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Keywords: Fuzzy Logic Applications, Fuzzy Logic Control, Lateral Control

Executive Summary

This paper investigates the feasibility of a fuzzy logic control (FLC) algorithm for lateral control in a lane change maneuver in an automated highway system (AHS). The lane change maneuver takes the vehicle from *lanefollowing* control in one lane to *lanefollowing* control in an adjacent lane. It is assumed that there is no reference/sensing system in between the two lanes. The only sensor used for feedback during the lane change maneuver is a lateral accelerometer. The rules of the FLC are developed based on human driving experience. A simulation result is presented to show the feasibility of using the designed FLC for the lane change maneuver.

1 Introduction

In this report a design is described for a fuzzy logic control (FLC) algorithm applied to automatic steering control of a vehicle for a lane change maneuver. The objective of the lane change maneuver is to laterally transfer the vehicle from one lane to an adjacent lane. The maneuver can be broken down into three modes: 1) *lanefollowing* mode on the first lane, 2) *lane changing* mode between two adjacent lanes, and 3) *lanefollowing* mode on the adjacent lane (see figure 1). This research is an extension of fuzzy logic control for lane following, where the theory, design, and experimental results are detailed in [2], and this research can be viewed as an alternative to linear controllers developed for the lane change maneuver [13].

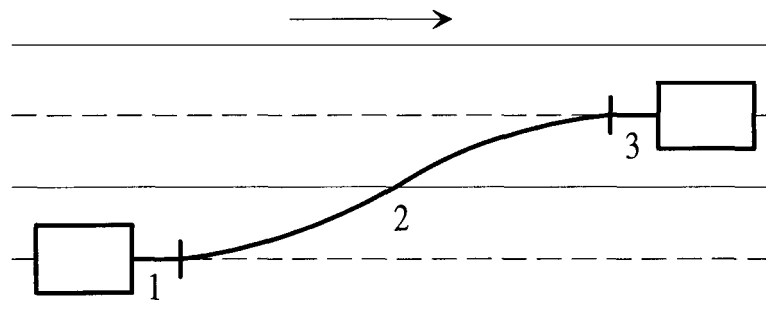


Figure 1: Lane Change Maneuver

2 Fuzzy Logic Control Design

The computation of a fuzzy system used for the control in this discussion is detailed in Hessburg [3]. The fuzzy rule base used for the lane change maneuver is developed based on human driving characteristics. The rule base consists of 24 linguistic rules using three control inputs and one control output, the change in front wheel steering angle, $\Delta\delta_c$. The FLC can be depicted by the following block diagram (see figure 2).

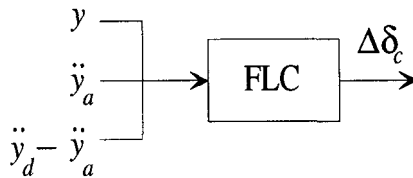


Figure 2: Fuzzy Logic Controller Block Diagram

The input variables, y and \ddot{y}_a have the convention according to figure 3. A positive advantage of a FLC is its ability to handle imprecise input variables. The lateral acceleration, \ddot{y}_a , is assumed to be measured from a lateral accelerometer. The lateral lane displacement, y , is estimated with some expected imprecision by integrating \ddot{y}_a twice, and assuming the yaw angle remains small during the lane change maneuver.

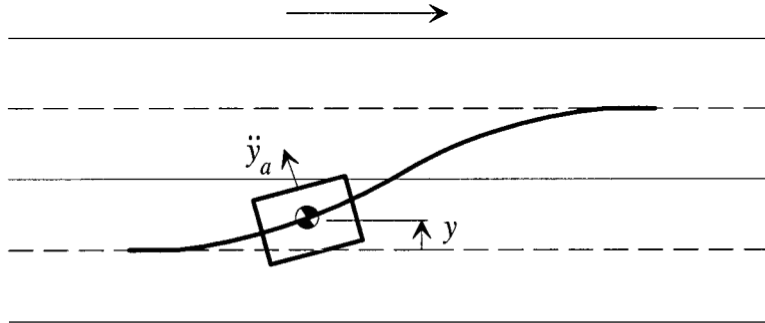


Figure 3: Convention for Input Variables

The desired lateral acceleration, \ddot{y}_d , is determined in eight stages. In fact, using the notation for lateral acceleration error, $\ddot{e}_a := \ddot{y}_d - \ddot{y}_a$, and linguistically describing \ddot{e}_a by three fuzzy subsets, the eight stages, based on the other two input variables y and \ddot{y}_a , account for the multiple of eight in the 24 rules (i.e., the eight in $8 \times 3 = 24$).

The eight stages will be described next. First, the lateral lane displacement, y , is linguistically described by four fuzzy subsets. If we call \tilde{Y} the linguistic variable of y , then can be described by the following four linguistic values.

$$\tilde{Y} \in \{first, second, third, final\} \quad (1)$$

In view of the lane, these linguistic values correspond fuzzy regions approximately depicted by figure 4.

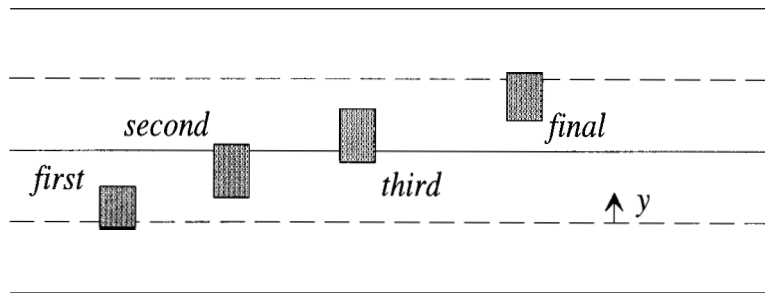


Figure 4: Linguistic Description of y

Each of the four regions form two stages, creating a total of eight stages. These stages can be articulated if the maximum allowable lateral acceleration is prescribed, \ddot{y}_{\max} . In the *first* region, it is desired to accelerate the vehicle to \ddot{y}_{\max} . Thus, the two stages for the *first* region are 1) "ramp up", until \ddot{y}_a reaches \ddot{y}_{\max} , and 2) "maintain \ddot{y}_{\max} ", when \ddot{y}_a reaches \ddot{y}_{\max} . The *second* region forms stage 3) "ramp down", until \ddot{y}_a reaches zero, and stage 4) "maintain zero acceleration", when \ddot{y}_a reaches zero. The *third* region forms stage 5) "ramp down", until \ddot{y}_a reaches $-\ddot{y}_{\max}$, and stage 6) "maintain $-\ddot{y}_{\max}$ ", when \ddot{y}_a reaches $-\ddot{y}_{\max}$. The *final* region forms stage 7) "ramp up", until \ddot{y}_a reaches zero, and stage 8) "maintain zero acceleration", when \ddot{y}_a reaches zero.

The rules are listed in eight sets (one set for each stage). Note that each set contains three rules, as the linguistic value \tilde{E} , describing \ddot{e}_a , has three fuzzy subsets.

$$\text{IF } (\tilde{Y} = \textit{first}) \text{ AND } (\tilde{Y}_a \textit{ LT } \tilde{Y}_{\max}) \text{ AND } \left(\tilde{E}_a \textit{ IS } \begin{pmatrix} N \\ Z \\ P \end{pmatrix} \right) \text{ THEN } \left(C\tilde{\Delta}_c \textit{ IS } \begin{pmatrix} \delta_{b3} \\ \delta_{b2} \\ \delta_{b1} \end{pmatrix} \right) \quad (2)$$

$$\text{IF } (\tilde{Y} = \textit{first}) \text{ AND } (\tilde{Y}_a \textit{ GE } \tilde{Y}_{\max}) \text{ AND } \left(\tilde{E}_a \textit{ IS } \begin{pmatrix} N \\ Z \\ P \end{pmatrix} \right) \text{ THEN } \left(C\tilde{\Delta}_c \textit{ IS } \begin{pmatrix} \delta_{s1} \\ 0 \\ -\delta_{s1} \end{pmatrix} \right) \quad (3)$$

$$\text{IF } (\tilde{Y} = \textit{second}) \text{ AND } (\tilde{Y}_a \textit{ GT } \textit{Zero}) \text{ AND } \left(\tilde{E}_a \textit{ IS } \begin{pmatrix} N \\ Z \\ P \end{pmatrix} \right) \text{ THEN } \left(C\tilde{\Delta}_c \textit{ IS } \begin{pmatrix} -\delta_{b1} \\ -\delta_{b2} \\ -\delta_{b3} \end{pmatrix} \right) \quad (4)$$

$$\mathbf{IF} (\tilde{Y} = \text{second}) \text{ AND } (\tilde{Y}_a \text{ LE Zero}) \text{ AND } \left(\tilde{E}_a \text{ IS } \begin{pmatrix} N \\ Z \\ P \end{pmatrix} \right) \text{ THEN } \left(C\tilde{\Delta}_c \text{ IS } \begin{pmatrix} \delta_{s1} \\ 0 \\ -\delta_{s1} \end{pmatrix} \right) \quad (5)$$

$$\mathbf{IF} (\tilde{Y} = \text{third}) \text{ AND } (\tilde{Y}_a \text{ GT } -\tilde{Y}_{\max}) \text{ AND } \left(\tilde{E}_a \text{ IS } \begin{pmatrix} N \\ Z \\ P \end{pmatrix} \right) \text{ THEN } \left(C\tilde{\Delta}_c \text{ IS } \begin{pmatrix} -\delta_{b1} \\ -\delta_{b2} \\ -\delta_{b3} \end{pmatrix} \right) \quad (6)$$

$$\mathbf{IF} (\tilde{Y} = \text{third}) \text{ AND } (\tilde{Y}_a \text{ LE } -\tilde{Y}_{\max}) \text{ AND } \left(\tilde{E}_a \text{ IS } \begin{pmatrix} N \\ Z \\ P \end{pmatrix} \right) \text{ THEN } \left(C\tilde{\Delta}_c \text{ IS } \begin{pmatrix} \delta_{s1} \\ 0 \\ -\delta_{s1} \end{pmatrix} \right) \quad (7)$$

$$\mathbf{IF} (\tilde{Y} = \text{final}) \text{ AND } (\tilde{Y}_a \text{ LT Zero}) \text{ AND } \left(\tilde{E}_a \text{ IS } \begin{pmatrix} N \\ Z \\ P \end{pmatrix} \right) \text{ THEN } \left(C\tilde{\Delta}_c \text{ IS } \begin{pmatrix} -\delta_{b1} \\ -\delta_{b2} \\ -\delta_{b3} \end{pmatrix} \right) \quad (8)$$

$$\mathbf{IF} (\tilde{Y} = \text{final}) \text{ AND } (\tilde{Y}_a \text{ GE zero}) \text{ AND } \left(\tilde{E}_a \text{ IS } \begin{pmatrix} N \\ Z \\ P \end{pmatrix} \right) \text{ THEN } \left(C\tilde{\Delta}_c \text{ IS } \begin{pmatrix} \delta_{s1} \\ 0 \\ -\delta_{s1} \end{pmatrix} \right) \quad (9)$$

The meanings of the above notation are listed as follows:

N : Negative

P : Positive

Z : Near Zero

LT : Less Than

GT : Greater Than

LE : Less Than or Equal

GE : Greater Than or Equal

δ_{ni} : Consequent singleton where $n = s$ implies small (fine) magnitude, and $n = b$ implies a big (coarse) magnitude such that $\delta_{b1} < \delta_{b2} < \delta_{b3}$, where

Incremental Change in Steering Angle (in degrees) Updated every 0.01 sec.

δ_{b3}	δ_{b2}	δ_{b1}	δ_{s1}
0.0046	0.004	0.0034	0.0006

Next, the value of \mathbf{y} is discussed. The value of \ddot{y}_d is determined and updated *during* the lane change maneuver. The value of \ddot{y}_d depends on the prescribed values of maximum lateral jerk, \ddot{y}_{\max} , and maximum lateral acceleration, \ddot{y}_{\max} , as well which of the eight stages the vehicle is at. For example, the first stage is a "ramp up". If the vehicle reaches the first stage at time $t = t_o$, then $\ddot{y}_d = \ddot{y}_{\max} \times (t - t_o)$. When the vehicle lateral acceleration reaches the second stage (initiated

at time $t = t_1$, when one of the three rules in Eqn. (3) reaches the maximum rule strength of all the rule), "maintain \ddot{y}_{\max} ", $\ddot{y}_d = \ddot{y}_{\max}$. In this way, \ddot{y}_d is updated stage by stage as opposed to being entirely prescribed before the lane change maneuver. Figure 5 shows a typical desired lateral acceleration profile.

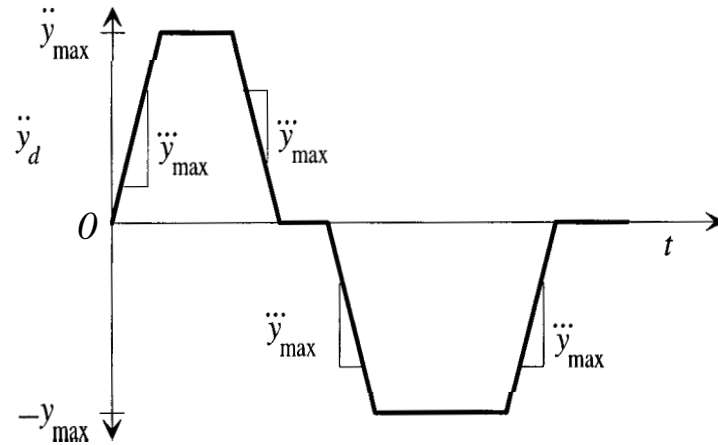


Figure 5: Desired Lateral Acceleration

Figure 6 shows the membership functions used for the three control input variables.

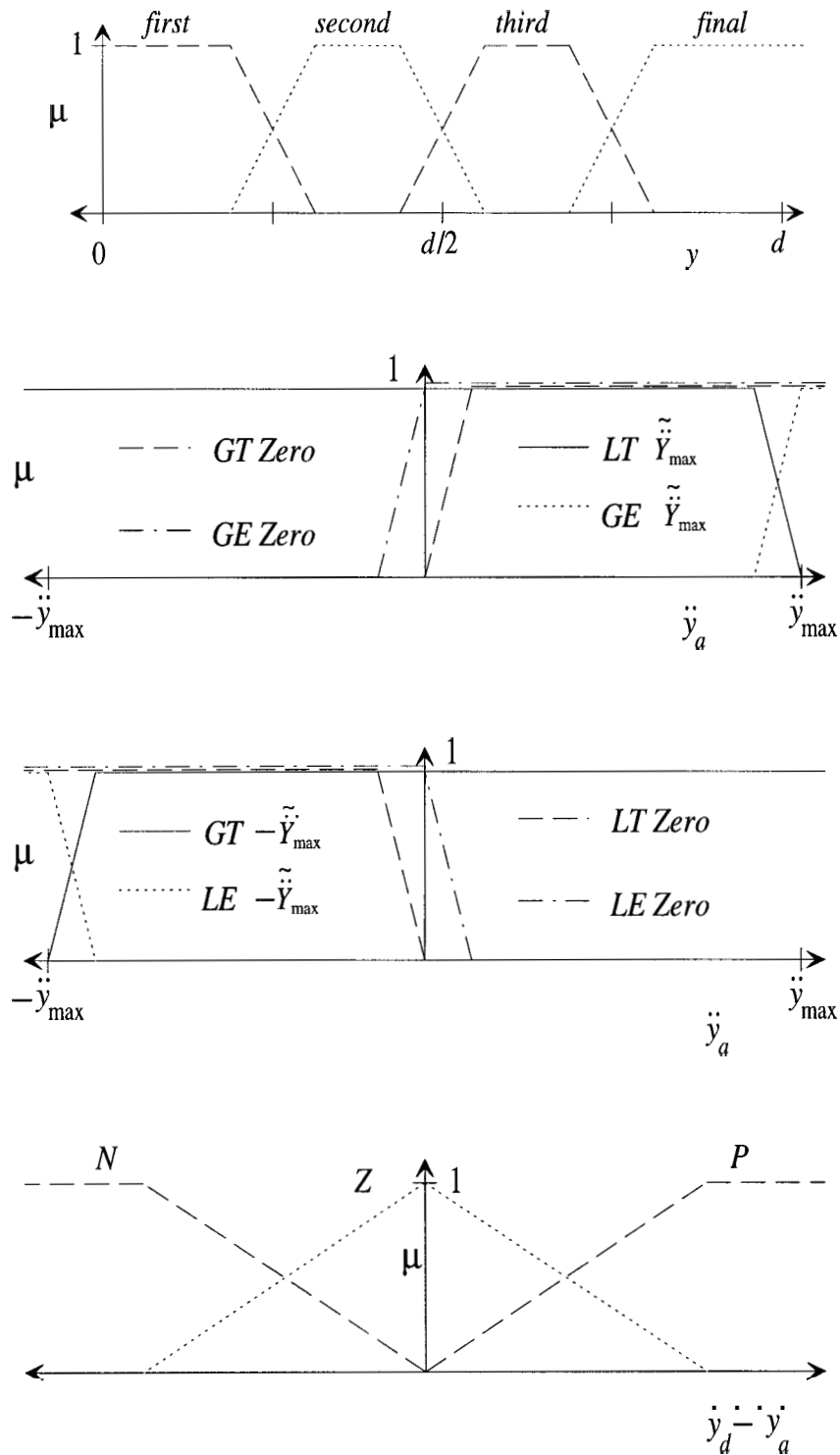


Figure 6: Membership Functions

3 Simulation Results

A simulation result is presented to show the feasibility of using the FLC discussed in the previous section for a lane change maneuver. Figure 7 shows the simulation results for a lane change maneuver between two adjacent lanes, spaced by 3.6 meters. The vehicle parameters are chosen to simulate a Toyota Celica, as used in [3]. The conditions are assumed to be nominal (i.e., there are no wind gust disturbances and the roadway is not slippery). The longitudinal velocity of the vehicle is 20 meters/second and the sampling time is 0.01 second.

The vehicle begins on a straight roadway under a lane following FLC controller as designed in [3]. At time $t = 0.5$ second, the vehicle switches into lane change FLC control. When the vehicle is within 0.1 meters of the center of the adjacent lane (also a straight roadway), the vehicle returns to lane following FLC control. In the simulation, the vehicle reaches the adjacent lane at approximately time $t = 6.2$ seconds.

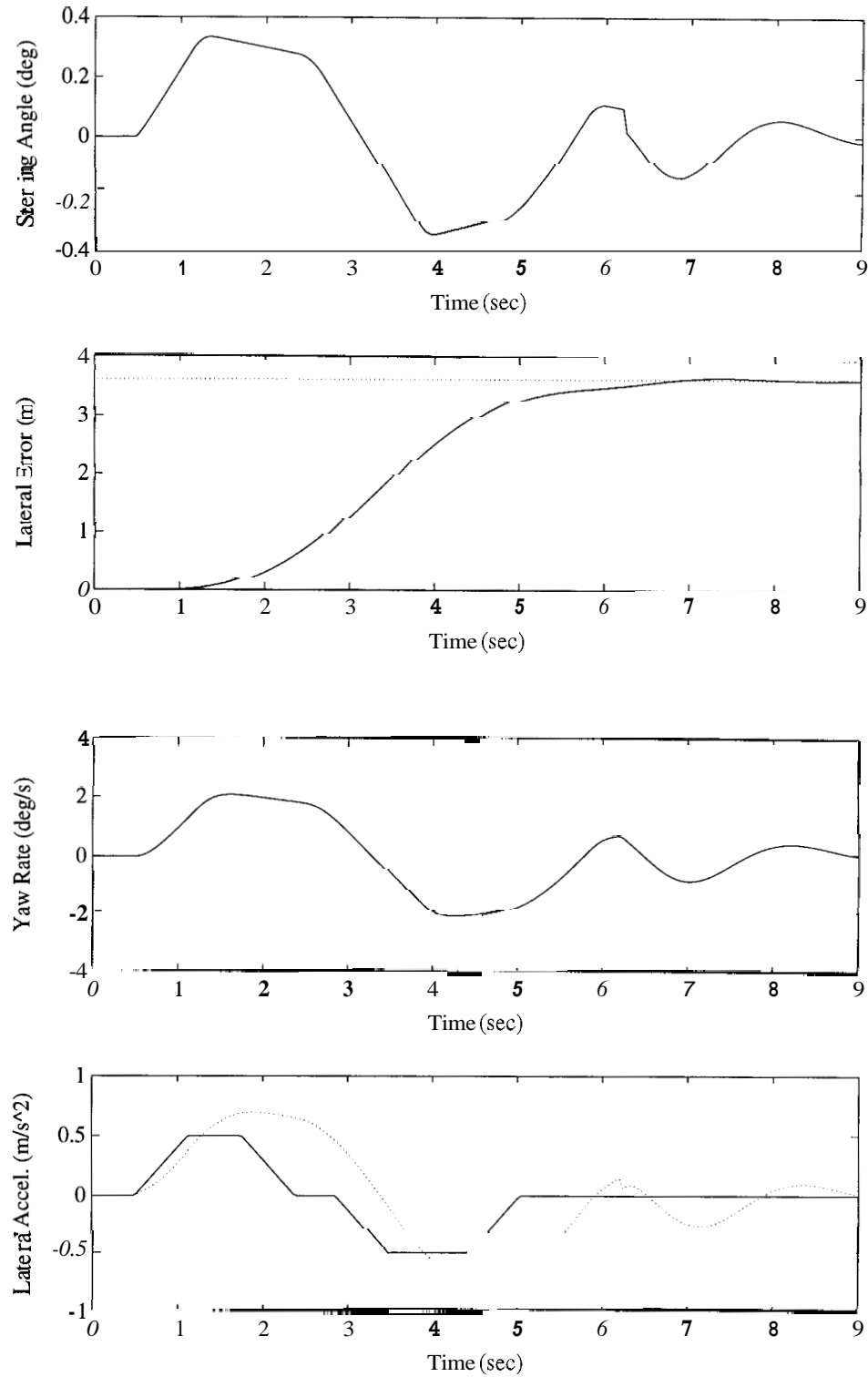


Figure 7: Simulation of Lane Change Maneuver; — Desired,Actual

4 Discussion and Conclusion

The successful results of the lane change maneuver using FLC came after several hours of manually tuning the parameters of the fuzzy system used for control. This implementation demonstrates some advantages of using FLC control. For example, the choice of inputs to the FLC was very flexible and depended on the simple nature of typical human operation in steering a vehicle for a lane change maneuver. This is in contrast to many model based controllers which require measured or estimated states as inputs to the controller. Another advantage of the FLC is that there is no reliance on an *explicit* mathematical model of the vehicle. The rule base design is based on an *implicit* model of the vehicle in the sense that rules developed based on human experience *implicitly* incorporate knowledge of the vehicle response to steering angle action. In addition, this FLC design incorporated highly nonlinear control action based on strategic aspects found in human experience for navigating lane change maneuvers.

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