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A Design Method for Vehicle Dynamic Systems Based on Fuzzy Logic Control*

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Abstract: In this paper we present a new approach using fuzzy logic control method based on reference model tracking to overcome the uncertainties of vehicle dynamic systems. Simulation of the lateral velocity and the yaw rate control show that it is satisfactory to apply this method to vehicle dynamic control resulting in close matching with the reference model.

Key words: vehicle dynamic systems; fuzzy logic control; model tracking; lateral velocity

1 Introduction

The automatic steering and the intelligent control for vehicle systems have drawn the great attention of researchers in the field of automotive engineering in recent years. It involves large numbers of aspects such as, road-following, obstacle avoidance, landmark recognition, cross country navigation and position estimation. A serious problem faced when designing the controller of steering systems for vehicles is the imprecise model. The vehicle dynamics have various structured uncertainties and nonlinear characteristics involved. The structured uncertainties could be due to incorrect parameter values such as that affected by road-tire condition and load variation, which are very difficult to be measured. Not only the uncertainties are unknown or poorly known, but they also may be subject to change as the vehicle goes about its navigation.

On the other hand, much effort has been spent on various control laws for lateral velocity and yaw rate control of vehicles [1~9]. Since the lateral and yaw motion dynamics of a vehicle are heavily influenced by vehicle parameters which vary during operation, the effect of road-tire interaction is more difficult to address in the controller design because it is practically impossible to measure directly[3]. Some design methods, adopting feedback and feedforward gains[3], and tracking the desired mode[10] are proposed but they are based on the parameters estimated.

In this paper we come up with a design method of fuzzy logic control based on model tracking. The objective is to minimize the tracking error by the proper selection of the fuzzy control action. The computer simulation investigation on the prototype vehicle steered by front wheels is carried out with one of the main parameters of the vehicle varying from

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-50 to $+50$ percent and simulation results show that with this method the vehicle dynamic control system will have better robust property with the uncertainty overcome in a large scale.

2 Model Tracking Principle

In order to overcome the effects of uncertainties on system properties the trajectory tracking algorithms are inferred and the fuzzy control method is adopted to develop a control rule. Consider the following dynamic system described by nonlinear state equations

$$\dot{X} = f(X,u,t) = F(X,t) + \Psi(X,u,t), \tag{2.1}$$

where $X \in \mathbb{R}^n$ is the system state vector and $u \in \mathbb{R}^r$ is a control vector. $F(X,t)u \in \mathbb{R}^n$ is the known part that may be linear, nonlinear and/or with time-variant parameters. $\Psi(X,u,t)$ represents the uncertainty part of the system, caused by unknown parameters or changes in them, as well as disturbances in detection. Select a linear time-invariant reference model described as:

$$\dot{X}_m = A_m X_m + B_m r, \tag{2.2}$$

where $X_m \in \mathbb{R}^n$ is the reference model state vector and $r \in \mathbb{R}^r$ is a command input vector. $A_m \in \mathbb{R}^{n\times n}$ is a constant state matrix and $B_m \in \mathbb{R}^{n\times r}$ is a constant input matrix. Define the difference between the system state vector and the reference model state vector as the error vector:

$$e = X_m - X \tag{2.3}$$

and the derivative of error vector is

$$\dot{e} = \dot{X}_m - \dot{X}. \tag{2.4}$$

Combine equation (2.1)~(2.4), the error state equation can be arranged as:

$$\dot{e} = A_m e + (A_m X + B_m r - F(X,t) - G(X,u,t) - Bu), \tag{2.5}$$

where $G(X,u,t) = \Psi(X,u,t) - Bu$ and B is a full-rank matrix selected by designer. Properly selecting control vector u^* so that: $A_m X + B_m r - F(X,t) - G(X,u,t) - Bu^* = 0$, the error will decrease gradually and the system vector will trace the reference model vector. Because the reference model state vector varies with time, the tracing rate has to be much faster than the convergent rate of the reference model. Therefore it should be necessary to compenstate the error system with a set of proper eigenvalues through error vector feedback. The error feedback system will be described as:

$$\dot{e} = (A_m + BK)e + A_m X + B_m r - F(X,t) - G(X,u,t) - BKe - Bu, \tag{2.6}$$

where $K \in \mathbb{R}^{r\times n}$ is the feedback gain matrix. If a control action u can be found so that:

$$A_m X + B_m r - F(X,t) - G(X,u^*,t) - BKe - Bu^* = 0, \tag{2.7}$$

or

$$u^* = B^+[A_m X + B_m r - F(X,t) - G(X,u^*,t) - BKe], \tag{2.8}$$

where B^+ is the pseudo inverse of B, the system vector will converge to the reference model vector with the rate of error system.

3 Fuzzy Control Algorithm

The developments show that the key to control the given uncertainty system is to obtain the control action u^* from equation (2.7) or (2.8) but that is difficult as we do not know the uncertainty part of the system. Therefore fuzzy logic algorithms are presented in this section to decide the control action.

Rewriting equation (2.6) in the form:

$$\dot{e}-(A_m+BK)e=A_mX+B_mr-F(X,t)-G(X,u,t)-BKe-Bu. \tag{2.9}$$

We can notice that if $[\dot{e}-(A_m+BK)e]=0$, the uncertainties have been compensated and if it is not zero, through left multiplying both sides of equation (2.9) with $[\dot{e}-(A_m+BK)e]^{\mathrm{T}}$, the equation takes the form:

$$\begin{aligned}&[\dot{e}-(A_m+BK)e]^{\mathrm{T}}[\dot{e}-(A_m+BK)e]\\&=[\dot{e}-(A_m+BK)e]^{\mathrm{T}}[-Bu]+[\dot{e}-(A_m+BK)e]^{\mathrm{T}}\\&[B_mr+A_mX-F(X,t)-G(X,u,t)-BKe].\end{aligned} \tag{2.10}$$

Since $[\dot{e}-(A_m+BK)e]^{\mathrm{T}}[\dot{e}-(A_m+BK)e]\geqslant 0$, the control action u should be modified to make the disturbances compensated by means of decreasing the relative item:

$$[\dot{e}-(A_m+BK)e]^{\mathrm{T}}[-Bu].$$

For the single input case, fuzzy logic rules are set up basing on the following linguist description:

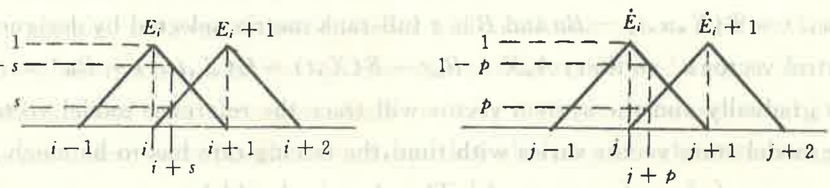
IF ε is large and $\Delta\varepsilon$ is positive large, THEN v is negative large;

IF ε is large and $\Delta\varepsilon$ is negative medium, THEN v is negative medium;

…;

IF ε is zero and $\Delta\varepsilon$ is zero, THEN v is zero

where $\varepsilon=[\dot{e}-(A_m+BK)e]^{\mathrm{T}}[\dot{e}-(A_m+BK)e]$; $\Delta\varepsilon$ is the increment of ε. $v=\mathrm{sgn}\{[(A_m+BK)e-\dot{e}]^{\mathrm{T}}B\}\Delta u$; Δu is the increment of control action u. In the fuzzy inference process we select both ε and its increment $\Delta\varepsilon$ as input variables and choose triangular membership functions for the linguist variables which is shown in Fig. 1.



(a) Membership of ε (b) Membership of $\Delta\varepsilon$

Fig. 1 Membership function of ε and $\Delta\varepsilon$

The membership functions are described by:

$$\mu_E(\varepsilon)=\begin{cases}1-s, & \varepsilon \text{ is } E_i,\\ s, & \varepsilon \text{ is } E_{i+1}, \quad (0\leqslant s<1),\\ 0, & \text{otherwise.}\end{cases} \tag{2.11}$$

$$\mu_{\dot{E}}(\Delta\varepsilon)=\begin{cases}1-p, & \Delta\varepsilon \text{ is } \dot{E}_j,\\ p, & \Delta\varepsilon \text{ is } \dot{E}_{j+1}, \quad (0\leqslant p<1),\\ 0, & \text{otherwise.}\end{cases} \tag{2.12}$$

Therefore there are only four of complete control rules fired in one calculation process:

$R(i,j)$: IF ε is E_i and $\Delta\varepsilon$ is $\dot{E}_j$ THEN v is $v_{i,j}$,

$R(i,j+1)$: IF ε is E_i and $\Delta\varepsilon$ is $\dot{E}_{j+1}$ THEN v is $v_{i,j+1}$,

$$R(i+1,j):\quad \text{IF } \varepsilon \text{ is } E_{i+1} \text{ and } \Delta\varepsilon \text{ is } \dot{E}_j \text{ THEN } v \text{ is } v_{i+1,j},$$

$$R(i+1,j+1):\quad \text{IF } \varepsilon \text{ is } E_{i+1} \text{ and } \Delta\varepsilon \text{ is } \dot{E}_{j+1} \text{ THEN } v \text{ is } v_{i+1,j+1}.$$

Since only four entries of the look up table are taken into account in every calculation procedure, the control action is given with $N = 4$ as:

$$v = \sum_{k=1}^{N} v_k \Big/ \sum_{k=1}^{N} \mu_k, \tag{2.13}$$

where E_i, $\dot{E}_j$ and $v_{i,j}$ are linguist variables and N is a total number of inference rules, $\mu_k = \min\{\mu_E(\varepsilon), \mu_{\dot{E}}(\Delta\varepsilon)\}$, $(k = 1,2,3,4)$, denotes the minimal membership value of input variables in the kth rule.

4 Vehicle Model

The controller presented has been applied to a model vehicle which is rear wheel driven by a DC motor and steered automatically by front wheels. Generally, a vehicle on planar motions can be regarded as a system with two degrees of freedom, that is vehicle velocity V and vehicle yaw rate ω which are not affected by the selection of the fixed-world coordinate system. The position or pose of a vehicle can be described by three parameters (x, y, θ), two for translation and one for orientation. The vehicle is considered traveling forward at a constant speed, while its lateral veocity v_y, measured in the vehicle's own frame at the center of gravity, and yaw rate ω are state variables. The vehicle dynamic equations are derived as:

$$\begin{bmatrix} \dot{v}_y \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} -\dfrac{g \cdot f_f(\lambda_f)}{v_x} & -g \cdot (l_f - l_r)\dfrac{f_f(\lambda_f)}{v_x} - v_x \\ -\dfrac{1}{I}\left(\dfrac{f_f(\lambda_f)}{v_x} + f_r(\lambda_r)\right) & \dfrac{1}{I}\left(f_r(\lambda_r)\dfrac{l_r^2}{l_f + l_r} - f_f(\lambda_f)\dfrac{l_f^2}{l_f + l_r}\dfrac{1}{v_x}\right) \end{bmatrix} \begin{bmatrix} v_y \\ \omega \end{bmatrix} + \begin{bmatrix} g(\mu_{xf} + f_f(\lambda_f))\dfrac{l_f}{l_f + l_r} \\ \dfrac{1}{I}(\mu_{xf} + f_f(\lambda_f))\dfrac{l_f^2}{l_f + l_r} \end{bmatrix} \cdot \delta_f, \tag{2.14}$$

where v_x and v_y are the components of vehicle speed v in the longitudinal and the lateral directions of vehicle body, ω is the yaw rate of vehicle; δ_f is the front steering angle, a system input. Here we have assumed that the steering angle, wheel slip angles, vehicle slip angle and yaw rate is small. The vehicle speed is assumed to be constant or slowly changed. The road-tire friction of both sides of the vehicle is assumed the same.

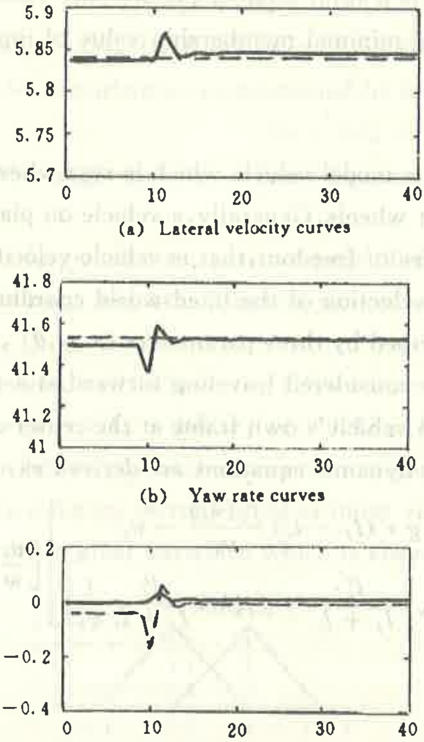
In equation (2.14) the parameter λ_i, $(i = f, r)$ is the slip ratio and $f_i(\lambda_i)$ is a nonlinear function depending on the road-tire condition and μ_{xf} is lateral road-tire friction coefficient. They would change in a large scale with different road-tire conditions and load variation, which are very difficult to be measured. Therefore the dynamics of a vehicle are heavily influenced by them, as well as vehicle speed.

5 Simulation Results

The simulation is done with respect to the prototype vehicle about its dynamic tracking and the property of robustness under the varied road-tire conditions. In the simulation the reference model is selected from the real vehicle dynamic model with the normal parameters when the vehicle velocity is $V = 100\text{m/s}$ as

$$\dot{X}_m = \begin{bmatrix} -7.21 & -11.9 \\ 2 & -0.14 \end{bmatrix} X_m + \begin{bmatrix} 100.06 \\ 0.826 \end{bmatrix} r \tag{2.15}$$

and the sample interval is 0.08s. The responses of the real vehicle dynamic system relative to that of the reference model are shown in simulation curves. Where the dotted lines express the dynamic processes of the reference model and the full lines express those of the vehicle.

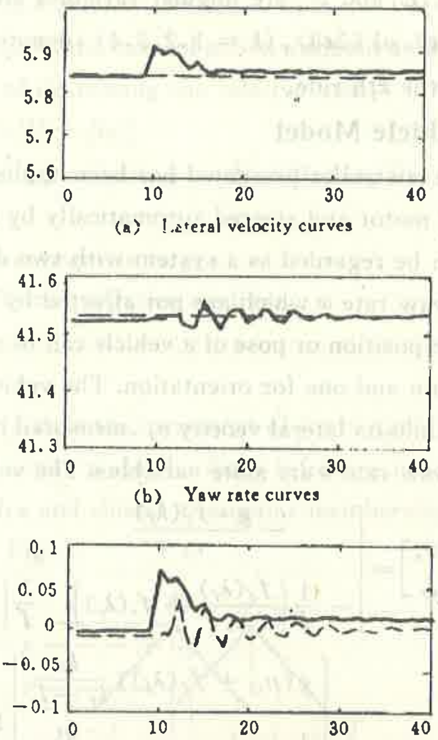


(a) Lateral velocity curves

(b) Yaw rate curves

(c) Error curves

Fig. 2 Responses affected by $f(\lambda)$ increasing



(a) Lateral velocity curves

(b) Yaw rate curves

(c) Error curves

Fig. 3 Responses affected by $f(\lambda)$ decreasing

Fig. 2 and Fig. 3 show the recovering ability of the vehicle system from a disturbance of parameter $f(\lambda)$ changing ± 50 percentage, respectively, where (a) is the lateral velocity, (b) is the yaw rate and (c) is the tracking error of vehicle response process to those of the reference model. From the simulation curves we can see that the system can track the reference model under the change of the system parameters but the stable tracking errors relative to the parameters changed, which is due to the PD fuzzy algorithm.

6 Conclusion

In this paper, the control method based on fuzzy logic and trajectory following for uncertainty systms is discussed. The simulation results on the prototype vehicle steered by front wheels show that with this method the vehicle dynamic control system will have better robust property with the uncertainty overcome in a large scale.

For the sake that this control method wouldn't base on the very accurate model of the controlled plant the control procedure of the vehicle dynamics can be simplified and the adaptability about the environmental factors can be improved.

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基于模糊逻辑控制的汽车动力系统的设计方法

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摘要：本文基于模型参考跟踪理论，提出了一种克服汽车动力系统不确定性的模糊控制方法．横向速度和偏航率控制仿真研究表明，采用此方案的控制结果比较令人满意．

关键词：汽车动力系统；模糊控制；模型跟踪；横向速度控制

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