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Sensor Fault Tolerant Control Strategy for Autonomous Vehicle Driving

M.R. Boukhari[1], A. Chaibet[1], M. Boukhnifer[1] & S. Glaser[2]
[(1)]Laboratoire Commande et Système, Ecole ESTACA, Paris, France
[(2)]Institut VeDeCoM, Paris, France
{ryad.boukhari, ahmed.chaibet, moussa.boukhnifer}@estaca.fr, sebastien.glaser@vedecom.fr

Abstract— **This paper is dedicated to the sensor fault tolerant control scheme for autonomous vehicle driving. The nonlinear lateral vehicle model is described by the fuzzy Takagi-Sugeno (TS) model. The contributions aspects of this work consist of the development of a descriptor observer to estimate the state system and faults by ensuring robustness against external disturbances. The gains of this observer are obtained by solving the LMI constraints, which are developed using a $\mathcal{L}_2$ gain technique and H∞ criterion. Indeed, the proposed fault tolerant control strategy is justified by its ability to maintain an acceptable performance in the presence of the sensor failure. Simulation results are addressed to demonstrate the capability of this fault tolerant control to counteract the effect of the sensor fault.**

Keywords — descriptor observer, fault tolerant control, LMI, lateral dynamics, sensors faults, Takagi-Sugeno fuzzy system.

I. INTRODUCTION

In the two last decades, a significant attention has been given to the driver assistance and safety systems, increasing considerably the vehicle automation degree. The aims works were focused on the collision warning, collision avoidance and safety improvement during emergency maneuvers and in critical driving conditions.

The aim is to increase the comfort and reduce the accidents and a driver stress, the road safety, by reducing the risks of accidents, the increasing of the efficiency of the vehicles, and adoption of an eco-driving aimed at reducing the CO2 emissions. Thereby, several vehicles, are being equipped with Traction Control System (TCS), anti-lock brake system (ABS), yaw stability system, and one of the variants of the Electronic Stability Program (ESP) [1],[3]. On the automated vehicle concept, the vehicle must be able to achieve a whole of autonomous functions. Among these functions, the heading variation, the lane change maneuver, double lane change and the lane keeping.

However, faults may abruptly change vehicle behavior. Indeed, to ensure the reliability of the measurements, the purpose is to propose controlling schemes which must be robust against faults, disturbances and uncertainties during the design phase. This control approach is based on robust control tools to ensure the insensitivity of the closed loop system to the occurring faults assumed to be unknown.

The fault tolerance is achieved by maintaining acceptable performance and stability properties with changing the structure of the controller, with requiring reconfiguration and with the information relating to the various failures[2][8].

The problem of fault- tolerant control, for the bicycle model of the vehicle lateral dynamics, was addressed by several research works involving various methods. In [2], a fuzzy Takagi-Sugeno representation of the bicycle model was adopted, coping with parametric uncertainties, this TS model was used to design an output feedback based-observer controller, exploiting a method based on an observer bank for detection, isolation and accommodation of sensor faults. In [3], an active fault tolerant tracking controller scheme dedicated to vehicle lateral dynamics was proposed, aimed to estimate both the state of the vehicle, and the additional sensor faults. Furthermore, the lateral control system must have fault tolerant ability such that the system maintains stability and acceptable performance even if failures occurs [9]. In this way, perfect fault estimation and feedback fault attenuation are essential. In [10], a multi-objectives H-/H∞ fault detection observer permitted the detection of senor faults with effectiveness sensibility of these faults, and with robustness against external perturbations. In [11], a descriptor observer is used to estimate the sensor faults, and a feedback controller is synthetized by the combination of two controllers, the first one is the nominal case, and the second one is used in the faulty case to attenuate the sensor faults.

In the present paper, a descriptor observer to estimate the sensor faults of lateral vehicle dynamics represented by a fuzzy Takagi-Sugeno (TS) is developed, in order to eliminate these failures using an active fault tolerant control strategy.

The aim is to design a control scheme that's is capable to control the vehicle with satisfactory performance even if one or several faults happen and is able of maintaining overall vehicle stability driving. This paper is structured as follows: section II deals with the vehicle lateral dynamics, which is described by the fuzzy Takagi-Sugeno modeling. Section III focuses on the

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fault tolerant control strategy adopted, illustrating in that fact the descriptor observer methodology. Section IV presents the simulation results and shows the effectiveness of the designed strategy and confirms the detection of failures when it occurs and the global stability of the vehicle. Conclusion and perspectives of this work are presented in Section V.

II. MODEL OF LATERAL DYNAMICS

This section allows to introduce the model of the vehicle used for control synthesis. The bicycle model is widely used in literature [2, 3]. Let us consider a bicycle model of the vehicle as shown in Fig.1. In the bicycle model, the front right and left wheels are represented by one single wheel in A. Similarly the rear wheels are represented by one single wheel in B.

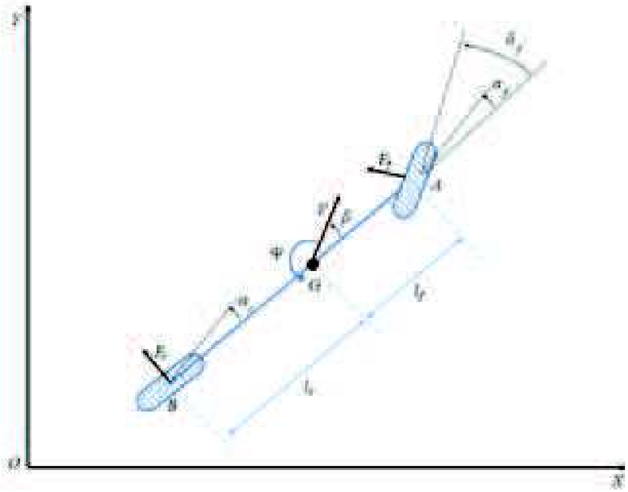


Fig.1. The simplified “bicycle model” of the vehicle lateral dynamics.

The slip angles of the front and rear tires are represented by α_f and α_r respectively. δ_f represents the front steering angle. l_f, l_r are distance from front/rear axle to center of gravity respectively, and F_f and F_r are the total front/rear tire lateral force, respectively. $\dot{\psi}$ represents the yaw rate of the vehicle, and β is the vehicle sideslip angle. The road is supposed plane with no gradient, no superelevation, and assuming that the longitudinal speed is constant, only the lateral and yaw motion of the vehicle are allowed.

Under the above assumptions, the vehicle motion can be described by two degrees of freedom (2DOF), here the first one characterizes the vehicle sideslip angle and the second one represents the yaw dynamic:

$$\begin{cases} \dot{\beta} = 2\frac{F_f}{mV} + 2\frac{F_r}{mV} - \dot{\psi} \\ \ddot{\psi} = 2\frac{l_f F_f}{J} - 2\frac{l_r F_r}{J} \end{cases} \quad (1)$$

Where m and J are the mass and the mass moment of inertia respectively.

In order to make the design and the analysis of the control of a vehicle to follow a desired path, we have to express the lateral deviation and the heading error.

For this purpose, the lateral deviation y_L and the heading error ψ_L(the angle between the tangent to the road and the vehicle orientation) are given by the vision system and can be defined as follows:

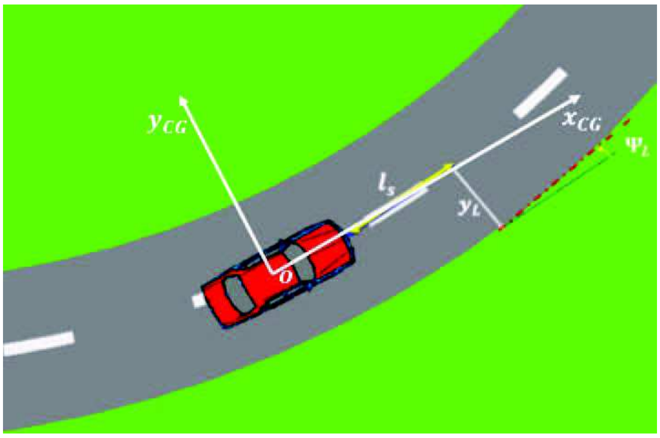


Fig.2. Bicycle model of vehicle control.

From [12, 13] the derivatives of these two quantities are given by:

$$\dot{\psi}_L = \dot{\psi} - V\rho_{ref} \quad (2)$$

$$\dot{y}_L = V\beta + l_s\dot{\psi} + V\psi_L - l_s V\rho_{ref} \quad (3)$$

Where l_s denotes the look-ahead distance, and ρ_{ref} represents the road curvature. Furthermore, we consider a wind gust as an external disturbance applied at distance l_w from the center of gravity.

We can combine the vehicle lateral dynamics and vision dynamics equations (1-3):

$$\begin{cases} \dot{\beta} = 2\frac{F_f}{mV} + 2\frac{F_r}{mV} - \dot{\psi} + \frac{F_v}{mV} \\ \ddot{\psi} = 2\frac{l_f F_f}{J} - 2\frac{l_r F_r}{J} + \frac{l_w F_v}{J} \\ \dot{\psi}_L = \dot{\psi} - V\rho_{ref} \\ \dot{y}_L = V\beta + l_s\dot{\psi} + V\psi_L - l_s V\rho_{ref} \end{cases} \quad (4)$$

The model (4) is nonlinear due to the fact of nonlinearities of both lateral forces F_f and F_r. In fact, in this paper, the nonlinear characteristic of the lateral tire force is described by Pacejka magic formula [14], which allows us to write the decoupled front and rear forces as follows:

$$F_f = D_i sin\left(C_i arctg\left(B_i\alpha_f - E_i\left(B_i\alpha_f - arctg(B_i\alpha_f)\right)\right)\right) \quad (5)$$

$$F_r = D_i sin\left(C_i arctg\left(B_i\alpha_r - E_i\left(B_i\alpha_r - arctg(B_i\alpha_r)\right)\right)\right) \quad (6)$$

With:

$$\alpha_f = \delta_f - \beta - \frac{l_f\dot{\psi}}{V}, \alpha_r = \frac{l_r\dot{\psi}}{V} - \beta \quad (7)$$

Where α_f and α_r are tire slip angle of the front and rear tires respectively (see Fig.1.). D_i, C_i, B_i, and E_i are parameters depending on characteristic of the tire. Indeed the nonlinear characteristic of the lateral forces can be described by Fuzzy Takagi-Sugeno (TS) model.

A. TS model for the Pacjeka forces

The TS model can approximate the nonlinear behavior of the Pacjeka forces by a sum of linear sub-models, the number of these sub-models is determinate as follows [15]:

$$r = 2^{nl} \tag{8}$$

r is an integer corresponds to the number of sub-models, and nl represents of nonlinearities in the model , in our case, the nonlinearity is due the Pacjeka lateral force, $nl = 1$, we obtain $r = 2$, that allows us to write the TS lateral forces as follows:

$$\begin{cases} F_f = h_1(|\alpha_f|)c_{yf1}\alpha_f + h_2(|\alpha_f|)c_{yf2}\alpha_f \\ F_r = h_1(|\alpha_f|)c_{yr1}\alpha_r + h_2(|\alpha_f|)c_{yr2}\alpha_r \end{cases} \tag{9}$$

Where c_{yfi}, c_{yri} are the front and rear stiffness coefficients respectively, $h_i(|\alpha_f|)$ are the weighting functions depending on the vector of the unmeasurable scheduling variable $|\alpha_f|$. These nonlinear functions must satisfy the following property:

$$\begin{cases} 0 \le h_i(|\alpha_f|) \le 1 \\ \sum_{i=1}^{2} h_i(|\alpha_f|) = 1 \end{cases} \tag{10}$$

With: $h_i(|\alpha_f|) = \frac{\xi_i(|\alpha_f|)}{\sum_{i=1}^{2} \xi_i(|\alpha_f|)}$ (11)

Several memberships functions are founded in the literature, in our case we choose the following one [2]:

$$\xi_i(|\alpha_f|) = \frac{1}{\left[1+\left|\frac{|\alpha_f|-c_i}{a_i}\right|\right]^{2b_i}} \tag{12}$$

This technique is based on parametric identification, in fact the membership parameters (a_i, b_i, and c_i), and the stiffness coefficients values are identified by least square method using a Levemberg-Marquadt algorithm. These values are obtained in [2], are:

$a_1 = 0.5077$, $a_2 = 0.4748$, $b_1 = 3.1893$, $b_2 = 5.3907$, $c_1 = -0.4356$, $c_2 = 0.5622$, $c_{yf1} = 60712.7$, $c_{yf2} = 4814$, $c_{yr1} = 60088$, $c_{yr2} = 3425$.

B. TS for vehicle model

By substituting TS forces (9) in the model given in equation (4) and taking into account equations (7), we can rewrite this model as TS approximation:

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\psi} \\ \dot{\psi}_L \\ \dot{y}_L \end{bmatrix} = \sum_{i=1}^{2} h_i(|\alpha_f|) \left[\begin{bmatrix} -2\frac{c_{yfi}+c_{yri}}{mV} & -1+2\frac{l_2c_{yri}-l_1c_{yfi}}{mV^2} & 0 & 0 \\ 2\frac{l_2c_{yri}-l_1c_{yfi}}{J} & 2\frac{{l_2}^2c_{yri}-{l_1}^2c_{yfi}}{J} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ V & l_s & V & 0 \end{bmatrix} \begin{bmatrix} \beta \\ \dot{\psi} \\ \psi_L \\ y_L \end{bmatrix} + \begin{bmatrix} 2\frac{c_{yfi}}{mV} & \frac{1}{mV} & 0 \\ 2\frac{l_1c_{yfi}}{J} & \frac{l_w}{J} & 0 \\ 0 & 0 & -V \\ 0 & 0 & -l_sV \end{bmatrix} \begin{bmatrix} \delta_f \\ F_v \\ \rho_{ref} \end{bmatrix} \right] \tag{13}$$

III. FTC STRATEGY DESIGN

The sensor fault is considered as an additive signal. This additive signal may mislead the controller, which deliver wrong signal control. The main purpose of this work is to estimate the fault in order to compensate its effect. The strategy adopted is shown in Fig.3.

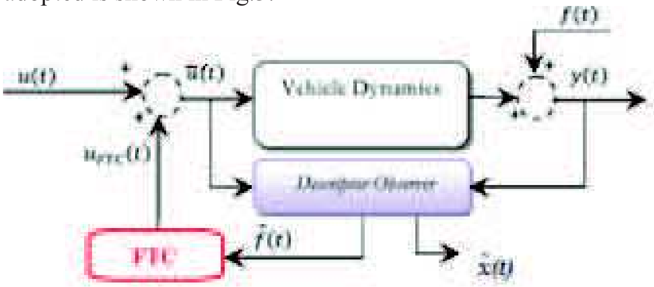


Fig.3. Fault tolerant control strategy

This technique is based on a descriptor observer which considers the sensor faults as state variables of the vehicle model. Thereby, a transition to a descriptor system is essential this leads to consider an augmented system.

Given the following TS system subject to disturbances and sensor faults:

$$\begin{cases} \dot{x} = \sum_{i=1}^{2} h_i(|\alpha_f|)(A_i x + B_i \bar{u} + B_d d) \\ y = Cx + Ff \end{cases} \tag{14}$$

Where $x(t)$, $y(t)$, $\bar{u}(t)$, $d(t)$, and $f(t)$ represent, respectively, the state vector, the faulty vector, the disturbances vector, and the faults vector. The matrices A_i, B_i, B_d, C, and F have the appropriate dimension, they represent respectively, the state matrix, the input matrix, the matrix of disturbances distribution, the measure matrix, and the matrix of faults distribution.

We can write the following augmented system as:

$$\begin{cases} E\dot{x} = \sum_{i=1}^{2} h_i(|\alpha_f|)(\bar{A}_i\bar{x} + \bar{B}_i\bar{u} + \overline{B_d}d + \bar{F}\bar{f}) \\ y = \bar{C}\bar{x} = C_0\bar{x} + \bar{f} \end{cases} \tag{15}$$

Where:

$$\bar{x} = \begin{bmatrix} x \\ \bar{f} \end{bmatrix}, E = \begin{bmatrix} I_n & 0 \\ 0 & 0 \end{bmatrix}, \bar{A}_i = \begin{bmatrix} A_i & 0 \\ 0 & -I_p \end{bmatrix}, \bar{B}_i = \begin{bmatrix} B_i \\ 0 \end{bmatrix}, \overline{B_d} = \begin{bmatrix} B_d \\ 0 \end{bmatrix}$$

$$\bar{F} = \begin{bmatrix} 0 \\ I_p \end{bmatrix}, \bar{C} = [C \quad I_p], C_0 = [C \quad 0], \bar{f} = Ff.$$

To compensate the sensor fault we consider the following FTC scheme as depicted in Fig.3:

$$\bar{u} = u + u_{FTC} \tag{16}$$

u is the nominal control input, it is designed with a PID controller. For the lateral control, the control purpose is thus to minimize a mixed criteria between lateral deviation and heading error. This criterion is $\varepsilon = y_L + \sigma\psi_L$. The weighting factor σ allows to favor one component against the other. This controller is finally:

$$u = K_p\varepsilon + K_i\int\varepsilon + K_d\dot{\varepsilon} \tag{17}$$

u_{FTC} leads to compensate the effect of the sensor failure it is given by:

$$u_{FTC} = K_p\hat{f} + K_i \int \hat{f} + K_d\dot{\hat{f}} \quad (18)$$

Where:

$$\hat{f}(t) = -(F^TF)^{-1}F^T\hat{\bar{f}}(t) \quad (19)$$

In order to implement the considering FTC law, we consider the following descriptor observer:

$$\begin{cases} \bar{E}\dot{z} = \sum_{j=1}^{2} h_j(|\alpha_f|)(S_j z + \bar{B}_j\bar{u}) \\ \hat{\bar{x}} = z + Ly \end{cases} \quad (20)$$

Where $\bar{E}$, S_j, and L are the observer gains to be determined in order to estimate both the state $x(t)$ and the sensor faults $f(t)$. $z(t)$ is an auxiliary state vector of the observer and $\hat{\bar{x}}(t)$ is the vector of the estimates of the state vector $\bar{x}(t)$. $\bar{B}_j$ is the augmented command matrix, it's given by $\bar{B}_j = [B_j \quad 0]^T$.

The problem is now summarized to find the observer gains $\bar{E}, S_j$, and L ensuring the perfect estimation in presence of external disturbances. To cope with that we consider a residual signal $r(t)$, and state error dynamic $e(t)$ as follows [10]:

$$\begin{cases} r(t) = W(y(t) - \hat{y}(t)) \\ e(t) = \bar{x}(t) - \hat{\bar{x}}(t) \end{cases} \quad (21)$$

Where W is a weighting matrix.

Definition 1

Considering TS model of equation (14), and scalar $\gamma > 0$, the observer (20) is called H∞ sensor fault detection observer, if (20) is asymptotically stable, and the following inequality is satisfied:

$$\int_0^\infty r^T(t)r(t)dt \le \gamma^2 \int_0^\infty d^T(t)d(t)dt \quad (22)$$

To determine the state error dynamics, we rewrite (15) as follows:

$$E\dot{\bar{x}} = \sum_{i=1}^{2}\sum_{i=1}^{2} h_i(|\alpha_f|)\, h_j(|\alpha_f|)(\bar{A}_i + \bar{A}_j - \bar{A}_j)\bar{x} + (\bar{B}_i + \bar{B}_j - \bar{B}_j)\bar{u} + \bar{F}\bar{f} + \overline{B_d}d \quad (23)$$

From (20) we can write $z = \hat{\bar{x}} - L\bar{C}\bar{x}$, substituting z in (22) we find:

$$\bar{E}\dot{\hat{\bar{x}}} - \bar{E}LC\dot{\bar{x}} = \sum_{j=1}^{2} h_j(|\alpha_f|)(S_j\hat{\bar{x}} - S_jL\bar{C}\bar{x} + \bar{B}_j\bar{u}) \quad (24)$$

Subtract (23) from (24), we obtain:

$$E\dot{\bar{x}} - \bar{E}\dot{\hat{\bar{x}}} + \bar{E}LC\dot{\bar{x}} = \sum_{i=1}^{2}\sum_{i=1}^{2} h_i(|\alpha_f|)\, h_j(|\alpha_f|)(\bar{A}_i + \bar{A}_j - \bar{A}_j)\bar{x} + (\bar{B}_i + \bar{B}_j - \bar{B}_j)\bar{u} + \bar{F}_f\bar{f} + \overline{B_d}\bar{d} - S_j\hat{\bar{x}} + S_jLC_0\bar{x} + S_jL\bar{f} - \bar{B}_j\bar{u} \quad (25)$$

Equivalent to:

$$(E + \bar{E}LC)\dot{\bar{x}} - \bar{E}\dot{\hat{\bar{x}}} = \sum_{i=1}^{2}\sum_{i=1}^{2} h_i(|\alpha_f|)h_j(|\alpha_f|)(\bar{A}_j + S_jLC_0)\,\bar{x} - S_j\hat{\bar{x}} + (\bar{A}_i - \bar{A}_j)\bar{x} + (\bar{B}_i - \bar{B}_j)\bar{u} + (\bar{F}_f + S_jL)\bar{f} + \overline{B_d}\bar{d} \quad (26)$$

Let us consider the following matrices:

$$S_j = \begin{bmatrix} A_j & 0 \\ -C & -I \end{bmatrix}, L = \begin{bmatrix} 0 \\ I \end{bmatrix}, \bar{E} = \begin{bmatrix} I + \Theta C & \Theta \\ RC & R \end{bmatrix} \quad (27)$$

Where Θ and R are chosen as non-singular, we note also that:

$$\bar{E} = E + \bar{E}LC, S_j = \bar{A}_j + S_jLC_0, S_jL = -\bar{F}_f \quad (28)$$

And:

$$(\bar{A}_i - \bar{A}_j)\bar{x} = \begin{bmatrix} A_i - A_j \\ 0 \end{bmatrix} x, (\bar{B}_i - \bar{B}_j)\bar{u} = \begin{bmatrix} B_i - B_j \\ 0 \end{bmatrix} u \quad (29)$$

Taking into account (21), (28), and (29), (26) is rewritten as follows:

$$\dot{e} = \sum_{i=1}^{2}\sum_{i=1}^{2} h_i(|\alpha_f|)h_j(|\alpha_f|)\,[\widetilde{S_j}e + \widetilde{A_{ij}}x + \widetilde{B_{ij}}u + \widetilde{B_d}d] \quad (30)$$

Where:

$$\bar{E}^{-1} = \begin{bmatrix} I_n & -\Theta R^{-1} \\ -C & R^{-1} + C\Theta R^{-1} \end{bmatrix} \quad (31\text{-a})$$

$$\widetilde{S_j} = \bar{E}^{-1}S_j = \begin{bmatrix} A_j + \Theta R^{-1}C & \Theta R^{-1} \\ -CA_j - (R^{-1} + C\Theta R^{-1})C & -R^{-1} - C\Theta R^{-1} \end{bmatrix} \quad (31\text{-b})$$

$$\widetilde{A_{ij}} = \bar{E}^{-1}\begin{bmatrix} A_i - A_j \\ 0 \end{bmatrix} = \begin{bmatrix} A_i - A_j \\ -C(A_i - A_j) \end{bmatrix} \quad (31\text{-c})$$

$$\widetilde{B_{ij}} = \bar{E}^{-1}\begin{bmatrix} B_i - B_j \\ 0 \end{bmatrix} = \begin{bmatrix} B_i - B_j \\ -C(B_i - B_j) \end{bmatrix} \quad (31\text{-d})$$

$$\widetilde{B_d} = \bar{E}^{-1}\bar{B}_d = \begin{bmatrix} B_d \\ -CB_d \end{bmatrix} \quad (31\text{-e})$$

The state space representation of the closed-loop dynamics describing the vehicle dynamics (14) and its error of state (31), allows us to create an augmented system as follows:

$$\begin{bmatrix} \dot{e} \\ \dot{x} \end{bmatrix} = \sum_{i=1}^{2}\sum_{i=1}^{2} h_i(|\alpha_f|)h_j(|\alpha_f|)\left\{\begin{bmatrix} \widetilde{S_j} & \widetilde{A_{ij}} \\ 0 & A_i \end{bmatrix}\begin{bmatrix} e \\ x \end{bmatrix} + \begin{bmatrix} \widetilde{B_{ij}} & \widetilde{B_d} \\ B_i & B_d \end{bmatrix}\begin{bmatrix} u \\ d \end{bmatrix}\right\} \quad (32)$$

To ensure a robustness to the state estimation, we consider definition 1, in order to bound the transfer from the residual signal to the disturbances signal, and we also consider an "$\mathcal{L}_2$-gains" criterion to bound the transfer from the command signal to the state error dynamics. The considered criterion is chosen as follows:

$$\dot{V}(e(t), x(t)) + e^T(t)e(t) + r^T(t)r(t) - \lambda^2u^T(t)u(t) - \gamma^2d^T(t)d(t) < 0 \quad (33)$$

The Criterion (33) ensures the stability of the closed-loop system (32), if the LMI constraint summarize in the following theorem hold.

Theorem 1:

Consider the system (14) with observer (20). The system (32) is asymptotically stable satisfying (22), and minimizing the $\mathcal{L}_2$ gain $\lambda > 0$ if there exist some symmetric positive definite matrices P_{11}, P_{12}, P_2, matrices N_1, N_2, matrix W and positive scalar γ such that the following LMI are satisfied:

$$\mathfrak{M}_{ij} \leq 0, \text{ for } i, j = 1, \ldots, r \tag{34}$$

Where $\mathfrak{M}_{ij}$ is defined by:

$$\mathfrak{M}_{ij} = \begin{bmatrix} \Delta_{1j} & * & * & * & * & * \\ \Delta_{2j} & -\mathcal{H}(N_2) & * & * & * & * \\ \widetilde{A_{ij}}^T P_{11} & -\widetilde{A_{ij}}^T C^T P_{12} & \mathcal{H}(P_2 A_i) & * & * & * \\ \Omega_{ij} & -\widetilde{B_{ij}}^T C^T P_{12} & B_i^T P_2 & -\lambda^2 I & * & * \\ B_d^T P_{11} & -B_d^T C^T P_{12} & B_d^T P_2 & 0 & -\gamma^2 I & * \\ WC & 0 & 0 & 0 & 0 & -I \end{bmatrix}$$

With:

$$\begin{cases} \Delta_{1j} = \mathcal{H}(P_{11} A_j) + \mathcal{H}(N_1 C) + I \\ \Delta_{2j} = N_1^T - P_{12}^T C A_j - N_2 C \end{cases}$$

$$\begin{cases} N_1 = P_{11} \Theta R^{-1} \\ N_2 = P_{12}(R^{-1} + C \Theta R^{-1}) \end{cases}$$

$$\begin{cases} \widetilde{A_{ij}}^T = A_i^T - A_j^T, \ \widetilde{B_{ij}}^T = B_i^T - B_j^T \\ \Omega_{ij} = (B_i^T - B_j^T) P_{11} \end{cases}$$

Proof. The proof is shown in ***Appendix A***.

IV. SIMULATION RESULTS

This section is dedicated to simulation tests performed with Matlab/Simulink in order to demonstrate the effectiveness and the applicability of the developed strategy in this work.

Firstly, the LMI elaborated in section III are solved using "penlab solver" of Matlab, and adopting the Schur complement, the gains are obtained for a nominal attenuation level $\lambda = 4.23$ as follows:

$$L = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T$$

$$S_2 = \begin{bmatrix} -153.7 & 60.1414 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.9903 & -154.7 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 20 & 5 & 20 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & -1 \end{bmatrix}$$

$$S_1 = 10^3 \begin{bmatrix} -2.255 & 9.9936 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.0174 & -2.4098 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.02 & 0.005 & 0.02 & 0 & 0 & 0 & 0 & 0 \\ -0.001 & 0 & 0 & 0 & -0.001 & 0 & 0 & 0 \\ 0 & -0.001 & 0 & 0 & 0 & -0.001 & 0 & 0 \\ 0 & 0 & -0.001 & 0 & 0 & 0 & -0.001 & 0 \\ 0 & 0 & 0 & -0.001 & 0 & 0 & 0 & -0.001 \end{bmatrix}$$

$$R = 10^4 \begin{bmatrix} -0.5688 & -1.2056 & -1.2493 & -1.2458 \\ -2.9458 & -0.1785 & -0.7605 & -0.8222 \\ -0.6254 & 0.1348 & 0.5370 & 0.4641 \\ -0.9255 & -0.0196 & 0.2996 & 0.3731 \end{bmatrix}$$

$$\Theta = \begin{bmatrix} -0.0796 & -0.0161 & 0.0115 & 0.0119 \\ -0.0752 & -0.0057 & -0.0143 & -0.0155 \\ -0.0213 & -0.0461 & -0.0555 & -0.0574 \\ -0.0456 & -0.0570 & -0.0664 & -0.0642 \end{bmatrix}$$

$$\bar{E} = 10^4 \begin{bmatrix} 0.0001 & -0.0000 & 0.0000 & 0.0000 & -0.0000 & -0.0000 & 0.0000 & 0.0000 \\ -0.0000 & 0.0001 & -0.0000 & -0.0000 & -0.0000 & -0.0000 & -0.0000 & -0.0000 \\ -0.0000 & -0.0000 & 0.0001 & -0.0000 & -0.0000 & -0.0000 & -0.0000 & -0.0000 \\ -0.0000 & -0.0000 & -0.0000 & 0.0001 & -0.0000 & -0.0000 & -0.0000 & -0.0000 \\ -0.5688 & -1.2056 & -1.2493 & -1.2458 & -0.5688 & -1.2056 & -1.2493 & -1.2458 \\ -2.9458 & -0.1785 & -0.7605 & -0.8222 & -2.9458 & -0.1785 & -0.7605 & -0.8222 \\ -0.6254 & 0.1348 & 0.5370 & 0.4641 & -0.6254 & 0.1348 & 0.5370 & 0.4641 \\ -0.9255 & -0.0196 & 0.2996 & 0.3731 & -0.9255 & -0.0196 & 0.2996 & 0.3731 \end{bmatrix}$$

In this section, several simulations have been carried in order to show the effectiveness of the proposed algorithm for a vehicle path planning problem. Our emphasis within the development of a descriptor observer to estimate the state system and faults where a high robustness is maintained when the faults are occurred, then after, a fault tolerant control law is designed to counteract these faults. These faults affect the yaw rate sensor.

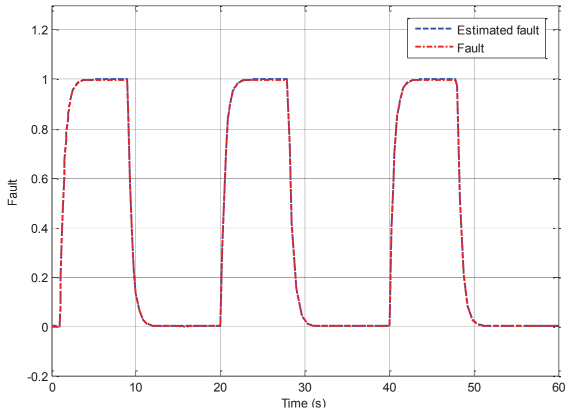
The considered additive sensor faults signals affecting the system behavior are described as follows:

$$f_{\dot{\psi}_L}(t) = \left(1 - e^{-\frac{(t-0.5)}{0.5}}\right) \qquad 0 < t < 60s \tag{35}$$

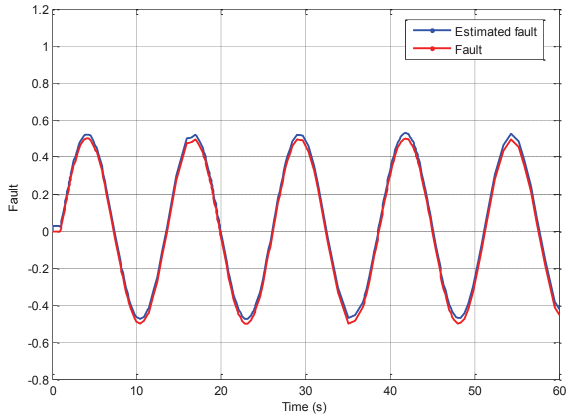
$$f_{y_L}(t) = 0.5 \sin(2\pi t) \qquad 0 < t < 60s \tag{36}$$

TABLE I
SIMULATION VEHICLE PARAMETERS

Symbol	Parameter	Values
m	Vehicle mass	1500 Kg
V	Longitudinal speed	20 ms^{-1}
J	Inertia moment	2208 $Kg\ m^2$
l_f	Distance from front axle to centre of gravity	1.0065 m
l_r	Distance from rear axle to centre of gravity	1.4625 m
l_s	Look-ahead distance	5 m
l_w	Distance between center of gravity and application of the wind	0.4 m

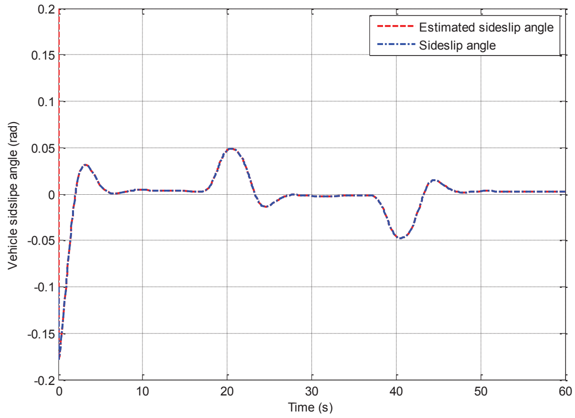


(a) : Heading angle fault

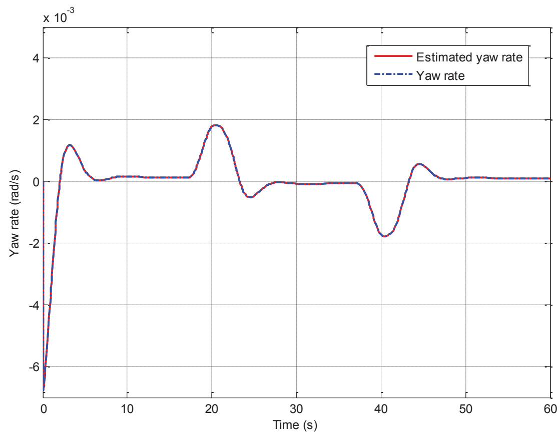


(b) : Lateral deviation fault

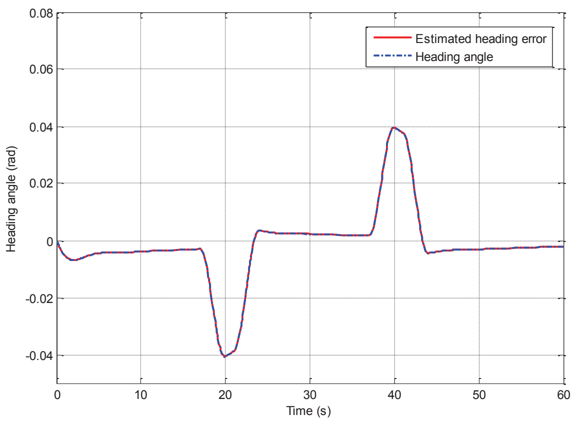
Fig.4. Faults and their estimations



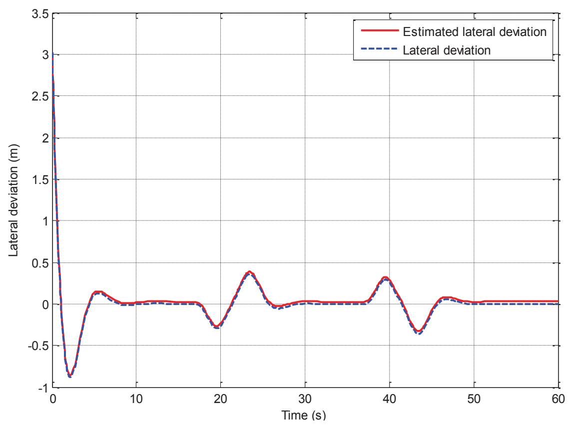
(a) : Sideslip angle



(b) : Yaw rate



(c) : Heading angle



(d) : Lateral deviation

Fig.5. Comparison between vehicle states and their estimations

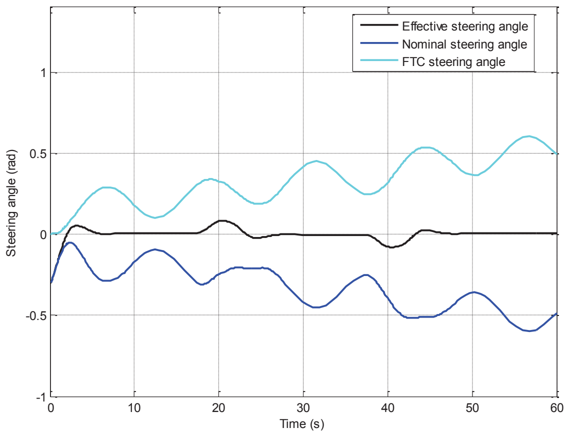


Fig.6. Nominal and FTC control inputs.

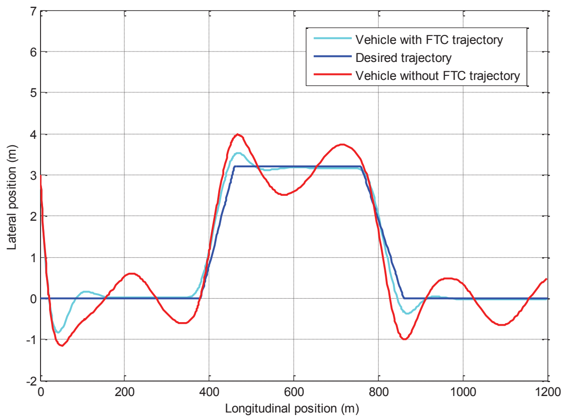


Fig.7. Profile of double lane change vehicle manoeuver comparison with/without FTC

In order to show in a realistic manner the effectiveness of the proposed control approach, simulations of different maneuvers are performed under various kinds of faults.

As we know that the heading angle and the lateral deviation of the vehicle are measured by gyroscopic sensor and vision system respectively, the purpose is to add a sensor fault (see equations 35-36).

This manoeuver is summarized as follow: initially the vehicle is located on the left lane and evolves with a speed of 20 m/s. The vehicle initiates an operation of lane change maneuver to reach the desired adjacent lane. Then afterwards, the vehicle performs the double lane change under fault sensors. The objective here is to highlight the performances of the FTC control. Figure 7, shows the profile of vehicle in (x;y) plane with FTC and nominal control in a faulty cases . The figures 4(a-d) represented the real states and their estimated. In these different figures one can noticed:

-The estimated states converge quickly toward the real states

-The performances obtained are good as well in dynamics as in statics

-The observation errors are steered to zero in finite time.

Figure 6 shows the nominal and the FTC steering angles, the second one compensate the fault effect, the effective steering angle is a result of the sum of the nominal and FTC steering angles.

V. Conclusion

The problem of vehicle fault control using a descriptor observer to estimate the state system and faults is investigated. The proposed control scheme is composed by a nominal control, which is designed in nominal case, a fault control input designed in faulty condition with a descriptor observer structure scheme. The proposed fault tolerant control strategy based on H∞ descriptor observer is designed to maintain vehicle stability and ensure handling in the presence of sensor faults. The simulations results confirm the ability of the developed FTC strategy to ensure and maintain an appreciable performances and robustness against the sensor fault.

Future work an experimental tests on vehicle prototype will be implemented to validate the proposed control technique.

Appendix A.

To ensure the stability of the augmented system (32), we consider the following candidate quadratic Lyapunov function $V(e(t),x(t))$:

$$V(e(t),x(t)) = \begin{bmatrix} e \\ x \end{bmatrix}^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} e \\ x \end{bmatrix} \tag{37}$$

Where P_1, and P_2 are symmetric positive definite matrices. The goal is to optimize the gains $\bar{E}$, S_j, and L, using the criterion (33), for that propose we derive equation (37), then we obtain:

$$\dot{V}(e(t),x(t)) = \begin{bmatrix} \dot{e} \\ \dot{x} \end{bmatrix}^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} e \\ x \end{bmatrix} + \begin{bmatrix} e \\ x \end{bmatrix}^T \begin{bmatrix} P_1 & 0 \\ 0 & P_2 \end{bmatrix} \begin{bmatrix} \dot{e} \\ \dot{x} \end{bmatrix} \tag{38}$$

Substituting (38) in (33), and taking into account equation (32), we get after development:

$$\begin{bmatrix} e(t) \\ x(t) \\ u(t) \\ d(t) \end{bmatrix}^T \begin{bmatrix} \Pi_j & * & * & * \\ \widetilde{A_{ij}}^T P_1 & \mathcal{H}(P_2 A_i) & * & * \\ \widetilde{B_{ij}}^T P_1 & B_i^T P_2 & -\lambda^2 I & * \\ \widetilde{B_d}^T P_1 & B_d^T P_2 & 0 & -\gamma^2 I \end{bmatrix} \begin{bmatrix} e(t) \\ x(t) \\ u(t) \\ d(t) \end{bmatrix} < 0 \tag{39}$$

Where:

$$\Pi_j = \mathcal{H}(P_1 \widetilde{S_j}) + C_0^T V^T V C_0 + I.$$

Using the Schur complement to inequality (39), we obtain:

$$\begin{bmatrix} \mathcal{H}(P_1 \widetilde{S_j}) + I & * & * & * & * \\ \widetilde{A_{ij}}^T P_1 & \mathcal{H}(P_2 A_i) & * & * & * \\ \widetilde{B_{ij}}^T P_1 & B_i^T P_2 & -\lambda^2 I & * & * \\ \widetilde{B_d}^T P_1 & B_d^T P_2 & 0 & -\gamma^2 I & * \\ W C_0 & 0 & 0 & 0 & -I \end{bmatrix} < 0 \tag{40}$$

We consider now that $P_1 = diag[P_{11} \quad P_{12}]$, and also the equations (31-b) (31-e), we get:

$$\begin{bmatrix} \Sigma_j^{11} & * & * & * & * & * \\ \Sigma_j^{21} & \Sigma_j^{22} & * & * & * & * \\ \widetilde{A_{ij}}^T P_{11} & -\widetilde{A_{ij}}^T C^T P_{12} & \Sigma_j^{33} & * & * & * \\ \Omega_{ij} & -\widetilde{B_{ij}}^T C^T P_{12} & B_i^T P_2 & -\lambda^2 I & * & * \\ B_d^T P_{11} & -B_d^T C^T P_{12} & B_d^T P_2 & 0 & -\gamma^2 I & * \\ WC & 0 & 0 & 0 & 0 & -I \end{bmatrix} < 0 \qquad (41)$$

Where:

$$\begin{cases} \Sigma_j^{11} = \mathcal{H}(P_{11}A_j) + \mathcal{H}(P_{11}\Theta R^{-1}C) + I \\ \Sigma_j^{21} = (\Theta R^{-1})^T P_{11} - P_{12}^T C A_j - P_{12}(R^{-1} + C\Theta R^{-1})C \\ \Sigma_j^{22} = -\mathcal{H}\left(P_{12}(R^{-1} + C\Theta R^{-1})\right) \\ \Sigma_j^{33} = \mathcal{H}(P_2 A_i) \\ \Omega_{ij} = \left(B_i^T - B_j^T\right) P_{11} \\ \widetilde{A_{ij}}^T = A_i^T - A_j^T \ , \ \widetilde{B_{ij}}^T = B_i^T - B_j^T \end{cases}$$

Due to nonlinearities caused by combination of definite positives variables, we consider the following:

$$\begin{cases} N_1 = P_{11}\Theta R^{-1} \\ N_2 = P_{12}(R^{-1} + C\Theta R^{-1}) \end{cases} \qquad (42)$$

Substituting (42) in (41), we obtain:

$$\begin{bmatrix} \Delta_{1j} & * & * & * & * & * \\ \Delta_{2j} & -\mathcal{H}(N_2) & * & * & * & * \\ \widetilde{A_{ij}}^T P_{11} & -\widetilde{A_{ij}}^T C^T P_{12} & \mathcal{H}(P_2 A_i) & * & * & * \\ \Omega_{ij} & -\widetilde{B_{ij}}^T C^T P_{12} & B_i^T P_2 & -\lambda^2 I & * & * \\ B_d^T P_{11} & -B_d^T C^T P_{12} & B_d^T P_2 & 0 & -\gamma^2 I & * \\ WC & 0 & 0 & 0 & 0 & -I \end{bmatrix} < 0 \qquad (43)$$

Where $\Delta_{1j} = \mathcal{H}(P_{11}A_j) + \mathcal{H}(N_1 C) + I$, and $\Delta_{2j} = N_1^T - P_{12}^T C A_j - N_2 C$.

Finally, equation (43) is satisfied if conditions of Theorem 1 hold.

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