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On the PID-structured model-free adaptive control: a comparison of different approaches

Soheil Salighe[1] and Dirk Söffker[2]

Abstract— **In this paper, a PID-structured controller with time-varying gains is introduced using model-free adaptive control (MFAC) methodologies. The MFAC uses a control-oriented linearized data-model to produce control input only using input/output (I/O) data of the system. One of the data-model structures is full form dynamic linearization (FFDL), which considers the effect of a time-window of previous I/O in the linearized model. A specific I/O window length in FFDL leads to a MFAC controller whose structure is similar to discrete multivariable type PID. By manipulating the control objective function, however, similar PID-structured (PIDs) controller can be realized using a less sophisticated data-model exploiting the compact form dynamic linearization (CFDL) technique. The complexity of the new PIDsMFAC-CFDL and the one realized by MFAC-FFDL are compared in terms of the total number of adjustable parameters when dealing with MIMO systems. The controllers are also applied on a simulated model of a nonlinear MIMO three-tank system (3TS). The results demonstrate that the number of parameters to be tuned can decrease heavily by considering the new approach. In addition, PIDsMFAC-CFDL delivers a smooth transition toward the given reference with less error and less consumed energy.**

I. INTRODUCTION

The well-known PID control, either the continuous or the discrete form [1], can still be considered as the most common controller exploited in industrial processes. Therefore, scientists are still interested in integrating PID scheme in their works; for instance, the intelligent PID (iPID), which is considered as a model-free controller, is introduced in [2]. The idea is to approximate the unknown dynamics through local models of the system. In the paper of Madadi and Söffker [3], the iPID is compared with other model-free control approaches, such as model-free adaptive control (MFAC). Baciu and Lazar [4] used the iterative feedback tuning (IFT) as a technique for tuning the parameters of the iPID controller by processing the data coming from the closed-loop system. For this purpose, the discrete version of the control algorithm, namely PID, is required [1], [5]. Guo et al. [6], designed a discrete PID to maximize stability margins of the system, and recently, Das et al. [7] applied an adaptive PID controller on a small wind turbine to attain the maximum power point of the wind system. Another form of adaptive PID control is presented in [8] to guarantee the stability of the system. Sayani and Dey [9] investigated the efficiency of a self-tuning PID controller working based on the instantaneous error and change of error of the system.

In addition to PID, there are many other control approaches categorized as model-free controllers, which use I/O data and does not rely on explicit prior knowledge of the plant. One of this approaches is the MFAC introduced by Hou and Jin [10]. By generating a linear data-model using I/O data of the system, the MFAC is able to make the plant track a certain path. According to [10], these data-models are categorized as compact form dynamic linearization form (CFDL), partial from dynamic linearization (PFDL), and full form dynamic linearization (FFDL); these data-models are generated only for control purpose. In [11], a simulation on controlling a tank truck model with sloshing phenomenon using the MFAC-FFDL is conducted. One of the advantages of the MFAC is its simple control algorithm, which provides the potential of performance improvement using different control features. For example, Ding et al. [12], combined the sliding-mode algorithm and the MFAC to actively suppress the chattering phenomenon in dry cutting experiments. The methodology of model-predictive control (MPC) was integrated into the MFAC leading to model-free adaptive predictive control (MFAPC) [10], [13]. The MFAC can also be used as a mean for self-tuning PID parameters to control a wind turbine [14].

The MFAC can also be modified to achieve certain functionality; Madadi and Söffker [3], for instance, enhanced the performance of conventional MFAC-CFDL and MFAC-PFDL by considering the minimization of the tracking error difference between two time intervals to tackle time-delay effects. The tracking error difference leads to an additional proportional term in the MFAC algorithm [15]. Xu et al. [16] also investigated the effectiveness of a weighted tracking error difference leading to a balanced contribution of output error and the rate of output error in the MFAC algorithm. In [11], [17], PD-control algorithm joins MFAC to extend the structure of MFAC to a more general form. According to [18], a special case of MFAC-FFDL can be expressed in form of PID control with time varying coefficients with better performance compared with the conventional PID with constant coefficients.

The MFAC-CFDL and MFAC-PFDL control algorithm consist of only the integral part of the well-known incremental PID-controller [19]. To enhance their practicality, MFAC-CFDL/PFDL and PD-control can be directly conjoin. The parameters of the added PD parts are constant [11], [17]. In this paper, a PID-structured MFAC (PIDsMFA-CFDL) following the principles of MMFAC-CFDL is introduced and

[1]Soheil Salighe is with the Chair of Dynamics and Control, University of Duisburg-Essen, Lotharstr. 1, 47057 Duisburg soheil.salighe@uni-due.de
[2]Dirk Söffker is with the Chair of Dynamics and Control, University of Duisburg-Essen, Lotharstr. 1, 47057 Duisburg, soeffker@uni-due.de

its structure is compared with discrete multivariable type PID [18] and the PID form of MFAC-FFDL. This new approach is obtained by manipulating the control objective function –rather than having a complex FFDL data-model– leading to similar control structure with less adjustable control parameters. Therefore, a less complex controller with similar structure is achieved by the new approach. The system to be controlled is a nonlinear three-tank system (3TS) used as a MIMO benchmark to show the applicability and efficiency of the proposed controllers in a simulation. Serhan and Noura [20] also used 3TS to conduct an experiment to investigate the performance of sliding mode control and model-free control. In [21], the bounded-input bounded-output stability and the tracking error convergence of MFAC-PFDL on 3TS are demonstrated. The results are compared with those of the PID controller.

The next section presents a summary of mathematical procedures of the proposed controllers; similarities and differences of these approaches are discussed. In section III, the system to be controlled is described, and the results of the comparison are shown. Finally, the overall summary and conclusions obtained from the results are included in section IV.

II. CONSIDERED CONTROL ALGORITHMS

A. Discrete PID control

Consider a nonlinear MIMO system with unknown dynamics [21]

$$y(k+1) = f(y(k), ..., y(k-n_y), u(k), ..., u(k-n_u)), \quad (1)$$

where $f(.) : \mathbb{R}^{(n_u+1)n+(n_y+1)m} \mapsto \mathbb{R}^m$ is an unknown nonlinear function, with $n_u, n_y \in \mathbb{N}$ as unknown orders of the system. The integers $n, m \in \mathbb{N}$ represent the number of inputs $u \in \mathbb{R}^n$ and measured outputs $y(k) \in \mathbb{R}^m$. The discrete PID-controller outweighs its continuous realization [22] because online manipulation of the gains can be more convenient in digital PID

$$\begin{aligned} u(k) &= u(k-1) \\ &+ K_P \Delta e(k) + K_I e(k) \\ &+ K_D(\Delta e(k) - \Delta e(k-1)), \end{aligned} \quad (2)$$

where $e(k) = y_d(k) - y(k)$ denotes the error at time instant k between the desired reference y_d and the system's output $y(k)$, and here Δ serves a finite difference operator. The constant parameters $K_P \in \mathbb{R}^{n\times m}$, $K_I \in \mathbb{R}^{n\times m}$, and $K_D \in \mathbb{R}^{n\times m}$ are the proportional, integral, and derivative gains, respectively. Here a multivariable PID controller [23], [24] is used and described in (2).

B. MFAC-FFDL

The FFDL data-model takes into account the influence of previous inputs and outputs

$$\begin{aligned} H(k) =&[y(k), \dots, y(k-L_y+1) \\ &, u(k), \dots, u(k-L_u+1)]^T, \end{aligned} \quad (3)$$

on the one-step ahead output of the system. Equation (3) consists of input-related time-window $[k-L_u+1]$ and output-related $[k-L_y+1]$ with $0 \leq L_y \leq n_y$ and $1 \leq L_y \leq n_u$.

Two assumptions are needed for generating the FFDL data-model.

- **Assumption 1**: The partial derivatives of $f(.)$ are continuous with respect to all variables.
- **Assumption 2**: System 1 satisfies the generalized Lipschitz condition, $|\Delta y(k+1)| \leq b|\Delta H(k+1)|$, $b \in \mathbb{R}^+$.

The nonlinear system (1), given the described assumptions, can be transformed to

$$\Delta y(k+1) = \Phi(k)\Delta H(k), \quad (4)$$

where

$$\Phi(k) = [\phi_1(k), \dots, \phi_{L_y}(k), \phi_{L_y+1}(k), \dots, \phi_{L_y+L_u}(k)]$$

is a bounded time-varying matrix with $\Phi(k) \in \mathbb{R}^{m\times(mL_y+nL_u)}$. According to [10], it is important to note that the FFDL is the most general dynamic linearization method used for MFAC leading to different dynamic linearization models by selecting different parameters, namely L_y and L_u.

To derive the MFAC-FFDL control algorithm, the objective function

$$\begin{aligned} J(u(k)) = &|y_d(k+1) - y(k+1)|^2 \\ &+ \lambda|u(k) - u(k-1)|^2 \end{aligned} \quad (5)$$

is considered, where $\lambda \in \mathbb{R}^+$ is a weighting factor. By substituting the FFDL linear data-model (4) in (5) and differentiating the objective function with respect to $u(k)$, the control algorithm

$$\begin{aligned} u(k) &= u(k-1) \\ &+ \Psi(k)\left[\varrho_{L_y+1}(y_d(k+1) - y(k))\right] \\ &- \Psi(k)\left[\sum_{i=1}^{L_y} \varrho_i \hat{\phi}_i(k)\Delta y(k-i+1)\right] \\ &- \Psi(k)\left[\sum_{i=L_y+2}^{L_y+L_u} \varrho_i \hat{\phi}_i(k)\Delta u(k+L_y-i+1)\right], \end{aligned} \quad (6)$$

with

$$\Psi(k) = \frac{\hat{\phi}^T_{L_y+1}(k)}{\lambda + \|\hat{\phi}_{L_y+1}(k)\|^2}$$

is obtained, where $\varrho = [\varrho_1, \dots, \dots, L_y + L_u] \in (0,\ 1]$ are step factors to make the control algorithm more general. In addition, $\hat{\phi}_i,\ i = 1, \dots, L_y + L_u$ are the elements of $\hat{\Phi}$ estimated by

$$\begin{aligned} \hat{\Phi}(k) &= \hat{\Phi}(k-1) \\ &+ \frac{\eta(y(k) - y(k-1))\Delta H^T(k-1)}{\mu + \|\Delta H(k-1)\|^2} \\ &- \eta\frac{\hat{\Phi}(k-1)\Delta H(k-1)\Delta H^T(k-1)}{\mu + \|\Delta H(k-1)\|^2}, \end{aligned} \quad (7)$$

with $\eta \in (0\ 1]$ and $\mu \in \mathbb{R}^+$. By considering $L_y = 2$, $L_u = 1$, and $y_d(k) = y_d = \text{const}$, the input (6) becomes

$$u(k) = u(k-1) + M_P(k)\Delta e(k) + M_I(k)e(k) + M_D(k)(\Delta e(k) - \Delta e(k-1)), \tag{8}$$

with

$$M_P(k) = \hat{\phi}_3(k)\frac{\varrho_1\hat{\phi}_1(k) + \varrho_2\hat{\phi}_2(k)}{\lambda + \|\hat{\phi}_3(k)\|^2},$$

$$M_I(k) = \frac{\varrho_3\hat{\phi}_3}{\lambda + \|\hat{\phi}_3(k)\|^2}, \text{ and}$$

$$M_D(k) = -\frac{\varrho_2\hat{\phi}_3(k)\hat{\phi}_2(k)}{\lambda + \|\hat{\phi}_3(k)\|^2}.$$

Equation (8) has the structure of incremental multivariable type PID (2) stating that conventional PID is a special case of MFAC-FFDL; however, the gains in (8) are no longer constant.

C. PIDsMFAC-CFDL

The flexibility of MFAC methodology gives the possibility of having the same control input structure in (8) using the CFDL data-model

$$\Delta y(k+1) = \phi(k)\Delta u(k), \tag{9}$$

which can be obtained from (4) by assuming $L_y = 0$ and $L_u = 1$ leading to $\phi(k) \in \mathbb{R}^{m\times n}$. The PIDsMFAC-CFDL can be achieved by manipulating the cost function (5) rather than assuming a complex dynamic linearized data-model such as FFDL.

Following the principles of MMFAC in [3], the cost function

$$J(u(k)) = |e(k+1)|^2 + s_1|\Delta_N e(k+1)|^2 + s_2|\Delta_N e(k+1) - \Delta_N e(k)|^2 + \tau|u(k) - u(k-1)|^2 \tag{10}$$

can be defined, which consists of tracking error, tracking error difference, and the rate of error difference. The parameters $\tau, s_1, s_2 \in \mathbb{R}^+$ are weighting factors. The operator Δ_N in (10) is defined as

$$\begin{aligned}\Delta_N e(k+1) &= e(k+1) - e(k+1-N)\\ &= y_d(k+1) - y(k+1)\\ &- (y_d(k+1-N) - y(k+1-N)),\end{aligned} \tag{11}$$

where $N \in \mathbb{N}$ defines an extended difference between two time intervals. By differentiating (10) with respect to $u(k)$ and using the following estimation algorithm

$$\hat{\phi}(k) = \hat{\phi}(k-1) + \frac{\eta(\Delta y(k) - \hat{\phi}(k-1)\Delta u(k-1))\Delta u(k-1)}{\mu + |\Delta u(k-1)|^2}, \tag{12}$$

the control algorithm can be obtained as

$$\begin{aligned}u(k) = u(k-1) &+ \frac{\rho\hat{\phi}(k)e(k)}{\tau + (1+s_1+s_2)\|\hat{\phi}(k)\|^2}\\ &+ \frac{s_1\hat{\phi}(k)\Delta_N e(k+1)}{\tau + (1+s_1+s_2)\|\hat{\phi}(k)\|^2}\\ &+ \frac{s_2\hat{\phi}(k)[\Delta_N e(k+1) - \Delta_N e(k)]}{\tau + (1+s_1+s_2)\|\hat{\phi}(k)\|^2}.\end{aligned} \tag{13}$$

Assuming $N = 2$ and $y_d(k) = y_d = \text{const}$, the control algorithm (13) can be rearranged as

$$u(k) = u(k-1) + W_P(k)\Delta e(k) + W_I(k)e(k) + W_D(k)(\Delta e(k) - \Delta e(k-1)), \tag{14}$$

with

$$W_P(k) = \frac{s_1\hat{\phi}(k)}{\tau + (1+s_1+s_2)\|\hat{\phi}(k)\|^2},$$

$$W_I(k) = \frac{\rho\hat{\phi}(k)}{\tau + (1+s_1+s_2)\|\hat{\phi}(k)\|^2}, \text{ and}$$

$$W_D(k) = \frac{s_2\hat{\phi}(k)}{\tau + (1+s_1+s_2)\|\hat{\phi}(k)\|^2}.$$

Equation (14) represents the structure of multivariable type PID. In [10], [25], the stability of MFAC approaches is referenced.

D. Goal description

The goal of this paper is to exploit the flexibility of MFAC methodology to obtain a control algorithm similar to the one produced by MFAC-FFDL but with a simpler control structure (fewer control parameters to adjust). The case of PID structure is chosen due to its wide range of use although more extended control algorithms can be derived using MFAC-FFDL (introduced in [18]) and also by objective function manipulation for MFAC-CFDL.

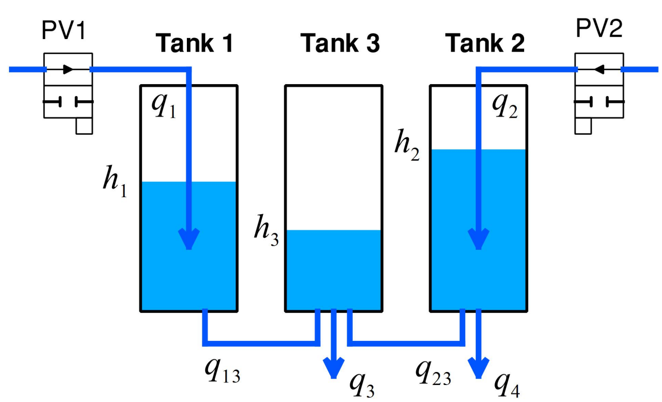

Fig. 1. Structure of MIMO 3TS

TABLE I

DEFINITION OF PARAMETERS OF THE 3TS.

Variables/parameters	Definitions	Range/Unit
h_1, h_2, h_3	Water level of tank 1, 2, 3	m
q_1, q_2	Input-flow of the tank 1, 2	$[0 \quad 3.5 \times 10^{-4}]$ m^3/s
q_3, q_4	Outlets from tank 3, 2	m^3/s
$q_{13},\ q_{23}$	Outflow from tank 1, 2 to tank 3	m^3/s
$az_{13},\ az_{23}$	Outflow coefficients of the pipes from tank 1, 2 to tank 3	$(0 \quad 1]$
$az_3,\ az_4$	Outlet coefficients of tank 3, 2	$(0 \quad 1]$
A_1, A_2, A_3	Cross sectional area of the tank 1, 2, and 3	m^2
$A_{13},\ A_{23}$	Cross sectional area of the outflow pipes from tank 1, 2 to tank 3	m^2
A_o	Cross sectional area of the outlet pipes from tank 2, 3	m^2
g	Gravitational acceleration	m/s^2

III. SIMULATION RESULTS

A. System description

The nonlinear MIMO system considered in this paper is a nonlinear 3TS with two inputs and two outputs. As it is shown in Fig. (1), the system constitutes three identical tanks with maximum liquid level of 60 [cm] and cross sections $A_i,\ i = 1, 2, 3$. Tank 3 in the middle has interconnections with tank 1 and tank 2 through pipes with cross sections A_{13} and A_{23}. Tank 2 and tank 3 are also provided with water-outflows q_4 and q_3 with cross section A_o. The pump delivers water from the reservoir to PV1 (proportional valve 1) and PV2 (proportional valve 2), which provides the input-flows q_1 and q_2 into tank 1 and tank 2, respectively. Water levels h_1 and h_2 are assigned as outputs. The dynamics of the MIMO 3TS system is formulated described by

$$\begin{aligned} A_1 \frac{dh_1(t)}{dt} &= q_1(t) - q_{13}(t), \\ A_2 \frac{dh_2(t)}{dt} &= q_2(t) - q_{23}(t) - q_4(t), \text{ and} \\ A_3 \frac{dh_3(t)}{dt} &= q_{13}(t) + q_{23}(t) - q_3(t), \end{aligned} \tag{15}$$

with

$$\begin{aligned} q_{13}(t) &= az_{13} \cdot A_{13} \cdot \mathrm{sgn}(h_1(t) - h_3(t)) \sqrt{2g|h_1(t) - h_3(t)|}, \\ q_{23}(t) &= az_{23} \cdot A_{23} \cdot \mathrm{sgn}(h_2(t) - h_3(t)) \sqrt{2g|h_2(t) - h_3(t)|}, \\ q_3(t) &= az_3 \cdot A_o \cdot \sqrt{2gh_3(t)}, \text{ and} \\ q_4(t) &= az_4 \cdot A_o \cdot \sqrt{2gh_2(t)}. \end{aligned}$$

In 15, $q_1(t)$ and $q_2(t)$ are the inputs while $h_1(t)$ and $h_2(t)$ are the outputs. The given parameters are also defined in Table I. It is worth emphasizing that there is no need for the mathematical representation of the system since model-free control methods operate solely based on I/O data. The model is used in a simulation to generate the required output derived by the input.

B. Evaluation metric

In addition to the number of design parameters, the performance of the controllers are also evaluated using the C-criterion index [26]. This metric takes into account both the error and the energy consumption by the controllers. It is a 2D illustration of mean squared error (MSE) on vertical and mean squared input (MSI) on horizontal axis

$$\text{MSE vs. MSI} = \left[\frac{1}{N_s} \sum_{k=1}^{N_s} e(k)^2 \ \ \frac{1}{N_s} \sum_{k=1}^{N_s} u(k)^2 \right]. \tag{16}$$

TABLE II

COMPARISON OF THE PARAMETERS TO BE TUNED

Controllers	Variables/parameters	Total
Discrete multivariable PID	$K_P \in \mathbb{R}^{n \times m}$ $K_I \in \mathbb{R}^{n \times m}$ $K_D \in \mathbb{R}^{n \times m}$	$3(n \times m)$
PIDsMFAC-FFDL $L_y = 2,\ L_u = 1$	$\hat{\Phi} \in \mathbb{R}^{m \times (2m+n)}$ $\varrho \in \mathbb{R}^{+3}$ $\lambda, \mu, \eta \in \mathbb{R}^+$	$m(2m+n)+6$
PIDsMFAC-CFDL $L_y = 0,\ L_u = 1$	$\hat{\phi} \in \mathbb{R}^{m \times n}$ $\rho, \tau, \mu, \eta, s_1, s_2 \in \mathbb{R}^+$	$(m \times n)+6$

C. Comparison results

A general principle within control systems and engineering design is that control algorithms with a larger number of tunable parameters may require more effort to fine-tune and maintain because there are more variables to adjust and optimize to achieve desired system performance. Table (II) gives information of the total number of parameters required for tuning purposes based on the number of input n and outputs m of a MIMO system. In Fig. (2), the complexity of the compared controllers in terms of their total number of parameters to be tuned is shown.

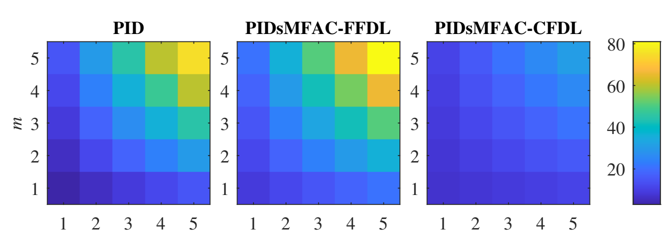

Fig. 2. Total number of control parameters to be tuned for a MIMO system

To compare the performance of the proposed controllers, the mathematical model of the MIMO 3TS with $m,\ n = 2$ is considered; according to Table (I), PIDsMFAC-FFDL and PIDsMFAC-CFDL need, respectively, 18 and 10 parameters to be selected. These parameters include the initial values $\hat{\Phi}(1)$ and $\hat{\phi}(1)$, design parameters η and μ for the estimation procedure of $\hat{\Phi}(k)$ and $\hat{\phi}(k)$, and the parameters directly manipulating the obtained control algorithms, such as ρ, ϱ, λ, τ, s_1, and s_2. The selected values of the given variables and parameters for performance comparison are

$$\begin{aligned}
&\hat{\Phi}(1) = \begin{bmatrix} 0.1 & 0.01 & 0.1 & 0.01 & 0.15 & 0.02 \\ 0.01 & 0.1 & 0.01 & 0.1 & 0.01 & 0.1 \end{bmatrix}, \\
&\hat{\phi}(1) = \begin{bmatrix} 0.15 & 0.02 \\ 0.01 & 0.1 \end{bmatrix}, \\
&\quad \varrho = \begin{bmatrix} 0.9 & 0.9 & 0.1 \end{bmatrix}, \\
&\quad \lambda = 0.1,\ \mu = 0.00001,\ \eta = 1 \\
&\quad \rho = 0.1,\ \tau = 7,\ s_1 = 7,\ \text{and}\ s_2 = 1
\end{aligned} \tag{17}$$

leading to the initial values

$$\begin{aligned}
M_P(1) &= \begin{bmatrix} 0.1076 & 0.0248 \\ 0.0142 & 0.0715 \end{bmatrix}, \\
M_I(1) &= \begin{bmatrix} 0.0590 & 0.0079 \\ 0.0039 & 0.0393 \end{bmatrix}, \\
M_D(1) &= \begin{bmatrix} -0.0538 & -0.0124 \\ -0.0071 & -0.0358 \end{bmatrix}, \\
W_P(1) &= \begin{bmatrix} 0.1252 & 0.0167 \\ 0.0083 & 0.0834 \end{bmatrix}, \\
W_I(1) &= \begin{bmatrix} 0.0018 & 0.0002 \\ 0.0001 & 0.0012 \end{bmatrix}, \ \text{and} \\
W_D(1) &= \begin{bmatrix} 0.0179 & 0.0024 \\ 0.0012 & 0.0119 \end{bmatrix}.
\end{aligned} \tag{18}$$

To obtain (17), different values are considered for ρ, ϱ, λ, τ, s_1, and s_2; these parameters are then combined in sets to generate a set of C-criterion data for each case. A subset of the obtained data-set is illustrated in Fig. (3) for both PIDsMFAC-FFDL and PIDsMFAC-FFDL using shaded areas; the values in (17) are members of this shaded areas. The controller performance on each tank is given as colored dots in Fig. (3). It can be seen from Fig. (3) that, firstly, the design parameters, which directly affect the control algorithm, are more for PIDsMFAC-CFDL (in comparison with PIDsMFAC-FFDL); this means more tuning flexibility toward the desired performance. Secondly, the pareto generated by PIDsMFAC-CFDL is closer to the origin of the C-criterion graph; in other words, PIDsMFAC-CFDL has the capability of performing better meaning lower error and lower energy if a specific set of parameters are selected.

Additionally, the tracking capabilities of PIDsMFAC-CFDL and PIDsMFAC-FFDL as well as their input flows are depicted in Fig. (4); therefore, by comparing the tracking performance of both controllers, it can be concluded that PIDsMFAC-CFDL delivers a smoother transient response toward the desired reference. This can also be confirmed by the graphs related to the input flows in Fig. (4), where

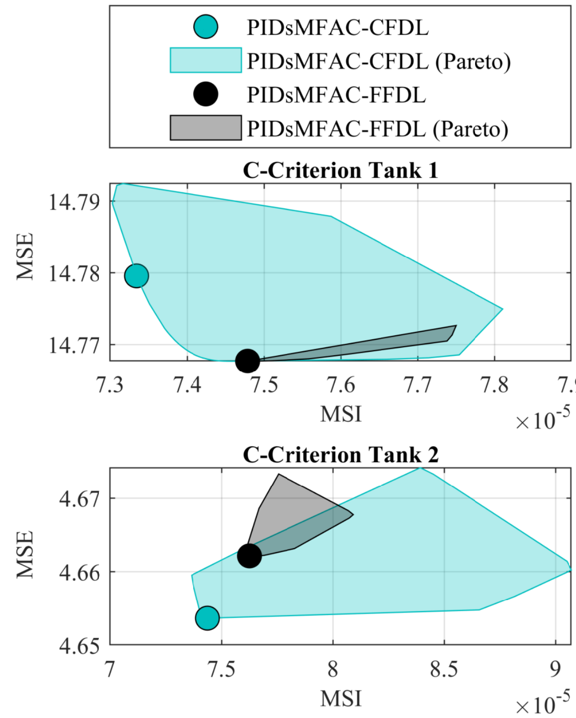

Fig. 3. Performance comparison of the applied controllers based on C-criterion metric

the PIDsMFAC-FFDL shows undesired oscillating behavior while tracking the reference.

IV. SUMMARY AND CONCLUSION

In this paper, the methodology of MFAC is used to derive and compare controllers which have the structure of the multivariable PID controller. The PIDsMFAC-FFDL is derived by manipulating the data model of the system while PIDsMFAC-CFDL –which is the novelty of this work– is obtained by modifying the control objective funtion. The comparison is conducted on the complexity of the derived controllers in terms of total number of parameters to be tuned as well as the performance of each controller in terms of the error and energy consumption. The results are obtained based on the implementation of PIDsMFAC-FFDL and PIDsMFAC-CFDL on the simulated MIMO non-linear model of a 3TS. The results demonstrate that the PIDsMFAC-CDFL can have in total less parameters and variables for adjustment which leads to a less complex control structure than PIDsMFAC-FFDL. Furthermore, the employed evaluation criterion confirms that for a specific set of parameters, PIDsMFAC-CFDL performs without oscillating behavior with less error and less energy in comparison to PIDsMFAC-FFDL.

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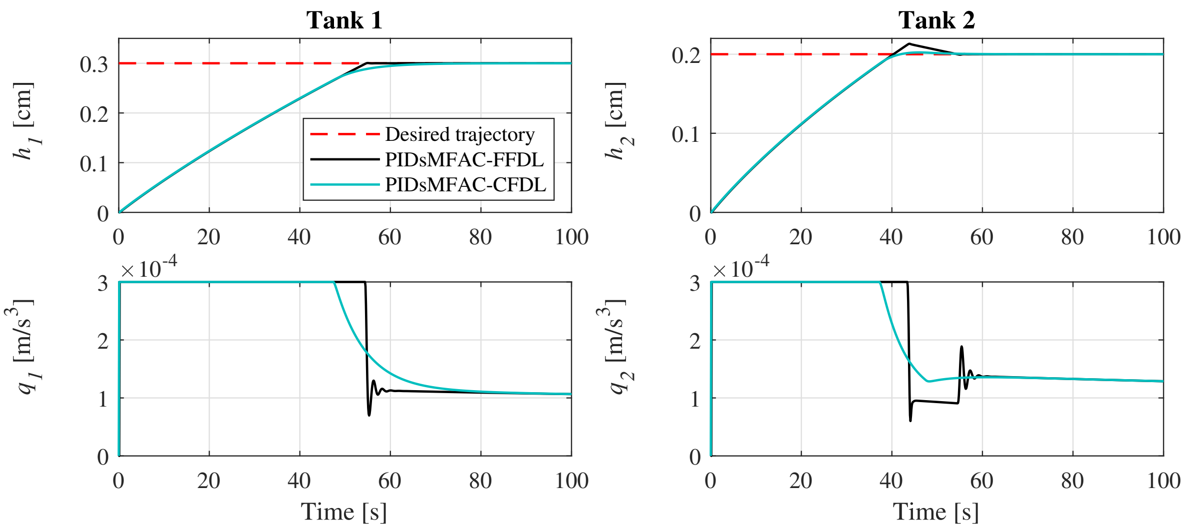

Fig. 4. Outputs and inputs of the applied controllers on the MIMO 3TS

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