Fuzzy Fault Tolerant Control Based Takagi-Sugeno Observer for Automotive Electronic Throttle Valve

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Abstract: In this paper, a novel Fuzzy Fault Tolerant Control (FFTC) approach for an Electronic Throttle Valve (ETV), based on Takagi-Sugeno (T-S) fuzzy models, is proposed in order to regulate the throttle valve opening angle position. Indeed, automotive ETV systems have several benefits in terms of enhancing fuel economy and thus reducing carbon dioxide emissions. However, an ETV control system would face challenges in the context of control performance as it features various non-smooth nonlinearities such as friction, nonlinear springs, gear backlashes and external perturbations. Consequently, the proposed FFTC approach involves a PDC-based control law combined with a T-S fuzzy observer, with the purpose of estimating system states and of detecting actuator faults. The observer and controller gains are obtained by solving Linear Matrix Inequalities (LMIs) derived from Lyapunov's stability theory. The obtained simulation results for an ETV control process are included in order to show the effectiveness of the proposed FFTC approach in terms of reference trajectory tracking even in the presence of actuator faults.

Keywords: Electronic throttle valve, FFTC, Takagi-Sugeno observer, Stability convergence, LMIs, Actuator faults, Trajectory tracking.

1. Introduction

The Electronic Throttle Valve (ETV) part is one of the major components of an automobile engine. Its function is to adjust the Air-Fuel Ratio (AFR) during combustion by changing the opening angle of the valve plate. By the control of the throttle valve opening angle, the air inflow into the automotive engine is regulated. In relation to the demand of the engine, the amount of air flow will directly affect its performance. However, a throttle valve system features nonlinearities due to nonlinear spring, gear backlash and stick-slip friction, which make controller design difficult. Recently, certain papers have analysed nonlinear control for electronic throttle control systems in order to ameliorate the above-mentioned drawbacks especially in automotive case studies, (Shahbaz & Amin, 2023; Gzam et al., 2023). In (Shun-Chang, 2021), chaos control and stability analysis for an electronic throttle dynamical system are proposed. In (Rui, Yang & Wei, 2018), the vehicular electronic throttle system description and its dynamic model are first given. Then, nonlinear backstepping tracking control, in the presence of external disturbance and input saturation, is tackled A recent design and novel control approaches for ETV are given in (Mahmood et al., 2023; Singureanu & Copae, 2021; Dolly & Kevala, 2019). A comparative study that concerns an advanced adaptive control scheme for position control of ETV is presented in (Humaidi & Hameed, 2019). Indeed, an adaptive control law, aiming to enhance control strategy robustness in the presence of parameter modifications caused by the occurrence of variations and deviations of external conditions, is elaborated. In (Gharsallaoui et al., 2023), a RST switching bi-controller based flatness for an ETV is proposed. Besides, Fault Tolerant Control (FTC) based on a PID-type fuzzy logic controller for switched discrete-time systems for the throttle has been successfully analysed previously in (Gritli, Gharsallaoui & Benrejeb, 2017). In this approach, a nonlinear model is replaced by dynamical linear models and the algorithm switches between them. Design and fuzzy logic based sliding mode control of an intelligent electronic throttle control system are depicted in (Yadav et al., 2017). In (Gritli, Gharsallaoui & Benrejeb, 2016), PID-type fuzzy scaling factors tuning using genetic algorithm and design optimization using MATLAB-Simulink for ETV is studied.

In the last decades, the Takagi-Sugeno (T-S) fuzzy model is considered as an important tool to approximate a complex nonlinear system.

In fact, many nonlinear analyses have been conducted and many design models have been created on the basis of exact polytypic representations of nonlinear systems, whose convex structure can exactly represent a nonlinear system in a compact set of the state space (Takagi & Sugeno, 1985).

Furthermore, the stability conditions for T-S continuous nonlinear models and the study of

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stability domain for TSK (Takagi-Sugeno-Kang) fuzzy systems are given in (Benrejeb et al., 2005; Benrejeb et al., 2008). Based on T-S fuzzy modeling, a new approach related to the tracking problem for nonlinear systems using LMI formulation based on MultiQuadratic Fuzzy Lyapunov (MQFL) function has been proposed in (Abdelkrim et al., 2010). In (Khedher et al., 2010a; Khedher et al., 2010b), the problem of fault detection and identification in systems described by T-S models is studied. In fact, a proportional integral observer and an adaptive one are designed to estimate the state and the faults that can affect the system.

In (Precup, Nguyen & Blažič, 2024), firstly, a review of T-S fuzzy control systems, taking in consideration the stability analysis and controller designs, has been proposed. Secondly, different aspects of data-driven fuzzy control are analyzed in detail including a classification of many data-driven control techniques and their combination with fuzzy control. Thus, an iterative feedback tuning-based fuzzy controller design was described. In addition, for each class of fuzzy control discussed, study cases of mechatronics applications have been investigated to illustrate the effectiveness of their performance.

In this context, as a kind of mechatronics process, an automotive ETV T-S fuzzy control based on nonlinear unknown input observers is proposed in (Gritli et al., 2018). T-S fuzzy modeling method and output tracking control are given for nonlinear systems in the existence of parameter perturbations and external disturbances (Zheng et al., 2002). In (Lin et al., 2006), a $H\infty$ output tracking control for nonlinear time-delay systems is presented. In (Guerra & Vermeiren, 2001), a new Parallel Distributed Compensation (PDC) fuzzy controller is proposed in which an integrator action is added. (Allouche et al., 2011) deals with the synthesis of fuzzy controller applied to an induction motor with a guaranteed $H\infty$ tracking performance.

Moreover, actuator faults can cause undesired system behavior and often lead to instability.

Hence, it is mandatory to design Fault Tolerant Control (FTC) methods against such faults of nonlinear systems. The study of this problem was extended to the nonlinear system described by T-S models in (Tanaka& Sugeno, 1992). In (Djemili et al., 2012), a FTC design scheme has been extended to the state estimation and the state feedback control law is proposed to guarantee the stabilization of the faulty Diesel Engine Air Path (DEAP) system. In (Chang et al. 2014), fault tolerant tracking control problem has been studied for continuous nonlinear systems that are represented by the T-S fuzzy models with occurrence of multiplicative noises. In (Ben Hamouda, Ayadi & Langlois, 2016), a fuzzy fault tolerant predictive control was proposed. Indeed, the proposed T-S fuzzy active control theory based on linear models is using a combination of PDC control law and model predictive control. In (Kharrat et al., 2018) an adaptive fuzzy observer based actuator FTC design for T-S fuzzy design system has been investigated.

The main contribution of this paper, based on these backgrounds, is to propose a fuzzy fault tolerant PDC control law combined with a T-S observer to an ETV control process. Thus, this paper proposes T-S fuzzy models describe the ETV. According to this kind of model, the system is linearized around functional operating points. Hence, a fuzzy fusion of all linear model outputs describes the global system behavior. Then, a novel Fuzzy Fault Tolerant Control (FFTC) strategy based T-S fuzzy observer is designed in order to estimate ETV states. The T-S fuzzy observer and the control law gains are obtained by solving Linear Matrix Inequalities (LMIs) derived from Lyapunov's stability theory.

The main purposes of the proposed FFTC based T-S observer approach are to maintain ETV system output close to the desired reference trajectory and to guarantee stability conditions, derived from Lyapunov's theory, even if actuator faults occur.

This paper is organized as follows. Section 2 presents the ETV and how it is transformed into T-S models. Then, the FFTC approach of the ETV is outlined in section 3. The results obtained after applying the proposed approach are discussed in Section 4. Finally, Section 5 sets forth the conclusion of this paper.

2. Electronic Throttle Valve Modeling

2.1 The Analysed ETV System Description

The studied Electronic Throttle Control System (ETCS) is composed of an Electronic Control Unit (ECU), a throttle body, an accelerator pedal, a reduction gear set, a valve plate, a DC motor, a position sensor and two nonlinear return springs.

The control signal, provided by the ECU, is the armature voltage of a DC-motor which is controlled by changing the Pulse Width Modulator (PWM) duty cycle which generates the rotational torque in order to control and to adjust the throttle plate position, (Jiao, Zhang & Shen, 2014).

The parameters and units of measurement related to this model are presented in Table 1.

Table 1. Nomenclature of the ETV system parameters

Parameters	Names	Units
J_{tot}	Total moment of inertia	$Kg.m^2$
B_{tot}	Total damping constant	$N.m / rad$
N_p	Tooth number of pinion gear	-
$N \text{ int } l$	Tooth number of large intermediate gear	-
$N \text{ int } s$	Tooth number of small intermediate gear	-
$N \sec t$	Tooth of sector gear	-
L	Motor inductance	H
R	Motor resistance	Ω
K_t	Motor torque constant	$N.m / A$
K_v	Motor back EMF constant	$V.s / rad$
θ_0	Spring default position	rad
$\theta_{\min}$	Spring min position	rad
$\theta_{\max}$	Spring max position	rad
m_1	Spring rate constant	$N.m / rad$

2.2 ETV State Space Representation

The electrical part of the throttle body is modelized by (1), the electromechanical one by (2) and the electrical torque C_e by (3) (Lebbal et al., 2007):

$$u = L\dot{i} + Ri + e_{fm} \tag{1}$$

$$e_{fm} = K_v \dot{\theta}_m \tag{2}$$

$$C_e = K_t\, i \tag{3}$$

where $u(t)$ and $i(t)$ are, respectively, the voltage and the armature current, respectively, θ_m is the motor angular position and e_{fm} the electromotive force.

Considering the nonlinear spring torque $T_{sp}(\theta)$ and the stick-slip torque $T_f(\omega)$, the mechanical part of the throttle body is modeled by:

$$J_{tot}\, \dot{\omega} = -B_{tot}\, \omega - T_f(\omega) - T_{sp}(\theta) + C_e \tag{4}$$

There are many types of friction involved in the motion of the throttle plate such as Coulomb, Stribeck, viscous, pre-sliding displacement and rising static frictions. In this paper, the Coulomb friction model $T_f(\omega)$ is considered to be expressed by:

$$T_f(\omega) = F_s \operatorname{sgn}(\omega) \tag{5}$$

where F_s is a positive constant parameter and the valve plate position is limited between $\theta_{\min}$ and $\theta_{\max}$ angles.

The nonlinear spring torque expression is given by:

$$T_{sp}(\theta) = m_1(\theta - \theta_0) + D \operatorname{sgn}(\theta - \theta_0) \tag{6}$$

and the gear ratio γ by:

$$\gamma = \frac{\theta_m}{\theta} = \frac{1}{K_{g1} K_{g2}} \tag{7}$$

with $K_{g1} = N_p / N_{\text{int } l}$ and $K_{g2} = N_{\text{int } s} / N_{\sec t}$.

From equations (1), (2), (3) and (7) and by substituting the expressions for $T_f(\omega)$ and $T_{sp}(\theta)$ into (4), the following third-order ETV model is obtained:

$$\begin{cases} \dot{\theta} = K_{g1} K_{g2} \omega \\ \dot{\omega} = -\dfrac{m_1}{J_{tot}}(\theta - \theta_0) - \dfrac{D}{J_{tot}} \operatorname{sgn}(\theta - \theta_0) - \dfrac{B_{tot}}{J_{tot}} \omega - \dfrac{F_s}{J_{tot}} \operatorname{sgn}(\omega) + \dfrac{K_t}{J_{tot}} i \\ L\dot{i} = -K_v \omega - Ri + u \end{cases} \tag{8}$$

It is essential to take into consideration the nonlinearities in the modeling phase. Indeed, in this case, a novel T-S fuzzy model of the ETV was proposed.

A reduced second-order model of the ETV can be provided by assuming the motor armature inductance L to be negligible.

Then, by substituting the expression for e_{fm}, equation (1) can be rewritten as:

$$-K_v \omega - Ri + u = 0 \tag{9}$$

For the variables $x_1 = \theta$ and $x_2 = K_{g1} K_{g2}\, \omega$, the state vector x of the studied system is $x(t) = \left[x_1(t)\ x_2(t) \right]^T$.

By substituting the expression of i in (8), the reduced second-order model is then obtained:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_{21}(x_1 - x_{10}) - \lambda \operatorname{sgn}(x_1 - x_{10}) \\ \qquad + (a_{22} - a_{23} \dfrac{a_{32}}{a_{33}}) x_2 - \mu \operatorname{sgn}(x_2) - \dfrac{a_{23}}{a_{33}} u \end{cases} \tag{10}$$

Hence, the state space representation of equation (10) can be rewritten as follows:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ a_{21}(x_1 - x_{10}) - \lambda \operatorname{sgn}(x_1 - x_{10}) \\ + (a_{22} - a_{23} \dfrac{a_{32}}{a_{33}}) x_2 - \mu \operatorname{sgn}(x_2) \end{bmatrix} + \begin{bmatrix} 0 \\ -\dfrac{a_{23}}{a_{33}} \end{bmatrix} u \tag{11}$$

The coefficients of the ETV model according to the model parameters are given by:

$a_{21} = m_1 K_{g1} K_{g2} / J_{tot}$, $a_{22} = -B_{tot} / J_{tot}$,
$a_{23} = -K_t K_{g1} K_{g2} / J_{tot}$, $a_{32} = -K_v / K_{g1} K_{g2}$, $a_{33} = -R$,
$\mu = F_s K_{g1} K_{g2} / J_{tot}$ and $\lambda = D K_{g1} K_{g2} / J_{tot}$.

2.3 ETV T-S Fuzzy Modeling

The number of the operating models depends on the nonlinear system complexity and the choice of the activation functions' structure (Ben Hamouda, Ayadi & Langlois, 2016). For the studied ETV system in (10), the premise variables are given by $\mathrm{sgn}(x_1 - x_{10})$ and $\mathrm{sgn}(x_2)$ nonlinear functions. The polytope is obtained with $N = 2^r$ peaks where *r* is the number of premise variables, considered to be equal to 2. In (Tanaka, Hori & Wang, 2001) this convex polytopic representation is obtained by a direct transform of an affine model using sector nonlinearity approach.

The system is fundamentally nonlinear, so smoothing the signum function contributes to the resolution of the problems, related to discontinuities. The signum function is here approximated by the following function:

$$\mathrm{sgn}(x) \approx \frac{2}{\pi}\arctan(\varpi x) \tag{12}$$

By using the approximation (12) in (11) and for $x_{10} = x_1(0) = \theta_0$ the following model is obtained:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_{21}(x_1 - x_{10}) - \dfrac{2\lambda}{\pi}\arctan\left(\varpi(x_1 - x_{10})\right) + \\ \quad + (a_{22} - a_{23}\dfrac{a_{32}}{a_{33}})x_2 - \dfrac{2\mu}{\pi}\arctan\left(\varpi(x_2)\right) - \dfrac{a_{23}}{a_{33}}u \end{cases} \tag{13}$$

The premise variables ξ_1 and ξ_2 are assumed to have lower and upper bounds such that:

$$\forall i \in \{1,2\}, \underline{\xi_i} \le \xi_i(t) \le \overline{\xi_i} \tag{14}$$

The first step of sector nonlinearity approach consists in transforming the model in (13) into a quasi-LPV model given by:

$$\begin{cases} \dot{x}(t) = A\left(\xi_1(x_1(t)), \xi_2(x_2(t))\right)x(t) + Bu(t) \\ y(t) = Cx(t) \end{cases} \tag{15}$$

or explicitly:

$$\begin{cases} \dot{x}(t) = \begin{pmatrix} 0 & 1 \\ a_{21} - \frac{2\lambda}{\pi}\xi_1(x_1(t)) & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \frac{2\mu}{\pi}\xi_2(x_2(t)) \end{pmatrix} x(t) + \begin{pmatrix} 0 \\ \frac{a_{23}}{a_{33}} \end{pmatrix} u(t) \\ y(t) = \begin{pmatrix} 1 & 0 \end{pmatrix} x(t) \end{cases} \tag{16}$$

The following step consists in applying the convex polytopic transformation for each premise variable $\xi_i(x_i(t)), i = 1,2$, and for each of the premise variables, a partition was performed into two zones such that:

$$\xi_1(x_1) = \overline{\mathrm{E}}_1\left(\xi_1(x_1)\right)\overline{\xi_1} + \underline{\mathrm{E}}_1\left(\xi_1(x_1)\right)\underline{\xi_1} \tag{17}$$

$$\xi_2(x_2) = \overline{\mathrm{E}}_2\left(\xi_2(x_2)\right)\overline{\xi_2} + \underline{\mathrm{E}}_2\left(\xi_2(x_2)\right)\underline{\xi_2} \tag{18}$$

with

$\underline{\xi_i} = \min\limits_x \left\{\left(\xi_i\left(x_i(t)\right)\right)\right\}$, $\overline{\xi_i} = \max\limits_x \left\{\left(\xi_i\left(x_i(t)\right)\right)\right\}$, and $\overline{\mathrm{E}}_1(.)$ and $\overline{\mathrm{E}}_2(.)$ as the partition functions.

Then, (16) becomes:

$$A\left(\xi_1(x_1), \xi_2(x_2)\right) = \begin{pmatrix} 0 & 1 \\ a_{21} - \frac{2\lambda}{\pi}\xi_1(x_1) & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \frac{2\mu}{\pi}\xi_2(x_2) \end{pmatrix} \tag{19}$$

With $\overline{\mathrm{E}}_i(\xi_i) + \underline{\mathrm{E}}_i(\xi_i) = 1$, $i = 1,2$ (19) becomes:

$$\begin{aligned} A\left(\xi_1(x_1), \xi_2(x_2)\right) = {} & \overline{\mathrm{E}}_2(\xi_2)\begin{pmatrix} 0 & 1 \\ a_{21} - \frac{2\lambda}{\pi}\xi_1(x_1) & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \frac{2\mu}{\pi}\xi_2(x_2) \end{pmatrix} \\ & + \underline{\mathrm{E}}_2(\xi_2)\begin{pmatrix} 0 & 1 \\ a_{21} - \frac{2\lambda}{\pi}\xi_1(x_1) & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \frac{2\mu}{\pi}\xi_2(x_2) \end{pmatrix} \end{aligned} \tag{20}$$

Then, by multiplying (20) by $\left(\overline{\mathrm{E}}_1(\xi_1) + \underline{\mathrm{E}}_1(\xi_1)\right)$, $A\left(\xi_1(x_1), \xi_2(x_2)\right)$ is obtained as follows:

$$\begin{aligned} A\left(\xi_1(x_1), \xi_2(x_2)\right) = {} & \underbrace{\overline{\mathrm{E}}_1(\xi_1)\overline{\mathrm{E}}_2(\xi_2)}_{\mu_1}\begin{pmatrix} 0 & 1 \\ a_{21} - \frac{2\lambda}{\pi}\overline{\xi_1} & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \frac{2\mu}{\pi}\overline{\xi_2} \end{pmatrix} \\ & + \underbrace{\overline{\mathrm{E}}_1(\xi_1)\underline{\mathrm{E}}_2(\xi_2)}_{\mu_2}\begin{pmatrix} 0 & 1 \\ a_{21} - \frac{2\lambda}{\pi}\overline{\xi_1} & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \frac{2\mu}{\pi}\underline{\xi}_2 \end{pmatrix} \\ & + \underbrace{\underline{\mathrm{E}}_1(\xi_1)\overline{\mathrm{E}}_2(\xi_2)}_{\mu_3}\begin{pmatrix} 0 & 1 \\ a_{21} - \frac{2\lambda}{\pi}\underline{\xi}_1 & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \frac{2\mu}{\pi}\overline{\xi_2} \end{pmatrix} \\ & + \underbrace{\underline{\mathrm{E}}_1(\xi_1)\underline{\mathrm{E}}_2(\xi_2)}_{\mu_1}\begin{pmatrix} 0 & 1 \\ a_{21} - \frac{2\lambda}{\pi}\underline{\xi}_1 & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \frac{2\mu}{\pi}\underline{\xi}_2 \end{pmatrix} \end{aligned} \tag{21}$$

The simplified form of $A(\xi_1(x_1), \xi_2(x_2))$ is given by:

$$A\left(\xi_1(x_1), \xi_2(x_2)\right) = \sum_{i=1}^{4} \mu_i(t) A_i \tag{22}$$

By using the aforementioned sector nonlinearity approach, the ETV system can be expressed as the following T-S models with $x_{10} = x_1(0) = \theta_0$ and for $i \in \psi = \{1, \ldots, 4\}$:

RULE i: **IF** $x_1(t) < x_{10}$ **AND** $x_2(t) < 0$ **THEN**

$$\begin{cases} \dot{x}(t) = A_i x(t) + B_i u(t) \\ y(t) = C_i x(t) \end{cases} \tag{23}$$

such that:

$$A_1 = \begin{pmatrix} 0 & 1 \\ a_{21}+\lambda & a_{22}-a_{23}\dfrac{a_{32}}{a_{33}}+\mu \end{pmatrix}, A_2 = \begin{pmatrix} 0 & 1 \\ a_{21}-\lambda & a_{22}-a_{23}\dfrac{a_{32}}{a_{33}}+\mu \end{pmatrix}$$

$$A_3 = \begin{pmatrix} 0 & 1 \\ a_{21}+\lambda & a_{22}-a_{23}\dfrac{a_{32}}{a_{33}}-\mu \end{pmatrix}, A_4 = \begin{pmatrix} 0 & 1 \\ a_{21}-\lambda & a_{22}-a_{23}\dfrac{a_{32}}{a_{33}}-\mu \end{pmatrix}$$

$$B_i = \begin{pmatrix} 0 \\ -\dfrac{a_{23}}{a_{33}} \end{pmatrix} \quad C_i = (1 \quad 0) \tag{24}$$

The system can be then modeled, for $i \in \psi = \{1,\ldots,4\}$, as follows:

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{4} \mu_i\left(\xi(t)\right)\left(A_i x(t) + B_i u(t)\right) \\ y(t) = \sum_{i=1}^{4} \mu_i\left(\xi(t)\right) C_i x(t) \end{cases} \tag{25}$$

with

$$\mu_i\left(\xi(t)\right) = \frac{\omega_i\left(\xi(t)\right)}{\sum_{i=1}^{4}\omega_i\left(\xi(t)\right)}, \; \omega_i\left(\xi(t)\right) = \prod_{j=1}^{2} M_j^i\left(\xi_j(t)\right) \tag{26}$$

such that:

$$\sum_{i=1}^{4}\mu_i(\xi(t)) = 1, \; \mu_i(\xi(t)) \geq 0 \; \forall \; i \in \psi \tag{27}$$

where M_j^i is the j^{th} fuzzy set with the i^{th} rule, $\xi_1(t)$, $\xi_2(t)$ are known premise variables and $M_j^i\left(\xi_j(t)\right)$ is the membership value of $\xi_j(t)$ in M_j^i.

In the next section, the proposed Fuzzy Fault Tolerant Control (FFTC) based T-S observer for ETV system, subject to actuator faults, is presented.

3. The Proposed ETV FFTC Based T-S Observer

3.1 Basic Structure of the Proposed FFTC

The proposed ETV FFTC based T-S observer scheme is given in Figure 1. Its main contribution is related to the design of a new FFTC based on a PDC control law combined with a T-S fuzzy observer, in order to estimate system states and to detect actuator faults.

The main purpose of the suggested FFTC approach is to attenuate the impact of faults and to maintain the stability of the faulty ETV system.

To determine the appropriate fuzzy controller, the proposed approach is described below.

Firstly, two supervisors are implemented to calculate the weighting functions $\mu_i(\xi(t))$ in both nominal and faulty cases.

The nominal control input $u(t)$ is a state feedback control law computed using the fuzzy PDC control law. It is designed, thereafter, for the non-faulty T-S fuzzy ETV model.

Then, a T-S observer was included to estimate the system state vector $\hat{x}_f(t)$ and actuator faults $\hat{f}(t)$. Therefore, a new FFTC law $u_f(t)$ was developed based on the parameters provided by the constructed T-S observer. Finally, FFTC is the control law to be implemented, afterwards, for the ETV faulty system in the presence of the actuator faults $f(t)$. $y_f(t)$ is the output vector of the faulty ETV system.

The aim of the proposed FFTC approach is to maintain system output $x_f(t)$ close to the desired reference signal $x_{ref}(t)$ and also to guarantee stability conditions despite the presence of actuator faults.

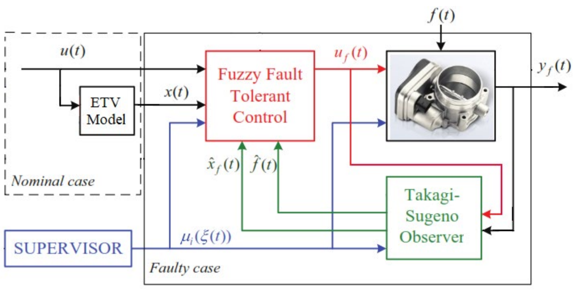

Figure 1. The ETV FFTC based T-S observer

Using Lyapunov's approach, a Linear Matrix Inequalities (LMIs) feasibility problem is formulated to provide the controller and the observer gains. Consequently, the stability of the whole system is proved by solving the LMIs constraints.

3.2 The Presentation of the FFTC based T-S Observer

Let us consider the ETV in the faulty case, described by the following model:

$$\begin{cases} \dot{x}_f(t) = \sum_{i=1}^{N} \mu_i(\xi(t))(A_i x_f(t) + B_i u_f(t) + E_i f(t)) \\ y_f(t) = \sum_{i=1}^{N} \mu_i(\xi(t)) C_i x_f(t) \end{cases} \tag{28}$$

E_i represents the fault matrix with appropriate dimension and $f(t)$ is the actuator fault signal with $\dot{f}(t)=0$.

The objective of FFTC design is to maintain the stability of the closed-loop system in (28) and the asymptotic convergence of $x_f(t)$ to $x_{ref}(t)$ even in the presence of actuator faults.

The following new control input $u_f(t)$ is then proposed:

$$u_f(t)=\sum_{j=1}^{N}\mu_j(\xi(t))(-S_j\hat{f}(t)+G_j(x(t)-\hat{x}_f(t)+u(t)) \quad (29)$$

where $\hat{f}(t)$ is the fault estimate, $u(t)$ is a state feedback control law using a PDC as described in (Tanaka& Sugeno, 1992), S_j satisfies the equality $B_iS_j=E_i$ and G_j represents unknown gains of the controller to be designed for $i=\{1,...,4\}$ and $j=\{1,...,4\}$.

A T-S observer, as it is given in (30), is used for the system in (28) to estimate the system state $x_f(t)$ and the actuator fault $f(t)$:

$$\begin{cases}\dot{\hat{x}}_f(t)=\sum_{i=1}^{N}\mu_i(\xi(t))(A_i\hat{x}_f(t)+B_iu_f(t))+E_i\hat{f}(t)+K_i(y_f(t)-C_i\hat{x}_f(t))) \\ \dot{\hat{f}}(t)=\sum_{i=1}^{N}\mu_i(\xi(t))(L_i(y_f(t)-C_i\hat{x}_f(t)))\end{cases} \quad (30)$$

The extended error system, containing the two dynamic errors $e_x(t)=x_f(t)-\hat{x}_f(t)$ and $e_f(t)=f(t)-\hat{f}(t)$, can be expressed as:

$$\begin{pmatrix}\dot{x}_f(t)-\dot{\hat{x}}_f(t)\\ \dot{f}(t)-\dot{\hat{f}}(t)\end{pmatrix}=\sum_{i=1}^{N}\mu_i(\xi(t))\begin{pmatrix}A_i-K_iC_i & -E_i\\ -L_iC_i & 0\end{pmatrix}\begin{pmatrix}x_f(t)-\hat{x}_f(t)\\ f(t)-\hat{f}(t)\end{pmatrix} \quad (31)$$

The tracking error dynamics $e(t)$, $e(t)=x(t)-x_f(t)$ is given by:

$$\dot{e}(t)=\sum_{i=1}^{N}\sum_{j=1}^{N}\mu_i(\xi(t))\mu_j(\xi(t))\begin{pmatrix}A_i\,e(t)+B_i\,u(t)\\ -B_j\begin{pmatrix}-S_j\hat{f}(t)\\ +G_j(x(t)-\hat{x}_f(t))\\ +u(t)\end{pmatrix}\\ -E_if(t)\end{pmatrix} \quad (32)$$

Thus,

$$\dot{e}(t)=\sum_{i=1}^{N}\sum_{j=1}^{N}\mu_i(\xi(t))\mu_j(\xi(t))\begin{pmatrix}(A_i-B_iG_j)e(t)\\ -E_i(f(t)-\hat{f}(t))\end{pmatrix} \quad (33)$$

An extended error system $\tilde{e}(t)$ containing the tracking error $e(t)$, the state estimation error $e_x(t)$ and the fault estimation error $e_f(t)$ can be expressed as:

$$\dot{\tilde{e}}(t)=\sum_{i=1}^{N}\sum_{j=1}^{N}\mu_i(\xi(t))\mu_j(\xi(t))\tilde{A}_{ij}\tilde{e}(t) \quad (34)$$

with

$$\tilde{e}(t)=\begin{pmatrix}e(t) & e_x(t) & e_f(t)\end{pmatrix}^T \quad (35)$$

and

$$\tilde{A}_{ij}=\begin{pmatrix}A_i-B_iG_j & 0 & -E_i\\ 0 & A_i-K_iC_i & -E_i\\ 0 & L_iC_i & 0\end{pmatrix} \quad (36)$$

The convergences of the controller and the observer have been formulated in terms of LMIs. The observer and controller gains are given by the ***Theorem*** below.

Theorem. The tracking error $e(t)$, the state estimation error $e_x(t)$ and the fault estimation error $e_f(t)$ converge asymptotically to zero, if there exist the symmetric positive definite matrices X and P_2, $P_3=I$, and gain matrices H_{1i} and H_{2i} such that the following LMIs are verified (Djemili, Aitouche & Cocquempot, 2012):

$$\begin{pmatrix}A_iX+XA_i^T & 0 & -E_i & -B_iG_j & X\\ 0 & A_i^TP_2-C_{1i}^TH_{1i}^T+P_2A_i-H_{1i}C_i & -C_i^TH_{2i}^T-P_2E_i & 0 & 0\\ -E_i^T & -E_i^TP_2-H_{2i}C_i & 0 & 0 & 0\\ * & * & * & -I & 0\\ * & * & * & * & -I\end{pmatrix}\le 0 \quad (37)$$

The symbol* denotes the transposed element in the symmetric position of a block matrix. The gains of the controller are represented by G_j and the gains of the observer are given by $L_i=H_{2i}$ and $K_i=P_2^{-1}H_{1i}$.

Proof. The proof is given in the Appendix.

4. Results and Discussion

In order to illustrate the effectiveness of the novel proposed FFTC strategy, a T-S fuzzy model of the ETV is firstly provided. The considered ETV model parameters, used in the numerical simulations, are included in Table 2, for data given in (Pan, Ozguner & Dagci, 2008).

Table 2. The parameters values for the simplified model

Parameters	The set values
a_{21}	1/18
a_{22}	-1.6801.10³
a_{23}	-32.9820
a_{32}	-0.0245
a_{33}	-1.0980
μ	4.7438.10²
λ	2.1073.10³

The considered model was given by (10) with the state regions $0\ rad < x_1(t) < \pi/2\ rad$ and $-80\ rad/\mathrm{s} < x_2(t) < 80\ rad/s$.

There are two premise variables, so four sub-models are considered. The performance of the proposed FFTC approach has been evaluated through numerical simulations for a PWM signal of an amplitude which ranged from 0 to 1.5708 *rad* and for the frequency $f = 0.2Hz$ in the presence of actuator faults.

The controller and observer gains were determined using LMIs while taking into account the stability of the system derived from Lyapunov's theory;16 LMIs were formulated for the analysed case.

Each (A_i, C_i) is observable. The resolution of the LMIs of the theorem above, using the MATLAB LMI Toolbox (Gahinet et al., 1994), results in the following matrices:

$$G_1 = 10^{-11}[0.1012 \quad 0.0661],\ G_2 = 10^{-11}[0.7721 \quad 0.2136],$$
$$G_3 = 10^{-11}[0.7330 \quad 0.0277],\ G_4 = 10^{-11}[0.7330 \quad 0.0277],$$
$$L_1 = L_2 = L_3 = L_4 = \begin{bmatrix} -356.0311 \\ -91.0371 \end{bmatrix},$$
$$K_1 = 10^6 \begin{bmatrix} 0 \\ 5.7547 \end{bmatrix},\ K_2 = 10^6 \begin{bmatrix} 0 \\ 5.7804 \end{bmatrix},$$
$$K_3 = 10^6 \begin{bmatrix} 0 \\ 5.7455 \end{bmatrix},\ K_4 = 10^6 \begin{bmatrix} 0 \\ 5.7712 \end{bmatrix}.$$

The system simulation results obtained by the use of the FFTC strategy based on the initial condition: $x(t) = [0.1 \quad 0]^T$ are shown in Figures 2 to 7.

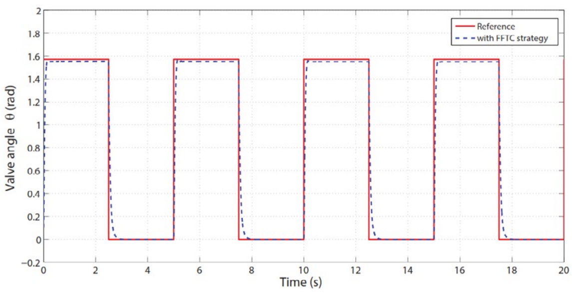

Figure 2. Valve angle opening tracking θ obtained by the proposed FFTC strategy

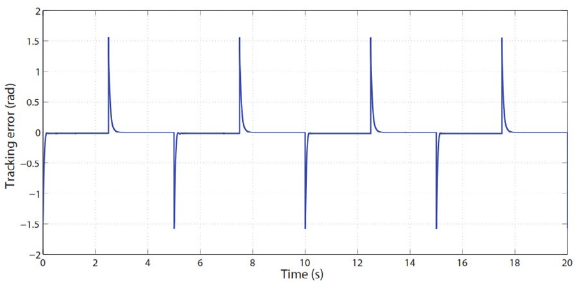

Figure 3. Tracking error e obtained by the proposed FFTC strategy

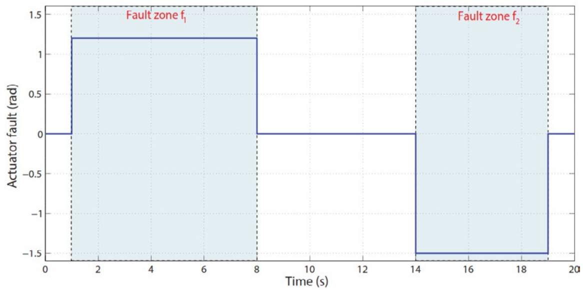

Figure 4. Actuator fault signals $f_1(t)$ and $f_2(t)$

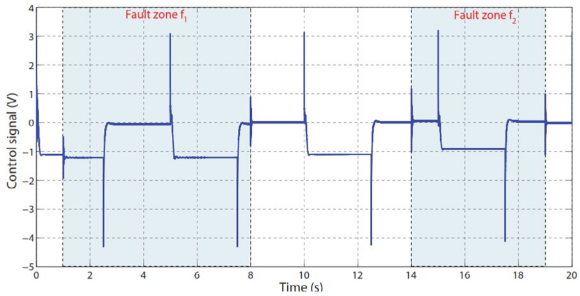

Figure 5. Control signal u_f obtained by the proposed FFTC strategy

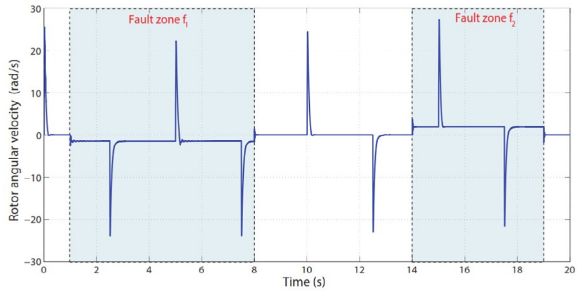

Figure 6. Rotor angular velocity $\dot{\theta}$ obtained by the proposed FFTCstrategy

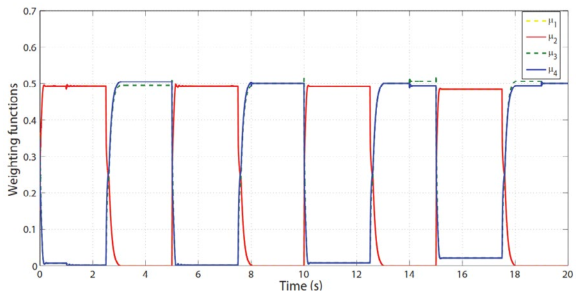

Figure 7. Weighting functions μ_i in the actuator faulty case

The system simulation results illustrate the effectiveness of the new FFTC designed from the parameters related to the constructed T-S observer. Indeed, in Figure 2, it can be observed that the proposed FFTC strategy maintains the valve angle close to the reference given by PWM signal in the presence of the actuator faults with a fast transient response almost equal to $0.15s$ against a response of $0.25s$ obtained for the ETV T-S fuzzy control based on nonlinear unknown input observers discussed in the work of Gritli et al. (2018).

The proposed FFTC allows one to obtain the tracking error e of the desired throttle position with accuracy even in the case of actuator faults occurrence as it is shown in Figure 3.

Thus, the performance of the proposed control strategy is satisfactory.

Indeed, in Figures 2, 3 and 5, it is obvious that the objective of estimation error convergence has been satisfied for the ETV system which proves the effectiveness of the employed T-S observer in successfully estimating the system state variables and in detecting actuator faults.

In order to attenuate the effect of the injected actuator faults, it can be observed that in the case of the control signal, illustrated in Figure 5, an offset was generated from 1*s* to 8*s* and from 14*s* to 19*s*.

This allowed the rotor angular velocity, illustrated in Figure 6, to increase or decrease adequately to ensure accurate tracking in the presence of actuator faults $f_1(t)$ and $f_2(t)$, depicted in Figure 4.

The actuator fault signal $f_1(t)$ is given by:

$$f_1(t) = \begin{cases} 0,\ 0s \le t \le 1s \\ 1.2\ rad,\ 1s \le t \le 8s \\ 0,\ t > 8s \end{cases}$$

and the actuator fault signal $f_2(t)$ by:

$$f_2(t) = \begin{cases} 0,\ 0s \le t \le 14s \\ -1.5\ rad,\ 14s \le t \le 19s \\ 0,\ t > 19s \end{cases}$$

Figure 7 illustrates the evolution of the weighting functions in the actuator faulty case.

It can be noticed that μ_3 and μ_4 increase when actuator faults occur, consequently, the proposed active FFTC law accommodates such faults immediately. The numerical results show that the performance of the proposed FFTC strategy is satisfactory in comparison with that of the FTC based on unknown input observers for switched ETV systems and to that of the FFTC based on nonlinear unknown input observers approaches given in (Gritli et al. 2018).

5. Conclusion

In this paper, the proposed novel Fuzzy Fault Tolerant Control (FFTC) for an Electronic Throttle Valve (ETV) based on a Takagi-Sugeno (T-S) observer has compensated the impact of actuator fault occurrence. Then, the T-S fuzzy observer estimated system states, and it detected and the occurring actuator faults.

The observer and controller convergences have been ensured by using Lyapunov's theory formulated in terms of Linear Matrix Inequalities (LMIs) to obtain the observer and controller gains. Finally, the obtained results show that the proposed FFTC approach accomplished the tracking of PWM reference signal successfully with a fast transient response and a high accuracy even in the presence of the actuator faults. In the future, this strategy could be employed for real-time automotive process control of an ETV.

Appendix. Proof of the Theorem

Lemma. Let us consider two matrices X and Y of appropriate dimensions. The following inequality is verified for each matrix Q: $X^T Y + XY^T \le X^T Q^{-1} X + YQY^T$.

The proof of the ***Theorem*** is elaborated using the following Lyapunov function:

$$V(\tilde{e}(t)) = \tilde{e}(t)^T P \tilde{e}(t),\ P = P^T > 0 \quad (38)$$

where the matrix P is defined as follows:

$$P = \begin{pmatrix} P_1 & 0 & 0 \\ 0 & P_2 & 0 \\ 0 & 0 & P_3 \end{pmatrix} \quad (39)$$

The derivative of $V(\tilde{e}(t))$ is written as:

$$\dot{V}(\tilde{e}(t)) = \sum_{i=1}^{N}\sum_{j=1}^{N} \mu_i(\xi(t))\mu_j(\xi(t))\left(\tilde{e}(t)^T M_{ij} \tilde{e}(t)\right) \quad (40)$$

$$M_{ij} = \mathbb{Z}\left(\begin{pmatrix} P_1A_i - P_1B_iG_i & 0 & -P_1E_i \\ 0 & P_2A_i - P_2K_iC_i & -P_2E_i \\ 0 & -P_3L_iC_i & 0 \end{pmatrix}\right) \quad (41)$$

denotes the Hermitian matrix X, i.e. $\mathbb{Z}(X) = X^T + X$. The derivative of the Lyapunov function is negative semi-definite if the following inequalities are satisfied:

$$M_{ij} \le 0\ i, j = 1,...,N \quad (42)$$

Using the ***lemma*** of congruence:

$$M_{ij} \le 0 \Leftrightarrow \begin{pmatrix} P_1^{-1} & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{pmatrix} M_{ij} \begin{pmatrix} P_1^{-1} & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{pmatrix} \le 0 \quad (43)$$

the following inequalities are obtained:

$$\begin{pmatrix} \Omega_{ij}^1 & 0 & -E_i \\ 0 & \Omega_{ij}^2 & -C_i L_i^T P_3 - P_2 E_i \\ -E_i^T & -E_i^T P_2 - P_3 L_i C_i & 0 \end{pmatrix} \leq 0 \qquad (44)$$

where $\Omega_{ij}^1 = XA_i^T - XG_i^T B_i^T + A_i X - B_i G_i X$ and $\Omega_{ij}^2 = A_i^T P_2 - C_i^T K_i^T P_2 + P_2 A_i - P_2 K_i C_i$ with $X = P_1^{-1}$. In order to use the ***lemma***, the inequalities in (44) can be written as:

$$\begin{pmatrix} A_i X + XA_i^T & 0 & -E_i \\ 0 & A_i^T P_2 - C_{1i}^T K_{1i}^T P_2 + P_2 A_i - P_2 K_i C_i & -C_i^T L_i^T P_3 - P_2 E_i \\ -E_i^T & -E_i^T P_2 - P_3 L_i C_i & 0 \end{pmatrix} + \begin{pmatrix} -B_i G_j \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} X \\ 0 \\ 0 \end{pmatrix}^T + \begin{pmatrix} X \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} -B_i G_j \\ 0 \\ 0 \end{pmatrix}^T < 0 \qquad (45)$$

Using the ***lemma***, one obtains:

$$\begin{pmatrix} A_i X + XA_i^T & 0 & -E_i \\ 0 & A_i^T P_2 - C_{1i}^T K_{1i}^T P_2 + P_2 A_i - P_2 K_i C_i & -C_i^T L_i^T P_3 - P_2 E_i \\ -E_i^T & -E_i^T P_2 - P_3 L_i C_i & 0 \end{pmatrix} + \begin{pmatrix} -B_i G_j \\ 0 \\ 0 \end{pmatrix} \mathbb{Q}^{-1} \begin{pmatrix} X \\ 0 \\ 0 \end{pmatrix}^T + \begin{pmatrix} X \\ 0 \\ 0 \end{pmatrix} \mathbb{Q} \begin{pmatrix} -B_i G_j \\ 0 \\ 0 \end{pmatrix}^T < 0 \qquad (46)$$

where $\mathbb{Q}$ is a symmetric positive definite matrix. Using *Schur's complement* and changes of variables $H_{1i} = P_2 K_i$ and $H_{2i} = P_3 L_i$, the LMIs of the theorem is obtained with $\mathbb{Q} = I$.

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