Level Process Control with Different Tank Configurations: *Hardware-in-the-Loop Technique*

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Level Process Control with Different Tank Configurations: *Hardware-in-the-Loop Technique*

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Abstract. This article presents a virtual laboratory of industrial processes focused on level variable, where non-linear MIMO advanced control algorithms are implemented based on the determined mathematical model, using Hardware-in-the-Loop simulation technique. An immersive and interactive virtual environment is presented in the Unity 3D graphic engine, where different tank configurations are shown for the monitoring, visualization and control of the process control states, which consequently brings the user closer to the industrial field in a dynamic approach, in addition, virtual reality is used as a tool for facilitating the teaching and learning about control. Thus, a low-cost solution is provided to evaluate control algorithms; in addition, simulation results for each controller are included, as well as the stability and robustness analysis of the system. Hardware-in-the-Loop technique and virtual environment allow to observe the behavior of control errors in a level process, finally it is determined that advanced controllers provide greater efficiency than conventional control techniques.

Key words: Hardware-in-the-Loop, Advanced Control, Virtual Environment, Level Control, Nonlinear MIMO.

1 Introduction

Control systems are found in the food and chemical process industry, in satellite technology, military, in extreme machinery and in domestic application technology. These systems have achieved a high level of sophistication through electronics, computing and signal transmission systems [1]. The most frequently controlled variables in industry are: flow, pressure, temperature and level. Level control is considered as an essential and highly utilized process in industrial processes. It has a large number of parameters that are necessary for its control and representation, which encourages researchers to develop improvements to the system and create new studies [2]. For example, Bieda, Blachuta & Grygiel [3] present three cascaded tank configurations, used as tools for teaching the implementation of controllers, however it allows the design, evaluation and comparison of different controllers.

It has been possible to automate and control processes through different control algorithms both classical and advanced, some of the most commonly used classical control techniques are PI, PD and PID controllers. A great benefit of the PID controller is its ease of design and application [4]. There are complex nonlinear and multiple input/output processes in industries that cannot be optimally controlled by classical control algorithms, something that was solved by advanced control techniques [5]. Some of these techniques are: Fuzzy Control, Based on Numerical Methods Control and Model Based Predictive Control (MPC). The MPC control is one of the most successful advanced control algorithms, given the strategy control action is found by an optimization criterion evaluated in a future time interval [6].

Using Hardware-in-the-Loop technique reduces costs and risky situations, since it is based in an interactive simulation and it is experienced with a process or controller running on a digital platform that interacts with the controller or real process. [7,8]. One of the main benefits of this technique is the cost reduction, furthermore, it decreases the percentage of accident or injury risk that may occur in a real system [9]. Virtual reality is usually defined as a group of technologies that allow to experience a world beyond reality in an immersive form [10]. Through virtual reality, the aim is to transfer skills and knowledge, as well as to raise the presence and the level of realism to the maximum [11]. Consequently, physical and virtual reality have increasingly merged [12]. In a study accomplished by Berg & Vance [10], a survey was applied to 18 companies that use virtual reality, to evaluate the state of the art in this field, the results showed that it works, it is stable and moreover useful. A virtual environment can provide a space for the user to explore problems and test solutions without any risk [11]. In the surveys performed by Berg & Vance [10], it was determined that several of the large US companies have opted in virtual reality as a training method for operators, since it allows experimentation and exploration in environments that in real life could be dangerous.

In the present research, advanced controllers MPC and based on Numerical Methods are implemented for level control in different tank configurations, the process will be simulated using Hardware-in-the-Loop technique and animated through a 3D virtual environment, which allows to evaluate the operation of the controllers.

The article consists of six sections, including the introduction, the description of the system in section two, then mathematical model obtaining of each tank configuration is presented in section three, the designs of the non-linear MIMO algorithms control are presented in section four; MPC and Numerical Methods based control, the development of a virtual environment in the Unity 3D graphics engine is detailed in the fifth section, while the analysis and results are shown in the sixth section, finally the conclusions are presented.

2 System Description

Evaluating control algorithms using physical prototypes represents a high cost, in addition, it is subjected to failures and risks in certain conditions, Hardware-in-the-Loop real-time simulation technique is frequently used in execution of laboratory tests that can be of control equipment, as well as of power, among others [13]. The HIL technique reduces costs and risks in the evaluation of controllers, bringing the variable to test conditions that cannot be executed in physical prototypes. In order to develop the behavior of the level process, the system of Figure 1 is implemented.

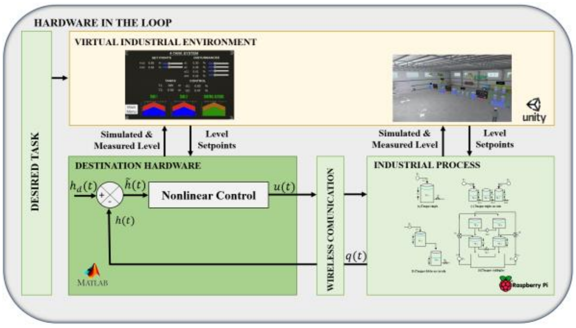

Fig. 1. Control Scheme.

The proposed scheme can be subdivided into three main stages: *i) Destination hardware:* Nonlinear MIMO advanced control algorithms are designed based on the mathematical model of each level tank configuration using MATLAB software; *ii) Mathematical model*: The mathematical modeling of each tank configuration is considered separately, which is expressed in mathematical equations that determine their dynamic behavior, each mathematical model is implemented in a Raspberry Pi card; *iii) Virtual Industrial Environment:* This module incorporates the design of an immersive and interactive virtual environment for the visualization, monitoring and control of the process, taking into account the fundamental parameters to implement a virtual laboratory of industrial processes in the Unity 3D graphic engine.

3 Virtual Environment

The use of Unity 3D graphics engine has been extended to engineering and control applications, in which industrial environments are simulated with a high level of realism through animations, sounds, lighting, etc., as the Figure 2 shows. This section explains in detail the development of the virtual environment (see Fig. 3), where the scenario of a virtual laboratory identical to the real operations of the process is recreated, four tank configurations are presented, which the user can interact with in order to visualize, monitor and control level process variables.

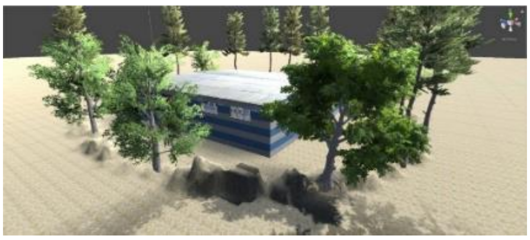

Fig. 2. Exterior view of Virtual Laboratory of level processes.

The level tank stations of the virtual environment are designed with the interaction of some programs focused on the design of industrial structures in 3D.

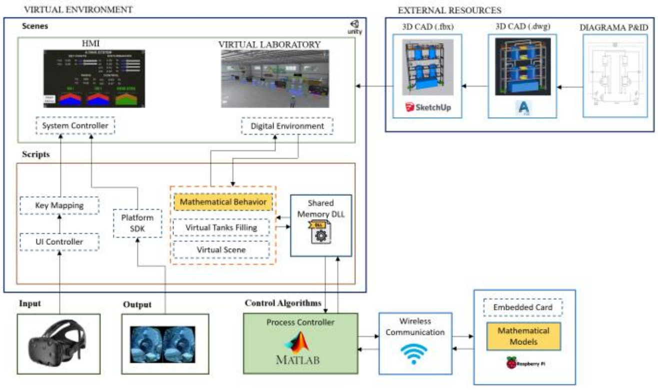

Fig. 3. Detailed description of the virtual environment.

Structures of the system are designed through Autocad Plant 3D software where all the components must be taken into account in the design of the structures are identified. The elements designed in the Plant 3D software contain a .dwg extension, therefore they are imported into SketchUp software in order to export in the .fbx format to be supported by Unity 3D. Figure 4 shows the level tank configurations in 3D.

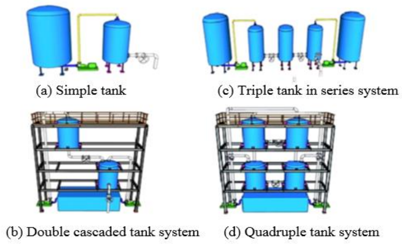

Fig. 4. Designed structures en Autocad Plant 3D.

The level tank configurations were designed in different software, in order to represent the same attributes that an industrial process possesses in real life, which are imported to the Unity 3D graphics engine.

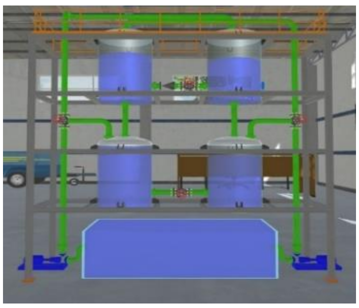

Fig. 5. Quadruple tanks by 3D Unity.

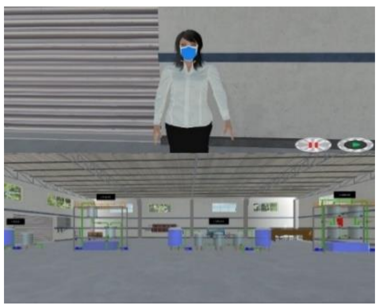

Fig. 6. Virtual environment by 3D Unity

Figure 6 shows the internal part of the virtual process laboratory, where a virtual assistant is presented to increase the degree of immersion in the virtual environment, which provides the user information about the parameters that can be modified in each configuration of the level tanks while simulation is running.

Through the use of scripts, particular characteristics are programmed, actions are executed and properties of the elements are modified in order to develop animations of the tanks that imitate the behavior of a real system, including risk test situations such as spills (see Fig. 7), this facilitates the understanding of the user about the operation of controllers for coupled tanks, providing an experience close to an industrial environment.

Fig. 7. Spill simulation.

Figure 8 shows the HMI interface, where it is possible to interact with the values of the Set Points and disturbance valves, the value of the tanks and the control actions are displayed.

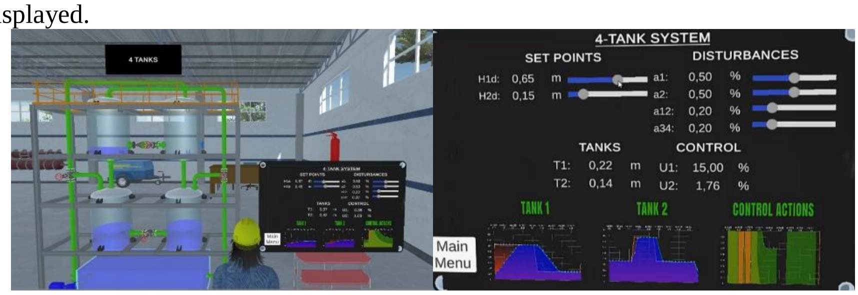

Fig. 8. HMI Interface.

4 Mathematical Modelling

This section presents the mathematical modeling of four tank configurations in order to represent the dynamic behavior of the level processes in virtual human-user environment. The mathematical model is determined based on the input being the signal of the control variable entered by the final control elements (pumps, valves, etc.) and based on the output being the signal of the process variable which is generated by the level sensors located in the process tanks. Tank configurations are indicated in Figure 9:

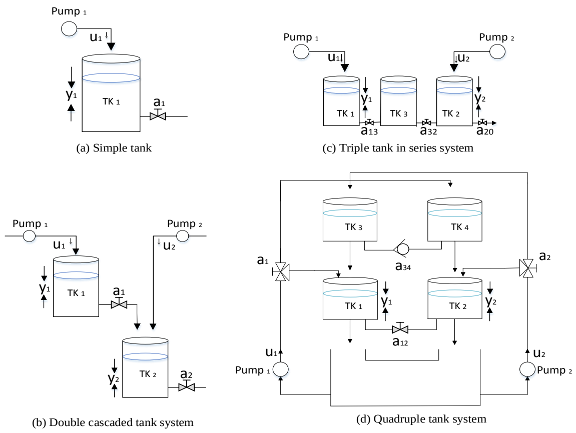

Fig. 9. Tanks configurations.

Next, the quadruple tank modeling procedure is explained, Figure 9. (d), where the purpose is to control the level of the lower tanks (y_1 , y_2) while manipulating the voltage of the pumps (u_1, u_2). Physical laws and theorems used are described below:

In order to find the equations of the mathematical model, the mass balance equation is applied, which establishes:

$$\left(Mass\ accumulation\ rate\right) = \left(mass\ \ flux\ in\right) - \left(mass\ \ flux\ out\right) + \left(net\ rate\ of\ \ chemical\ \ production\right) \quad (1)$$

Given that there isn't any chemical production, only mass flux in and out are considered. According to the volumetric flow law, which states:

$$Q = \frac{V}{t} = \frac{Ay}{t} \quad (2)$$

$$A_j \frac{dy_j}{dt} = qi_j - qo_j ;\ j = 1,2,3,4 \quad (3)$$

where, Q is the fluid flow, V is the tank volume, t is the time, A is the tank area, y is the tank level, q_i is the mass flux in, while q_o is the mass flux out.

Bernoulli's theorem establishes:

$$P_1 + \rho g y_1 + \frac{1}{2}\rho V_1^{\ 2} = P_2 + \rho g y_2 + \frac{1}{2}\rho V_2^{\ 2} \quad (4)$$

while Torriceli's principle, being a derivation of Bernoulli's theorem, describes the relation between the liquid coming out of a hole and the liquid's height in a tank, Figure 9. (a), thus it states that:

$$V = \sqrt{2gy} \tag{5}$$

with P being the fluid pressure, ρ being the fluid density, g being the gravity acceleration, and V being the fluid velocity.

The mass balance equations obtained from (3) are:

$$\begin{cases} A_1 \dfrac{dy_1}{dt} = a_1 k_1 \mu_1 + S_3 \sqrt{2gy_3} - S_1 \sqrt{2gy_1} - sgn\left(y_1 - y_2\right) a_{12} k_{12} \sqrt{2g\left(y_1 - y_2\right)} \\ A_2 \dfrac{dy_2}{dt} = a_2 k_2 \mu_2 + S_4 \sqrt{2gy_4} + sgn\left(y_1 - y_2\right) a_{12} k_{12} \sqrt{2g\left(y_1 - y_2\right)} - S_2 \sqrt{2gy_2} \\ A_3 \dfrac{dy_3}{dt} = \left(1 - a_2\right) k_2 \mu_2 - S_3 \sqrt{2gy_3} + a_{34} k_{34} \sqrt{2g\left(y_4 - y_3\right)} \\ A_4 \dfrac{dy_4}{dt} = \left(1 - a_1\right) k_1 \mu_1 - S_4 \sqrt{2gy_4} - a_{34} k_{34} \sqrt{2g\left(y_4 - y_3\right)} \end{cases} \tag{6}$$

where the function $sgn(.)$ defines the sign of the subtraction of the tank's levels values, which determines the fluid direction, a_j is the valve opening; k_j is friction constant; u_j is voltage of the pump; s_j is pipe cross section.

From the same methodology, the mathematical models belonging to the configurations (a), (b) and (c) of Figure 9 are determined, defined by equations (7), (8) and (9) respectively:

$$A_1 \frac{dy_1}{dt} = u_1 - a_1 k_1 \sqrt{2gy_1} \tag{7}$$

$$\begin{cases} A_1 \dfrac{dy_1}{dt} = u_1 - s_1 \sqrt{2gy_1} \\ A_2 \dfrac{dy_2}{dt} = s_1 \sqrt{2gy_1} - a_1 k_1 \sqrt{2gy_2} \end{cases} \tag{8}$$

$$\begin{cases} A_1 \dfrac{dy_1}{dt} = u_1 - a_{13} k_{13} \sqrt{2g \mid y_1 - y_3 \mid} \\ A_2 \dfrac{dy_2}{dt} = u_2 + a_{32} k_{32} \sqrt{2g \mid y_3 - y_2 \mid} - a_{20} k_{20} \sqrt{2gy_2} \\ A_3 \dfrac{dy_3}{dt} = a_{13} k_{13} \sqrt{2g \mid y_1 - y_3 \mid} - a_{32} k_{32} \sqrt{2g \mid y_3 - y_2 \mid} \end{cases} \tag{9}$$

5 Control Algorithms

5.1 Model Based Predictive Control

The MPC control uses a cost function that predicts the future behavior of the system in a certain time horizon, called prediction horizon and a function that represents the restriction of the system. Prediction horizon N is defined, in which the future values of the outputs are predicted for each instant t .

$$C(N_1, N_2, N_n) = \sum_{k=N_1}^{N_2} \delta_1(k)\left[\tilde{y}\left(t+k|t\right) - w\left(t+k\right)\right]^2 + \sum_{k=1}^{N_n} \delta_2\left(k\right)\left[\Delta u\left(t+k-1\right)\right]^2$$

The prediction model represents the behavior of the pumps voltage to be controlled, which only depend on two parameters; the values reached up to time t and future control signals [14]. Tanks level predicted: $\tilde{y}(t+k\,|\,t)$ for k=1,2,3, … N depends on the values of the inputs and outputs up to t and the control action $u\left(t+k\,|\,t\right)$, $k = 0,1,2,3,...\,N-1$ where, N_n is the control horizon, at the same time, it must be different from N_2 , with $\delta(k)$ being weights, $\left[\tilde{y}\left(t+k|t\right) - w\left(t+k\right)\right]^2$ being the Quadratic Steady State Error, while $\left[\Delta u\left(t+j-1\right)\right]^2$ being the Minimal Change in the Control Action.

Delays decrease lead to reference path in a prediction horizon, based on a previous reference signal $r(t+k)$, which is different to $w(t+k)$. Therefore, an approximation is expressed from current output value is used, obtaining:

$$w(t+k) = \alpha w(t+k-1) + (1-\alpha) r(t+k) \qquad k = 1,..,N$$

where the function is smooth if α is close to one, while it is a fast approach when it is close to zero.

Stability Analysis

In order to demonstrate the stability of the proposed controller, it is assumed that:

1. The model function $f\left(y,u\right)$ is continuous according to Lipschitz and $f\left(0,0\right)=0$.
2. The function $g_y\left(p_s\right)$ is continuous according to Lipschitz in λ_s .
3. Coast function of the offset $\delta : \mathbb{R}^p \rightarrow \mathbb{R}$ is convex and positive. Besides, the minimum of the function $p_s = \arg \min_{p_s \in \lambda_s} \delta\left(p_s - p_t\right)$ is unique.
4. According to the weak controllability property in each balance point, a function $\sum_{j=0}^{N-1}\left|u\left(i\right)-u_s\right| \leq \varsigma\left(\left|y-y_s\right|\right)$ exist.
5. The allowed output set λ_s , is convex.

Assuming that the five previous points are fulfilled, the following restrictions are satisfied:

(i) if $p_t \in \lambda_s$, then $\lim_{k\to\infty} | p(k) - p_t | = 0$.

(ii) if $p_t \notin \lambda_s$, then $\lim_{k\to\infty} | p(k) - \overset{*}{p_t} | = 0$, where $\overset{*}{p_s} = \arg \min_{p_s \in \lambda_s} \delta(p_s - p_t)$.

5.2 Numerical method-based control

In control by numerical methods, mathematical concepts are used to create an algorithm that approximates the state of the system in a future instant of time, thus, the necessary control actions are calculated to make the output of the system go from a current value to a desired value [16]. The evolution of the system is approximated through Euler method, with the model being:

$$\begin{cases} A_1 \dfrac{y_1(k+1) - h_1(k)}{ts} = a_1 k_1 \mu_1 + S_3 \sqrt{2gy_3} - S_1 \sqrt{2gy_1} - sgn(y_1 - y_2) a_{12} k_{12} \sqrt{2g(y_1 - y_2)} \\ A_2 \dfrac{y_2(k+1) - h_2(k)}{ts} = a_2 k_2 \mu_2 + S_4 \sqrt{2gy_4} + sgn(y_1 - y_2) a_{12} k_{12} \sqrt{2g(y_1 - y_2)} - S_2 \sqrt{2gy_2} \\ A_3 \dfrac{y_3(k+1) - h_3(k)}{ts} = (1 - a_2) k_2 \mu_2 - S_3 \sqrt{2gy_3} + a_{34} k_{34} \sqrt{2g(y_4 - y_3)} \\ A_4 \dfrac{y_4(k+1) - h_4(k)}{ts} = (1 - a_1) k_1 \mu_1 - S_4 \sqrt{2gy_4} - a_{34} k_{34} \sqrt{2g(y_4 - y_3)} \end{cases} \tag{10}$$

where, values of y_i belonged to tanks level in discrete time $t = kT_0$ are denominated $y_i(k)$ with T_0 being sample period and $k \in \{0,1,2,3,...\}$ [16]. Through Markov method, in order to stablish control law, the state $h_i(k+1)$ is expressed as:

$$y_i(k+1) = yd_i(k+1) - \mathbf{W}_i(yd_i(k) - y_i(k)) \tag{11}$$

The equations of the system are reformulated as follows: **Au = b**

$$\begin{bmatrix} \dfrac{a_1 k_1}{A_1} & 0 \\ 0 & \dfrac{a_2 k_2}{A_2} \\ 0 & \dfrac{(1-a_2) k_2}{A_3} \\ \dfrac{(1-a_1) k_1}{A_4} & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} \dfrac{y_{d_1}(k+1) - \mathbf{W}_1(y_{d_1}(k) - y_1(k)) - y_1(k)}{T_0} + \dfrac{S_3}{A_1}\sqrt{2gy_3} - \dfrac{S_1}{A_1}\sqrt{2gy_1} - \dfrac{sgn(y_1 - y_2)}{A_1} a_{12} k_{12} \sqrt{2g(y_1 - y_2)} \\ \dfrac{y_{d2}(k+1) - \mathbf{W}_2(y_{d_{21}}(k) - y_2(k)) - y_2(k)}{T_0} + \dfrac{S_4}{A_2}\sqrt{2gy_4} + \dfrac{sgn(y_1 - y_2)}{A_2} a_{12} k_{12} \sqrt{2g(y_1 - y_2)} - \dfrac{S_2}{A_2}\sqrt{2gy_2} \\ \dfrac{y_{d_3}(k+1) - \mathbf{W}_3(y_{d_3}(k) - y_3(k)) - y_3(k)}{T_0} - \dfrac{S_3}{A_3}\sqrt{2gy_3} + \dfrac{a_{34} k_{34}}{A_3}\sqrt{2g(y_4 - y_3)} \\ \dfrac{y_{d_4}(k+1) - \mathbf{W}_4(y_{d4}(k) - y_4(k)) - y_4(k)}{T_0} - \dfrac{S_4}{A_4}\sqrt{2gy_4} - \dfrac{a_{34} k_{34}}{A_4}\sqrt{2g(y_4 - y_3)} \end{bmatrix} \tag{12}$$

where, y_d is the desired trajectory, while $\mathbf{W}$ is the weight matrix and its values are defined in a range from 0 to 1.

The conditions for the system to have an exact solution is through:

$$\frac{\mathbf{A}_{1,1}}{\mathbf{A}_{4,1}} = \frac{\mathbf{b}_{1,1}}{\mathbf{b}_{4,1}} \; ; \; \frac{\mathbf{A}_{2,2}}{\mathbf{A}_{3,2}} = \frac{\mathbf{b}_{2,1}}{\mathbf{b}_{3,1}} \tag{13}$$

where the subscripts represent the position in the matrix; since the purpose is to control the lower levels, y_1 and y_2, a "sacrificed" variable is taken into account, in order to reduce the system solution:

$$\begin{cases} \dfrac{\frac{a_1 k_1}{A_1}}{\frac{(1-a_1)k_1}{A_4}} = \dfrac{\frac{y_{d_1}(k+1)-W_1\left(y_{d_1}(k)-y_1(k)\right)-y_1(k)}{T_0}+\frac{S_3}{A_1}\sqrt{2gy_3}-\frac{S_1}{A_1}\sqrt{2gy_1}-\frac{\operatorname{sgn}(y_1-y_2)}{A_1}a_{12}k_{12}\sqrt{2g(y_1-y_2)}}{\frac{y_{s_4}(k+1)-W_4\left(y_{d4}(k)-y_4(k)\right)-y_4(k)}{T_0}-\frac{S_4}{A_4}\sqrt{2gy_4}-\frac{a_{34}k_{34}}{A_4}\sqrt{2g(y_4-y_3)}} \\ \dfrac{\frac{a_2 k_2}{A_2}}{\frac{(1-a_2)k_2}{A_3}} = \dfrac{\frac{y_{d2}(k+1)-W_2\left(y_{d_{21}}(k)-y_2(k)\right)-y_2(k)}{T_0}+\frac{S_4}{A_2}\sqrt{2gy_4}+\frac{\operatorname{sgn}(y_1-y_2)}{A_2}a_{12}k_{12}\sqrt{2g(y_1-y_2)}-\frac{S_2}{A_2}\sqrt{2gy_2}}{\frac{y_{s_3}(k+1)-W_3\left(y_{d_3}(k)-y_3(k)\right)-y_3(k)}{T_0}-\frac{S_3}{A_3}\sqrt{2gy_3}+\frac{a_{34}k_{34}}{A_3}\sqrt{2g(y_4-y_3)}} \end{cases} \tag{14}$$

with $y_{s_i}(k)$ being the "sacrified" variable at the current sample time, meanwhile, $y_{s_i}(k+1)$ is obtained from (14). Through Taylor approximation, $y_{s_i}(k+1) = y_{s_i}(k)$ is defined. In order to achieve the errors to tend to zero, it is used least squares to obtain the control actions. [16] Given the equations number is greater than unknowns in matrix, pseudoinverse concept is used, where, $\mathbf{A} \in \Re^{mxn}$, considering $m > n$, it is stablished: $[u_1 \quad u_2] = \left(\mathbf{A}^{\mathbf{T}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathbf{T}}\mathbf{b}$.

Stability Analysis

Considering that the mathematical model from (6) is expressed as a matrix $\mathbf{M}$ with dimensions $4x4$, the closed loop equation is defined as:

$$y(k+1) - y(k) = T_0\mathbf{M}\left(\mathbf{M}^T\left(\mathbf{M}\mathbf{M}^T\right)^{-1} b\right)$$

where $\mathbf{M}^T\left(\mathbf{M}\mathbf{M}^T\right)^{-1} = \mathbf{I_m}$

$$y(k+1) - y(k) = T_0\mathbf{I_m}\mathbf{b}$$

Using identity matrix properties, it is stablished:

$$y(k+1) - y(k) = \mathbf{T_0}\left(\frac{y_d(k+1) - \mathbf{W}\left(y_d(k) - y(k)\right) - y(k)}{\mathbf{T_0}}\right)$$

The error given by $y_d(k+1) - y(k+1)$ depends only on the previous error by a gain $\mathbf{W}\left(yd(k) - y(k)\right)$.

$$\begin{bmatrix} y_1(k+1) \\ y_2(k+1) \end{bmatrix} = \begin{bmatrix} y_{1d}(k+1) - w_1(e_1) \\ y_{2d}(k+1) - w_2(e_2) \end{bmatrix}$$

$$\begin{bmatrix} e_1(k+1) \\ e_2(k+1) \end{bmatrix} = \begin{bmatrix} w_1(e_1(k)) \\ w_2(e_2(k)) \end{bmatrix}$$

The errors on the next states are given by:

$$
\begin{aligned}
e_i(k+1) &= w_i e_i(k) \\
e_i(k+2) &= w_i e_i(k+1) = w_i^2 e(k) \\
e_i(k+3) &= w_i e_i(k+2) = w_i^3 e(k) \\
&\vdots \\
e_i(k+n) &= w_i e_i(k+n-1) = w_i^n e(k)
\end{aligned}
$$

Since, when $0 < w_i < 1$ y $n \to \infty$ the error approximates asymptotically to cero, the closed-loop equilibrium point is asymptotically stable. Therefore, it is verified that $\tilde{y}_i(t) \to 0$ when $t \to \infty$.

6 Analysis and Results

As it can be seen in Figure 10, for the implementation of the Hardware-in-the-Loop technique, a main computer is used, where the advanced control algorithms are designed, on the other hand, a 2Gb Raspberry Pi embedded card is used, in which the mathematical model of each level tank configuration is implemented. Bidirectional communication between the computer and the Raspberry Pi card is implemented through wireless technology using Xbee cards.

Fig. 10. Hardware-in-the-Loop.

Fig. 11. Main Menu.

The main menu is presented in Fig. 11, where certain parameters such as the avatar, the configuration of level tanks and the type of control algorithms proposed in section 5 can be selected, as shown in Figure 12. Finally, in Fig. 13 the execution of the virtual environment is observed. In addition, the user can receive instructions through audio in order to help understand the use of the process which the operator is immersed in.

Inside the virtual laboratory, four tank configurations are shown, each one has a control panel that allows the user to interact with the values of the variables that intervene in the process, such as the set point values and the disturbances (opening of the valves), as well as observing the values and response curves of the filling level of the controlled tanks and the control actions.

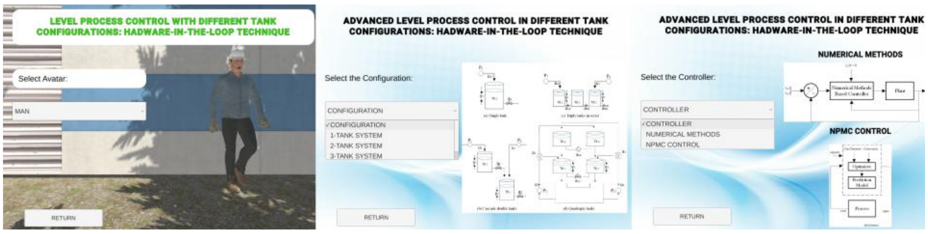

Fig. 12. Virtual environment scenes.

Fig. 13. MPC Control simulation by Unity.

Following, the results of the response curves are presented:

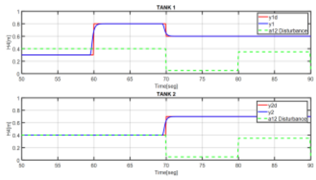

Fig. 14. Response curve of the MPC control in reference to the desired output of the process.

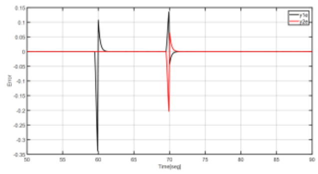

Fig. 15. Errors control curve of the process controller MPC.

According on the response curves in reference to the desired outputs, it can be seen that the MPC controller is an instant ahead of the future, it also depends on the optimization algorithm, therefore it presents a relatively high response speed.

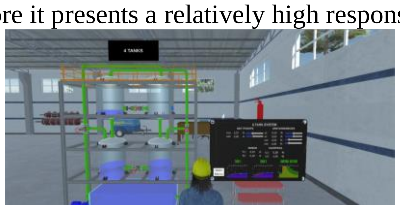

Fig. 16. Numerical methods-based control simulation by Unity.

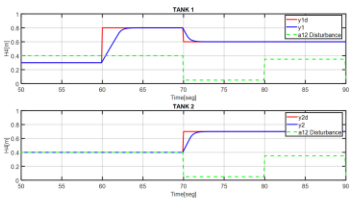

Fig. 17. Response curve of the control based on numerical methods in reference to the desired output of the process.

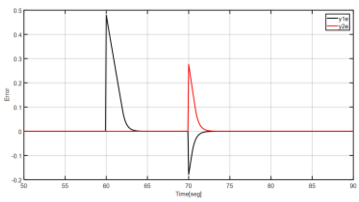

Fig. 18. Control error curves of the controller based on numerical methods of the process.

As it can be seen in the response curves in reference to the desired outputs, the controller by numerical method is not affected by the disturbances applied to the process, given the disturbance matrix is considered in the control law.

The user can control and observe the behavior of the simulated system, both in Matlab software where the controllers are designed, and inside the virtual laboratory through the HMI interface.

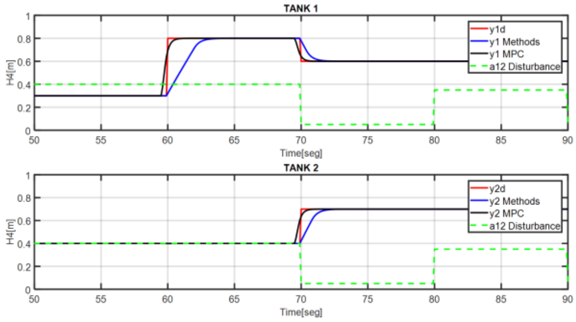

Fig. 19. Comparison curve of the MPC control and numerical methods-based control in reference to the desired outputs of the process.

In Figure 19, the curves in reference to the desired outputs of the process are shown, the establishment time and the percentage of overshoot are analyzed comparing the performance of each of the controllers: MPC and numerical methods. It is determined that the stabilization time of the MPC control is faster than the control by numerical methods, presenting a higher response speed. None of the advanced controllers feature overshoot, which guarantees the life of the final control elements. In Figure 15 and Figure 18, the curves of the errors are shown, where the evolution of the errors is observed, which tend asymptotically to zero.

7 Conclusions

The present work represents a great contribution in the research and academic field, since it facilitates the teaching and learning about the operation of advanced controllers by immersing the user in a virtual environment, giving a realistic impression of an industrial environment. In addition, based on the results obtained from the simulations and from the analysis of the response curves, it was found that the MPC control presents more precise results with respect to the control based on numerical methods, given it uses an optimization strategy that anticipates the effect of future control action. Thus, the Hardware in the Loop technique allows rigorous evaluation of advanced control algorithms without the need of physical equipment.

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