A New Observer-Based Fault Tolerant Shared Control for SbW Systems with Actuator Fault for Driver Assistance

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Abstract: This paper addresses the problem of fault tolerant shared control (FTSC) of Steer-by-Wire (SbW) systems with actuator fault for driver lane keeping assistance system. The main contribution of this work is to propose a novel co-design of a robust adaptive simultaneous estimation of system state and actuator faults associated with an adaptive control law for the stability purposes and also to ensure lane keeping performance even in faulty situations by limiting the influence of actuator faults on the vehicle trajectory. An LPV observer architecture is proposed to estimate the vehicle state and unknown actuator faults considering real-time unmeasurable variations in longitudinal and lateral velocities, represented within a polytope with finite vertices. Subsequently, a robust and adaptive state feedback active fault-tolerant controller is proposed using the Takagi-Sugeno (T-S) approach. An optimization problem is formulated in terms of linear matrix inequalities (LMI) to guarantee system stability and the asymptotic convergence of state and fault estimation errors. Lyapunov stability arguments are used to allow more relaxation and additional robustness against immeasurable nonlinearities. Hardware validation carried out with the SHERPA dynamic car simulator in real driving situations demonstrated the performance and the effectiveness of the proposed FTSC scheme.

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1 INTRODUCTION

The integration of computers and electronics into modern vehicles has paved the way for innovations such as electric vehicles (EVs) equipped with Steer-by-Wire (SbW) systems. These systems present unique advantages over traditional mechanical steering systems by eliminating the mechanical linkage between the steering wheel and the front wheels. Instead, SbW systems use two motors and an electronic control unit (ECU) to generate feedback torque and steering angle, coupled with sensors that measure the driver's steering input and the front wheel angle. The ECU processes the electronic signals from these sensors and translates them into mechanical motion (Altby and Majdanzic, 2014). Before the commercialization of SbW systems can proceed, two of the most pressing issues that must be resolved are maintaining reliability and fault-tolerance capabilities. Sensor faults in autonomous vehicles can result in a partial or complete loss of critical information needed to perform driving tasks. In contrast, actuator failures can cause a total loss of vehicle control, leading to ineffective or unstable maneuvers with potentially catastrophic consequences (Sentouh et al., 2024).

When an actuator motor suddenly fails, it becomes difficult for the driver to maintain the same steering behavior as before, potentially causing the vehicle to deviate from its intended lane. In such situations, the driver must exert considerable effort to keep the vehicle on course and ensure its stability through manual steering operations. This research aims to support the driver's steering actions and enhance the performance and fault-tolerance capabilities of the SbW system, especially during actuator failures. Hence, actuator faults detection and compensation schemes ensuring that the system remains operational even when failures occur, play an important role in achieving the reliability of SbW system. In the literature, many studies have been reported on fault detection and isolation (FDI), fault diagnosis (FD), and fault-tolerant control (FTC) to address these concerns (Zinoune et al.,

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2015) (Kommuri et al., 2016) (Xiong et al., 2019) (Khelladi et al., 2020) (Abbaspour et al., 2020).

Substantial research has been conducted on fault-tolerant control (FTC) of SbW systems with actuator or sensor failures. FTC systems can be categorized into active FTC systems (AFTCS) and passive FTC systems (PFTCS). Active FTC systems react to failures through a reconfiguration mechanism, adapting the control system based on real-time fault information from an FDI scheme. In contrast, passive FTC systems assume a predefined set of potential malfunctions known a priori and do not require an FDI scheme or controller reconfiguration. The goal of a passive FTC design is to synthesize a single fixed controller that makes the closed-loop system as insensitive as possible to these predefined faults. Reliable passive FTC of an autonomous electric vehicle affected by front wheel steering actuator faults was proposed in (Chen et al., 2019) for path following. A robust H_∞ fault-tolerant observer-based PID path tracking control strategies have been developed to integrate both actuator and sensor faults as well as control saturation is proposed in (Chen et al., 2024).

Despite these advances, passive FTC systems often struggle to achieve optimal performance under varying fault conditions compared to active FTC systems. Most work on SbW FTC systems has focused on active approaches, where FDI plays a vital role in providing information about faults, enabling corresponding actions to eliminate or minimize their effects and maintain overall system performance. FDI aims to monitor the system, identify faults as they occur, and pinpoint their type and location. Two fundamental analytical redundancy-based approaches for FDI are residual-based FDI and fault estimation-based FDI. Residual-based FDI methods generate residuals, the difference between measured and calculated variables, which have a nominal zero mean value under normal conditions. Common residual generation methods for SbW systems include unknown input observers (dos Santos et al., 2016), sliding mode observers (Anwar and Niu, 2014), Kalman filters (Gadda, 2009), and interval observers (Ifqir et al., 2019). However, residual methods do not provide direct information about the fault itself. In contrast, observer-based fault estimation techniques use observers to estimate faults directly, providing information on their size, severity, and nature. By using the fault estimation dynamics, the controller can be designed to compensate for the effect of the fault. Two stage Kalman filter is presented in (Huang et al., 2021) to estimate state and efficiency loss factor simulaniously in the presence of front wheel actuator fault and based on the fault information the MPC-based reconfigurable controller replaces the old fault-free model with a new faulty model to maintain vehicle stability and steering tracking performance. In (Zhao et al., 2020), through the forgetting factor recursive least squares (FFRLS) algorithm, the state and the partial damage degree of the motor are transferred to ECU then they propose an individual auxiliary and fault-tolerant control considering different drivers steering characteristics in the case of actuator fault. An interval observer is used to estimate the actuator fault as though as if it were another (unmeasurable) state of the system in (Lamouchi et al., 2022). Adaptive fault diagnosis observer (AFDO) approaches have also gained attention for their ability to estimate both the state vector and actuator fault vector simultaneously (Jiang et al., 2006)(Wang and Daley, 1996)(Zhang et al., 2008). A fuzzy fast adaptive fault estimation (FAFE) algorithm for T-S fuzzy nonlinear systems is proposed in (Zhang et al., 2009)(Zhang et al., 2008).

The aforementioned works offer valuable insights and solutions, primarily focus on the quadratic approach to study the asymptotic convergence of the system and the observer separately. However, they do not address the robust co-design needed to achieve simultaneously an adaptive fault estimation (FE) and FTC strategy.

In this paper, we focus on the front wheel subsystem of the SbW system to assist the driver in faulty situation. The main objective is to utilize the steering command to reduce the physical steering workload of the driver during faulty steering actuator situations. One of the main challenges we address is providing a natural and a smoother transition mode by offering fault-tolerant shared control between the controller and the driver, especially in cases where the actuators fail. When the steering actuator suddenly fails, it is difficult for the driver to maintain the steering behavior, which can lead to a vehicle lateral deviation from its desired lane. The driver then must exert considerable effort to keep the vehicle in the lane and ensure the vehicle stability through steering operations.

Under these conditions of steering motor failure, the purpose of this work is to propose a novel co-design to achieve both adaptive fault estimation (FE) and fault-tolerant control (FTC) strategy. For that, a robust adaptive observer for simultaneous state and actuator fault estimation is combined with an adaptive feedback control to guarantee the observer-based fault-tolerant system stability while ensuring the lane keeping performance by restricting the impact of actuators' faults on the vehicle trajectory.

The remainder of the paper is structured as follows. The vehicle system modeling is given in

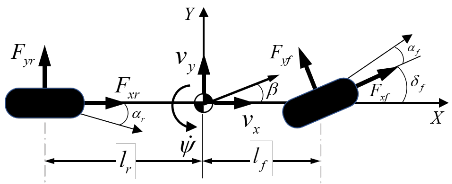

Figure 1: Bicycle model for lateral dynamics.

Sec.2. Sec.3 presents the representation of this model through the T-S fuzzy model. Then, the adaptive observer design is given in Sec. 4 while Sec.5 presents the proposed fault-tolerant shared control and the closed-loop stability. Finally, the experimental validation are discussed in Ses.6.

2 VEHICLE SYSTEM MODELING

NOMENCLATURE

m	Mass of vehicle [kg]
I_z	Yaw inertia $[\text{kg.m}^2]$
v_y, v_x	Lateral and longitudinal velocity $[\text{m/s}]$
F_{yf}, F_{yr}	Front/rear wheels lateral tire forces [N]
C_y	Lateral aerodynamic drag coefficient[Kg/m]
F_{xf}	Front wheels longitudinal tire forces [N]
δ_f	Steering wheel angle [rad]
F_w	Crosswinds force [N]
ψ_L	Heading error [rad]
y_L	Lateral position error [m]
ρ_c	Road curvature $[\text{m}^{-1}]$
$C_{\alpha_f}, C_{\alpha_r}$	Front/rear cornering stiffness [N/rad]
α_f, α_r	Front/rear side slip angle [rad]
$\dot{\psi}$	Yaw rate $[\text{rad/s}]$
l_f, l_r	Distance from COG to front and rear axles [m]

2.1 Lateral Dynamic Model

In this section, we explore the modeling of vehicle lateral motion by considering the non-linear dynamics of a bicycle model. The vehicle is modeled as a symmetric single-track bicycle in a fixed frame with six degrees of freedom (6 DoF). Neglecting roll and pitch motions, the left and right wheels at each axle are combined into a single equivalent tire as described by (Rajamani, 2011) and illustrated in Fig.1. The lateral dynamics of the vehicle, characterized by variations in lateral speed v_y and yaw rate $\dot{\psi}$, are represented by the following equations:

$$\begin{cases} m\dot{v}_y = F_{xf}\sin(\delta_f) + F_{yf}\cos(\delta_f) + F_{yr} - mv_x\dot{\psi} - C_y v_y^2 \\ \qquad +F_w \\ I_z\ddot{\psi} = l_f F_{yf}\cos(\delta_f) - l_r F_{yr} + l_f F_{xf}\sin(\delta_f) + l_w F_w \end{cases} \tag{1}$$

2.2 Tire Force Dynamics

Most tire models used in the literature primarily consider a small values of the slip ratio λ and the slip angle α and maintain the tire behavior within the linear zone (Rajamani, 2011). Thus, the longitudinal and lateral forces of the front and rear tires are expressed as:

$$\begin{cases} F_{y_{f,r}} = C_{\alpha_{f,r}}\alpha_{f,r} \\ F_{x_{f,r}} = C_{\lambda_{f,r}}\lambda_{f,r} \end{cases} \tag{2}$$

Although this model describes static behavior, the elastic deformation of tires introduces a transient behavior. To account for this transient behavior, some literature incorporates a first-order low-pass filter dynamics $(\frac{\sigma_t}{v_x})$, as described in (Vantsevich and Gray, 2015) and (Rajamani, 2011) where σ_t is the time constant. So, the tire-ground forces are then dynamically modeled as:

$$\begin{cases} \dot{F}_{y_{f,r}} = -\frac{v_x}{\sigma_t}F_{y_{f,r}} + \frac{v_x}{\sigma_t}C_{\alpha_{f,r}}\alpha_{f,r} \\ \dot{F}_{x_{f,r}} = -\frac{v_x}{\sigma_t}F_{x_{f,r}} + \frac{v_x}{\sigma_t}C_{\lambda_{f,r}}\lambda_{f,r} \end{cases} \tag{3}$$

2.3 Lateral Positioning

To ensure effective lane keeping when control is shared between the driver and the system, it is essential to minimize the lateral position error y_L and the heading error ψ_L at a lookahead distance l_p. The dynamics of these two errors are given by (Sentouh et al., 2018):

$$\begin{aligned} \dot{\psi}_L &= \dot{\psi} - \rho_c v_x \\ \dot{y}_L &= v_y + l_p\dot{\psi} + \psi_L v_x \end{aligned} \tag{4}$$

3 T-S FUZZY MODELING OF VEHICLE DYNAMICS

3.1 Actuator Faults

Actuator faults in the vehicular system can be additive or multiplicative, as shown in Tab.1. The faulty control input to the system can be defined as $f_a(t) = (I_{n_u} - \rho_a)u(t)$ for given feedback control $u(t)$. This fault can be easily rewritten as an external additive signal $(u(t) + f_a(t))$ where $f_a(t) = -\rho_a u(t)$.

3.2 T-S Model Formulation in the Presence of Actuator Faults

Note that the system nonlinearity is caused by the variation of longitudinal and lateral velocities. These

Table 1: Actuator faults.

Fault Kind	Conditions	Fault Name
Additive	if f_{a_i} constant	Bias
$u_i(t)+f_{a_i}(t)$	if $f_{a_i}=\lambda_i t$, $0<\lambda\ll 1$	Drift
Multiplicative	if $\rho_{a_i}=1$	Totally effective
$\rho_{a_i}u_i(t)$	if $\rho_{a_i}=0$	Totally loss
	if $0<\rho_{a_i}(t)\leq 1$ for all t	Loss of effectiveness

variations are treated as premise parameters ($q=2$) and transformed into T-S representation by the upper and lower bounds using the sector nonlinearity concept (Tanaka and Wang, 2004) with $r=2^q=4$ sub-models weighted by membership functions $\eta_i(\theta)$. By assuming a small variation of the steering angle under normal driving conditions, a continuous LPV road-vehicle system with actuator faults can be described from Eq.(1)(3)(4) by the following state-space equations:

$$\begin{cases} \dot{x}(t)=A(\theta)x(t)+B(\theta)u(t)+d(\theta)w(t)+E(\theta)f_a(t) \\ y(t)=Cx(t) \end{cases} \tag{5}$$

where $x=\begin{bmatrix} v_y & \dot{\psi} & F_{yf} & F_{yr} & \psi_L & y_L \end{bmatrix}^\top$ is the state space vector, $u=\begin{bmatrix} \delta_f \end{bmatrix}^\top$ is the control input for the SbW system, $y=\begin{bmatrix} \dot{\psi} & a_y & \psi_L & y_L \end{bmatrix}^\top$ is the output vector. Whereas $w=\begin{bmatrix} f_w & \rho_c \end{bmatrix}^\top$ is the disturbance vector. $f_a(t)$ represent the actuator faults. Since we consider only the steering angle as a control input then $E(\theta)=B(\theta)$ and the state space equation (5) can be written as:

$$\begin{cases} \dot{x}(t)=A(\theta)x(t)+B(\theta)(u(t)+f_a(t))+d(\theta)w(t) \\ y(t)=Cx(t) \end{cases} \tag{6}$$

Note that the system matrices $A(\theta)$, $B(\theta)$, $d(\theta)$ and $E(\theta)$ in (5) explicitly depend on the premise variables vector θ given as:

$$\theta=\{v_x\ ,\ v_y\},\ q=2 \tag{7}$$

It is assumed that θ is bounded and also included in a convex polytopic domain of vertices such that:

$$\Theta=\{\theta(t)\in R^r|\ v_x\in[v_x^{min},\ v_x^{max}];\ v_y\in[v_y^{min},\ v_y^{max}]\} \tag{8}$$

Where v_x^{min} and v_x^{max} (respectively v_y^{min} and v_y^{max}) are known lower and upper bounds on longitudinal and lateral speeds. Considering the time-varying matrices $S\in\{A,\ B,\ d,\ E\}$ in (5), and using the sector nonlinearity approach in (Tanaka and Wang, 2004), we can derive the following polytopic LPV representation of model (5) with :

$$S=\sum_{i=0}^{r}\eta_i(\theta)S_i \tag{9}$$

Where $S_i\in\{A_i,\ B_i,\ d_i,\ E_i\}$ are constant for all $i\in[0,\ldots,r]$. The variable $r=2^q$ represents the number of local sub-models, with the q non-linearities related to $\theta\in\Theta$ captured via membership weighting functions $\eta_i(\theta)$. The membership functions adhere to the convex-sum property within the compact set of the state space:

$$\begin{cases} \sum_{i=0}^{r}\eta_i(\theta)=1, \quad \sum_{i=0}^{r}\dot{\eta}_i(\theta)=0, \quad \eta_i\in[0\ 1] \\ \forall i=\{1,2,\ldots,r\} \end{cases} \tag{10}$$

4 ADAPTIVE LPV-TS OBSERVER FOR STATE AND FAULT ESTIMATION

In this section, we are interested to propose an adaptive LPV-TS observer to estimate the system state and detect the actuator fault at the same time. For this purpose, the following assumptions must be verified

Assumption 1. *The triples (A,B,C) are controllable and observable to guarantee the LMI solution.*

Assumption 2. *The matching condition for the faults hold*

$$rank(CB_i)=rank(B_i) \tag{11}$$

Assumption 3. *The faults $f_a(t)$ are assumed to be a time varying signal, and have a norm-bounded first-time derivative.*

$$\parallel \dot{f}_a(t)\parallel\leq f_{a_{max}}, \quad 0\leq f_{a_{max}}\leq\infty \tag{12}$$

Motivated by the adaptive observer proposed in (Zhang et al., 2009) and (Sentouh et al., 2024), an adaptive Luenberger nonlinear observer for a vehicle equipped with SbW system considering actuator faults (5) is proposed as:

$$\begin{cases} \dot{\hat{x}}(t)=A(\theta)\hat{x}(t)+B(\theta)(u(t)+\hat{f}_a(t))+d(\theta)w(t) \\ \qquad\qquad +L(\hat{y}(t)-y(t)) \\ \hat{y}(t)=C\hat{x}(t) \\ \dot{\hat{f}}_a(t)=\Gamma H(\dot{e}_y-\sigma e_y) \end{cases} \tag{13}$$

Where $\hat{x}\in R^n$ is the observer state vector, $\hat{y}\in R^m$ is the observer output vector, $L\in R^{n\times m}$ and $H\in R^{f\times m}$ are the observer gain matrices, and $\hat{f}\in R^f$ is the estimated fault vector which depends on the output error vector e_y and its derivative. Note that the observer's

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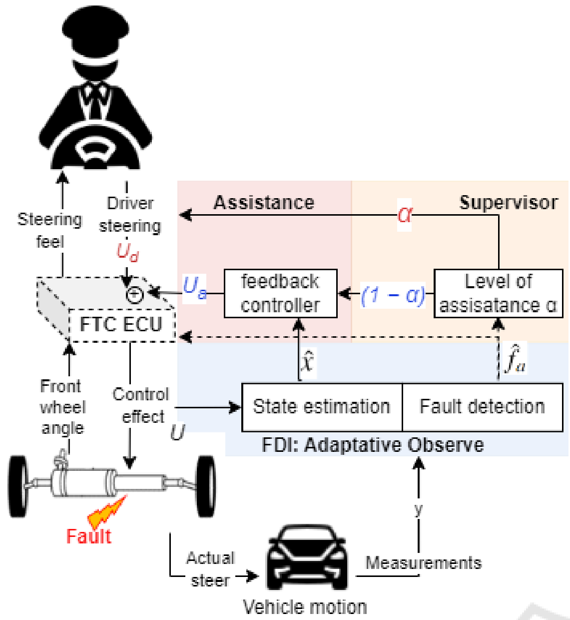

Figure 2: Driver assistance in SbW system with actuator fault.

matrices L and H are parameter varying with the same LPV form (9) and given by:

$$L = \sum_{i=0}^{r} \eta_i(\theta) L_i, \qquad H = \sum_{i=0}^{r} \eta_i(\theta) H_i \tag{14}$$

This adaptive fault estimation algorithm can guarantee $\lim_{t\to\infty} e_x(t) = 0$ and $\lim_{t\to\infty} e_f(t) = 0$ where e_x is the state estimation error and e_f is the fault estimation error, $\Gamma \in R^{f\times f}$ is the learning rate and σ is a tuning parameter.

5 FTC SHARED CONTROL FOR ACUATOR FAULT COMPENSATION

In this work, the objective is to compute a new shared control law $u(t)$ in order to compensate the effect of the actuators' faults and minimize the driver physical steering workload as shown in the architecture Fig. 2. for that, the FTC shared controller is given by:

$$u = \alpha u_d + (1-\alpha) u_a - \hat{f}_a \tag{15}$$

Where u_d is the driver steering angle and u_a is the feedback controller given by:

$$u_a = -K\hat{x} \tag{16}$$

Where the controller gain k is parameter varying with the same LPV form (9) and given by

$$K = \sum_{i=0}^{r} \eta_i(\theta) K_i \tag{17}$$

The purpose of the feedback controller u_a is to assist the driver in keeping the vehicle on the lane, especially when the actuator fails. To take into account the lane-keeping performance, we define the performance output of system (6) as:

$$y = \begin{bmatrix} \dot{\psi} & a_y & \psi_L & y_L \end{bmatrix}^\top \tag{18}$$

We define the following cost function:

$$\mathcal{J} = \int_0^\infty y^\top Q y + u_a^\top R u_a \, dt \tag{19}$$

Where Q and R are two symmetric positive definite matrices and are referred as the weighting matrices. The automatic system can takes over the control of the vehicle ($\alpha = 0$) when the actuator becomes faulty. The SbW control reconfigures the fault tolerant controller for a good steering performance.

In the following, we present the robust co-design conditions of adaptive fault estimation and FTSC strategy expressed as an LMIs optimization problem. The design process is based on a Lyapunov function, which takes into account both the observer and the system stability, as well as the lane keeping performance and robustness against actuator faults and disturbances. Considering the following polytopic Lyapunov function defined by:

$$\mathcal{V}(t) = x^\top(t) P x(t) + e_x^\top(t) P_e e_x(t) + \frac{1}{\sigma} e_f^\top(t) \Gamma^{-1} e_f(t) \tag{20}$$

Where $P \in R^{n\times n}$ and $P_e \in R^{n\times n}$ are symmetric positive definite matrices.

In order to stabilize the vehicle system (6), as well as the observer (13) and to guarantee an upper-bound for the cost function (19) under zero-initial condition we apply the following condition:

$$\dot{\mathcal{V}}(t) + x^\top(t) Q x(t) + u^\top(t) R u(t) \le \gamma f_a^\top f_a + \gamma w^\top w \tag{21}$$

Where $\dot{\mathcal{V}}(t)$ is the time-derivative of the Lyapunov function (20) along the trajectory of (6).

Lemma 1. *For every positive definite matrix $G > 0$ the following property holds (Fouka et al., 2021)*

$$2 e_f^\top \Gamma^{-1} \dot{f}_a \le e_f^\top G + \dot{f}_a \Gamma^{-1} G^{-1} \Gamma^{-1} \dot{f}_a \tag{22}$$

Using successively Schur complement lemma (Boyd et al., 1994) and Lemma.1 with $X = P^{-1}$, $M = KX$ and $N = P_e L$ it follows that we can obtain the LMI optimization problem after some algebraic

$$\begin{bmatrix}
\mathcal{H}_e(AX-BM) & X^\top C^\top & M^\top & 0 & B & D & 0 & 0 & I_x & M^\top R \\
* & -Q^{-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
* & * & -R^{-1} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
* & * & * & \mathcal{H}_e(P_eA-NC) & -\frac{1}{\sigma}(A^\top P_eB - C^\top N^\top B - P_eB) & 0 & P_eD & P_e & 0 & 0 \\
* & * & * & * & \frac{1}{\sigma}G & 0 & \frac{-B^\top P_eD}{\sigma} & \frac{-B^\top P_e}{\sigma} & 0 & 0 \\
* & * & * & * & * & -\gamma & 0 & 0 & 0 & 0 \\
* & * & * & * & * & * & -\varepsilon I_d & 0 & 0 & 0 \\
* & * & * & * & * & * & * & -\varepsilon I_x & 0 & 0 \\
* & * & * & * & * & * & * & * & -\varepsilon I_x & 0 \\
* & * & * & * & * & * & * & * & * & -\gamma+R
\end{bmatrix} < 0 \tag{23}$$

manipulations as shown in the matrix at the top of the next page (see Equation 23), with $I_x \in R^{n\times n}$ and $I_d \in R^{\omega\times\omega}$ are identity matrix. γ, ε are positive scalars, and the operator $\mathcal{H}_e(A) = A^\top A$. When the above condition hold, the observer gain matrix is given by:

$$L = P_e^{-1}N \tag{24}$$

And the controller gain matrix is given by:

$$K = MX^{-1} \tag{25}$$

On the other hand, if the assumption $\text{rank}(CB) = \text{rank}(B)$ holds, it is possible to obtain matrices H such that (see (Corless and Tu, 1998)):

$$HC = B^\top P_e \tag{26}$$

The control and observer co-design conditions expressed in terms of LMIs (23) are solved with YALMIP toolbox and SeDuMi solver (Lofberg, 2004).

6 EXPERIMENTAL VALIDATION

The experimental validation involves the implementation in a SHERPA-LAMIH road vehicle dynamic simulator as shown in Fig.3. Note that in this work, the steering wheel feedback motor is controlled by a PD regulator of the tracking error between the actual steering wheel angle and front wheel angle to provide the driver with the true feeling of the steering effort.

In this section, we explain our main results through two use cases. The first one (Fig. 4 and Fig. 5), the human driver takes over the control authority and undergoes a lane-keeping maneuver. During this maneuver, time-varying fault signals for the steering are generated to represent a varying degree of efficiency loss in the actuator, as discussed in Section 3.1. These fault signals simulate real-world scenarios where the steering system might not operate optimally due to various reasons. Figure 4 illustrates the observer performance, showing that the proposed observer provides an accurate estimation of both the system states and actuator faults accurately. This demonstrates the robustness and reliability of the proposed fault estimation approach.

The performance of the actuator fault compensation system are depicted in Figure 5, where the vehicle dynamics behavior with and without the fault compensation are compared to that of the normal driving condition (without faults). This figure highlights the effectiveness of our compensation strategy in minimizing the impact of actuator faults during manual driving. However, even though a driver can manipulate the steering wheel angle and correct the deviation path through the compensation of the steering wheel angle, he/she does not have a good understanding of the driving situation and can deviate from the desired lane.

In the second use case, we are interested by the purpose of further assisting the steering behavior of the driver especially during an actuator faults. Figures 6 and 7 show the main results of the FTC shared control. We performed a test by injecting an actuator fault at time $t = 30s$ as shown in Fig. 6. When the fault is detected, the control is shared between the driver and the system. Hence, driver authority decreases, and the need for assistance increases by activating the weighting decision parameter α for shared control to guarantee a smooth control transition between the driver and the lane keeping assist system. We can observe from Fig. 7 the good performance of the proposed fault-tolerant shared control to maintain a lower vehicle lateral deviation after the appearance of the actuator fault. After activating the driving assistance during the actuator fault compensation, the lateral position error becomes smaller compared to the manual driving mode with actuator fault compensation, ensuring that the vehicle maintains its desired trajectory and stability more efficiently even in the presence of faults. The observed results clearly indicate that our fault compensation mechanism can effectively restore the vehicle's positioning performance as the nominal driving situation, thereby enhancing safety and reliability.

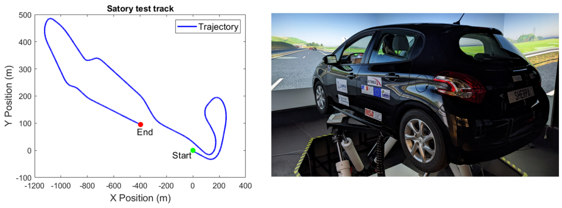

Figure 3: SHERPA dynamic driving simulator on the Satoty test.

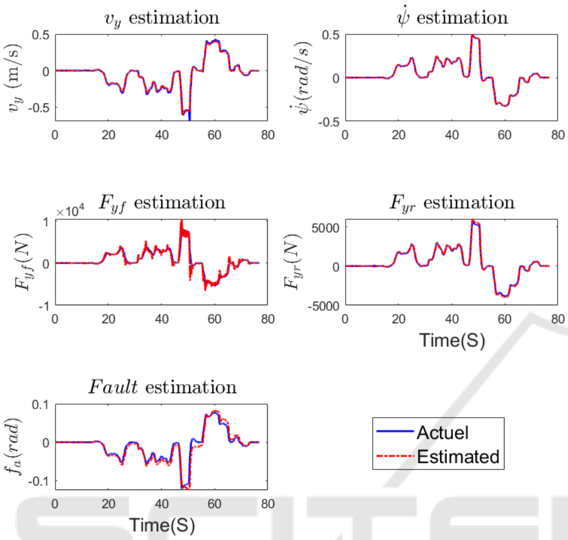

Figure 4: Observer performance: state and fault estimation.

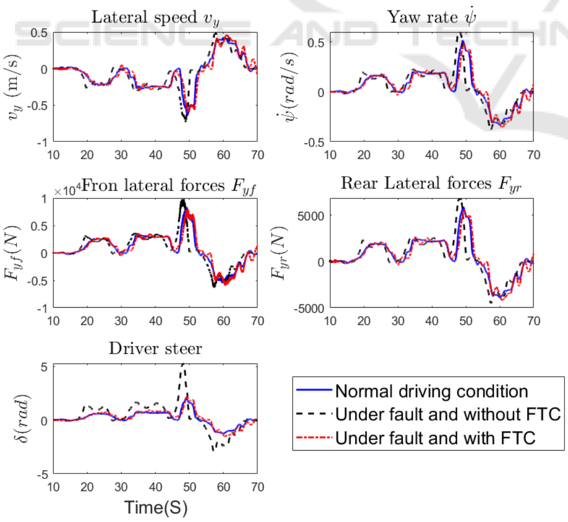

Figure 5: FTC performance: Actuator Fault Compensation in manual driving.

7 CONCLUSIONS

This paper proposed a new co-design of the observer-based fault-tolerant shared control strategy of Steer-

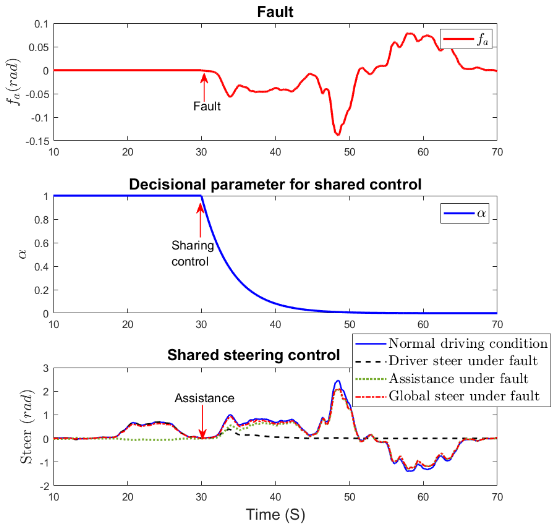

Figure 6: FTC shared control.

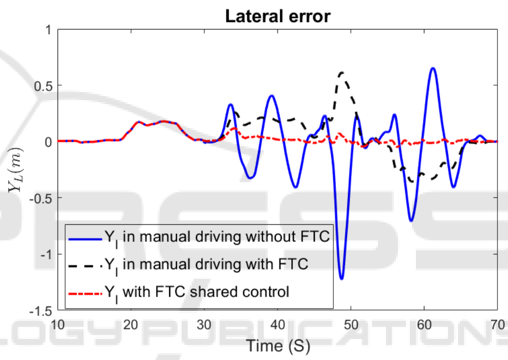

Figure 7: FTC shared control performance: lateral error in manual and assistance driving during actuator fault.

by-Wire (SbW) systems with actuator fault for driver lane keeping assistance system. An LPV observer architecture was proposed to estimate simultaneously the vehicle state and unknown actuator faults considering real-time unmeasurable variations in longitudinal and lateral velocities based on T-S representation with polytopic approach. Based on the Lyapunov stability arguments, the system stability and the asymptotic convergence of state and fault estimation errors has been proved. The control and observer co-design conditions have been obtained through an optimization problem which is formulated in terms of linear matrix inequalities (LMI). Experimental validation was performed using the LAMIH-SHERPA dynamic car simulator in real driving situations. The experimental results showed that the LPV observer provides an accurate estimation of both the vehicle state and actuator faults. On the other hand, the fault-tolerant controller effectively minimizes the impact of such faults, where the shared control mechanism al-

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lows to guarantee a smooth control transition between the driver and the lane keeping assist system, which enhance safety and system reliability. The obtained results demonstrated the performance and the effectiveness of the proposed FTSC strategy.

8 FUTURE WORK

In this work, we addressed the issue of loss of actuator effectiveness as a fault. Our control system strategy is effective in cases of additive or multiplicative faults with a loss of actuator efficiency of up to 90%. However, we did not consider scenarios where the nature of the fault changes or there is a total loss of the actuator. Investigating these scenarios will be the focus of our future work.

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