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Robust Output H_∞ Fuzzy Control for Active Fault Tolerant Vehicle Stability

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Abstract: This paper presents an active Fault Tolerant Control (FTC) strategy for vehicle lateral dynamics. A bicycle vehicle model using small angle approximations is used to represent vehicle behavior. Firstly, the nonlinear lateral vehicle dynamics is approximated by a Takagi-Sugeno fuzzy model with parametric uncertainties and sensor faults. Secondly a robust H_∞ output controller is used. A method based on a bank of observers is used for detection and isolation of sensor faults. The effectiveness of the proposed strategy have been illustrated in simulation.

Keywords: Fault Tolerant Control; Vehicle Dynamics; Takagi-Sugeno fuzzy model; H_∞Robust Control, LMI.

Nomenclature

a_f	Front axle distance from the center of gravity (m)
a_r	Rear axle distance from the center of gravity (m)
C_f	Front lateral cornering stiffness (N/rad)
C_r	Rear lateral cornering stiffness (N/rad)
J	yaw moment of inertia (kg m^2)
μ	road adherence
$\alpha_{f,r}$	Front and rear tyre slip-angles (rad)
δ_f	Road wheel steer angle (rad)
u	longitudinal velocity (m/s)
v	lateral velocity (m/s)
a_y	lateral acceleration (m/s^2)
r	yaw rate about the center of gravity (rad/s)
M_z	yaw moment (Nm^2)

1. INTRODUCTION

Vehicle active control systems aim to enhance handling and comfort characteristics ensuring stability in critical situations. In this context, several systems have been developed these last years (ABS, ASR, TCS, DYC ...) and some of theme have already been commercialized and becoming a standard equipment in many vehicles. However, faults or abnormal operations of any or some of components of such a system can prove extremely costly and in some cases create situations that are dangerous to the safety of passengers. Our objective is to develop an active fault tolerant controller for vehicle lateral dynamics against sensors failures. To do so, a new strategy based on a method of Fault Detection and Isolation (FDI) (Isermann (2001); Ding et al (2005); Blanke et al (2003)) is developed so as to avoid sensor fault effect on vehicle system where faults are assumed to be incipient, abrupt but not generate a total sensor faults. The fault detection scheme uses a bank of observers each utilizing a different output measurement to estimate the vehicle states. The analytical redundancy provided by the bank of observers is then used to construct residuals that have unique signatures in the presence of faults.

Two fuzzy robust H_∞ observer-based controllers developed in (Oudghiri et al (2007a)) have been used, each one utilizes different output sensor to reconstruct vehicle state variables, after the detection and the isolation of sensor fault, a switching block selects the controller which has used the output of the healthy sensor in order to maintain the stability of the vehicle.

The proposed method is based on the uncertain Takagi-Sugeno (T-S) fuzzy representation largely used in control and estimation problems of nonlinear systems these last years (Kim et al (1999); Tanaka and Wang (1998); Korba et al (2003); Chadli and El hajjaji (2006); Chadli et al (2008)). This representation allows to describe the vehicle dynamics in large domain and by the same way to improve the stability of vehicle lateral dynamics.The proposed stability conditions of the closed loop system are given in terms of Linear Matrix inequalities (LMI) (Boyd et al (1994)) and can be solved in a single-step procedure. Based on work given in (Oudghiri et al (2007b)), this paper introduces some improvement by taking account extern disturbance and considering uncertainties on all system matrices.

This paper is organized as follows. Section II briefly describes the used vehicle models in uncertain T-S representation. Section III gives the robust H_∞ fuzzy observer based controller. Section IV presents the Fault Tolerant Control (FTC) scheme used to stabilize the lateral vehicle dynamics. Section V presents the simulation results that validate the proposed algorithm. Conclusions are given in

Section VI.

Notations : The symbol $*$ denotes the transpose elements in the symmetric positions. $P > 0$ means a positive-definite symmetric matrix P.

2. UNCERTAIN TAKAGI-SUGENO FUZZY VEHICLE MODEL

Let us consider the following two freedom degree vehicle lateral dynamics model, it is given in terms of the lateral velocity v and the yaw rate r

$$\begin{pmatrix} \dot{v}(t) \\ \dot{r}(t) \end{pmatrix} = \begin{pmatrix} 2\dfrac{F_{yf}(t)+F_{yr}(t)}{m} - u(t)r(t) \\ 2\dfrac{a_f F_{yf}(t) - a_r F_{yr}(t)}{J} + \dfrac{M_z(t)}{J} \end{pmatrix} \quad (1)$$

where F_{yf} and F_{yr} are front and rear lateral forces respectively, their nonlinear expressions are given in **?**, Bakkern et al (1989). They have been approximated by two fuzzy rules as follows

$$\begin{cases} F_{yf} = \sum_{i=1}^{2} h_i(\alpha_f) C_{fi}(\mu)\alpha_f \\ F_{yr} = \sum_{i=1}^{2} h_i(\alpha_r) C_{ri}(\mu)\alpha_r \end{cases} \quad (2)$$

where $h_i (i = 1, 2)$ are the membership functions, they satisfy the following conditions

$$\begin{cases} \sum_{i=1}^{2} h_i(\alpha_f) = 1, \\ 0 \le h_i(\alpha_f) \le 1, \forall i = 1, 2. \end{cases} \quad (3)$$

α_f and α_r represent tyre slip-angles at the front and rear of the vehicle respectively such that

$$\alpha_f = -\frac{v + a_f r}{u} + \delta_f(t), \qquad \alpha_r = -\frac{v - a_r r}{u}, \quad (4)$$

C_{fi} and C_{ri} represent front and rear lateral tyre stiffnesses, they are difficult to estimate accurately and also exhibits large variations due to the road adhesion μ. To take into these variations, we assume that these coefficients vary as follows

$$\begin{cases} C_{fi} = C_{fi0}(1 + d_i f_i) \\ C_{ri} = C_{ri0}(1 + d_i f_i) \end{cases} \quad (5)$$

with $\|f_i(t)\| \le 1$ where d_i indicates the deviation magnitude of the stiffnesses coefficients from their nominal values C_{fi0} and C_{ri0}. By considering (1, 2, 4, 5), the uncertain T-S fuzzy model of the lateral vehicle dynamics is obtained as

$$\begin{aligned} \dot{x}(t) &= \sum_{i=1}^{2} h_i(\alpha_f)((A_i + \Delta A_i)x(t) + BM_z(t) + B_{fi}\delta_f(t)), \\ z(t) &= \sum_{i=1}^{2} h_i(\alpha_f) C_{1i} x(t), \\ y(t) &= \sum_{i=1}^{2} h_i(\alpha_f)((C_{2i} + \Delta C_i)x(t) + D_i \delta_f(t)) \end{aligned} \quad (6)$$

where $x = [\, v \;\; r \,]^T$, $y = [\, a_y \;\; r \,]^T$, $z = r$

$z(t)$ is the controlled output vector and $y(t)$ is the output vector of the system, ΔA_i and ΔC_i represent parametric uncertainties with appropriate dimensions.

$$A_i = \begin{bmatrix} -2\dfrac{C_{fi}+C_{ri}}{mu} & -2\dfrac{C_{fi}a_f - C_{ri}a_r}{mu} - u \\ -2\dfrac{C_{fi}a_f - C_{ri}a_r}{Ju} & -2\dfrac{C_{fi}a_f^2 + C_{ri}a_r^2}{Ju} \end{bmatrix},$$

$$B_{fi} = \begin{bmatrix} 2\dfrac{C_{fi}}{mu} \\ 2\dfrac{a_f C_{fi}}{J} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \dfrac{1}{J} \end{bmatrix}, D_i = \begin{bmatrix} 2\dfrac{C_{fi}}{m} \\ 0 \end{bmatrix},$$

$$C_{1i} = [\, 0 \;\; 1 \,], C_{2i} = \begin{bmatrix} -2\dfrac{C_{fi}+C_{ri}}{mu} & -2\dfrac{C_{fi}a_f - C_{ri}a_r}{mu} \\ 0 & 1 \end{bmatrix},$$

we assume that the uncertainties can be formulated as follows

$$\Delta A_i = D_{Ai} F_i(t) E_{Ai}, \quad \Delta C_i = D_{Ci} F_i(t) E_{Ci} \quad (7)$$

where $F_i(t), i = 1, 2$ are matrices uncertain parameters such that $F(t)_i^T F(t)_i < I, i = 1, 2$. I is the identity matrix of appropriate dimension. E_{Ai}, E_{Ci}, D_{Ai} and D_{Ci} are known real matrices of appropriate dimensions that characterize the structures of uncertainties.

3. H_∞ FUZZY OBSERVER BASED CONTROLLER DESIGN

In this section, stability conditions formulated in LMI constraints that guarantee the stability of the uncertain T-S fuzzy model (6) with H_∞ disturbance attenuation γ are presented.
The structure of the fuzzy output feedback controller is given as

$$M_z(t) = \sum_{i=1}^{2} h_i(\alpha_f) K_i \hat{x}(t), \quad (8)$$

where $\hat{x}(t) \in \Re^2$ is the estimated state and $K_i \in \Re^{1\times 2} (i = 1, 2)$ are the controller gains to be determined. The proposed fuzzy observers for the uncertain T-S fuzzy system (6) is as follows (9)