Design of Fuzzy Controller for Automatic Steering

Sang-Jin Ko [1], Jun-Woo Lee [2], Byoung-Suk Choi [3] and Ju-Jang Lee[4]

[1] Graduate School of Automobile Technology, KAIST, Daejeon, Korea
(Tel : +82-42-869-8032; E-mail: sjko@kaist.ac.kr)
[2] Robotics Program, KAIST, Daejeon, Korea
(Tel : +82-42-869-8032; E-mail: sjko@kaist.ac.kr)
[3] Department of Electrical Engineering and Computer Science, KAIST, Daejeon, Korea
(Tel : +82-42-869-8032; E-mail: sjko@kaist.ac.kr)
[4] Department of Electrical Engineering and Computer Science, KAIST, Daejeon, Korea
(Tel : +82-42-869-8032; E-mail: jjlee@ee.kaist.ac.kr)

Abstract: Unmanned vehicle is future vehicle technology. Lateral control technology and longitudinal control technology are needed for unmanned vehicle. Automatic steering system is lateral control technology. A automatic steering system automatically controls the steering to keep the vehicle in its land and also to follow the lane as it curves around. This paper proposes automatic steering system based on fuzzy logic. If the fuzzy rules are set properly, the fuzzy controller can control the objective system nicely. To design an automatic steering system, lateral error dynamics of a vehicle is derived. The proposed automatic steering system is evaluated by SIMULINK in MATLAB. The simulation results show that the proposed automatic steering system works satisfactorily for keeping the vehicle in its land and following the lane.

Keywords: Lateral Vehicle Dynamics, Fuzzy Control, Automatic Steering System, Lane Keeping System, Intelligent Vehicle

1. INTRODUCTION

Unmanned vehicle have researched for a long time. One of unmanned vehicle is an automatic steering system. An automatic steering system controls the steering to keep the vehicle in the lane and follow the lane. There are several researches about an automatic system. Tesheng Hsiao and Masayoshi Tomizuka proposed position feedback controller for automatic steering.[1] J.R Lee, H.W. Kim, R. Kim, J.K. Lee and B.S. Kim proposed feed-forward and feedback controller for automatic steering.[2] Shinq-Jen Wu, Hsin-Han Chiang, Jau-Woei Perng, Tsu-Tian Lee and 'Chao-Jung Chen proposed an automatic steering controller with feedback controller and fuzzy controller. The fuzzy controller just compensates the feedback control to achieve satisfactory automatic steering.[3] S.J. Ko and J.J. Lee proposed fully fuzzy logic based automated lane keeping system.[6] But this controller has too many rules. Rule reduction is needed. J.R. Zhang, A. Rachild and S. J. Xu considered lateral and longitudinal motion for automatic steering.[4] But this research considers only lateral motion.

This research designs fully fuzzy logic based automatic steering system. The number of rules of this controller is proper. Lateral error dynamics of a vehicle is derived for this research. For evaluation simulation is conducted by Simlink .

2. VEHICLE LATERAL DYNAMICS

1) Lateral Error Dynamics of Vehicle

Lateral error dynamics of vehicle is derived for this research. The following figure is lateral vehicle dynamics.

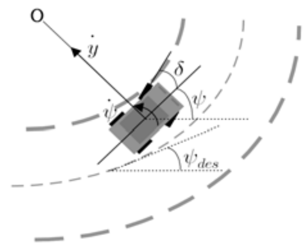

Fig. 1 Lateral Vehicle Dynamics

The following figure is show variables related with tire, vehicle velocity, steering angle and tire slip-angle.

Fig. 2 Variables related with tire

Lateral acceleration is as follows.

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

The equation for the lateral translational motion of the vehicle is obtained as

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

Moment balance about z axis yields the equation for the yaw dynamics as

$$I_z \ddot{\psi} = l_f F_{yf} - l_r F_{yr} \tag{3}$$

The lateral tire force for the front wheels and the rear wheels of the vehicle is written as

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

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

To obtain θ_{Vf} and θ_{Vr} , the following relations are used.

$$\tan(\theta_{Vf}) = \frac{V_y + l_f \dot{\psi}}{V_x} \tag{6}$$

$$\tan(\theta_{Vr}) = \frac{V_y - l_r \dot{\psi}}{V_x} \tag{7}$$

The rate of change of the desired orientation of the vehicle is defined as follows.

$$\dot{\psi}_{des} = \frac{V_x}{R} \tag{8}$$

Then, the desired acceleration can be written as

$$\frac{V_x{}^2}{R} = V_x \dot{\psi}_{des} \tag{9}$$

Therefore, lateral error is defined as follows.

$$\ddot{e}_1 = (\ddot{y} + V_x \dot{\psi}) - \frac{V_x^2}{R} = \ddot{y} + V_x(\dot{\psi} - \dot{\psi}_{des}) \tag{10}$$

Thus, derivative of lateral error is defined as follows.

$$\dot{e}_1 = \dot{y} + V_x(\psi - \psi_{des}) \tag{11}$$

Rotational error is defined as follows.

$$e_2 = \psi - \psi_{des} \tag{12}$$

2) State Space Equation of Vehicle

Substituting from equations (4), (5), (6), (7), (8), (9), (10), (11) and (12) into (2) and (3), following equations are obtained.

$$m\ddot{e}_1 = \dot{e}_1\left[-\frac{2}{V_x}C_{af} - \frac{2}{V_x}C_{ar}\right] + e_2\left[2C_{af} + 2C_{ar}\right] + \dot{\psi}_{des}\left[-\frac{2C_{af}l_f}{V_x} + \frac{2C_{ar}l_r}{V_x}\right] + \dot{\psi}_{des}\left[-\frac{2C_{af}l_f}{V_x} + \frac{2C_{ar}l_r}{V_x}\right] + 2C_{af}\delta \tag{13}$$

$$I_z\ddot{e}_2 = 2C_{af}l_1\delta + \dot{e}_1\left[-\frac{2C_{af}l_f}{V_x} + \frac{2C_{ar}l_r}{V_x}\right] + e_2\left[2C_{af}l_f - 2C_{ar}l_r\right] + \dot{e}_2\left[-\frac{2C_{af}l_f^2}{V_x} - \frac{2C_{ar}l_r^2}{V_x}\right] - I_z\ddot{\psi}_{des} + \dot{\psi}_{des}\left[-\frac{2C_{af}l_f^2}{V_x} - \frac{2C_{ar}l_r^2}{V_x}\right] \tag{14}$$

From equation (11) and (12), state space model can be obtained. The state space model in tracking error variables is therefore written

$$\frac{d}{dt}\begin{bmatrix} e_1 \\ \dot{e}_1 \\ e_2 \\ \dot{e}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & a_{22} & a_{23} & a_{24} \\ 0 & 0 & 0 & 1 \\ 0 & a_{42} & a_{43} & a_{44} \end{bmatrix}\begin{bmatrix} e_1 \\ \dot{e}_1 \\ e_2 \\ \dot{e}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{2C_{af}}{m} \\ 0 \\ \frac{2C_{af}l_f}{I_z} \end{bmatrix}\delta + \begin{bmatrix} 0 \\ -\frac{2C_{af}l_f - 2C_{ar}l_r}{mV_x} - V_x \\ 0 \\ -\frac{2C_{af}l_f^2 + 2C_{ar}l_r^2}{I_zV_x} \end{bmatrix}\dot{\psi}_{des} \tag{15}$$

$$a_{22} = -\frac{2C_{af} + 2C_{ar}}{mV_x} \tag{16}$$

$$a_{23} = \frac{2C_{af} + 2C_{ar}}{m} \tag{17}$$

$$a_{24} = \frac{-2C_{af}l_f + 2C_{ar}l_r}{mV_x} \tag{18}$$

$$a_{42} = -\frac{2C_{af}l_f - 2C_{ar}l_r}{I_zV_x} \tag{19}$$

$$a_{43} = \frac{2C_{af}l_f - 2C_{ar}l_r}{I_z} \tag{20}$$

$$a_{44} = -\frac{2C_{af}l_f^2 + 2C_{ar}l_r^2}{I_zV_x} \tag{21}$$

There are two inputs of the state space model, steering and desired yaw rate. The control input of the state space model is steering angle and the external input is the desired yaw rate.

3. DESIGN OF AUTOMATIC STEERING SYSTEM

1) Architecture of Automatic Steering System

The proposed fuzzy rules based automatic steering controller consists of two controllers. One of these is lateral error controller and the other is rotational error controller. Gain tuning of automatic steering controller is conducted by try and error method. The architecture of automatic steering system is as follows.

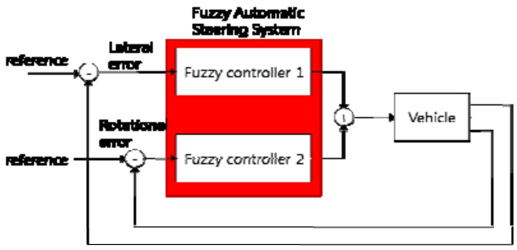

Fig. 3 Architecture of Automatic Steering System

2) Fuzzy Rules for Automatic Steering

Inputs of fuzzy controller for lateral distance error are lateral distance error, derivative of lateral distance error. And inputs of fuzzy controller for rotational error are rotational error and derivative of rotational error. Output of each controller is steering angle.

The rule base of lateral distance control is as follows.

Table 1. Rule base of lateral distance error controller

e_1 (lateral error) \ $\dot{e}_1$ (derivative of lateral error)	NB	NM	NS	ZO	PS	PM	PB
NB				NB	NB		
NM				NB			
NS				NM	NM		NS
ZO	NB	NB	NM	NS	NM	NS	ZO
PS	NB		NM	NM			
PM				NS			
PB			NS	ZO			

The rule base of lateral distance control is as follows.

Table 2. Rule base of rotational error controller

e_2 (rotational error) \ $\dot{e}_2$ (derivative of rotational error)	NB	NM	NS	ZO	PS	PM	PB
NB				NB	NB		
NM				NB			
NS				NM	NM		NS
ZO	NB	NB	NM	NS	NM	NS	ZO
PS	NB		NM	NM			
PM				NS			
PB			NS	ZO			

The inputs and the output of the fuzzy controller consist of seven membership functions and they are as follows.

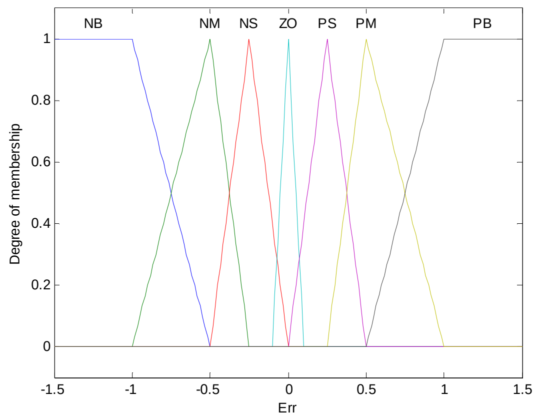

Fig. 4 Membership function of lateral distance error

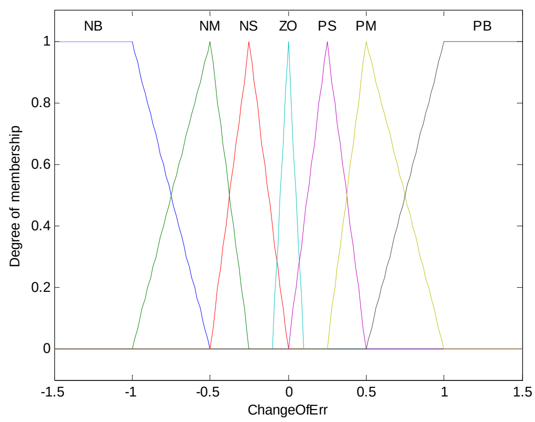

Fig. 5 Membership function of derivative of lateral distance error

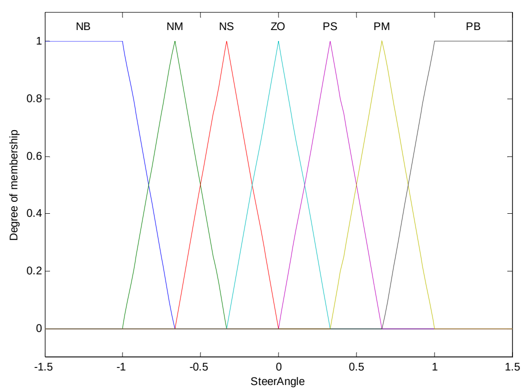

Fig. 6 Membership function of output

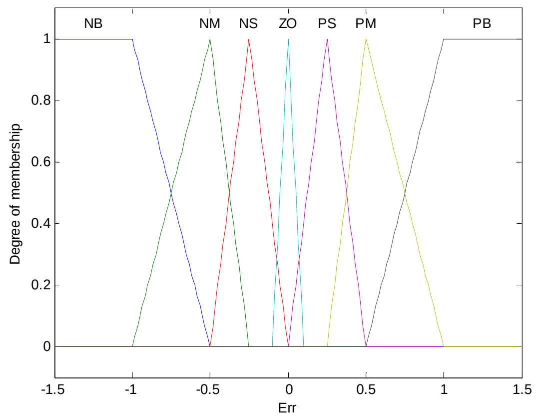

Fig. 7 Membership function of rotational error

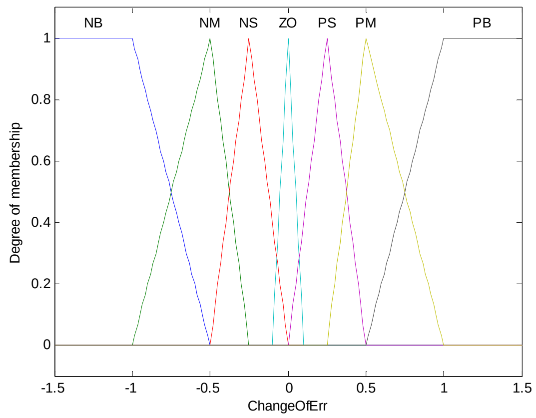

Fig. 8 Membership function of derivative of rotational error

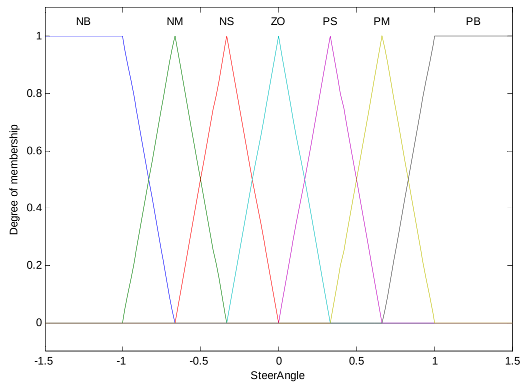

Fig. 9 Membership function of output

To reduce output error oscillation of vehicle, membership functions of inputs of each fuzzy controller are defined to be narrow to zero. But if membership functions of output of fuzzy controller were defined to be narrow to zero, output of vehicle oscillated more. So membership functions of output are defined to be different from membership functions of inputs. In the defuzzification strategy, the widely used center of area method (COA) is adopted.

4. SIMULATION RESULTS

Evaluation was conducted by SIMULIK in MATLAB. Two kinds of simulation are conducted. First, performance of proposed fuzzy logic based automatic steering system is evaluated through step input. Second, proposed automatic controller is compared to existing steering controller, such as feedback and feedback-feedforward controller through sinusoidal.

1) Simulation of step input

Simulation was executed under desired yaw rate which is the external input of the vehicle. Desired yaw rate is as follows.

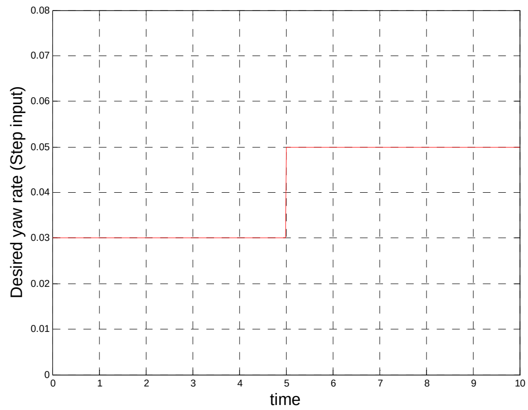

Fig. 10 Desired yaw rate - step input

Lateral distance error of the vehicle and its derivative are as follows.

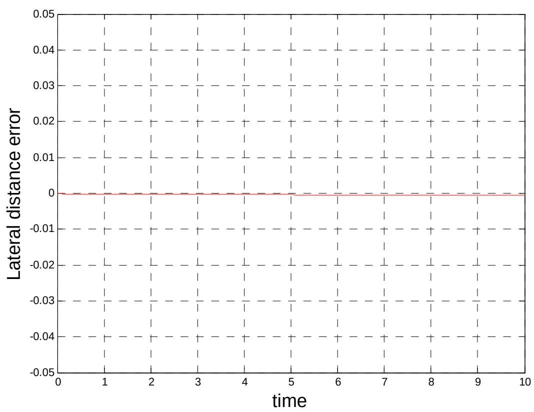

Fig. 11 Lateral distance error

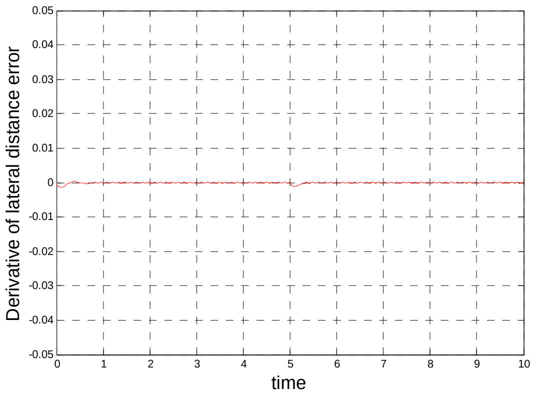

Fig. 12 Derivative of lateral distance error

The lateral distance error converges to almost zero. It means that the vehicle follows the desired path. Derivative of the lateral distance error also converges to zero, although it has oscillations in the transient area. It means that there are no oscillations of the lateral error in the steady state.

Rotational error of the vehicle and its derivative are as follows.

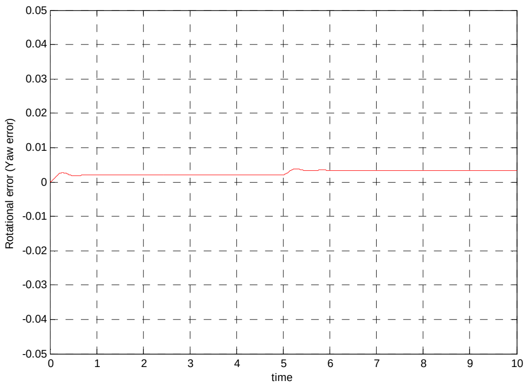

Fig. 13 Rotational error (Yaw error)

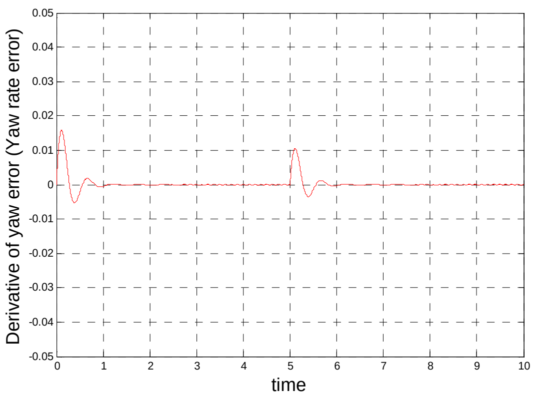

Fig. 14 Derivative of rotational error (Yaw-rate error)

2) Simulation of sinusoidal for Comparison

For evaluation of the proposed lane keeping system, simulation results of feedback controller, feedback-feedforward controller and fuzzy controller are compared under sinusoidal desired yaw rate. It is as follows.

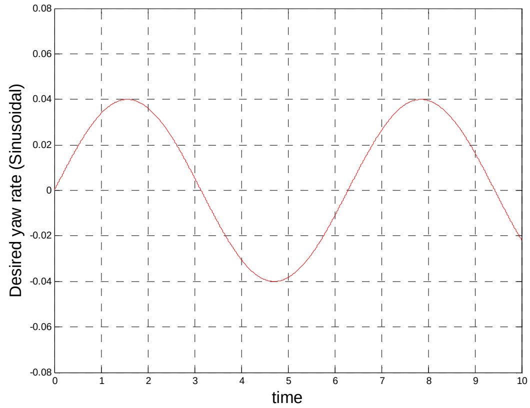

Fig. 15 Desired yaw rate - sinusoidal

Compared results are as follows.

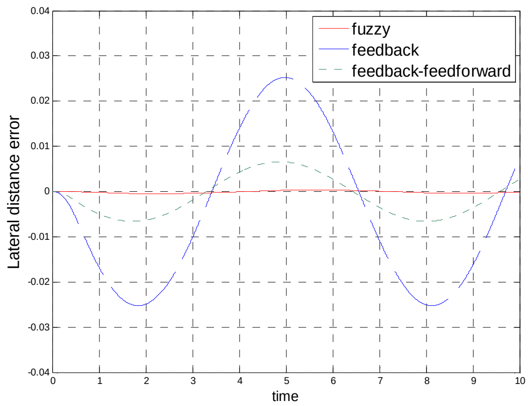

Fig. 16 Lateral distance error

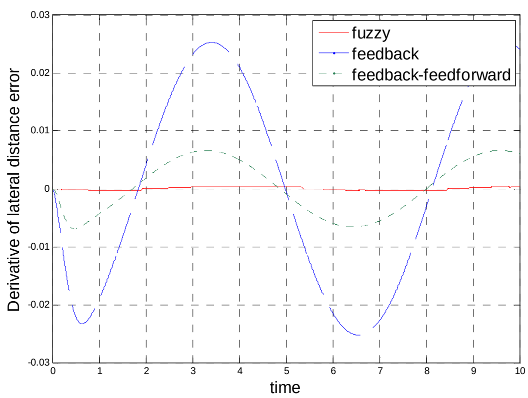

Fig. 17 Derivative of lateral distance error

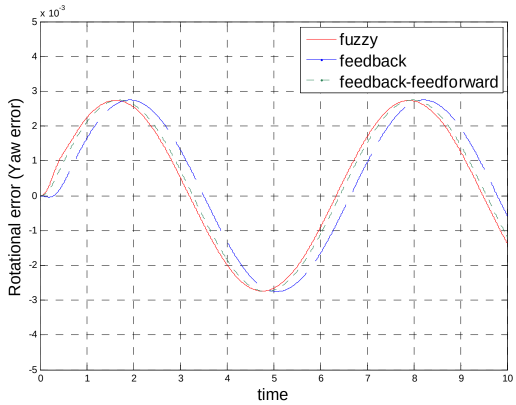

Fig. 18 Rotational error (Yaw error)

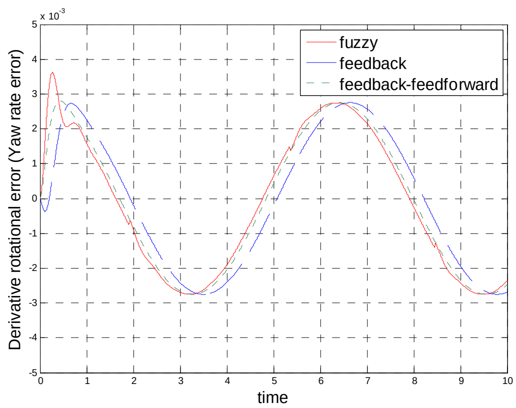

Fig. 19 Derivative of rotational error (Yaw rate error)

Simulation results show that lateral distance and derivative of lateral distance error of proposed automatic steering system are reduced remarkably compared to the others. Lateral distance and derivative of lateral distance error of proposed automatic steering system are holding near zero. But lateral distance error and derivative of lateral distance error of others oscillate. It means that the proposed automatic steering system follows the desired path better than others based on feedback control or feedback-feedforward control. But simulation results about rotational error and its derivative are similar with others.

5. CONCLUSION

Fully fuzzy logic based controller for automatic steering is proposed. Also vehicle lateral dynamics is derived for this research. Simulation was conducted by Simulink. The performance was evaluated by lateral distance error, derivative of lateral distance error, rotational error and derivative of rotational error (yaw rate). Simulation results show that performances of existing steering controller about lateral distance error and derivative of lateral distance error are improved. Proposed fuzzy steering controller controls the steering satisfactorily to keep the vehicle in its land and to follow the lane as it curves around. But, rotational error and its derivative are not improved. Researches about improvement of rotational error and its derivative will be needed and fuzzy parameter's tuning using evolutionary computation, such as genetic algorithms, and considering both lateral and longitudinal motion, as a future works.

REFERENCES

[1] Tesheng Hsiao and Masayoshi Tomizuka, "Design of position feedback controllers for vehicle lateral motion", Proceedings of the American Control Conference Minneapolis, Minnesota, USA, June 14-16, 2006

[2] J.R Lee, H.W. Kim, R. Kim, J.K. Lee and B.S. Kim, "Development of Active Safety Controller for Lane Keeping Support System", Electrical and Electronics, ITS Symposium of KSAE, pp.94-99, 2005

[3] Shinq-Jen Wu, Hsin-Han Chiang, Jau-Woei Perng, Tsu-Tian Lee and 'Chao-Jung Chen, "The automated lane-keeping design for an intelligent vehicle", Proceedings of Intelligent Vehicles Symposium, IEEE pp508-513, June 6-8, 2005

[4] J.R. Zhang, A. Rachild and S. J. Xu, "Velocity controller design for automatic steering of vehicles", Proceedings of the American Control Conference, pp196-197, June, 2001.

[5] Rajesh Rajamani, "Vehicle Dynamics and Control", pp27-39, Springer, 2006

[6] Sang-Jin Ko and Ju-Jang Lee, "Design of fuzzy logic based automated lane keeping system", Proceedings of spring conference of KSAE, pp1850-1856, June, 2007

[7] Sanggyum Kim, Hayoung Lim and Jungha Kim, "Research of the unmanned vehicle control and modeling for lane tracking", Transactions of KSAE, Vol. 11, No. 6, pp213-221, 2003