Adaptive Control of Twin Rotor MIMO System Using Fuzzy Logic

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Abstract

In this paper, an intelligent adaptive controller is designed to position the yaw and pitch angles of a twin rotor MIMO system (TRMS) in two degrees of freedom, based on fuzzy logic. The control objective is to make the TRMS move quickly and accurately to the desired attitudes. Gradient descent algorithm has been used for updating parameters of fuzzy controller in order to increase its robustness against external disturbances and changes of system parameters. Experimental results is compared with the PID controller to show the effectiveness of the proposed method, especially when it encounters system uncertainties and external disturbances.

Keywords: Adaptive fuzzy controller, Twin rotor MIMO system, Gradient descent algorithm.

1. INTRODUCTION

The twin rotor MIMO system (TRMS) is a laboratory set-up designed for control experiments [1]. Due to the complicated nonlinearity and the high coupling effect between two propellers (Fig.1), the control problem of the TRMS has been considered as a challenging research topic [2, 3].

Among different control strategies, fuzzy logic has been widely used with different control schemes to cope with difficult control objectives in nonlinear system such as the TRMS. It has been shown that Fuzzy Logic Controller (FLC) can improve the response of TRMS in terms of tracking and transient responses [4, 5].

In [3] a novel fuzzy-sliding and fuzzy-integral-sliding controller has been designed to position the yaw and pitch angles. Adaptive neural fuzzy inference system (ANFIS) and fuzzy subtractive clustering method (FSCM) have been used in [6, 7] to solve non-linearity, trajectory, and interaction problems of TRMS. FLC has been utilized in many different hybrid schemes to cope with TRMS control objectives. Hybrid schemes could be implemented with the use of classical and/or intelligent control. In [8-14] fuzzy logic has been proposed in different schemes with the use of Genetic Algorithms (GA) and conventional PID controller. Another use of fuzzy logic based on switching grey prediction has been proposed in [15, 16].

In most of the aforementioned works, a simple fuzzy control system was investigated, whose advantage was simple and easy to use. However, a major limitation is the lack of a systematic methodology for developing fuzzy rules. A set of fuzzy rules often needs to be manually adjusted by trial-and-error before it reaches the desired level of performance. Hence, it is desirable to develop an adaptive fuzzy controller, which can improve its performances based on adaptation of its parameters in relation to variations in the system dynamic [7].

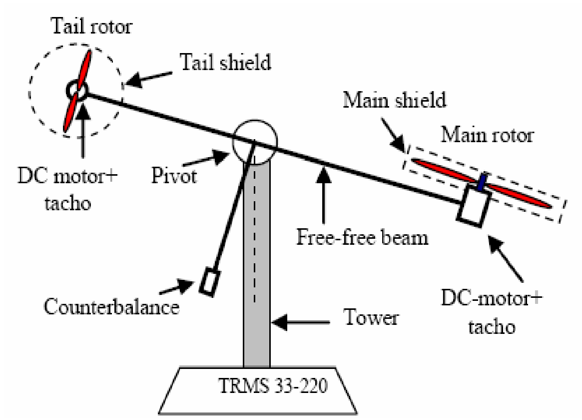

Fig. 1. The twin rotor MIMO system

The remainder of the paper is organized as follows. Description of the system is presented in Section 2. Section 3 comprehensively discusses the process of designing the adaptive fuzzy controller. Experimental results to demonstrate the effectiveness of the proposed controller are presented in Section 4. And finally, concluding remarks are provided in Section 5.

2. TWIN ROTOR MIMO SYSTEM

The TRMS, as shown in Fig. 1, is characterized by complexity, high nonlinearity and inaccessibility of some states and outputs for measurements, and hence can be considered as a challenging engineering problem. The control objective is to make the beam of the TRMS move quickly and accurately to the desired attitudes, both the pitch angle and the yaw angle.

The TRMS is driven by two DC motors. Its two propellers are perpendicular to each other and joined by a beam pivoted on its base that can rotate freely on the horizontal and vertical planes. The joined beam can be moved by changing the input voltage to control the rotational speed of these two propellers. There is a

Pendulum Counter-Weight hanging on the joined beam which is used for balancing the angular momentum in steady state or with load.

In certain aspects, the behavior of TRMS resembles that of a helicopter. It is difficult to design a suitable controller because of the influence between two axes and nonlinear movement. From the control point of view, it exemplifies a high order nonlinear system with significant cross coupling [1].

3. ADAPTIVE FUZZY CONTROLLER DESIGN

In this section, designing the adaptive fuzzy controller using the gradient descent algorithm will be studied. First, summary of gradient descent algorithm is represented and then, the process of designing the controller is discussed.

3.1. GRADIENT DESCENT ALGORITHM

Primary structure of the employed fuzzy system is made up of Mamdani multiplication inference engine, the singleton fuzzifier, the center average defuzzifier and Gaussian membership functions

$$f(x)=\frac{\sum_{l=1}^{M}\bar{y}^{l}\left[\prod_{i=1}^{n}\exp\left(-\left(\frac{x_i-\bar{x}_i^{l}}{\sigma_i^{l}}\right)^2\right)\right]}{\sum_{l=1}^{M}\left[\prod_{i=1}^{n}\exp\left(-\left(\frac{x_i-\bar{x}_i^{l}}{\sigma_i^{l}}\right)^2\right)\right]} \quad (1)$$

where M and n are the number of rules and the number of fuzzy controller inputs, respectively. $\bar{x}_i^l$ and σ_i^l are the center and the width of membership functions of i^{th} input and l^{th} rule, respectively, $\bar{y}_l$ is the center of the output membership function corresponding to l^{th} rule.

The objective in the gradient descent algorithm is changing the parameters of the fuzzy system (e.g. $\bar{x}_i^l$, σ_i^l and $\bar{y}_l$ in (1)) in a way that minimizes the following performance index:

$$E(k)=\frac{1}{2}\left(f(x(k))-y(k)\right)^2 \quad (2)$$

where $f(x(k))$ is the output of the fuzzy system and $y(k)$ is the actual system output.

Adaptation laws for determining the optimal parameters by the use of gradient descent algorithm are

$$\bar{y}^l(k+1)=\bar{y}^l(k)-\alpha\frac{\partial E(k)}{\partial \bar{y}^l(k)} \quad (3)$$

$$\bar{x}_i^l(k+1)=\bar{x}_i^l(k)-\alpha\frac{\partial E(k)}{\partial \bar{x}_i^l(k)} \quad (4)$$

$$\sigma_i^l(k+1)=\sigma_i^l(k)-\alpha\frac{\partial E(k)}{\partial \sigma_i^l(k)} \quad (5)$$

where $0<\alpha<1$ is the learning rate.

3.2. DESIGN OF THE FUZZY CONTROLLER

Fuzzy controllers have been successfully applied to many nonlinear systems, where: 1) no accurate mathematical models of the systems under control are available; 2) human experts are available to provide linguistic fuzzy controller rules. The most important advantage of adaptive fuzzy control over conventional adaptive control is that adaptive fuzzy controllers are capable of incorporating linguistic information from human operators, whereas conventional adaptive controllers are not. This is especially important for the systems with a high degree of uncertainty, e.g., in chemical processes and air vehicles, because although these systems are difficult to control using automatic control theories, they are often successfully controlled by human operators [17].

In order to control the TRMS with two degrees of freedom, two fuzzy controllers need to be developed: one for the horizontal axis and the other one for the vertical axis. Then, the gradient descent algorithm is used for updating parameters of these fuzzy controllers. The block diagram of the TRMS control system with adaptive fuzzy controllers is shown in Fig. 2. Regarding this figure, fuzzy controllers have two inputs which are the corresponding beam angle error and its derivatives. The output of these controllers is the input voltage to the main and tail DC servomotor. Hence, the tracking errors of the closed-loop system are

$$e_h(k)=r_h^d(k)-y_h(k) \quad (6)$$

$$e_v(k)=r_v^d(k)-y_v(k) \quad (7)$$

where $e_h(k)$, $r_h^d(k)$, and $y_h(k)$ are the yaw angle error, the reference input, and the actual output of the horizontal axis, respectively. Similarly, $e_v(k)$, $r_v^d(k)$, and $y_v(k)$ are the pitch angle error, the reference input, and the actual output of vertical axis, respectively.

In order to reduce the steady state error of the horizontal axis, an integrator is incorporated with the adaptive fuzzy controller.

The most important part in the design of a fuzzy controller is the determination of fuzzy rules. The fuzzy rule bases of the controllers have been determined in accordance with the system behavior (using data gathered from the TRMS) and have been shown in Tables 1 and 2.

The range of changes in fuzzy system inputs and output for the vertical and the horizontal subsystem are

$$\begin{aligned} &e_v(k)\in[-1.5 \quad 1.5] && \text{rad}\\ &\dot{e}_v(k)\in[-1.5 \quad 1.5] && \text{rad/s}\\ &U_v(k)\in[-2.5 \quad 2.5] && \text{V}\end{aligned} \quad (8)$$

$$\begin{aligned} &e_h(k)\in[-1.5 \quad 1.5] && \text{rad}\\ &\dot{e}_h(k)\in[-1.5 \quad 1.5] && \text{rad/s}\\ &U_h(k)\in[-2.5 \quad 2.5] && \text{V}\end{aligned} \quad (9)$$

where $U_v(k)$ and $U_h(k)$ are the input voltages of the main and tail rotors, respectively.

Based on (3), the fuzzy controllers for two axes have the following form:

$$U_h(k)=\frac{\sum_{l=1}^{49}\bar{y}_h^l\left[\prod_{i=1}^{2}\exp\left(-\left(\frac{x_{h_i}-\bar{x}_{h_i}^l}{\sigma_{h_i}^l}\right)^2\right)\right]}{\sum_{l=1}^{49}\left[\prod_{i=1}^{2}\exp\left(-\left(\frac{x_{h_i}-\bar{x}_{h_i}^l}{\sigma_{h_i}^l}\right)^2\right)\right]} \quad (10)$$

$$U_v(k)=\frac{\sum_{l=1}^{35}\bar{y}_v^l\left[\prod_{i=1}^{2}\exp\left(-\left(\frac{x_{v_i}-\bar{x}_{v_i}^l}{\sigma_i^l}\right)^2\right)\right]}{\sum_{l=1}^{35}\left[\prod_{i=1}^{2}\exp\left(-\left(\frac{x_{v_i}-\bar{x}_{v_i}^l}{\sigma_{v_i}^l}\right)^2\right)\right]} \quad (11)$$

where $x_{h_i}(k)$, $\bar{y}_h^l(k)$, $\bar{x}_{h_i}^l(k)$, and $\sigma_{h_i}^l(k)$ are i^{th} input of the fuzzy controller, the center of the output membership functions for l^{th} rule, the center and the width of i^{th} input membership functions for l^{th} rule, all for the horizontal controller, respectively. Moreover, $x_{v_i}(k)$, $\bar{y}_v^l(k)$, $\bar{x}_{v_i}^l(k)$, and $\sigma_{v_i}^l(k)$ are i^{th} input of the fuzzy controller, the center of the output membership functions in l^{th} rule, center and width of i^{th} input membership functions for l^{th} rule, all for the vertical controller, respectively.

The performance indexes for the horizontal and the vertical axes are

$$E_h(k)=\frac{1}{2}(r_h^d(k)-y_h(k))^2 \quad (12)$$

$$E_v(k)=\frac{1}{2}(r_v^d(k)-y_v(k))^2 \quad (13)$$

In order to calculate the adaptation laws in (3) to (5), the following partial derivatives need to be determined first:

$$\frac{\partial E_h(k)}{\partial w_i^h(k)}=\frac{\partial E_h(k)}{\partial y_h(k)}\cdot\frac{\partial y_h(k)}{\partial U_h(k)}\cdot\frac{\partial U_h(k)}{\partial w_i^h(k)} \quad (14)$$

$$\frac{\partial E_v(k)}{\partial w_i^v(k)}=\frac{\partial E_v(k)}{\partial y_v(k)}\cdot\frac{\partial y_v(k)}{\partial U_v(k)}\cdot\frac{\partial U_v(k)}{\partial w_i^v(k)} \quad (15)$$

where $i=1,2,3$ and

$$w^h(k)=\left[\bar{y}_h^l(k) \quad \bar{x}_{h_i}^l(k) \quad \sigma_{h_i}^l(k)\right],$$

$$w^v(k)=\left[\bar{y}_v^l(k) \quad \bar{x}_{v_i}^l(k) \quad \sigma_{v_i}^l(k)\right]$$

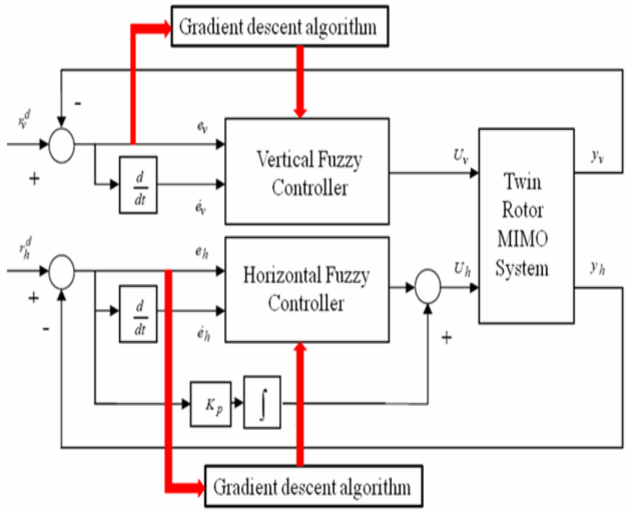

Fig. 2. Block diagram of TRMS with fuzzy controller

Table. 1. Fuzzy rules of vertical fuzzy controller

e_v \ $\dot{e}_v$	NB	NS	Z	PS	PB
NB	NVB	NVB	NVB	NB	NS
NM	NVB	NVB	NB	NS	PS
NS	NVB	NB	NS	Z	PM
Z	NB	NS	Z	PS	PB
PS	NM	Z	PS	PB	PVB
PM	NS	PS	PB	PVB	PVB
PB	PS	PB	PVB	PVB	PVB

Table. 2. Fuzzy rules of horizontal fuzzy controller

e_h \ $\dot{e}_h$	NB	NM	NS	Z	PS	PM	PB
NB	NVB	NVB	NVB	NVB	NB	NM	NS
NM	NVB	NVB	NVB	NB	NS	Z	PS
NS	NVB	NVB	NB	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PB	PVB	PVB
PM	NS	Z	PS	PB	PVB	PVB	PVB
PB	PS	PM	PB	PVB	PVB	PVB	PVB

4. EXPERIMENTAL RESULTS

In this paper, the TRMS with two degrees of freedom is considered. Two adaptive fuzzy controllers are applied to two subsystems simultaneously and in real time.

The responses of various reference inputs of the proposed controllers are presented in this section and are compared with those of the PID controllers. In addition, robustness of these controllers against external disturbances and change in system parameters is shown.

The sensitivity functions $\partial y_h(k)/\partial U_h(k)$ and $\partial y_v(k)/\partial U_v(k)$ in (14) and (15), respectively, cannot be obtained in simple process due to the lack of an accurate model of the TRMS. They are calculated using different conditions and types of the reference signal as

$$\frac{\partial y_h(k)}{\partial U_h(k)} = -0.002, \quad \frac{\partial y_v(k)}{\partial U_v(k)} = -0.003 \qquad (16)$$

For better performance of adaptive controllers, the learning rates are selected as

$$\alpha_h = 0.05, \quad \alpha_v = 0.1 \qquad (17)$$

The objective of this subsection is to show the ability of fuzzy controllers to follow different types of reference signals. Experimental results are shown in Fig. 3 and 4. The characteristics of reference signals are presented in Table 3. To compare performance of controllers, the Mean Squared Errors (MSEs) for the sine wave reference signal are shown in Table 4. As these figures and table show, the adaptive fuzzy controllers have a better performance in terms of following the sine wave reference signal as compared with the PID controller in vertical axis.

Figs. 5 and 6 show the step responses of the fuzzy and PID controllers. The results show that the fuzzy controller performs better than the PID controller in terms of overshoot and steady state error. However, PID controller has smaller rise times (see Table 5).

In order to evaluation of controller's robustness against external disturbances, a step input as shown in Fig.7 is applied to the forward path of the horizontal and vertical control's loops. As Figs. 8 and 9 show, the adaptive fuzzy controller convergences much faster than the PID controller in vertical axis.

In order to exhibit the adaptation capability of the proposed method against changes in system parameters, the counterbalance (see Fig. 1) has been removed from the TRMS (Fig. 10). Experimental results are shown in Figs. 11-- 14. As Figs. 11 and 12 show, performance of the PID controller is not acceptable and system becomes unstable (the TRMS hits the physical limitations), while the proposed fuzzy controller can cope very well with changes in system parameters. It should be noted that in this case the same PID coefficient have been used as before, which may not be suitable for the TRMS in this case, because the dynamic of the plant has been changes significantly. Figs. 13 and 14 show performance of the PID controller with newly tuned coefficients. It can be observed that the PID controller still does not have good performance as compared with the adaptive fuzzy controller.

Table. 3. Characteristics of the set of reference inputs

Frequency (Hz)	Amplitude (rad)	Type		
0.015	0.2	Sine	Vertical	Mode 1
0.03	0.3	Sine	Horizontal	
-	0.3	Step	Vertical	Mode 2
-	0.8	Step	Horizontal	

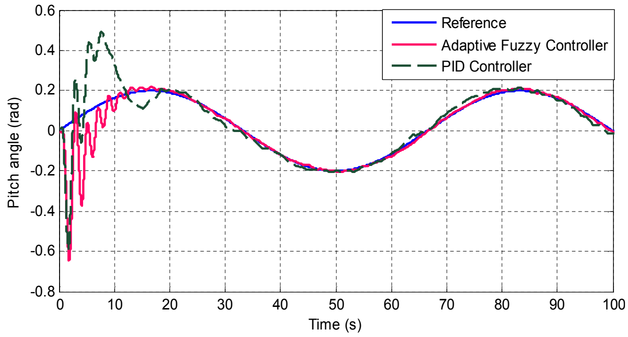

Fig. 3. Pitch angle of the TRMS in mode 1

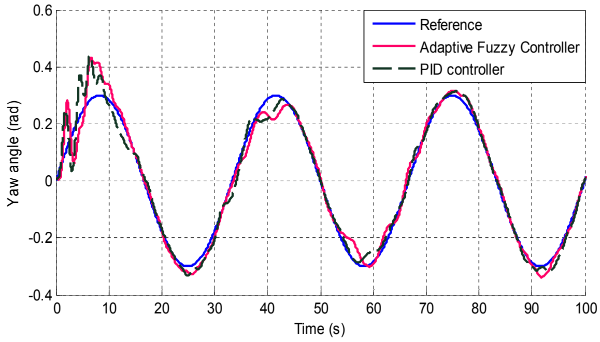

Fig. 4. Yaw angle of the TRMS in mode 1

Table 4. MSE of sine input

Horizontal MSE	Vertical MSE	
0.0013	0.0032	Adaptive Fuzzy Controller
0.0012	0.0082	PID Controller

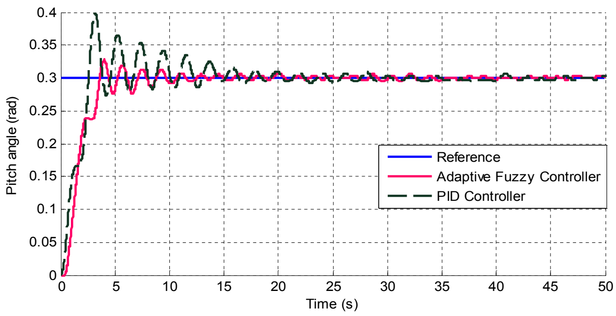

Fig. 5. Pitch angle of the TRMS in mode 2

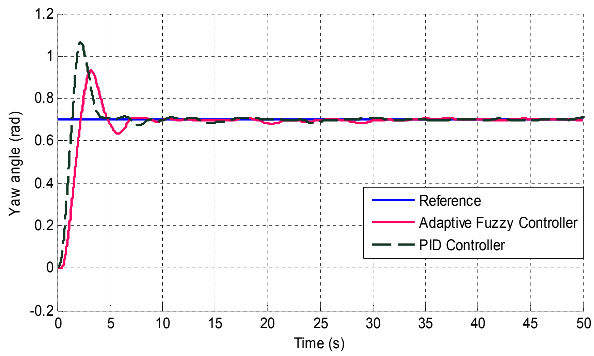

Fig. 6. Yaw angle of the TRMS in mode 2

Table. 5. Characteristics of controller's step response

Steady State Error (rad)	Rise Time (s)	Maximum Overshoot (%)		
-0.003	3.6	9.43	Vertical	Adaptive Fuzzy Controller
0.0005	2.24	33.24	Horizontal	
0.003	2.77	32.93	Vertical	PID Controller
0.005	1.5 s	58.57	Horizontal	

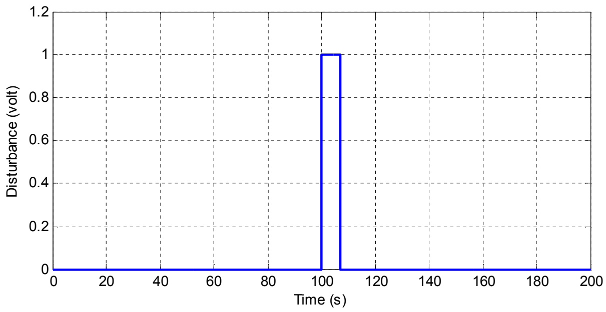

Fig. 7. Disturbance input for each axis

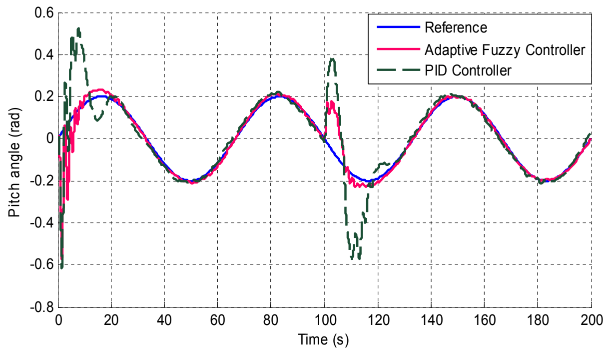

Fig. 8. Pitch angle under the disturbance

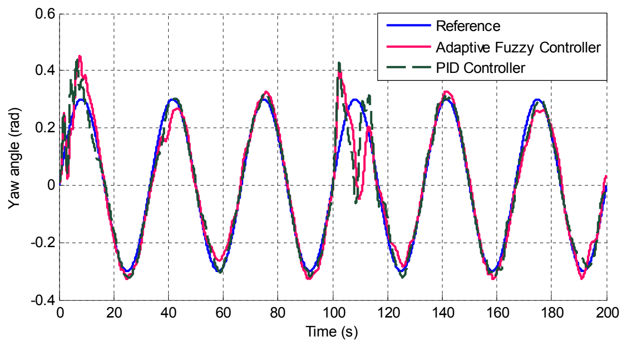

Fig. 9. Yaw angle under the disturbance

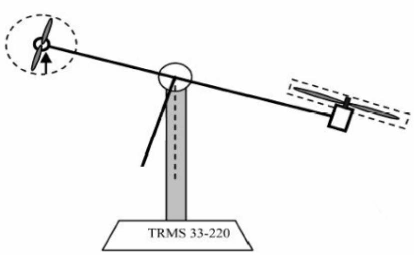

Fig. 10. The TRMS without counterbalance

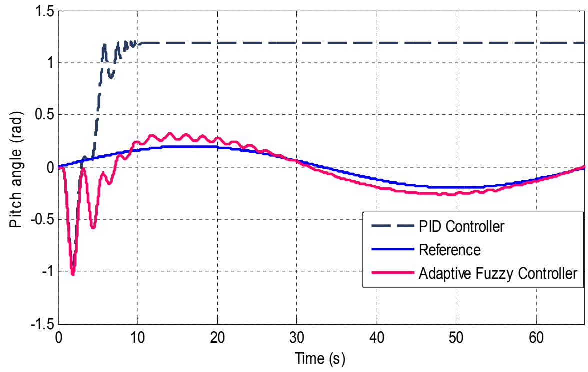

Fig. 11. The pitch angle of TRMS without counterbalance

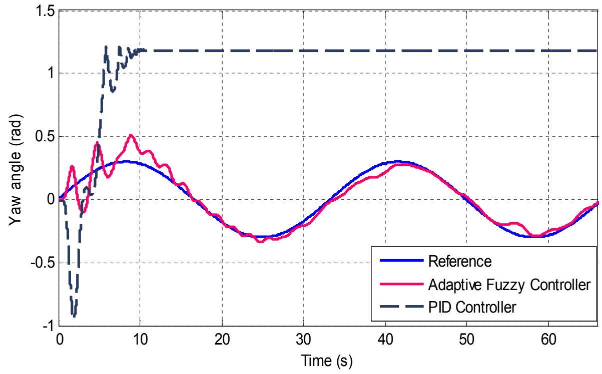

Fig. 12 The yaw angle of TRMS without counterbalance

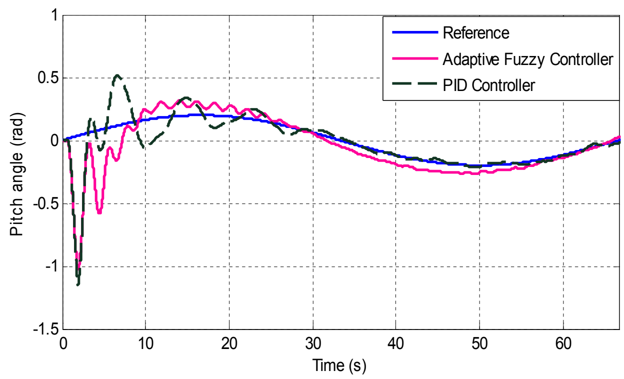

Fig. 13. The pitch angle of TRMS without counterbalance and new PID controller

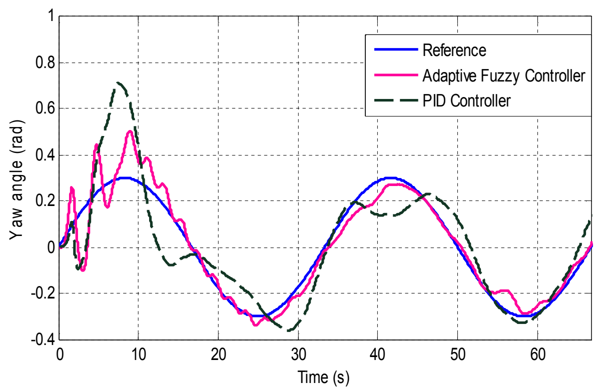

Fig. 14. The yaw angle of TRMS without counterbalance and new PID controller

5. CONCLUSION

In this paper, the TRMS with two degrees of freedom and cross-coupling influence between the vertical and the horizontal axes was considered. Two fuzzy controllers were designed based to control the system in real time. The gradient descent algorithm has been then used for updating parameters of these controllers in order to increase its robustness against external disturbances and changes in system parameters. The performance of the designed controllers has been evaluated with various reference inputs and it has been shown that the TRMS can track desired trajectories efficiently and accurately. The experimental results of the fuzzy controller have also been compared with the PID controller. The performance of the fuzzy controller in terms of overshoot and steady state error is better than those of the PID controller. In addition, comparison of the experimental results show the effectiveness of the adaptive fuzzy controller in resisting to external disturbances and changing in system parameters.

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