FUZZY LOGIC CONTROLLER FOR ACTIVE STEERING CONTROL SYSTEM

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ABSTRACT: The aim of this study is to introduce a fuzzy logic controller for active steering control of a vehicle. A lot of unexpected events might occur on the road due to slippery road condition which can be considered as one of the major factors of accidents. Hence, a nonlinear fuzzy logic observer based active steering controller is proposed that will overcome the disturbances such as wet and icy road conditions and crosswind. The controller has proved that it can stabilize the steering wheel and reduce the time for system to achieve the steady state condition. In the simulations, comparisons are made between the uncontrolled output, Sliding Mode Control (SMC), Sliding Mode Observer Based Controller (SMCO) and Linear Quadratic Regulator (LQR). It can be seen that Fuzzy controller performance is comparable to SMCO but much better when compared to LQR.

KEYWORDS: *Fuzzy Control; Sliding Mode Control; Membership Function; Nonlinear System*

1.0 INTRODUCTION

On the road, inexperienced and young drivers have high tendencies to overreact on wet and icy conditions when driving that may result to an accident due to the lack of tire friction and the driver might lose control of the car and the steering system becomes unstable [1]. With lateral tire forces modulation, the active steering can be designed and regulate the tire slip angle and affect vehicle handling behavior affectively. There are three types of active steering which Active Front Steering (AFS) [2-4], Active Rear Steering (ARS) [2, 5], and Four-Wheel Active Steering (4WAS) [6]. Different road friction and using of various disturbances method [7] such as sliding mode control [6-7], linear quadratic regulator [8], fuzzy logic controller [9-10], or other control techniques [11-12].

Several researches on sliding mode controller have been published such as [13] that developed a vehicle model based on sliding mode controller in order to obtain desired vehicle performance via a two degree of freedom bicycle model. Another publication in [14] investigated the application of SMC by using the nonlinear sliding surface for yaw rate tracking of active front steering control where it identifies the cornering stiffness as the parameter. Hu et al. [15] developed an integral sliding mode control (ISMC) approach for in-wheel- motor driven electric vehicles steered by differential drive assistance steering.

This study relates to active steering system which is an integrated steering support system for cars. The system is close to the steering systems on conventional cars but with additional functionality to withstand with disturbances such μ-split which is a split adhesion coefficient between wheels, and wind gusts or decreased road adhesion conditions. By influencing in [1] and [7] therefore, the main purpose of this study is to propose a fuzzy logic controller (FLC) for a single-track model.

There are two main features of this study:

i. The controller design that is based on the fuzzy logic controller (FLC).
ii. The controller's performance is then compared to SMC, SMCO and LQR to prove its effectiveness. It will be shown that this controller is very effective and comparable to SMC but better than LQR.

Finally, simulations are given to prove the validity of the controller. The rest of the paper is organized as follows. Section 2 presents the problem statement and the model of the vehicle. Next, Section 3 provides first main contribution of this paper, the design of the fuzzy logic controller. In order to validate the effectiveness of the controller proposed, Section 4 provides the simulation examples and finally Section 5 concludes the paper.

2.0 PROBLEM STATEMENT

The uncertain linear time invariant system given by is considered as

$$x(t) = Ax(t) + Bu(t) + Df(t) \tag{1}$$

and

$$y(t) = Cx(t) \tag{2}$$

where the state vector is $x(t) \in \boldsymbol{R}^n$, $y \in \boldsymbol{R}^p$ and the control input is $u(t) \in \boldsymbol{R}^m$the uncertain function or disturbance vector is $f(t) \in R^l$, which the p, n, m and l are the number of states, inputs and disturbances respectively. The system matrix is $A \in \boldsymbol{R}^{n\times n}$, the input matrix is $B \in \boldsymbol{R}^{n\times m}$ and the disturbance matrix is $D \in \boldsymbol{R}^{n\times l}$. It can be assumed that the input disturbance matrices B and D are in full rank without loss of generality.

Table 1: The active steering car system (BMW 735i) parameter values [14-15]

Parameters	Values
Mass of the car body, $\boldsymbol{m}$	1864 kg
Moment of inertia for the car body, $\boldsymbol{J}$	3654kgm²
Velocity of the car, $\boldsymbol{v}$	70 m/s
Cornering stiffness of the rear axle, $\boldsymbol{c_R}$	213800 N/rad
Cornering stiffness of the front axle, $\boldsymbol{c_F}$	101600 N/rad
Wheelbase of the rear axle, $\boldsymbol{l_R}$	1.32 m
Wheelbase of the front axle, $\boldsymbol{l_F}$	1.51 m

Based on the work of Isira et al. [1] and Ghani et al. [7], the parameter values are shown in Table 1 and the linearized version of the system is shown as

$$\begin{bmatrix} \dot{\beta} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} \delta_F \\ \delta_R \end{bmatrix} + \begin{bmatrix} \delta_F \\ \delta_R \end{bmatrix} M_{zD} \tag{3}$$

where

r = Yaw rate; β = Slide slip angle; δF& δR = Front and rear steering angles;

$$a_{11} = \frac{-\mu(c_R + c_F)}{mv}; a_{12} = -1 + \frac{\mu(c_R l_R - c_F l_F)}{mv^2}; a_{21} = \mu(c_R l_R - c_F l_F)J;$$

$$b_{11} = \frac{\mu c_F}{mv}; b_{12} = \frac{\mu c_R}{mv}; \mathrm{b}_{21} = \frac{\mu c_F l_F}{J}; b_{22} = \frac{\mu c_R l_R}{J}; bz = \frac{1}{J}.$$

The following assumptions are taken as standard from this study:

i. A, B is a controllable matrix pair.
ii. The input distribution matrix B has full rank.
iii. System with uncertainties satisfy the matching condition such as $rank[B|f(t)] = rank[B]$

3.0 FUZZY LOGIC CONTROLLER DESIGN

Definition in Table 2 is used in the study while a common method known as Mamdany's fuzzy [16] is employ to develop

$$\text{If } e(\dot{\psi}) \text{ is } A \text{ AND } \dot{e}(\dot{\psi}) \text{ is } B \text{ THEN } \delta_{corr} \text{ is } C \tag{4}$$

Table 2: Definitions of the input and output variables of the fuzzy active steering controller [17]

Variable	Definition
Input 1	$e(\dot{\psi}) = \dot{\psi}_{desired} - \dot{\psi}_{actual}$
Input 2	$\dot{e}_k(\dot{\psi}) = e_k(\psi) - e_{(k-1)}(\psi) / T_{sampling}$
Output	$\delta_{corrective}$

Table 3 illustrates the fuzzy rule base and the corresponding control surface for the fuzzy active steering system using the initial untuned fuzzy membership functions. The defuzzification procedure called as center of gravity (COG) is used for the conversion. The equation that governed the conversion is given by

$$f = \frac{\int f \times \mu_D(f)df}{\int \mu_D(f)df} \tag{5}$$

where $\mu_D(f)$ is the membership function.

Table 3: Rule bases in fuzzy: NVL → negative very large, NL → negative large, NM → negative medium, NS → negative small, ZE → zero, PS → positive small, PM → positive medium, PL → positive large, and PVL → positive very large

Rule Base No.	$e(\dot{\psi})$	$\dot{e}(\dot{\psi})$	δ_{corr}	**Rule Base No.**	$e(\dot{\psi})$	$\dot{e}(\dot{\psi})$	δ_{corr}
Rule No. 1	NL	NL	NVL	Rule No. 26	ZE	PS	ZE
Rule No. 2	NL	NM	NVL	Rule No. 27	ZE	PM	PS
Rule No. 3	NL	NS	NL	Rule No. 28	ZE	PL	PM
Rule No. 4	NL	ZE	NL	Rule No. 29	PS	NL	NS
Rule No. 5	NL	PS	NM	Rule No. 30	PS	NM	ZE
Rule No. 6	NL	PM	NS	Rule No. 31	PS	NS	ZE
Rule No. 7	NL	PL	ZE	Rule No. 32	PS	ZE	PS
Rule No. 8	NM	NL	NVL	Rule No. 33	PS	PS	PS
Rule No. 9	NM	NM	NVL	Rule No. 34	PS	PM	PM
Rule No. 10	NM	NS	NM	Rule No. 35	NL	NL	NVL
Rule No. 11	NM	ZE	NM	Rule No. 36	PM	NL	ZE
Rule No. 12	NM	PS	NS	Rule No. 37	PM	NM	ZE
Rule No. 13	NM	PM	ZE	Rule No. 38	PM	NS	PN
Rule No. 14	NM	PL	ZE	Rule No. 39	PM	ZE	PM
Rule No. 15	NS	NL	NL	Rule No. 40	PM	PS	PM
Rule No. 16	NS	NM	NM	Rule No. 41	PM	PM	PL
Rule No. 17	NS	NS	NS	Rule No. 42	PM	PL	PVL
Rule No. 18	NS	ZE	NS	Rule No. 43	PL	NL	ZE
Rule No. 19	NS	PS	ZE	Rule No. 44	PL	NM	PS
Rule No. 20	NS	PM	ZE	Rule No. 45	PL	NS	PM
Rule No. 21	NS	PL	PS	Rule No. 46	PL	ZE	PL
Rule No. 22	ZE	NL	NM	Rule No. 47	PL	PS	PL
Rule No. 23	ZE	NM	NS	Rule No. 48	PL	PM	PVL
Rule No. 24	ZE	NS	ZE	Rule No. 49	PL	PL	PVL
Rule No. 25	ZE	ZE	ZE				

4.0 SIMULATION

In this section, an example will be given to show some details on the fuzzy logic based controller design. The performance of the controller will be compared with Sliding Mode Controller (SMC), Sliding Mode Observer Controller (SMCO) and Linear Quadratic Regulator (LQR) from [7]. A single track car model for car steering has been acquired from [7] and [15]. From Equation (3), the dynamics of system in Equation (1) can be represented as

$$\begin{bmatrix} \dot{\beta} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -1.2086 & -0.9929 \\ 17.6245 & 1.18105 \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} 0.38935 & 0.8193 \\ 20.9929 & -38.6174 \end{bmatrix} \begin{bmatrix} \delta_F \\ \delta_R \end{bmatrix} + \begin{bmatrix} 0 \\ 0.0002737 \end{bmatrix} f(t) \tag{6}$$

The road disturbance *f*(t) is defined by Definition 2 and Definition 1 from [1, 14]. The performance of the controller will be evaluated under two types of road conditions, represented by $\mu = 0.5$ for wet road and $\mu = 1$ for dry road condition. The observer gain L, controller gain K and matrix C are chosen as

$$L = \begin{bmatrix} -240 & 1625 \\ -240 & 1625 \end{bmatrix} \tag{9}$$

$$K = \begin{bmatrix} -623.7288 & -2.6722 \\ 120.6039 & 1.7099 \end{bmatrix} \tag{10}$$

$$C = \begin{bmatrix} 0.0035 & 0.0050 \\ -0.0205 & 0.0822 \end{bmatrix} \tag{11}$$

The values such as $\rho = 0.045$, $\delta = 0.0025$ and $\gamma = 1$ are chosen from [1].

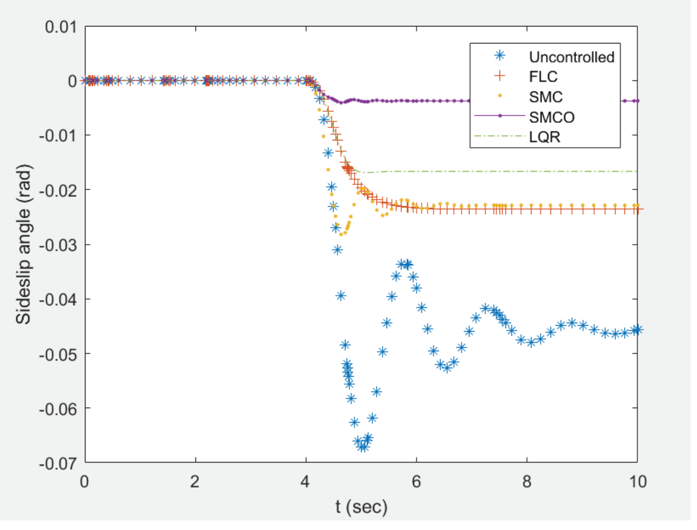

Figure 1: Sideslip angle displacement effect on the performance of FLC with SMCO, SMC and LQR under the influence of extreme braking action during wet road condition (μ = 0.5)

4.1 Performance of Fuzzy Logic Controller during Braking Action

At $\mu = 0.5$, Figure 1 shows that fuzzy logic controller is able to prevent larger amount of sideslip angle compared to SMC during braking action. However the performance of SMCO is slightly better than fuzzy logic controller at both μ. In Figure 2, fuzzy logic controller achieved lesser yaw angle displacement at $\mu = 0.5$ which is slightly better than SMC. This shows that fuzzy logic controller is affective and able to avoid large sideslip and yaw angle displacement due to braking action compared to SMC where the difference is very small as shown in all the figures.

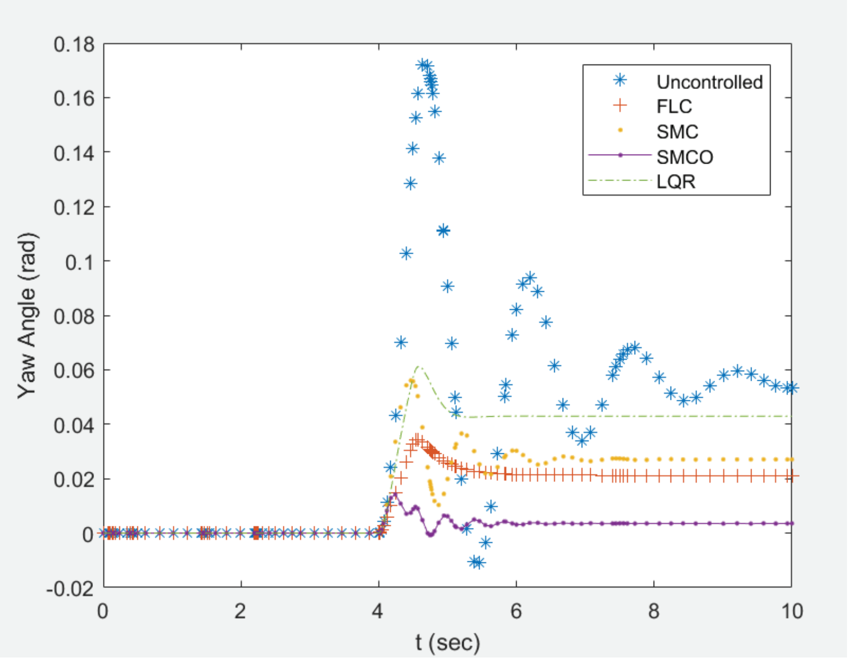

Figure 2: Yaw angle displacement effect on the performance of FLC with SMCO, SMC and LQR under the influence of extreme braking action during dry road SMC and LQR under the influence of extreme braking action during dry road condition (μ = 0.5)

4.2 Performance of Fuzzy Logic Controller during Crosswind Disturbance

At $\mu = 0.5$, the fuzzy logic is able to perform quite well when the car is under crosswind where it managed to avoid large sideslip and yaw angle displacement and comparable to SMC but better than LQR.

5.0 CONCLUSION

In this paper, fuzzy logic controller has been proposed for a single-track car model under the influence of external disturbances such as braking action torque and crosswind force. Simulations using Simulink has been carried out to verify the effectiveness of the proposed fuzzy logic controller. The stability of the controller is ensured by carefully analyzing the structure of the model and the idea of the disturbance. From the simulations, it was shown that the fuzzy logic controller can perform well by avoiding large sideslip and yaw angle displacement. It is comparable to SMCO but better than SMC controller. The controller produces good result and promise due it has utilized an observer that is normally used in situation where not all states can be measured.

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