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Design and Implementation of LMI-Based H2 Control for Vertical Nonlinear Coupled-Tank System

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ABSTRACT

This paper presents the mathematical design and implementation of a robust H2 output feedback controller for the vertical nonlinear coupled-tank system. Considering the growth of the complicated chemical processes in industries in the last decades, the necessity for the controllers with high robustness and proficiency is demanded. Therefore, to overcome some deficiencies of classical controllers such as proportional integral (PI), the robust H2 output feedback controller is proposed to control the liquid level of the coupled tank system benchmark. Because of the nonlinearity of the system and the interactions between two tanks, the behavior of the controller in terms of the performance and disturbance rejection is on the main scene. The linear matrix inequalities (LMI) is used to derive the design procedure. The effectiveness of the proposed approach in the setpoint tracking is highlighted in comparison with the PI plus feedforward controller and the acceptable results are achieved.

KEYWORDS

H2 Controller, LMI, Mean Absolute Error, Nonlinear Model, Order Reduction, Output Feedback, PI+Feedforward, Robust Performance, Vertical Coupled-Tank

INTRODUCTION

In the last decades, the complexity of the chemical processes in the industries has undeniable growth and the need for appropriate controllers to control these complicated processes properly is highlighted as the main scenario (Aslani, Akbari, & Tabasi, 2018; Salima, Loubna, & Riad, 2018). The common and well-known controllers such as Proportional Integral (PI) and Linear Quadratic Regulator (LQR) have the main role in the control of chemical processes such as level, flow, or pressure control in the industries because of their low cost of implementation. On the other hand, considering the complexity and the nonlinear characteristics of the processes, the performance of this type of conventional controller decreases. Therefore according to the low performance of the abovementioned control methods as their disadvantage, the need for the robust, fast and high-performance controllers is

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increased. To study and analyse the behaviour and performance of different control strategies in process systems, the coupled-tank system is designed and implemented as one of the well-known benchmark systems in control of the nonlinear processes. Goutta, Said, Barhoumi, and M'Sahli (2015) propose the Observer-based Backstepping controller for the coupled-tank system in comparison with the PID controller. In this research, a robust controller based on backstepping strategy is designed to obtain the stabilization of the nonlinear system. The simulation and experimental results show a good improvement in the tank level tracking in comparison with the PID controller, but tracking error is considerable and the output signals are not smooth enough. Jaafar, Hussien, Selamat, Aras, and Rashid (2014) introduce a new conventional PID controller. Considering the fact that the parameter tuning of the PID controller is done with traditional methods such as Z-N and auto-tuning based on the try and error, it will be time-consuming to obtain good gains of the controllers. Therefore, the optimization methodology is proposed and used to achieve the optimal parameters of the controller. Saad, Albagul, and Abueejela (2014) introduce a comparison study between the PI and Model Reference Adaptive Control (MRAC) controllers to control the liquid level on the second tank of the coupled-tank system. The simulation results show that the MRAC approach has a better performance than the conventional PI controller in the steady-state and transient regions of the system response. In the other research, a comparison study between the well-known PID and LQR controllers using PSE(Particle Swarm Optimization) is done (Selamat, Daud, Jaafar, & Shamsudin, 2015) and the results show that the LQR controller gives a better performance compared to PID. The coupled-tank liquid level control system is introduced as one of the best benchmarks in designing the chemical process control approaches. Hence, some of the researches use this framework as the base model in the design and test of the controller performance. In the complicated processes with the nonlinear model of the system, the performance of the aforementioned controllers decreases. To improve the performance of these common controllers, other types of control methodologies such as Sliding Mode Control (SMC) and Neuro-Fuzzy Control (NFC) are considered (Ghabi, Rhif, & Vaidyanathan, 2018; Bouzaida & Sakly, 2018). Basci and Derdiyok (2016) present an experimental research study on the coupled tank system using an adaptive fuzzy controller to control the liquid level in the tanks. The results are compared to a PI controller and have better reference tracking. A chattering-free sliding mode control methodology is proposed for liquid level control (Derdiyok & Basci, 2013). The results are compared to a general sliding mode controller and the proposed methodology gives better experimental performance. In the other research study, the SMC controller with the conditional integrators is proposed to control the liquid level in the quadruple tank system (Prusty, Seshagiri, Pati, & Mahapatra, 2016). The simulation results demonstrate a good level of tracking of the system. These approaches have satisfying reference tracking besides large chattering and energy consumption as their disadvantage.

In literature, the combination of the aforementioned controllers such as PI-Fuzzy control and Fuzzy SMC and some other types are suggested in different studies and similar results are obtained (Arif, 2020; Ghabi et al., 2018). Arun and Mohan (2017), Fang, Shen, and Feng (2009) suggest a new nonlinear fuzzy controller to control and track the flow level in the coupled tank system. In other research work Souran, Abbasi, and Shabaninia (2013) introduced a comparative study between PID and fuzzy controllers. The simulation results show the better performance of the fuzzy controller than the PID one. Some studies have used fractional order methodologies (Nabavi, & Balochian, 2018; Balochian, & Rajaee, 2018) and similar results are obtained.

Also, in some researches, the Genetic Algorithm (GA) is considered to the nonlinear design of the system. These types of controllers have adaptive learning and fault tolerance characteristics, while the learning algorithm is one of their disadvantages, which sometimes increases the response time of the system and needs high memory requirements in the implementation on a digital computer. Multi-objective optimization of the PID controller using a genetic algorithm is proposed is used to control the tank level of the coupled tank system (Singh, Katal, & Modani, 2012). The simulation results of the proposed methodology are compared to a general PID controller and the smoothy reference tracking is obtained. In another work, Wu and Tan (2006) suggest a genetic learning algorithm to set the type-2 fuzzy controller to control the liquid level of the coupled tank system. The experimental results illustrate the improvement and better performance of the proposed approach than the type-1 fuzzy controller does. All of the control approaches mentioned above have their pros and cons. In other words, all of these studies have their own contribution to level tracking and try to maximize the efficiency of their proposed methodologies. In the aforementioned research studies, it's hard to attain to all of the control objectives perfectly such as robustness and the good tracking with minimum error besides the optimal control signal, because of existing conflict and tradeoff between these control goals in the nonlinear model of the system. Therefore, all of these methods try to introduce a better tradeoff between these conflicting design objectives by tuning controller parameters to achieve the desired robustness and performance in the system. In general, considering the difficulties of these controllers in facing with nonlinear systems and to overcome their disadvantages, the H_2 control methodology is proposed in this study to control of the nonlinear model of the coupled-tank system.

The main goal of the controller design in this configuration is to set the liquid level in tank 2 in its set-point level in the existence of two inputs: the pump input and the tank 1 output as the disturbance of the system. The H_2 norm minimizes the Root Mean Square (RMS) of the signal in all frequencies in response to all inputs, especially stochastic inputs such as white noise. Therefore, this characteristic of the H_2 norm helps to improve the design objectives in terms of tracking and regulation. The main objective of the design procedure is good reference tracking besides the minimum control force and energy consumption. Because of the existence of the exogenous inputs in the system such as disturbance and sensor noise, some singularities maybe produce in system state-space equations. Therefore, to overcome these types of mathematical problems the LMIs are used to design the H_2 controller. To illustrate the effectiveness of the proposed methodology, the experimental results are compared to the PI+feedforward controller and the acceptable results are obtained. Also, as most of the other research works mentioned above are done on the horizontal coupled tank system, this study deals with the vertical structure of the system and differs from them. On the other hand, as mentioned before the H_2 output feedback control methodology for the first time is used in this structure.

This paper is structured as follows; in section 2, the model of the coupled-tank benchmark is described. In section 3, the H_2 controller design procedure is introduced in LMIs. Section 4 contains simulation and experimental results compared to the PI+feedforward controller. In section 5, the concluding remarks of this study are presented.

COUPLED-TANK SYSTEM DESCRIPTION

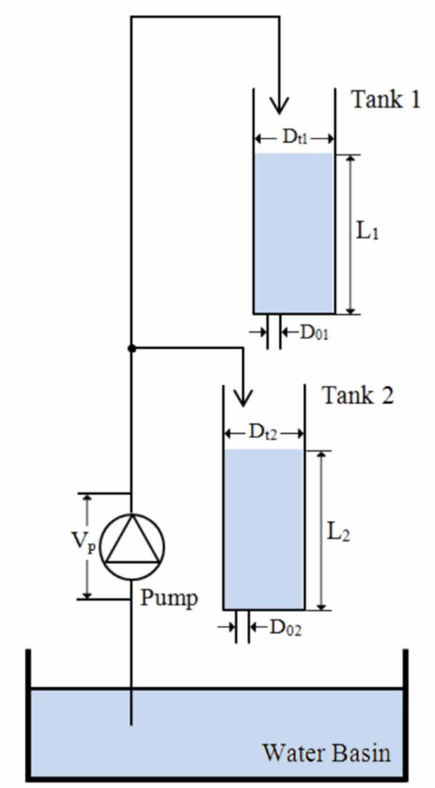
As mentioned in the previous section, control of the liquid level in the second tank of the coupled-tank system is the main purpose in this study and this configuration is shown in Figure 1. In the coupled-tank system, the second tank feeds with two exogenous inputs: the output of tank 1 and the pump input. The pump flow rate is different for each tank and feeds both tanks with the different percentage of a gain parameter named Gamma.

The mathematical model of the tank 1 is calculated as follows:

$$f_{i1} = K_p V_p \tag{1}$$

$$f_{o1} = A_{o1} v_{o1} \tag{2}$$

Figure 1. Coupled-tank system benchmark



where K_p and V_p are the pump volumetric constant and pump voltage, respectively. v_{o1} is the velocity of the outflow from tank 1 and A_{o1} is defined as the cross-sectional area of the tank 1 and calculated from below:

$$A_{o1} = \frac{1}{4}\pi D_{o1}^2 \tag{3}$$

$$v_{o1} = \sqrt{2gL_1} \tag{4}$$

which D_{o1} , g and L_1 represent the tank 1 outlet diameter, gravitational constant ($\cong 980cm / sec^2$) and height of the flow in tank 1, respectively. The outflow of the tank 1 is obtained with substituting the (4) into (2) as follow:

$$f_{o1} = A_{o1}\sqrt{2gL_1} \tag{5}$$

Mass balance principle of the liquid level in tank 1, which is introduced as the difference of the inflow and outflow of the tank, can be written as following first-order differential equation:

$$A_{t1}\left(\frac{\partial}{\partial t}L_1\right) = f_{i1} - f_{o1} \tag{6}$$

where A_{t1} is the inside cross-sectional area of the tank 1. Substituting (3), (4), and (5) in equation (6) gives the state-space equation of the first tank as given below:

$$\frac{\partial}{\partial t}L_1 = -\frac{A_{o1}}{A_{t1}}\sqrt{2gL_1} + \left(1-\gamma\right)\frac{K_p}{A_{t1}}V_p \tag{7}$$

For the bottom tank as named tank 2, the outflow can be calculated as:

$$f_{o2} = A_{o2}v_{o2} \tag{8}$$

where v_{o2} is the velocity of the outflow and described by Bernoulli's formula as:

$$v_{o2} = \sqrt{2gL_2} \tag{9}$$

The cross-sectional area of the second tank is the same one in the first tank as given below:

$$A_{o2} = \frac{1}{4}\pi D_{o2}^2 \tag{10}$$

As shown in Figure 1 the second tank has two inputs that are the outflow of the tank 1 and the pump flow. So input flow of tank 2 is described as below:

$$f_{i2} = f_{o1} + \gamma V_p = A_{o1}\sqrt{2gL_1} + \gamma V_p \tag{11}$$

Hence, the mass balance principle for the second tank is described as a first-order differential equation:

$$A_{t2}\left(\frac{\partial}{\partial t}L_2\right) = f_{i2} - f_{o2} \tag{12}$$

With substituting (8), (9), and (11) in (12) the state-space equation of the second tank is obtained as follow:

$$\frac{\partial}{\partial t}L_2 = \frac{A_{o1}}{A_{t2}}\sqrt{2gL_1} - \frac{A_{o2}}{A_{t2}}\sqrt{2gL_2} + \gamma\frac{K_p}{A_{t2}}V_p \tag{13}$$

Considering the states of the system as the height of the liquid in two tanks, the state-space realization of the system is described below:

$$x_1(t) = L_1$$
$$x_2(t) = L_2$$
$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$A = \begin{bmatrix} -\frac{A_{o1}}{A_{t1}}\sqrt{\frac{g}{2L_{01}}} & 0 \\ \frac{A_{o1}}{A_{t2}}\sqrt{\frac{g}{2L_{01}}} & -\frac{A_{o2}}{A_{t2}}\sqrt{\frac{g}{2L_{02}}} \end{bmatrix},\ B = \begin{bmatrix} (1-\gamma)\frac{K_p}{A_{t1}} \\ \gamma\frac{K_p}{A_{t2}} \end{bmatrix} \tag{14}$$

where the matrixes A and B are obtained by linearization of the nonlinear coupled-tank system around its equilibrium point (L_{01}, L_{02}). The interested readers about the coupled-tank system setup parameters are referred to (Apkarian, 1999). The schematic diagram of the liquid level control system is demonstrated in Figure 2.

LMI-BASED H$_2$ NORM SYNTHESIS

According to the design objectives, the design schematic illustrated in Figure 3 is used. This structure contains the exogenous inputs with their weights and design objectives. Input weights represent the frequency content of the inputs such as noise and the output weight denotes the interested frequencies of controlled output (Esmaeili, Akbari, & Karimi, 2015). These design objectives are listed below:

- **Minimizing tracking error:** The main objective of the controller design is to minimize the tracking error of the liquid level in the second tank beside the disturbance rejection in the system. The importance of this minimization is related to the needed accuracy in the industrial processes.

Figure 2. Schematic diagram of the liquid level control system

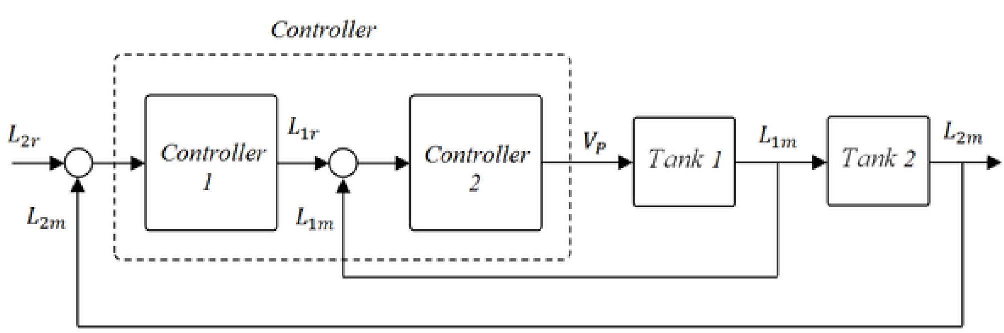
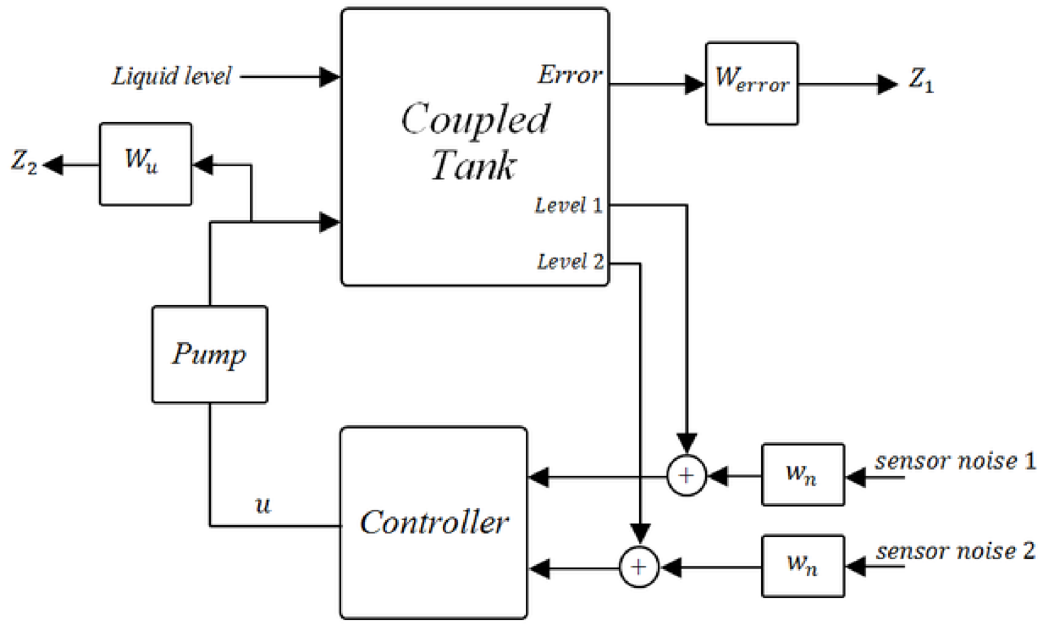


Figure 3. Generalized system block diagram



- **Control signal:** According to the structural constraints presented by the company on the input current of the pump, the designed control force must be limited to its structural bounds. On the other hand, low energy consumption is desirable in the controller designing procedure.

H_2 SYNTHESIS

According to the previous section, some frequency conditions have to be designated related to reducing noise effects around high frequencies to reject the sensors' noise effects. On the other hand, considering the frequency characteristics of the plant, some weights are needed to handle the properties of the controlled outputs.

The augmented system of the coupled-tank system is described below:

$$\dot{x}(t) = Ax(t) + B_1 w(t) + B_2 u(t) \tag{15a}$$

$$z(t) = C_1 x(t) + D_{11} w(t) + D_{12} u(t) \tag{15b}$$

$$y(t) = C_2 x(t) + D_{21} w(t) + D_{22} u(t) \tag{15c}$$

The output feedback controller has to be designed to satisfy the robust stability of the closed-loop system besides improving the performance of the system. So, the controller is described as:

$$K:\begin{cases}\dot{x}_k = A_k x_k + B_k y \\ u = C_k x_k + D_k y\end{cases} \tag{16}$$

where x_k represents the states of the controller. The state-space realization of the closed-loop system is described as following:

$$CL:\begin{bmatrix}\dot{\eta} \\ z\end{bmatrix} = \begin{bmatrix}\mathcal{A}_{cl} & \mathcal{B}_{cl} \\ \mathcal{C}_{cl} & \mathcal{D}_{cl}\end{bmatrix}\begin{bmatrix}\eta \\ w\end{bmatrix} \tag{17}$$

where η is the closed-loop state.

In the following lemma, the closed-loop system stability principle of the H_2 controller is reviewed (Scherer, Gahinet, & Chilali, 1997):

Lemma: The closed-loop system is stable and the H_2 norm from exogenous inputs to controlled outputs is less than γ if and only if there exist symmetric positive definite matrices P and Q satisfying the following inequalities (Scherer et al., 1997):

$$\begin{pmatrix}\mathcal{A}_{cl}P + P\mathcal{A}_{cl}^T & \mathcal{B}_{cl} \\ * & -I\end{pmatrix} \prec 0$$

$$\begin{pmatrix}Q & \mathcal{C}_{cl}P \\ * & P\end{pmatrix} \succ 0 \tag{18}$$

$$Trace\left(Q\right) < \gamma^2,\ \mathcal{D}_{cl} = 0$$

According to the abovementioned lemma, the matrix P is a Lyapunov symmetric positive definite matrix ($P = P^T > 0$) and the Q is defined as the symmetric decision variables matrix. As the inequalities represented in (18) involve Bilinear Matrix Inequality (BMI) in P and controller matrices, so it needs change of parameters and congruence transformation to make changes in these BMIs and changes them to LMIs (Scherer et al., 1997; Xie et al., 2005). To do this, the following introduced new parameters that are affine to the new variables are used (Scherer et al., 1997; Xie & Yao, 2005):

$$\left(P,\begin{pmatrix}A_k & B_k \\ C_k & D_k\end{pmatrix}\right) \rightarrow v = \left(R, S, \begin{pmatrix}K & L \\ M & N\end{pmatrix}\right) \tag{19}$$

$$P \rightarrow P\left(v\right) = \begin{pmatrix}R & I \\ I & S\end{pmatrix} \tag{20}$$

$$\begin{pmatrix} \mathcal{A}_{cl}\mathcal{X} & \mathcal{B}_{cl}\left(v\right) \\ \mathcal{C}_{cl}\mathcal{X} & \mathcal{D}_{cl}\left(v\right) \end{pmatrix} \rightarrow \begin{pmatrix} A\left(v\right) & B\left(v\right) \\ C\left(v\right) & D\left(v\right) \end{pmatrix} \tag{21}$$

Using the above transformation, the new LMIs are produced as below:

$$\begin{pmatrix} AR + RA^T + B_2M + M^TB_2^T & A + K^T + B_2NC_2 & B_1 + B_2ND_{21} \\ * & SA + A^TS + LC_2 + C_2^TL^T & SB_1 + LD_{21} \\ * & * & -I \end{pmatrix} \prec 0$$

$$\begin{pmatrix} Q & C_1R + D_{12}M & C_1 + D_{12}NC_2 \\ * & R & I \\ * & * & S \end{pmatrix} \succ 0 \tag{22}$$

$$Trace\left(Q\right) < \gamma^2, \mathcal{D}_{cl} = 0$$

It is meant from the last condition in (22) that the controller must be strictly proper. These new inequalities depend linearly on controller *K* and Lyapunov matrix *P* with the new variables R, S, K, L, M, N (Xie et al., 2005). The H_2 controller parameters are obtained through an inverse transformation as the follow (Xie et al., 2005):

$$\begin{pmatrix} A_k & B_k \\ C_k & D_k \end{pmatrix} = \begin{pmatrix} U & SB_2 \\ 0 & I \end{pmatrix}^{-1} \begin{pmatrix} K - SAR & L \\ M & N \end{pmatrix} \begin{pmatrix} V^T & 0 \\ CR & N \end{pmatrix} \tag{23}$$

where U, V are nonsingular matrices with $UV^T = I - SR$.

PI+Feedforward Controller

The simulation setup of the PI plus feedforward controller used to control the liquid level in tank 2 is shown in Figure 4. The Proportional Integral gains in this system are gained from the Quanser manufacturer.

As the PI controller compensates small variations such as disturbances from the linearized operating point, so the feedforward action is required. In other words, as illustrated in Figure 4, the level feedforward has the task of the compensation of the liquid level reduction due to the gravity through tank 2, while the PI controller is designed to compensate for the dynamic disturbances. The interested readers are referred to (Astrom & Hagglund, 2004; Ziegler & Nichols, 1942) for more details. The experimental setup of the Quanser coupled-tank system is illustrated in Figure 5.

Simulation and Experimental Results

According to the design objectives and the frequency characteristics of the system's exogenous inputs and the controlled outputs, some weights are added to the system to satisfy the frequency properties of the design procedure of the H_2 controller. In other words, in the pure form, the H_2 norm in all frequencies treats the same. Therefore, these weights help to set the desired objectives across the

Figure 4. Simulation block diagram of PI+feedforward controller

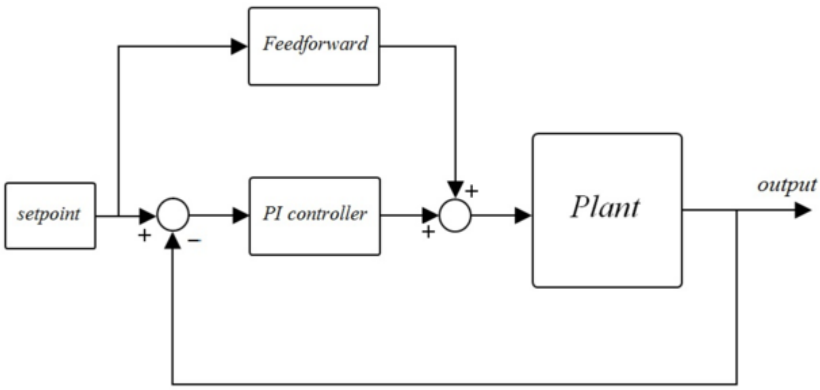


Figure 5. Quanser setup for Coupled-tank system

frequencies. The weights have to cover the frequency properties of their reference input or output and are described as below:

$$W_{error} = \frac{150}{s+90}$$

$$W_n = \frac{2}{s+0.35}$$

$$W_u = 0.0001$$

W_{error} represents the weight on the tracking error as the first objective, W_n and W_u describe as the measurement and the control signal weights, respectively.

As the sensor noise has high-frequency properties, so W_n is chosen as a low-pass filter to eliminate the effects of the noise and make the system robust to the noise effects. To liquidate the possibility of causing a singularity in the controller, the W_u is chosen enough small near to zero. As the added weights to the system increase the order of the designed controller to four, the closed-loop system will have a high order. Therefore, the order reduction methodology has been done on the controller to reduce the order of the controller to order of two. According to the frequency response of the controller and the reduced order one, which is shown in Figure 6, the reduced-order controller maintains the whole frequency properties of the main controller.

Figure 7 illustrates the simulation and experimental results of the H_2 controller compared to the PI+feedforward. Figure 7a includes the simulation results consist of liquid levels in tank 2, reference tracking errors and the pump voltages. Figure 7b contains the experimental results of the real-time process. The setpoint reference liquid level consists of a constant value of 15 cm plus a sinusoidal part with a period of 80 seconds.

According to Figure 7, it is clearly demonstrated that the performance of the PI+feedforward controller in reference tracking is obtained with the big changes in the voltage of the pump as a control signal that is described as a disadvantage of this controller. On the other hand, considering the fast response time and minimum error of the reference tracking by the proposed H_2 controller besides the smooth pump voltage as the objectives of the design procedure, the effectiveness of the proposed approach in the control of the coupled-tank system is motivated.

In Figure 8, a comparison between the two controllers is done in response to the constant input value plus a square signal. In this scenario, the changes in the square part of the input are considered as an input disturbance and the robustness of the H_2 controller is guaranteed. Performances of two controllers are compared in terms of the tracking error and the control signal. As the same in response to the sinusoidal input, in square one, the H_2 control approach has an effective and satisfying performance.

Mean Absolute Error (MAE)

There are various mathematical methods to measure the quality of the system output tracking to the desired setpoint. In other words, to compare and illustrate the effectiveness of the proposed controller it is needed to a mathematical method, which can calculate an error between the setpoint and the experimental output tracking. One of these useful methods is Mean Absolute Error (MAE), which calculates the errors between the desired and experimental data. MAE is calculated as:

Figure 6. Frequency response of the controller and its reduced order

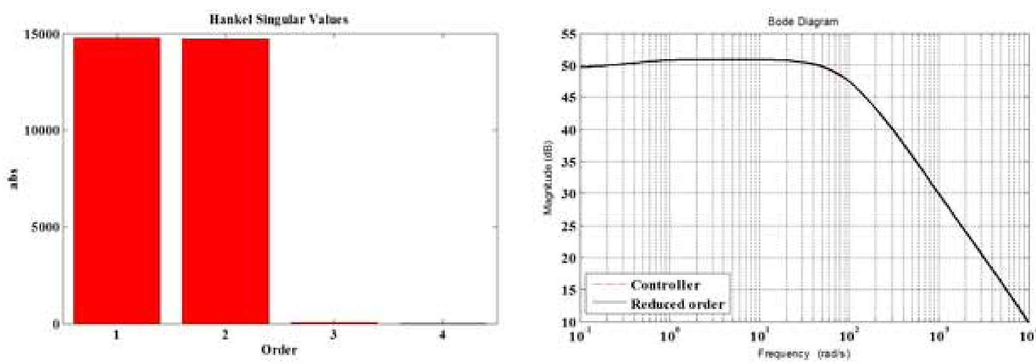
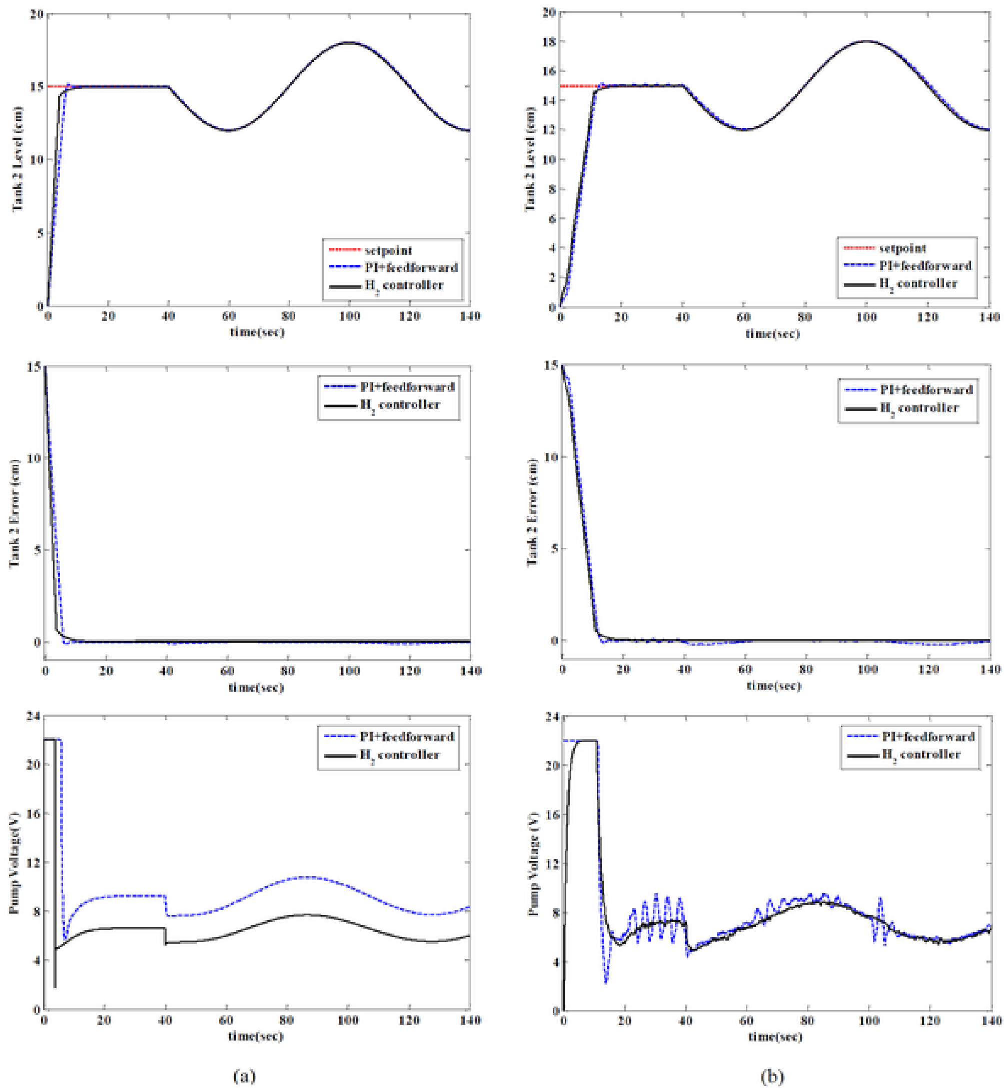


Figure 7. Comparison of H2 and PI+feedforward controllers' performance in response to the constant input plus sinusoidal reference setpoint: a) simulation; b) experimental

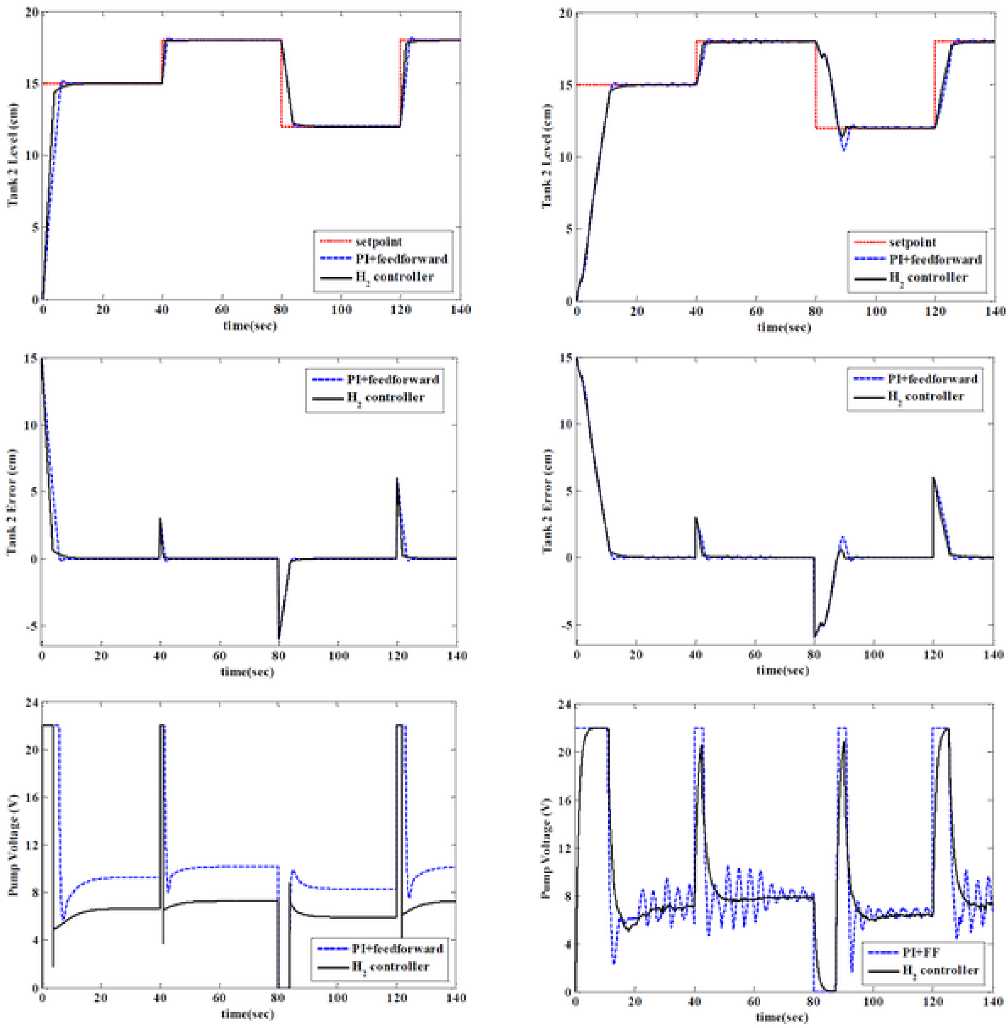


$$MAE = \frac{\sum_{i=1}^{n} \left| y_i - \hat{y}_i \right|}{n} = \frac{\sum_{i=1}^{n} \left| e_i \right|}{n} \tag{24}$$

which y_i is the desired and $\hat{y}_i$ is the experimental value and *n* is the number of samples. The Mean Absolute Error (MAE) of the reference tracking for both controllers is compared in Table 1.

According to the Table 1, it is illustrated that the considerable improvement in the tracking error has been occurred using the H_2 controller. It is also necessary to consider that this improvement is obtained besides the optimized control signal. The improvement in the control signal as one of the

Figure 8. Comparison of H2 and PI+feedforward controllers' performance in response to the constant input plus square reference setpoint: a) simulation; b) experimental



(a) (b)

Table 1. Mean Absolute Error (MAE) of Controllers' Reference Tracking

Controller	Reference Liquid Level of tank 2	
	Constant plus sinusoidal	*Constant plus square*
PI+feedforward	0.7759	1.1046
H_2 controller	0.6520	1.0030
Total improvement	15.97%	9.2%

Table 2. Improvement of the Control Signal of H_2 Controller

Setpoint input	*Constant plus sinusoidal*	*Constant plus square*
Total improvement	68%	142%

control objectives using the proposed H_2 approach is shown in Table 2. The structural limitation of the pump voltage is specified on 0-22 volts.

CONCLUSION

In this study, the LMI-based H_2 controller is proposed to control the liquid level in the second tank of a vertical nonlinear coupled-tank system. As the H_2 norm minimizes the RMS value of the signal's energy in all frequencies and considering the fact that all noises are modeled as white noise, the performance of the H_2 controller in eliminating the effects of the noises and disturbance rejection is taken into consideration. The LMI methodology is used in the H_2 controller designing procedure to eliminate the possibility of singularity in the system. The main objectives of the controller design consist of best reference tracking besides optimal control signal. So, some weights are added to the exogenous inputs and outputs to satisfy the frequency behavior of the design objectives. To highlight the effectiveness of the proposed approach, simulation results are compared to the well-known PI+feedforward controller in terms of the tracking error and the pump voltage as a control signal. Also, to verify the effectiveness and performance of the designed controller in the real world, the controller is tested on the Quanser coupled-tank system. Acceptable improvements of 9-15% and 68-142% in terms of the reference tracking error and the control signal, respectively, are obtained from the proposed methodology compared to the PI+feedforward controller. Besides, according to the output plots of the system, the robust performance of the H_2 controller in disturbance rejection is confirmed. In terms of the robust performance analysis, the robust H_∞ output feedback control is on the point of view as future work and similarly acceptable results in the presence of the system disturbances and uncertainties are expected in terms of robustness and performance.

REFERENCES

Apkarian, J. (1999). *Coupled water tank experiments manual*. Quanser Consulting Inc.

Arif, M. (2020). Fuzzy Modelling and Chaos Control in the Photogravitational Magnetic Binary Problem With Potential From a Belt. *International Journal of System Dynamics Applications*, *9*(3), 26–39. doi:10.4018/IJSDA.2020070102

Arun, N. K., & Mohan, B. M. (2017). Modeling, stability analysis, and computational aspects of some simplest nonlinear fuzzy two-term controllers derived via the center of area/gravity defuzzification. *ISA Transactions*, *70*, 16–29. doi:10.1016/j.isatra.2017.04.023 PMID:28532591

Aslani, A., Akbari, S., & Tabasi, S. (2018). The Robustness of Natural Gas Energy Supply: System Dynamics Modelling. *International Journal of System Dynamics Applications*, *7*(3), 57–71. doi:10.4018/IJSDA.2018070103

Åström, K. J., & Hägglund, T. (2004). Revisiting the Ziegler–Nichols step response method for PID control. *Journal of Process Control*, *14*(6), 635–650. doi:10.1016/j.jprocont.2004.01.002

Balochian, S., & Rajaee, N. (2018). Fractional-Order Optimal Control of Fractional-Order Linear Vibration Systems with Time Delay. *International Journal of System Dynamics Applications*, *7*(3), 72–93. doi:10.4018/IJSDA.2018070104

Başçi, A., & Derdiyok, A. (2016). Implementation of an adaptive fuzzy compensator for coupled tank liquid level control system. *Measurement*, *91*, 12–18. doi:10.1016/j.measurement.2016.05.026

Bouzaida, S., & Sakly, A. (2018). Adaptive Neuro-Fuzzy Sliding Mode Controller. *International Journal of System Dynamics Applications*, *7*(2), 34–54. doi:10.4018/IJSDA.2018040103

Derdiyok, A., & Başçi, A. (2013). The application of chattering-free sliding mode controller in coupled tank liquid-level control system. *Korean Journal of Chemical Engineering*, *30*(3), 540–545. doi:10.1007/s11814-012-0177-y

Esmaeili, J. S., Akbari, A., & Karimi, H. R. (2015). Load-dependent LPV/H2 output-feedback control of semi-active suspension systems equipped with MR damper. *International Journal of Vehicle Design*, *68*(1-3), 119–140. doi:10.1504/IJVD.2015.071077

Fang, X., Shen, T., & Feng, X. (2009, August). The Bang-Bang control of water tank system based on fuzzy decision. In *2009 Ninth International Conference on Hybrid Intelligent Systems* (Vol. 2, pp. 127-131). IEEE. doi:10.1109/HIS.2009.138

Ghabi, J., Rhif, A., & Vaidyanathan, S. (2018). Discrete time sliding mode control scheme for nonlinear systems with bounded uncertainties. *International Journal of System Dynamics Applications*, *7*(2), 15–33. doi:10.4018/IJSDA.2018040102

Gouta, H., Said, S. H., Barhoumi, N., & M'Sahli, F. (2015). Observer-based backstepping controller for a state-coupled two-tank system. *Journal of the Institution of Electronics and Telecommunication Engineers*, *61*(3), 259–268. doi:10.1080/03772063.2015.1018846

Jaafar, H. I., Hussien, S. Y. S., Selamat, N. A., Aras, M. S. M., & Rashid, M. Z. A. (2014). Development of PID controller for controlling desired level of coupled tank system. *International Journal of Innovative Technology and Exploring Engineering*, *3*(9), 32–36.

Nabavi, S. H., & Balochian, S. (2018). The Stability of a class of fractional order switching system with time-delay actuator. *International Journal of System Dynamics Applications*, *7*(1), 85–96. doi:10.4018/IJSDA.2018010105

Prusty, S. B., Seshagiri, S., Pati, U. C., & Mahapatra, K. K. (2016, January). Sliding mode control of coupled tanks using conditional integrators. In *2016 Indian Control Conference (ICC)* (pp. 146-151). IEEE. https://www.quanser.com

Saad, M., Albagul, A., & Abueejela, Y. (2014). Performance comparison between PI and MRAC for coupled-tank system. *Journal of Automation and Control Engineering, 2*(3).

Salima, M., Loubna, A., & Riad, T. (2018). A global stability of linearizing control of induction motor for PV water pumping application. *International Journal of System Dynamics Applications*, *7*(3), 31–56. doi:10.4018/IJSDA.2018070102

Scherer, C., Gahinet, P., & Chilali, M. (1997). Multiobjective output-feedback control via LMI optimization. *IEEE Transactions on Automatic Control*, *42*(7), 896–911. doi:10.1109/9.599969

Selamat, N. A., Daud, F. S., Jaafar, H. I., & Shamsudin, N. H. (2015, March). Comparison of LQR and PID controller tuning using PSO for Coupled Tank System. In *2015 IEEE 11th International Colloquium on Signal Processing & Its Applications (CSPA)* (pp. 46-51). IEEE. doi:10.1109/CSPA.2015.7225616

Singh, S. K., Katal, N., & Modani, S. G. (2014). Multi-objective optimization of PID controller for coupled-tank liquid-level control system using genetic algorithm. In *Proceedings of the Second International Conference on Soft Computing for Problem Solving (SocProS 2012), December 28-30, 2012* (pp. 59-66). Springer. doi:10.1007/978-81-322-1602-5_7

Souran, D. M., Abbasi, S. H., & Shabaninia, F. (2013). Comparative Study between Tank's Water Level Control Using PID and Fuzzy Logic Controller. In *Soft computing applications* (pp. 141–153). Springer. doi:10.1007/978-3-642-33941-7_15

Wu, D., & Tan, W. W. (2006). Genetic learning and performance evaluation of interval type-2 fuzzy logic controllers. *Engineering Applications of Artificial Intelligence*, *19*(8), 829–841. doi:10.1016/j.engappai.2005.12.011

Xie, B., & Yao, B. (2005, January). Multi-objective optimization of tip tracking control using LMI. In *ASME International Mechanical Engineering Congress and Exposition* (Vol. 42169, pp. 1533-1542). doi:10.1115/IMECE2005-81313

Ziegler, J. G., & Nichols, N. B. (1942). Optimum settings for automatic controllers. *Trans. ASME, 64*(11).

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