Low Cost Experiment for Control Systems

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Abstract— **The usefulness of the balls-in-tubes experiment as a platform for research and education in traditional and advanced control systems is discussed. A re-design of an original experiment is presented, including its principal characteristics. Physical theoretical issues and a dynamical model of the system are analyzed. A study case using traditional PID control applied to a SISO system in the balls-in tubes is illustrated. Moreover, a fuzzy logic control algorithm is implemented for the whole system showing the possibilities of implementing different type of algorithms in a low cost experiment.**

I. INTRODUCTION

Experimental platforms or testbeds are key elements for the practical approach of hypothesis and theories in control systems. One of the main contributions of these testbeds is the fact that they are a main tool for the technological transfer and the innovation process. In these platforms, students can link theoretical concepts with applications, which helps to reduce the gap between industry and academia.

In the last decades, several platforms have been developed in order to illustrate some of these theoretical concepts. Classical control testbeds as the inverted pendulum, the magnetic levitation system, the inclined plane systems (ball and beam), ball and hoop and ball and wheel, are used to study and design of control algorithms for tracking, stability, and positioning of unstable open loop systems [11]. Commonly, these experiments are intended to work over a linearized model. In the same way, linear open loop stable electric systems are used to illustrate traditional control objectives. In [16], an embedded PID control is implemented over an RC-RC circuit. In [15], a two zones temperature control is used to study decentralized and decoupled PID control strategies. Although these experiments have been a key tool to study control algorithms, there exists an interest in the development of new experimental platforms with advanced control objectives.

Nonlinear systems and intelligent control are usually issues addressed in more complex experiments. In [7], a nonlinear plant is oriented to the study of classical and intelligent control strategies. The plant consists on a vehicle that transports a load mass over a metal bridge. The control objective is to reduce the mass damping during the displacement and vehicle stop. Under this control objective a linear quadratic regulator (LQR) is implemented. Moreover, intelligent controllers based on fuzzy logic and neural networks are developed. In [14], a full state feedback linealization controller is implemented over a ball and wheel. In the system, the position of a metal ball placed over a reel is controlled by the speed of a DC motor attached to it. In [8], a scale model for an antilock braking system (ABS) is used for the comparative study of control strategies under an energy efficiency criterion. Gain scheduling, fuzzy logic and frequency control techniques are implemented. While these type of experimental platforms show an increase in complexity for the design and analysis of controllers, they do not show new structures or dynamics that can motivate the research of new control algorithms.

Proposals in terms of new structures and hardware that refresh the study and teaching of control are a concern for new experimental platforms. In [9], a broad study of the bicycle dynamics is used to develop an experimental platform for the study and visualization of control issues such as system identification, stability, and feedback. In [13], a self-balancing human vehicle system whose dynamics based on inverted pendulum equilibrium and spinning control is used for the study of real-time discrete control. In [12], a vehicle mounted inverted pendulum implemented with a low cost RCX LEGO-kit is used to study the way in which the communication over a wireless network can affect the control performance. In [20], a two coupled inverted pendulum system is used to study networked control systems.

Many of these experiments are costly and cannot be used in most universities around the globe. In this way, part of the academic control community has orientated their efforts to diversify the access to experimental platforms with virtual and remote control laboratories where the user can access from anywhere [17]. Graphical User Interface (GUI) developments and virtual experiments as presented in [10] and [19] show a definite simple example of this kind of platforms. In [10], a GUI experimental platform is designed to study predictive control algorithms. This tool allows a real-time design process where the system dynamics response changes over time with the modified parameters. In [19], a virtual experimental platform of a ball and plate testbed interact with a laptop servo in which the velocity can be controlled guaranteeing stability to the ball. The principal disadvantages of the remote and virtual experiments are the requirements of network and processor capacity, limiting the access time and number of users, which decreases the possibilities of implementing several control strategies.

A useful experimental platform that addresses some of the previous issues is the one shown in [4]. In this low

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The data acquisition card was originally designed by Diego M. Rivera.

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cost system, a simple structure illustrates traditional control issues, as well as the implementation of complex dynamics and nontraditional control objectives. It also gives the user visual sensations that helps understanding theoretical concepts. The balls-in-tubes is part of a set of low cost experiments for scheduling, dynamic resource allocation, and decision-making. In [4], the prototype of each experiment is described with basic control solutions for different control strategies. The results and future work proposed in that paper for the balls-in-tubes experiment let us reinventing the experiment so that new physical characteristics are included. In this way, new experimental controllers can be implemented for research and education in control.

In this article, first, we design a new structure for the balls-in-tubes system, where the experiment is not just modular in terms of adding new tubes in the system but in terms of reconfigurable manifolds. In this way, it is possible to change the interactions between tubes creating different manifold topologies. Moreover, the manifold size is changed to guarantee a better air distribution and to store enough air for experiments with more than four tubes. Second, a low cost data acquisition card is included to decrease the cost of data processing. In this way, the experiment presented here is less expensive than the experiment in [4], because it does not require a commercial and expensive data acquisition card[1]. Finally, a couple of control algorithms are developed in order to illustrate the versatility of the testbed.

The paper is organized as follows: Section II describes the prototype, their pieces and characteristics, and their system dynamics. Section III presents the control system algorithms implemented, and a discussion of the results obtained is presented in Section IV. Section V presents some conclusions.

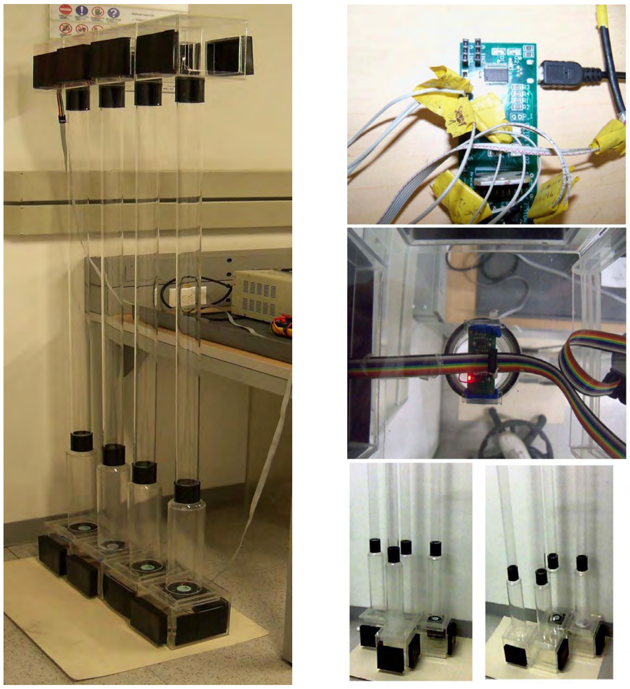

Fig. 1. Left: Balls-in-tubes prototype with manifolds horizontal configuration. Right: data acquisition card, ultrasonic sensor mounted in output manifold, and two different manifold topologies.

II. SYSTEM DESCRIPTION

In this section, the designed prototype is presented with its principal characteristics. In addition, a dynamical system model is developed. This model includes the influence generated by the geometrical structure of the system, the charge losses for interactions between tubes, and the interaction of balls due to the manifold geometries. This model allows us to work over real conditions, improving old approximations that focused on the balls floating in the air column without the restriction of the tube layers.

A. *Balls-in-Tubes Description*

The balls-in-tubes experiment is a system composed of four modules, where each one of them has a fan to blow air into the tube moving a styrofoam ball inside it, similar to the one developed in [4]. The modules are instrumented with an ultrasonic sensor to sense the ball height. The air flux coming from the fan is transferred to the tube using a pressurization cylinder whose objective is to reduce the turbulence produced by the fan, which delivers an almost laminar flux. Each module is coupled with the others by a common manifold. Fig. 1 shows the prototype designed. The base box corresponds to the input manifold. The air flows into the manifold by the unique input located at the left side of the box. The air in the input manifold is distributed over each module in a parallel way. Depending on the power applied by the fans and the input size of the manifold, the air flux continues its trajectory moving the ball inside it. The air from the tubes is combined again in the output manifold (upper box in Fig. 1), and ejected through the output, in the right side of the box. This reconfigurable structure possesses input and output manifolds in individual boxes that can be connected between them by their design as a Lego piece. In this way, it is possible to make different interconnection topologies between the tubes. The cylinder-tube piece could easily be uncoupled by the upper and base boxes, facilitating the reconfiguration and the replacement of damaged sensor, fans, and cables. When a topology is selected, the manifolds are sealed by rubber caps and covers leaving free just one input and one output of air. The data taken by the sensors is processed by an acquisition card based on a microprocessor PIC16F690, (see Fig. 1). The data acquisition card sends data to a Matlab platform via serial communication. The actuator controls the signals via pulse width modulation (PWM) working in the nominal voltage that supports each fan. The voltage control interval is from 40% to 100% of duty cycle for a maximum voltage of 15V. The data acquisition card includes a power driver L298 to give enough current to the actuators.

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[1] The data acquisition card was originally designed by Diego M. Rivera.

B. System Dynamics

The ball-in-tube dynamical model comprises an energy transfer by airflow from the fan to the ball. This transfer is typically nonlinear. The model is obtained by analyzing mass conservation, quantity of movement, and cutting force acting in the air variable volume control under the ball. As a basic model, let us consider the first's Newton law applied to the ball forces F_{ball}, i.e.,

$$\sum F_{ball} = D + E - W = m_{ball}\frac{d^2 z_2}{dt^2} \quad (1)$$

In Eq. (1), D represents the lift aerodynamic force raising the ball, $E = \rho_a g v_m$ the buoyancy force with mass volume v_m and air density ρ_a, W the gravitational force, m_{ball} the ball mass, and, z_2 the ball height [2].

For this system, the lift aerodynamic force commonly used is $D = \frac{\pi}{4}\Delta p D_s^2$, where Δp is the pressure changes in fan flow, and D_s is the ball diameter [6]. Here, we have consider the drag force D in terms of the volume control dynamics. In this way, the model includes dynamics due to the air flux caudal, the ball height changes inside the tube, and air losses due to the connection the between tube and the cylinder.

First, a control volume defined by the dotted lines in Fig. 2 is used to identify the variables and parameters that affect the fluid. The control volume is defined by the beginning of the tube in z_1 until the ball height in z_2. Indeed, we can observe that the control volume changes because of the ball height. For this reason, we can assume that the states affecting the ball height not only depend on the fan velocity, but also by the pressure and mass changes in the control volume. Second, to identify the force acting over the volume control F_{vc}, we use the quantity of movement equation over the volume control by the surface and ball forces [2]. To do that, let us consider the forces acting over the volume control as in Fig. 2.

F is the exerted force by the ball over the control volume, $A(P_1 - P_2)$ the difference pressure force over the volume control (where A is the cross sectional tube area), and the air mass weight $G = \rho_a g A(z_2 - z_1)$ (where g is gravity).We obtain then,

$$\sum F_{vc} = P_1 A - P_2 A - F - G \quad (2)$$

In Eq. (2), if the control volume is in equilibrium, the ball maintains a constant height. Then, the ball forces acting over the control volume will be equivalent to the pressure forces minus the air mass weight. In fact, this equilibrium point is obtained when the forces in the air mass are equivalent to the ball weight and flotation force, i.e., by Eq. (1) $F = -D = E - W$. Meanwhile, the forces are not in equilibrium. F will be the magnitude of the draft force exerted by the air mass over the ball. Third, to consider the acting forces due to the work done by the fan in the air fluid, we use quantity of movement equation for the velocities V_1 at the beginning of the tube, and V_2 around the ball as seen in Fig. 2, i.e.,

$$\sum F_{vc} = \rho_a Q_{fan}(V1 - V2) \quad (3)$$

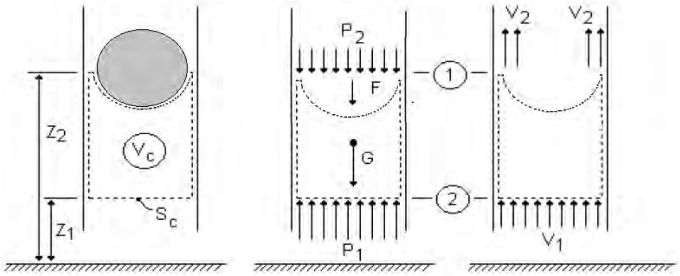

Fig. 2. Left: volume control definition over the ball, where $z_2 - z_1$ corresponds to the variable length. Middle: forces over the control volume, pressures P_1 and P_2, weight of the air mass G, and the ball force F acting in the air control volume. Right: velocity components over the volume control. Figure adapted from [1].

where Q_{fan} is the caudal flux injected by the fan. In order to meet the property of mass conservation we have that

$$Q_{in} = \frac{V_1}{A} = Q_{out} = \frac{V_2}{a} \quad (4)$$

where Q_{in} is the caudal flux entering the tube, Q_{out} the caudal flux at the end of the tube, and a the cross sectional area between the tube and the ball. In this way, Eq. (3) is written in terms of $Q_{fan} = Q_{in} = Q_{out}$, i.e.,

$$\begin{aligned}\sum F_{vc} &= \rho_a Q_{fan}(V1 - V2) \\ &= \rho_a Q_{fan}\left(A Q_{fan} - a Q_{fan}\right)\end{aligned}$$

$$\sum F_{vc} = \rho_a Q_{fan}^2 \left(A - a\right) \quad (5)$$

Finally, matching Eqs. (2) and (5) we obtain the drag force $F = -D$ in terms of the balls height $z_2 - z_1$, the pressure differences, and flux input Q_{fan}, i.e.,

$$\rho_a Q_{fan}^2 \left(A - a\right) = (P_1 - P_2)A - \rho_a g A(z_2 - z_1) - F \quad (6)$$

Solving for F,we get:

$$F = (P_1 - P_2)A - \rho_a g A(z_2 - z_1) - \rho_a Q_{fan}^2 \left(A - a\right) \quad (7)$$

To obtain a model that includes the geometric restriction from manifolds and coupling between tube and the pressure cylinder we include the following statements: losses in charge must be considered for couples between input cylinder and tube, i.e., loss charge by a suddenly contraction $h_m = \frac{V_{fan}^2}{2g}K$ and $K \approx 0.42\left(1 - \frac{d^2}{D^2}\right)$, where D is the cylinder diameter, d is the tube diameter, K is the losses constant for contractions, and V_{fan} is the media velocity of the flux injected in the system.

To include the interactions between the different modules and the manifolds we assume that $P_1 = \beta P_{im}$, where P_{im} is the pressure associated to the air in the input manifold. $P_2 = \alpha P_{om}$ will be the pressure associated to the combined air in the output manifold. According to [3], the pressure $P_{im} - P_{om}$ is local for each module because pressures are associated with the tube position over the manifold and its distance from the air input and output. The relation between

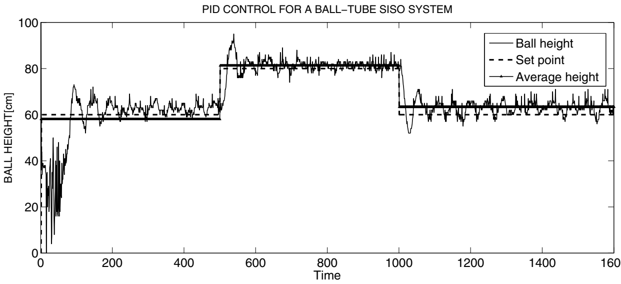

Fig. 3. Balls height for a PID control law applied to ball in tube system following two different tracking objectives, reference = $60cm$, reference = $80cm$.

pressure and position will be defined by α_i for P_2 in tube i for $i = 1, 2, 3, 4$, and β_i for P_1 in tube i. These dimensionless parameters are defined by the flux distribution and manifold length [3].

Finally, the dynamical model of a ball-in-tube system i including losses charges is defined by replacing $D = -F$ in Eq.(1), where $x_1^i = h = z_2 - z_1$ with $z_1 = 0$ is the height of the ball and $x_2^i = \frac{dh}{dt}$ the velocity in tube i for $i = 1, \ldots, 4$, i.e.,

$$\begin{aligned}
\dot{x}_1^i &= x_2^i \\
\dot{x}_2^i &= \frac{1}{m_{ball}} g \rho_a v_b - \frac{A}{m}(\beta_i P_{im} - \alpha_i P_{om}) + \frac{1}{m} \rho_a g A x_1^i + \cdots \\
&\quad \cdots + \frac{1}{m} \rho_a Q_{fan\,i}^2 \left(\frac{1}{a} - \frac{1}{A} \right) - \frac{A}{m} \rho_a g h_m^i - g
\end{aligned}$$

These equations define a decoupled system model for the MIMO system in which α_i and β_i includes the dynamics differences between modules due to the air flow distribution used for the experiments.

III. CONTROL ALGORITHMS

This section describes two different control strategies and their results. First, a PID control is implemented in order to study systems with basic control objectives for just one tube. Similar results for a ball in a tube system can be seen in [5]. Second, a fuzzy control algorithm is described and its results show how intelligent control theories can be implemented in this testbed.

A. Control Algorithms for SISO System

A PID control for a ball-in-tube system is derived by identifying a second order open loop system and performing a pole-placement allocation strategy.

The system response for a sinusoidal input with magnitude of 2.5V, frequency 0.1Hz, and voltage offset of $9V$ is used to identify a second order ARMAX [22] model of the form $A(s)y(t) = B(s)u(t) + c(s)e(t)$ where,

$$\begin{aligned}
A(s) &= s^2 + 0.004254s + 0.0006171 \\
B(s) &= -0.1186s + 0.0004491 \\
C(s) &= s^2 + 2.003s + 3.985
\end{aligned}$$

Indeed, analyzing the model behavior, with LTIVIEW in Matlab, we observe that the root-locus diagram corresponds to a minimum phase system. Without considering the relation between output and noise input, the system is a marginally stable minimum phase system. In this way, we use a pole placement strategy to move the poles to guarantee stability and to make the system to achieve stability around the set point without strong oscillations.

TABLE I

MEMBERSHIP FUNCTIONS CENTERS FOR ERROR AND CONTROL OUTPUT ASSOCIATED WITH THEIR LINGUISTIC VARIABLES.

linguistic variable	e_i [cm]	u_i [v]
”neghuge” NH	-30	-2.1093
”neglarge” NL	-24	-1.6875
”negbig” NB	-18	-1.2656
”negmed” NM	-12	-0.6381
”negsmall” NS	-6	-0.2109
”zero” Z	0	0
”possmall” PS	6	0.2109
”posmed” PM	12	0.6381
”posbig” PB	18	1.2656
”poslarge” PL	24	1.6875
”poshuge” PH	30	2.1093

A parallel PID control algorithm with a transfer function of the form $G_c(s) = K_c + \frac{1}{\tau_i s} + \tau_d s$ has been designed with parameters:

$$K_p = 2.5, \tau_d = 0.56, \tau_i = 0.08 \tag{8}$$

The sampling time used to implement this controller is $T_{sample} = 0.08s$.

Fig.3 shows the results for the real-time implementation of the PID control in the system. The system response follows the tracking objectives for $ref = $ 60cm and $ref = $ 80cm. For these results, we can observe that the second order model identified for the system is useful because its characteristics of minimum phase. High order models can be considered to describe the ball behavior. Although precision of high order models would have been better in terms of simulation dynamics, all the models derived correspond to minimum phase systems. In this way, the simplest model possesses the necessary characteristics to develop the control law.

B. Fuzzy Logic Control

To design a fuzzy logic controller for the system, we use our previous knowledge of the system. The main conclusion of the observations is that it is possible to identify tube pairs where the behavior of each one affects others stronger than other couplings. First, we observe that tubes one and two affect principally the behavior of the third and fourth tube. This is due to the closeness of the tubes. According to [3], the input and output positions in manifolds affect the air flux direction. For our experiment, we have taken the air input at the left side, and the air output at the right. This produces a parallel air flow that benefits the allocation of air in the tubes closer to the input. Based on this, we have decided to use four multiple input- single output (MISO) fuzzy controllers where the inputs would correspond to the most significant errors for a given tube. In this way, let us consider e_i and u_i,

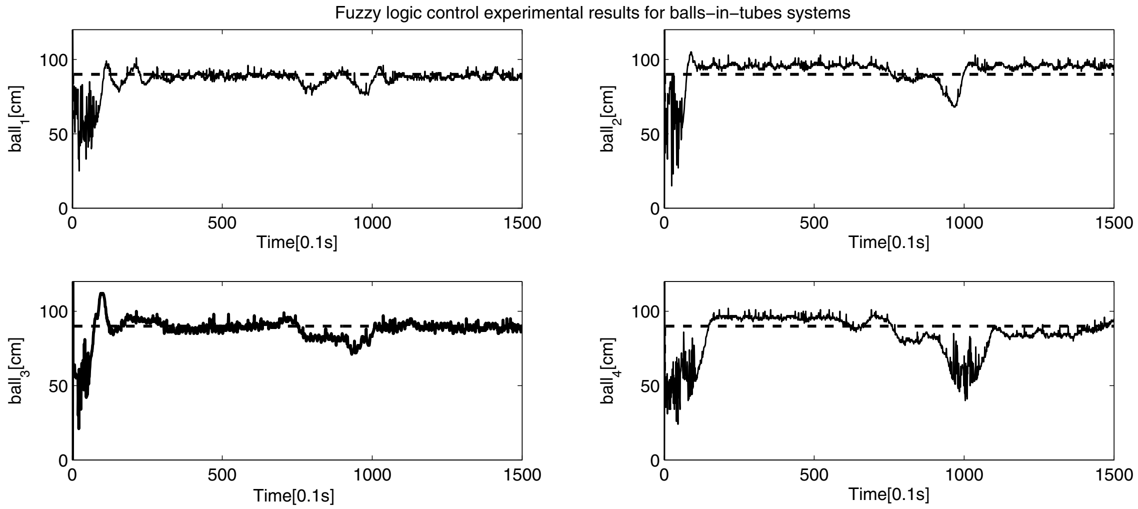

Fig. 4. Experimental results, for fuzzy logic control application over the balls in tubes experiment. Reference = 90cm. A disturbance is applied after $70s$.

for $i = 1, \ldots, 4$, to be the error, and the output control signal for each tube, respectively. Simultaneously, consider A_i^j, for $i = 1, \ldots, 4$, $j = 1, \ldots, 11$ the error universe of discourse for each tube, and B_i^j, for $i = 1, \ldots, 4$, $j = 1, \ldots, 11$ the output universe of discourse for each one. In this way, we define a set of eleven rules for each tube with relations as follows [21]:

For tube 1: **If** $e_1\ is\ A_1^j$ **and** $e_2\ is\ A_2^j$ **then** $u_1\ is\ B_1^j$
For tube 2: **If** $e_2\ is\ A_2^j$ **and** $e_3\ is\ A_3^j$ **then** $u_2\ is\ B_2^j$
For tube 3: **If** $e_3\ is\ A_3^j$ **and** $e_1\ is\ A_1^j$ **then** $u_3\ is\ B_3^j$
For tube 4: **If** $e_4\ is\ A_4^j$ **and** $e_2\ is\ A_2^j$ **then** $u_4\ is\ B_4^j$

For the fuzzification process, triangular membership functions are used both for input and output. The universe of discourse for all the errors is the same over an interval $A_i^j \in [-30, 30]$ in centimeters. Moreover, to the output, the universe of discourse is the same for all the tubes and is defined over the interval $B_i^j \in [-2.11, 2.11]$ in Volts. Table I summarizes the membership functions centers for the input and output universe of discourse. It can bee seen that the centers of the membership functions for the output are not uniformly distributed. There exists high density of centers around zero to guarantee that the actions around the reference are smooth. To obtain the control signals we use a center of gravity (COG) defuzzification method described by,

$$u_i = \frac{\sum_j B_i^j \int \mu_{(j)}}{\sum_j \int \mu_{(j)}} \tag{9}$$

where $\mu_{(j)}$ are the implied fuzzy set. The control values u_i obtained of the fuzzy control algorithm are added to the minimum reference voltage necessary to maintain the balls in an operable velocity range. If these minimum voltages are not used, the system tends to be saturated. In other words, if the balls have not reached these minimum values the fans cannot move the ball from rest. Similarly, if we use a longer voltage control interval, the first action of controller will drift quickly the ball and moves it from that position causing larger swings. The values used for the tubes independently of the controller algorithm are: 8.32V for tube 1; 9.59V for tube 2; 9.37V for tube 3; and 6.84V for tube 4. Fig. 4 presents the results obtained with a tracking control objective with reference at 90 cm. As a result, all the balls achieve the reference. Indeed, balls one and three have a better performance, because their achieve zero error. However, balls two and four have a good performance because they maintain stability with a 4% error. After $70s$ a disturbance is added to the system decreasing the air flux output in the manifold. All the balls react to these perturbation loosing altitude. However, the controller allows to stabilize the system again around the reference.

IV. DISCUSSION

Our results shows that traditional and intelligent control algorithms can be implemented in the balls-in-tubes system in a successfully way despite the air complex dynamics, environmental perturbations, sensing noise, and topology restrictions. This type of restrictions in the system can be seen in the oscillatory behavior for the system shown in Fig. 3. However, this kind of behavior decreases when all the modules are operated at the same time. For the fuzzy control algorithm, we can observe a lower oscillations in steady state due to the pressure dynamics.

In terms of control performance, for the PID control we observe that despite the low order model estimation used for the design, the performance is good in terms of tracking and stability. Moreover, this controller can be used in any tube with the same performance characteristics. Using another synthesis control methodologies, parameter values can be tunned with precision to obtain better results. For the fuzzy algorithm the control objective is achieved. Control performance in tubes 2 and 4 would be improved designing fuzzy rules for MISO systems where the four errors are considered for each system. In fact, the designed algorithms in these experiments show the balls-in-tubes usefulness as a testbed for control experiments. Over this fact, these algorithms show how many different control strategies can be implement in this plant.

An important characteristic observed in the results is the emergency of a relation between the balls-in-tubes experiment and the dynamics on a multilateral well drilling system. For these systems, the reservoir fluid streamlines and drilling pressures may be affected by the existence of multiple fluid-flow branches connected to the primary well. As a consequence, the pressure and flows transient response are related with the structure of the system. In addition, pressure and fluid flow in the primary well have to be controlled for changes in the reservoir pressure, or to optimize the process of drilling and recovery in each one of the stages. In order to understand the relationship, let us see the input manifold in our experiment as an oil or gas reservoir with proper pressure characteristics. From this reservoir we extract oil in each branch with some topological restrictions, branches quantity, and pressure drops. Similarly, let us see the output manifold as the primary well. Hence, all the fluxes are combined producing couples due to the recirculating fluids, pressure drops, or injection of fluid that can create perturbation in pressure variables. Based on this analogy, it is clear that the balls-in-tubes experiment illustrates basic control techniques, as well as complex process control problems.

V. CONCLUSIONS

We have proposed a new design for the balls-in-tubes experiment introduced in [4], in which modularity and the independence from commercial data acquisition systems are its principal characteristics. We have justified how multiple dynamics can be achieved by the geometric topologies dependence for the flow air distribution. The dynamical model described allows to decouple the modules dynamics. We have shown experimental results for control algorithms for a single ball in tube system and for the MIMO experiment. The work presented here expands the vision about the chances that balls-in-tubes system presents for its use as a research and educational tool. Likewise, it can motivate the introduction of intelligent control strategies in basic control courses. Also, the possibility to work in a Matlab platform facilitates the implementation of real-time experiments using its toolboxes. In the future, we would like to test nonconventional control strategies in the testbed. For instance, we would like to see how decision making algorithms (e.g., foraging theory), performs in this type of experiments.

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