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Real-Time Implementation of Constrained Control System on Experimental Hybrid Plant Using RT-Lab

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Abstract— **In a real system, constraints develop due to different reasons such as actuator limits and safety requirements. The design a control system that achieves system constraints without considerable effect on the overall system performance is called constrained control system. Many techniques for designing a control system with constraints are scattered in literature. Some of them are implemented here. Controller design with constraints requires a real-time and fast operating system in order to achieve its goal successfully. RT-Lab is a real time operating system that runs in target and host node. The main feature and components of RT-lab are introduced. Moreover, two different techniques of control design with constraints are discussed and implemented on an experimental hybrid plant using RT-Lab.**

I. Introduction

THE objective of constrained control system is to fulfill the constraints in addition to achieve acceptable performance. No doubt most real processes have constraints due to different reasons such as safety requirements, actuator and sensor limits, uncertainties, etc. Many techniques to design constrained control are scattered in literature. Most of them based on optimal control principles. Model Predictive Control (MPC) [1]-[3] and invariant set theory [4].

To achieve the required performance the system may violate these constraints due to external effect such as large disturbance and faults. The ability to handle explicitly hard constraints on control and states signals may be viewed as one of the major factors of the success of MPC in process control. Although constraints improve the appeal of MPC as an advanced control strategy, they make difficult the controller implementation [4]. The main drawbacks of such type of control design are first, the computation burden is high so it is mainly applied in slow process; second, the infeasibilities of MPC, which means that there is no solution of the MPC that minimize the objective function and satisfies the constraints [2]. Some approaches to deal with the infeasibilities are addressed by different ways see for example,[4]-[6],[7].

Invariant sets play a central role in control problem with control and state constraints. That is because constraints violations can be avoided if and only if the initial state belongs to a controlled invariant set, associated to a stabilizing state feedback control law. The key issue for using the invariant sets principle is the determination of the invariant set [4]. Determination of the invariant set is not easy especially for large scale system. Moreover, for some system it is difficult to obtain a linear feedback control law which maintains the state within this invariant set.

The adaptive control can also be used for constrained control design [16]. The necessary and sufficient condition to design and adapt a controller, which achieve the system performance and satisfies the constraints by recovering the system state to the safe operation region using the concept of Dynamic Safety Margin (DSM) [9] are discussed in [8]. Since PID controller is one of the most popular controller in real application, its parameter tuning to fulfill system constraints is introduced [8].

Since most of the constrained control design scattered in literature require high computation burden, fast operating system is required to implement these techniques.

The majority of the real processes have hybrid characteristics due to the combination of binary and continuous variables in particular batch processes. Binary variables such as the on off values, sensors, limit switches, etc. The hybrid characteristic makes that it is difficult to model the system using single continuous model. Therefore, the system is modeled by a set of models combined together according to the binary variables as shown in (1)

$$M = M_1\delta_1 + M_2\delta_2 + M_3\delta_3 + \cdots + M_n\delta_n \quad (1)$$

where M is the system model, M_i is the model number i, δ_i is the binary variables number i, $i \in \{1, 2, \ldots, n\}$and n is the number of models. M_i is active when δ_i is high.

Modeling, analysis and control design of a hybrid system is an interesting and open field see for example [10] for more details.

Control design for constrained hybrid system bases mainly on optimal control specially MPC [11].

Since hybrid plat requires multi tasks that have to be executed at the same time such as fault diagnosis, supervision, control design, adaptation, etc…, a real time operating system is required in order to achieve all tasks within the specified time. Constrained controller is one of these tasks, which requires fast processing as discussed before. Therefore, a fast and real-time operating system is required in order to implements multi tasks of hybrid plant.

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Host/Target configuration is the most common configuration to implement real time systems. The host is a digital computer not necessary with real-time requirements, which represent Human Machine Interface (HMI). The real time system runs in the target, which can be an embedded system based on a board with DSP (Digital Signal Processing), Micro-controller, or a second PC [12]. RT-lab is one of the real/timed systems that have the target-host configuration.

Since most of the constrained control approaches are theoretical but they have not been implemented in real system yet, as far as I know, MPC and adapted control system are implemented on an experimental hybrid plant, as two different constrained control design techniques, using RT-Lab in this paper.

The paper is organized as follows: RT-Lab configuration is described in section 2. The experimental setup configuration and modeling are described in Section 3. It is followed by Section 4, constrained control system using MPC and adapted PID are discussed. The practical results implementation is illustrated in section 5. Finally, a conclusion is highlighted in Section 6.

I. RT-LAB CONFIGURATION

RT-LAB is an industrial-grade software package for engineers who use mathematical block diagrams for simulation, control and related applications. The software use popular programming tools such as MATLAB/Simulink and works with viewers such as Lab VIEW and programming languages including C++.

RT-LAB allows the user to readily convert Simulink Models to real-time simulations, via Real-Time Workshop (RTW) and run them over one or more PC processors. This is used particularly for Hardware-in-the-Loop (HIL) and rapid control prototyping applications. For more details see [14].

A. Hardware Configuration

RT-LAB software runs on a hardware configuration consisting of command station (host node), target nodes, the communication links (real-time and Ethernet), and the I/O boards.

1) The Command Station

The command station is a PC workstation that operates under Windows, and serves as the user interface. The command station allows users to: edit and modify models; see model data; run the original model under its simulation software (Simulink, SystemBuild, etc.); generate and separate code; and control the simulator's Go/Stop sequences.

2) Target nodes

The target nodes are real-time processing and communication computers that use commercial processors interconnected by an Ethernet adapter.

The real-time target nodes perform:

- Real-time execution of the model's simulation;
- Real-time communication between the nodes and I/Os;
- Acquisition of the model's internal variables and external outputs through I/O modules;

The system may have a single target or multiple target configurations according to the size of the controlled process

Single target configuration, as shown in Fig. 1, is typically used for rapid control prototyping, in which a single computer runs the plant simulation or control logic. One or more hosts may connect to the target via an Ethernet link. The target can either run QNX or RedHawk Linux for applications where real-time performance is required or for fast simulations, or Windows XP as a simulation accelerator.

Fig. 1 Single target node

Single target configuration (Fig. 1) is sufficient for the application of the described laboratory process. The command node and target node are commercial PC's with different operating system. A PCI-626 I/O card (from Sensory Company Inc.) is used which satisfies all I/O requirements. Moreover, it is supported by QNX real-time operating system. In this configuration the only communication link used is between the target and command station using Ethernet communication.

B. Software Configuration

For the above configuration of RT-Lab, the software in the command station (console) is Windows XP, and the simulation software is Matlab-Simulink to program the simulation and control tasks. The simulation program is coded into C code in the consol unit and transferred to the target node, which has QNX operating system [13]. The target unit compiles and executes the C code file in parallel with the simulation program in the console. The data is transferred on-line between the target and console throw communication Ethernet. In the consol station, the program is written in two main blocks (Consol-Master) as shown in Fig. 2.

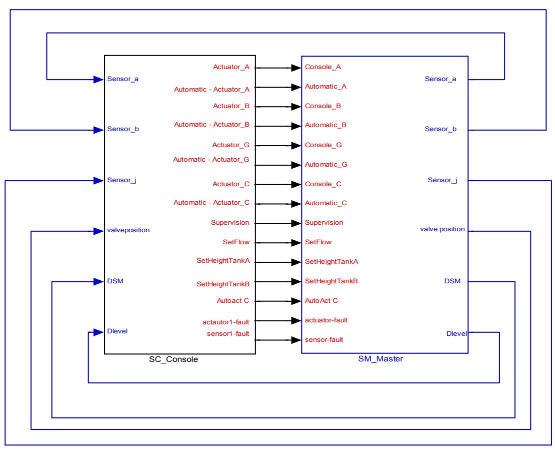

Fig. 2 Consol-master connection

II. PLANT DESCRIPTION

Fig. 3 shows an overview of the set-up. The plant consists essentially of two tanks of 100 l, a sump of 300 l, a pump (11kW), a heat exchanger, three control valves, seven on/off valves, six temperature sensors, three level sensors, 3 pressure sensors, and one flow rate sensor. All these components are industrial ones. Valves are actuated by compressed air and all signals sensor/actuator and the computer systems are transmitted by using 4-20 mA standards. The plant works as follows: water is pumped from the sump and it circulates around the plant following a selected (by on/off valves) path to come back to the sump closing the loop. The pump works at a constant rotational speed and the flow rate is controlled by means of an electric modulating valve. Manual/automatic valves are used to change parameters and select different operating points.

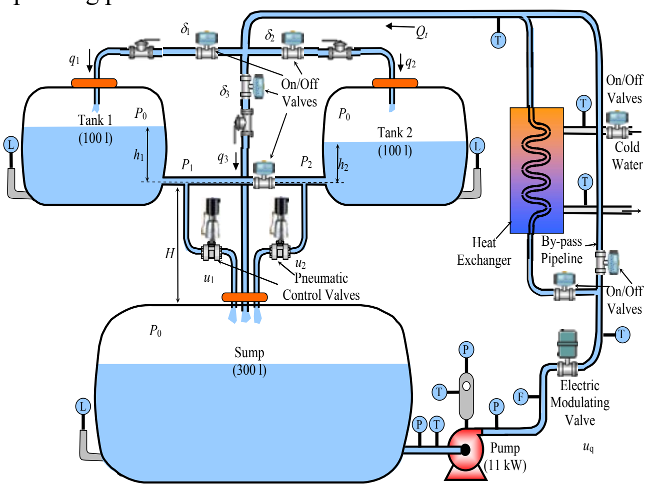

Fig. 3 Schematic diagram of two tank system

The hybrid characteristics of the plant are obtained due to the existence of discrete inputs, outputs and discrete control signal in addition to the continuous input and output signals. The combination of discrete and continuous signals makes the dynamical model is not fixed but varies according to the discrete state.

The process has the ability to be controlled either manually using on/off switches and proportional analog tuner or automatically using PC control program.

The complete hybrid model of the two-tank system without considering the heat-exchange unit, is derived in [12] as follow:

$$\frac{dh_1}{dt} = \frac{1}{A(h_1)}(\delta_1 q_{i1} - q_1(t)) \quad (2)$$

$$\frac{dh_2}{dt} = \frac{1}{A(h_2)}(\delta_2 q_{i2} - q_1(t)) \quad (3)$$

Where $q_1(t) = C_1\sqrt{\rho g h_1 + (P_0 - P_1)}$, (4)

$$q_2(t) = C_2\sqrt{\rho g h_2 + (P_o - P_2)} \quad (5)$$

The outflow rates are given by

$$q_{o1}(t) = C_{v1}K_{u1}\sqrt{\rho g H + (P_1 - P_o)}u_1(t) \quad (6)$$

$$q_{o2}(t) = C_{v2}K_{u2}\sqrt{\rho g H + (P_2 - P_o)}u_2(t) \quad (7)$$

$$Q_t = \delta_1 q_{i1} + \delta_2 q_{i2} + \delta_3 q_{i3} \quad (8)$$

q_{i1}, q_{i2}, and q_{i3} are the input flow to the tank number 1, 2 and the sump tank respectively; h_1 and h_2 are the levels in the first and second tank respectively; u_1 and u_2 are the input signals to the control valves of each tank; k_{u1} and k_{u2} are constant factors of the valves; C_1 and C_2 are the overall conductance of each tank; C_{v1} and C_{v2} are the conductance of the control valve 1 and 2; H is the height of the pipeline; δ_1, δ_2 and δ_3 are discrete signals $\in\{0,1\}$ that represent the state of each discrete valve feeding each tank, 0 means that the valve is closed and contrarily 1 is open; Q_t is the total input flow controlled by the flow valve.

The flow rates must satisfy mass balance equations, i.e.

$$q_1 = q_{1o} + q_{12} \text{ and } q_2 = q_{2o} - q_{12} \quad (9)$$

Where $q_{12} = \delta_{12}\,\mathrm{sgn}(P_1 - P_2)C_{12}\sqrt{|P_1 - P_2|}$ (10)

C_{12} is the conductance of the inter-connected valve; δ_{12} is the discrete signal $\in\{0,1\}$ that represent the state of each interconnected valve

The model of the two-tank system could be approximated as follows:

$$\frac{dh_1}{dt} = \frac{1}{A(h_1)}\begin{pmatrix}\delta_1 q_{i1} - C_{v1}K_{u1}\sqrt{\rho g(h_1 + H)}u_1 \\ -\delta_{12}sig(h_1 - h_2)C_{12}\sqrt{\delta g|h_1 - h_2|}\end{pmatrix} \quad (11)$$

$$\frac{dh_2}{dt} = \frac{1}{A(h_2)}\begin{pmatrix}\delta_2 q_{i2} - C_{v2}K_{u2}\sqrt{\rho g(h_2 + H)}u_2 \\ +\delta_{12}sig(h_1 - h_2)C_{12}\sqrt{\delta g|h_1 - h_2|}\end{pmatrix}$$

In our experiments, the setup is set as one-tank or two-tank configuration. The input flow (Q_t) is set to 1 l/sec by controlling the flow value (u_v) either manual or automatic. In one-tank configuration, the discrete signals δ_2 , δ_3 and δ_{12} are set to zero, while δ_1 is set to one, i.e. $Q_t = q_1$=1 l/s and q_{12}=0. The level is controlled through the outflow control valve (u_1). The system is nonlinear and the discrete linearized state space model at the operating point (h_1=0.3m, u_1=50%) of one-tank is shown in Table 1 [15]. The discrete linear model is a second order that represents the dynamic of the tank and the valve movements.

In two tank configuration, the discrete signals δ_2 ,and δ_3 are set to zero, while δ_1 and δ_{12} are set to one, i.e. $Q_t = q_1$=1 l/s and q_{12} is calculated from (10). The linearized discrete model of two tank system about the operating point ($h_1 = h_2$=0.3m, u_1=35% and u_2=10%) is shown in Table 2. The control input is u1, and the input u_2 represents the load disturbance or leakage. The controlled variable, in this case, is h_1, while h_2 is floating.

TABLE 1: LINEAR STATE-SPACE MODEL OF THE ONE-TANK SYSTEM

A	B
$\begin{bmatrix}0.999741 & -6.94e-4 \\ 0 & 0.740818\end{bmatrix}$	$\begin{bmatrix}-1.0932e-5 \\ 0.25918177\end{bmatrix}$
C	D
$\begin{bmatrix}1 & 0\end{bmatrix}$	$\begin{bmatrix}0\end{bmatrix}$

TABLE 2 LINEAR STATE SPACE MODEL OF TWO TANK SYSTEM MODEL

A	B

$\begin{bmatrix} 0.9748 & 0.0019 & -0.0146 \\ -0.1616 & -0.2104 & 0.5555 \\ -2.4323 & -1.1408 & 0.2307 \end{bmatrix}$	$\begin{bmatrix} -0.0004 \\ -0.0105 \\ -0.0173 \end{bmatrix}$
C	D
[1 0 0]	[0]

Based on the experimental measurements of the system operation the safe operation region is defined as follow:

one-tank system operation

$$\begin{aligned} &dh_1/dt + 0.8\, v_i - 0.08 \le 0; \\ &dh1/dt + 0.75\, v_i + 0.14 \ge 0; \\ &-0.4 \le dh_1/dt \le 0.4; \\ &-0.5 \le v_i \le 0.5, \\ &0.25 \le h_1 \le 0.35 \end{aligned} \qquad (12)$$

two-tank system operation

The safe operation region is defined by the same constraints of the one-tank configuration, in addition to the following constraint:

$0. \le (h_1 - h_2) \le 0.05$.

where the valve opening is normalized within [-0.5, 0.5] i.e. 0.5 means fully opened and -0.5 completely closed. The level rate change (dh_1/dt) is in [mm/s].

Note that, the state vector is x= $[h_1\ h_2\ v_i]^T$ in case of two tank system and $\mathbf{x} = [h_1 \quad v_i]^T$ in case of one tank system

III. CONSTRAINED CONTROL SYSTEM

The system state with constraints can be defined as

$$x(k) = Ax(k) + Bu(k)$$

$$u(k) = Cx(k)$$

Subject to

$$x \in \Phi$$

where $\Phi \subset R^n, \Phi = \{x | A_c x(k) - Cc \ge 0\}$

These constraints can be defined by the distance vector between the current state the constraints boundaries

$$d = d_c - D_a x(k) \qquad (13)$$

Where

$$d_i(k) = \frac{C_c(i) - A_c(i)x(k)}{\|A_c(i)\|}$$

and $d \ge 0$ if and only if $x \in \Phi$

Therefore, the controller which satisfies the constraints should achieve the performance specification in addition to $d \ge 0$.

A. Model Predictive Control with constraints

The control law of predictive controllers with constraints, for a system defined by the state-space model, is obtained by minimizing the 2-norm measure of the predicted performance given by

$$J = \sum_{i=N_1}^{N} \left\|\hat{\mathbf{e}}(i+k|k)\right\|_{Q_i}^2 + \sum_{i=0}^{N_u-1} \left\|\mathbf{u}(i+k)\right\|_{R_i}^2 \qquad (14)$$

subject to

$$\left.\begin{aligned} &\mathbf{x}(k+1) = \mathbf{A}\,\mathbf{x}(k) + \mathbf{B}\,\mathbf{u}(k) \\ &\mathbf{y}(k) = \mathbf{C}\,\mathbf{x}(k) + \mathbf{D}\,\mathbf{u}(k) \\ &\hat{\mathbf{d}}(k+1|k) \ge 0 \\ &\mathbf{u}_{\min} \le \mathbf{u}(k+i) \le \mathbf{u}_{\max} \end{aligned}\right\} \qquad (15)$$

where $\underset{\rightarrow}{\mathbf{u}} = [\mathbf{u}(k)\,\mathbf{u}(k+1)\cdots\mathbf{u}(k+N_u-1)]^T \in \Re^{r.N_u}$,

$\hat{\mathbf{e}}(k+i|k) = \mathbf{y}_d(k+i) - \hat{\mathbf{y}}(k+i|k)$, and $\|\mathbf{e}\|_Q^2 = \mathbf{e}^T\mathbf{Q}\,\mathbf{e}$.

$\hat{\mathbf{e}}(k+i|k) \in \Re^m$ is the predicted error between the desired and predicted response. x∈ℜn is the system state vector; yd∈ℜm is the reference output vector. $\hat{\mathbf{x}}(k+i|k)$ is the prediction of $\mathbf{x}(k+i)$ made at instance k, $\hat{d}(k+1|k) \ge 0$ is the prediction of distance vector between the constraints. **A**, **B**, **C** and **D** are the system parameter matrices of adequate dimensions. $\mathbf{Q}_i$ are error weighting matrices, Ri are input weighting matrices. N, N_1 and Nu are the maximum, minimum and control horizons, respectively. Notice that **Q**, **R**, N, N_1 and N_u are free design parameters.

The solution of defined MPC are explained in[16] and [17]

B. Adaptive PID controller for constrained control system

The PID controller is one of the popular controllers used in more than 80% of industrial SISO process. The reason is that the PID control has a simple structure, which is easy to be understood by field engineers, and it is robust to disturbance and system uncertainty.

To generalize the method, consider a MIMO system with the number of input is equal to the output, and the system is represented by a state space model (15). The control law is represented in the form

$$\mathbf{u}(k) = \mathbf{K}_P\mathbf{e}(k) + (T/2)\mathbf{K}_I \sum_{j=1}^{k}(\mathbf{e}(j) + \mathbf{e}(j-1)) + \mathbf{K}_D\frac{\mathbf{e}(k) - \mathbf{e}(k-1)}{T} \qquad (16)$$

Define a new state vector

$$\mathbf{x}_t = [\mathbf{x} \quad \mathbf{z}]^T, \qquad (17)$$

$$\mathbf{z}(k) = \begin{bmatrix} \mathbf{e}(k) & \sum_{j=0}^{k-1}\mathbf{e}(j) & \mathbf{e}(k-1) \end{bmatrix}^T$$

The new state space model in this case will be

$$\mathbf{x}(k+1) = [\mathbf{A} \quad \mathbf{BK}]\begin{bmatrix}\mathbf{x}(k) \\ \mathbf{z}(k)\end{bmatrix} \qquad (18)$$

where

$$\mathbf{K} = [\mathbf{K}_1 \quad \mathbf{K}_2 \quad \mathbf{K}_3]$$

$$\mathbf{K}_1 = [\mathbf{K}_P + (T/2)\mathbf{K}_I + (1/T)\mathbf{K}_D]$$

$$\mathbf{K}_2 = [(T/2)\mathbf{K}_I - (1/T)\mathbf{K}_D]$$

$$\mathbf{K}_3 = [(T/2)\mathbf{K}_I]$$

K_P, K_I, and K_D are the controller proportional; integral; and derivative gains respectively.

The control problem, here, is to obtain the vector K which achieve the system constraints in addition to the control objective. The techniques to design and adapt K are discussed in [8]. The method is stated here briefly.

Suppose that the number of constraints is q and the violated constraints is v then the violated distance vector $\mathbf{d}_v$ is obtained from () as

$\mathbf{d}_v(k+1) = \mathbf{d}_a^v - \mathbf{D}_a^v \mathbf{x}(k+1)$, where $\mathbf{D}_a^v \in \Re^{vxn} \subseteq \mathbf{D}_a \in \Re^{qxn}$ and $\mathbf{d}_a^v \in \Re^{vx1} \subseteq \mathbf{d}_a \in \Re^{qx1}$.

The condition to recover the violated constraints should be

$$\mathbf{d}_v(k+1) - \mathbf{d}_v(k) > 0$$

which implies that

$$-\mathbf{D}_a^v(\mathbf{A}-\mathbf{I})\mathbf{x}(k) - \mathbf{D}_a^v \mathbf{ABKz}(k) < 0 \qquad (19)$$

the controller gains, **K,** which satisfy (19) is the controller parameters that improve the constraints**.** The solution of these inequalities depends on the current state vector. Therefore this inequality has to be solved on line each sample.

It is difficult to find the gain **K**, which satisfies (19). Therefore adapting K based on the distance vector can be simplify the solution. The adapted parameter can be obtained by

$$\left.\begin{aligned} k_P(k+1) &= k_P(k) + \alpha_P \left\|(-\mathbf{D}_a^v \mathbf{b} e(k))\right\|_\infty \\ k_I(k+1) &= k_I(k) + \alpha_I \left\|(-\mathbf{D}_a^v(\mathbf{b}\sum_{j=1}^{k} e(j)))\right\|_\infty \\ k_D(k+1) &= k_D(k) + \alpha_D \left\|(-\mathbf{D}_a^v(\mathbf{b}\frac{e(k)-e(k-1)}{T}))\right\|_\infty \end{aligned}\right\} \qquad (22)$$

where α_P, α_I and α_D are the adaptation parameters of the proportional, integral and derivative gain respectively.

The initial values of the controller parameters are designed in order to satisfy the output performance in normal operation.

IV. EXPERIMENTAL RESULTS

Adapted PID and MPC based on constraints are tested, which are explained in section 4.

In this experiment, the plant is configured (Fig. 3) where the level in the left tank (h) was selected as controlled variable and the control signal u is applied to the left control valve. On the right tank, the valve was selected at a variable opening to simulate different load disturbance (output flow) of the left tank. The interconnecting valve is commanded according to the following criteria: the valve becomes off, before the level in the left tank reaches the desired value and then on after that (Fig. 4). At the first instance, the plant behaves as a one-tank system until the level of the left tank reaches a certain steady state limit and two-tank system after the interconnected valve is opened. Fig. 4 shows the hybrid automaton of this experiment.

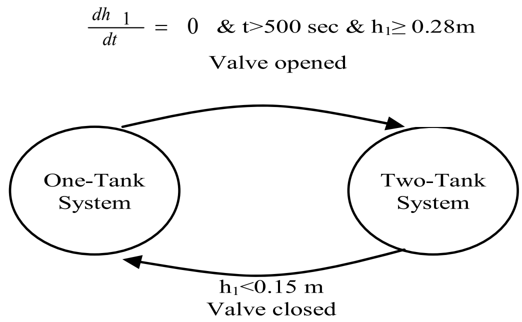

Fig. 4 Hybird automaton of two-tank system

Fig. 5 shows the real time response and control signal variation using fixed PID controller parameters (K_P=4, K_I=0.08, K_D=0.1), and the disturbance valve was opened with the sequence 0%, 10%, 30%, 50% and 40% respectively.

Fig. 6 shows the real-time response and control signal using linear adapted proportional gain of the PID controller as in (13) with the same disturbances as Fig. 5, where adapting parameter α_{Kp}=2. Comparing the two responses (fixed PID parameters and adapted proportional PID), it is clear that in case of one-tank or two-tank system, the system response using adapted PID controller based on safety boundary is better than fixed PID, for either a normal or a disturbed system. The results insure that considering DSM in adapting controller parameters improves system performance.

The level responses of Fig. 5 and Fig. 6 have not changed with leakage 10% and 30%, but it began to change with 50% leakage with small rate and recovered at 40% leakage.

It is clear that adapting controller parameters, based on DSM, improves the system output performance and can help in safety control of safety critical system.

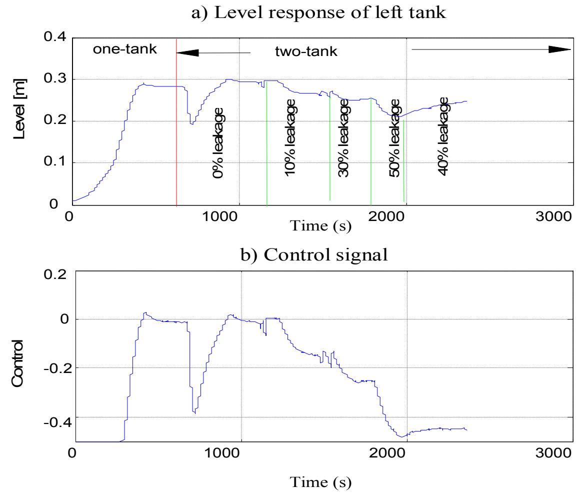

Fig. 5 Level respons using fixed PID parameters

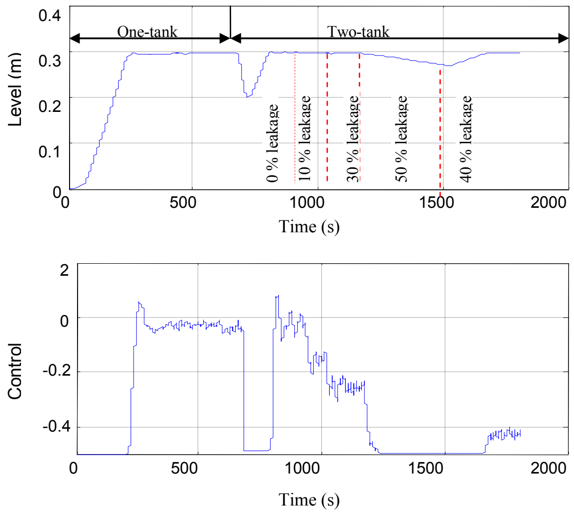

Fig. 6 Level response using adapted PID parameter

The MPC design with and without constraints, either soft or hard, are discussed [17]. In the current experiment, the interconnecting valve is fully opened, the disturbance valve was adjusted to simulate a different load discharge disturbance and the control valve, of the first tank, is used to adjust the level in both tanks.

Fig. 7 shows the MPC responses using two different MPC controllers when there is a disturbance in the control value by 20% bias. For the first disturbance the MPC without constraints is used. The other controller is MPC with constraints for the second disturbance. It is clear that the constrained MPC controller recovers the system performance faster that normal MPC.

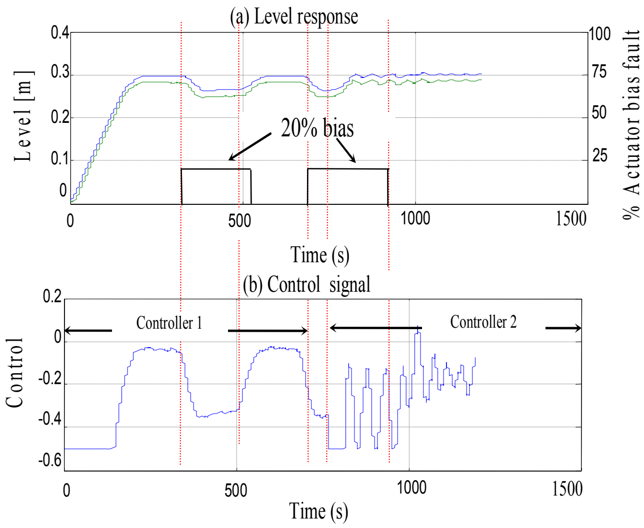

Fig. 7 MPC responses with and without constraints

V. CONCLUSION

The RT-lab real time system is used to implement the control design with constraints for hybrid laboratory pant. The main feature and configuration of RT_Lab are introduced. The process description, which consists of two tank system, is stated. The hardware and software required to implement the control tasks of the process are explained. Several experiments have been tested on the process in order to show the useful ness of RT-Lab and the stated control design technique.

Two types of controller design for constrained system are tested, PID and MPC. Adapting PID controller improves the system response, mainly the system that is exposed to non-considerable and non-measurable disturbance, whether the system model is well known or there is uncertainty in the system parameters. The main advantage of this adaptation method is that the exact model of the system is less important, and we do not need to identify the system parameter each time to reconfigure the controller. The purpose of the paper is not to compare between the techniques for control design with constraints but to state some of them and show how to implement using RT-Lab.

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