

*Full Length Research Paper*

# Intelligent-classical hybrid scheme controller for better transient response and steady state error of twin rotor MIMO system

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Accepted 12 November, 2012

A hybrid control scheme of Sugeno Fuzzy PD-like System (SFPDS) and PID controller is introduced in this work. The idea of the proposed strategy is to manipulate the control error signal in two stages: the SFPDS first, and then the PID. The manipulated signal is finally provided as a control action to the system. The proposed control strategy aims at combining the benefits of utilizing the artificial intelligence in getting a better transient, and the PID in getting a better steady state error. In this work, the proposed Sugeno Fuzzy design is developed from modeling a self tuning Mamdani fuzzy system. The later is modeled using Adaptive Neuro Fuzzy Inference System (ANFIS) to reduce its number of rules, thus reducing its complexity. In case of PID, parameters selection was decided based on the value of Integral Square of Error (ISE). To prove the effectiveness of the proposed strategy, the proposed control scheme is applied to solve Twin Rotor MIMO System (TRMS) control problems. Simulation studies proved the effectiveness of proposed method. The results have proved the effectiveness of the proposed strategy in terms of achieving satisfactory control response in both planes of motion as compared with other peoples work.

**Key words:** Fuzzy PD-like System (SFPDS), Adaptive Neuro Fuzzy Inference System (ANFIS), Twin Rotor MIMO System (TRMS), Square of Error (ISE).

## INTRODUCTION

In recent years, unmanned aerial vehicles (UAVs) have attracted significant research interests. UAVs can achieve piloted aerial vehicles jobs in risky places without risking pilot's life. They can do missions in hostile environments, and they can be smaller and more maneuverable. Helicopter control has a practical interesting dynamic feature among autonomous flying systems. The main difficulties in designing controllers for them come from nonlinearities and couplings. Twin Rotor MIMO System (TRMS) is a laboratory set-up design for which it has been used for control experiments, control

theories developments and applications of the autonomous helicopter. Firstly, it resembles in certain aspects the behavior of helicopter. It introduces some of the platforms and control architectures, and exemplifies a high order non-linear system with significant cross-couplings from control engineering point of view. A detailed approach to the control problems connected with the TRMS involves some theoretical knowledge of laws and physics (Ltd, 2012). Modeling and controlling TRMS are considered control problems for control community. It has been attracted by many researchers in the

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last decade. This work is concerning the control interests part on TRMS.

The researchers have started working of solving TRMS control problems with conventional type PID controller. It seems to be inadequate for this complex problem, and resulting to a poor performance with the non-linearity and coupling effects. PID controller performance can be improved by adjusting gains, but this still has its limitations. Intelligent control strategies have taken a significant part in solving Unmanned Air Vehicles (UAVs) control problems in recent years. As a part of that, TRMS control problems have been targeted to be solved with intelligent control schemes. It seems that most of the works have utilized the intelligent control strategies to solve TRMS control problems. Among different control approaches, fuzzy logic has been widely used with different control schemes to cope with control objectives of TRMS (Aldebraz et al., 2006; Chiu, 1994; Chuan-Sheng et al., 2006; Islam et al., 2006; Juang et al., 2006, 2008; Juang and Liu, 2006). It has been noticed that the major limitation of FLC 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 a Self-Tuning Fuzzy System (STFS) that can improve its performance based on its experience and to adapt its response in relation to variations in the process dynamics. It has been shown that Fuzzy Logic Controller (FLC) could improve response of TRMS in terms of tracking and transient response (Islam et al., 2003; Juang et al., 2006). 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. As in Aldebraz et al. (2006), Chuan-Sheng et al. (2006), Jih-Gau et al. (2006), Juang et al. (2008, 2006), Juang and Liu (2006) and Rahideh and Shaheed (2006), fuzzy logic has been proposed in different schemes with the use of Genetic Algorithms (GA) and conventional PID controller. As the use of hybrid control has been proven to be successful, adaptive Fuzzy control has also been detailed (Kubalčík, 2005). The work has proved to the success of using adaptation for fuzzy rules in order to perform better control actions.

The computation of matrix controller is realized and processed by one central computer for the real time control applications, and uses a lot of memory to achieve control objectives on MIMO control systems. The simple advantage of this approach is the possibility of reaching optimal control courses, because the controller can use all information known about the controlled system (Shih et al., 2008). The disadvantage of the usage of the central matrix controller is its high demands for computation resources, due to the number of operations. The used memory is depending on the square of the number of controlled signals (Jih-Gau and Wen-Kai, 2008). Although, this problem has been solved before

many times; each with different approach, the problem of hardware requirements has not been solved yet. For achieving control objectives using fuzzy logic control, time and memory used are comparatively high.

Therefore, there is a need to develop or use new approaches of the intelligent control strategies to achieve control objectives with considering the controller implementation complexity.

In previous study (Mahmoud et al., 2010), the use of self tuning controller with less number of rules based on ANFIS modeling has been investigated. In this study, Self Tuning Fuzzy PD-like System (STFPDS) has been used to compensate for the measured error between the actual and desired output of the system. The compensated error is used to control the system by a PID controller in the next step of error manipulation which gives the final control action to the system. This proposed control scheme is used in this study to prove the superiority on classical FLC and PID controller in improving time domain characteristics of the UAVs.

### Twin Rotor MIMO System

TRMS is a laboratory set-up which is designed to perform control experiments. It exemplifies a high-order non-linear system with significant cross-couplings from control point of view. A laboratory set-up of TRMS is depicted in Figure 1. A detailed approach to control problems connected with TRMS involves some theoretical knowledge of laws of physics (Ltd, 2012). The main parts of TRMS are the pedestal, the jib connected to pedestal and two propellers at each end of the jib. These two propellers are driven by two Direct Current (DC) motors. The system jib can freely rotate around vertical axes by about  $330^\circ$  and horizontal axis by about  $100^\circ$ . The system inputs are the voltages used to drive the DC motors of the propellers, and the outputs are the angular rotations with respect to horizontal and vertical axes. A counterbalance arm with a weight at its end is fixed to the beam at the pivot. More details about TRMS and its mathematical model used in this work are all provided in Ltd (2012).

### MATERIALS AND METHODS

Basically, the proposed controller design depends on two stages for error manipulation. First, Sugeno fuzzy system is used to manipulate the error signal and supply it to PID for giving the control action to the plant. In this work, Sugeno fuzzy system design was developed from modeling the adaptive mamdani fuzzy system. Fuzzy inference system is called "adaptive", if any of its tunable parameters (scaling factors, membership functions and rules) is changed on-line when system is operating; otherwise, it is a "non-adaptive" or "conventional fuzzy" (Mudi and Pal, 2000). An adaptive fuzzy inference system that fine tunes an operating fuzzy inference system by modifying either its membership functions or scaling factors or both of them is called "a self-tuning fuzzy system". The block diagram of the proposed self tuning fuzzy inference system is shown in Figure 2. Figure 2 shows that the output of fuzzy

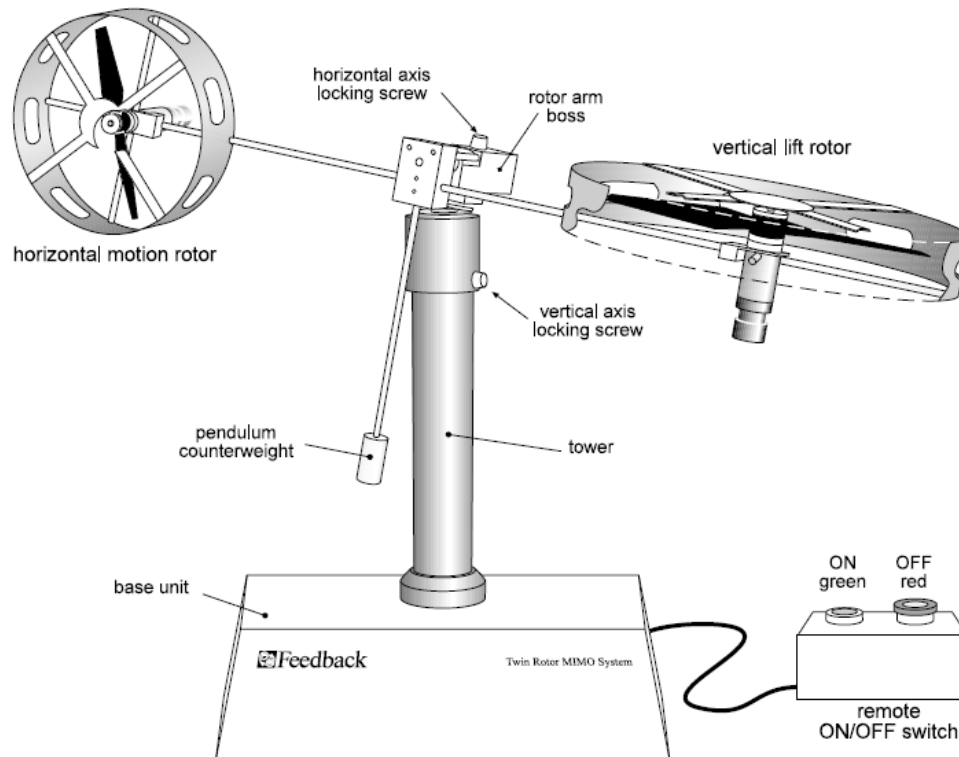


Figure 1. Laboratory set-up of TRMS (Ltd, 2012).

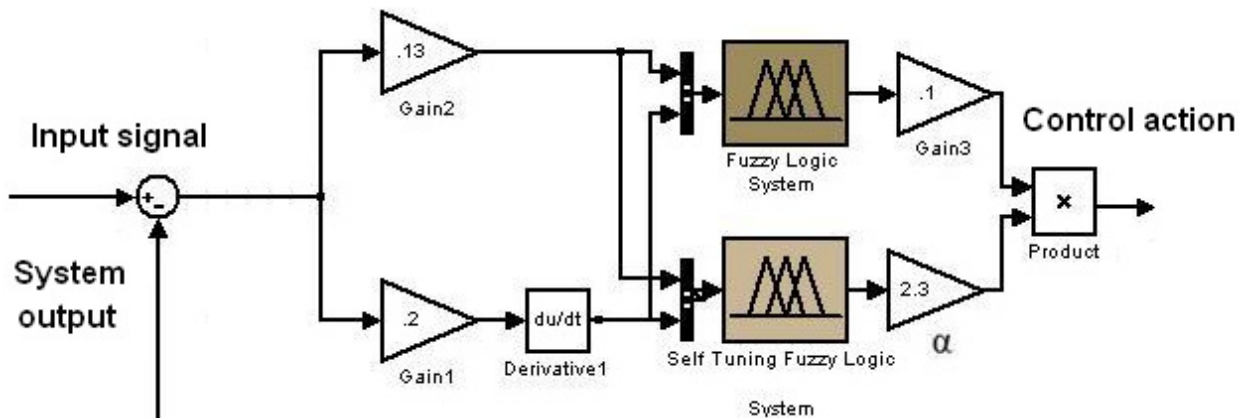


Figure 2. Self tuning PD-like fuzzy system.

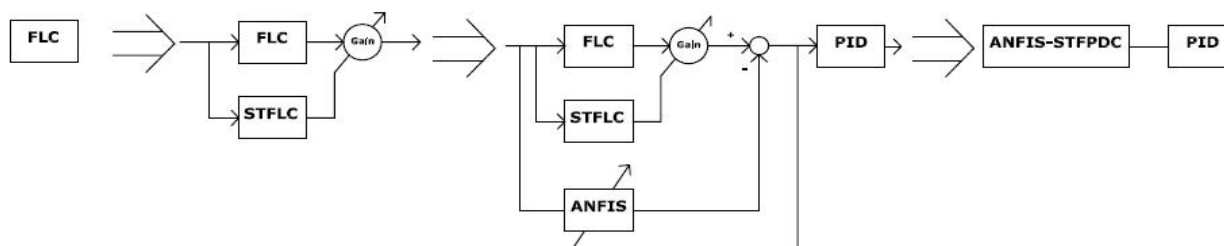
inference system (gain 3) is modified by a self-tuning mechanism. Thus, the output-scaling factor ( $\alpha$ ) of the self-tuning fuzzy inference system does not remain fixed while the system is in operation; rather it is modified in each sampling time by the gain updating factor  $\alpha$ , depending on the trend of the controlled process output. The membership functions for the factor  $\alpha$  for each of the four Fuzzy systems applied to control TRMS are defined in different domains in Table 1. In Table 1,  $G_e$  represents the gain of the error for the used fuzzy systems, while  $G_{\Delta e}$  represents the gain for the change of error for the used fuzzy systems. H, HV, V and VH are representing main fuzzy systems in horizontal, horizontal to vertical interaction, vertical and vertical to horizontal interaction parts respectively, while Hst, HV, Vst and VHst are representing self

tuning fuzzy systems in horizontal, horizontal to vertical interaction, vertical and vertical to horizontal interaction parts respectively.

After applying the self tuning fuzzy systems for controlling the two degrees of freedom for TRMS, the enhancements for the proposed controllers' design will pass through several stages. The controllers' evolution stages are explained in Figure 3. Basically, the design has been developed to deal with error signal in two stages. First, error signal is manipulated with a Self Tuning Fuzzy PD-like Manipulator (STFPDM), which is an enhanced design of a Fuzzy Logic Manipulator (FLM). In STFPDM, the output-scaling factor is adjusted on-line by updating factor  $\alpha$ . The value of  $\alpha$  is determined from a fuzzy rule-base defined on error ( $e$ ) and change of error ( $\Delta e$ ) of the controlled system.

**Table 1.** Self tuning fuzzy controllers design parameters.

Controller	e domain	$\Delta e$ domain	Output domain	$G_e$	$G_{\Delta e}$	$\alpha$
V	[-1 1]	[-1 1]	[-2 2]	0.40	0.7	0.20
Vst	[-1 1]	[-2 2]	[-5 5]	0.40	0.4	5.00
VH	[-1 1]	[-1 1]	[-0.2 0.2]	0.1	0.1	0.55
VHst	[-1 1]	[-1 1]	[-2 2]	0.1	0.1	5.00
HV	[-1 1]	[-1 1]	[-1.1 1.1]	0.5	0.5	0.55
HVst	[-1 1]	[-1 1]	[0 2]	0.5	0.5	0.10
H	[-2.5 2.5]	[-2.5 2.5]	[-12 12]	0.32	0.4	0.55
Hst	[-3 3]	[-0.1 0.1]	[-1 1]	0.32	0.4	5.00

**Figure 3.** Controller design evolution stages.

The membership functions designs of PD-like Fuzzy Systems (PDFSs) in vertical and horizontal parts of TRMS are depicted in Figure 4(a) and (b), respectively. All the STFPDSs membership functions designs have used the same shapes but different domains as listed in Table 1. Figure 3(c) shows the membership function design of the self tuning fuzzy systems. The membership function shape of cross coupling controllers have the same shape of vertical part controller, but set with different domains. The domains of all fuzzy systems are listed in Table 1. Each of the two inputs ( $e$  and  $\Delta e$ ) to the fuzzy rule base (corresponding to  $\alpha$ ) has seven fuzzified variables. The rule base system has 49 rules for computing the value of  $\alpha$  and control output of PDFSs. Table 2 shows the rule base used in these designs. Triangular membership functions shapes are selected for this work due to their linearity, simplicity and applicability.

Seven states are specified for representing  $e$  and  $\Delta e$  in all fuzzy systems included with this work. The states are represented as: NB, NM, NS, M, PS, PM and PB. NB is negative big, NM is negative medium, NS is negative small, M is medium, PS is positive small, PM is positive medium and PB is positive big. The output of the system is represented by nine membership functions. The output states are the same as input states, except for the output states there are two more states, that is, NVB is negative very big and PVB is positive very big. After manipulating the error signal by STFPDS, the next stage is supplying the manipulated signal to a PID controller to give the control action to the system. PID parameters values selection is selected based on a cost function which represents the Integrated Square of Error (ISE) between the input signal and actual system output. More details about PID parameters design can be found in Ltd (2012). Figure 5 shows the proposed control scheme for controlling TRMS.

Fuzzy Subtractive Clustering Method (FSCM) is a method which extracts rules from supplied input-output training data. It is a statistical classification technique which is used for discovering whether the individuals of a population fall into different groups by making quantitative comparison of multiple characteristics. Subtractive clustering method was firstly proposed by Chiu (1994) and explained in details in Jang (1997). In this work, the four

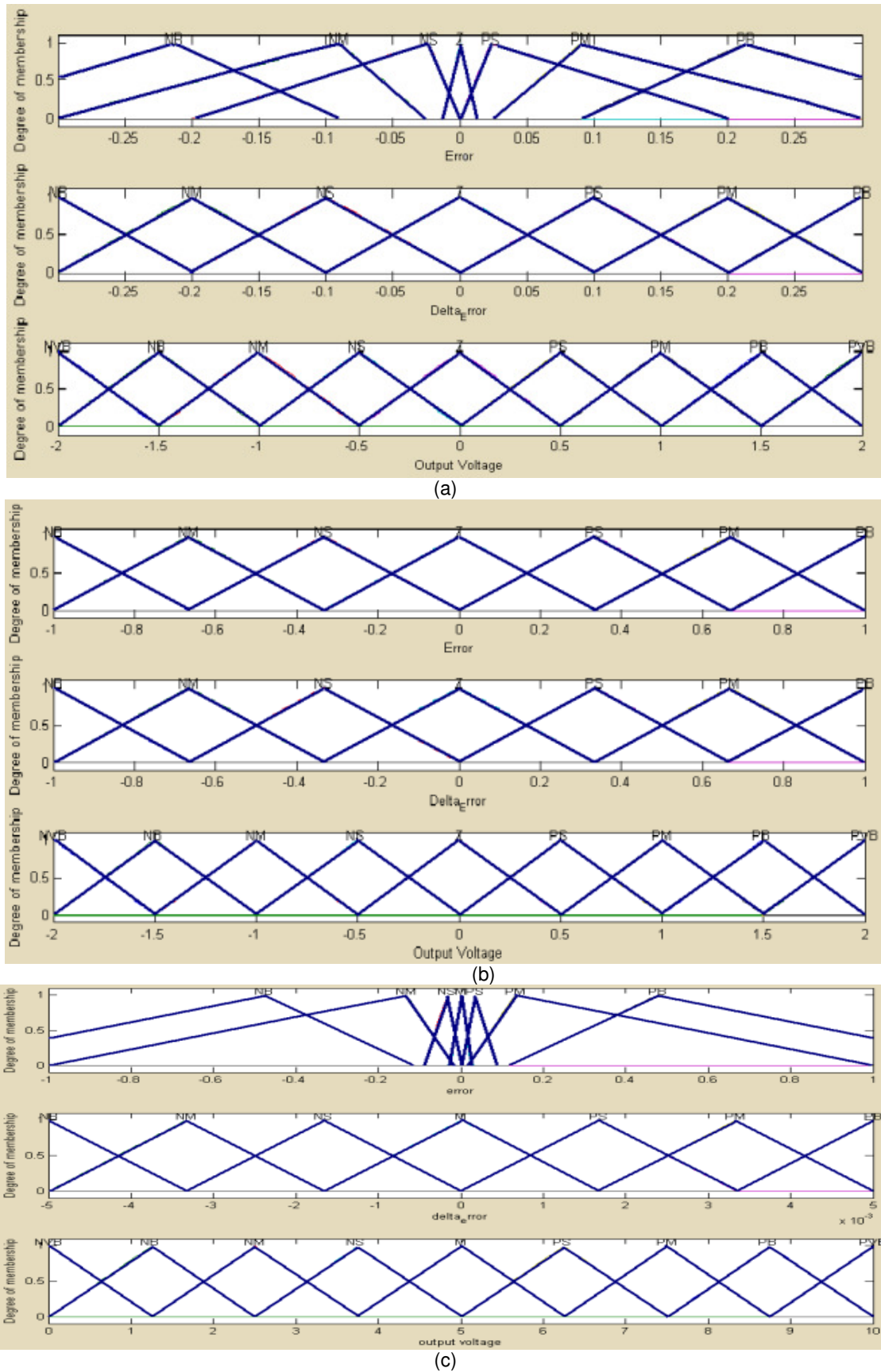
controllers were trained by random input signals for each of their two inputs, and the set of data were used to extract a new controllers using FSCM. ANFIS was used to train the new extracted FISs using the same sets of data for each (Chopra, 2006, 2007). Figure 6 shows the self tuning fuzzy controllers modeling strategy using FSCM based ANFIS.

After extracting the rules of the new proposed fuzzy controllers, parameters of new controllers are trained using neuro-fuzzy structure. MATLAB/ANFIS (Inc., 2012) was used to train the extracted rules. The training is stopped after 10000 epochs. The training scheme is illustrated by Figure 7. Sugeno Fuzzy systems were developed from controllers' ANFIS modeling. The developed Sugeno Fuzzy systems are used to manipulate the error signal based on an adaptive mamdani Fuzzy systems for better attitude and less number of rules than those in STFPDM. The developed neural networks are representing the developed Sugeno controllers that achieve the control objectives in each plane of motion in TRMS. Figures 8 and 9 show the developed neural networks for the proposed controllers in horizontal plane of motion.

For vertical and vertical to horizontal interaction part, the developed neural networks have been resulted in 15 and 18 neurons respectively. These developed neurons are representing the structure of the developed Sugeno fuzzy controllers with same number of membership function as that of neuron in the developed neural networks. For the PID parameters design, the selected values were set based on a cost function which represents the Integrated Square of Error (ISE) signal of the system. PID parameters values selection has been made using trail and error methodology based on the best obtained value of the ISE for both planes of motion. From Matlab simulink simulation environment, Figure 9 is illustrating the simulated control scheme of TRMS, which includes the developed Sugeno fuzzy systems with the proposed PID controllers.

## RESULTS

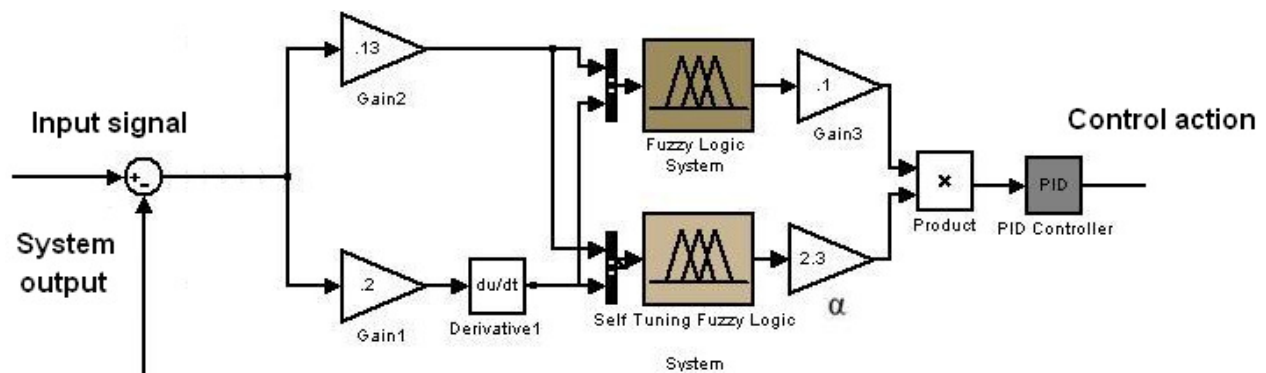
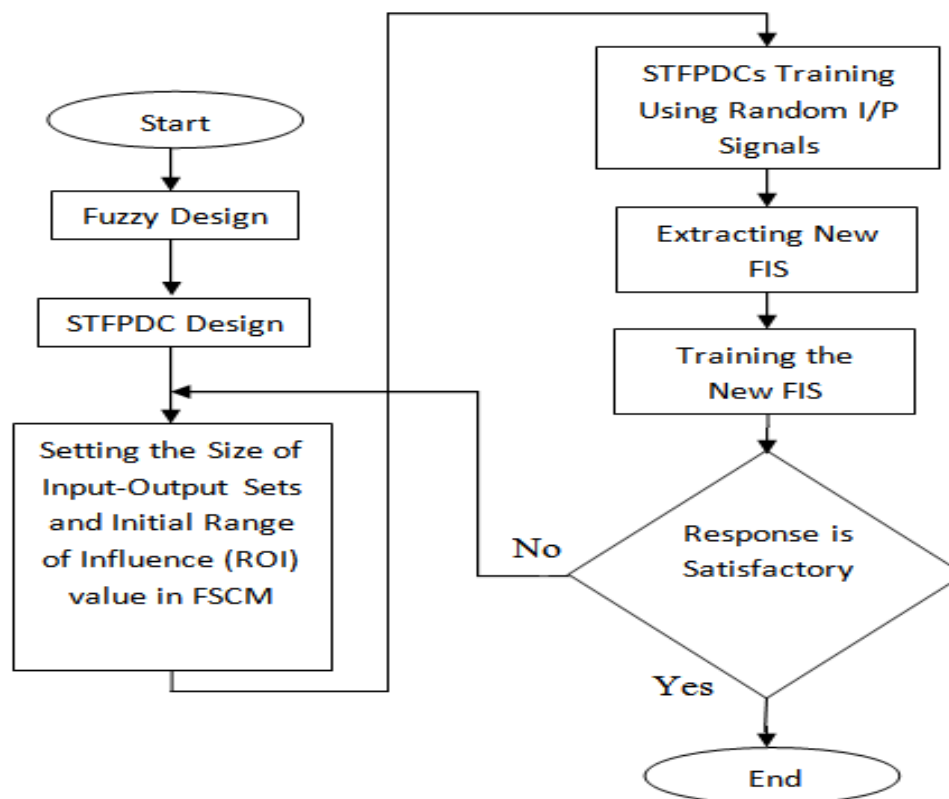
To evaluate the effectiveness of the proposed control



**Figure 4.** Membership functions design for STFPDS: (a) for vertical, (b) for horizontal and (c) for self tuning FS.

**Table 2.** Rules table for proposed fuzzy systems.

$\Delta e$	NB	NM	NS	M	PS	PM	PB
NB	NVB	NB	NB	NM	NS	NS	M
NM	NB	NB	NM	NM	NS	M	[S
NS	NB	NM	NM	NS	M	PS	PM
M	NM	NS	NS	M	PS	PS	PM
PS	NM	NS	M	PS	PS	PM	PM
PM	NS	M	PS	PS	PS	PM	PB
PB	M	PS	PM	PM	PB	PB	NVB

**Figure 5.** Self tuning fuzzy PD-like-PID controller.**Figure 6.** Self tuning fuzzy controllers modeling strategy using FSCM based ANFIS (Sugeno fuzzy systems extraction).

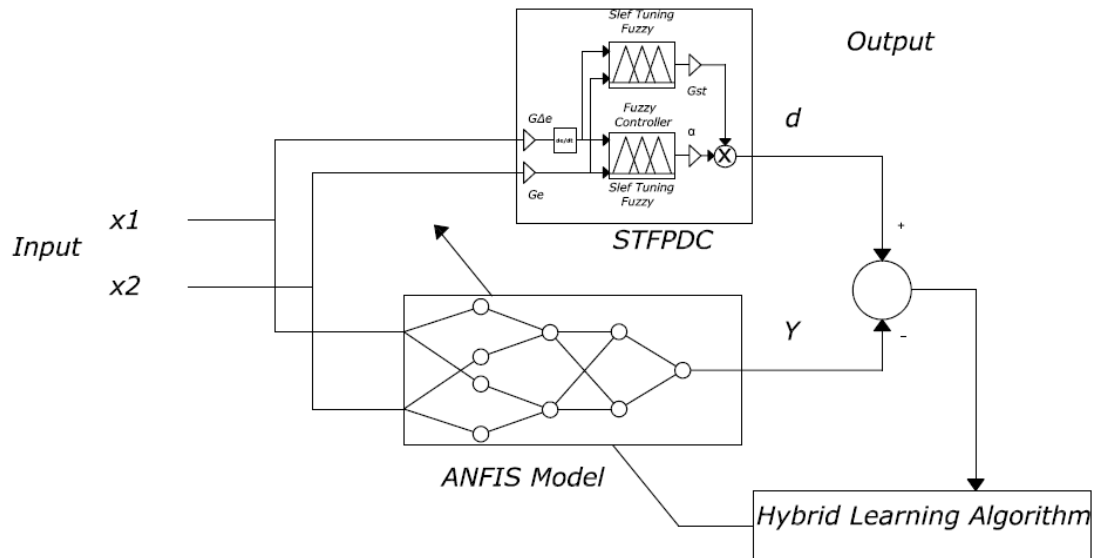


Figure 7. ANFIS parameters training scheme.

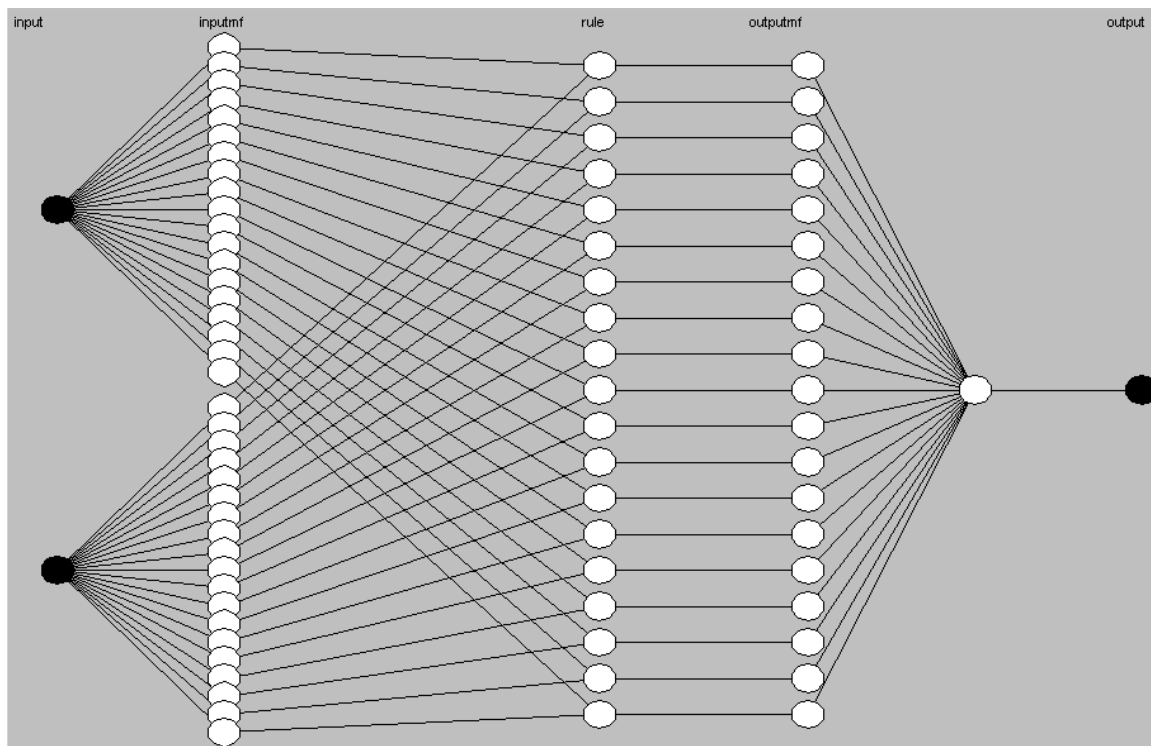


Figure 8. Developed neural network for Horizontal and Horizontal to Vertical interaction Sugeno systems.

method, several simulation studies for TRMS attitude control have been done. The results are presented according to the type of input signal for each of the horizontal and vertical planes of motions in TRMS. Figures 10, 11 and 12 show the horizontal part control responses under step, square and sinusoidal input

signals respectively. For the horizontal plane of motion, the simulation has been performed with 10 s simulation time under step input signal, and has been performed with 100 s simulation time under each of the square and sinusoidal input signals. The initial position of the beam started from 0 rad in all of the three input signals cases in



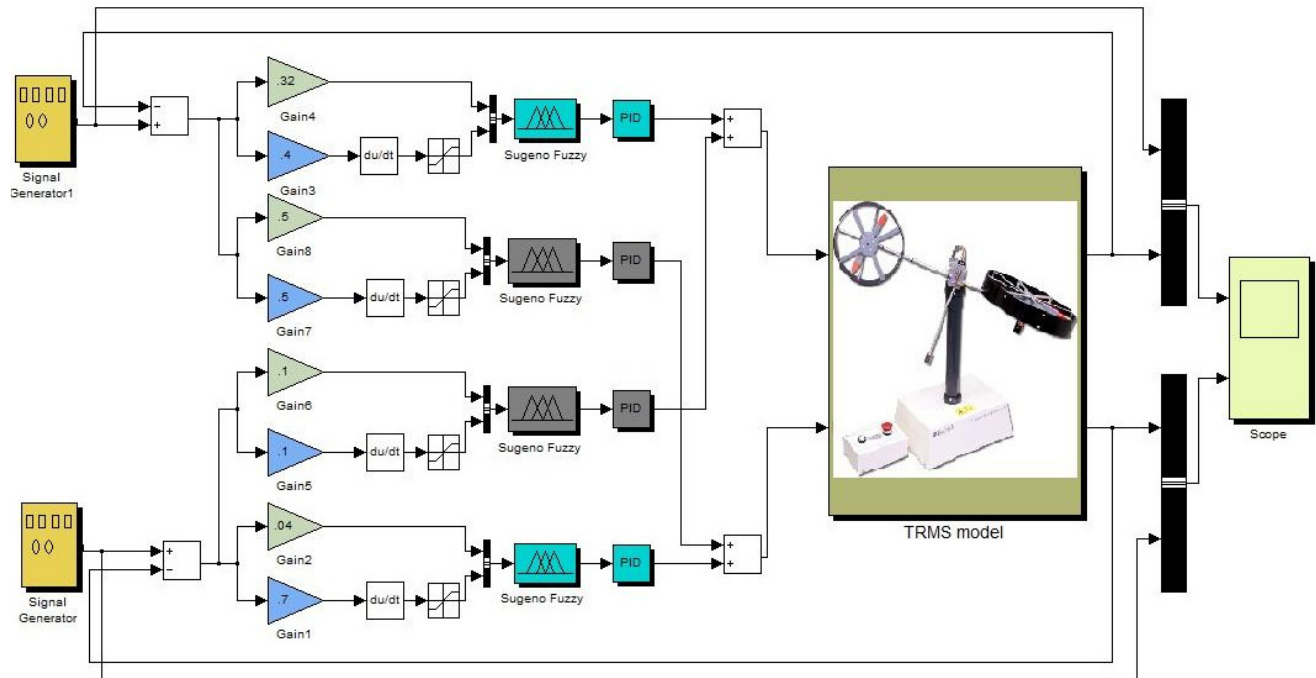


Figure 9. Simulink model of the proposed control scheme for TRMS.

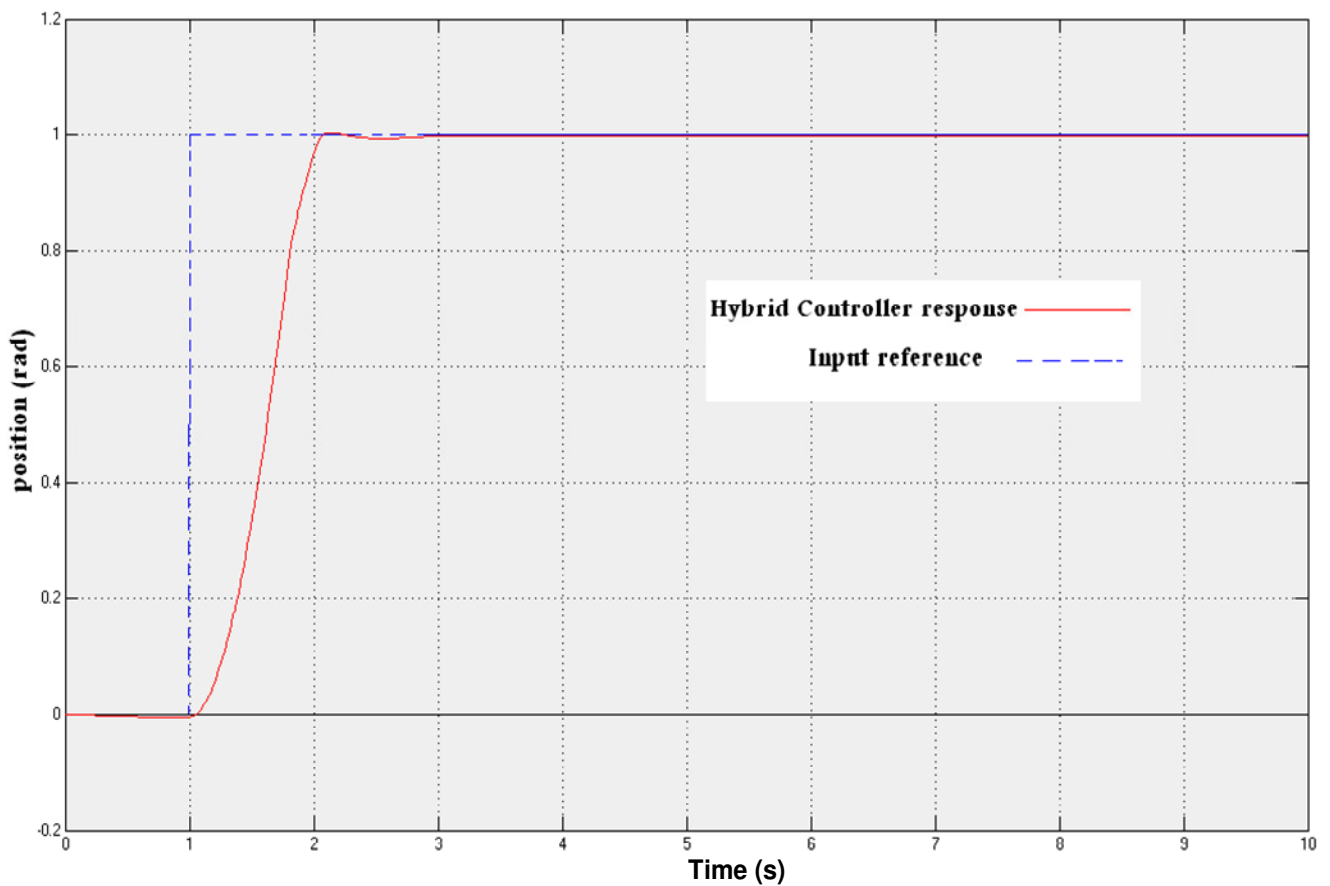
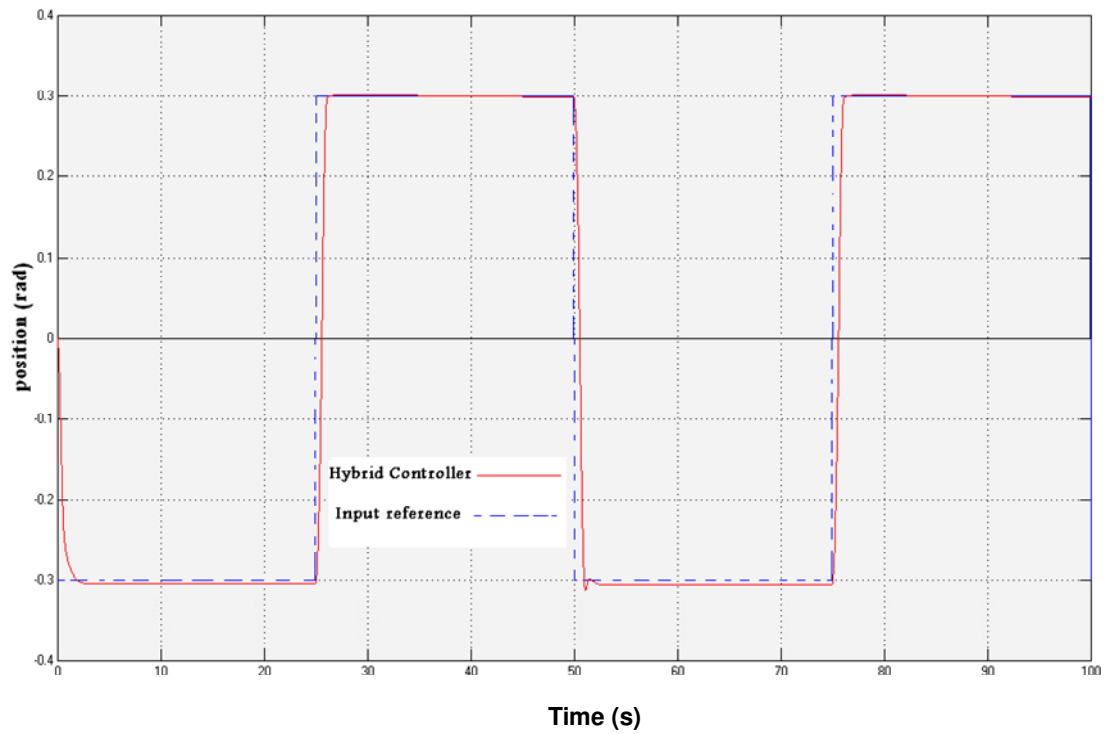
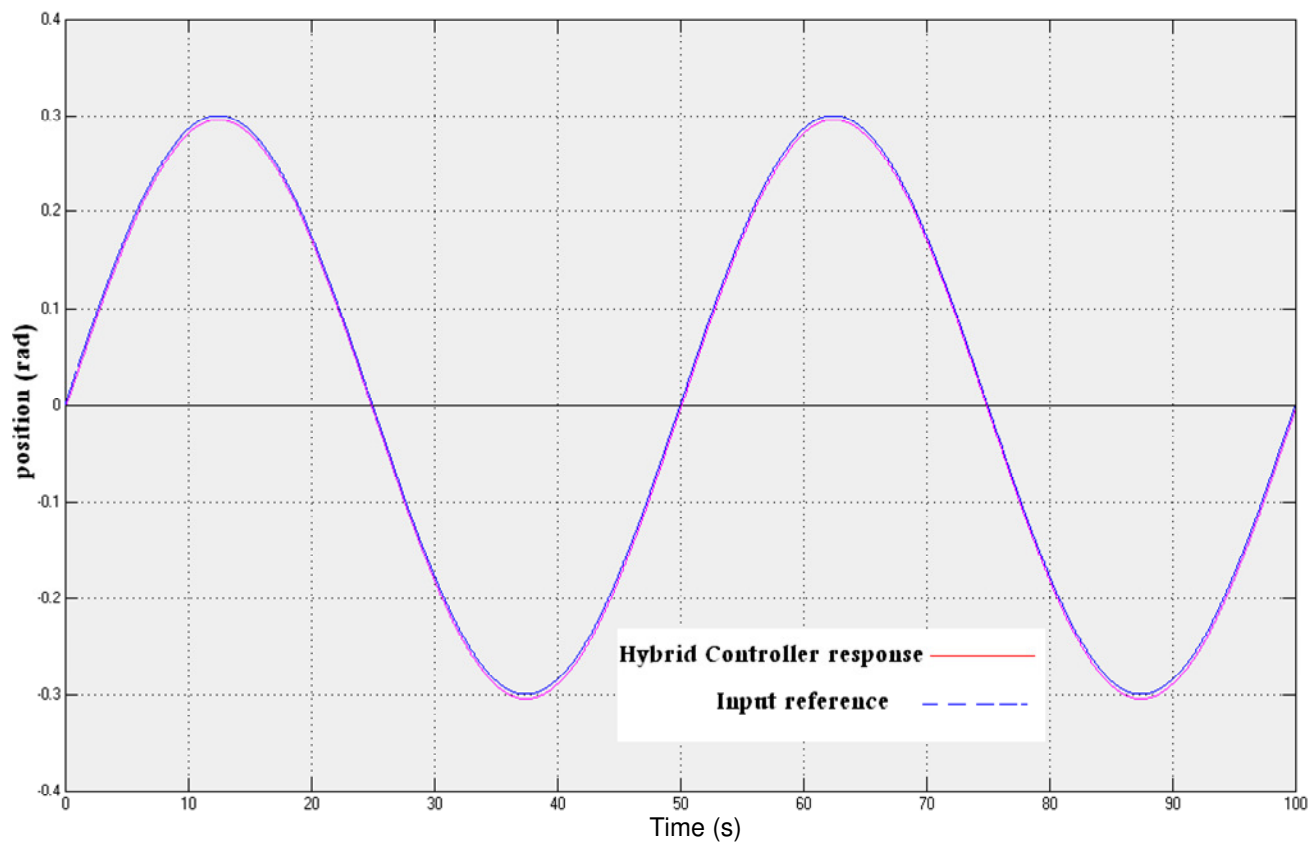


Figure 10. Horizontal plane response under step input signal.





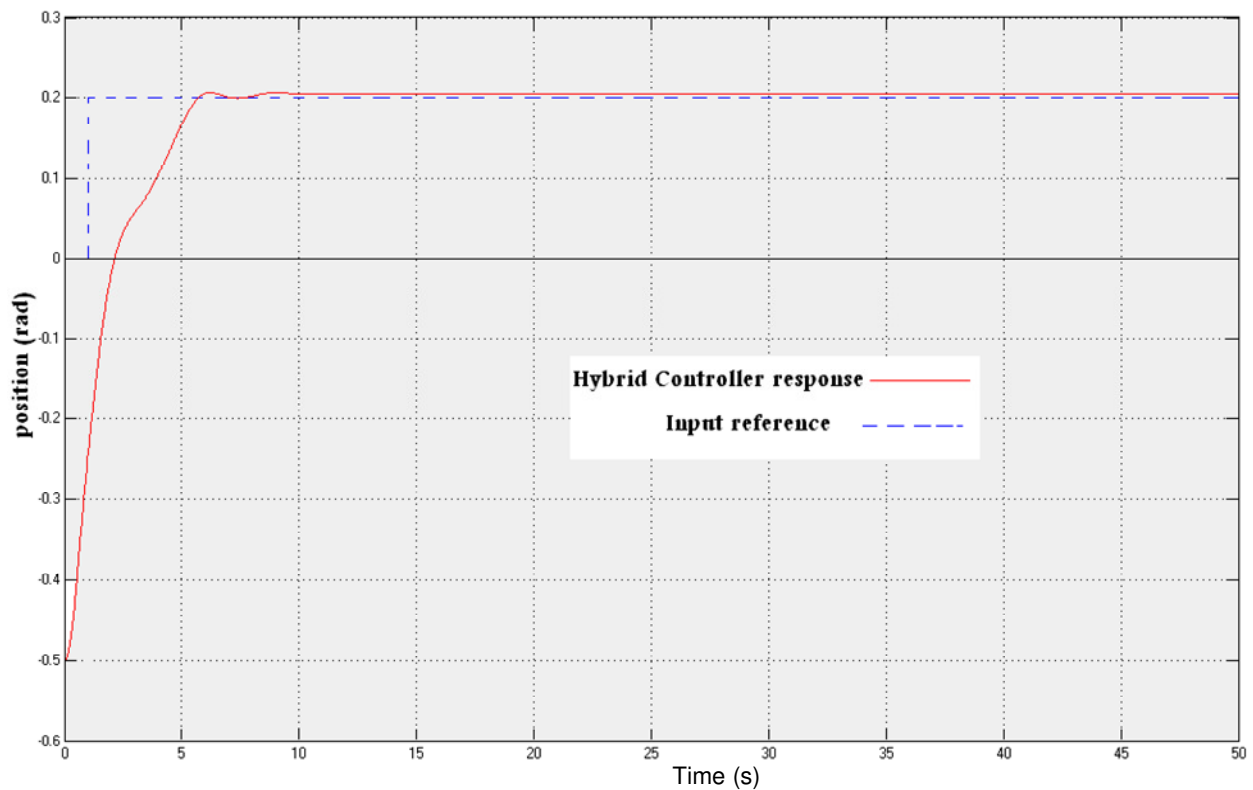
**Figure 11.** Horizontal plane response under square input signal.



**Figure 12.** Horizontal plane response under sine input signal.

**Table 3.** TRMS horizontal part step input responses comparison regarding other works.

Response\works	This work	GA-PID [8]	RGA-fuzzy [9]
Overshoot	zero	zero	12%
Rise time	1 s	2 s	2 s
Settling time	1.7 s	7 s	8 s

**Figure 13.** Vertical plane response under sine input signal.

horizontal part. It has been shown that under step input signal the system could reach the desired position after 1 s rising time with zero overshoot and 1.7 s settling time. For the square input signal, the system achieved 1 s rising time and 1.5 s settling time with zero overshoot. For the sinusoidal signal, the system could achieve 3% steady state error at each of the upper and lower peaks.

A comparison between this work and other works' results for horizontal part of TRMS under step input signal is illustrated in Table 3. Figures 13, 14 and 15 show the vertical part control responses under step, square and sinusoidal input signals respectively. For the vertical plane of motion, the simulation has been performed within 50 s simulation time under the step input signal, and has been performed with 100 s simulation time under each of the square and sinusoidal input signals. The initial position of the beam started from -5 rad in vertical part. It has been found that under step

input signal, the system could reach the desired position after 6 s rising time with 1.5% overshoot and 9 s settling time. For the square input signal, the system achieved 3 s rising time and 12 s settling time with 4% overshoot. For the sinusoidal signal, the system could achieve 18% overshoot, 3 s rising time and 4% steady state error at each of the upper and lower peaks.

A comparison between this work and other works' results for vertical part of TRMS under step input signal is illustrated in Table 4.

## DISCUSSION

From analyzing the results, it was clear to notice that the vertical part was harder to control, although controllers were successful in maintaining satisfactory transit and steady state in that plane of motion. Adding the tuning

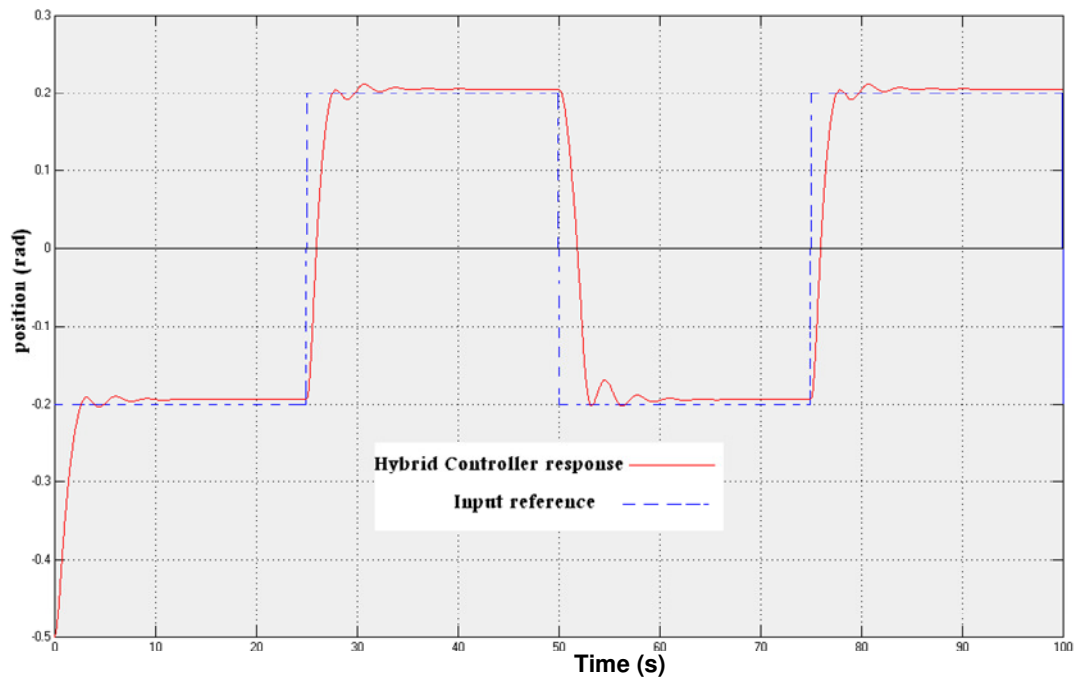


Figure 14. Vertical plane response under sine input signal.

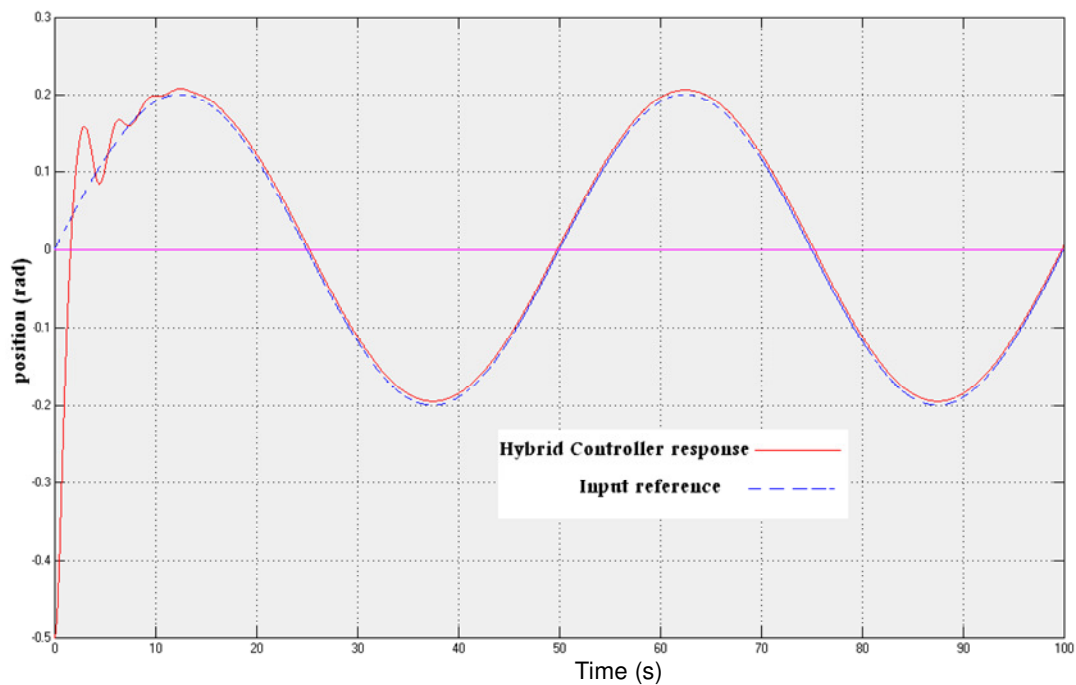


Figure 15. Vertical plane response under sine input signal.

fuzzy system to the main fuzzy system controller could increase the controller stability and improve the response of the TRMS due to covering the critical operation points of the TRMS by the added rules of the tuning fuzzy

systems. The STFPDS could achieve a good error manipulation before supplying it to the PID. Ultimately, the benefits of using classical and intelligent control strategies came up with fast transient response and less

**Table 4.** TRMS vertical part step input response comparison with other works.

Response\work	This work	GA-PID [8]	RGA-Fuzzy [9]
Overshoot	1.5%	0.5%	4%
Rise time	6 s	3 s	6.5 S
Settling time	9 s	10 s	17 s

settling time, overshoot and steady state error. Although, that resulted in a higher number of rules, the response was encouraging to have such kind of controller. However, modeling these STFPDS with ANFIS did not witness big accuracy deterioration. Thus, utilizing this control implementation was attractive from the complexity and the response wise.

Considering the error between the desired input signal and the output of the controlled system through a multi-stage for manipulation, to get the optimum control action, has proved its success in achieving competitive results in both planes of motions. In each of these, the results achieved satisfactory responses under different input signals.

## Conclusions

In this work, hybrid control scheme of Sugeno Fuzzy PD-like Manipulator and PID controller design was proposed. The purpose of combining the two stages of error manipulations was to get the benefit of having better transient response using fuzzy inference systems and better steady state error using PID controllers. The strategy is to manipulate the error signal through two stages. The error signal is manipulated by the STPDM first, and then fed to PID to give the control action to the system. The proposed control scheme has been applied to solve Twin Rotor MIMO System (TRMS) control problems. Simulation studies have proved the effectiveness of proposed method. The results have been presented in terms of showing the output responses under different input signals. The results have proved the effectiveness of the proposed strategy in terms of achieving satisfactory responses in both planes of motion.

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