Springer

KSME

Journal of Mechanical Science and Technology 28 (12) (2014) 5169~5174

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-014-1140-0

Fuzzy logic based yaw stability control for active front steering of a vehicle[†]

S. Krishna[*], S. Narayanan and S. Denis Ashok

School of Mechanical and Building Sciences, VIT University, Vellore, 632-014, India

(Manuscript Received July 17, 2013; Revised August 27, 2014; Accepted August 27, 2014)

Abstract

Yaw stability control is an important consideration for improving the stability and handling behavior of a vehicle during extreme steering maneuvers. This paper proposes a fuzzy logic based yaw stability controller for an active front steering of a four-wheeled road vehicle by using steer-by-wire system. The proposed control system takes the yaw rate error, the steering angle given by the driver and the vehicle body side slip angle as inputs, for calculating the additional steering angle as output for stabilizing the yaw moment of the vehicle. A three degrees-of-freedom vehicle model is considered. Performance of the proposed system is simulated for sinusoidal, step maneuver using Matlab/Simulink tool, and the results are compared with the existing fuzzy control system which uses two inputs such steering angle and yaw rate. The simulation results show better performance of the proposed fuzzy based yaw controller as compared with the existing control system.

Keywords: Yaw stability control; Steer-by-wire; Fuzzy controller

---

1. Introduction

Yaw stability is one of the most significant aspects of vehicle safety, and yaw stability control can avoid dangerous, undesirable behaviors of the vehicles in extreme maneuvers. Active front steering is one of the most practical approaches for yaw stability control in which a correction of steering angle is added to the driver's steering input, when the desired yaw rate of the vehicle varies due to external disturbances. Steering actuated yaw stability control provides maximum benefit in steer by wire systems, as mechanical linkages between the steering wheel and road wheels are replaced by electronic actuators, which motivates easier implementation of active front wheel steering control based on feedback.

Many research works have been attempted for developing yaw stability control systems in steer-by-wire systems. Ackermann (1994) proposed a steering control system which achieves robust decoupling of the vehicle's yaw stabilization [1]. Robust yaw stability control based on active front steering for road vehicle was developed and its performance was verified using hardware in loop simulation [2]. Internal model control and sliding mode control approaches for yaw stability control were designed and their performances were verified using simulation studies [3]. Falcone and Murakami (2007) proposed direct yaw moment control method using in wheel motor control for enhancing vehicle stability [4]. Disturbance observer-based yaw stability controller is proposed for a light commercial vehicle [5]. A control system consisting of a steering angle disturbance observer and proportional integral type tracking controller is developed for robust control of yaw stability of an electric vehicle [6]. Qiang Li et al. (2009) proposed a proportional integral and derivative (PID) control system for yaw stability control based on road wheel steer angel as control input [7]. Binachi et al. (2010) proposed an adaptive integrated control system using active front steering and rear torque vectoring [8]. Arabi and Behroozi, (2010) proposed an integrated vehicle dynamics control system based on the combination of active front steering (AFS) and active rear differential (ARD) for yaw rate stability of the vehicle [9]. Hakima and Ameli (2010) presented an integrated control approach for four wheel automotive system steering [10]. These control techniques are complex and the implementation is difficult, as they require coordinated control of vehicle subsystems for performing the desired control function.

Many researchers have applied a fuzzy logic approach for developing active front wheel steering based yaw stability control systems. Boada et al. (2005) applied fuzzy logic approach for developing a control system to maintain the targeted values of yaw rate and side slip angle for a vehicle [11]. Hasan and Anwar (2006) designed a yaw stability controller of a vehicle via steer-by-wire system [12]. Sang-Jin Ko et al. (2007) proposed the fuzzy logic-based yaw stability controller based on the input parameters such as yaw rate and steering angle [13]. Goodarzi et al. (2010) designed a fuzzy controller based on yaw rate error, side slip angle and a lateral accelera-

---

[*] Corresponding author. Tel.: +91 416 2243091
E-mail address: krishna.s@vit.ac.in

[†] Recommended by Associate Editor Bongsob Song

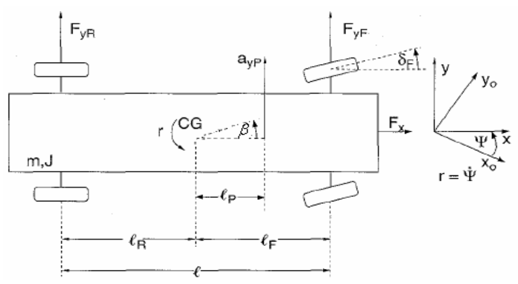


Fig. 1. 3-DOF vehicle model [1].

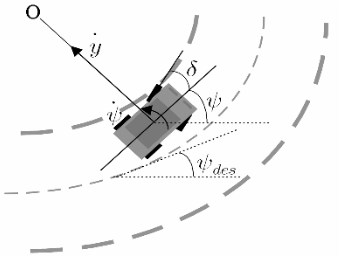


Fig. 2. Lateral vehicle dynamics [14].

tion of the vehicle for calculating the corrected steering angles of the front inner and outer wheels of the vehicle [14]. Ghosh et al. (2012) proposed a fuzzy logic-based active yaw control algorithm, which receives yaw rate and steering angle as inputs for generating additional steering angle [15]. The existing fuzzy logic-based control strategies rely only on measurement of steering angle and yaw rate. However, the side slip angle is an important parameter for yaw stability, which is predominantly significant during the under-steer or over-steer of the vehicle. Hence, it is necessary to develop a new approach which uses the available measurement signals such as yaw rate and side slip angle for yaw stability control of vehicle.

This paper presents a fuzzy-based yaw stability control system which requires three input parameters, such as yaw rate error, steering angle and vehicle body side slip angle of the vehicle, for maintaining yaw rate of the vehicle by generating additional steering angle to the front wheels of the vehicle. In distinction to the existing methods, the proposed fuzzy control system uses the body side slip angle for better maintenance of vehicle yaw stability. Simulation results are presented for analyzing the performance of the proposed approach.

2. Vehicle dynamics model

In the present work, we considered a three degrees-of-freedom (DOF) vehicle model for analyzing lateral dynamics of the vehicle, which is adapted from Ref. [14]. The vehicle dynamics model used is shown in Fig. 1. This model describes the important parameters of the lateral dynamics such as yaw rate ($\dot{\psi}$), lateral acceleration (a_y), tire forces on front and rear wheels.

Lateral acceleration of the vehicle is given by the following equation:

$$a_y = \ddot{y} + v_x\dot{\psi} , \tag{1}$$

where $\ddot{y}$ refers to acceleration of the vehicle in *Y*- direction and ‘v_x’ refers the longitudinal velocity of the vehicle.

The equation of lateral translation motion is:

$$ma_y = m(\ddot{y} + v_x\dot{\psi}) = F_{yf} - F_{yr} . \tag{2}$$

The terms F_{yf}, and F_{yr} are the respective tire forces on front and rear wheels in ‘*Y*’ directions of the vehicle. ‘*m*’ refers to the mass of vehicle yaw angle of the vehicle, which describes the orientation of the vehicle and it is shown in Fig. 2.

The actual yaw moment of the vehicle is given by:

$$I_z\ddot{\psi} = l_fF_{yf} - l_rF_{yr} , \tag{3}$$

where l_f and l_r refer to the longitudinal distance from CG to front and rear tires, respectively, as shown in Fig. 1. The F_{yf} and F_{yr} can be calculated using following equation:

$$F_{yf} = 2C_{af}(\delta - \theta_{vf}) , \tag{4}$$

$$F_{yr} = 2C_{ar}(-\theta_{vr}) . \tag{5}$$

Here C_{af} and C_{ar} represent the cornering force of front and rear wheels, respectively. θ_{vf} and θ_{vr} are the velocity angle of the front and rear tires. The θ_{vf} and θ_{vr} can be calculated using following equations:

$$\tan(\theta_{vf}) = \frac{v_y + l_f\dot{\psi}}{v_x} , \tag{6}$$

$$\tan(\theta_{vr}) = \frac{v_y - l_r\dot{\psi}}{v_x} . \tag{7}$$

The vehicle body side slip angle β is one of the important parameters which give the information about the chassis direction of the vehicle and it is calculated using the following equation:

$$\beta = \arctan(\frac{v_y}{v_x}) . \tag{8}$$

The rate of desired yaw orientation or yaw rate is defined as follows:

$$\dot{\psi}_{des} = \frac{v_x}{l_f + l_r}\delta . \tag{9}$$

From the above equation, the desired yaw rate depends on steering angle given by the driver, speed of the vehicle. Desired yaw rate provides the desired path information; however, due to external disturbance such as cross wind, asymmetric

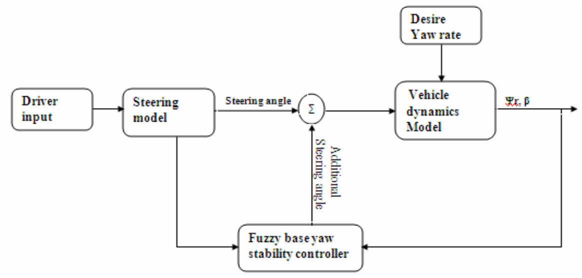


Fig. 3. Block diagram of proposed yaw stability controller.

friction coefficients on front and rear tires, there exists an error in the yaw rate and it can be calculated using the following equation:

$$e_r = \dot{\psi} - \dot{\psi}_{des} . \tag{10}$$

To analyze the above vehicle dynamics in time domain, a state space representation is used for analyzing yaw rate and side slip angle of the vehicle as given below:

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} -\dfrac{C_{af}+C_{ar}}{mv} & -v-\dfrac{C_{af}-C_{ar}}{mv} \\ \dfrac{C_{ar}l_r - C_{af}l_f}{I_z v} & -\dfrac{C_{af}l_f^2 + C_{ar}l_r^2}{I_z v} \end{bmatrix} \begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} \dfrac{C_{af}}{m} \\ \dfrac{C_{af}l_f}{I_z} \end{bmatrix} \delta \tag{11}$$

$$Y = \begin{bmatrix} 1 & 1 \end{bmatrix} \begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \delta .$$

In the present work, a fuzzy logic based control system design is proposed for minimizing the yaw rate error of the vehicle, which will improve the vehicle maneuvering, and stability of the vehicle.

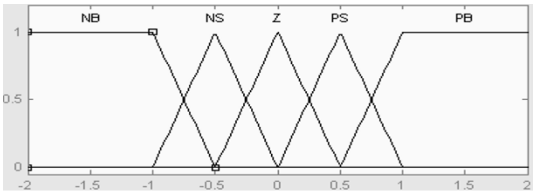
3. Control system design

The structure of the proposed control system is shown in Fig. 3. As the desired path of the vehicle depends upon the steering angle, yaw rate error, side slip angle, these parameters are taken as inputs to the proposed control system. The steer-by-wire system receives the yaw rate of a vehicle using a yaw rate sensor, and yaw rate error is calculated using the actual vehicle model. Based on the yaw rate error, steering angle of the front wheel and side slip angle, a correction in the steering angle is estimated using the fuzzy logic control system, which will be applied to the front wheels of the vehicle for maintaining the desired path of the vehicle.

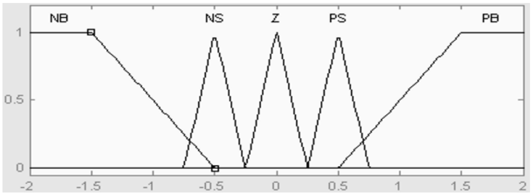
A fuzzy control system can be usually divided into three parts such as fuzzification, fuzzy rules and inference, defuzzification, which are discussed in the following sub-sections.

3.1 Fuzzification

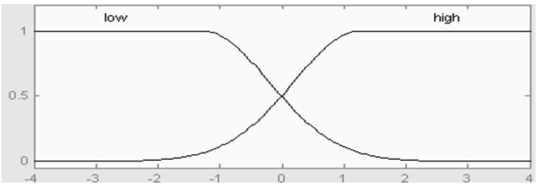
A fuzzy control system with three inputs and one output is developed. The input variable, side slip angle is fuzzified to have two fuzzy sets: low and high.



(a) Steering angle



(b) Yaw rate error



(c) Side slip angle

Fig. 4. Membership functions for input variables.

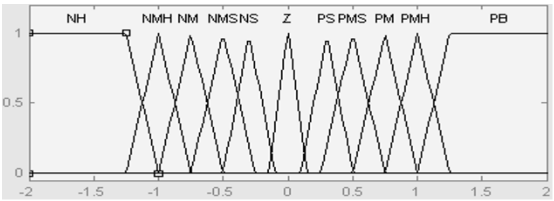


Fig. 5. Membership function for the output variable: correction angle.

The steering angle and yaw rate error are fuzzified into five fuzzy sets: negative big (NB), negative small (NS), zero (Z), positive small (PS), and positive big (PB).

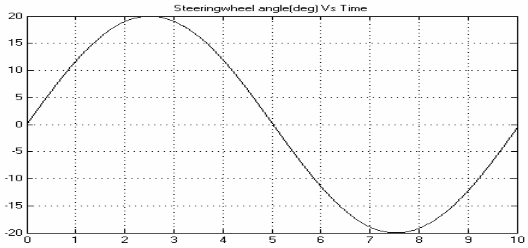
The output variable, steering correction angle are fuzzified to have eleven fuzzy sets: (NB, NMH, NM, NMS, NS, Z, PS, PMS, PM, PMH, PB), where NMH and PMH represent negative medium high, and positive medium high, respectively. NMS and PMS represent negative medium emall, and positive medium small, respectively. NM and PM represent negative medium, and positive medium, respectively. Membership functions for the input and output variables of the fuzzy control system are shown in Figs. 4 and 5, respectively.

3.2 Fuzzy rules

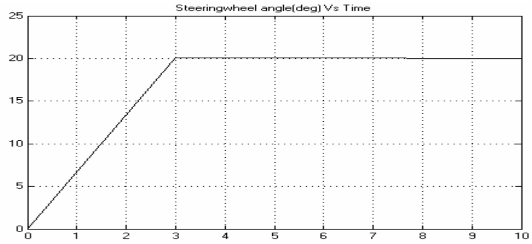
For the given input values of steering angle, side slip angle and yaw rate error, fuzzy rules were formulated for inferring the output correction angle to the front wheel. By using fuzzy theory, the proposed fuzzy control system uses Mamdani

Table 1. Fuzzy interference rule.

Side slip angle	Steering angle	Yaw rate error				
		NB	NS	Z	PS	PB
Low	NB	NS	NS	Z	PB	PB
	NS	NMS	NMS	Z	PMH	PMH
	Z	NM	NM	Z	PM	PM
	PS	NMH	NMH	Z	PMS	PMS
	PB	NH	NH	Z	PS	PS
High	NB	NH	NH	Z	PS	PS
	NS	NMH	NMH	Z	PMS	PMS
	Z	NM	NM	NS	PMS	PMS
	PS	NMS	NMS	NS	NS	NS
	PB	NS	NS	NS	NS	NS



(a) Sinusoidal input



(b) Step input

Fig. 6. Steering inputs.

fuzzy inference system, which is characterized by the following fuzzy rules as shown in Table 1.

4. Simulation results and analysis

To demonstrate the improved performance of the proposed fuzzy control system, simulation studies were carried out using SIMULINK and compared with the existing fuzzy control system, which uses only two inputs such as steering angle of the front wheel and yaw rate error [15]. To test the performance of the control system, simulation was conducted for sinusoidal and step input maneuver as shown in Fig. 6.

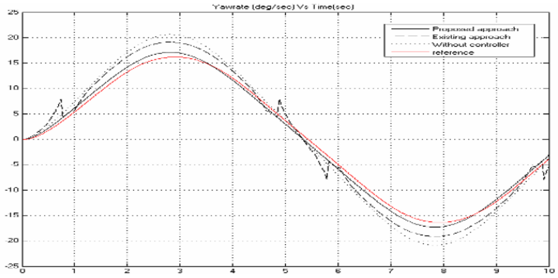
The vehicle parameters used for the computer simulations are given in Table 2.

4.1 Sinusoidal maneuver

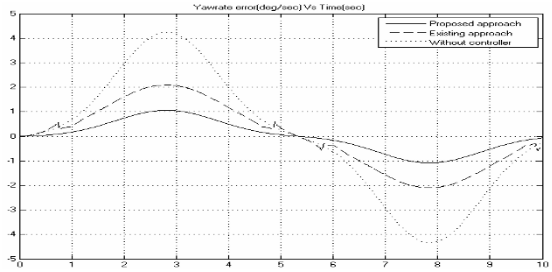
A sinusoidal steering input can be associated with a slalom test, which is performed for assessing the yaw roll stability of a vehicle. Fig. 7 shows the comparison of vehicle responses for the yaw rate, yaw rate error and side slip angle of the vehicle during sinusoidal maneuver. It is observed that the yaw rate error is much lesser for the proposed control system than the existing model and uncontrolled vehicle for sinusoidal maneuver. It means that vehicle with the proposed controlled system follows the desired path much closer than the uncontrolled vehicle.

Table 2. Vehicle parameters.

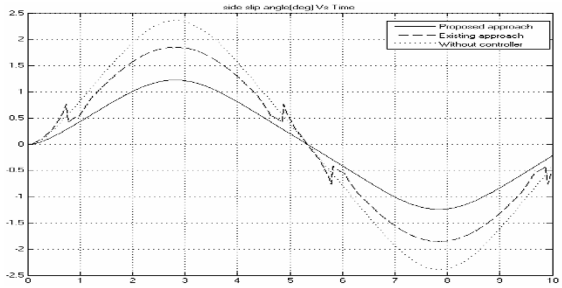
Vehicle mass (m)	1740 Kg
Yaw moment of inertia (I_z)	3545 Kg/m^2
Distance from front axle to CG(l_f)	1.12 m
Distance from rear axle to CG(l_r)	1.28 m
Wheel base (l)	2.4 m
Front tire cornering stiffness (C_{af})	27500 N/rad
Rear tire cornering stiffness (C_{ar})	65000 N/rad
Vehicle speed (v)	100 Km/hr



(a) Yaw rate

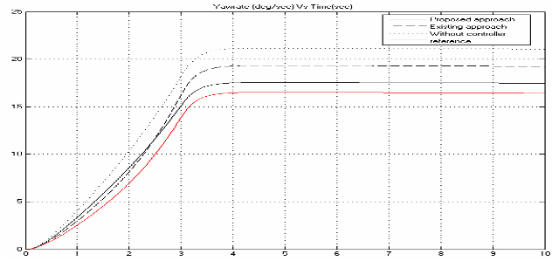


(b) Yaw rate error

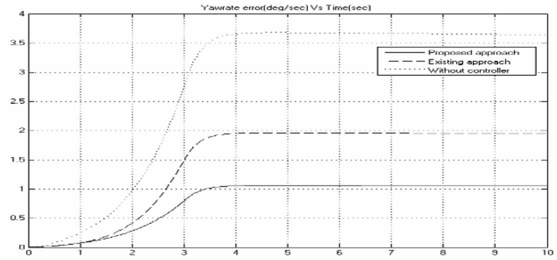


(c) Side slip angle

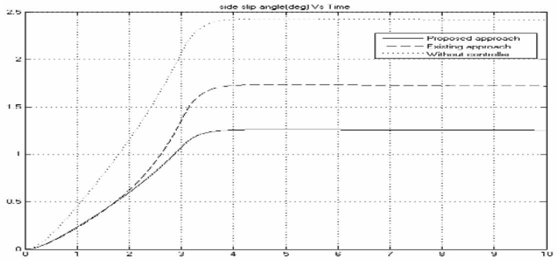
Fig. 7. Vehicle response for sinusoidal input.



(a) Yaw rate



(b) Yaw rate error



(c) Side slip angle

Fig. 8. Vehicle response for step input.

4.2 Step maneuver

The step input has been used to simulate conditions similar to the straight line cornering test. Responses for the yaw rate, side slip angle and yaw rate error of proposed model are compared with the existing approach and uncontrolled vehicles for step steering input as shown in Fig. 8. As in the previous case of sinusoidal steering input, the vehicle with the proposed control system behaves in a stable manner with low yaw rate error as compared with the uncontrolled vehicle. Also, the responses for yaw rate of vehicle with the proposed control system are closer to the reference as shown in Fig. 8(a).

The uncontrolled vehicle and the vehicle with the existing control system display a high yaw rate error with respect to the reference vehicle. From the simulation results, it can be concluded that the vehicle handling and stability are improved.

5. Conclusion

This paper proposes a fuzzy logic-based yaw stability controller for active front steering of the vehicle. The proposed control system takes steering angle, yaw rate error, side slip angle as inputs and estimates the additional steering angle to be applied to the front wheel of the vehicle for maintaining vehicle yaw stability. A mathematical model for the lateral dynamics of vehicle is derived for determining the yaw rate error of the vehicle. The performance of the proposed fuzzy based yaw stability control system has been evaluated using computer simulations with sinusoidal and step input maneuver. Simulation results show that the proposed system has smaller yaw rate error and vehicle body side slip angle, as compared with the existing model and uncontrolled vehicle.

Nomenclature

a_y : Lateral acceleration
F_{yf} : Lateral tire force on front wheels
v_x : Longitudinal velocity
F_{yr} : Lateral tire force on rear wheels
v_y : Lateral velocity
l_f : Longitudinal distance from CG to front tires
m : Mass of the Vehicle
l_r : Longitudinal distance from CG to rear tires
I_z : Yaw moment of inertia of vehicle
C_{af} : Cornering stiffness of front tires
Ψ : Yaw angle of vehicle
C_{ar} : Cornering stiffness of rear tires
$\dot{\psi}$: Yaw velocity of vehicle
θ_{vf} : Velocity angle of front tires
δ : Road wheel angle

Reference

[1] J. Ackermann, Robust decoupling, ideal steering dynamics and yaw stabilization of 4WS cars, *Automatica*, 30 (11) (1994) 1761-1768.

[2] B. A. Guvenc, L. Guvenc and S. Karaman, Robust yaw stability controller design and hardware-in-the-loop testing for a road vehicle, *IEEE Transactions on Vehicular Technology*, 58 (2) (2009) 555-571.

[3] M. Canale and A. Ferrara, Vehicle yaw control via second-order sliding-mode technique, *IEEE Transactions on Industrial Electronics*, 55 (11) (2008) 3908-3916.

[4] P. Falcone, F. Borrelli, J. Asgari, H. E. Tseng and D. Hrovat, Predictive active steering control for autonomous vehicle systems, *IEEE Trans. Control Syst. Technol.*, 15 (3) (2007) 566-580.

[5] S. Oncu, S. Karaman and L. Guvenc, Robust yaw stability controller design for a light commercial vehicle using a hardware in the loop steering test rig, *IEEE proceedings on Intelligent Vehicles Symposium* (2007) 852-859.

[6] K. Nam, S. OH, H. Fujimoto and Y. Hori, Robust yaw stability control for electric vehicles based on active front steering control through a steer-by-wire system, *International Journal of Automotive Technology*, 13 (7) (2012) 1169-1176.

[7] Q. Li, G. Shi, J. Wei and Y. Lin, Yaw stability control of active front steering with fractional-order PID controller, *International Conference on Information Engineering and*

Computer Science (2009) 1-4.

[8] D. Bianchi, A. Borri, M. Domenica Di-Benedetto and S. Di Gennaro, Adaptive integrated vehicle control using active front steering and rear torque vectoring, *International Journal of Vehicle Autonomous Systems*, 8 (2/3/4) (2010) 85-105.

[9] S. Arabi and M. Behroozi, Design of an integrated active front steering and active rear differential controller using fuzzy logic control, *Proceedings of the World Congress on Engineering*, II (2010) ISBN: 978-988-18210-7-2.

[10] A. Hakima and S. Ameli, Improvement of vehicle handling by an integrated control system of four wheel steering and ESP with fuzzy logic approach, *2nd International Conference on Mechanical and Electrical Technology (ICMET)*, September 10-12 (2010) 738-744.

[11] B. L. Boada, M. J. L. Boada and V. D´ıaz, Fuzzy-logic applied to yaw moment control for vehicle stability, *Vehicle System Dynamics*, 43 (10) (2005) 753-770.

[12] M. S. Hasan and S. l. Anwar, Yaw stability control system for an automobile via steer-by-wire, *4th International Conference on Electrical and Computer Engineering*, (2006) 345-348.

[13] S.-J. Ko, J.-J. Kim and J.-J. Lee, Yaw stabilization of a vehicle by yaw stability controller based on fuzzy logic, *ISIS 2007 Proceedings of the 8th symposium onAdvanced Intelligent Systems*, Korea (2007).

[14] A. Goodarzi, S. Arabi and E. Esmailzadeh, *Design of an integrated Afs/Acd control system to enhance 4wd vehicles dynamics and stability*, IDETC/CIE (2010).

[15] S. Ghosh, A. Deb, M. Mahala, M. Tanbakuchi and M. Makowski, Active yaw control of a vehicle using fuzzy logic algorithm, *SAE International*, 2012-01-0229.

S. Krishna is an Assistant Professor at Mechatronics Division, VIT University, Vellore. He received his B.S. degree in Electronics and Communication and M.S. degree in Mechatronics from VIT University His research areas include automotive steering systems, modern control systems.

S. Narayanan is Senior Professor and Pro-Vice Chancellor at VIT University, Vellore. He received his degree.S. in Mechanical Engineering, M.S. and Ph.D. degrees in Industrial Engineering and Management from Pondicherry University. His areas of interest include industrial engineering and management, and manufacturing.

S. Denis Ashok a Professor at VIT University, Vellore. His B.S. degree in Mechanical Engineering and M.S. degree in Production Engineering are from Madurai Kamaraj University and his Ph.D. is from IIT Madras. His research interests include spindle metrology, soft computing techniques, mechatronic systems.