VIRTUAL REALITY ANIMATION OF ANFIS CONTROLLER FOR MOBILE ROBOT STABILIZATION

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الملخص

يعتبر التحكم بالروبوت المتحرك وسيلة جيدة لاختبار جميع أنواع نظريات التحكم في الوقت الحاضر، حيث يستخدم هذا النوع من الروبوتات في الكثير من التطبيقات المختلفة. إن استقرار وتتبع المسار ومنع النظام من السقوط أثناء الحركة إلى الأمام أو للخلف والتحكم بزاوية الدوران الي اليمين أو اليسار أثناء الحركة تعتبر المشكلة الرئيسية. ولحل هذه المشكلة تم تصميم وحدة تحكم تعتمد في عملها على مبدأ التحكم الضبابي المتكيف الذي يمكن أن يولد العزم الصحيح واللازم للوصول الي الهدف بدقة عالية. ومن خلال نتائج المحاكاة المتحصل عليها من هذا التصميم أتضح أن هناك مطابقة جيدة بين حركة التتبع للربوت للمسارات المختلفة والمحددة مسبقا. كما تم في هذا البحث تصميم ومحاكاة نموذج مرئي للربوت في الواقع الافتراضي وذلك لملاحظة الحركة في نظام ثلاثي الأبعاد وبالتالي يمكن مشاهدة حركة الربوت أثناء تتبعه للمسار المحدد.

ABSTRACT

The control wheeled mobile robot is a good way to test control theories. Two Wheeled Inverted Pendulum Mobile Robot (TWIPMR) is used in different applications. Stabilizing and tracking trajectory will prevent system from falling down when it moves in the forward and backward directions. In addition, the steering angle regulation when it turns left or right is also considered. These are the major problems that have to be taken into account during control design and analysis. To avoid these problems, an intelligent controller based ***Adaptive Network Based Fuzzy Inference System (ANFIS)*** method is presented to generate the required optimal control signals. The simulation results are provided to show the effectiveness of the proposed control design method for an accurate tracking of the desired trajectory. Furthermore, the 3D representation of the simulation and a visualization model to observe behavior of the robot in different scenarios are included.

KEYWORDS: TWIPMR; FLC; ANFIS Controller; VRML Model.

INTRODUCTION

Development and control of two wheeled balancing mobile robot or wheeled inverted pendulum is a popular research topics in verifying various control theories over the last decade, the motion control problem of a robot that can self-balancing on wheels has received much attention in both academic and industry worldwide. Two wheeled robot system is not only an intricate multiple-input multiple-output nonlinear system, but also a kind of typical non-holonomic system with time-varying dynamics. It is also a complicated coupled dynamic system with non-linear saturation dynamic characteristics [1,2]. In real movement, two-wheeled robot suffers from uncertain factors, such as load change, the friction, road conditions and external interference, this will bring great difficulties to motion control for two wheeled robot. In this work the performance of the dynamical system being controlled is desired to be optimized. Fuzzy logic control and Adaptive Networks based Fuzzy Inference system (ANFIS) is designed and implemented to stabilize TWIPMR system [3]. In addition, the tracking performance of the robot displacement under the influence of the disturbance is investigated. The work in this paper can be arranged as follows. In section 2, the mathematical model of TWIPMR is written, in section 3, the system analysis is considered, the fuzzy logic controller is designed in section 4, the ANFIS is designed in section 5, the virtual reality animation for simulation and analysis is shown in section 6, finally the conclusion is presented.

MATHEMATICAL MODEL OF TWIPMR

The performance of a balancing robot depends on the efficiency of the control algorithms and the dynamic model of the system. By adopting the coordinate system shown in Figure (1) using Newtonian mechanics, it can be shown that the dynamics of the TWIPMR under consideration is governed by the following equations of motion, Linear displacement of the vehicle is denoted by x, angular rotation about the y-axis (pitch) by θ, and angular rotation about the z-axis (yaw) by δ [4]. The definitions of parameters are in listed in Table (1).

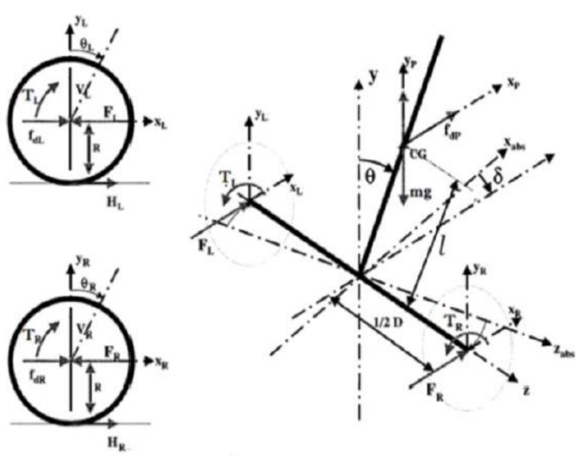

Figure 1: Diagram of forces and moments acting on the TWIPMR system

Table 1: Definition of system parameters

Parameter	Definition
m	Mass of robot body
R	Radius of wheel
D	Distance between wheels
f_p	Disturbances applied CG
CG	Center of gravity of robot body
l	Distance between CG and wheel axis.
J_δ	Moment of inertia of chassis with respect to Y-axis
J_{mo}	Moment of inertia of chassis
J_{po}	Moment of inertia of pendulum
F_P	Horizontal force
T_L, T_R	Torques generated from the motors
θ_L, θ_R	Rotation angles of wheels
H_L, H_R	Friction forces with ground surface
F_{dL}, F_{dR}	Outside Disturbances applied to wheels
F_L, F_R	Interacting forces between wheels and chassis
J_L, J_R	Moment of inertia of left and right wheels with respect to Z-axis
M_L, M_R	Mass of each wheel

A mechanical 3 DOF system can be modeled using six state space variables. The following variable have been chosen:

x: straight line position	[m]	ν: : straight line speed	[m/s]
θ: pitch angle	[rad]	ω : pitch rate	[rad/s]
δ: yaw angle	[rad]	$\dot{\delta}$: yaw rate	[rad/s]

Based on these parameters the state space equation for the system is obtained as [5]:

$$\dot{x} = \nu \tag{1}$$

$$\dot{\nu} = \frac{T_L}{\alpha R} + \frac{T_R}{\alpha R} + \frac{F_{dL}}{\alpha} + \frac{F_{dR}}{\alpha} + \frac{f_p}{\alpha} - m\, l \cos\theta \left(\frac{m\, g\, l \sin\theta + f_p\, l \cos\theta}{\alpha(J_{mo}+J_{po})}\right) \tag{2}$$

$$\dot{\theta} = \omega \tag{3}$$

$$\dot{\omega} = \frac{(m\, g\, l \sin\theta + f_p\, l\cos\theta)\left(M+m+4M_w+\frac{2J_w}{R^2}\right) + m\, l \cos\theta\left(\frac{T_L}{R}+\frac{T_R}{R}+F_{dL}+F_{dR}+f_p\right)}{\beta} \tag{4}$$

$$\dot{\delta} = \Omega \tag{5}$$

$$\dot{\Omega} = \frac{D}{2}\left[\frac{\frac{T_L}{R}-\frac{T_R}{R}+F_{dL}-F_{dR}}{J_\delta+\frac{D^2}{2}\left[\frac{J_w}{R^2}+M_w\right]}\right] \tag{6}$$

With α and β are defined as following:

$$\alpha = M + m + 4M_w + \frac{2J_w}{R^2} + \left(\frac{m^2\, l^2 \cos^2\theta}{(J_{mo}+J_{po})}\right),$$

$$\beta = (J_{mo} + J_{po})\left(M + m + 4M_w + \frac{2J_w}{R^2}\right) + m^2\, l^2 \cos^2\theta$$

The nonlinear dynamic equations are implemented by Simulink model as shown in Figure (2). The model gives the exact relationships among all the variables involved.

Figure 2: Simulink model of the nonlinear TWIPMR dynamics system

Due to small variation about operating conditions at $\theta = 0$, the above equations are linearized to get the following linearized model [5].

$$\dot{x} = \nu \tag{7}$$

$$\dot{v} = \frac{T_L}{\alpha R} + \frac{T_R}{\alpha R} + \frac{F_{dL}}{\alpha} + \frac{F_{dR}}{\alpha} + \frac{(J_{mo}+J_{po})-ml^2}{\alpha(J_{mo}+J_{po})} f_p - \frac{m^2 g\, l^2}{\alpha(J_{mo}+J_{po})}\theta \tag{8}$$

$$\dot{\theta} = \omega \tag{9}$$

$$\dot{\omega} = \frac{\left(\frac{mlT_L}{R} + \frac{mlT_R}{R} + mlF_{dL} + mlF_{dR}\right) + (mg\, l\theta + f_p l)\left(M + m + 4M_w + \frac{2J_w}{R^2}\right) + ml\, f_p}{\beta} \tag{10}$$

$$\dot{\delta} = \Omega \tag{11}$$

$$\dot{\Omega} = \frac{D}{2}\left[\frac{\frac{T_L}{R} - \frac{T_R}{R} + F_{dL} - F_{dR}}{J_\delta + \frac{D^2}{2}\left(\frac{J_w}{R^2} + M_w\right)}\right] \tag{12}$$

The above general state-space, representation of a continuous LTI system can be expressed in the following form:

$$\begin{bmatrix} \dot{x} \\ \dot{v} \\ \dot{\theta} \\ \dot{\omega} \\ \dot{\delta} \\ \ddot{\delta} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & x_{23} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & x_{43} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ v \\ \theta \\ \omega \\ \delta \\ \dot{\delta} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ y_{21} & y_{22} & y_{23} & y_{24} & y_{25} \\ 0 & 0 & 0 & 0 & 0 \\ y_{41} & y_{42} & y_{43} & y_{44} & y_{45} \\ 0 & 0 & 0 & 0 & 0 \\ y_{61} & y_{62} & y_{63} & y_{64} & 0 \end{bmatrix} \begin{bmatrix} T_L \\ T_R \\ F_{dL} \\ F_{dR} \\ f_p \end{bmatrix} \tag{13}$$

Where

$$x_{23} = -\frac{m^2 g\, l^2}{\alpha(J_{mo}+J_{po})} \qquad x_{43} = \frac{\left(M + m + 4M_w + \frac{2J_w}{R^2}\right)mgl}{\beta} \qquad y_{21} = y_{22} = \frac{1}{R\alpha}$$

$$y_{23} = y_{24} = \frac{1}{\alpha} \qquad y_{25} = \frac{(J_{mo}+J_{po}) - m\, l^2}{\alpha(J_{mo}+J_{po})} \qquad y_{41} = y_{42} = \frac{ml}{R\beta}$$

$$y_{43} = y_{44} = \frac{ml}{\beta} \qquad y_{45} = \frac{\left(M + m + 4M_w + \frac{2J_w}{R^2}\right)l + ml}{\beta} \qquad y_{61} = \frac{D}{2R}\left[\frac{1}{J_\delta + \frac{D^2}{2}\left(\frac{J_\omega}{R^2} + M_\omega\right)}\right]$$

$$y_{62} = -y_{61} \qquad y_{63} = \frac{D}{2}\left[\frac{1}{J_\delta + \frac{D^2}{2}\left(\frac{J_\omega}{R^2} + M_\omega\right)}\right] \qquad y_{64} = -y_{63}$$

SYSTEM ANALYSIS

The considered robotic system is defined as a MIMO system. The system transfer functions are summarized in Table (2) which has at least one or more unstable poles. The open loop step and impulse responses are shown in Figure (3). Where, it is seen that all responses are diverging and the system is unstable. And a rapid divergence in the output is observed when a little variations in the input signal is occur [6,7]. Consequently, in order to avoid this degradation in stability and tracking performance, the intelligent controller is designed as will be explained in the next section

Table 2: Transfer Function Matrix

	T_L	T_R	F_{dR}	F_{dL}	f_p
x	$\frac{1.3\,s^2-15.4}{s^4-11.19s^2}$	$\frac{1.3\,s^2-15.4}{s^4-11.19s^2}$	$\frac{0.23\,s^2-2.6}{s^4-11.19s^2}$	$\frac{0.2\,s^2-2.6}{s^4-11.19s^2}$	$\frac{0.17\,s^2-2.6}{s^4-11.19s^2}$
$\dot{x}$	$\frac{1.3\,s^2-15.4}{s^3-11.19s}$	$\frac{1.3\,s^2-15.4}{s^3-11.19s}$	$\frac{0.23\,s^2-2.6}{s^3-11.19s}$	$\frac{0.2\,s^2-2.6}{s^3-11.19s}$	$\frac{0.17\,s^2-2.6}{s^3-11.19s}$
θ	$\frac{1.58}{s^2-11.19}$	$\frac{1.58}{s^2-11.19}$	$\frac{0.27}{s^2-11.19}$	$\frac{0.27}{s^2-11.19}$	$\frac{1.03}{s^2-11.19}$
$\dot{\theta}$	$\frac{1.58\,s}{s^2-11.19}$	$\frac{1.58\,s}{s^2-11.19}$	$\frac{0.27\,s}{s^2-11.19}$	$\frac{0.27\,s}{s^2-11.19}$	$\frac{1.03s}{s^2-11.19}$
δ	$\frac{18.85}{s^2}$	$-\frac{18.85}{s^2}$	$\frac{3.2}{s^2}$	$\frac{-3.2}{s^2}$	0
$\dot{\delta}$	$\frac{18.85}{s}$	$-\frac{18.85}{s}$	$\frac{3.2}{s}$	$\frac{-3.2}{s}$	0

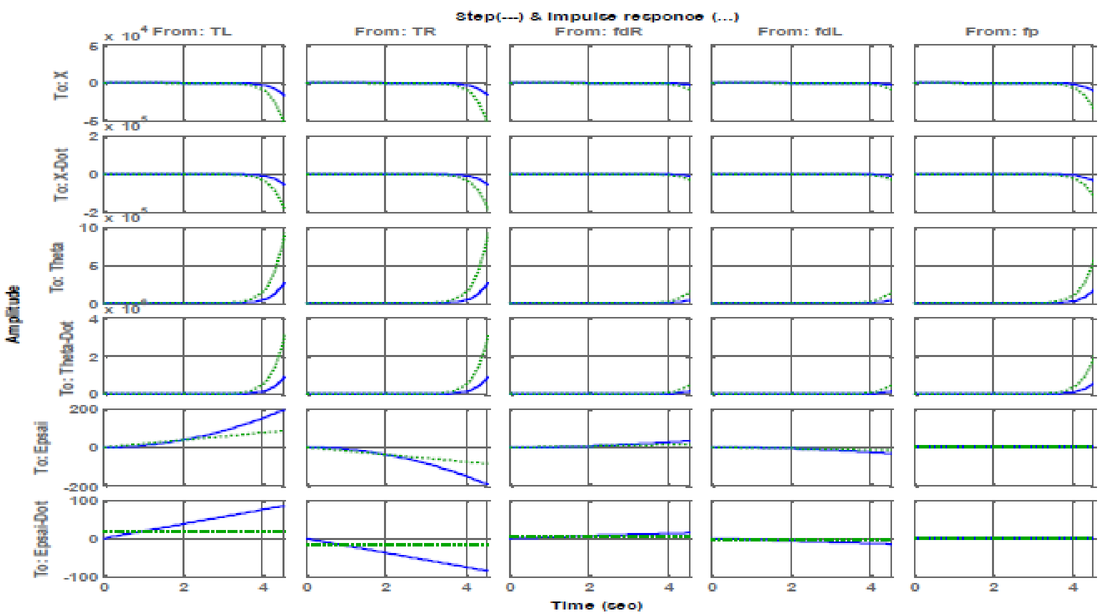

Figure 3: Open loop unit step and impulse response of the transfer matrix

FUZZY LOGIC CONTROLLER

Fuzzy logic controller is unlike any conditional logic, while in traditional logic the variables may take on true or false values, in fuzzy logic the truth of any statement is a matter of degree where it may range between completely true and completely false by a value between 1 to 0. In recent years, FLC has attracted considerable attention as a tool for novel control approaches because of the variety of advantages that it offers over classical control techniques. FLC does not require a mathematical model of the plant and can be applied equally to linear and nonlinear systems [8].

TWIPMR Control Using Fuzzy Inference Controller

Fuzzy logic controller has been designed for stabilization and tracking of the robot. This will result in a multi input multi-output (MIMO) fuzzy controller, which will incur a huge time consuming rule-base. Therefore, for simplicity and reducing the processing time, the fuzzy controller was split into two fuzzy controllers, utilizing the error and the derivative of error for both the measured tilt angle of IB and linear displacement of the vehicle. This will reduce the rule-base drastically and the associated processing time [9]. The FLC were divided into FLCP and FLCA as illustrated in Figure (4). FLCP controls the linear position on x-axis and FLCA controls the angular position y-axis of the balancing robot.

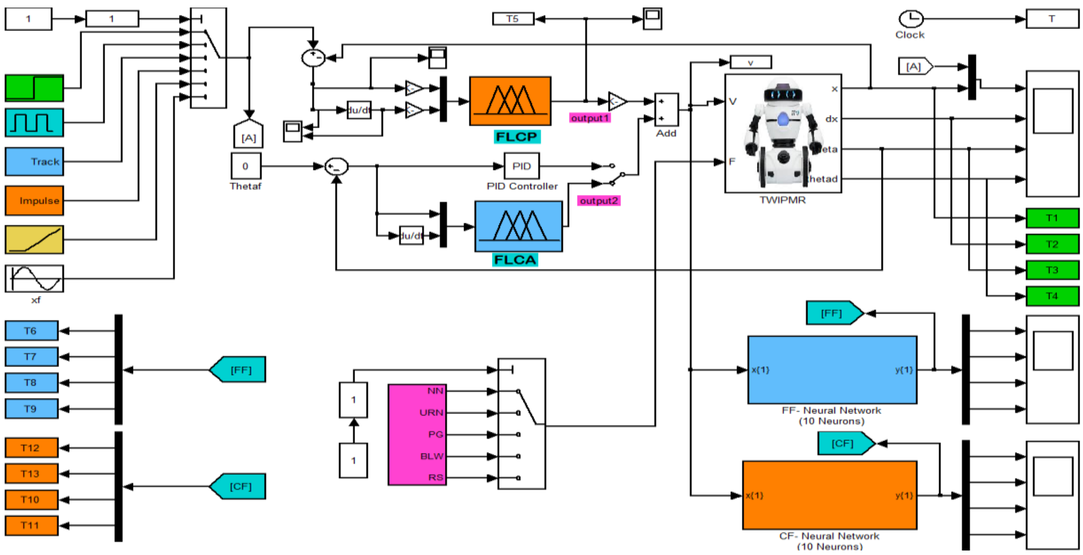

Figure 4: Simulink model of actual and neuro model with Fuzzy Logic Controller

Designing of Fuzzy Logic Controller

To design of a fuzzy logic controller, it requires the choice of membership functions. After the appropriate membership functions are chosen, a rule base is created. The fuzzy control rules for both the fuzzy controllers were designed using the experience of experts and varies from one expert to another. The main parameters that determine the fuzzy inference are related to the shapes and ranges of the applied membership functions. Varying the shape, position and range of these functions different control performance is achieved. Five linguistic variables for the error and derivative of error shown in Table (2) are chosen for each inputs and outputs: negative big (NB), negative small (NS), zero (Z), positive small (PS) and positive big (PB) [10]. The membership functions of error and derivative of error for vehicle and IB shown in Figure (5). A 3-D view of surface viewer for FLCP and FLCA are shown in Figure (6).

Table 2: Fuzzy control rules for FLCP and FLCP

		Change of Error									
		FLCP					FLCP				
		NB	NS	Z	PS	PB	NB	NS	Z	PS	PB
Error	NB	NB	NB	NS	NS	Z	NB	NB	NB	NS	Z
	NS	NB	NB	Z	Z	PS	NB	NB	NS	Z	PS
	Z	NB	NS	PS	PS	PB		NS	Z	PS	
	PS	NS	Z	PB	PB	PB	NS	NS	Z		
	PB	Z	PS	PB	PB	PB	Z	Z			

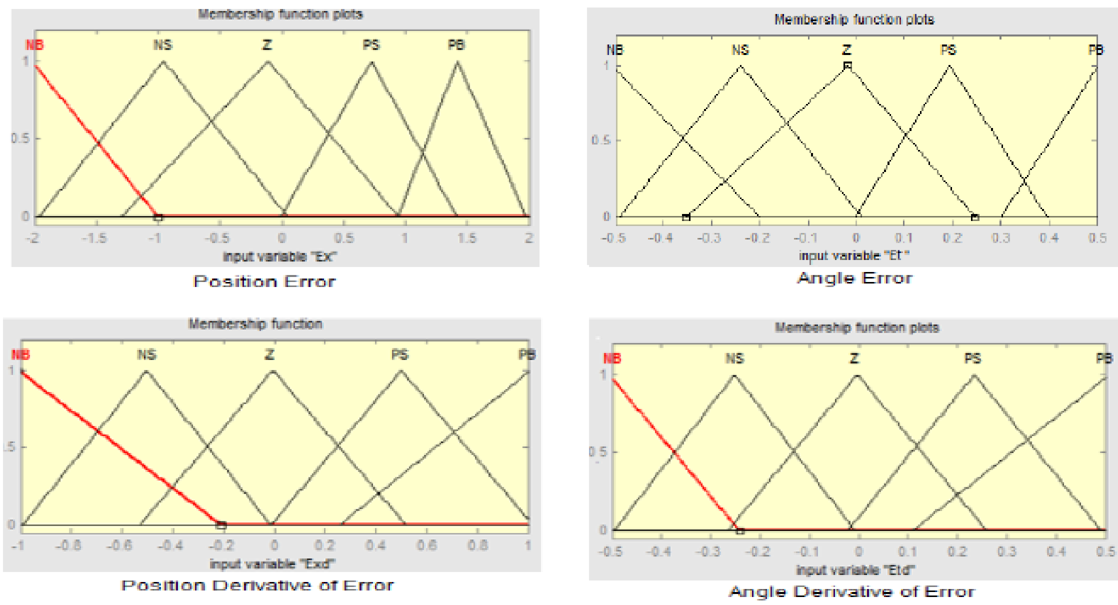

Figure 5: Membership functions of FLCP and FLCA

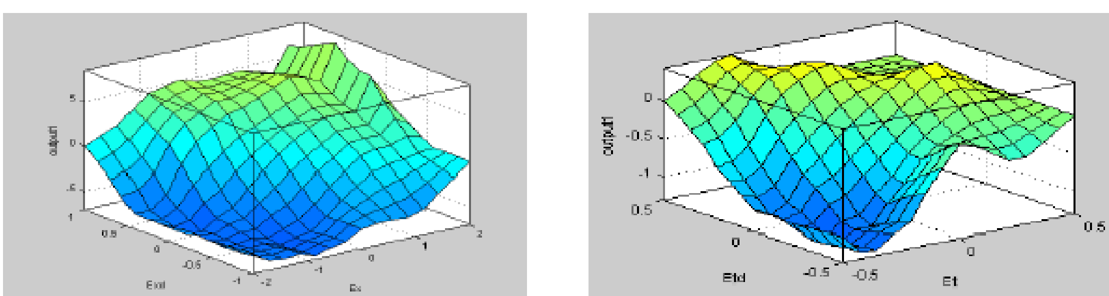

Figure 6: Surface viewer for FLCP and FLCA

Simulation results of FLC for TWIPMR

The simulation results using fuzzy controllers for TWIPMR are shown Figure (7). It is clearly seen that tracking capability of TWIPMR with given step (Ref1) and different step level reference (Ref3) is acceptable and the body angle is seen making smooth movements. Input voltage is not exceeding the limitations. And also sinusoidal type of reference (Ref3) applied. Tracking capability is not good as (Ref1 and Ref3). But to improve the performance and make the system faster the number of rules used in Fuzzy system needs to be optimized. Further, to reduce the numbers of rules Neural Network along with fuzzy controller can also be applied to train a new controller using data sets were taken previously occurred simulations.

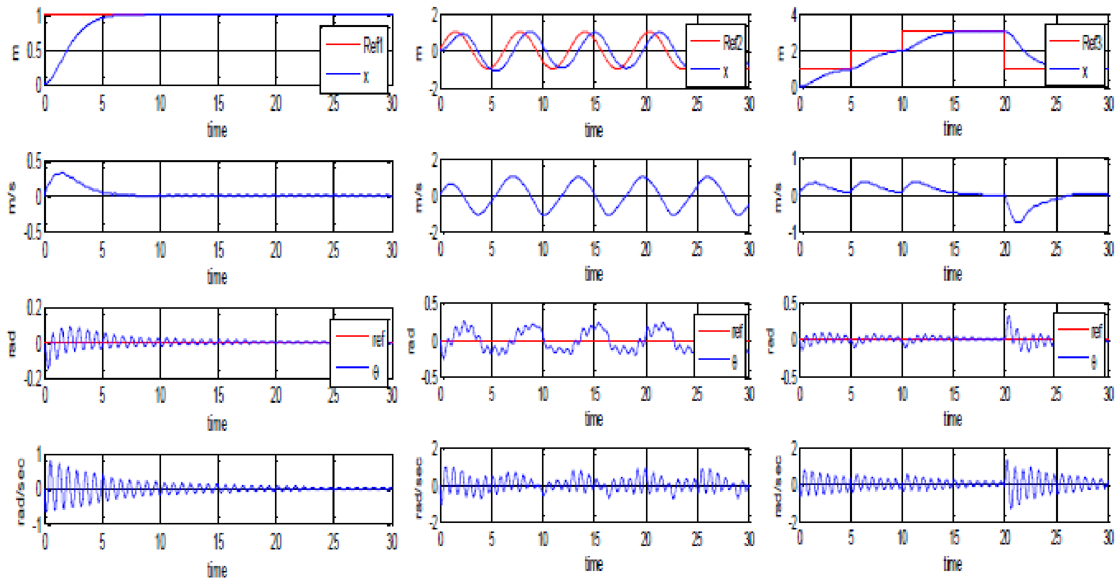

Figure 7: Simulation results of FLC for neuro model of TWIPMR

ADAPTIVE NETWORK BASED FUZZY INFERENCE SYSTEM (ANFIS)

A novel design of an adaptive neuro fuzzy inference strategy for controlling TWIPMR is presented in this section. Adaptive Neuro-Fuzzy Inference System (ANFIS) is a Fuzzy Neural Network. An ANFIS is a simple data learning technique that uses Fuzzy Logic to transform given inputs into a desired output through highly interconnected Neural Network processing elements and information connections, which are weighted to map the numerical inputs into an output [11].

Design of ANFIS Controller for TWIPMR

To start the ANFIS learning; first, a training data set that contains the desired input and output data pairs of target system is to be required. The design parameters required for any ANFIS controller are, number of data pairs, training data set & checking data sets, fuzzy inference systems for training, number of epochs to be chosen to start the training, Learning results to be verified after mentioning the step size [11]. The basic flow diagram of computations in ANFIS using matlab without use ***ANFIS GUI*** presented in Figure (8).

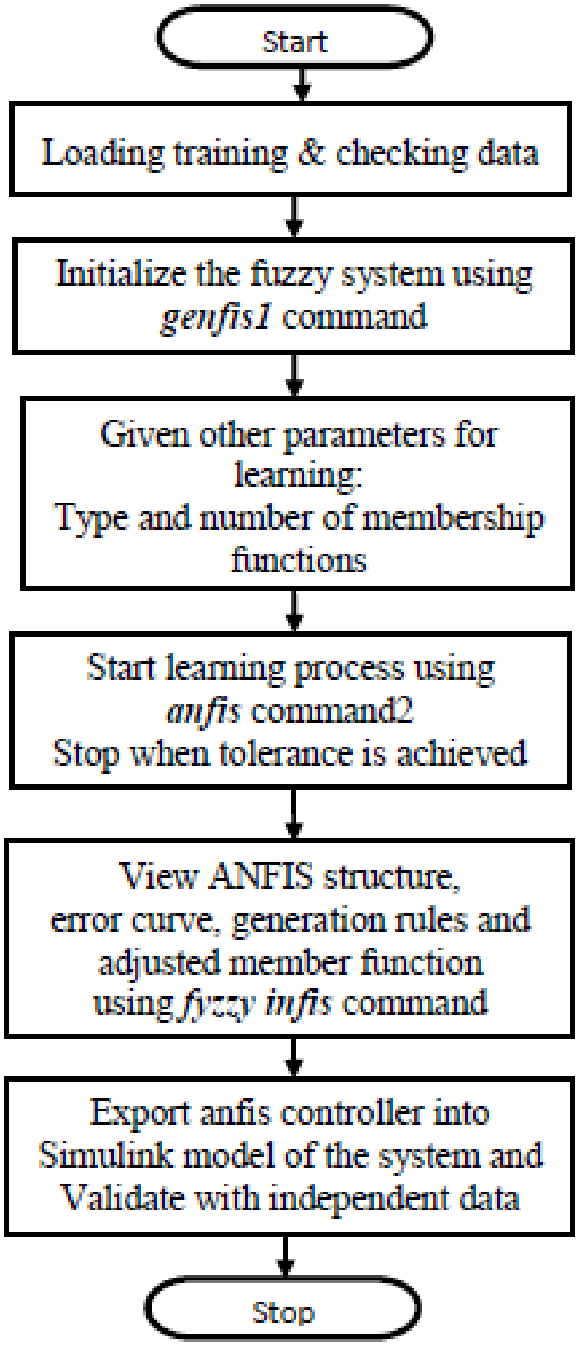

Figure 8: Computations in ANFIS using matlab

Simulation results of ANFIS Controller for TWIPMR

The ANFIS trains for the inputs, angle, angular velocity, position and velocity and also output is the voltage control signal. The pre-designed fuzzy controller for TWIPMR was used to generate data sets. A total of 3000 data sets were collected which were further divided into training and checking data sets as shown in Figure (9), and three membership functions ***(gaussmf,trimf, trapmf ,gbellmf)*** were used for training. After the training has ended we can export ANFIS model to simulink file or work space and use it directly to control the system.

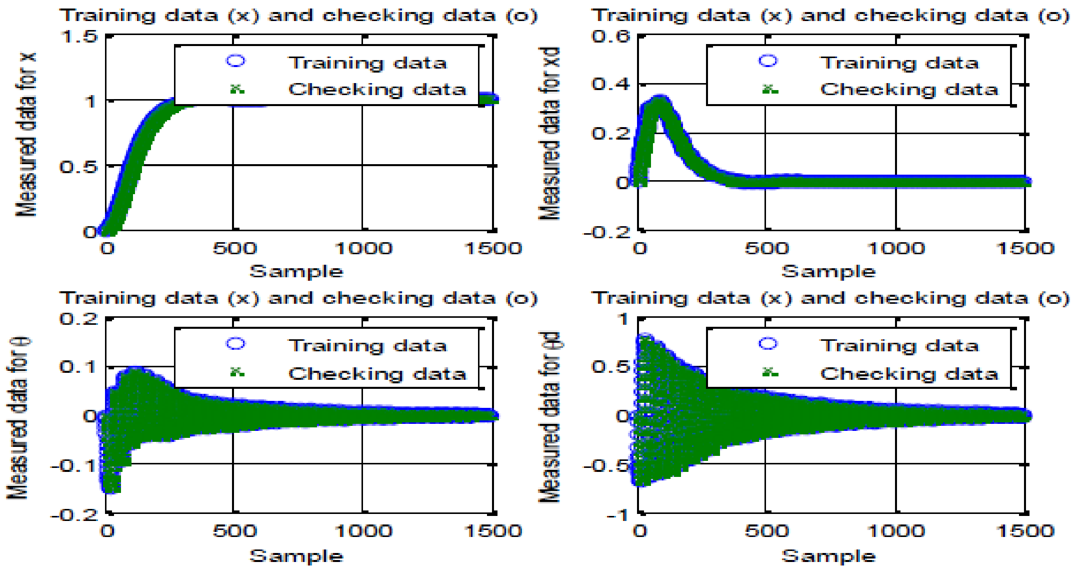

Figure 9: ANFIS showing training and checking data

Training and ANFIS outputs data are shown in Figure (10). The training error is the difference between the training data output value and the output of the ANFIS corresponding to the same training data input value. As the number of epochs increases the training error decreases. So finally there comes a point at which the error becomes saturated with the increasing number of epochs. The basic structure of the type of ANFIS controller in Figure (11) maps input characteristics to input membership functions, input membership function to rules, rules to a set of output characteristics, output characteristics to output membership functions, and the output membership function to a single-valued output or a decision associated with the output.

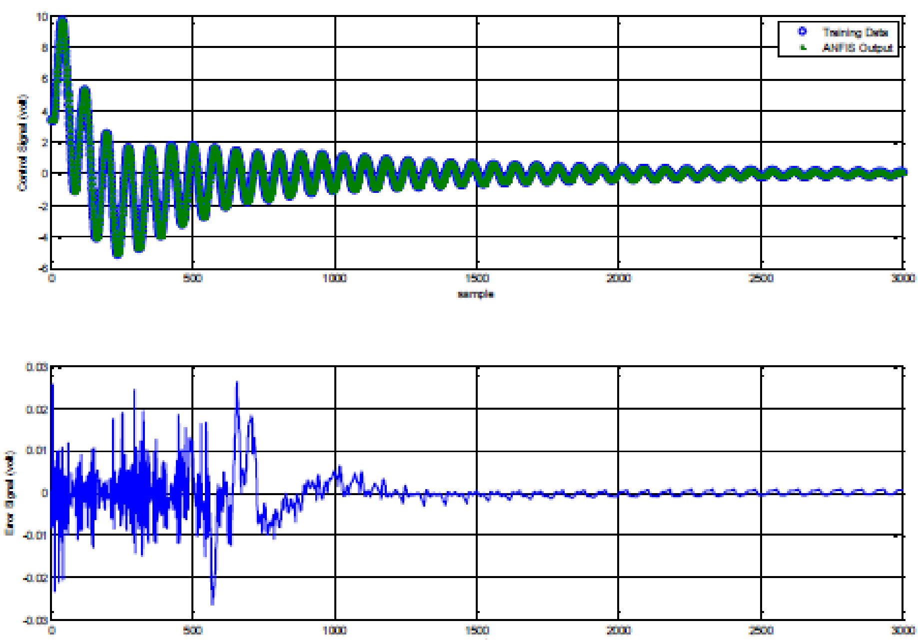

Figure 10: Training and ANFIS output data

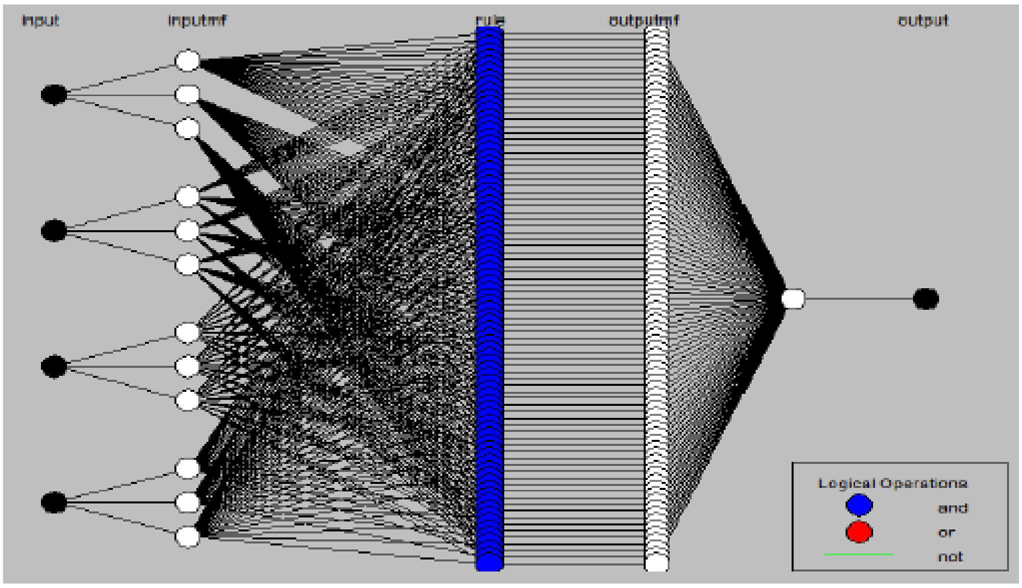

Figure 11: Structure of ANFIS

The simulink structure of TWIPMR controller based on adaptive neuro fuzzy network simulation is shown in Figure (12). The performances results are depicted in Figure (13). The results showed better performance of ANFIS controller over the original FLC controllers. According to the comparison of the simulation curves, the ANFIS controller can improve the dynamic performance of the TWIPMR system and it also shows good adaptability of the controlled plant.

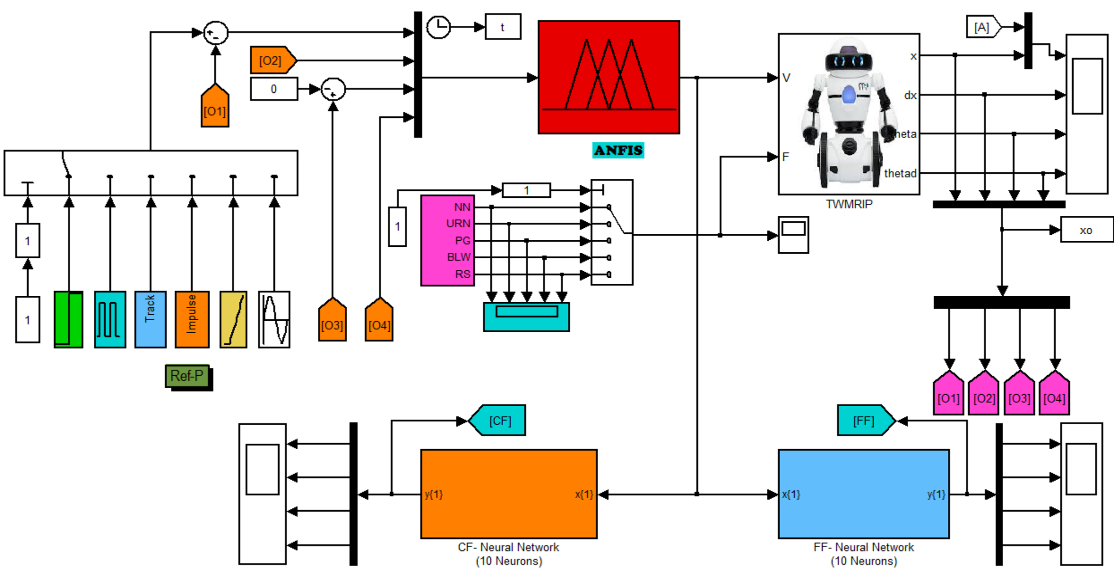

Figure 12: Simulink model of TWIPMR using neuro-fuzzy scheme

ANFIS provides better performance when it comes to a relationship which is nonlinear between input and output. The ANFIS controller learns the training data quickly with a very low amount of error tolerance. In case of Fuzzy System the rules are large in number. So by using neural network with fuzzy controller the numbers of rules are reduced.

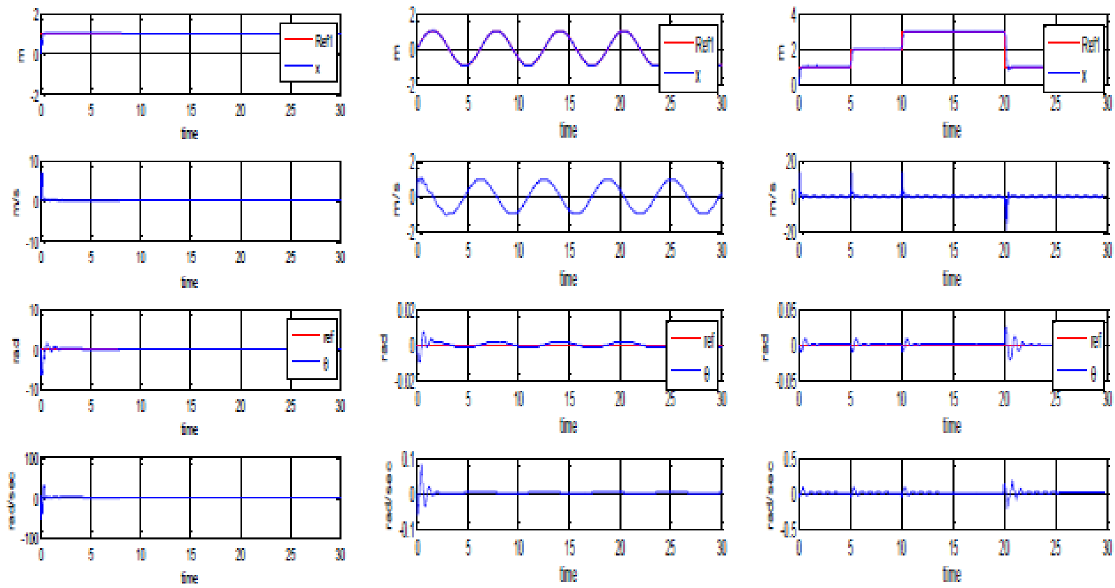

Figure 13: Performance of TWIPMR with ANFIS Controller

VIRTUAL REALITY ANIMATION

The link between the TWIPMR system and the virtual reality model is done through the virtual reality toolbox. In this section the performance of ANFIS control scheme is analyzed. A visualization model is created to make it easier to observe and actually see how the robot behaves in different scenarios. Previously, the user can view the results in 2D after the simulation is complete, by including a virtual world of a TWIPMR system the simulation in 3D animation during the simulation run time [6]. The virtual model is created using the standard Virtual Reality Modeling Language (VRML) [12]. It is a text language used for describing 3-D shapes and interactive environments. Design in VRML depends on the information available to the designer and the imaging of the object. The VRML model of TWIPMR is processed using the V-Realm Builder as shown in Figure (14).

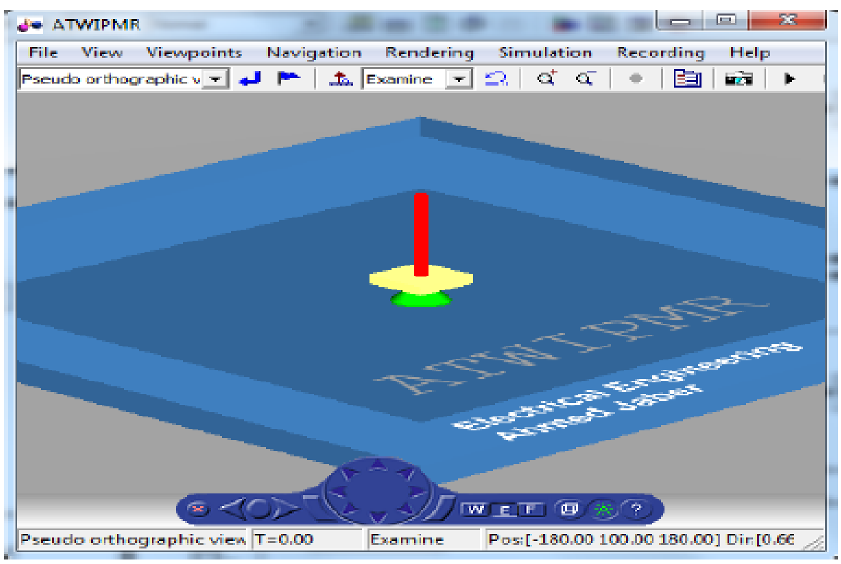

Figure 14: VRML model of the ATWIPMR in V-Realm

Figure (15) shows a complete simulink model for testing the controllers. Every part of the system is implemented in a simulink model as a separate block. The effects of disturbances (FdL , FdR) are investigated and taken into consideration.

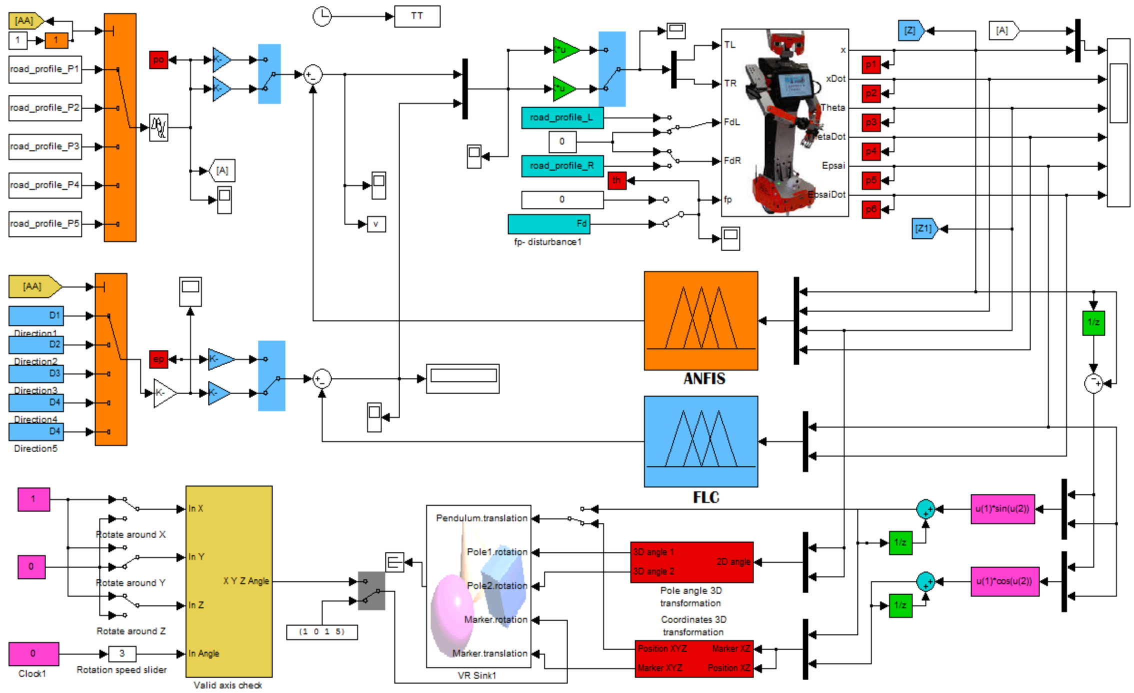

Figure 15: The link between Simulink model and virtual world

To ensure that the controller is able to give the best performance, the system will be tested with a different set of paths as shown in Figure (16). The TWIPMR plant model will be subjected to a ***road_profile_L*** and ***road_profile_R*** disturbance acting to the left and right wheel respectively (FdL, FdR) as shown in Figure (17) For the purpose of controller testing, a simulation using MATLAB's Virtual Reality toolbox is achieved in next section.

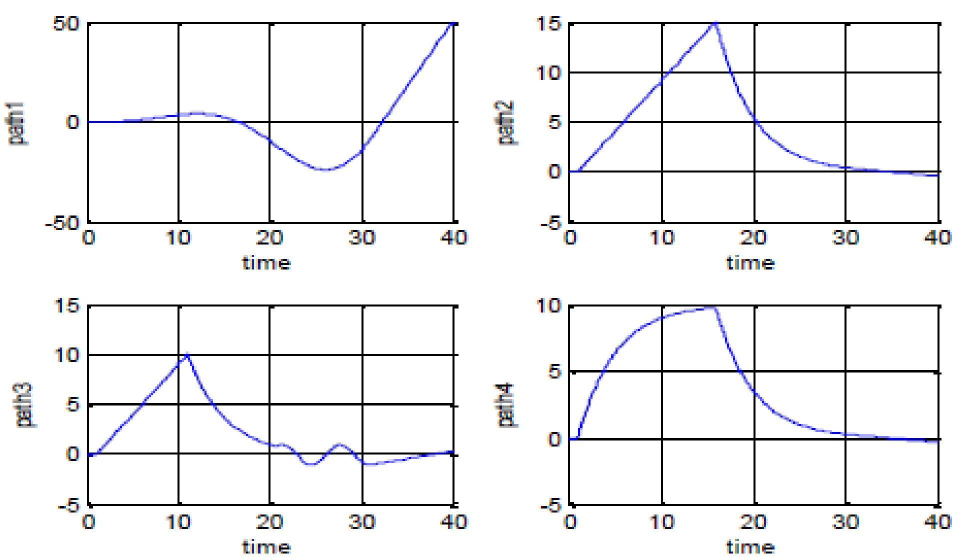

Figure 16: Profile of different reference tracking for robot

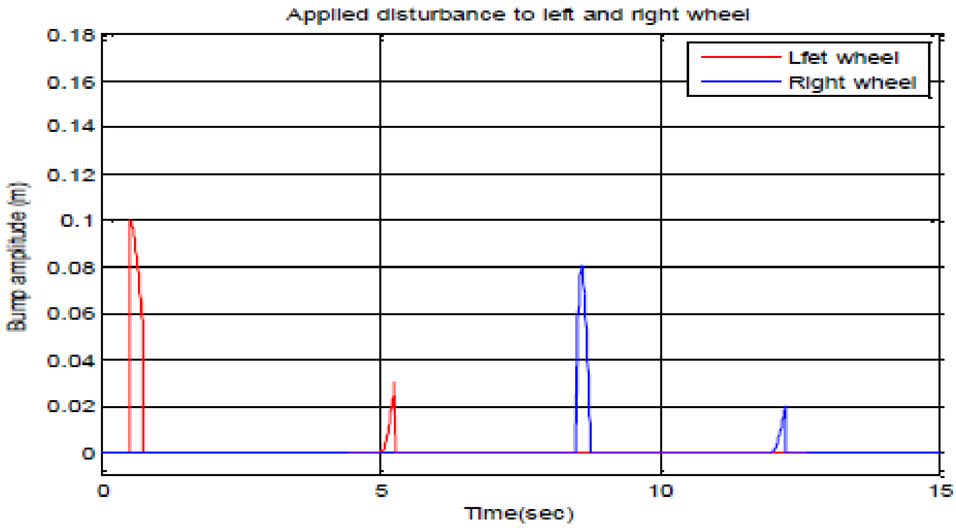

Figure 17: Profile of left and right wheel disturbance

The simulation result in Figures (18) show the performance of the considered designed control method with different reference input signals are applied. Where, an accurate tracking of the linear displacement x, rotation angle θ and rotation angle δ trajectories to these reference signals is observed. For any reference, the ANFIS controller has the better transient response and the steadier state response than does a FLC controller. The ANFIS controller does not require an accurate model of the plant. Its relative simplicity makes it fairly easy to construct and implement. High-level knowledge of system is not needed to build a set of rules for a fuzzy controller.

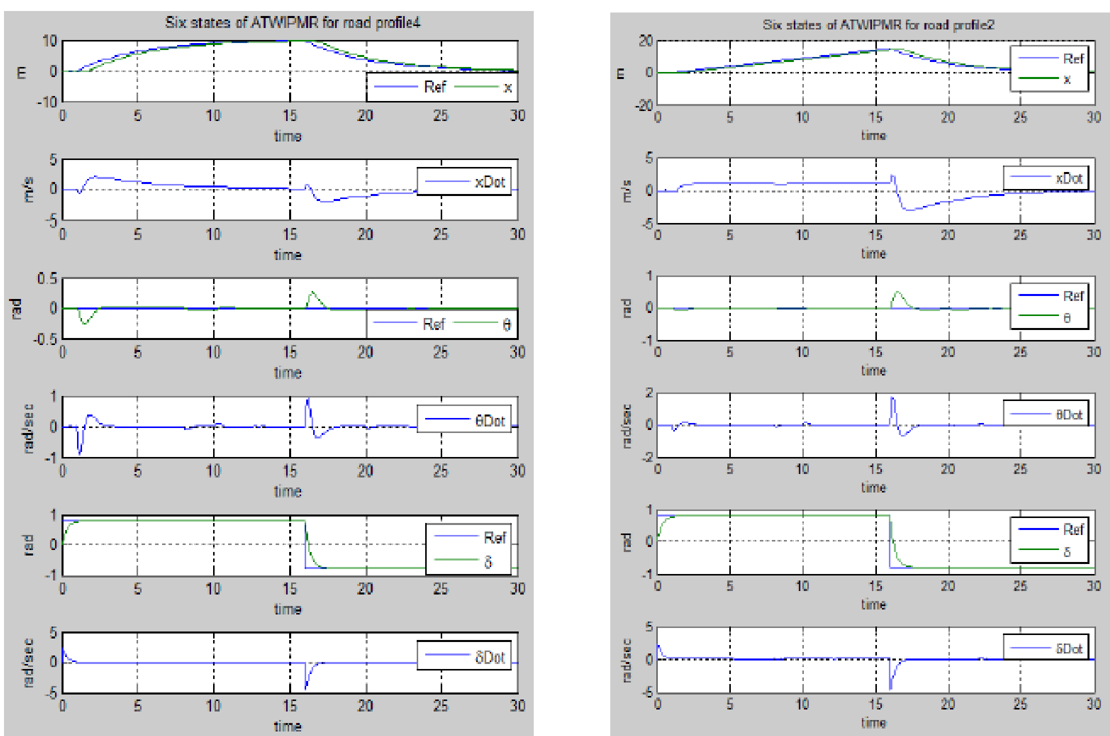

Figure 18: Six states of ATWIPMR for different road profiles

CONCLUSION

In this paper, the mathematical model of the TWIPMR is presented. The balance and tracking control of the two wheeled mobile robot has been studied and analyzed. ANFIS have been applied as a controller to improve the system performance according to an optimal control parameters adjustment. Different input reference signals have been applied to test the effectiveness of this controller and it is demonstrated that an acceptable tracking accuracy can be achieved. It is concluded that, under the influence of these signals the decoupling controller is successful to achieve a high tracking performance in transient and steady state time.

REFERENCES

[1] Jian Xin, Zhao Qin Guo and Tong Heng Lee "*Design and Implementation of Integral Sliding-Mode Control on an Underactuated Two-Wheeled Mobile Robot*," IEEE Transactions on industrial electronics, Vol. 61, No. 7, JULY 2014.

[2] Chenguang Yang, Zhijun Li Rongxin Cui and Bugong, "*Neural Network Based Motion Control of Underactuated Wheeled Inverted Pendulum Models*," IEEE Transactions on neural Networks and learning systems, Vol. 25, No. 11, November 2014.

[3] Hongguo Niu, Niu Wang and Nan Li, "*The adaptive Control Based on BP Neural Network Identification for Two Wheeled Robot*," 12th World Congress on Intelligent Control and Automation (WCICA), China ,June 12-15, 2016.

[4] Ahmad and Osman, *Real-Time Control System for a Two-Wheeled Inverted Pendulum Mobile Robot*, Advanced Knowledge Application in Practice University Technology, Malaysia, 2015.

[5] Steven J. Witzand, *Coordinated LEGO Segways*, MSc The University of New South Wales, 2009.

[6] Munzir Zafar, *Towards Stable Balancing*, Georgia Institute of Technology, Technical Report, 2014.

[7] Felix Grasser, *JOE: A Mobile, Inverted Pendulum*, Laboratory of IndustrialElectronics Switzerland, 2015.

[8] Kevin M. Passino and Stephen Yurkovich, Fuzzy controller, Addison Wesley Longman, Menlo Park, (1998).

[9] Gagan Soni and Himmat Singh, "*Designing of Fuzzy Logic Controller for Set-Point Weight Tuning of PID Controllers "*International Journal of intelligence and Application for smart devices. Vol.3, No.2, 2015.

[10] Ashwani Kharola , *A PID Based ANFIS & Fuzzy Control Of Inverted Pendulum On Inclined Plane (Ipip)*, International Journal on Smart Sensing and Intelligent Systems, Vol. 9, No. 2, June 2016.

[11] S. F. Kodad, B V. Sankar Ram, *Modeling, Design & Simulation of an Adaptive Neuro Fuzzy Inference System (ANFIS) for Speed Control of Induction Motor*. International Journal of Computer Applications, Vol. 6, No.12, September 2010.

[12] The Math Works Inc., *Virtual Reality Toolbox Users Guide for Use with MATLAB and Simulink*, 2010.