Data-based Tuning of PI Controllers for Vertical Three-Tank Systems

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Abstract: This paper suggests the application of Iterative Feedback Tuning (IFT) as a data-based control technique to parameter tuning of PI controllers dedicated to vertical three-tank systems. The level control in the first two tanks is carried out using a multivariable control system structure which consists of two control loops, one for each level. The two PI controllers in these control loops are first tuned in terms of the Modulus Optimum method. New IFT algorithms are proposed in order to ensure the performance improvement of level control systems by means of six steps assisted by experiments. The experimental results show the strong performance improvement obtained after few iterations of IFT algorithms in terms of a model reference tracking optimization problem.

1 INTRODUCTION

Vertical three-tank systems are nonlinear Multi Input-Multi Output (MIMO) benchmarks which convincingly illustrate control design, fault detection and diagnosis problems. Some current approaches to the level control of vertical three-tank systems include fault diagnosis using sliding mode observers (Orani et al., 2010), fuzzy model-based predictive control (Ahmed et al., 2010), discrete-time model identification (Nikolić et al., 2010), sensitivity analysis of process models (Antić et al., 2011) and optimal tuning of PID controllers by nature-inspired algorithms (Kumar and Dhiman, 2011).

The improvement of control system performance indices (settling time, overshoot, etc.) for these nonlinear MIMO processes can be carried out by data-based tuning in terms of experiment-based solving of optimization problems. Iterative Feedback Tuning (IFT) (Hjalmarsson et al., 1994, 1998); (Hjalmarsson, 2002) is a popular data-based control technique which makes use of the input-output data measured from the closed-loop system during its operation to calculate the estimates of the gradients and eventually Hessians of the objective functions. Several experiments are conducted per iteration and the updated controller parameters are obtained on the basis of input-output data and estimates.

The efficiency of IFT applied to MIMO processes is proved in several applications (Hjalmarsson, 1998); (Sjöberg et al., 2003); (Huusom et al., 2009); (Rădac et al., 2009); (McDaid et al., 2010); (Precup et al., 2010); (Precup et al., 2012). This paper is built upon the IFT algorithms applied to tuning of PID controllers and PI-fuzzy controllers in level control problems for horizontal three-tank systems (Precup et al., 2010); (Precup et al., 2012). MIMO control systems which consist of two control loops for each level control are involved. The main contribution of this paper is represented by new IFT algorithms which ensure the performance improvement of PI control systems dedicated to the first two tanks. The two PI controllers are first tuned using simple process in terms of the Modulus Optimum (MO) method referred by Åström and Hägglund (1995). The six steps of the IFT algorithms are next applied making use of a unified formulation.

Our approach offers twofold advantages with respect to the state-of-the-art. First, a cost-effective systematic tuning approach for nonlinear MIMO processes is offered. Second, the experimental validation is carried out.

This paper is structured as follows. The problem setting concerning IFT applied to level control of vertical three-tank systems is presented in the next section. The nonlinear process models and the

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simplified process models used in the initial controller tuning are given in Section 3. The new IFT algorithms are presented in Section 4. The experimental results offered in Section 5 convincingly show the performance improvement. The conclusions are highlighted in Section 6.

2 PROBLEM SETTING

The process in vertical three-tank systems (Figure 1, derived from (Inteco, 2007)) consists of three tanks of different shapes located vertically (T1, T2 and T3), a fourth reflux tank (T4) placed under the lower tank, a variable speed pump driven by a DC motor that supplies the upper tank T1, and three electrical servo valves (SV1, SV2 and SV3) which determine the outflow from each tank. The three tanks are equipped with piezo-resistive pressure sensors PS1, PS2 and PS3 which measure the water levels H_1, H_2 and H_3, respectively.

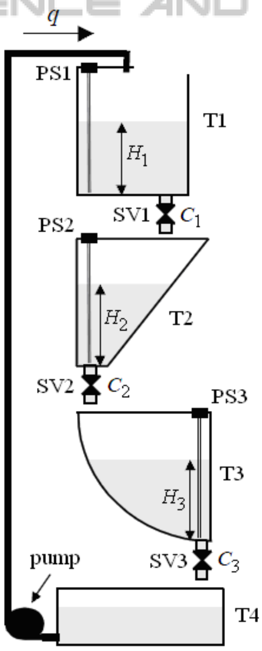

Figure 1: Structure of controlled process in vertical three-tank systems viewed as multi-tank systems according to (Inteco, 2007).

Several Single Input-Single Output (SISO) and MIMO control system structures can be considered as shown by Bigher (2011) on the basis of Figure 1 using different combinations of the four inputs q – the inflow to T1, C_1 – the resistance of the output orifice of T1, C_2 – the resistance of the output orifice of T2, and C_3 – the resistance of the output orifice of T3. This paper considers the MIMO control system dedicated to the levels H_1 and H_2 and organized in terms of Figure 2.

The typical control objectives concerning the control system structure presented in Figure 2 are to keep the desired liquid levels in the tanks T1 and T2, viz. H_1 and H_2, as specified by the two reference inputs r_1 and r_2, respectively, which belong to the reference input vector $\mathbf{r} = [r_1 \quad r_2]^T$ (T stands for matrix transposition) and carry out the rejection of two possible disturbances (gathered in the disturbance input vector **d**) represented by C_2 and/or C_3. These disturbances usually model sudden demands of water from the downstream water distribution networks. The control system structure given in Figure 2 assumes that the level in the tank T3, H_3, is a response which is uncontrollable, and that the pressure sensors PS1, PS2 and PS3 are included in the process dynamics (P).

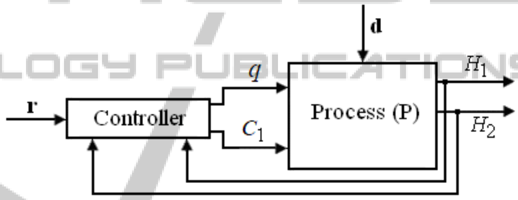

Figure 2: Structure of MIMO control system.

As suggested by Precup et al. (2010), a simple control system structure that can fulfil these control objectives is presented in Figure 3. Figure 3 points out a MIMO control system structure with two control loops dedicated to the separate control of H_1 and H_2, where, $e_1 = r_1 - H_1$ and $e_2 = r_2 - H_2$ are the control errors, $C_1(s)$ and $C_2(s)$ are the SISO controllers which build the MIMO controller emphasized in Figure 2, and the two control signals (in relation with Figure 2) are:

$$u_1 = q,\ u_2 = C_1 . \qquad (1)$$

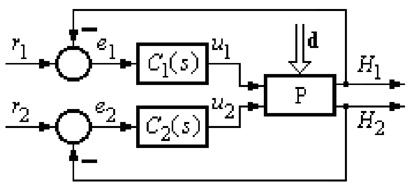

Figure 3: Structure of two control loops in MIMO control system.

The separate control of H_1 and H_2 by means of the control system structure presented in Figure 3 is justified as:

- There is no need for decoupling controllers because it is considered that the two channels (which correspond to H_1 and H_2) represent additional disturbances and included in **d**. Controllers with integral components solve the disturbance rejection and thus the decoupling.
- It is very convenient to design and tune separately the controllers with the transfer functions $C_1(s)$ and $C_2(s)$.

IFT will be used in the sequel to tune the parameters of the controllers with the transfer functions $C_1(s)$ and $C_2(s)$ by two IFT algorithms. Accepting, for simplicity, the control system structure for one of the two controllers, the structure of this IFT-based control system is illustrated in Figure 4, where: r – the reference input (r_1 or r_2), d – the disturbance input (an element of **d**), e – the control error (e_1 or e_2), u – the control signal (u_1 or u_2), $\boldsymbol{\rho}$ – the parameter vector containing the controller parameters, $C(\boldsymbol{\rho})$ – the controller transfer function ($C_1(s)$ or $C_2(s)$, and the argument s is omitted to simplify the presentation), F – the reference model transfer function, P – the process transfer function, y – the controlled output (H_1 or H_2), y_d – the desired output (of reference model), and $\delta y = y - y_d$ – the tracking error.

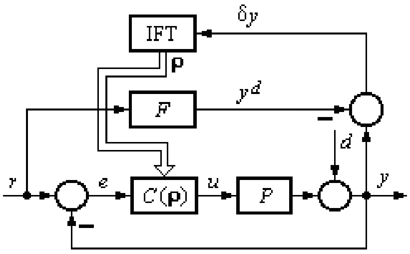

Figure 4: IFT-based control system structure for one control loop.

The model reference tracking optimization problem, numerically solved in an experiment-based iterative way by IFT algorithms, is defined as

$$\boldsymbol{\rho}^* = \arg\min_{\boldsymbol{\rho} \in D_{\boldsymbol{\rho}}} J(\boldsymbol{\rho}), \tag{2}$$

where $J(\boldsymbol{\rho})$ is the objective function:

$$J(\boldsymbol{\rho}) = (0.5/N)\sum_{k=1}^{N}[\delta y(k,\boldsymbol{\rho})]^2, \tag{3}$$

N is the number of samples, i.e., the length of an experiment conducted in the framework of IFT algorithms, $\boldsymbol{\rho}^*$ is the optimal parameter vector produced by IFT algorithms, and $D_{\boldsymbol{\rho}}$ is the feasible domain for $\boldsymbol{\rho}$ which accounts for several constraints including stability ones (Hjalmarsson, 2002); (Sjöberg et al., 2003); (Huusom et al., 2009); (Rădac et al., 2011).

3 PROCESS MODELS

The mass-balance equations lead to the following first principle state-space equations of the process (Inteco, 2007):

$$\begin{aligned} \dot{H}_1 &= q/\beta_1(H_1) - C_1 H_1^{\alpha_1}/\beta_1(H_1), \\ \dot{H}_2 &= C_1 H_1^{\alpha_1}/\beta_2(H_2) - C_2 H_2^{\alpha_{12}}/\beta_2(H_2), \\ \dot{H}_3 &= C_2 H_2^{\alpha_2}/\beta_3(H_3) - C_3 H_3^{\alpha_3}/\beta_3(H_3), \end{aligned} \tag{4}$$

where α_l, $l \in \{1,2,3\}$, is the flow coefficient of i^{th} tank, and $\beta_l(H_l)$, $l \in \{1,2,3\}$, is the cross sectional area of i^{th} tank at the level H_i:

$$\begin{aligned} &\beta_1(H_1) = a\,w,\ \ \beta_2(H_2) = c\,w + H_2/H_{2\max}, \\ &\beta_3(H_3) = \sqrt{R^2 - (R - H_3)^2}, \end{aligned} \tag{5}$$

and the geometrical parameters in (5) depend on the shapes of the three tanks (Inteco, 2007).

Since the nonlinear state-space equations (4) are complicated to use in the design, the least-squares identification is applied to obtain the parameters of the following transfer functions of the simplified models which correspond to the processes in the two control loops in Figure 3 (Bigher, 2011):

$$\begin{aligned} &P_1(s) = H_1(s)/q(s) \\ &= k_{P1}/[(1+T_{\Sigma 1}s)(1+T_1 s)],\ T_{\Sigma 1} << T_1, \\ &P_2(s) = H_2(s)/C_1(s) \\ &= k_{P2}/[(1+T_{\Sigma 2}s)(1+T_2 s)],\ T_{\Sigma 2} << T_2, \end{aligned} \tag{6}$$

where: k_{P1}, k_{P2} – the process gains, $T_{\Sigma 1}, T_{\Sigma 2}$ – the small time constants, and T_1, T_2 – the large time constants. As shown in (Åström and Hägglund, 1995), PI controllers can offer good control system performance indices for processes characterized by the transfer functions $P_1(s)$ and $P_2(s)$. The transfer functions of the two continuous-time PI controllers are:

$$C_j(s) = k_{c\,j}(1 + T_{c\,j}s)/s,\ j \in \{1,2\}, \tag{7}$$

where $k_{c\,j}$ is the controller gain and $T_{c\,j}$ is the integral time constant, $j \in \{1,2\}$.

The performance of the two control system with these two PI controllers is improved by two IFT algorithms presented in the next section. The improvement involves the iterative data-based solving of the optimization problem (2).

4 IFT ALGORITHMS

The two IFT algorithms applied to tune the parameters of the two PI controllers in the control system structure given in Figure 3 are expressed in terms of the following unified steps, with the steps 2 to 6 repeated at each iteration:

- Step 1. The MO method is applied to tune the parameters of the initial PI controllers with the transfer functions given in (7). The tuning equations of the two PI controllers are:

$$k_{c\,j} = 1/(2k_{P\,j}T_{\Sigma\,j}),\ T_{c\,j} = T_j,\ \ j \in \{1,2\}. \tag{8}$$

The sampling period T_s is set and the continuous-time PI controllers are discretized to obtain the transfer functions of the two discrete-time PI controllers:

$$C_j(z^{-1}) = (\rho^i_{1\,j} + \rho^i_{2\,j} z^{-1})/(1 - z^{-1}),\quad j \in \{1,2\}, \tag{9}$$

where the superscript i stands for the iteration index, $i = 0$ at step 1, and the parameter vectors of the two controllers are

$$\boldsymbol{\rho}^i = [\rho^i_{1\,j} \quad \rho^i_{2\,j}]^T,\ \ j \in \{1,2\}. \tag{10}$$

The reference models for the two control loops are obtained by discretizing the continuous-time reference model with the transfer function

$$F(s) = \omega_0^2/(s^2 + 2\varsigma\omega_0 s + \omega_0^2), \tag{11}$$

where the damping ratio ς and the natural resonant frequency ω_0 are set such that to fulfil the performance specifications imposed to the MIMO control system.

- Step 2. A first experiment, referred to as the normal experiment, is conducted with the reference input vector **r** applied to the control system, and the controlled outputs $y_1(\boldsymbol{\rho}^i)$ are recorded for each level. The tracking error is calculated as $\delta y(k,\boldsymbol{\rho}^i) = y^1(k,\boldsymbol{\rho}^i) - y_d(k)$, where the superscript 1 indicates this first experiment.
- Step 3. A second experiment, referred to as the gradient experiment, is conducted with the output vector from the first experiment applied to the control system as reference input, and the controlled outputs $y^2(\boldsymbol{\rho}^i)$ are recorded for each level, where the superscript 2 indicates this second experiment.
- Step 4. The estimate of the gradient of δy is calculated in terms of:

$$\begin{aligned} est\left[\frac{\partial \delta y}{\partial \boldsymbol{\rho}}(k,\boldsymbol{\rho}^i)\right] &= \frac{1}{C_j(q^{-1},\boldsymbol{\rho}^i)} \\ &\cdot \frac{\partial C_j}{\partial \boldsymbol{\rho}}(q^{-1},\boldsymbol{\rho}^i)[y^1(k,\boldsymbol{\rho}^i) - y^2(k,\boldsymbol{\rho}^i)] \\ &= \begin{bmatrix} 1/(\rho^i_{1\,j} + \rho^i_{2\,j}q^{-1}) \\ q^{-1}(\rho^i_{1\,j} + \rho^i_{2\,j}q^{-1}) \end{bmatrix}[y^1(k,\boldsymbol{\rho}^i) \\ &- y^2(k,\boldsymbol{\rho}^i)], \end{aligned} \tag{12}$$

where q^{-1} is the backward shift operator.

- Step 5. The gradient of the objective function is calculated using (12) and

$$\begin{aligned} &est\left[\frac{\partial J}{\partial \boldsymbol{\rho}}(\boldsymbol{\rho}^i)\right] \\ &= (1/N)\sum_{k=1}^{N}\left\{\delta y(k,\boldsymbol{\rho}^i) est\left[\frac{\partial \delta y}{\partial \boldsymbol{\rho}}(k,\boldsymbol{\rho}^i)\right]\right\}. \end{aligned} \tag{13}$$

- Step 6. The next set of parameters $\boldsymbol{\rho}^{i+1}$ is calculated according to the update law

$$\boldsymbol{\rho}^{i+1} = \boldsymbol{\rho}^i - \gamma_i \mathbf{R}_i^{-1} est\left[\frac{\partial J}{\partial \boldsymbol{\rho}}(\boldsymbol{\rho}^i)\right], \tag{14}$$

where $\gamma_i > 0$ is the step size, and the positive definite regular matrix $\mathbf{R}_i$ is typically a Gauss-Newton approximation of the Hessian of J or the identity matrix in the simplest case. The identity matrix corresponding to the steepest descent method is set in these two IFT algorithms.

The IFT algorithms are stopped after observing a sufficient decrease of the objective function. A trade-off to the number of experiments and to the performance improvement should be ensured.

The convergence of the IFT algorithms is ensured if the following step sizes are employed (Hjalmarsson, 2002; Huusom et al., 2009):

$$\sum_{i=0}^{\infty}\gamma_i = \infty,\ \sum_{i=0}^{\infty}\gamma_i^2 < \infty, \tag{15}$$

and a convenient choice for the step size sequence is (Rădac et al., 2011):

$$\gamma_i = \frac{\gamma_0}{i^{\alpha}},\ i \in \mathbf{N},\ i \geq 1,\ 0.5 < \alpha \leq 1, \tag{16}$$

where the initial step size $\gamma_0 > 0$ is set such that to ensure a compromise to the numerical stability and to the convergence speed. In the situation where the noise affects the measurements, a third normal experiment should be performed in order to obtain an unbiased estimate of the gradient of the objective function.

5 EXPERIMENTAL RESULTS

The two IFT algorithms expressed in the unified given in the previous section are applied to tune the parameters of the PI controllers of the INTECO multi-tank system laboratory equipment (Inteco, 2007). The values of the parameters of the simplified process models (6) are (Bigher, 2011): $k_{P1} = 0.83$, $k_{P2} = 0.5$, $T_{\Sigma 1} = 2\,\text{s}$, $T_{\Sigma 2} = 5\,\text{s}$, $T_1 = T_2 = 50\,\text{s}$. The main results related to the application of the IFT algorithms are presented as follows.

The reference model (11) with the parameters $\varsigma = 0.9$ and $\omega_0 = 0.2292\,\text{s}^{-1}$ is set for the IFT algorithm dedicated to H_1, and $\varsigma = 1$ and $\omega_0 = 0.1719\,\text{s}^{-1}$ for the IFT algorithm dedicated to H_2. The reference models are chosen to be similar to the initial closed loop response in order to ensure the convexity of the cost function (Bazanella et al., 2008). Several intermediate reference models can be chosen before arriving at the final design, known as the windsurfing approach (Hjalmarsson 2002). The step size sequence (16) with $\alpha = 1$ and $\gamma_0 = 100$ is introduced in the update law (14) of the IFT algorithm dedicated to H_1, and $\alpha = 1$ and $\gamma_0 = 50$ for the IFT algorithm dedicated to H_2. From the application point of view, the typical IFT gradient experimental setup in which the control error from the normal experiment is injected as reference can not be used here. Instead, the output from the normal experiment is used as a reference input since it is just a filtered version of the reference from the normal experiment and therefore it brings the closed loop in the vicinity of the original trajectory. This setup is also possible because the closed-loop system has no resonant modes which could amplify the corresponding frequencies.

The application of MO tuning equations (8), setting the sampling period $T_s = 1\,\text{s}$ and the application of Tustin's discretization method lead to the following initial values of the parameters of the discrete-time PI controllers:

$$\begin{aligned} &\rho_{11}^0 = 15.15,\ \rho_{21}^0 = -14.85, \\ &\rho_{12}^0 = 10.1,\ \rho_{22}^0 = -9.9. \end{aligned} \quad (17)$$

The parameters of the discrete-time PI controllers after nine iterations of the IFT algorithm dedicated to H_1 and five iterations of the IFT algorithm dedicated to H_2 are:

$$\begin{aligned} &\rho_{11}^9 = 15.1758,\ \rho_{21}^9 = -14.8256, \\ &\rho_{12}^5 = 10.1489,\ \rho_{22}^5 = -9.8534. \end{aligned} \quad (18)$$

The evolution of the objective function corresponding to H_1 is illustrated in Figure 5.

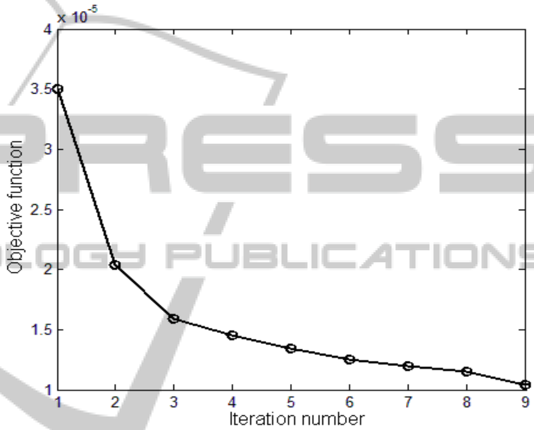

Figure 5: Objective function versus iteration number for control loop controlling H_1.

The experimental results concerning the behaviour of the control loop for H_1 before and after the application of the IFT algorithm are presented in Figure 6 and in Figure 7 in terms of level responses and of control signal responses, respectively.

The evolution of the objective function corresponding to H_2 is illustrated in Figure 8. The experimental results concerning the behaviour of the control loop for H_2 before and after the application of the IFT algorithm are presented in Figure 9 and in Figure 10 in terms of level responses and of control signal responses, respectively. The zeros of the two controllers are shifted as follows (in the corresponding s-domain): from $s = -0.02$ to $s = -0.0233$ for C_1 (this means the corresponding time constant decreases from $T = 50\,\text{s}$ to $T = 42.8\,\text{s}$) and from $s = -0.02$ to $s = -0.0295$ for C2 (this means the corresponding time constant decreases from $T = 50\,\text{s}$ to $T = 33.84\,\text{s}$). The achieved performance is the best one with respect to the current controller parameterization which is a simple one.

Even if the change in the control signal is not remarkable after IFT, the effect is visible in the modification of the outputs and the random effects induced by the pump/sensors dynamic characteristics, and noise can be excluded because the objective function decreases smoothly but significantly.

These results illustrate the performance improvement ensured by the IFT algorithms suggested in this paper. However different conclusions can be drawn for other processes as those treated in (Petres et al., 2007); (Giua and Seatzu, 2008); (Blažič et al., 2009); (Ferreira and Ruano, 2009); (Iglesias et al., 2010); (Tar et al., 2009); (Johanyák, 2010); (Vaščák and Madarász, 2010); (Kasabov and Hamed, 2011); (Leva and Maggio, 2011); (Linda and Manic, 2011).

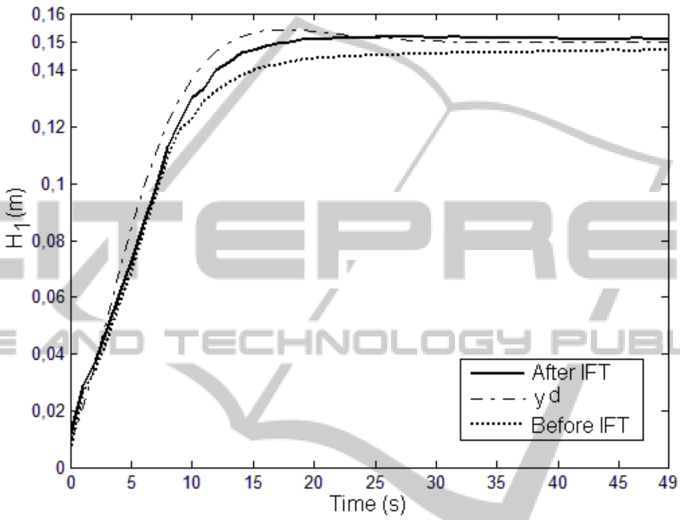

Figure 6: Experimental results expressed as level H_1 versus time before and after IFT algorithm.

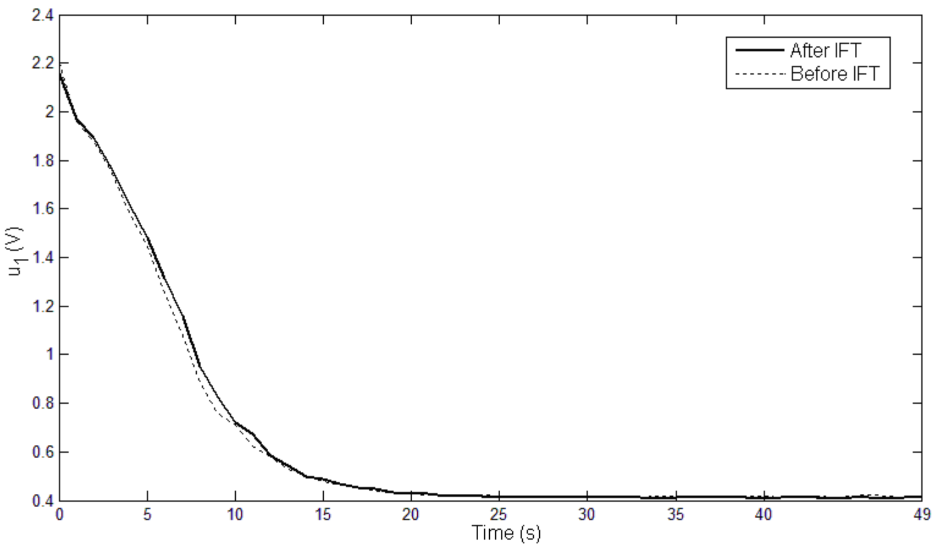

Figure 7: Experimental results expressed as control signal u_1 versus time before and after IFT algorithm.

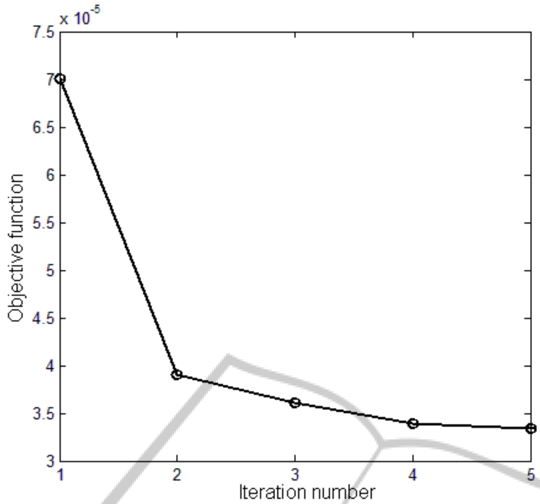

Figure 8: Objective function versus iteration number for control loop controlling H_2.

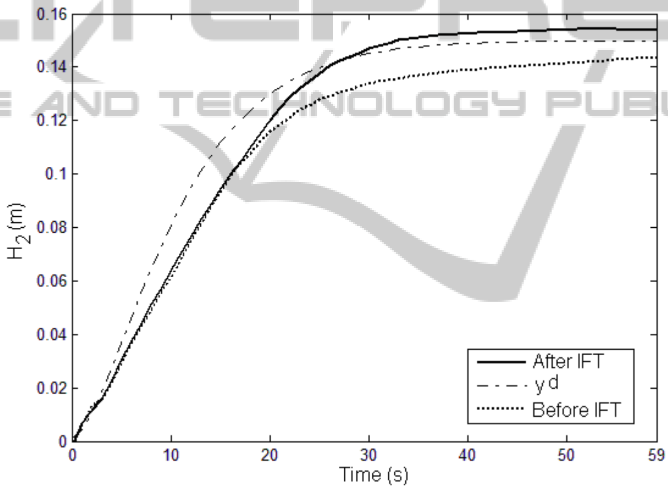

Figure 9: Experimental results expressed as level H_2 versus time before and after IFT algorithm.

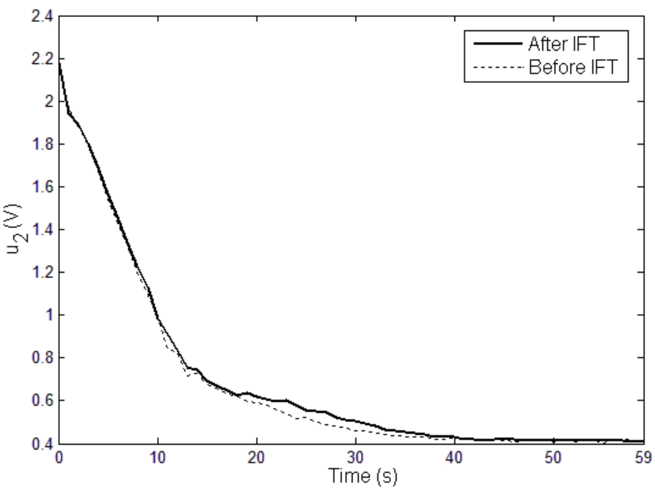

Figure 10: Experimental results expressed as control signal u_2 versus time before and after IFT algorithm.

6 CONCLUSIONS

This paper has suggested new IFT algorithms meant for parameter tuning of PI controllers dedicated to the level control of the first two tanks in vertical three-tank systems. A complete data-based experiment-based approach is proposed with this regard.

The experimental results show that the six steps of our IFT algorithms ensure the performance improvement of a representative nonlinear MIMO benchmark process. An improved model reference tracking is observed after few iterations of IFT algorithms. The control system structure presented in this paper does not employ an adaptive model reference approach.

The results concerning the control system behaviour with respect to modifications of disturbance inputs have not been presented. The integral components of PI controllers ensure the disturbance rejection.

One limitation of this data-based technique is the need for initial PI stabilizing controllers tuned by a model-based approach represented, for example, by the MO method. The integral components of PI controllers cope with the cross-couplings specific to MIMO systems. However, different organizations of the experiments specific to MIMO systems can be applied in this context in order to ensure further control system performance improvement (Sjöberg et al., 2003; Huusom et al., 2009; Rădac et al., 2009; McDaid et al., 2010; Precup et al., 2010).

Future research will be focused on other data-based tuning techniques applied to nonlinear MIMO systems and on comparison of the performance of similar tuning techniques. Special gradient experiments for MIMO systems should be constructed with this regard in order to fit the normal operating regimes of control systems.

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