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Fuzzy Adaptive Application for Control of Single Wheel Mobile Robot (SWMR)

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Abstract

Single Wheeled Mobile Robot (SWMR) comprises of a robot chassis mounted on a single wheel and capable of performing 360° orientation rotation while maintaining its stable position. The objective is to control robot orientation and wheel motion at desired location. The single wheel makes the system more difficult to control as compared to double wheel robot. This paper presents the control of highly non-linear, multivariable and complex SWMR system using fuzzy and ANFIS controllers. The fuzzy controllers were used to train the ANFIS controllers using gbell membership functions. A Matlab-Simulink model of the system was initially developed from mathematical equations derived using Newton's second law of motion. The simulation results are shown with the help of graphs and tables which proves the superiority of fuzzy technique over ANFIS approach. The results showed that fuzzy controllers were able to stabilize the SWMR system within 4.5 sec. The steady state error for both the controllers shows an excellent response. The maximum overshoot for chassis controller are within specified limits whereas it needs to be lowered for wheel controller. The performance parameters i.e. settling time, maximum overshoot and steady state error further highlights the effectiveness of both the controllers.

Keywords- SWMR; Fuzzy Logic; ANFIS; Matlab; Simulink; Membership Function.

1. Introduction

A Single Wheel Mobile Robot (SWMR) is a non-linear, multi-variable, non-holonomic and static unbalanced system having a minimal number of point contact to the ground. SWMR dynamics mimics the behaviour of a human riding a unicycle (Ruan and Xie, 2015). The control of single wheel robot is more challenging and complex as compared to two or three-wheel mobile robot because of a single spherical wheel (Ha and Jung, 2015). The single spherical wheel enables the robot to obtain omni-directional motion and also overcomes the limitations associated with the two-wheeled robots (Nagarajan et al., 2012). The control of SWMR has been an area of keen interest for researchers in the past few decades. Various soft computing techniques has been effectively applied for control of these non-linear systems. Kayacan et al. (2012) presented control of spherical rolling robot by using an adaptive neuro fuzzy controller in combination with a Sliding-Mode Controller (SMC) algorithm. The updating parameters of neuro-fuzzy controller were derived using SMC and the stability of learning is proven using a Lyapunov function. The simulation results proved the validity of proposed controller. Otani et al. (2006) studied the problem of position and attitude control of spherical rolling robot. The authors derived two types of models, a kinematic model and a dynamic model from the equation of motion of the system. The feedback controller for the kinematic model was based on Lyapunov control which was further used to obtain a feedback controller for the dynamic model by back stepping technique. Kayacan et al. (2012) studied the dynamic modeling analysis and control of a spherical rolling robot. The dynamic modeling of the system was done using Euler-Lagrange approach. A feedback linearization loop with fuzzy controller has been designed for the control of non-linear system. Rolling of the system over linear and curvilinear trajectories has been simulated and analysis of the radius of curvature over curvilinear trajectories has also been investigated.

Das and Kar (2006) proposed a control structure which integrates a kinematic controller and an adaptive fuzzy controller for trajectory tracking of Non-holonomic mobile robots. The stability and convergence of tracking errors for the system were proved using Lyapunov stability theory. The effectiveness of the proposed control law was confirmed by computer simulations. Rashid (2007) developed a simulation platform for testing various control tactics to stabilize a single wheel mobile robot. Visual basic was employed to integrate the graphic representation, dynamic solution and control scheme for the robot. Takagi-sugeno fuzzy controller with 25 fuzzy rules was further used to train a neuro-fuzzy controller. Huang (2010) proposed a model for One-Wheeled Vehicles (OWVs). The system stability was obtained through pole-placement and Linear Quadratic Regulator (LQR) method. The simulation results proved the validity of the proposed techniques. Jae-oh et al. (2011) proposed a method to stabilise a unicycle mobile inverted pendulum for pitch and roll motion control. The study assumed that both roll dynamics and pitch dynamics were decoupled. Experimental results proved the validity of proposed technique. Li et al. (2012) authors proposed control of a single wheel balanced robot using two independent control laws. The mobile inverted pendulum control laws were used for controlling pitch axis and reaction wheel pendulum control was used for controlling roll axis. Each of the control law was separately implemented using a controller. Experimental results verified the performance of proposed controllers. Peng et al. (2009) designed an Omni-directional spherical mobile robot which can move in any direction. The fuzzy control was used for stabilisation of proposed system which effectively deals with unknown nonlinearities and external disturbances as demonstrated by simulation results. Islam et al. (2006) designed a fuzzy controller algorithm for designing an autonomous Mobile Robot Controller (MRC) which was able to navigate in different terrains without human intervention. The codes of MRC has been written and developed in Matlab and further converted to VHDL codes for hardware implementation. Li et al. (2012) developed a dynamic model of bicycle robot based on Lagrange method. A fuzzy logic control was further applied for dynamic and steady state performance of robot. Initially fuzzy control was used for swing up of bicycle robot to equilibrium position and later an adaptive fuzzy PID method was employed to provide static behaviour.

Cieslak et al. (2011) presented mathematical description and mechanical design of mono-wheel robot. The study also describes electronic structure for complete description of robot. The simulation process and prototype testing were performed for achieving dynamic stability of the robot. Castillo et al. (2006) proposed back stepping based fuzzy trajectory control of unicycle mobile robot. The objective was to achieve asymptotic stabilisation of the robot position and orientation around desired trajectory. A Mamdani based inference controller with nine fuzzy rules was constructed to achieve the desired control. Jin et al. (2011) proposed and verified a posture balancing control strategy for One Wheel Pendulum Robot (OWPR). The Lagrange method was used for deriving dynamics of system to represent torques during rolling, yawing and pitching of the robot. The OWPR dynamics were further represented in form of state space model which were used for performing simulations and experimental verifications. Al-Mamun and Zhu (2010) designed a Fuzzy Logic Controller (FLC) for steering control of single wheel robot. The Particle Swarm Optimization (PSO) method was used to optimise the fuzzy membership functions. The issue of selecting various functions and parameters for FLC remained to be resolved. Zhen et al. (2009) designed a 3-dimensional simulation platform for complex Mechatronics systems. The study presented the dynamic analysis of single wheel robot. The simulation platform integrates the 3-D simulator ADAMS with Matlab. Buratowski et al. (2012) proposed a mathematical description of a SWMR. The mechanical design and electronic configuration of the robot was also elaborated. The validity of the proposed technique was proved through simulation and prototype testing. Park and Jung (2013) proposed a mechatronic technique for control of SWMR named Gyrobo. The Gyrobo has the ability to navigate through different terrains while maintaining its stability. The experiments confirmed the functionality and concept of proposed approach. Xu and Au (2004) developed a three-dimensional non-linear model for a single wheel gyroscopically stabilized robot. The study proposed a linear state feedback to stabilize the robot at different lean angles. The simulations and experiments showed the significance of proposed controller. In this paper two different control techniques i.e. fuzzy and ANFIS are employed to control a highly non-linear SWMR system. The mathematical equations for the system has been derived which were further used to built a simulink model of the proposed system. A fuzzy based ANFIS controller has been proposed in the study. The offline simulations proves the validity and effectiveness of the applied techniques.

2. Mathematical Model of SWMR

A 2-dimensional view of SWMR is shown in Figure 1 (Lauwers et al., 2006). The system comprises of a spherical wheel of mass (M_w) and radius (r_w), wheel is free to move in horizontal or inclined surface in any direction. Attached to wheel is a robot body or chassis of mass (M_c) and length (L). The chassis is inclined at an angle (θ) to the vertical axis. Force, F is required to move the robot along horizontal direction under action of gravity (g). The objective is to control the robot chassis in upright position while the wheels are free to move along X-axis. A view of robot wheels is shown in Figure 2.

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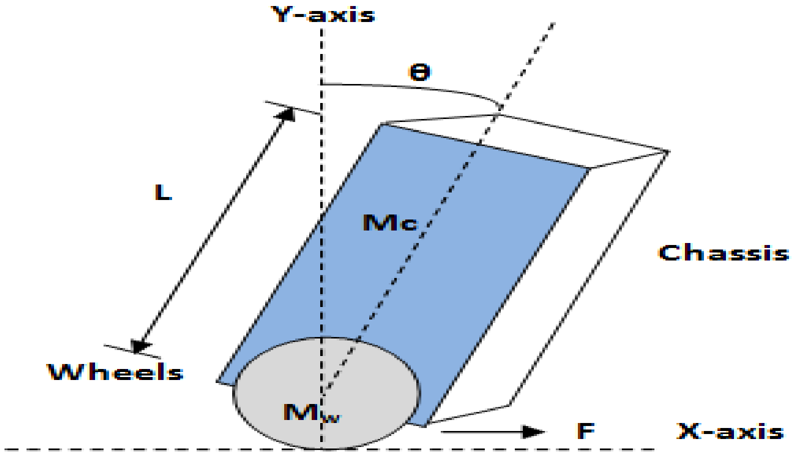

Figure 1. View of SWR system

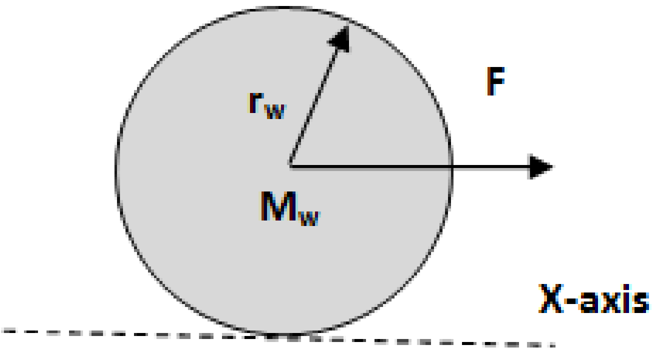

Figure 2. View of robot wheels

The mathematical equations for SWMR (Huang, 2010) were derived using Newton's second law of motion. The final governing mathematical equations are given below.

$$\ddot{x} = \frac{-{M_c}^2 L^2 g\theta}{M_t(M_c L^2 + J) - {M_c}^2 L^2} + \frac{({M_c}^2 L^2 + J)F}{M_t(M_c L^2 + J) - {M_c}^2 L^2 r_w} \tag{1}$$

$$\ddot{\theta} = \frac{M_c g L \;\; M_e \theta}{M_t(M_c L^2 + J) - {M_c}^2 L^2} - \frac{(M_c L)F}{M_t(M_c L^2 + J) - {M_c}^2 L^2 r_w} \tag{2}$$

where, $M_t = M_w + M_c + \frac{J}{{r_w}^2}$.

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In the above equations $\ddot{x}$ and $\ddot{\theta}$, represents the acceleration and angular acceleration of robot wheel and chassis respectively. The force, F is required to be controlled so that the robot can move freely robot in the horizontal direction. The values of various input parameters considered in the paper are shown in Table 1.

Table 1. Values of various input parameters

Symbol	Parameter	Value
L	Length of robot chassis	0.1 m
M_w	Mass of robot wheel	1.0 kg
M_c	Mass of robot chassis	0.5 kg
r_w	Radius of robot wheel	0.1 m
J	Inertia of robot wheels	0.01kg-m^2
I	Inertia of robot chassis	0.1 kg-m^2
g	Acceleration due to gravity	9.81 m/s^2

3. Simulink Model of SWMR

The mathematical equations derived in previous section were used for building a Matlab-Simulink model of SWMR. The SWMR model was further masked into a sub-system for simulations. The simulations were performed using ode23tb (stiff/TR-BDF2) solver with simulation time of 10 sec. The Simulink model for SWMR and its sub-system is shown in Figure 3 and Figure 4 respectively.

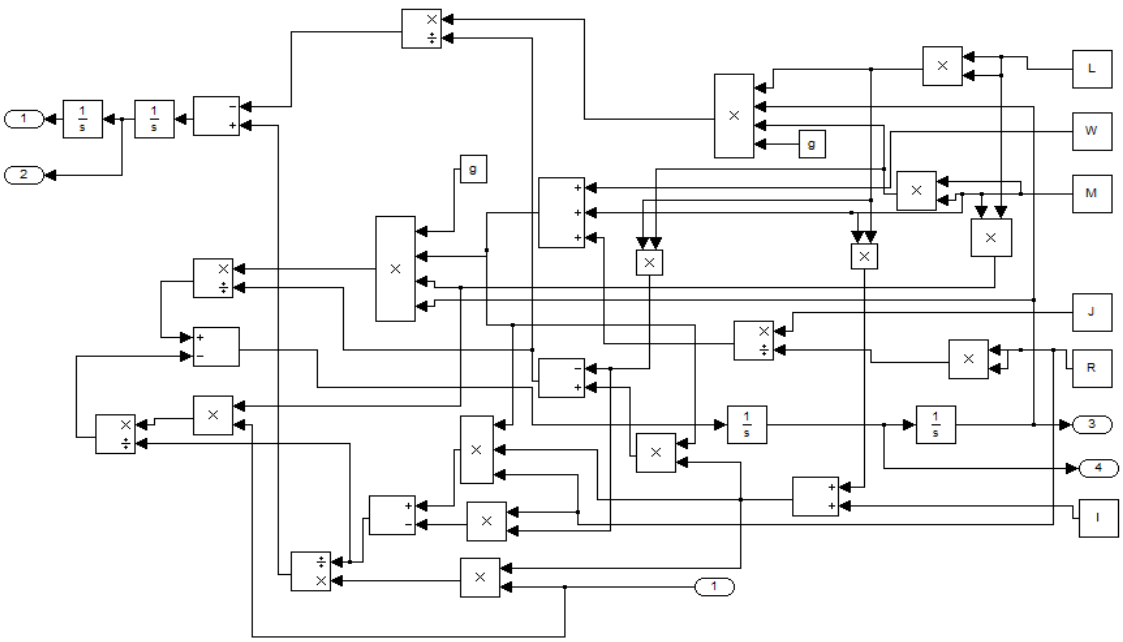

Figure 3. SWMR Simulink model

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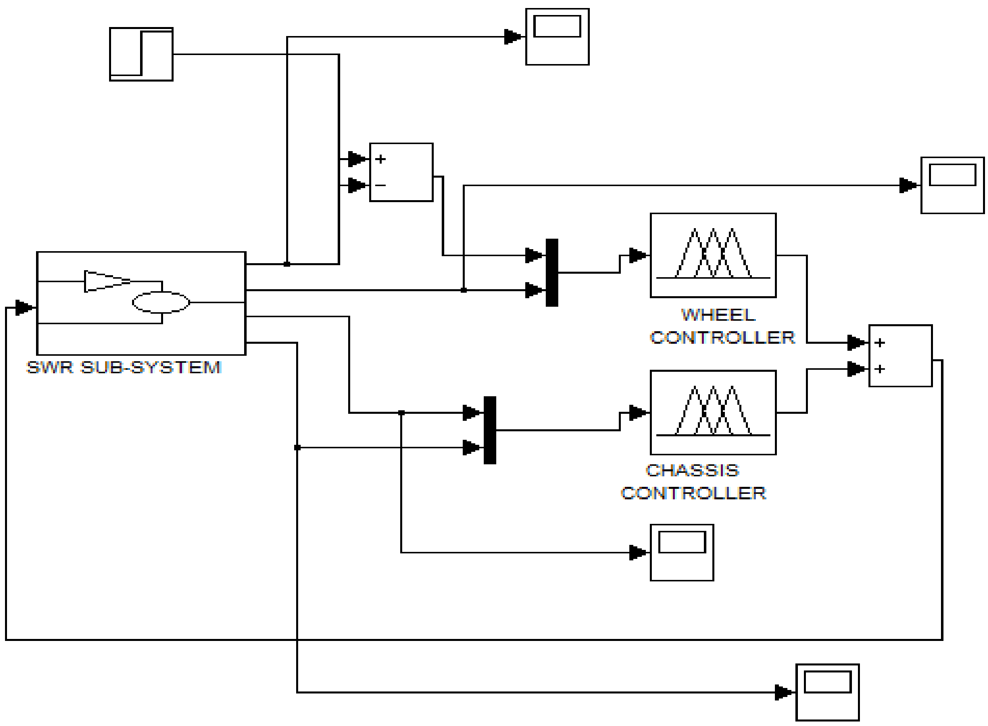

Figure 4. SWMR Sub-system Simulink model

4. Fuzzy Control of SWMR

Fuzzy logic theory was introduced by L. A. Zadeh at University of California (Zadeh, 1965). The theory is based on human judgment of decision making and intelligence. It is widely used in conditions when conventional logic fails to handle complex situations (Moraga, 2005). One of the most important feature of fuzzy logic is application of linguistic variables (Zadeh, 1975). Fuzzy logic is based on user-simplified human rules built using if-then logic. The fuzzy controllers were used for converting these rules into mathematical equivalents. The fuzzy controllers are more simple and flexible as compared to other conventional controllers and handles data easily with imprecise and incomplete data. In this paper Mamdani based gbell MF's (Sivanandam et al., 2007) were employed for designing of Fuzzy Logic Controllers (FLC's). The gbell membership functions were selected because they provide better performance as compared to other membership functions. A view of gbell MF's for chassis and wheel controller are shown in Figure 5 and Figure 6 respectively.

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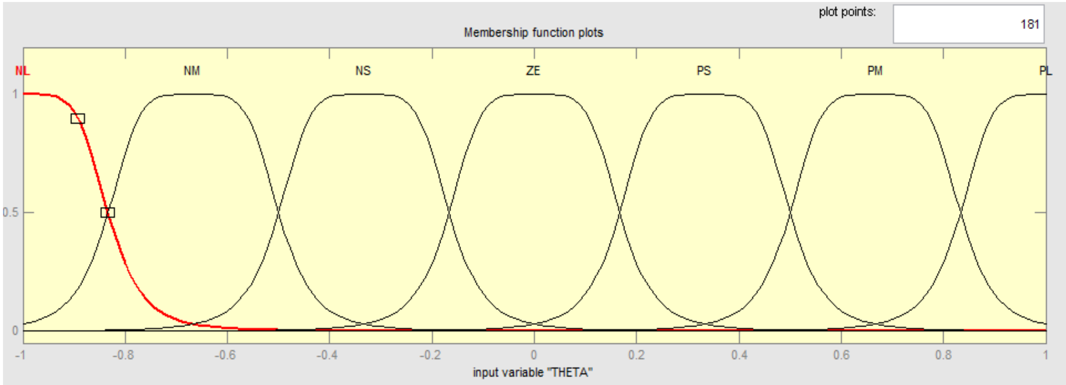

Figure 5. Gbell MF's for chassis angle controller

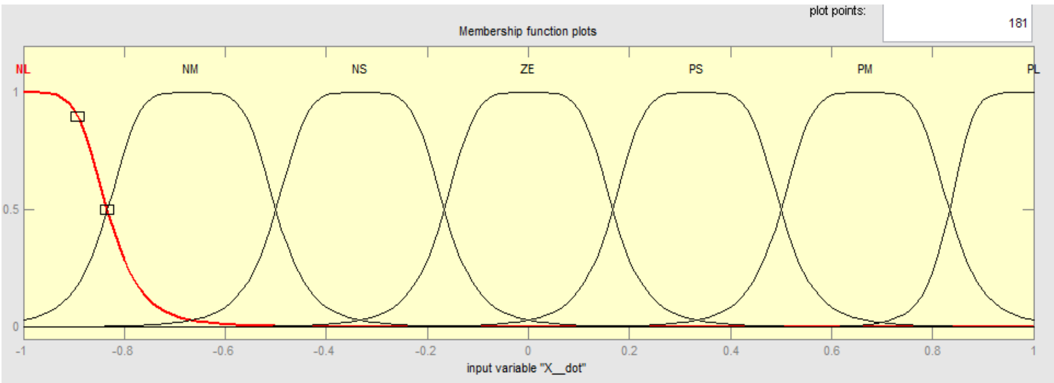

Figure 6. Gbell MF's for wheel velocity controller

The Surface viewers obtained from if-then fuzzy rules for chassis and wheel controller are shown in Figure 7 and Figure 8 respectively. As shown in Figure 7, chassis angle and chassis angular velocity are on X and Y axis respectively whereas control force is on Z-axis. Therefore, a surface viewer can be easily employed for obtaining relationships among these three attributes.

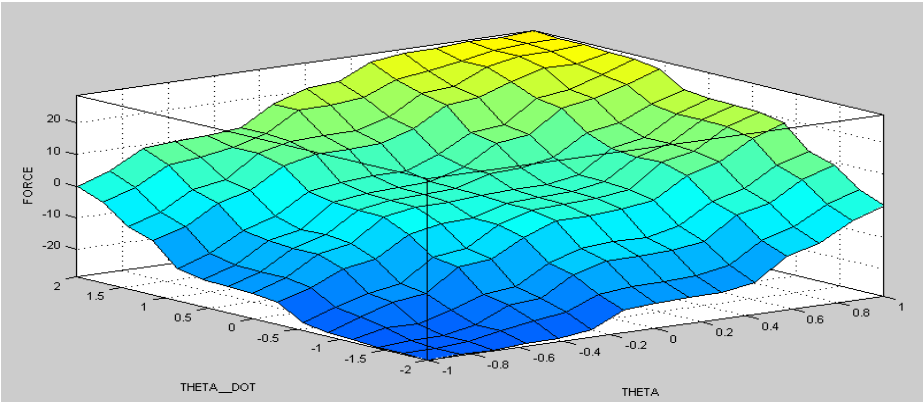

Figure 7. Surface viewer for chassis controller

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As shown in Figure 8, wheel position and wheel velocity are on X and Y axis respectively whereas control force is on Z-axis. A surface viewer is basically a 3-D representation of fuzzy rules.

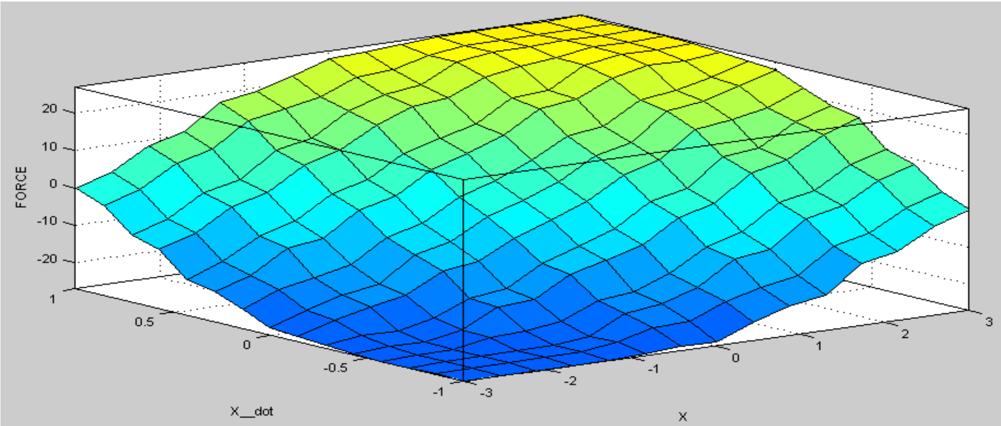

Figure 8. Surface viewer for wheel controller

The results obtained after simulation of fuzzy controller are shown with the help of Figure 9, 10, 11 and Table 2, 3, 4. The performance parameters considered for analysis were settling time, maximum overshoot and steady state error.

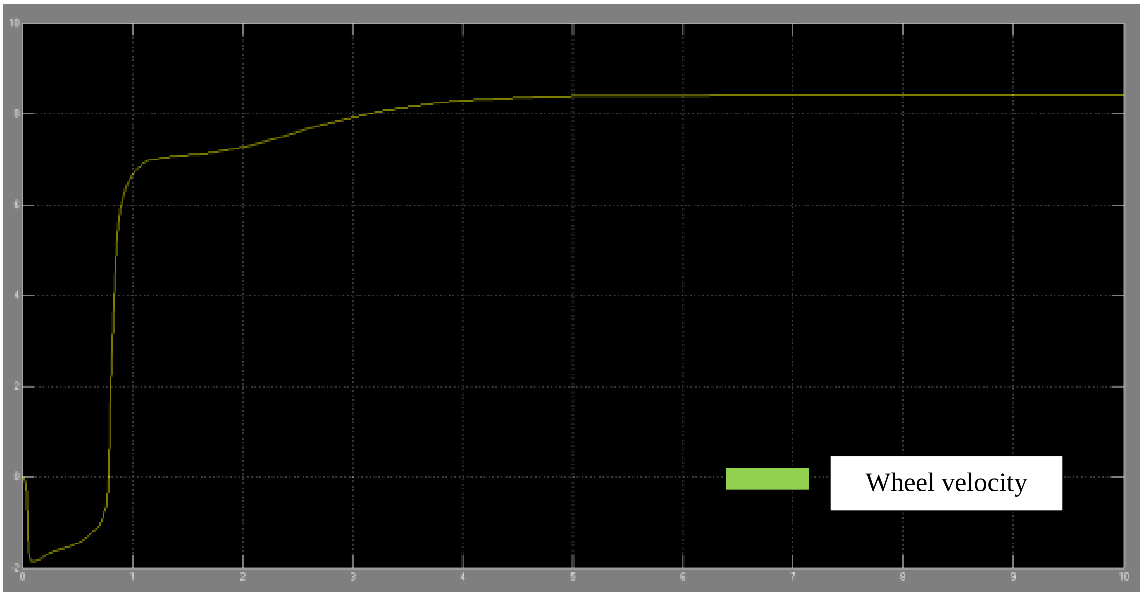

Figure 9. Simulation response for wheel velocity using fuzzy controllers

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Table 2. Simulation results for wheel velocity using fuzzy controllers

Performance parameter	Output
Settling time (sec)	4 sec
Max. Overshoot (degrees)	8.4° to -1.8°
Steady state error	0

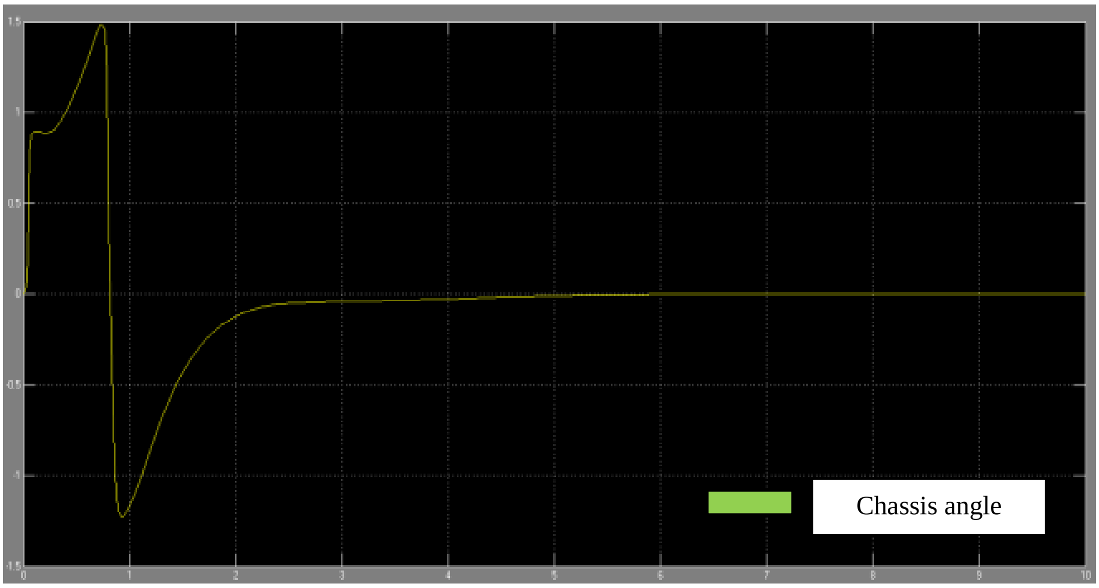

Figure 10. Simulation response for chassis angle using fuzzy controllers

Table 3. Simulation results for chassis angle using fuzzy controllers

Performance parameter	Output
Settling time (sec)	2.3 sec
Max. Overshoot (degrees)	1.48° to -1.25°
Steady state error	0

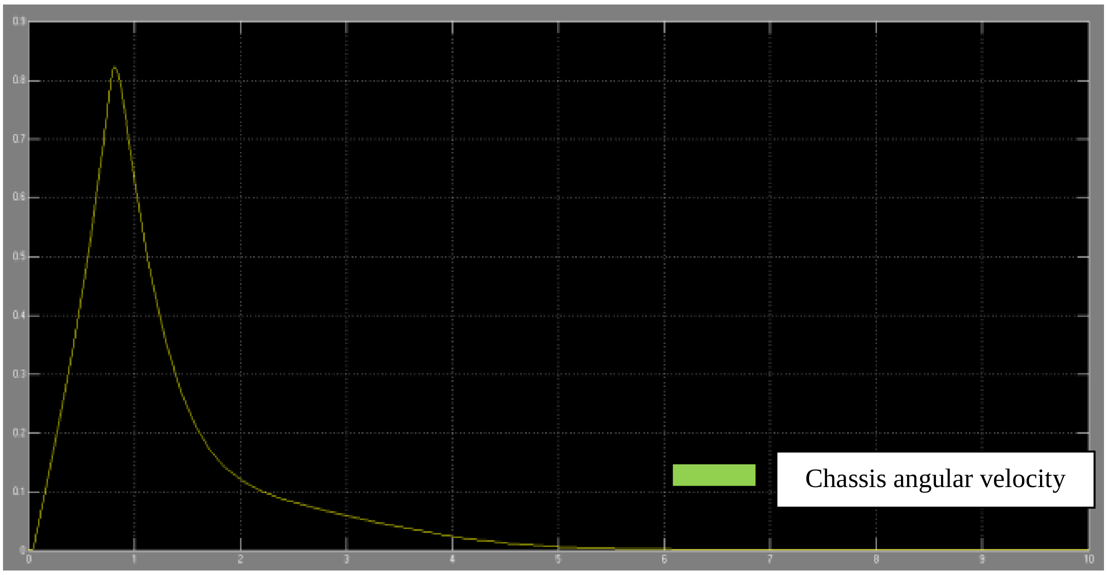

Figure 11. Simulation response for chassis angular velocity using fuzzy controllers

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Table 4. Simulation results for chassis angular velocity using fuzzy controllers

Performance parameter	Output
Settling time (sec)	4.5 sec
Max. Overshoot (degrees)	0.82°
Steady state error	0

It is clearly observed from the simulation results that fuzzy controllers were able to stabilize the wheel velocity, chassis angle and chassis angular velocity within 4.0 sec, 2.3 sec and 4.5 sec respectively. The overshoot values obtained for wheel velocity, chassis angle and chassis angular velocity were 8.4° to -1.8°, 1.48° to -1.25° and 0.82° respectively. It is also observed that both the controllers show an excellent response towards steady state error. The wheel velocity is smoothly controlled after one under shoot followed by overshoot, chassis angle is smoothly controlled after one overshoot followed by undershoot whereas chassis angular velocity is controlled smoothly after one overshoot. The simulation results clearly showed excellent performance of fuzzy logic controllers.

5. ANFIS Control of SWMR

Adaptive Neuro Fuzzy Inference Systems (ANFIS) are a class of adaptive networks based on Fuzzy Inference System (FIS) which can construct an input-output mapping based on both human knowledge and set of stipulated input-output data sets (Jang, 1993). These are an extension of fuzzy logic systems which are based on Takagi-Sugeno inference system and combines the learning ability of NN's and linguistic applications of fuzzy logic reasoning (Mary and Marimuthu, 2009). The data sets can be generated from previous simulation and collected in Matlab workspace. The data stored in Matlab workspace can be further imported for training of ANFIS controller. In this paper a total of 162 data sets were collected from simulation results of fuzzy controller. These data sets were used to train ANFIS controller. The training error tolerance and epochs were set to 0 and 100 respectively. The initial FIS structure was generated using Grid-Partition method. The training of FIS was done using Hybrid method which is a combination of Back-propagation and least square method (Pfister and Rojas, 1994). The training of ANFIS controllers were done using 9 Gbell MF's.

5.1 Designing of Wheel Controller for SWMR

The loading and training of data sets for wheel controller is shown Figure 12 and Figure 13 respectively. The data sets were initially loaded and further trained to yield error close to zero. It was observed that the error initially decreases up to 60 epochs and further becomes constant i.e. no further improvement in learning was obtained. The error obtained after training 100 epochs is 0.54692.

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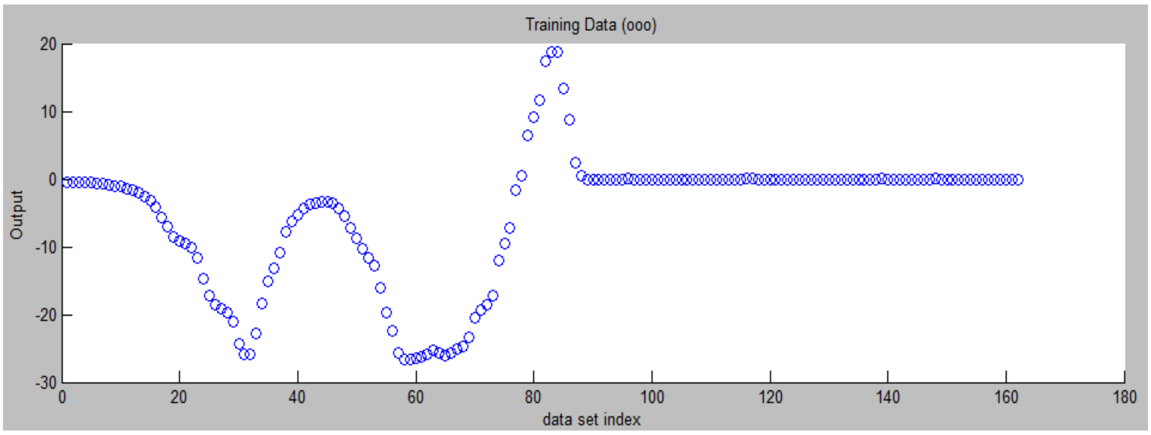

Figure 12. Loading of data sets for wheel controller

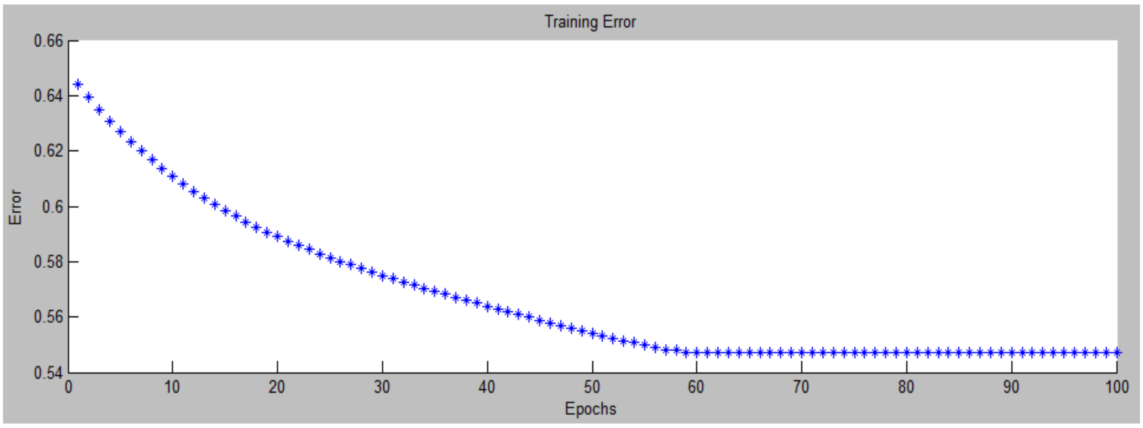

Figure 13. Training of data sets for wheel controller

The ANFIS structure obtained after training of wheel controller is shown in Figure 14. It is a representation of input, output, membership functions and rules obtained after training.

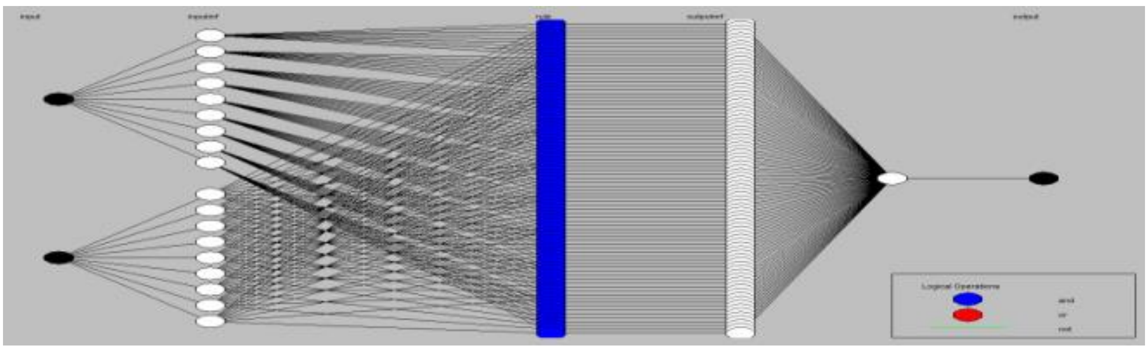

Figure 14. ANFIS structure for wheel controller

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During training in ANFIS, fuzzy MF's and rules were modified according to the training data sets. A view of MF's obtained after training of wheel controller are shown in Figure 15 and Figure 16 respectively. It is clearly observed from the figures that the membership functions parameters were tuned and adjusted according to the values of input data sets.

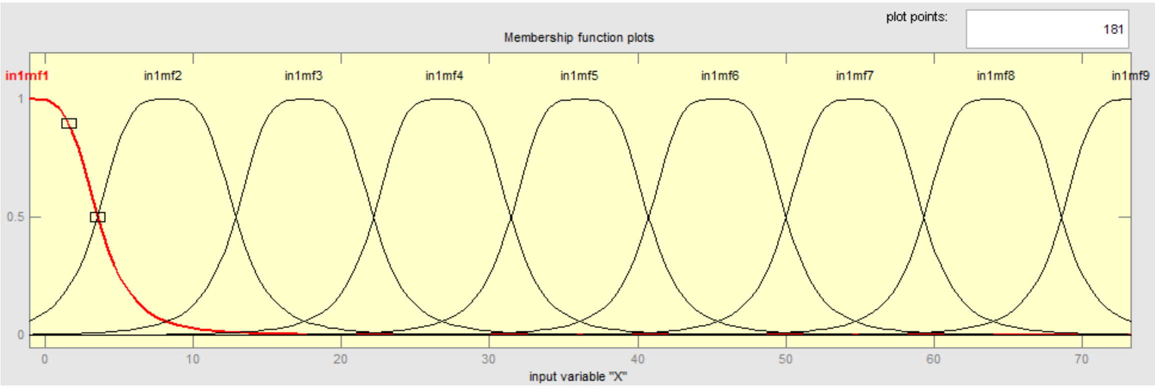

Figure 15. MF's obtained after training for wheel position

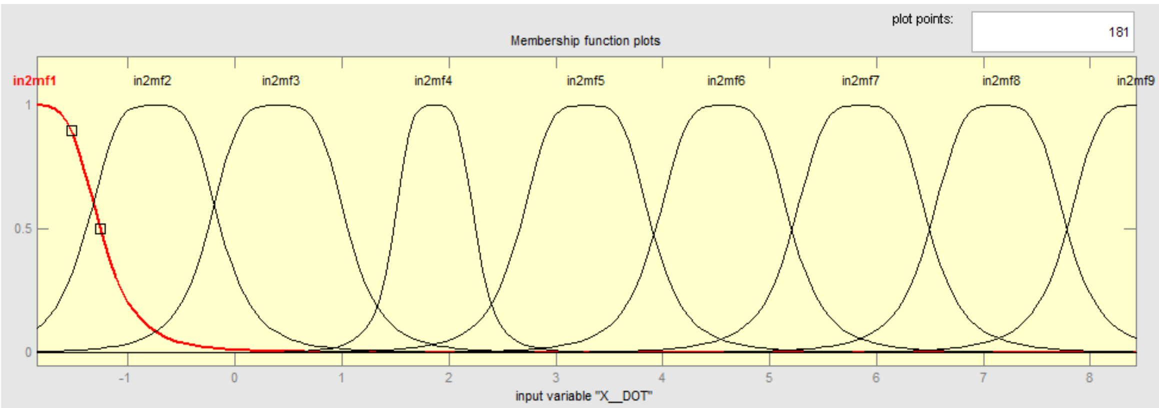

Figure 16. MF's obtained after training for wheel velocity

The surface viewer obtained after training of wheel controller is shown in Figure 17.

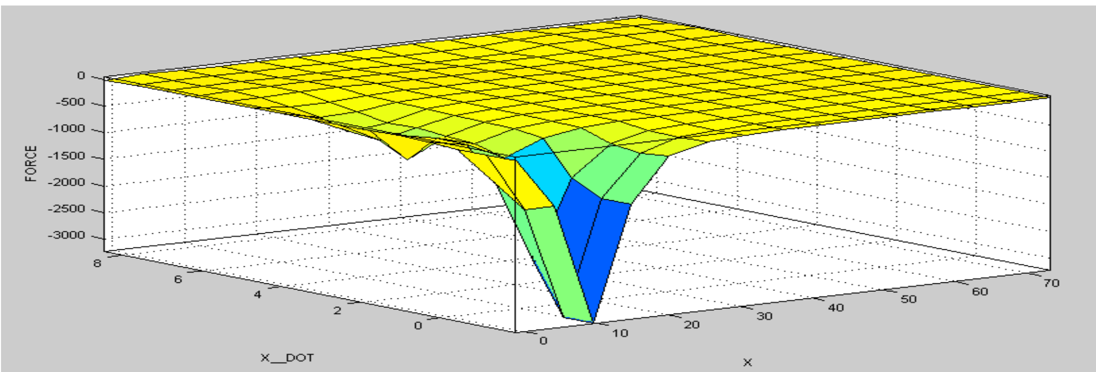

Figure 17. Surface viewer obtained for wheel controller after training

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5.2 Designing of Chassis Controller for SWMR

The loading and training of data sets for chassis controller is shown Figure 18 and Figure 19 respectively. It is observed from the training results that the error value becomes constant after 10 epochs and error obtained after training 100 epochs is 0.0084557.

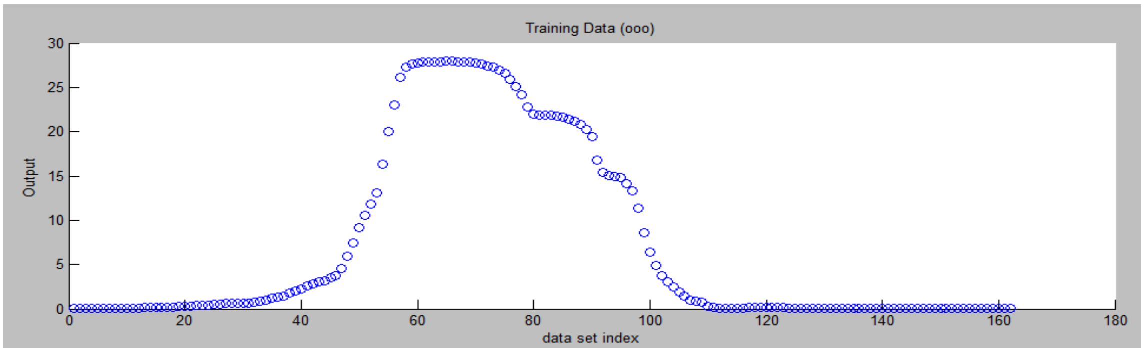

Figure 18. Loading of data sets for chassis controller

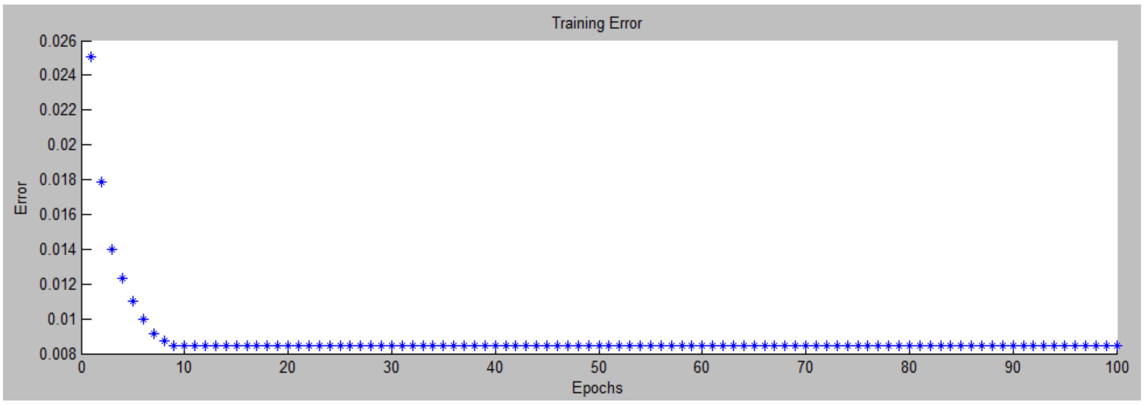

Figure 19. Training of data sets for chassis controller

The MF's obtained after training of chassis controller is shown in Figure 20 and Figure 21 respectively.

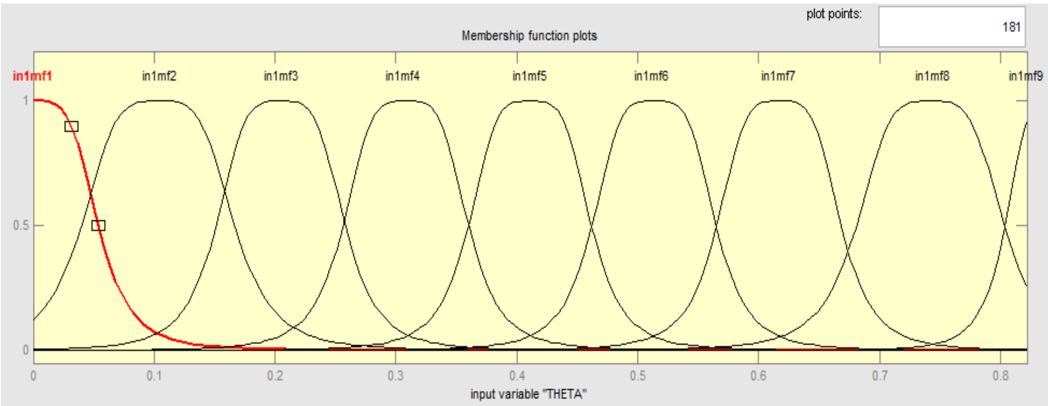

Figure 20. MF's obtained after training for chassis angle

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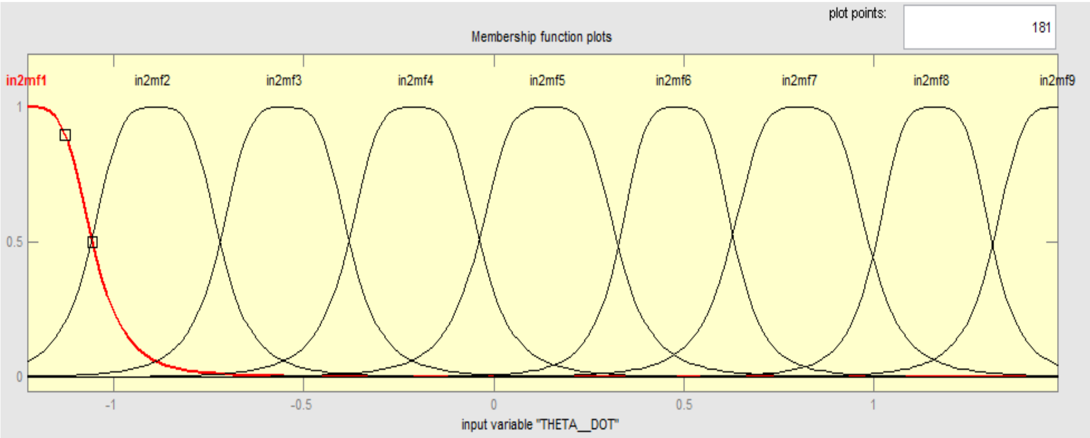

Figure 21. MF's obtained after training for chassis angular velocity

The surface viewer obtained after training of chassis controller is shown in Figure 22.

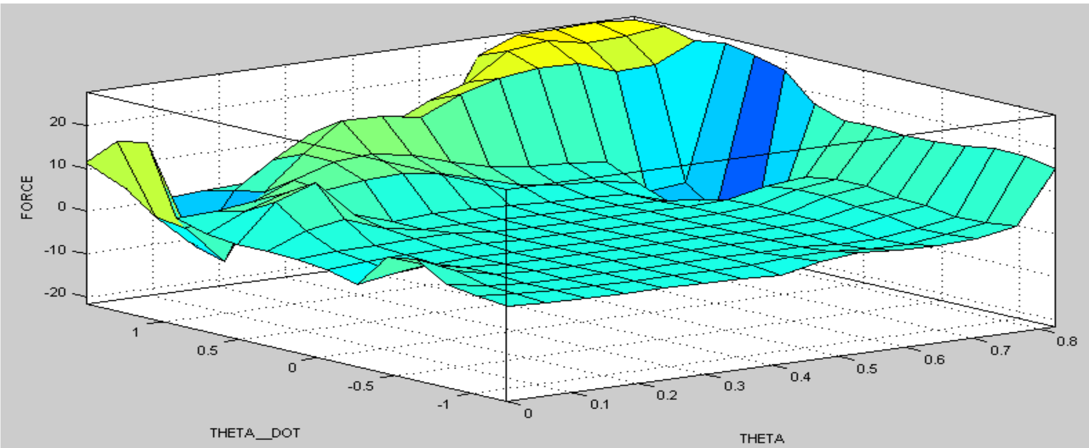

Figure 22. Surface viewer obtained for chassis controller after training

The results obtained after simulation of ANFIS controller are shown with the help of Figure 23, 24, 25.

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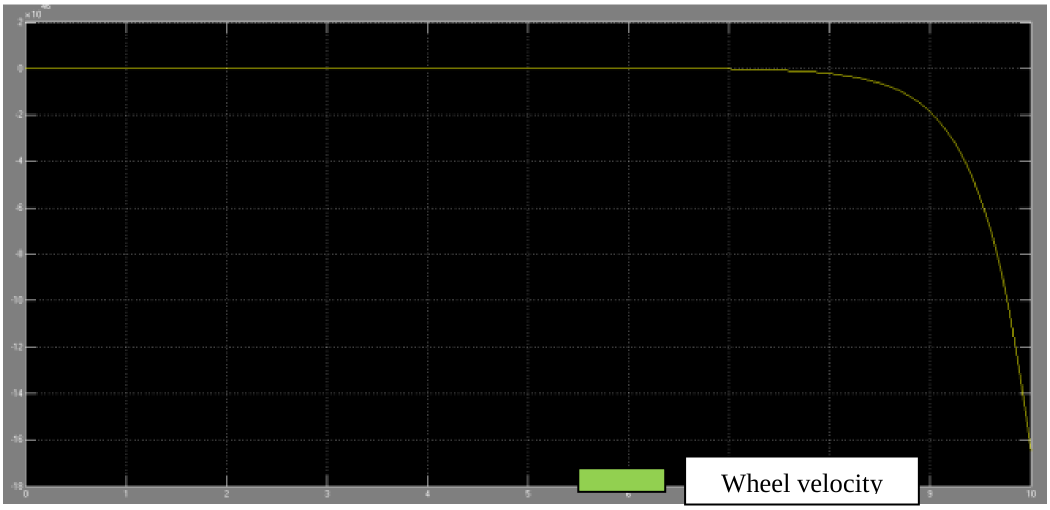

Figure 23. Simulation results for wheel velocity using ANFIS controllers

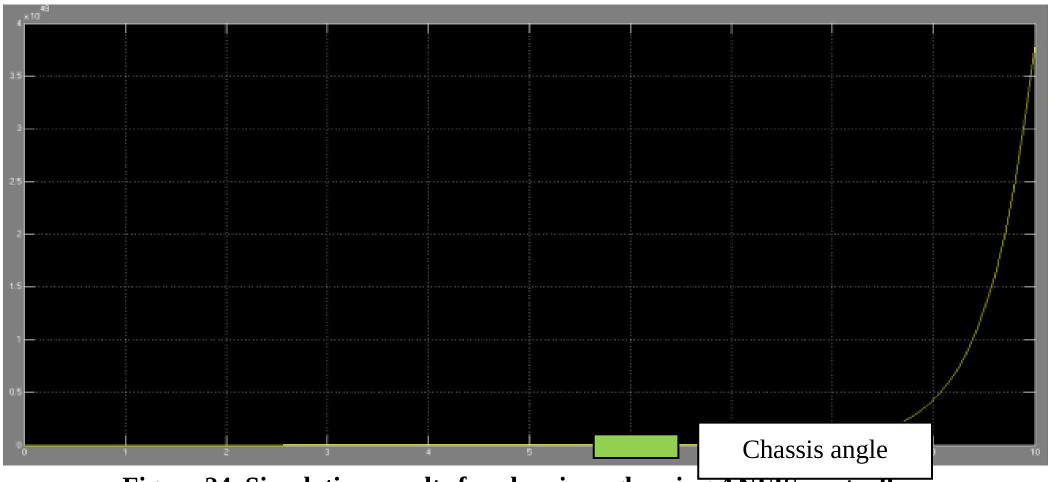

Figure 24. Simulation results for chassis angle using ANFIS controllers

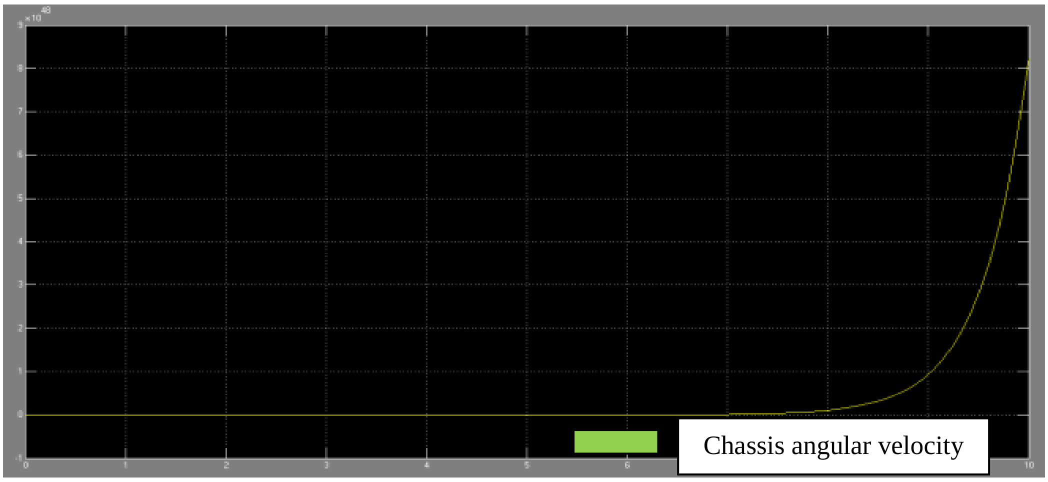

Figure 25. Simulation results for chassis angular velocity using ANFIS controllers

It is clearly observed from simulation results that the ANFIS controllers were not able to stabilize SWMR system. Further optimization of MF's and fuzzy rules need to be done to obtain better results. The training error for wheel controller further needs to be further minimised whereas it is optimum for chassis controller. This could be achieved by increasing the number of membership functions or changing the shape of membership functions. The data sets generated from simulation results of fuzzy controllers can be further increased to obtain better training of ANFIS controllers.

6. Conclusion

The research objective of controlling highly non-linear SWMR system using fuzzy based ANFIS approach has been successfully illustrated. The study considers two different control techniques i.e. fuzzy and ANFIS for the stabilization of the proposed system. The comparison of both the control strategies has been shown. The simulation results proved the superiority of fuzzy control over ANFIS technique in terms of settling time, steady state error and overshoot. The wheel velocity is controlled after one undershoot followed by overshoot, chassis angle is controlled after one overshoot followed by under shoot whereas chassis angular velocity is controlled smoothly after one overshoot. The simulation results shows that the fuzzy controllers were able to control the wheel velocity within 4 sec, with a zero amount of steady state error and overshoot of 1.48° to -1.25°. The settling time for chassis angle and angular velocity were 2.3 sec and 4.5 sec respectively. The steady state error obtained for chassis controller was zero. The maximum overshoot for angular velocity response was 0.82° which was better as compared to angle response. It has been also observed that ANFIS technique fails to control the SWMR system. Further improvement in training error for wheel controller is in progress to achieve better results. For this increase in number of membership function and change in their shapes can be carried out for effective control. Some other control techniques like Neural networks, Particle swarm optimization, Genetic algorithm are also been investigated for obtain better control of SWMR systems.

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