}_2 = 20[\mathrm{g/l}]$, the nominal values for the state variables are evaluated to be $\overline{x}_1 = 5.58807[\mathrm{g/l}]$, $\overline{x}_2 = 1.3731[\mathrm{g/l}]$ and $\overline{x}_3 = 19.7445[\mathrm{g/l}]$. Using the above presented data and nominal values, it can be verified that $T_{\max} = 38.51[\mathrm{h}]$. Assume that $p_1, p_2 \in [-0.25, 0.25]\times 100\%$, $\mu = 0.3$, $e_1 = 10\%$ and $\tilde{e} = 15\%$. In Figures 1 and 2, contour plots for of the metrics J_1 and $\tilde{J}$ are presented. Note that, in all colored areas in the contour plot, the constraints in (6) are satisfied.

It is important to mention that the potential for the use of the linear approximant (2) for controller design purposes has also been demonstrated in [19], where in an open loop system behavior examination it is observed that for up to 30% dilution rate changes the input/output behavior is nearly linear. In the same study, significant nonlinear behavior is observed for changes in the feed substrate concentration. Applying series of computations as well as using the results in [19], it can be verified that the open loop system (1) is stable. Regarding the stability of (2), it is observed that the degree of its characteristic polynomial is three, while the coefficients of this polynomial depend entirely upon the model parameters and the nominal points of the process. For typical values of the model parameters and the nominal points of the process, the roots of the polynomial lay in the left half complex plain. Indicatively, using the values of the model parameters and the nominal point, presented in the previous paragraph, it is observed that the roots are $\pi_1 = -0.906$, $\pi_2 = -0.157$ and $\pi_3 = -0.15$. Let $H_1(s)$ and $H_2(s)$ be the transfer functions mapping $\delta u_1(t)$ and $\delta u_2(t)$ to the performance output, respectively. Using the values of the model parameters and the nominal point, presented above, it can be verified that the gain margins for $H_1(s)$ and $H_2(s)$ are 0.015307 and infinity, respectively. The phase margins are $91.7°$ and infinity, respectively.

III. A Metaheuristic Multivariable PI Control Scheme

A. Controller Structure

A multivariable PI controller for the regulation of the performance output of the system will be designed. Both actuatable inputs are available for manipulation, while only the ethanol concentration is considered to be measurable. In the frequency domain, the proposed controller structure is

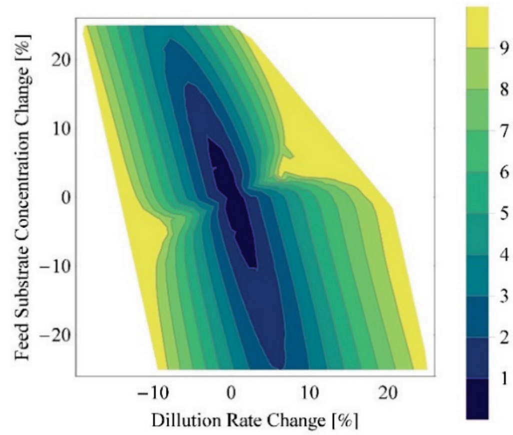

Fig. 1. Accuracy metric J_1 for various input changes.

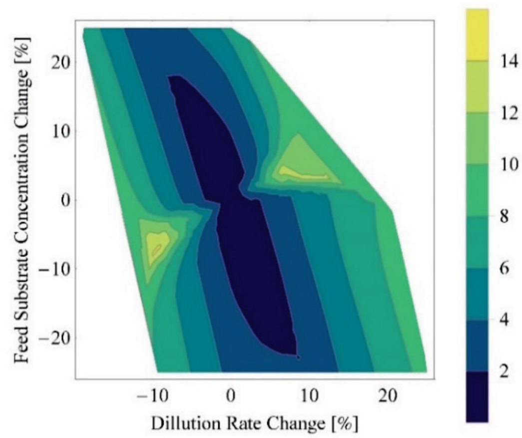

Fig. 2. Accuracy metric $\tilde{J}$ for various input changes.

$$\delta U(s) = \begin{bmatrix} f_{P,1} + f_{I,1}\dfrac{1}{s} & f_{P,2} + f_{I,2}\dfrac{1}{s}\end{bmatrix}^T (\kappa W(s) - \delta X_3(s)) \tag{7}$$

where $f_{P,j}, f_{I,j} \in \mathbb{R}$ ($j = 1,2$), $\kappa \in \mathbb{R}$, $W(s) = \mathcal{L}\{w(t)\}$, $\delta X_3(s) = \mathcal{L}\{\delta x_3(t)\}$, where $\mathcal{L}\{\bullet\}$ denotes the Laplace transform of the argument signal $\bullet$, and $w(t)$ is the external command.

B. Analysis of the Design Goal

The design goal is to find appropriate controller parameters $f_{P,j}$, $f_{I,j}$ ($j = 1,2$) and κ such that the linear approximant closed loop satisfies the following design requirements:

i. Stability,
ii. Asymptotic command following,
iii. The transfer function resembles as possible an ideal stable model, namely a desired transfer function.

The design requirement (i), is satisfied if and only if

$$\mathrm{Re}\{\rho_q\} < 0;\ q = 1,\dots 4 \tag{8}$$

where $\rho_q \in \mathbb{C}$ ($q=1,\ldots 4$) are the roots of the closed loop characteristic polynomial $p_c(s)=s^4+\alpha_3 s^3+\alpha_2 s^2+\alpha_1 s+\alpha_0$. Applying appropriate manipulations, the coefficients α_j ($j=0,\ldots,3$) are derived to depend upon the nominal values of the inputs and the state variables, the model parameters and the free controller parameters. Stability can be guaranteed by applying a classical Routh-Hurwitz criterion and choosing the controller parameters satisfying the resulting inequalities.

Regarding the design requirement in (ii) and assuming that the closed loop system is stable, it is observed that asymptotic command following for the performance output is guaranteed if and only if $\kappa=1$.

Regarding the requirement (iii), an approach similar to that presented in [21] will be used. Applying series of computations, it can be observed that the transfer function mapping the external command to the performance output is of the form

$$H_y(s)=\left(\beta_3 s^3+\beta_2 s^2+\beta_1 s+\beta_0\right)/\,p_c(s), \tag{9}$$

where the coefficients β_j ($j=0,\ldots,3$) depend upon the nominal values of the inputs and the state variables, the model parameters and the free controller parameters. Define the following H-infinity cost function

$$J\left(f_{P,1}, f_{I,1}, f_{P,2}, f_{I,2}\right)=\left\|H_m(s)-H_y(s)\right\|_\infty \tag{10}$$

where $H_m(s)$ is a model transfer function to be selected by the designer. The target is to find appropriate controller parameters $f_{P,j}$ and $f_{I,j}$, satisfying the inequality in (8) while J is minimized. Here, it is proposed that the model transfer function is of a 3rd order all pole expression with real poles, i.e. $H_m(s)=$ $1/\left[\left(T_1 s+1\right)\left(T_2 s+1\right)\left(T_3 s+1\right)\right]$. The selection of the controller parameters does not depend upon the external command.

C. Controller Parameter Selection via a Metaheuristic Algorithm

Considering the highly nonlinear nature of the cost function in (10) and the form of the inequality constraints coming from the conditions in (8), it is concluded that the analytical determination of the controller parameters is a quite difficult task. To this end, a metaheuristic algorithm, similar to that presented in [22] and [23], will be proposed. The basic idea of the algorithm is to define an initial search area for the controller parameters and after several loops to contract to a suboptimal solution that minimizes the cost criterion in (10) under the constraints imposed by (8). The proposed metaheuristic algorithm is of the form:

<u>*Initial Data and Performance Criterion*</u>

1) Center values and half widths for the initial search area of the controller parameters $\left(f_{P,j}\right)_c, \left(f_{I,j}\right)_c, \left(f_{P,j}\right)_w$ and $\left(f_{I,j}\right)_w$ ($j=1,2$).

2) Performance criterion $J\left(f_{P,1}, f_{I,1}, f_{P,2}, f_{I,2}\right)$.

3) Iteration parameters n_{loop}, n_{rep}, $n_{total} \in \mathbb{N}$.

4) Search algorithm threshold γ.

<u>*Algorithm*</u>

Step 0: Set the numbering index $i_{\max}=0$.

Step 1: Determine a search area $\Im$ for the controller parameters according to the inequalities $\left(f_{P,j}\right)_c-\left(f_{P,j}\right)_w \le f_{P,j} \le \left(f_{P,j}\right)_c+\left(f_{P,j}\right)_w$ and $\left(f_{i,j}\right)_c-\left(f_{i,j}\right)_w \le f_{i,j} \le \left(f_{i,j}\right)_c+\left(f_{i,j}\right)_w$

Step 2: Set the numbering index $i_1=0$.

Step 3: Set the numbering index $i_1=i_1+1$.

Step 4: Set the numbering index $i_2=0$.

Step 5: Set the numbering index $i_{\max}=i_{\max}+1$. If $i_{\max}>n_{total}$ go to Step 15.

Step 6: Set the numbering index $i_2=i_2+1$.

Step 7: Select randomly a set of controller parameters within the search area $\Im$, let $f_{P,j}=\left(f_{P,j}\right)_{i_2}$ and $f_{I,j}=\left(f_{I,j}\right)_{i_2}$.

Step 8: Check if the closed loop system is stable. If the closed loop system is stable, proceed to the next step. If the closed loop system is unstable, go to Step 7.

Step 9: Evaluate $J_{i_2}=J\left(\left(f_{P,1}\right)_{i_2},\left(f_{I,1}\right)_{i_2},\left(f_{P,2}\right)_{i_2},\left(f_{I,2}\right)_{i_2}\right)$

Step 10: If $i_2<n_{loop}$, then go to Step 5.

Step11: Find $J_{i_1,\min}=\min\{J_{i_2}, i_2=1,\ldots,n_{loop}\}$ and the corresponding controller parameters, let $\left(f_{P,j}\right)_{i_1}$ and $\left(f_{I,j}\right)_{i_1}$.

Step 12: If $i_1 \ge n_{rep}$ then find the controller parameters $\left(f_{P,j}\right)_{\min}$, $\left(f_{I,j}\right)_{\min}$, $\left(f_{P,j}\right)_{\max}$ and $\left(f_{I,j}\right)_{\max}$ ($j=1,2$), corresponding to $J_{\min}=\min\{J_{i_1,\min}, i_1=1,\ldots,n_{rep}\}$ and $J_{\max}=$ $\max\{J_{i_1,\min}, i_1=1,\ldots,n_{rep}\}$. Else go to Step 3.

Step 13: Define $\left(f_{P,j}\right)_c=\left(f_{P,j}\right)_{\min}$, $\left(f_{I,j}\right)_c=\left(f_{I,j}\right)_{\min}$, $\left(f_{P,j}\right)_w=\left|\left(f_{P,j}\right)_{\min}-\left(f_{P,j}\right)_{\max}\right|$, $\left(f_{I,j}\right)_w=\left|\left(f_{I,j}\right)_{\min}-\left(f_{I,j}\right)_{\max}\right|$

Step 14: If $\max\left\{\left|\left(f_{P,j}\right)_w/\left(f_{P,j}\right)_c\right|,\left|\left(f_{I,j}\right)_w/\left(f_{I,j}\right)_c\right|\right\}>\gamma$ and $i_{\max}<n_{total}$, go to Step 1. If $\max\left\{\left|\left(f_{P,j}\right)_w/\left(f_{P,j}\right)_c\right|,\right.$ $\left.\left|\left(f_{I,j}\right)_w/\left(f_{I,j}\right)_c\right|\right\} \le \gamma$ or $i_{\max} \ge n_{total}$, go to Step 15.

Step 15: Set $f_{P,j}=\left(f_{P,j}\right)_{\min}$ and $f_{I,j}=\left(f_{I,j}\right)_{\min}$.

IV. SIMULATION RESULTS

To demonstrate the efficiency of the proposed control scheme, consider the data presented in Section 2. Furthermore, let the model transfer function parameters be $T_1=5$, $T_2=10$ and $T_3=15$. Also, let the metaheuristic algorithm parameters be $n_{loop}=100$, $n_{rep}=20$, $n_{total}=10^7[-]$, $\gamma=10^{-3}[-]$, $\left(f_{P,1}\right)_c=\left(f_{I,1}\right)_c=\left(f_{P,2}\right)_c=\left(f_{I,2}\right)_c=0$, $\left(f_{P,1}\right)_w=\left(f_{I,1}\right)_w=$ $\left(f_{P,2}\right)_w=\left(f_{I,2}\right)_w=0.01$. Applying the metaheuristic algorithm, the following controller parameters, are derived $f_{P,1}=0.00010255$, $f_{I,1}=-0.00026625$, $f_{P,2}=-0.068287$, $f_{I,2}=0.018998$. The resulting cost criterion is $J=0.03556$.

To demonstrate the efficiency of the controller, let $w(t)=w_s u_s(t)$ where $w_s=0.1[\text{g/l}]$. In Figures 3 to 7, the closed loop responses of the state and actuatable input variables (both for the nonlinear and linear approximant models) are presented. From all figures it is observer that the nonlinear and linear approximant closed loop responses are visually identical. Furthermore, all responses remain appropriately bounded.

With respect to the performance variable (see Figure 5), it is observed that asymptotic command following is achieved both for the linear and nonlinear closed loop responses. Comparing a) the nonlinear closed loop response to the linear closed loop response, b) the nonlinear closed loop response to the reference response and c) the linear closed loop response to the reference response it is observed that there exist minimal deviation between the responses being smaller than $3.6825 \cdot 10^{-6} [\%]$, $9.67596 \cdot 10^{-3} [\%]$ and $9.6642 \cdot 10^{-3} [\%]$, respectively. To examine the performance of the controller for larger external commands, as compared to the model response, a metric like that in (5), will be used. Performing series of computational experiments for different values of the amplitude w_s of the external command, ranging from -10% to 10% of the nominal value of the ethanol concentration, it is observed that the composite error remains within acceptable limits (see Figure 8). Efficiency of the proposed control scheme is expected to deteriorate as the external commands become larger and the system diverges from the operating point upon which the controller has been designed. To widen the range of the external commands, multiple controllers, for different operating conditions, can be designed and orchestrated be a step wise controller switching algorithm (indicatively see [20] and [24]).

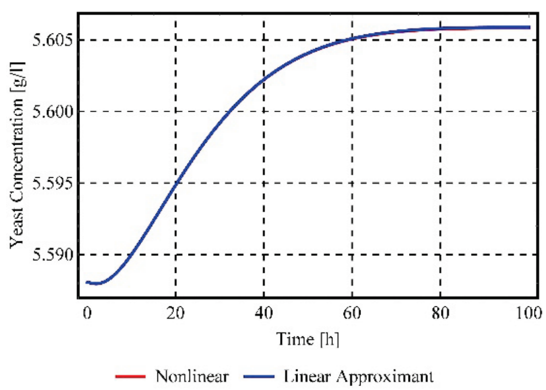

Fig. 3. Closed loop response for the yeast concentration

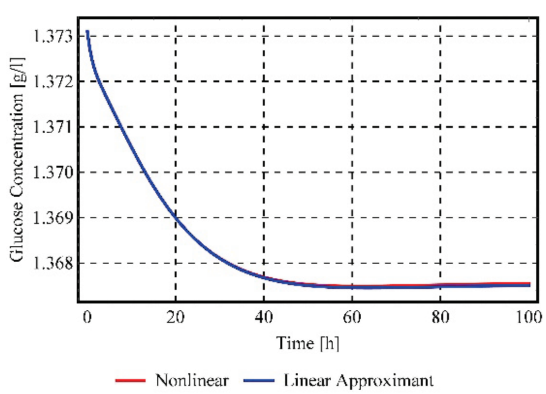

Fig. 4. Closed loop response for the glucose concentration

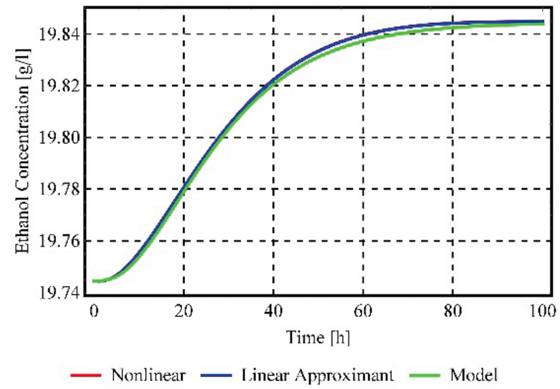

Fig. 5. Closed loop response for the ethanol concentration

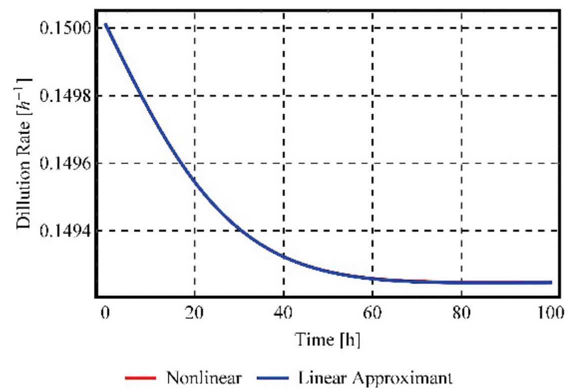

Fig. 6. Closed loop response for the dillution rate

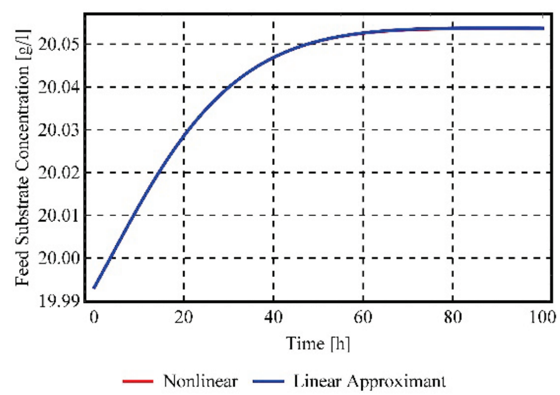

Fig. 7. Closed loop response for the feed substrate concentration

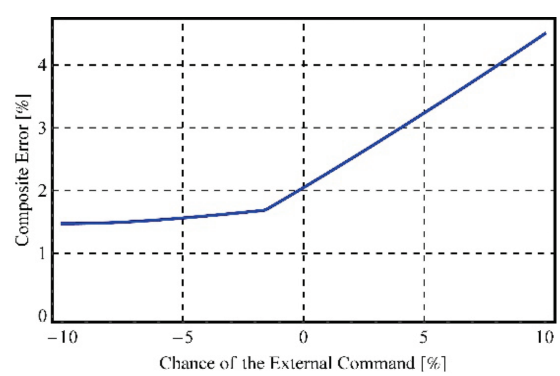

Fig. 8. Composite error for various external command.

V. CONCLUSIONS

A multivariable PI type of controller has been designed for the regulation of ethanol concentration in a continuous fermenter. Based upon the nonlinear model of the process, its nominal values have been evaluated and a linear approximant of the nonlinear model has been produced. The accuracy of the linear approximant as compared to the original nonlinear model has been quantitatively examined, using a mixed norm criterion as well as performing series of computational experiments. Based upon the linear approximant, a multivariable PI controller has been designed to achieve stability of the closed loop system, asymptotic command following of the performance output of the system and model following of the closed loop linear approximant system. The above goals have been satisfied by appropriate tuning of the controller parameters, via a metaheuristic algorithm. Application of the controller to the original nonlinear model, through series of computational experiments has been proven to be satisfactory, even for large external commands.

Future research includes more rich feedback controllers, based on the state variable observation approach in [25], towards compensation of model uncertainties and measurement noise. The issue of the design of common PI controllers (see [26]) of continuous fermenters is currently under investigation. Also, the study of the control of fermenters that include delays in their mathematical model (see [7]) and protocols for remote control (see [27]), using multivariable control design methods with time delays (see [28]) is currently under investigation.

ACKNOWLEDGMENT

Research supported by the MSc Program in "Advanced Control Systems and Robotics", National and Kapodistrian University of Athens, Euripus Campus, Greece.

REFERENCES

[1] M. A. J. Mazumder and A. Al-Ahmed, "Medical Applications of Fermentation Technology," Advanced Materials Research, vol. 810, pp. 127-157, 2013.

[2] S. A. Survase and R. S.Singhal, "Novel Applications and Non-Food Uses of Potato: Potatoes in Biomedical/Pharmaceutical and Fermentation Applications," Advances in Potato Chemistry and Technology, pp. 447-463, 2009.

[3] D. R. Corzo Salinas, A. Sordelli, L. A. Martínez, G. Villoldo, C. Bernal, M. S. Pérez, P. Cerrutti, M. L. Foresti, "Production of bacterial cellulose tubes for biomedical applications: Analysis of the effect of fermentation time on selected properties," International Journal of Biological Macromolecules, vol. 189, pp. 1-10, 2021.

[4] M. S. Singhvi, S. S. Zinjarde and D. V. Gokhale, "Polylactic acid: synthesis and biomedical applications," Journal of Applied Microbiology, vol. 127, pp. 1612-1626, 2019.

[5] L. Mears, S. M. Stocks, G. Sin and K. V. Gernaey, "A review of control strategies for manipulating the feed rate in fed-batch fermentation processes," Journal of Biotechnology, vol. 245, pp. 34-46, 2017.

[6] T. Shaqarin and M. Hajaya, "Nonlinear control strategies for a continuous alcoholic fermentation bioreactor used for bioethanol production," Proceedings of the 2022 8th Int. Conference on Control, Decision and Information Technologies (CoDIT), Istanbul, Turkey, 17-20 May 2022.

[7] P. Skupin and M. Metzger, "PI Control for a Continuous Fermentation Process with delayed product inhibition," Journal of Process Control, vol. 72, pp. 30-38, 2018.

[8] A.-H. Ajbar and E. Ali, "Study of Advanced Control of Ethanol Production through Continuous Fermentation," Journal of King Saud University – Engineering Sciences, vol. 29, no. 1 pp. 1-11, 2017.

[9] N. Pachauri, V. Singh and A. Rani, "Two degree of freedom PID based inferential control of continuous bioreactor for ethanol production," ISA Transactions, vol. 68, pp. 235-250 , 2017.

[10] A. Ciesielski and R. Grzywacz, "The dumping of oscillatory phenomena in the process of bioethanol production by continuous fermentation," Czasopismo Techniczne, vol. 3, pp. 119-132, 2019.

[11] J. Nandong and I. M. Chew, "Stability-based Decentralized PI Controller Tuning: Control of Co-Fermentation for Bioethanol Production," Proceedings of the 2021 Int. Conference on Green Energy, Computing and Sustainable Technology (GECOST), Miri, Malaysia, 7-9 July 2021.

[12] A. Persad, V. R. Chopda, A. S. Rathore and J. Gomes, "Comparative performance of decoupled input-output linearizing controller and linear interpolation PID controller enhancing biomass and ethanol production in Saccharomyces cerevisiae", Applied Biochemistry and Biotechnology, vol. 169, no. 4, pp. 1219-1240, 2013.

[13] H. Hernandez-Escoto, D. Rodriguez-Gomez and R. Morales-Rodriguez, "Regulatory control for the operation of simultaneous saccharification and co-fermentation reactor for bioethanol production,", Computer Aided Chemical Engineering, vol. 32, pp. 43-48, 2013.

[14] F. C. Diehl and J. O. Trierweiler, "Control Strategy for a Zymomonas mobilis Bioreactor Used in Ethanol Production," Computer Aided Chemical Engineering, vol. 27, pp. 1605-1610, 2009.

[15] R. Kociszewski, "Implementation of PI Controller in Reconfigurable PSoC Microcontroller to Control the Speed of Mobile Robot Drives," Proceedings of the 15th Int. Conference 2020 Mechatronic Systems and Materials (MSM), 2020, pp. 1-6, Bialystok, Poland, 1-3 July 2020

[16] I. Klimo, P. Drahoš and M. Kocúr, "PI controller implementation based on FPGA," Proceedings of the 29th Int. Conference 2018 Cybernetics & Informatics (K&I), Lazy pod Makytou, Slovakia, pp. 1-6, 31 January – 3 February 3 2018.

[17] F. N. Koumboulis, Industrial Control, New Technology Editions (in greek), 1999.

[18] P.E. Bhaskaran, C. Maheswari, S. Thangavel, M. Ponnibala, T. Kalavathidevi, N. Sivakumar, "IoT based monitoring and control of fluid transportation using machine learning," Computers and Electrical Engineering, vol. 89 p. 106899, 2021.

[19] M. A. Henson and D. E. Seborg, "Nonlinear Control Strategies for Contiuous Fermenters," Chemical Engineering Science, vol. 47, no. 4, pp. 821-835, 1992.

[20] G. L. Giannaris, N. D. Kouvakas, F. N. Koumboulis and D. Vouyioukas, "Switching Wireless Control for Longitudinal Quadrotor Maneuvers," Journal of Intelligent Robotic Systems, vol. 102, no. 42, 2021.

[21] N. D. Kouvakas, F. N. Koumboulis and K. Xydi, "Model Following through a Metaheuristic PD Controller for a Magnetic Levitation System," Proceedings of the IEEE Int. Conference on Industrial Informatics (INDIN'22), Perth, Australia, 25-28 July 2022.

[22] G. L. Giannaris, N. D. Kouvakas, F. N. Koumboulis and D. Vouyioukas, Towards Remote Control of Planar Redundant Robotic Manipulators, Proceedings of the IEEE 21st Int. Conf. on Intelligent Engineering Systems (INES 2017), pp. 231-236, Larnaca, Cyprus, 20-23 October 2017.

[23] F. N. Koumboulis and N. D. Kouvakas, "A three term controller for ride comfort improvement," Proceedings of the 19th Mediterranean Conference on Control & Automation (MED), pp. 114-119, Corfu, Greece, 20-23 June 2011.

[24] F. N. Koumboulis and M. P. Tzamtzi, "Multivariable step-wise safe switching controllers," Int. Conference on Computational Intelligence for Modelling, Control and Automation and Int. Conference on Intelligent Agents, Web Technologies and Internet Commerce (CIMCA-IAWTIC'06), pp. 624-630, Vienna, Austria, 8-10 July 2009.

[25] F. N. Koumboulis and D. G. Fragkoulis, "Switching Design for the Observation of the Biomass in Alcoholic Fermentation Processes," Proceedings of the 2017 XXVI Int. Conference on Information, Communication and Automation Technologies (ICAT), pp. 156-161, Sarajevo, Bosnia & Herzegovina, 26-28 October 2017.

[26] F. N. Koumboulis, On the heuristic design of common PI controllers for multi-model plants, Proceedings of the 2005 IEEE Conf. on Emerging Technologies and Factory Automation, pp. 975-982, Catania, Italy, September 19-22, 2005.

[27] F. N. Koumboulis, N. D. Kouvakas, G. L Giannaris and D. Vouyioukas, "Independent motion control of a tower crane through wireless sensor and actuator networks", ISA Transactions. vol. 60, pp. 312–320, 2016.

[28] F. N. Koumboulis, N. D. Kouvakas and P. N. Paraskevopoulos, "On the Morgan's problem for neutral time delay systems via dynamic controllers with application to a test case central heating system," Proceedings of the IEEE Control Applications (CCA) & Intelligent Control (ISIC), pp. 1195-1202, St. Petersburg, Russia, 8-10 July 2009.