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Decentralized Control Based on Active Disturbance Rejection Controller: An Application Quadruple Tank System

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Abstract**:** ***This paper presents Decentralized Control for the Quadruple Tank System (QTS) Based on Active Disturbance Rejection Controller (ADRC). The most remarkable advantages of the proposed approach are that it is not depend on the accuracy of mathematical model of the plant along with its simple structure and the ability of strong disturbance rejection. Often, there are some difficulties in designing of suitable controller for Quadruple Tank System due to the interaction between the inputs and outputs of this system. With the proposed control method, the cross coupling within the system treated as a disturbance, which is estimated using extended state observer (ESO) and then actively rejected. The Quadruple Tank System is represented using set of nonlinear differential equations and the ADRC controller is applied directly on the nonlinear model of the system. The effectiveness of the proposed approach is validated via simulation results obtained under MATLAB environment. The results show that the ADRC gives better results compared to nonlinear optimal control strategy.***

Index Terms**:** ***Active Disturbance Rejection Controller, Decentralized Control, Quadruple Tank System, The Nonlinear Coupling.***

I. INTRODUCTION

In industrial applications of quadruple tank system, the level of liquid and flow between tanks are very important in order to meet the high and precise energy consumption requirements of the process. It needs to be controlled and maintained according to the desired level but presence of an obstacle prevents achieving this goal. The obstacle always appears in a form of complicated interactions existing between the measurement signals and control signals which are deemed as disturbances. Therefore, it is difficult to design a suitable controller for Multiple Input and Multiple Output (MIMO) systems because of these interactions between input and output variables. This case is interesting since it has attracted the attention of many researchers in the recent years.

The design of controllers for (MIMO) processes in industrial applications can be classified into three categories. The first category is the Centralized Controller, also known as Model Predicative Control (MPC). This type is considered to be practical means to handle all sorts of interactions. This controller is based on the designing of Proportional-Integral or Proportional- Integral-Derivative (PI/PID) controller for each transfers function of multi-variable system [1-3]. Several tuning methods have been provided for designing the centralized controller [4-6]. The problem is that implementing it in basic process control level is limited due to computation complexity [7]. The second type is referred to as Decouple Controller. The main goal of this system is to eliminate the interactions. It also allows all measurements to be passed through its channels in order to get a complete decoupling. This in turn allows individual design of Single-input Single-output (SISO) controllers for each loop by selecting proper input-output pairing [8]. Its success depends on the measures of process variable interactions [9].

The third category is the Decentralized Controller which is widely used in industry for providing a good dynamic behavior to multi-variable systems. Many decentralized systems have been developed for multi-input multi-output process control including the interaction analysis. Auto tuned decentralized PI controller using decoupling and Particle Swarm Optimization (PSO) to overcome issue of interactions in quadruple tank process is indicated in [10]. The state feedback control system which depends on combining both structural and algebraic constraints for decentralized control of MIMO system has also been developed by [11]. Liquid level control for a four − tank systems using unconstrained H ∞ and decentralized PID controllers was showed by [12]. In [13] the model reference adaptive controller (MRAC) technique has been used to adjust decentralized PI parameters applied for quadruple tank process. However, the decentralized control usually requires repeatedly controller tuning since the adjustment of one controller parameters may affect the other loops.

Active Disturbance Rejection Control is a robust control system for disturbance rejection in nonlinear system with uncertainties parameter and significant external disturbances. The idea of ADRC was initiated by [14]. The system is based on the representation of uncertainties and external disturbances (sometimes denoted as a total disturbance.) that are not included in the mathematical description of the process in term of a new state and then the online estimation of this a new state is performed by using a state observer called Extended State Observer. In order to decouple the system from the actual perturbation acting on the plant, a nonlinear control law has been used [15]. The system is often found in various applications in industry [15-18].

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In this paper, the decentralized robust version of Active Disturbance Rejection Control is conducted on nonlinear Quadruple Tanks process to overcome the interactions issue and offer a comprehensive robust control for nonlinear (MIMO) system based on the concept of liquid level. The mathematical model of a quadruple tank in [10] has been used to illustrate the performance of ADRC. The main feature of the proposed method is that it is directly applied for each nonlinear subsystem without a need to approximate linearization taking into account the interactions between the loops (i.e. disturbances).The results are compared with a decentralized control method based on a proportion-integral (PI) controller using local feedback and it is improved by integral minimum principle of pontryagin [19].

The Quadruple Tank process is regarded as a suitable test for comparing the performance of different control systems since the nature of Quadruple Tank system has nonlinearity, complexity and uncertainty characteristics. In the multiple tank system, the passive flow interconnection is an impediment to most of approaches to control liquid level. Many researches have dealt with flow between tanks through gravity, and pressure differentials [19-21]. The control of the liquid levels in each tank would no longer be available if the fluid between tanks were to fail. At best, the passive flow scheme will allow for a common fluid level in each tank, but if discharge is involved then all tanks will eventually drain out which makes the associated control issue very challenging.

II. SYSTEM DESCRIPTION

This section includes brief description of the quadruple tank system that will be used in this paper. This system has been presented in [10]. The process is considered as two coupled subsystems. The system consists of four interconnected tanks, valves, reservoir and two pumps. In addition, there is a discharge hole at the bottom of each of the tanks through which the water in upper Tanks flows into lower Tanks by means of pressure and gravity force. The electrical pumps used to control the overall system pump water from the reservoir feedback to the upper level tanks. Each pump output goes to two tanks, one lower and the other upper, diagonally opposite and the ratio of the split is controlled by two sections of the three way valves two of which are manually operated. With the change in position of the two valves, the system can be either in the minimum phase or in the non-minimum phase. The Quadruple tank system has two transmission zeros and their position depend on split fraction γ_1 and γ_2 in valves 1 and 2 respectively. The minimum and non-minimum phase mode can be realized as:

Minimum Phase: $1 < (\gamma_1 + \gamma_2) < 2$

Non-minimum Phase: $0 < (\gamma_1 + \gamma_2) < 1$

The system inputs are v1 and v2 (voltages applied to the pumps), and the outputs are y1 and y2 (level the two lower tanks). The objective is to control the level of tank 1 and tank 2 respectively and reject the external disturbance present in the plant and the uncertainty that may be associated with some parameters by using decentralized Active Disturbance Rejection Control. The schematic equation of the quadruple tank equipment is presented in Fig 1.

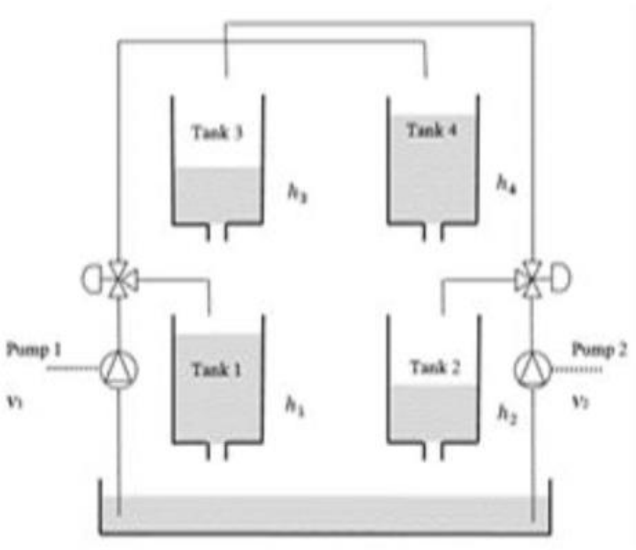

Figure 1: The Schematic of the Quadruple Tank

The nonlinear plant equations can be obtained by mass balance equation and Bernoulli's law.

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_2}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 K_1}{A_1}V_1 \quad (1)$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 K_2}{A_2}V_2 \quad (2)$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)K_2}{A_3}V_2 \quad (3)$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)K_1}{A_4}V_1 \quad (4)$$

Where

a_i is the cross-section area of orifice hole of tank "i".

h_i is the liquid level in tank "i".

A_i is the cross-section area of tank "i".

g is the acceleration due to gravity.

γ_i is the flow coefficient of tank "i".

K_i is the pump gain "i".

v_i is the voltage applied to pump "i".

The flow rate of the pump1 to the tank 1 and 4 are $(\gamma_1 K_1 v_1)$,$(1-\gamma_1)$ respectively, and for the flow rate of the pump 2 to the tank 2 and 3 are defined in the same way. The valve parameters was achieved to be 0.7 and 0.6.

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III. CONTROLLER DESIGN

As we mentioned in Sec.2, the quadruple tank system can be regarded as two SISO coupled systems. Tank 1 and tank 3 forming the first subsystem, and tanks 2 and 4 forming the second. In other words, the fourth order system under study splitted into two second order subsystems (i.e. n=2). From this point of view, two ADRC algorithms will be implemented for each subsystem as depicted in Fig. 2.

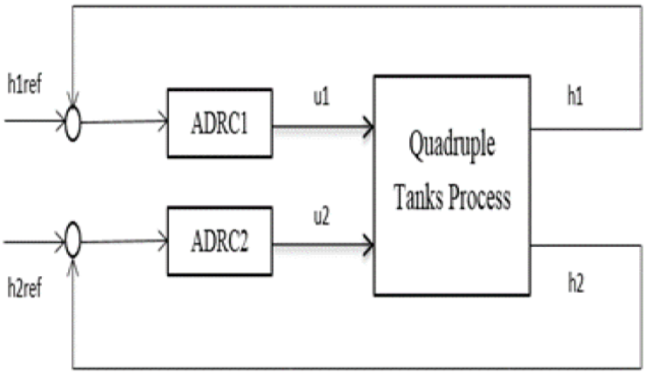

Figure 2: The decentralized ADRC for the Quadruple Tank system

In ADRC, the system information is gotten through the input-output data of the considered plant. Consequently, this strategy gives the ability to reject the total disturbance of the plant. Such perturbation is estimated using (ESO) and further cancelled out by the control law. Furthermore, by using this approach the cross-couplings effects can be treated as part of the external disturbance.

Based on the principle of ESO, the total disturbance of n-th order two coupled subsystems can be estimated through the following expression [22].

$$\begin{aligned} y_i^{n} &= b_i u_i + \left[d_{\text{int}}\left(t, u_i, \dot{y}_i, \ddot{y}_i, \dots, y_i^{(n-1)}\right) + d_{ext} \right] \\ &= b_i u_i + f_i \qquad i = 1,2 \end{aligned} \tag{5}$$

Where

y is the plant output signal (level of liquid in lower tanks), u is the control signal, d_{int} represents the overall internal disturbances (i.e. unmolded system dynamics, parameter uncertainty, etc.), d_{ext} represents the overall external disturbances, b is the system parameter, and f is the total disturbance.

Let

$$x_{i1} = y_i,\ x_{i2} = y_i^{(1)}, \dots\dots\dots x_{in} = y_i^{(n-1)} \qquad i = 1,2 \tag{6}$$

Where (n) is the order of i-th subsystem.

Assuming that f is m-times differentiable, then (6) can be augmented as:

$$\left.\begin{aligned} \dot{x}_{i1} &= x_{i2} \\ \dot{x}_{i2} &= x_{i3} \\ &\vdots \\ \dot{x}_{in} &= x_{i(n+1)} + b_i u_i \\ &\vdots \\ \dot{x}_{i(n+m)} &= f_i^{(m)} \end{aligned}\right\} \tag{7}$$

Assuming the total disturbance f is constant (i.e. $\dot{f}$=0 and m=1).

By substituting m=1, n=2, in (7), the extended model of the first subsystem (i=1) is:

$$\left.\begin{aligned} \dot{x}_{11} &= x_{12} \\ \dot{x}_{12} &= x_{13} + b_1 u_1 \\ \dot{x}_{13} &= \dot{f}_1 \end{aligned}\right\} \tag{8}$$

Now the extended state observer can be designed to estimate the states (x_{11}, x_{12}, x_{13}). The dynamic equation of ESO is given by

$$\left.\begin{aligned} \dot{z}_{11} &= z_{12} + L_1(y_1 - z_{11}) \\ \dot{z}_{12} &= z_{13} + L_2(y_1 - z_{11}) + \hat{b}_1 u_1 \\ \dot{z}_{13} &= L_3(y_1 - z_{11}) \end{aligned}\right\} \tag{9}$$

Where

(z_{11}, z_{12}, z_{13}) are the estimation of the extended system states. ($L_1, L_2, L_3, \hat{b}_1$) are ESO parameters. (y_1) is the output of the first subsystem. (u_1) is input control signal to the first subsystem.

With well tuning of the observer gain, the estimation of the extended system states will track the plant output and the overall external disturbances respectively. By choosing the control law as:

$$u_1 = \frac{u_{c1} - z_{13}}{\hat{b}_1} \tag{10}$$

And substituting (10) into (5) we will get:

$$\ddot{y}_i = b_1 u_1 + f_1 = b_1\left(\frac{u_{c1} - z_{13}}{\hat{b}_1}\right) + f_1 \approx u \tag{11}$$

Based on the equivalent controlled plant (11), the extended model of the first subsystem can be rewritten using tracking error:

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$$\left.\begin{aligned} e_1 &= -x_{11}+x_{ref11} = -y_1 + y_{1ref}\\ \dot{e}_1 &= -x_{21}+x_{ref22} = -\dot{y}_1+\dot{y}_{1ref}\\ \ddot{e}_1 &= -u_{c1}+\ddot{x}_{ref11}\end{aligned}\right\} \qquad (12)$$

Where the elements x_{ref11} and x_{ref21} are the references values of states x_{11} and x_{21} respectively. The element u_{c1} is the control signal from a feedback controller (PD), which utilized for the first ADRC control loop to decrease the tracking error.

$$u_{c1} = \ddot{x}_{ref11} + [K_{p1} \quad K_{d1}][e_1 \quad \dot{e}_1]^T \qquad (13)$$

Where K_{p1} and K_{d1} are the parameters of PD controller respectively.

The error dynamics equation is defined by substituting equation (13) into (12) as:

$$\ddot{e}_1 + K_{p1}\dot{e}_1 + K_{d1}e_1 = 0 \qquad (14)$$

It is obviously there are six parameters for each ADRC ($L_1, L_2, L_3, \hat{b}_1, K_p, K_d$). In order to reduce the number of the tuning parameters, (L_1, L_2, L_3) can be made as functions of observer bandwidth (ω_o) and K_p, K_d as functions of controller bandwidth (ω_c) [1].

$$L_1 = \omega_o,\ L_2 = 3\omega_o^{\,2},\ L_3 = \omega_o^{\,3},\ K_p = K_d\ \omega_c$$

In addition the observer bandwidth is usually chosen 3-5 times of controller bandwidth [24]. As result the overall tuning parameters become only two ($\omega_c, \hat{b}$).

On other hand, by following the same former approach, the design of ADRC for the second subsystem (i.e. i=2) can be done. The result is two separate ADRC controllers, one for each subsystem as presented on Fig. 3.

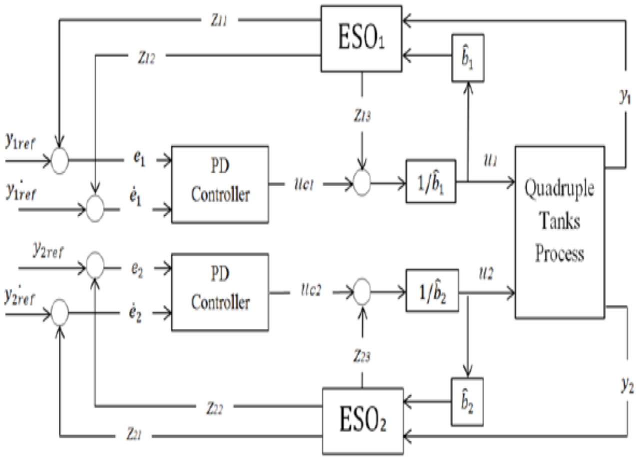

Figure 3: Block Diagram of the Decentralized ADRC design for the Quadruple Tanks system

IV. SIMULATION AND RESULTS

In this section, we will present the responses of the Quadruple Tank system discussed in Section (2) for ADRC approach. The results will be compared to the controller presented in [19] to evaluate the effectiveness of proposed ADRC algorithm. The results are implemented by using MATLAB/SIMULINK toolbox.

For simulation, the plant data used in this paper that obtained from [10], the operating parameters of minimum-phase system and the parameters of ADRC controller are illustrated in Table 1 and Table 2 respectively.

Table 1: Specification of Quadruple Tank System

Parameter Description		Value
Cross section area of tank 1 and tank 3	$[A_1, A_3]$	28 cm^2
Cross section area of tank 2 and tank 4	$[A_2, A_4]$	32 cm^2
Cross section area of orifice hole of tank 1,3	$[a_1, a_3]$	0.071 cm^2
Cross section area of orifice hole of tank 2,4	$[a_2, a_4]$	0.057 cm^2
Inlet valve ratio	$[\gamma_1, \gamma_2]$	(0.70,0.60)
The acceleration due to gravity	g	981 cm/sec^2

Table 2: The Operating Parameters of Minimum-Phase System

Parameter Description		Value
Initial level in tanks 1,2	$[h_1(0), h_2(0)]$	12.4 cm
Initial level in tanks 3,4	$[h_3(0), h_4(0)]$	12.7 cm
The desired liquid level in tanks 1	h_{1ref}	20 cm
The desired liquid level in tanks 2	h_{2ref}	16 cm
Gain for Pumps 1,2	$[K_1, K_2]$	(3.33,3.35) cm^2/Vs
The voltages applied to pumps 1,2	$[v_1(0), v_2(0)]$	(3.00,3.00)

Table 3: ADRC Parameters

$K_{p1} = 1.02$	$K_{p2} = 1.02$	$K_{d1} = 2$	$K_{d2} = 2$
$\omega_{c1} = 0.51$	$\omega_{c2} = 0.51$	$\hat{b}_1 = 0.0401$	$\hat{b}_2 = 0.123$

Fig. 4, 5. Show the responses of Quadruple Tank process by utilizing ADRC algorithm and controller that considered in [19] to track desired level liquid in lower tanks without disturbances.

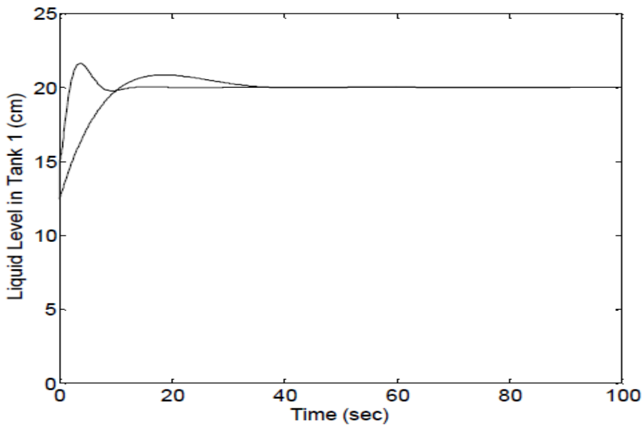

Figure 4: The performance of the controllers applied on QTS for controlling the level of liquid in tank 1 (ADRC:______; controller considered in [19] ;-------)

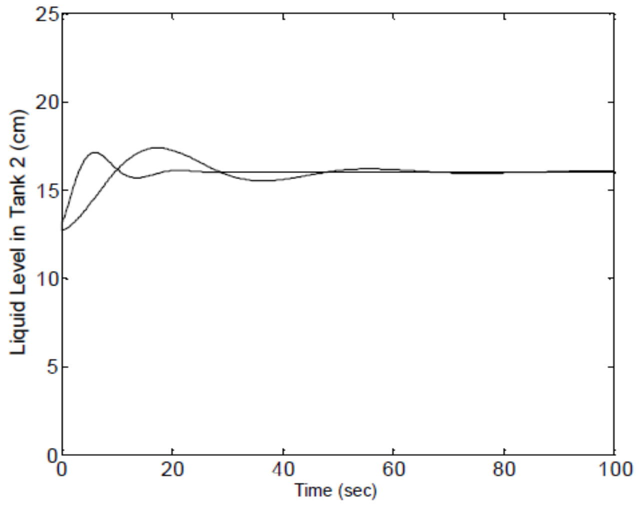

Figure 5: The performance of the controllers applied on QTS for controlling the level of liquid in tank 2 (ADRC:______; controller considered in [19] ;-------)

It can be observed from Fig 4, 5, with ADRC the liquid level in lower tanks track the desired level faster than the controller considered in [2]. It's also shown that ADRC gives y_1, y_2 less overshooting.

In real time process, levels of tanks are continuously disturbed because of continuous opening and closing of the drain valves and the efficiency of the pumps. These disturbances can be represented as a +20% changing in the flow coefficients (λ_i), and +20% changing in pumps gain (K_i). The simulation results shown in Fig 6, 7 present the performance of proposed controller to reject the disturbance acted on tank1 and tank2 at t=50 sec.

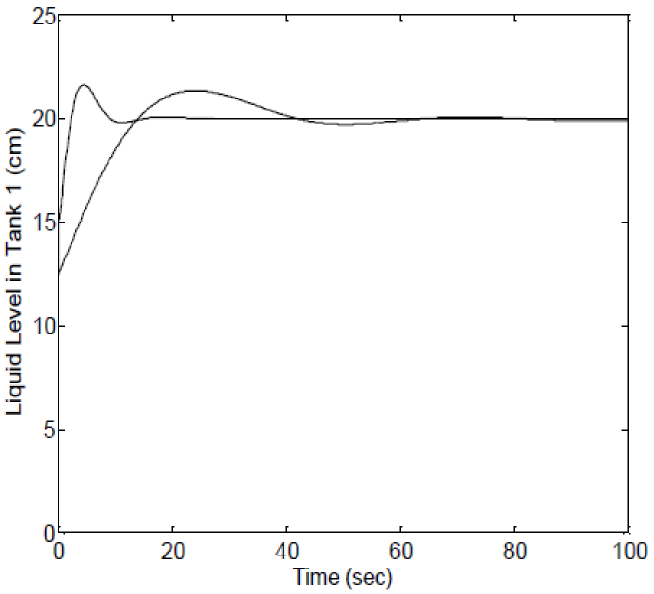

Figure 6: Liquid level of tank 1 in Presence of +20 % Disturbances

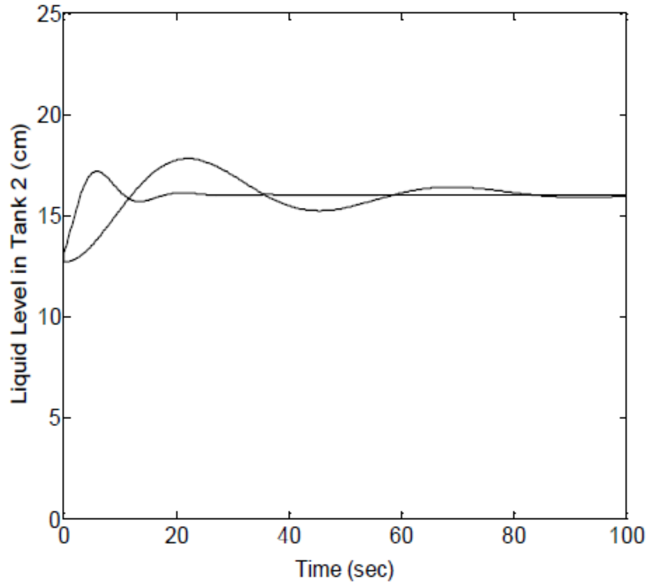

Figure 7: Liquid level of tank 2 in Presence of +20 % Disturbances

From the Fig 6, 7, it is clear that ADRC has ability to reject the disturbance inserted to tank1 and to tank 2 at t=50 sec. The proposed controller provides high performance and capability to handle the disturbance.

V. CONCLUSIONS

This paper introduced Decentralized Active Disturbance Rejection Controller applied for nonlinear Quadruple Tank interconnected system to deal with trajectory tracking and disturbances rejecting issues. The effectiveness of the proposed controller has been compared to the controller that considered in [19]. The quadruple tank system has been regarded as two SISO coupled systems and for each subsystem the decentralized version ADRC algorithm has been designed. Hence, the process of tuning ADRC parameters has been simplified. The ADRC is implemented on the nonlinear cross-coupled system directly. The obtained simulation results show good performances of the proposed controller in response to trajectory tracking (capability of maintaining the liquid heights in lower tanks at the desired level) as well as disturbance rejection property which has been defined as interaction between process variables and the uncertainties of system parameters compared to the controller introduced in [19].

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