VOL. 13, NO. 10, MAY 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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DESIGN AND IMPLEMENTATION OF AN OPTIMAL HYBRID CONTROL FOR A HYDRAULIC SYSTEM OF COUPLED TANKS

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ABSTRACT

In this document, we investigate the problem of optimal hybrid control for a non-stationary hydraulic system with autonomous location transitions. Using the Lagrange approach and the reduced gradient technique, we derive the optimality conditions necessary for the class of problems considered. These conditions of optimality are closely relate to a variant of the Maximum Hybrid Principle, are simulated in Matlab and implemented in Labview. They can be used for constructive optimization algorithms.

Keywords: hybrid control, hydraulic system, labview, couple tank.

INTRODUCTION

Currently the optimal hybrid control systems have become a new approach to non-linear control theory (see e.g., [1], [2], [3]). Hybrid control systems are mathematical models of heterogeneous systems that consists of a continuous part, a finite number of continuous controllers and a discrete supervisor [4], [5], [6]. The main tool for an optimal hybrid control problem is the construction of optimal trajectories using the Maximum Hybrid principle, which is the generalized result of the classical Pontryagin maximum principle [7], [8], [9].

The techniques of "needle variations" are the fundamental tests of the Pontryagin Maximum Principle, and the possibility of using this technique changes according to the character of the problem of optimal hybrid control [10], [11], [12].

Consequently, a variation of the Maximum Hybrid Principle for our hydraulic system can be tested under the assumption of certain restrictive. In this way, these assumptions will ensure that classic "needle variations" will still be acceptable variations [13], [14], [15].

Likewise, in the implementation scenario in Labview of the Maximo Hybrid principle, we need to simulate in Matlab a concurrent solution of a large dimensional limit value problem and a group of complex problems to minimize the best [17], [18], [19].

Modern microprocessors are each time faster for being used in more complicated and demanding work [20], [21], [22]. Hence the unavoidable need to develop applications that allow implementing real-world situations to consolidate the acquired knowledge [23], [24], [25].

In this article, we must bear in mind that our plant is a hydraulic system to which we are going to apply optimal hybrid control with autonomous location transitions (not controlled). For the general theory of hybrid systems and the basic definitions, we can mention, for example [26], [27]. Using Matlab and using an approach based on Lagrange-type techniques and at reduced gradients; we obtain a set of necessary first-order optimality conditions for this class of problems. This will allow the application of some optimization algorithms based on efficient gradients for optimal hybrid control problems [28].

This article is distributed as follows. Section 2 contains the methodology and materials of the optimal initial hybrid control problem and some basic aspects. Session 3 is dedicated to show the results and the discussion of the evaluation obtained from the optimal hybrid control problem of the hydraulic system. In section 4, we present the conclusions obtained from the computational approach used gradient-based for the initial problem [29], [30].

PROBLEM FORMULATIONOPTIMAL CONTROL CLASSIC

We consider a dynamical system represented by the following linear equation:

$$\begin{cases} \dot{x}(t) = f\big(t, x(t), u(t)\big), & t \in [t_0\ ,\ t_f] \\ & x(t_0) = x_0 \end{cases} \quad (1)$$

Where $f : [t_0\ , t_f]$x $\boldsymbol{R}^n$x $\boldsymbol{R}^m \rightarrow \boldsymbol{R}^n$. Mapping $u(.) : [t_0\ , t_f] \rightarrow \boldsymbol{R}^m$ month called control where $x_0 \in \boldsymbol{R}^n$is the primary phase and the response of (1) is a function continuous $x(.) : [t_0\ , t_f] \rightarrow \mathbf{R}^n$ called path state control $u(.)$ [13], [14].

Now we assume that for any x_0 and any controls $u(.)$ there is one answer to the equation (1). Performance control applied to the system as follows is also evaluated:

$$J\big(u(.)\big) = \int_{t_0}^{t_f} g\big(t, x(t), u(t)\big)dt + h(x(t_f)) \quad (2)$$

Where $g : [t_0\ , t_f]$x $\boldsymbol{R}^n$x $\boldsymbol{R}^m \rightarrow \boldsymbol{Ryh} : \boldsymbol{R}^n \rightarrow \boldsymbol{R}$.the term of the right side of the equation described above is called 'running cost' and the term on the left is called 'cost terminal' [15]. It is common to find optimal

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control restrictions in the states and control, they are characterized as follows:

$x(t) \in S, u(t) \in U, \forall t \in [t_0, t_f]$.

Where $S \subseteq \boldsymbol{R}^n$ y $U \subseteq \boldsymbol{R}^m$. $u(.)$Or control is called admissible control, and the pair $(x(.), u(.))$ Admissible if:

a) $u(.) \in U$.
b) $x(.)$is the only continuous solution (1).
c) the restriction status is satisfied.
d) $t \to f(t, x(t), u(t)) \in L_1[t_0, t_f]$.

The group of admissible controls is framed by $U_{adm}[t_0, t_f]$.

PONTRYAGIN'S PRINCIPLE OF MAXIMUM

The principle of maximum is very important in the optimal control theory. It says that any optimal control along with state trajectory must satisfy the condition called Hamiltonian system [16], [17]. In addition to the mathematics of the maximum principle, it is easy to maximize the Hamiltonian system as the main topic. Maximum principle: let $x^*(.), u^*(.))$. An optimal pair of classical optimal control, then there is a continuous function $p(.): [t_0, t_f] \to \boldsymbol{R}$

$$\begin{cases} \dot{p}(t) = f_t(x^*(t), u^*(t))^T p(t) + g_x(t, x^*(t), u^*(t)), \\ \qquad t \in [t_0, t_f] \\ p(t_f) = -h_f(x^*(t_f)) \end{cases} \quad (3)$$

Where x is the partial derivative, o be;

$$f_x = \frac{\partial f}{\partial x}, \quad g_x = \frac{\partial g}{\partial x}, h_x = \frac{\partial h}{\partial x}$$

$$H(t, x^*(t), u^*(t), p(t)) = \frac{max}{u \in U}$$

$$H(t, x^*(t), u, p(t)), \quad t \in [t_0, t_f].$$

Where U represents the set of admissible controls plus:

$$H(t, x, u, p) = \langle p, f(t, x, u)\rangle - g(t, x, u), \quad (t, x, u, p) \in [t_0, t_f] X \boldsymbol{R}^n X \boldsymbol{U} X \boldsymbol{R}^n.$$

With $\langle .,. \rangle$Represents the standard domestic product in $\boldsymbol{R}^n$.

THE HAMILTON-JACOBI-BELLMAN EQUATION AND DYNAMIC PROGRAMMING SYSTEM

We consider a dynamic system as follows:

$$\begin{cases} \dot{x}(t) = f(t, x(t), u(t)), & t \in [t_0, t_f] \\ x(t_0) = x_0 \end{cases} \quad (4)$$

It seeks to minimize performance control applied to the given system:

$$J(u(.)) = \int_{t_0}^{t_f} g(x(t), u(t), t)dt + h(x(t_f)) \quad (5)$$

It should be noted that the initial time $t_0$and the initial state$x(t_0) = x_0$, which are represented in the problem, remain static [18].

A. Minimum time switched control

As an application case for the principle of the maximum, the problem of minimum time control is presented, in which an optimization problem with restrictions is proposed, where:

$$J(u(.)) = \int_{t_0}^{t_f} 1dt = t_f - t_0$$

Subjected to $-1 \leq u(t) \leq 1$ and desired null end conditions for the vector of states (i.e.$\Psi(x(t_f)) = 0$), starting from arbitrary initial conditions [19].Thus, the form taken by the Lagrangian system:

$$\mathrm{L(X, U)} = 1$$

Where it is possible to formulate the corresponding Hamiltonian:

$$H(t, x^*(t), u, \lambda(t)) = 1 + \lambda^T f(x, u)$$

That for the case of a linear system:

$$\dot{x} = Ax(t) + B\,u(t)$$

By the principle of maximum, in an optimal solution of type [20]:

$$u(t) = -sign(B^T \lambda(t))$$

B. Optimal hybrid control of the coupled hybrid system

Figure-1. Hydraulic system consisting of three tanks, Source: Labvolt.

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In the following Figure-1, we can see the schematic diagram of the hydraulic system of three coupled tanks. All tanks are identical therefore; they have the same cross sectional area S. Two cylindrical tubes with a cross-sectional area S_c interconnect the tanks. The output flow coefficients of tank 1 and tank 2 are a_1 anda_2, respectively.

The measured variables are the level of tank 1 (h_1), tank 2 (h_2) and tank 3 (h_3).The nominal inflow q_1 is located for tank 1 and the nominal inflow q_2 for tank 3.

The control objective is to control level of tank 1 and tank 3 by manipulating the inflow rates $q_1$and q_2.Using the mass balance can be represented the following hydraulic system consisting of three tanks mediating the following equations:

$$\frac{dh_1}{dt} = \frac{q_1 - s_1 a_1 (h_1 - h_2)\sqrt{2g(h_1 - h_2)}}{s}$$

$$\frac{dh_2}{dt} = \frac{s_1 a_1 (h_1 - h_2)\sqrt{2g(h_1 - h_2)} - s_2 a_2 (h_2 - h_3)\sqrt{2g(h_2 - h_3)}}{s}$$

$$\frac{dh_3}{dt} = \frac{q_2 - s_2 a_2 (h_2 - h_3)\sqrt{2g(h_2 - h_3)} - s_3 a_3 \sqrt{2gh_3}}{s} \tag{6}$$

In the following

Table-1. We can see the physical parameters of the hydraulic system of three tanks.

Parameters	Values
Maximum in-flow rate	$q_{max} = 0.9x10^{-4}\frac{m^3}{s}$
Maximum level	$h_{max} = 2.0\ m$
Pipe cross- section area	$S_c = S_1 = S_2 = S_3 = 0.00075\ m^2$
Pipe outflow coefficients	$a_1 = 0.383\ a_2 = 0.395\ a_3 = 0{,}548$
Tank cross-section area	$S = 0.025\ m^2$

The equations of the hydraulic system constituted by the three tanks present nonlinearities of quadratic order and the flows present in the system have linear behaviour to the square root of the level of each of the tanks.For the process of linearized equations of the robotic arm, Taylor series are used to design a state feedback controller.

$$f_a = (x, u) = f_a(x_r, u_r) + \frac{\partial f}{\partial x}|x_r, u_r\,(x - x_r) + \frac{\partial f}{\partial u}|x_r, u_r\,(u - u_r)$$

Being x∈ $R^{nx1}$the state vector, u is the input signal to the robotic arm; x_r and x_r are the equilibrium points, then to find and evaluate the partial derivative f (x_r ,u_r) at breakeven, it is f (0, 0):

$$\frac{\partial f}{\partial x}|(0,0) = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial x_3} \end{bmatrix}$$

$$\frac{\partial f}{\partial u}|(0,0) = \begin{bmatrix} \frac{\partial f_1}{\partial u} \\ \frac{\partial f_2}{\partial u} \\ \frac{\partial f_3}{\partial u} \end{bmatrix}$$

The linearized state space model in continuous form is given in Equation:

Above
$\dot{x}_i(t) = Ax(t) + Bu(t)$

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} \frac{\partial \dot{h_1}}{\partial h_1} & \frac{\partial \dot{h_1}}{\partial h_2} & \frac{\partial \dot{h_1}}{\partial h_3} \\ \frac{\partial \dot{h_2}}{\partial h_1} & \frac{\partial \dot{h_2}}{\partial h_2} & \frac{\partial \dot{h_2}}{\partial h_3} \\ \frac{\partial \dot{h_3}}{\partial h_1} & \frac{\partial \dot{h_3}}{\partial h_2} & \frac{\partial \dot{h_3}}{\partial h_3} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \frac{1}{s} & 0 \\ 0 & 0 \\ 0 & \frac{1}{s} \end{bmatrix} u(t)$$

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} -\frac{a_1 S_1 \sqrt{2g}}{2S\sqrt{h_1 - h_2}} & -\frac{a_1 S_1 \sqrt{2g}}{2S\sqrt{h_1 - h_2}} & 0 \\ -\frac{a_1 S_1 \sqrt{2g}}{2S\sqrt{h_1 - h_2}} & -\left[\frac{(a_1 S_1 + a_2 S_2)\sqrt{2g}}{2S(\sqrt{h_1 - h_2} - \sqrt{h_2 - h_3})}\right] & \frac{a_2 S_2 \sqrt{2g}}{\sqrt{h_2 - h_3}} \\ 0 & \frac{a_2 S_2 \sqrt{2g}}{\sqrt{h_2 - h_3}} & -\left[\frac{(a_2 S_2 + a_3 S_3)\sqrt{2g}}{2S(\sqrt{h_2 - h_3} - \sqrt{h_3})}\right] \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} \frac{1}{s} & 0 \\ 0 & 0 \\ 0 & \frac{1}{s} \end{bmatrix} u(t) \tag{7}$$

Arrays are described above in the continuous space, to need credit in our system: $x_{k+1} = G\,x_k + K\,u_k$0.002 seconds.

Our goal is to find a permissible control law, which minimizes the value of the second functional level costs

$$J(u(.)) = \frac{1}{2}\int_{t_0}^{t_f}[X^T(t) + QX(t) + u^T(t) + Ru(t)]dt \rightarrow \underset{u(.)}{\min} \tag{8}$$

The resulting Linear Quadratic Regulator has the following form

$$u^{opt}(t) = -R^{-1}(t)B^t(t)P(t)X^{opt}(t) \tag{9}$$

where P (t) is a solution of the Riccati equation:

$$P(t) = -(A^T P(t) + P(t)A(t) + \dot{P}(t)B(t)R^{-1}(t)B^T(t)P(t) - Q(t) \tag{10}$$

With the final condition:

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$$P(t_f) = 0 \tag{11}$$

RESULTS

With the data obtained by modeling the system, the system matrices were obtained in state variables and analyzed in the toolbox for Hybrid Systems of Matlab.

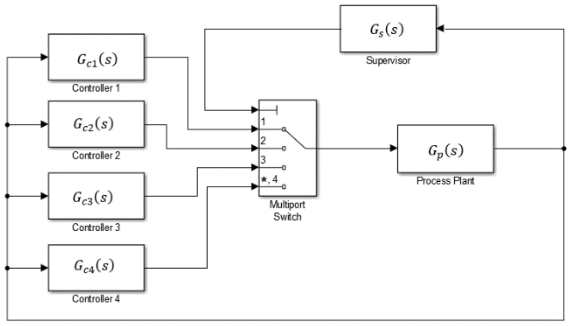

Figure-2. Block diagram of the hybrid control system developed in Simulik.

With these results, the optimal hybrid control was implemented, obtaining the following results from the modeled system.

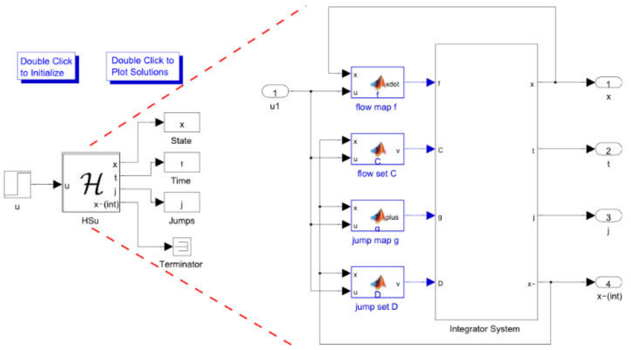

Figure-3. Hybrid systems simulated in MATLAB/ Simulink. Includes Simulink implementation and MATLAB.

In Figures 4 and 5, we can see the behavior of pump 2 in front of the optimal hybrid controller with Hybrid Equations Toolbox. It can be seen that the jumps present in the pump and the behavior of the electrovalves.

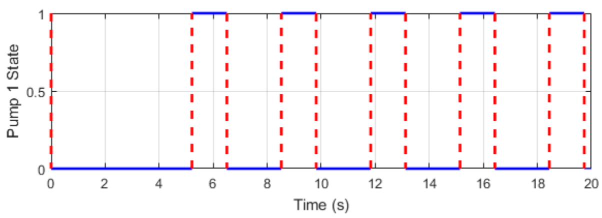

Figure-4. Pump status as a function of time in Matlab/Simulink.

We can see that the signal that reaches the pumps has a frequency of 0.25 Hz. This frequency can vary through the application of a generator of P.W.M. With the technique in which the work cycle of a periodic signal is modified, control is exerted on the pump.

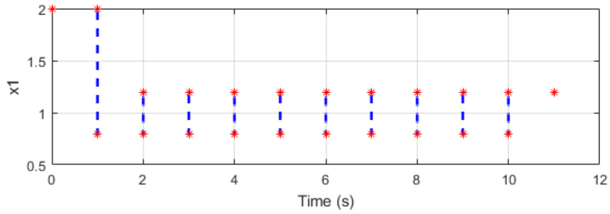

Figure-5. Jump applied to the simulated pump in Matlab/Simulink.

In Figures 6 and 7, we can see the dynamic behavior of a system tank by using the optimal hybrid controller. It can be seen that the maximum height of the tank will be 1.3m; it has a minimum height of 0.8 m. It has an inlet flow in valve 1 of 0.5 m3 / s, starting from a height of 2.0 m.

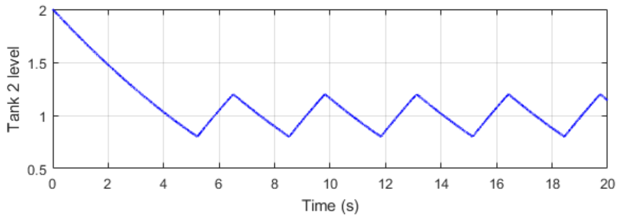

Figure-6. Level of the tank obtained through the simulation toolbox of hybrid systems.

In Figure-7, it can be observed how the behavior of tank 2 is. It is observed that it has an initial height of 2 m, which decreases but remains at a stable level given the presence of the optimal hybrid control action.

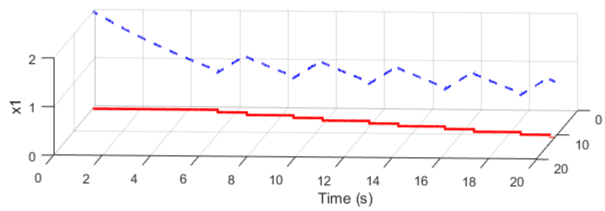

Figure-7. Level of the water tank with respect to the jump applied to the pump.

Labview has the optimal hydraulic system control consisting of three coupled tanks after obtaining the results in Matlab / Simulink, using the MyRIO card of the National Instrument. MyRIO is an embedded device that provides configurable inputs and outputs that allows you to design and implement various concepts with a single device. It includes analog inputs, analog outputs, digital I / O lines, LEDs, a push-button, an internal accelerometer, a Xilinx FPGA and a dual-core ARM Cortex-A9 processor. Some models also include support for Wi-Fi. Work with Labview's programming language.

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The following figure shows the front panel implemented in Labview for the visualization of the optimal hybrid control system for the coupled tank system. It has horizontal displays that show the operator the level of each of the tanks. Likewise, control knobs are provided for the valves of the two keys present in the system.

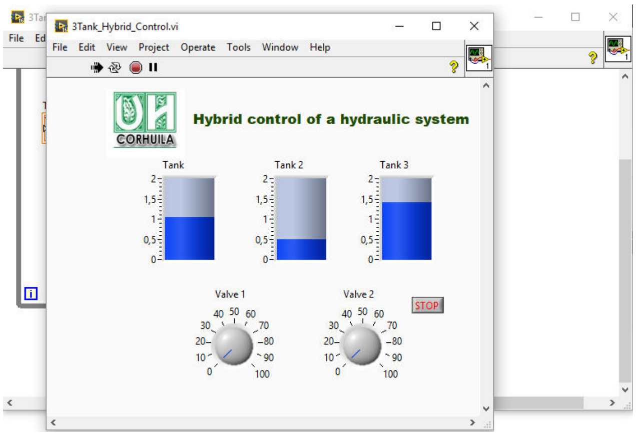


Figure-8. Front panel developed in Labview of the display hybrid control system.

The following program code developed in G language shows the configuration of the tasks developed for the start of operation of the hydraulic system. The start of the electro valves, the filling of the tanks, the starting of the sensors, the communication with the embedded MyRIO system, among others.

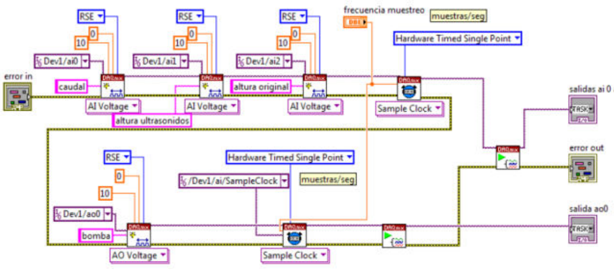


Figure-9. Configurator of the starting tasks of the hybrid control system of the coupled tanks implemented in Labview.

Figure-10 shows the supervisor system $G_s(s)$ refers to software technology programmable in G language capable of performing the switching based on the previously implemented control algorithm.

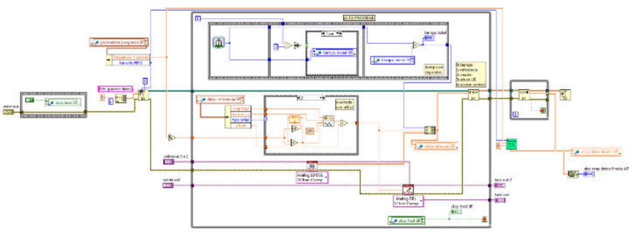


Figure-10. Part the supervisor system developed in Labview.

The level sensor is used by radar, Micropilot FMR20, it has the following characteristics: Temperature: -40 to +80 ° C (-40 to +176 ° F), Pressure: -1 to +3 bar (-14.5 a +43 psi), Accuracy: ± 2 mm. Likewise, the valve model 750-80-X is used as a hydraulic operation level control valve. Below is the code in Labview G language developed for the configuration of the previous devices.

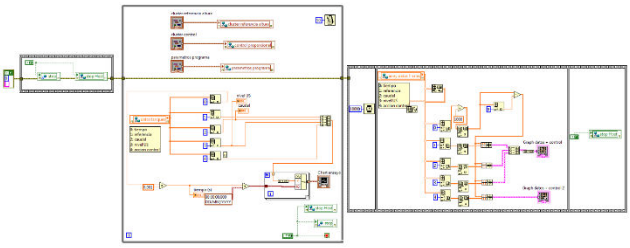
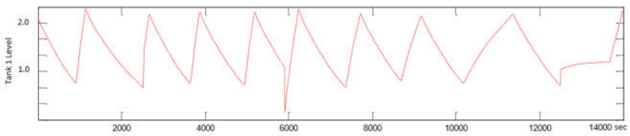
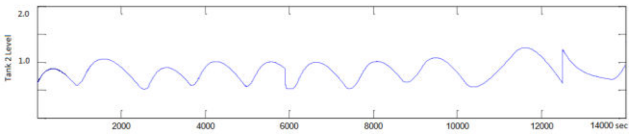


Figure-11. Configuration of the instrumentation devices of the hydraulic system.

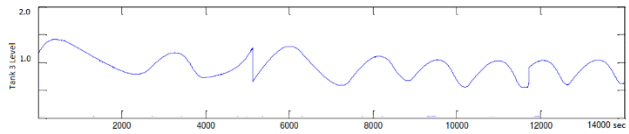
The following graphs correspond to the level of the three coupled tanks of the hydraulic system using the optimal hybrid control. Figure-11 (a) shows the behavior of the level of tank 1 that is affected by the flow of liquid delivered by the valve or key 1, represented by the red line. (b) and (c) represent the behavior of tanks 2 and 3, respectively and (d) the position of control valve 1, with green color.



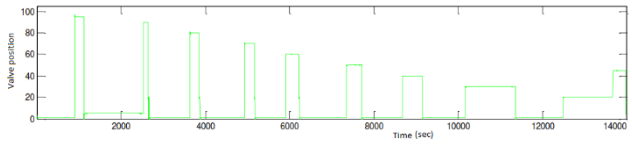
(a)



(b)



(c)



(d)

Figure-12. Configuration of the instrumentation devices of the hydraulic system.

CONCLUSIONS

In the development of optimal hybrid system control, the stability of the system could be guaranteed a priori using the Hamiltonian. One of the problems found in this implementation of the control was the discontinuities in the control actions that in the future could cause damage to the actuator, as a solution to this, it was proposed to tune LQR controllers for each submodel of the dynamic hybrid system and subsequently guarantee the stability of the system through the Ricatti equation.

The results through the optimal hybrid system were acceptable, allowing the reduction of the discontinuities in the control signal with respect to the obtained with the Maximum Principle of Pontryagin.

It can also be seen that these control signals are not saturated, which allows the system pump not to work in extreme conditions.

For future work the modification of the Hamiltonian in its hybrid version is proposed, with the objective that the control to be used is an observer of states, this in order to guarantee the stability of the system a priori and the discontinuities in the actions of control can be worked through the method proposed in [11].

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