Integrated design of fault-tolerant control for nonlinear systems based on fault estimation and T-S fuzzy modelling

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***Abstract*—This paper proposes an integrated design of fault-tolerant control (FTC) for nonlinear systems using Takagi-Sugeno (T-S) fuzzy models in the presence of modelling uncertainty along with actuator/sensor faults and external disturbance. An augmented state unknown input observer is proposed to estimate the faults and system states simultaneously, and using the estimates an FTC controller is developed to ensure robust stability of the closed-loop system. The main challenge arises from the bi-directional robustness interactions since the fault estimation (FE) and FTC functions have an uncertain effect on each other. The proposed strategy uses a single-step linear matrix inequality formulation to integrate together the designs of FE and FTC functions to satisfy the required robustness. The integrated strategy is demonstrated to be effective through a tutorial example of an inverted pendulum system (based on robust T-S fuzzy designs).**

***Index Terms*—Integrated fault-tolerant control, augmented state unknown input observer, nonlinear systems, T-S fuzzy systems, H_∞ optimization**

I. INTRODUCTION

During two decades there has been a growing interest in robust fault-tolerant control (FTC) system designs which are capable of tolerating faults whilst accounting for effect of modelling uncertainties [1], [2]. Recent attention has turned to methods of handling nonlinearity in FTC considering specific system structure [3], [4]. The nonlinear nature of dynamic systems means that methods such as Takagi-Sugeno (T-S) fuzzy [5] inference reasoning can be combined with the appropriate FTC theory as an extension to the linear robustness strategies. Using this approach a continuous nonlinear system can be modelled as a multiple-model representation corresponding to a number of regions of state space behaviour. Each of the multiple T-S models is represented by an IF-THEN rule corresponding to a linear system. Based on this the existing robust FTC theory can be applied to each of the local linear models, so that the T-S system can then have both local and global robust FTC properties (including good fault-tolerance, etc.) [3], [4], [6]–[9].

Existing FTC approaches based on T-S approaches may be either *passive* or *active*. The *passive* approach treats the faults as system uncertainties using optimization methods (as an extension of robust control), but the *active* methods actively estimate fault magnitudes and use the estimates to compensate the fault effects with closed-loop control systems. Although *passive FTC* might achieve acceptable control performance [3], [4], [10], [11], it cannot obtain local fault magnitude information and this approach is not suitable for on-line system repair in the presence of faults.

The traditional *active* FTC approach makes use of fault detection and isolation (FDI) that generates information about the occurrence and severity of the fault which could be used to facilitate a closed-loop system reconfiguration based on various forms of redundancy. In addition to obtaining fault information one important goal is to achieve suitable fault tolerance and acceptable control performance and approaches based on FDI have been proposed to achieve this [7], [9]. However, these approaches are complex in design and implementation requiring fault residual design in some optimal sense including robust design of detection thresholds. This strategy also requires the development and design of a suitable system reconfiguration mechanism and this is a subject of considerable complexity involving requirements for discrete-event, adaptive and time-delay system concepts. The resulting detection and reconfigurable delays and uncertainty impose additional complexities leading to potential lack of reliability in the overall FTC system design.

The alternative *active* FTC approach seeks to overcome several of these difficulties by using fault estimation (FE) as an alternative to FDI (see Fig. 1). This active approach comprises an FE observer and an FTC control modules without the need for active reconfiguration. The FE module is expected to generate all the required fault information (magnitude, location and time occurrence) using a robust observer-based approach. The robust fault estimates are used in the control system to directly compensate the fault effects subject to acceptable control performance and robustness.

Several FE strategies based on T-S fuzzy systems have been proposed, e.g. using: adaptive observers (AO) [12]–[16], augmented state observers (ASO) [17], unknown input observers (UIO) [6], and sliding mode augmented state observers (SMASO) [8], [18]. These approaches are based on robustness concepts and are thus good candidates to include in active FE based FTC system analysis and design.

The direct use of the observer-based FE brings significant convenience and application potential to the subject of active FTC system design. Beyond just T-S based FE estimation several FTC studies combine these methods within observer-based T-S fuzzy FTC schemes are proposed. A UIO based FE

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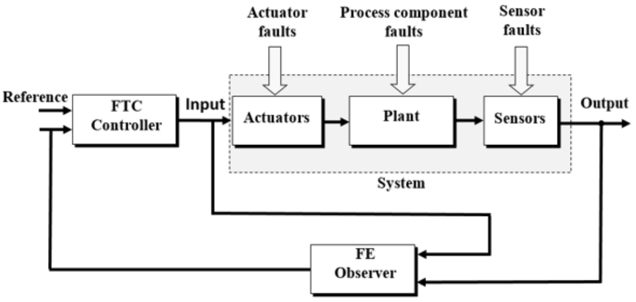

Fig. 1. Framework of FE based FTC systems

and FTC design is proposed in [6] for systems with actuator faults. AO based reconfigurable FTC designs are developed in [13] which also include model reference tracking control. An AO based dynamic output feedback FTC design, focusing on actuator faults and external disturbance is presented in [12]. [8] and [18] deal with the FE/FTC for stochastic systems with actuator/sensor faults and disturbance within the framework of SMASO. [17] proposes an ASO FE/FTC design for time-delay systems in the presence of actuator faults and external disturbance. [14] proposes an ASO fault tolerant tracking control problem application to an offshore wind turbine system with sensor faults and external disturbance. [15] develops an AO based FTC strategy for systems with actuator fault using a delta operator approach. Finally, [16] proposes an AO based FTC scheme for descriptor systems subject to actuator faults and disturbance.

However, few studies take into account the system modelling uncertainty, and the FE and FTC modules are designed separately. Actually, the uncertainty quite often exists in practical applications and might degrade the control system performance if not taken into account *a priori* in the design procedure. It has become apparent that the observer based FE and FTC modules must be designed together to achieve optimal control system performance and robustness [1], [19]–[21]. However, no systematic strategies were proposed in these studies. Moreover, due to the presence of uncertainty and disturbance, there are bi-directional robustness interactions between FE and FTC controller modules as defined by [22]. This bi-directional robustness coupling implies immediately that the generally known Separation Principle cannot apply. In this respect, the separated FE/FTC design results in a suboptimal solution of the overall FTC system design causing degraded overall system performance.

The above studies motivate the proposal in this paper to integrate the observer based FE and FTC designs for application to a class of nonlinear systems subjected to actuator/sensor faults. The modelling strategy considers external disturbance and uncertainty by using the T-S fuzzy approach. Compared with the literature, contributes of this paper are:

- *An augmented state unknown input observer (ASUIO) is proposed.* Although there are many FE observers as listed above, the proposed AO estimates the faults with finite error. The UIO is designed subject to a well-known rank condition concerned with the number of measurements and the number of disturbances. The ASO and the SMASO both require *a priori* knowledge of the fault bounds. In this study, an ASUIO is proposed to estimate the T-S fuzzy system states and faults using a continuous linear observer with no requirements for fault bounds or rank conditions. The fault is assumed to be in polynomial form with bounded v-th (highest) derivatives corresponding to known positive constants v. This approach is non-conservative in the robustness sense and it can estimate time-varying or even unbounded faults [23].
- *A systematic strategy for integrated FE/FTC design is developed.* The integrated observer and state estimate controller designs (based on T-S fuzzy systems) aim to obtain the observer and controller gains simultaneously. This is the widely known strategy for robust state estimate control using H_∞ optimization which is typically achieved using a single-step linear matrix inequality (LMI) formulation [24]. However, this optimization approach does not take into account the system modelling uncertainty [24] and furthermore, FTC is out of the scope of this study considered.

In this work the bi-directional concept described by [22] is extended here to take into account properly the robustness interactions between the FE and FTC modules for nonlinear systems using T-S fuzzy modelling approach. An FTC strategy is proposed for the nonlinear systems considered in the presence of model uncertainty, faults, and external disturbance. The ASUUIO based FE and FTC designs are re-formulated into an integrated design problem solved using a single-step LMI procedure.

The paper is organized as follows. Section II formulates the problem. Sections III - V present the designs of the ASUIO based FE and FTC controller. A tutorial example of a nonlinear inverted pendulum and cart system is provided in Section VI. This is followed by the Conclusion in Section VII.

In the paper the symbol † represents the Moore-Penrose pseudo inverse, $\mathrm{He}(W) = W + W^\top$, and $\star$ represents the symmetric part of a matrix.

II. Problem formulation

Consider a class of nonlinear systems described by

$$\begin{aligned} \dot{x} &= f_x(x, u, f_a, d) \\ y &= f_y(x, f_s) \end{aligned} \tag{1}$$

where $x \in R^n$, $u \in R^m$, and $y \in R^p$ stand for the state, control input, and output, respectively. $f_a \in R^q$ and $f_s \in R^{q_1}$ denote the actuator and sensor faults, respectively. $d \in R^l$ denotes the external disturbance. It is assumed that the nonlinear functions $f_x(\cdot)$ and $f_y(\cdot)$ are continuous and bounded in some sector $x \in [a, b]$ with some constants a and b. It should be noted that without loss of generality the system properties studied in this paper, including controllability, observability, and stability, are all local properties.

Considering modelling uncertainty, the system (1) can be modelled by the following T-S fuzzy system using sector nonlinearity [5]

$$\begin{aligned} \dot{x} &= \sum_{i=1}^{h} \rho_i(\theta(t)) \left[(A_i + \Delta A_i)x + B_i u + F_i f_a + D_i d \right] \\ y &= Cx + F_s f_s \end{aligned} \tag{2}$$

where $A_i \in R^{n\times n}$, $B_i \in R^{n\times m}$, $F_i \in R^{n\times q}$, $D_i \in R^{n\times l}$, $C_i \in R^{p\times n}$, and $F_s \in R^{p\times q_1}$ are known constant matrices. $\Delta A_i \in R^{n\times n}$ are perturbed matrices with structures $\Delta A_i = M_{0i}F_{0i}N_{0i}$, where F_{0i} are known Lebesgue measurable matrices satisfying $F_{0i}^\top(t)F_{0i}(t) \leq \mu_i I$ for some known scalars μ_i and matrices M_{0i} and N_{0i} of appropriate dimensions. h is the number of sub-models, and $\rho_i(\theta(t))$ are the membership functions depending on the premise variable vector $\theta(t) = [\theta_1, \ldots, \theta_s]$, where s is the number of the premise variables. The premise variables are some measurable variables of the system states.

Define η_{ij} ($i = 1, \ldots, h$ and $j = 1, \ldots, s$) as the fuzzy sets characterized by the membership functions. Further define $\eta_{ij}(\theta_j)$ as the grades of the membership of θ_j in the fuzzy sets η_{ij}. Then the membership functions can be defined by

$$\rho_i(\theta) = \frac{\sigma_i(\theta)}{\sum_{i=1}^h \sigma_i(\theta)},\ \sigma_i(\theta) = \prod_{j=1}^s \eta_{ij}(\theta_j)$$

which satisfies $0 \leq \rho_i(\theta) \leq 1$ and $\sum_{i=1}^h \rho_i(\theta) = 1$.

Throughout this study, the following assumptions are made.

Assumption 2.1: All the sub-models of (2) are observable and controllable in the fuzzy sets which they are defined, i.e., the pairs (A_i, C) are observable and the pairs (A_i, B_i) are controllable. Moreover, the fuzzy system (2) is observable and controllable in the sector $x \in [a, b]$.

Assumption 2.2: The actuator fault f_a is in the range space of the control input, i.e., $\mathrm{rank}(B_i, F_i) = \mathrm{rank}(B_i)$, $i = 1, 2, \ldots, h$.

Assumption 2.3: The k-th derivative of f_a and the k_1-th derivative of f_s are bounded for some given scalars k and k_1.

Remark 2.1: Assumption 2.1 implies that the i-th ($i = 1, 2, \ldots, h$) sub-models are locally observable/controllable, and the whole fuzzy system (2) is globally observable and controllable within the entire sector $x \in [a, b]$. The local observability/controllability together with Assumption 2.2 allow the existence of observers/controllers for each of the fuzzy models to achieve FE/FTC functions. The global observability/controllability guarantee the existence of an observer and a controller to achieve FE/FTC performance for the whole fuzzy system. In this paper, the observer and controller for the whole fuzzy system are fuzzy observer/controller, obtained by combining the observers/controllers of each sub-models with membership functions.

The local observability and controllability can be verified using the following criteria: the i-th sub-model of (2) is (a) observable if $\mathrm{rank}[C; CA_i; CA_i^2; \ldots; CA_i^{n-1}] = n$, and (b) controllable if $\mathrm{rank}[B_i, A_iB_i, A_i^2B_i, \ldots, A_i^{n-1}B_i] = n$. Sufficient criteria of robust observability and controllability for fuzzy systems are given in [25] and [26]. This paper considers only the observability and controllability of each triple (A_i, B_i, C) of the fuzzy system (2), which are special cases of [25], [26]. Therefore, the sufficient criteria in [25], [26] can be directly modified to verify the global observability and controllability of the fuzzy system (2).

III. AUGMENTED STATE UNKNOWN INPUT OBSERVER BASED FE

Define $\omega_s = f_a^{(s)}$ and $\upsilon_t = f_s^{(t)}$ where $s = 0, 1, \ldots, k-1$ and $t = 0, 1, \ldots, k_1 - 1$, then the system (2) is augmented into

$$\begin{aligned} \dot{\bar{x}} &= \sum_{i=1}^h \rho_i(\bar{A}_i\bar{x} + \bar{B}_iu + \Delta\bar{A}_i\bar{x} + \bar{D}_i\bar{d}) \\ y &= \bar{C}\bar{x} \end{aligned} \tag{3}$$

where

$$\bar{x} = \begin{bmatrix} x \\ \omega \\ \upsilon \end{bmatrix}, \omega = \begin{bmatrix} \omega_0 \\ \omega_1 \\ \vdots \\ \omega_{k-1} \end{bmatrix}, \upsilon = \begin{bmatrix} \upsilon_0 \\ \upsilon_1 \\ \vdots \\ \upsilon_{k_1-1} \end{bmatrix}$$

$$\bar{d} = \begin{bmatrix} d \\ \omega_{k-1} \\ \upsilon_{k_1-1} \end{bmatrix}, \bar{A}_i = \begin{bmatrix} A_i & F_i & 0 & 0 & 0 \\ 0 & 0 & I_{(k-1)q} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{(k_1-1)q_1} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\Delta\bar{A}_i = \begin{bmatrix} \Delta A_i & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix}, \bar{B}_i = \begin{bmatrix} B_i \\ 0_{(kq+k_1q_1)\times m} \end{bmatrix}$$

$$\bar{D}_i = \begin{bmatrix} D_i & 0 & 0 \\ 0 & 0_{(k-1)q\times q} & 0 \\ 0 & I_q & 0 \\ 0 & 0 & 0_{(k_1-1)q_1\times q_1} \\ 0 & 0 & I_{q_1} \end{bmatrix}$$

$\bar{C} = \begin{bmatrix} C \ 0_{p\times kq} \ F_s \ 0_{p\times(k_1-1)q_1} \end{bmatrix}$.

Remark 3.1: Since the pairs (A_i, C) are observable for all $i = 1, \ldots, h$, it follows that

$$\mathrm{rank}\begin{bmatrix} sI_n - A_i \\ C \end{bmatrix} = n,\ \forall s \in \mathcal{C}$$

which leads to

$$\begin{aligned} &\mathrm{rank}\begin{bmatrix} sI_{n+kq+k_1q_1} - \bar{A}_i \\ \bar{C} \end{bmatrix} \\ = \ &\mathrm{rank}\begin{bmatrix} sI_n - A_i & [-F_i\ 0] & 0 \\ 0 & J_s(I_q) & 0 \\ 0 & [0\ sI_q] & 0 \\ 0 & 0 & J_s(I_{q_1}) \\ 0 & 0 & [0\ sI_{q_1}] \\ C & 0 & [F_s\ 0] \end{bmatrix} \\ = \ &n + kq + k_1q_1 \end{aligned}$$

with $J_s(I_\kappa) = \begin{bmatrix} sI_\kappa & -I_\kappa & & \\ & sI_\kappa & \ddots & \\ & & \ddots & -I_\kappa \\ & & & sI_\kappa \end{bmatrix}$.

Thus, all the sub-models of the augmented system (3) are observable so that the overall augmented system is observable.

The new state $\bar{x}$ is estimated by an ASUIO in the form of

$$\begin{aligned} \dot{z} &= \sum_{i=1}^{h} \rho_i (M_i z + G_i u + L_i y) \\ \hat{x} &= z + Hy \end{aligned} \tag{4}$$

where $z,\ \hat{x} \in R^{n+kq+k_1q_1}$ are the observer state and the estimate of $\bar{x}$, respectively. The design matrices M_i, G_i, L_i, and H are of compatible dimensions.

Define the estimation error as $e = \bar{x} - \hat{x}$, then

$$\begin{aligned} \dot{e} &= \sum_{i=1}^{h} \rho_i \left[(\Xi \bar{A}_i - L_{1i}\bar{C})e + \Theta_1 z + \Theta_2 u + \Theta_3 y \right. \\ &\quad \left. + \Xi \Delta \bar{A}_i \bar{x} + \Xi \bar{D}_i \bar{d} \right] \end{aligned} \tag{5}$$

where $\Xi = I_{n+kq+k_1q_1} - H\bar{C}$, $L_i = L_{1i} + L_{2i}$, $\Theta_1 = \Xi\bar{A}_i - L_{1i}\bar{C} - M_i$, $\Theta_2 = \Xi\bar{B}_i - G_i$ and $\Theta_3 = (\Xi\bar{A}_i - L_{1i}\bar{C})H - L_{2i}$.

Lemma 3.1: Without uncertainty and disturbance, the error dynamics (5) are asymptotically stable if it holds that for all $i = 1, \ldots, h$,

$$M_i \text{ are Hurwitz} \tag{6}$$

$$\Xi\bar{A}_i - L_{1i}\bar{C} - M_i = 0 \tag{7}$$

$$\Xi\bar{B}_i - G_i = 0 \tag{8}$$

$$(\Xi\bar{A}_i - L_{1i}\bar{C})H - L_{2i} = 0. \tag{9}$$

Proof: Consider that no uncertainty and disturbance are acting on the system and the conditions (6) - (9) hold, the error dynamics (5) then become

$$\dot{e} = \sum_{i=1}^{h} \rho_i M_i e$$

which are stable and $\lim\limits_{t\to\infty} e(t) = 0$ for all $i = 1, \ldots, h$. ■

Upon the satisfaction of conditions (7) - (9) and considering the uncertainty and disturbance, (5) can be rearranged as

$$\dot{e} = \sum_{i=1}^{h} \rho_i \left[(\Xi\bar{A}_i - L_{1i}\bar{C})e + \Xi\Delta\bar{A}_i\bar{x} + \Xi\bar{D}_i\bar{d} \right]. \tag{10}$$

Remark 3.2: It should be noted that $G_i = \Xi B_i$, and the remaining matrices L_{2i} and M_i can be derived immediately from (7) - (9) once the matrices L_{1i} and H are designed to ensure the robust stability of (10) in the sequel. Thus, the design of the observer (4) is reduced to a comparatively simple design of L_{1i} and H, which facilitates the FE/FTC design procedure.

IV. FTC CONTROLLER

Design an FTC controller for the system (2) as

$$u = \sum_{i=1}^{h} \rho_i K_i \hat{x} \tag{11}$$

where $K_i = \left[K_{xi}\ K_{fi}\ 0_{m\times((k-1)q+k_1q_1)} \right]$ with $K_{xi} \in R^{m\times n}$ and $K_{fi} \in R^{m\times q}$ the state-feedback control gains and actuator fault compensation gains, respectively. According to Assumption 2.2, K_{fi} are chosen as $K_{fi} = -B_i^{\dagger}F_i$.

Substituting (11) into (2) gives the closed-loop system

$$\begin{aligned} \dot{x} &= \sum_{i=1}^{h}\sum_{j=1}^{h} \rho_i\rho_j \left[(A_i + B_iK_{xj})x + E_{ij}e \right. \\ &\quad \left. + \Delta A_i x + D_i d \right] \end{aligned} \tag{12}$$

where $E_{ij} = [-B_iK_{xj}\ F_i\ 0]$.

V. FE AND FTC SYNTHESIS

A. Separated Designs of FE/FTC

As summarized in the Introduction, the state-of-art of the way to synthesize the FE and FTC modules is the separated design approach, by designing first the FE observer and then the FTC controller. This separated FE/FTC design idea is achieved based on the satisfaction of the Separation Principle and it neglects the bi-directional robustness interactions between the observer and the controller which results from the disturbance and uncertainty. In this respect, the error dynamics are rearranged into

$$\begin{aligned} \dot{e} &= \sum_{i=1}^{h} \rho_i \left[(\Xi\bar{A}_i - L_{1i}\bar{C})e + \Xi\bar{D}_i\bar{d} \right] \\ z_e &= C_{e_1} e \end{aligned} \tag{13}$$

where $z_e \in R^{z_1}$ is the measured output and C_{e_1} is a constant matrix of appropriate dimension. Suppose that the observer has already been made stable, i.e., $e = 0$, then the feedback control system becomes

$$\begin{aligned} \dot{x} &= \sum_{i=1}^{h}\sum_{j=1}^{h} \rho_i\rho_j \left[(A_i + B_iK_{xj})x + \Delta A_i x + D_i d \right] \\ y_c &= y - F_s\hat{f}_s \\ z_x &= C_{x_1} x \end{aligned} \tag{14}$$

where y_c is the compensated system output, $\hat{f}_s$ is the sensor fault estimate, $z_x \in R^{z_2}$ is the measured output, and the constant matrix C_{x_1} is of appropriate dimension.

Theorems 5.1 and 5.2 are sufficient pre-requisites to the determination of the observer and controller gains, respectively.

Theorem 5.1: Given a positive scalar γ_1, the error dynamics (13) are stable with H_∞ performance $\|G_{z_e\bar{d}}\| < \gamma_1$, if there exists a symmetric positive definite matrix Y_1, and matrices W_1, W_{2i}, such that for all $i = 1, 2, \ldots, h$,

$$\begin{bmatrix} \Psi_1 & Y_1\bar{D}_i - W_1\bar{C}\bar{D}_i & C_{e_1}^{\top} \\ \star & -\gamma_1^2 I & 0 \\ \star & \star & -I \end{bmatrix} < 0$$

where $\Psi_1 = \mathrm{He}(Y_1\bar{A}_i - W_1\bar{C}\bar{A}_i - W_{2i}\bar{C})$. Then the gains are given by $H = Y_1^{-1}W_1$ and $L_{1i} = Y_1^{-1}W_{2i}$.

Proof: The proof of Theorem 5.1 directly follows from the Bounded Real Lemma [27] with $W_1 = Y_1H$ and $W_{2i} = Y_1L_{1i}$, $i = 1, 2, \ldots, h$. ■

Theorem 5.2: Given positive scalars γ_2 and ϵ_{0i}, the control system (14) is stable with H_∞ performance $\|G_{z_xd}\| < \gamma_2$, if there exists a symmetric positive definite matrix X_1 and matrices W_{3j}, $j = 1, 2, \cdots, h$, such that for all $i, j = 1, 2, \ldots, h$,

$$\begin{bmatrix} \Psi_2 & D_i & X_1 C_{x_1}^\top & M_{0i} & X_1 N_{0i}^\top \\ \star & -\gamma_2^2 I & 0 & 0 & 0 \\ \star & \star & -I & 0 & 0 \\ \star & \star & \star & -\epsilon_{0i} I & 0 \\ \star & \star & \star & \star & -(\epsilon_{0i}\mu_i)^{-1} I \end{bmatrix} < 0 \quad (15)$$

where $\Psi_2 = \mathrm{He}(A_i X_1 + B_i W_{3j})$. Then the control gains are given by $K_{xj} = W_{3j} X_1^{-1}$.

Proof: Denote $\chi_{0i} = x^\top \Delta A_i^\top X_0 x + x^\top X_0 \Delta A_i x$, it follows that for some positive scalars ϵ_{0i},

$$\begin{aligned} \chi_{0i} &= -\left[\sqrt{\epsilon_{0i}}^{-1} M_{0i}^\top X_0 x - \sqrt{\epsilon_{0i}} F_{0i} N_{0i} x\right]^\top \\ &\quad \times \left[\sqrt{\epsilon_{0i}}^{-1} M_{0i}^\top X_0 x - \sqrt{\epsilon_{0i}} F_{0i} N_{0i} x\right] \\ &\quad + \epsilon_{0i}^{-1} x^\top X_0 M_{0i} M_{0i}^\top X_0 x + \epsilon_{0i} x^\top N_{0i}^\top F_{0i}^\top F_{0i} N_{0i} x \\ &\leq \epsilon_{0i}^{-1} x^\top X_0 M_{0i} M_{0i}^\top X_0 x + \epsilon_{0i}\mu_i x^\top N_{0i}^\top N_{0i} x. \end{aligned}$$

Consider a Lyapunov function $V_{x0} = x^\top X_0 x$, then

$$\begin{aligned} \dot{V}_{x0} &= \sum_{i=1}^{h}\sum_{j=1}^{h} \rho_i \rho_j \left[x^\top \mathrm{He}(X_0(A_i + B_i K_{xj}))x + \chi_{0i}\right. \\ &\quad \left. + \mathrm{He}(x^\top X_0 D_i d)\right] \\ &\leq \sum_{i=1}^{h}\sum_{j=1}^{h} \rho_i \rho_j \left\{x^\top \left[\mathrm{He}(X_0(A_i + B_i K_{xj}))\right.\right. \\ &\quad \left. + \epsilon_{0i}^{-1} X_0 M_{0i} M_{0i}^\top X_0 + \epsilon_{0i}\mu_i N_{0i}^\top N_{0i}\right] x \\ &\quad \left. + \mathrm{He}(x^\top X_0 D_i d)\right\}. \end{aligned}$$

By the Bounded Real Lemma [27], the system (14) is stable with H_∞ performance $\|G_{z_x d}\| < \gamma_2$, if it holds that

$$\begin{bmatrix} \mathit{\Theta} & X_0 D_i & C_{x_1}^\top \\ \star & -\gamma_2^2 I & 0 \\ \star & \star & -I \end{bmatrix} < 0 \quad (16)$$

where $\mathit{\Theta} = \mathrm{He}\left[X_0(A_i + B_i K_{xj})\right] + \epsilon_{0i}^{-1} X_0 M_{0i} M_{0i}^\top X_0 + \epsilon_{0i}\mu_i N_{0i}^\top N_{0i}$.

Note that the inequality (16) is nonlinear. Define $X_1 = X_0^{-1}$. Multiplying both sides of (16) by $\mathrm{diag}(X_1, I, I)$ and its transpose and using the Schur complement, then (16) becomes

$$\begin{bmatrix} \Psi_2 & D_i & X_1 C_{x_1}^\top & M_{0i} & X_1 N_{0i}^\top \\ \star & -\gamma_2^2 I & 0 & 0 & 0 \\ \star & \star & -I & 0 & 0 \\ \star & \star & \star & -\epsilon_{0i} I & 0 \\ \star & \star & \star & \star & -(\epsilon_{0i}\mu_i)^{-1} I \end{bmatrix} < 0 \quad (17)$$

where $\Psi_2 = \mathrm{He}(A_i X_1 + B_i K_{xj} X_1)$. Further define $W_{3j} = K_{xj} X_1$, then (17) directly leads to (15). ■

Recalling here the error dynamics (10) and the closed-loop system (12)

$$\begin{aligned} \dot{e} &= \sum_{i=1}^{h} \rho_i [(\Xi \bar{A}_i - L_{1i}\bar{C})e + \Xi \Delta \bar{A}_i \bar{x} + \Xi \bar{D}_i \bar{d}] \\ \dot{x} &= \sum_{i=1}^{h}\sum_{j=1}^{h} \rho_i \rho_j \left[(A_i + B_i K_{xj})x + E_{ij} e\right. \\ &\quad \left. + \Delta A_i x + D_i d\right]. \end{aligned} \quad (18)$$

Define $H = [H_1; H_2; H_3; H_4; H_5]$, it follows that

$$\Xi \Delta \bar{A}_i \bar{x} = \begin{bmatrix} (I_n - H_1 C)\Delta A_i x \\ -H_2 C \Delta A_i x \\ -H_3 C \Delta A_i x \\ -H_4 C \Delta A_i x \\ -H_5 C \Delta A_i x \end{bmatrix}$$

$$\Xi \bar{D}_i \bar{d} = \begin{bmatrix} (I_n - H_1 C) D_i d \\ -H_2 C D_i d \\ -H_3 C D_i d + \omega_{k-1} \\ -H_4 C D_i d \\ -H_5 C D_i d + v_{k_1 - 1} \end{bmatrix}. \quad (19)$$

From (18) and (19) we can see that: (i) The state estimation and FE are affected by the disturbance d and the uncertainty $\Delta A_i x$, whilst the FE is also affected by the fault modelling errors, i.e., ω_{k-1} and v_{k_1-1}; (ii) The feedback control system is affected by the uncertainty, disturbance, and estimation errors. This important phenomenon of bi-directional robustness interactions between the FE and FTC modules has been defined in [22] as a robustness issue for uncertain linear systems. This paper extends the notion of this robustness interaction into the framework of a T-S fuzzy system representation of a nonlinear system.

Usually when controllers and state observers are designed for nonlinear systems it is assumed that in a state space region close to the system operation a locally linear dynamical system can be used for design. Hence, for such systems it is well known that the Separation Principle cannot apply in general. In this work we consider the application of a T-S fuzzy approach to a nonlinear system problem and hence a form of specially integrated design must be used to achieve the robustness in the estimator and controller designs. From the statement above for the FE and FTC problems bi-directional robustness interactions exist between the FE and FTC controller modules and hence a true integration of these module designs must be achieved to obtain satisfactory robust FTC performance.

So, although the separated design method in Section V-A can avoid the design complexity resulting from the coupling between the observer and controller, it only permits a suboptimal solution of the overall FTC system design to be achieved, leading to degraded FE/FTC performance. To overcome this, Section V-B describes an integrated FE/FTC design strategy (see Fig. 2) for the system (2) by taking into account the bi-directional interaction.

B. Integrated Design of FE/FTC

Combining (10) and (12) gives the following composite closed-loop system including fault estimation with fault compensation control, based on the T-S formulation given in (2),

$$\begin{aligned} \dot{x} &= \sum_{i=1}^{h}\sum_{j=1}^{h} \rho_i \rho_j [(A_i + B_i K_{xj})x + E_{ij} e + \Delta A_i x + \hat{D}_i \bar{d}] \\ \dot{e} &= \sum_{i=1}^{h} \rho_i \left[(\Xi \bar{A}_i - L_{1i}\bar{C})e + \Xi \Delta \bar{A}_i \bar{x} + \Xi \bar{D}_i \bar{d}\right] \\ y_c &= y - F_s \hat{f}_s \\ z_r &= C_x x + C_e e \end{aligned} \quad (20)$$

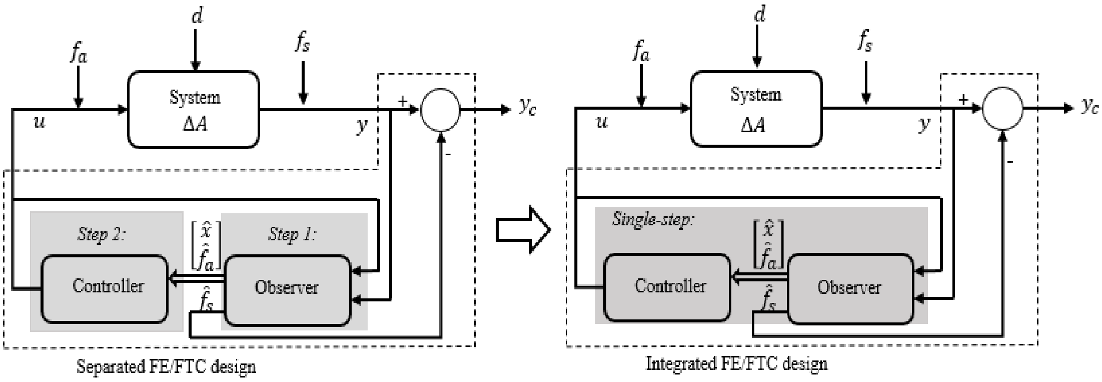

Fig. 2. Frameworks of the separated and integrated FE/FTC design systems

where y_c is the compensated system output, $\hat{f}_s$ is the sensor fault estimate, $z_r \in R^r$ is the measured output, and the matrices C_x and C_e are of appropriate dimensions. $\hat{D}_i = [D_i\ 0]$.

Note that the integrated FE/FTC design for the T-S fuzzy system (2) is now reformulated into an observer-based robust control problem of the composite closed-loop system (20), which will be solved in the sequel using H_∞ optimization with a single-step LMI formulation.

The strategy for solving the integrated FE/FTC robust design is in general a bilinear matrix inequality (BMI) problem as outlined in Lemma 5.1 below. However, Lemma 5.1 leads to a statement that Lemma 5.2 will transform the integrated design into a single-step LMI problem, which facilitates the solution strategy. Lemma 5.1 is inspired by [28] as follows.

Lemma 5.1: Given positive scalars γ, ϵ_{1i}, and ϵ_{2i}, the closed-loop system (20) is stable with H_∞ performance $\|G_{z_r\bar{d}}\| < \gamma$, if there exist two symmetric positive definite matrices X and Y, and matrices K_{xi}, L_{1i}, X_{ii}, $X_{ij} = X_{ji}$, $i \neq j$, $i, j = 1, 2, \dots, h$, such that

$$\begin{bmatrix} \mathrm{He}(X\mathit{\Lambda}_{ii}) & XE_{ii} \\ \star & \mathrm{He}(Y\mathit{\Gamma}_{ii}) \end{bmatrix} < X_{ii} \tag{21}$$

$$\begin{bmatrix} \mathrm{He}(X\mathit{\Lambda}_{ij}) & X(E_{ij}+E_{ji}) \\ \star & \mathrm{He}(Y\mathit{\Gamma}_{ij}) \end{bmatrix} < X_{ij} + X_{ij}^\top \tag{22}$$

$$\begin{bmatrix} X_{11} & \cdots & X_{1h} & \Pi_1 \\ \vdots & \ddots & \vdots & \vdots \\ X_{1h}^\top & \cdots & X_{hh} & \Pi_h \\ \Pi_1^\top & \cdots & \Pi_h^\top & -I \end{bmatrix} < 0 \tag{23}$$

where $\mathit{\Lambda}_{ii} = A_i + B_iK_{xi}$, $E_{ii} = [-B_iK_{xi}\ F_i\ 0]$, $\mathit{\Gamma}_{ii} = \Xi\bar{A}_i - L_{1i}\bar{C}$, $\mathit{\Lambda}_{ij} = A_i + A_j + B_iK_{xj} + B_jK_{xi}$, $\mathit{\Gamma}_{ij} = 2(\Xi\bar{A}_i - L_{1i}\bar{C})$, $E_{ij} = [-B_iK_{xj}\ \ F_i\ \ 0]$, $E_{ji} = [-B_jK_{xi}\ \ F_j\ \ 0]$, $\Pi_i = \mathrm{diag}(\Pi_{1i}, \Pi_{2i})$, $\Pi_{1i} = [\lambda_{1i}XM_{0i}\ \ \lambda_{2i}N_{0i}^\top\ \ 0\ \ \lambda_{4i}X\hat{D}_i\ \ C_x^\top]$, $\Pi_{2i} = [0\ \ 0\ \ \lambda_{3i}Y\Xi\bar{M}_{0i}\ \ \lambda_{4i}Y\Xi\bar{D}_i\ \ C_e^\top]$, $\lambda_{1i} = \sqrt{\epsilon_{2i}^{-1}}$, $\lambda_{2i} = \sqrt{\mu_\epsilon}$, $\lambda_{3i} = \sqrt{\epsilon_{1i}^{-1}}$, and $\lambda_{4i} = \gamma^{-1}$.

Proof: Consider a Lyapunov function $V_e = e^\top Ye$. Define $\bar{M}_{0i} = [M_{0i}^\top\ 0]^\top$ and $\chi_{1i} = \bar{x}^\top\Delta\bar{A}_i^\top\Xi^\top Ye + e^\top Y\Xi\Delta\bar{A}_i\bar{x}$, then for some positive scalars ϵ_{1i},

$$\begin{aligned} \chi_{1i} &= -\left[\sqrt{\epsilon_{1i}}^{-1}\bar{M}_{0i}^\top\Xi^\top Ye - \sqrt{\epsilon_{1i}}F_{0i}N_{0i}x\right]^\top \\ &\quad\times\left[\sqrt{\epsilon_{1i}}^{-1}\bar{M}_{0i}^\top\Xi^\top Ye - \sqrt{\epsilon_{1i}}F_{0i}N_{0i}x\right] \\ &\quad+\epsilon_{1i}^{-1}e^\top Y\Xi\bar{M}_{0i}\bar{M}_{0i}^\top\Xi^\top Ye + \epsilon_{1i}x^\top N_{0i}^\top F_{0i}^\top F_{0i}N_{0i}x \\ &\leq \epsilon_{1i}^{-1}e^\top Y\Xi\bar{M}_{0i}\bar{M}_{0i}^\top\Xi^\top Ye + \epsilon_{1i}\mu_i x^\top N_{0i}^\top N_{0i}x. \end{aligned}$$

Thus the time derivative of V_e is

$$\begin{aligned} \dot{V}_e &= \sum_{i=1}^{h}\rho_i\left[e^\top\mathrm{He}(Y(\Xi\bar{A}_i - L_{1i}\bar{C}))e + \mathrm{He}(e^\top Y\Xi\bar{D}_i\bar{d})\right. \\ &\quad\left.+\chi_{1i}\right] \\ &\leq \sum_{i=1}^{h}\rho_i\left\{e^\top[\mathrm{He}(Y(\Xi\bar{A}_i - L_{1i}\bar{C}))\right. \\ &\quad+\epsilon_{1i}^{-1}Y\Xi\bar{M}_{0i}\bar{M}_{0i}^\top\Xi^\top Y]e + \mathrm{He}(e^\top Y\Xi\bar{D}_i\bar{d}) \\ &\quad\left.+\epsilon_{1i}\mu_i x^\top N_{0i}^\top N_{0i}x\right\}. \end{aligned} \tag{24}$$

Consider a Lyapunov function $V_x = x^\top Xx$ for the control system. Define $\chi_{2i} = x^\top\Delta A_i^\top Xx + x^\top X\Delta A_ix$, it follows that for some positive scalars ϵ_{2i},

$$\begin{aligned} \chi_{2i} &= -\left[\sqrt{\epsilon_{2i}}^{-1}M_{0i}^\top Xx - \sqrt{\epsilon_{2i}}F_{0i}N_{0i}x\right]^\top \\ &\quad\times\left[\sqrt{\epsilon_{2i}}^{-1}M_{0i}^\top Xx - \sqrt{\epsilon_{2i}}F_{0i}N_{0i}x\right] \\ &\quad+\epsilon_{2i}^{-1}x^\top XM_{0i}M_{0i}^\top Xx + \epsilon_{2i}x^\top N_{0i}^\top F_{0i}^\top F_{0i}N_{0i}x \\ &\leq \epsilon_{2i}^{-1}x^\top XM_{0i}M_{0i}^\top Xx + \epsilon_{2i}\mu_i x^\top N_{0i}^\top N_{0i}x. \end{aligned}$$

Similarly, the time derivative of V_x is

$$\begin{aligned} \dot{V}_x &= \sum_{i=1}^{h}\sum_{j=1}^{h}\rho_i\rho_j\Big[x^\top\mathrm{He}(X(A_i + B_iK_{xj}))x \\ &\quad+\mathrm{He}(x^\top X\bar{F}_{ij}e) + \chi_{2i} + \mathrm{He}(x^\top X\hat{D}_i\bar{d})\Big] \\ &\leq \sum_{i=1}^{h}\sum_{j=1}^{h}\rho_i\rho_j\Big\{x^\top[\mathrm{He}(X(A_i + B_iK_{xj})) \\ &\quad+\epsilon_{2i}^{-1}XM_{0i}M_{0i}^\top X + \epsilon_{2i}\mu_iN_{0i}^\top N_{0i}]x \\ &\quad+\mathrm{He}(x^\top XE_{ij}e) + \mathrm{He}(x^\top X\hat{D}_i\bar{d})\Big\}. \end{aligned} \tag{25}$$

Define $\xi = [x^\top \ e^\top]^\top$ and $V = V_e + V_x$. By (24) and (25),

$$\begin{aligned} \dot{V} &= \sum_{i=1}^{h}\sum_{j=1}^{h}\rho_i\rho_j\xi^\top \begin{bmatrix} J_{1ij} & XE_{ij} \\ \star & J_{2ii} \end{bmatrix}\xi \\ &\quad -\sum_{i=1}^{h}\sum_{j=1}^{h}\rho_i\rho_j\frac{1}{\gamma^2}\xi^\top P\tilde{D}_i\tilde{D}_i^\top P\xi \\ &\quad +\sum_{i=1}^{h}\rho_i(\bar{d}^\top\tilde{D}_i^\top P\xi + \xi^\top P\tilde{D}_i\bar{d}) - z_r^\top z_r \end{aligned} \tag{26}$$

where $\tilde{D}_i = [\hat{D}_i \ \bar{D}_i]$, $P = \mathrm{diag}(X, Y)$, $\mu_\epsilon = (\epsilon_{1i} + \epsilon_{2i})\mu_i$, $J_{1ij} = \mathrm{He}\left[X(A_i + B_iK_{xj})\right] + \epsilon_{2i}^{-1}XM_{0i}M_{0i}^\top X + \mu_\epsilon N_{0i}^\top N_{0i} + \frac{1}{\gamma^2}X\hat{D}_i\hat{D}_i^\top X + C_x^\top C_x$, and $J_{2ij} = \mathrm{He}\left[Y(\Xi\bar{A}_i - L_{1i}\bar{C})\right] + \frac{1}{\gamma^2}Y\Xi\bar{D}_i\bar{D}_i^\top\Xi^\top Y + \epsilon_{1i}^{-1}Y\Xi\bar{M}_{0i}\bar{M}_{0i}^\top\Xi^\top Y + C_e^\top C_e$.

The H_∞ performance $\|G_{z_r\bar{d}}\| < \gamma$ is represented by

$$J = \int_0^\infty (z_r^\top z_r - \gamma^2\bar{d}^\top\bar{d})dt < 0. \tag{27}$$

Under zero initial conditions,

$$\begin{aligned} J &= \int_0^\infty (z_r^\top z_r - \gamma^2\bar{d}^\top\bar{d} + \dot{V})dt - \int_0^\infty \dot{V}dt \\ &\le \int_0^\infty (z_r^\top z_r - \gamma^2\bar{d}^\top\bar{d} + \dot{V})dt. \end{aligned}$$

Subsequently, a sufficient condition for (27) is

$$J_1 = z_r^\top z_r - \gamma^2\bar{d}^\top\bar{d} + \dot{V} < 0.$$

Define $\bar{\xi} = [\xi^\top \ \bar{d}^\top]^\top$ and use (26), then equivalently

$$\begin{aligned} J_1 &= \sum_{i=1}^{h}\sum_{j=1}^{h}\rho_i\rho_j\bar{\xi}^\top \begin{bmatrix} J_{1ij} & XE_{ij} \\ \star & J_{2ii} \end{bmatrix}\bar{\xi} \\ &\quad -\left(\gamma\bar{d} - \frac{1}{\gamma}\sum_{i=1}^{h}\rho_i\tilde{D}_i^\top P\bar{\xi}\right)^\top \\ &\quad \times\left(\gamma\bar{d} - \frac{1}{\gamma}\sum_{i=1}^{h}\rho_i\tilde{D}_i^\top P\bar{\xi}\right) \\ &= \sum_{i=1}^{h}\sum_{j=1}^{h}\rho_i\rho_j\bar{\xi}^\top \begin{bmatrix} J_{1ij} & XE_{ij} \\ \star & J_{2ii} \end{bmatrix}\bar{\xi} \\ &< 0. \end{aligned} \tag{28}$$

By applying the Schur complement to (28), we have

$$\sum_{i=1}^{h}\sum_{j=1}^{h}\rho_i\rho_j\left(\Phi_{ij} + \Pi_i\Pi_i^\top\right) < 0 \tag{29}$$

where $\Pi_i = \mathrm{diag}(\Pi_{1i}, \Pi_{2i})$,
$\Phi_{ij} = \begin{bmatrix} \mathrm{He}\left[X(A_i + B_iK_{xj})\right] & XE_{ij} \\ \star & \mathrm{He}\left[Y(\Xi\bar{A}_i - L_{1i}\bar{C})\right] \end{bmatrix}$,
with $\Pi_{1i} = [\lambda_{1i}XM_{0i} \ \lambda_{2i}N_{0i}^\top \ 0 \ \lambda_{4i}X\hat{D}_i \ C_x^\top]$ and $\Pi_{2i} = [0 \ 0 \ \lambda_{3i}Y\Xi\bar{M}_{0i} \ \lambda_{4i}Y\Xi\bar{D}_i \ C_e^\top]$.

Actually, if (21) - (22) hold, then it follows from (29) that

$$\sum_{i=1}^{h}\sum_{j=1}^{h}\rho_i\rho_j\left(X_{ij} + \Pi_i\Pi_i^\top\right) < 0,$$

which can be ensured by (23). ■

It should be noted that (21) - (22) are nonlinear inequalities which cannot be solved by LMI tools directly. To tackle this problem, Lemma 5.1 is further converted into the following equivalent Lemma 5.2 with LMI constraints.

Lemma 5.2: There exist two symmetric positive definite matrices X and Y, and matrices K_{xi}, L_{1i}, X_{ii}, $X_{ij} = X_{ji}$, $i \ne j$, $i, j = 1, 2, \dots, h$, such that (21) - (23) hold if and only if there exist two symmetric positive definite matrices $\bar{X}$ and Y, and matrices K_{xi}, L_{1i}, P_{ij}, and Q_{ij} with P_{ii} and Q_{ii} symmetric, $i < j$, $i, j = 1, 2, \dots, h$, such that

$$\begin{aligned} &\mathrm{He}(\mathit{\Lambda}_{ii}\bar{X}) < P_{ii}, \\ &\mathrm{He}(Y\mathit{\Gamma}_{ii}) < Q_{ii}, \\ &\mathrm{He}(\mathit{\Lambda}_{ij}\bar{X}) < P_{ij} + P_{ij}^\top, \\ &\mathrm{He}(Y\mathit{\Gamma}_{ij}) < Q_{ij} + Q_{ij}^\top, \ i < j, \\ &\begin{bmatrix} P_{11} & \cdots & P_{1h} & \hat{\Pi}_{11} \\ \vdots & \ddots & \vdots & \vdots \\ P_{1h}^\top & \cdots & P_{hh} & \hat{\Pi}_{1h}, \\ \hat{\Pi}_{11}^\top & \cdots & \hat{\Pi}_{1h}^\top & -I \end{bmatrix} < 0, \\ &\begin{bmatrix} Q_{11} & \cdots & Q_{1h} \\ \vdots & \ddots & \vdots \\ Q_{1h}^\top & \cdots & Q_{hh} \end{bmatrix} < 0 \end{aligned}$$

where $\hat{\Pi}_{1i} = [\lambda_{1i}M_{0i} \ \lambda_{2i}\bar{X}N_{0i}^\top \ 0 \ \lambda_{4i}D_i \ \bar{X}C_x^\top]$.

Proof: The proof of Lemma 5.2 is achieved with minor modification according to the proof of Lemma 2 in [24], and thus is omitted here. ■

Now Theorem 5.3 based on Lemma 5.2 is given to solve the integrated design problem for the composite closed-loop system (20).

Theorem 5.3: Given positive scalars γ, ϵ_{1i}, and ϵ_{2i}, the system (20) is stable with the H_∞ performance $\|G_{z_r\bar{d}}\| < \gamma$, if there exist two symmetric positive definite matrices $\bar{X}$ and Y, and matrices $\hat{K}_i$, $\hat{H}$, $\hat{L}_i$, P_{ij}, and Q_{ij} with P_{ii} and Q_{ii} symmetric, $i < j$, $i, j = 1, 2, \dots, h$, such that

$$\begin{aligned} &\mathrm{He}(A_i\bar{X} + B_i\hat{K}_i) < P_{ii}, \\ &\mathrm{He}((Y - \hat{H}\bar{C})\bar{A}_i - \hat{L}_i\bar{C}) < Q_{ii}, \\ &\mathrm{He}(A_i\bar{X} + A_j\bar{X} + B_i\hat{K}_j + B_j\hat{K}_i) < P_{ij} + P_{ij}^\top, \\ &\mathrm{He}(2((Y - \hat{H}\bar{C})\bar{A}_i - \hat{L}_i\bar{C})) < Q_{ij} + Q_{ij}^\top, \\ &\begin{bmatrix} P_{11} & \cdots & P_{1h} & \hat{\Pi}_{11} \\ \vdots & \ddots & \vdots & \vdots \\ P_{1h}^\top & \cdots & P_{hh} & \hat{\Pi}_{1h}, \\ \hat{\Pi}_{11}^\top & \cdots & \hat{\Pi}_{1h}^\top & -I \end{bmatrix} < 0, \\ &\begin{bmatrix} Q_{11} & \cdots & Q_{1h} \\ \vdots & \ddots & \vdots \\ Q_{1h}^\top & \cdots & Q_{hh} \end{bmatrix} < 0 \end{aligned}$$

where $\hat{\Pi}_{1i} = [\lambda_{1i}M_{0i} \ \lambda_{2i}\bar{X}N_{0i}^\top \ 0 \ \lambda_{4i}D_i \ \bar{X}C_x^\top]$. Then the gains are given by: $K_{xi} = \hat{K}_i\bar{X}^{-1}$, $H = Y^{-1}\hat{H}$, and $L_{1i} = Y^{-1}\hat{L}_i$, $i = 1, 2, \dots, h$.

Proof: Denote $\hat{K}_i = K_{xi}\bar{X}$, $\hat{H} = YH$, and $\hat{L}_i = YL_{1i}$, $i = 1, 2, \dots, h$, then the proof of Theorem 5.3 follows directly from Lemma 5.2. ■

C. Computational Complexity Analysis

The design parameters of the observer (4) and the controller (11) are obtained mainly by solving the LMIs in Theorem 5.3 using the Matlab LMI toolbox [29]. For the LMIs in Theorem 5.3, define R_0 and S_0 as the total row size and the total number of scalar variables, respectively. According to [29], the computational complexity (or number of flops) $N(\varepsilon)$ needed to get an ε-accurate solution of the LMIs in Theorem 5.3 is $N(\varepsilon) = R_0 S_0^3 \log(V/\varepsilon)$, where V is a data-dependent scaling factor. For the proposed integrated FE/FTC approach, $R_0 = (h^2+3h+1)n + (h^2+3h)(kq+k_1q_1)/2$ and $S_0 = hnm + p(n+kq+k_1q_1) + (h^2+h+2)[n(n+1)+(n+kq+k_1q_1)(n+kq+k_1q_1+1)]/4$. Similarly, it can be calculated for the separated FE/FTC approach $R_0 = h\,[4n+(k+2)q+(k_1+2)q+2l+z_1+p]$ and $S_0 = hnm + (1+h)p(n+kq+k_1q_1) + [n(n+1)+(n+kq+k_1q_1)(n+kq+k_1q_1+1)]/2$.

Compared with the separated approach, the proposed integrated approach has higher computational complexity. The computational complexity of the integrated design mainly depends on (i) the system and fault dimensions, (ii) the sub-model numbers of the fuzzy system and (iii) the fault orders. Among the above three factors, (ii) and (iii) can be tuned. Although increasing (ii) and (iii) can provide more accurate approximation of the nonlinear system and fault modelling, it leads to higher computational complexity. Therefore, a trade-off needs to be made for choosing the numbers of fuzzy rules and fault modelling orders.

Furthermore, since the combined observer and controller structures of the integrated and separately designed FTC systems are the same, it also follows that their online computational loads are identical. As the design parameters of the observer/controller are obtained from the LMIs off-line the resulting on-line computational burden is expected to be low.

Remark 5.1: Two more groups of scalars ϵ_{1i} and ϵ_{2i}, $i = 1, 2, \ldots, h$, need to be chosen to solve Theorem 5.3, due to the consideration of the presence of the uncertainty. Note that although [24] and [28] in their T-S fuzzy system control problems use observer-based state feedback, they do not consider the presence of faults. In the light of this the current work faces a bigger challenge since both the robust fault estimation and fault tolerant compensation are included. However, by taking into account *a priori* the presence of uncertainty and disturbance and the subsequent bi-directional robustness interactions between the FE observer and the FTC control system, the proposed integrated approach is applicable to systems with faults, uncertainty, and external disturbance.

Remark 5.2: As reviewed in the Introduction, there is no such a systematic integrated FE/FTC design strategy for T-S fuzzy systems. The existing works mostly follow the separated FE/FTC design idea, although using different FE observers and control designs. Thus, without loss of generality, a brief presentation of the separated design idea and its conservativeness are provided in Section V-A for the proposed ASUIO and FTC controller. This motivates the research on the integrated FE/FTC design in this paper. Comparisons of the performance of these two design methods are provided in the simulation results shown in Section VI, which then help to illustrate the importance and advantages of the integrated design idea.

VI. SIMULATION EXAMPLE

In this section the effectiveness of the proposed integrated approach is demonstrated by applying it to the stabilization for an inverted pendulum on a cart. The pendulum used has a nonlinear model [30]

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \frac{g\sin(x_1) - amlx_2^2\sin(2x_1)/2 - a\cos(x_1)u}{4l/3 - aml\cos^2(x_1)} \\ y &= [x_1 \; x_2]^\top \end{aligned}$$

where x_1 and x_2 represent the angle of the pendulum from the vertical and the angular velocity, respectively. g is the gravity constant, m is the pendulum mass, M is the cart mass, $2l$ is the pendulum length, u is the force applied to the cart, and $a = 1/(m+M)$. The model parameters used in this study are $m = 2.0$ kg, $M = 8.0$ kg, and $2l = 1.0$ m.

The balancing problem for the pendulum with actuator faults and disturbance is studied in [12] using separately designed adaptive observer and dynamic output feedback controller. The pendulum system is nonlinear but two points in (x_1, x_2) are considered to derive the two-rule T-S fuzzy pendulum model. Moreover, the pendulum system model is assumed to have uncertainty, disturbance, and actuator/sensor faults. According to [30], the following two-rule pendulum system model is valid in the controllable region $x_1 \in (-90, 90)$ deg,

$$\begin{aligned} \dot{x} &= \sum_{i=1}^{2} \rho_i(x_1)\,[(A_i + \Delta A_i)x + B_i(u + f_a) + D_i d] \\ y &= Cx + F_s f_s \end{aligned} \tag{30}$$

where $\rho_1(x_1) = 1 - \frac{2}{\pi}|x_1|$, $\rho_2(x_1) = \frac{2}{\pi}|x_1|$,
$A_1 = \begin{bmatrix} 0 & 1 \\ \frac{g}{4l/3-aml} & 0 \end{bmatrix}$, $B_1 = \begin{bmatrix} 0 \\ -\frac{a}{4l/3-aml} \end{bmatrix}$, $C = I_2$,
$A_2 = \begin{bmatrix} 0 & 1 \\ \frac{2g}{\pi(4l/3-aml\beta^2)} & 0 \end{bmatrix}$, $B_2 = \begin{bmatrix} 0 \\ -\frac{a\beta}{4l/3-aml\beta^2} \end{bmatrix}$,
$D_1 = D_2 = \begin{bmatrix} 0 \\ 0.01 \end{bmatrix}$, $F_s = \begin{bmatrix} 0.1 \\ 0.3 \end{bmatrix}$, and $\beta = \cos(88°)$.

The uncertainties are $\Delta A_1 = \Delta A_2 = \begin{bmatrix} 0 & \sigma_1 \\ \sigma_2 & 0 \end{bmatrix}$ where $\sigma_1 = 0.1\cos(t)$ and $\sigma_2 = 0.1\sin(t)$. The disturbance is $d = 0.01\sin(10t)$ and the faults are

$$f_a = \begin{cases} 1, & 0 \le t \le 5 \\ \sin(t), & 5 < t \le 20 \\ 1, & t > 20 \end{cases}, \quad f_s = \begin{cases} 0.1, & 0 \le t \le 14 \\ 0.2, & 14 < t \le 23 \\ 0.1, & t > 23 \end{cases}.$$

The two sub-models of fuzzy system (30) are verified to be locally observable and controllable, whilst the whole fuzzy system is also verified to be globally observable and controllable using the methods proposed in [25] and [26].

The integrated FE/FTC design for the pendulum system is solved with parameters: $k = 3$, $k_1 = 2$, $C_x = I_2$, $C_e = I_7$, $\alpha_s = 0.1$, $\beta_s = 0.1$, $\mu = 1$, $\epsilon_1 = 100$, $\epsilon_2 = 15$, and $\gamma = 1$. For comparison, the separated FE/FTC design is also simulated with the same system parameters and $\gamma_1 = 0.86$ and $\gamma_2 = 0.5$.

The H_∞ attenuation levels together with computational complexity (see Section V-C) of the integrated and separated designs are listed in Table I. Compared with the separated FE/FTC approach, the proposed integrated approach loses a certain degree of FTC robustness resulting from the sharing of the common Lyapunov matrices in the observer and controller designs. The proposed integrate design also has higher on-line design computational complexity. However, it is shown in the table that for these two approaches the solutions for the gains are not time consuming (performed on a PC computer with a 3.10 GHz 4 cores Intel i5-2400 CPU).

TABLE I
H_∞ ATTENUATION LEVEL AND CONSUMING TIME

	Integrated design	Separated design	
		Observer	Controller
$\gamma_{\min}$	0.10	0.77	0.01
R_0, S_0	47, 142	34, 70	22, 7
CPU time (s)	0.156	0.0468	0.0312

Solving Theorem 5.3 with the chosen parameters gives the following observer and controller gains of the integrated approach

$$K_{x_1} = [1062\ 309.2]\,,\ K_{x_2} = [2379.1\ 672.7]\,,$$

$$M_1 = \begin{bmatrix} -0.4482 & -14.1330 & -0.0878 & 0 & 0 & -0.1698 & -1.5424 \\ 14.3939 & -0.7661 & -1.0144 & 0 & 0 & -0.4324 & -0.5709 \\ 7.2944 & 69.8885 & -64.1764 & 1 & 0 & -125.1272 & -2.8279 \\ 2.8023 & 27.7887 & -25.4464 & 0 & 1 & -49.7641 & -1.0664 \\ 0.5608 & 6.2677 & -5.6391 & 0 & 0 & -11.1597 & -0.1835 \\ -0.8619 & 1.3328 & 1.9833 & 0 & 0 & -1.2495 & 3.1209 \\ -2.0198 & 1.9634 & 0.9344 & 0 & 0 & -2.0623 & 1.5702 \end{bmatrix},$$

$$M_2 = \begin{bmatrix} -0.9877 & -9.5573 & -0.0019 & 0 & 0 & 1.3561 & -1.5424 \\ 9.5774 & -1.5836 & -0.0221 & 0 & 0 & 1.2341 & -0.5709 \\ 2.9603 & -1.6618 & -1.4005 & 1 & 0 & 4.4030 & -2.8279 \\ 1.0841 & -0.5824 & -0.5553 & 0 & 1 & 1.5952 & -1.0664 \\ 0.1947 & -0.0669 & -0.1231 & 0 & 0 & 0.2092 & -0.1835 \\ -1.5368 & 1.9598 & 0.0433 & 0 & 0 & -5.8085 & 3.1209 \\ -1.6108 & 1.8959 & 0.0204 & 0 & 0 & -4.2464 & 1.5702 \end{bmatrix},$$

$$L_1 = \begin{bmatrix} -107 & 16 \\ -81 & 98 \\ -15150 & 5936 \\ -6029 & 2361 \\ -1340 & 525 \\ 588 & -182 \\ 307 & -87 \end{bmatrix},\ G_1 = \begin{bmatrix} -0.0878 \\ -1.0144 \\ -64.1764 \\ -25.4464 \\ -5.6391 \\ 1.9833 \\ 0.9344 \end{bmatrix},$$

$$L_2 = \begin{bmatrix} -99.1268 & 3.7239 \\ 111.3488 & -0.9468 \\ 601.9768 & -229.2507 \\ 216.8746 & -83.4618 \\ 44.6287 & -16.3783 \\ 93.7791 & 9.0680 \\ 83.5292 & 3.6323 \end{bmatrix},\ G_2 = \begin{bmatrix} -0.0019 \\ -0.0221 \\ -1.4005 \\ -0.5553 \\ -0.1231 \\ 0.0433 \\ 0.0204 \end{bmatrix},$$

$$H = \begin{bmatrix} 15.8632 & -0.1463 \\ 7.7810 & -0.6906 \\ 349.1615 & -106.9607 \\ 137.8961 & -42.4106 \\ 30.0311 & -9.3986 \\ -31.1252 & 3.3054 \\ -20.3739 & 1.5573 \end{bmatrix}.$$

A. Comparison of Linear FTC and T-S Fuzzy Integrated FTC

This section demonstrates the superiority of the proposed T-S fuzzy integrated FTC design to the linear FTC design (with the pendulum model linearized around the stable point, i.e., $\rho_2(x_1) = 0$). The ranges of the balancing initial angle considered for each of the methods are examined here with $z(0) = [0.1; 0.1; 0.1; 0.1; 0.1; 0.1; 0.1]$ and $x_2(0) = 0$, along with different initial angles.

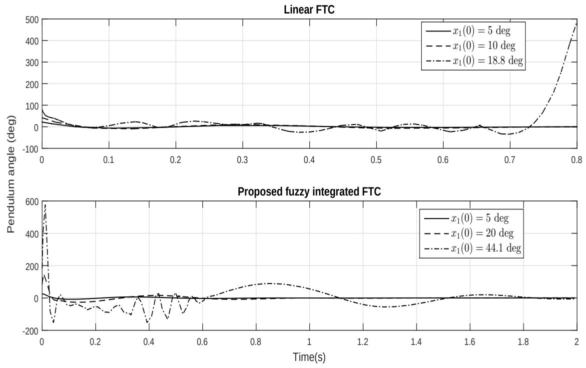

Fig. 3. Angle response using linear and T-S fuzzy integrated FTC

TABLE II
MAXIMUM INITIAL ANGLE $|x_1(0)|$ OF THE PENDULUM

Cases	T-S fuzzy design	linear design
Actuator fault case	45 deg	19.5 deg
Sensor fault case	44.1 deg	18.8 deg
Actuator/sensor faults case	44.1 deg	18.8 deg

In the presence of both actuator and sensor faults, simulation results in Fig. 3 indicate that the proposed T-S fuzzy integrated FTC can balance the pendulum for initial angles $|x_1(0)| \leq 44.1$ deg ($x_2(0) = 0$). In contrast, the linear control fails to balance the pendulum for initial angles $|x_1(0)| >= 18.8$ deg. Similar simulations are performed for the cases when the pendulum has either an actuator fault or a sensor fault. The maximum initial angles of the pendulum for all the three cases are summarized in Table II, from which it is concluded that the proposed T-S fuzzy integrated FTC design balances the pendulum for much larger initial angles than the linear FTC.

B. Comparison of Integrated and Separated FE/FTC Designs

In order to demonstrate well the effectiveness of the proposed integrated FE/FTC design and its superior FE/FTC performance compared with the separated design, two sets of simulations are carried out for the pendulum with different initial angles and different uncertainties, respectively.

1) Performance with Different Initial Angles: Simulations are performed with uncertainties $\sigma_1 = 0.1\cos(t)$ and $\sigma_2 = 0.1\sin(t)$ in three cases: *Case 1:* The pendulum has only actuator fault; *Case 2:* The pendulum has only sensor fault; *Case 3:* The pendulum has both actuator and sensor faults.

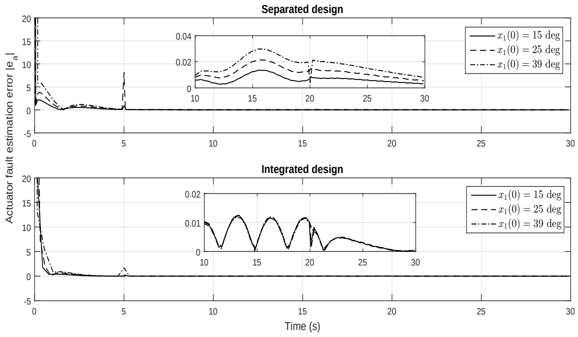

Fig. 4. Actuator fault estimation with different initial angles: *Case 1*

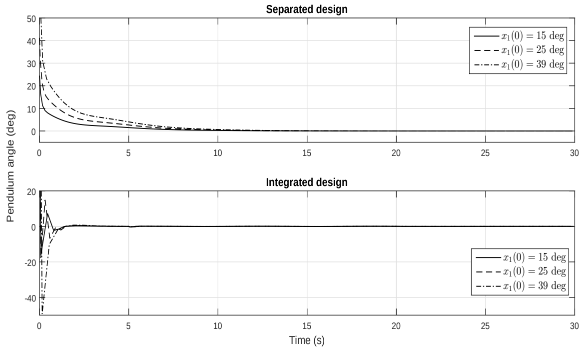

Fig. 5. Angle response with different initial angles: *Case 1*

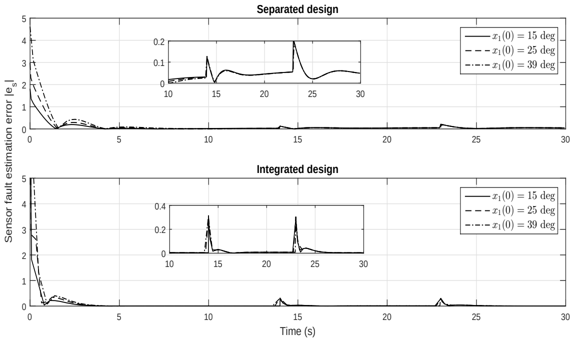

Fig. 6. Sensor fault estimation with different initial angles: *Case 2*

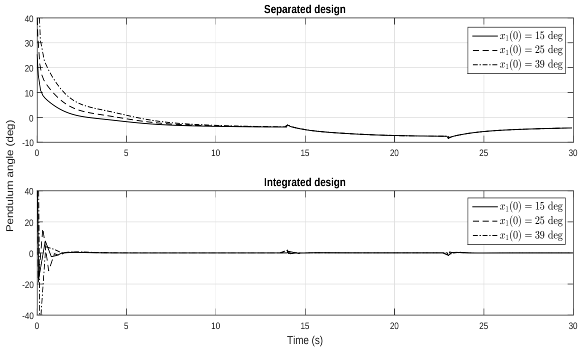

Fig. 7. Angle response with different initial angles: *Case 2*

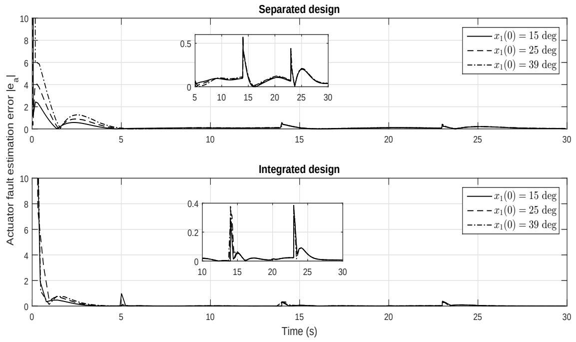

Fig. 8. Actuator fault estimation with different initial angles: *Case 3*

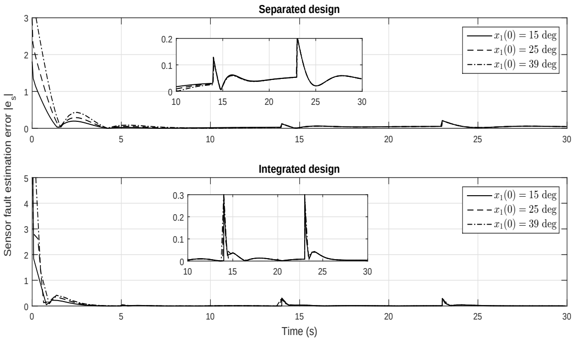

Fig. 9. Sensor fault estimation with different initial angles: *Case 3*

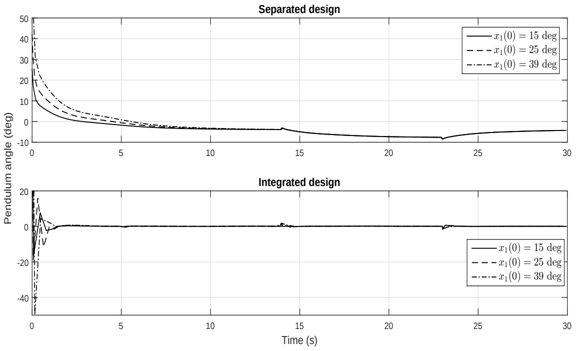

Fig. 10. Angle response with different initial angles: *Case 3*

From Figs. 4 - 10, it is observed that in the whole range of the balancing initial angles listed in Table II, the proposed integrated FE/FTC design achieves better FE/FTC performance than the separated design in all the three cases simulated. Except for *Case 2* when the pendulum has only actuator fault, the separated design cannot balance the pendulum.

2) Performance with Different Uncertainties: To test the robustness of the proposed integrated FE/FTC design, comparative simulations of the integrated design and separated design are performed initial conditions $z(0) = [0.1; 0.1; 0.1; 0.1; 0.1; 0.1; 0.1]$ and $x_2(0) = 0$ and with different uncertainties. The initial angle is set as $x_1(0) = 15$ deg. Simulations are performed for the following three cases: *Case 1:* The pendulum has one actuator fault (with no sensor faults); *Case 2:* The pendulum has only a single sensor fault (with no actuator faults); *Case 3:* The pendulum has one actuator fault and one sensor fault.

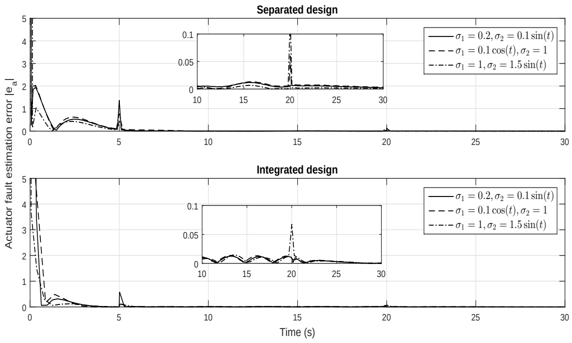

Fig. 11. Actuator fault estimation with different uncertainties: *Case 1*

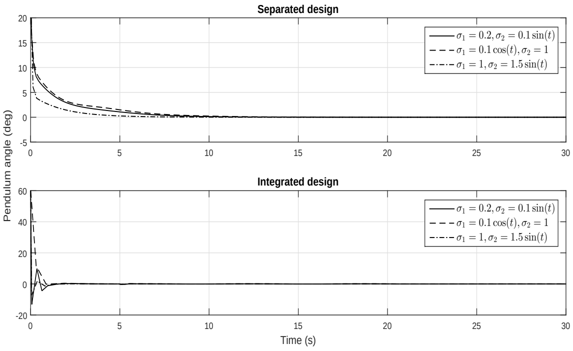

Fig. 12. Angle response with different uncertainties: *Case 1*

In the presence of different uncertainties, it is observed from Figs. 11 - 17 that the proposed integrated design performs well with better FE/FTC robustness to the uncertainties than the separated design for all the three fault cases considered.

Summarizing the results, in the presence of uncertainty, disturbance and faults, the proposed integrated design achieves better FE/FTC performance with higher robustness to the uncertainty than the separated design. Moreover, the separated design is unable to balance the pendulum when sensor faults exist.

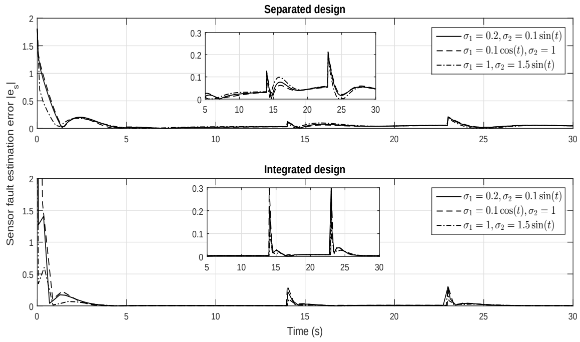

Fig. 13. Sensor fault estimation with different uncertainties: *Case 2*

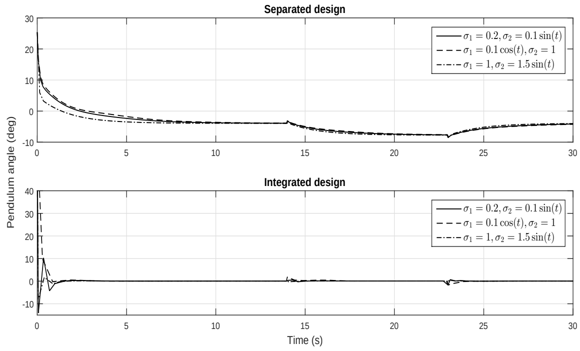

Fig. 14. Angle response with different uncertainties: *Case 2*

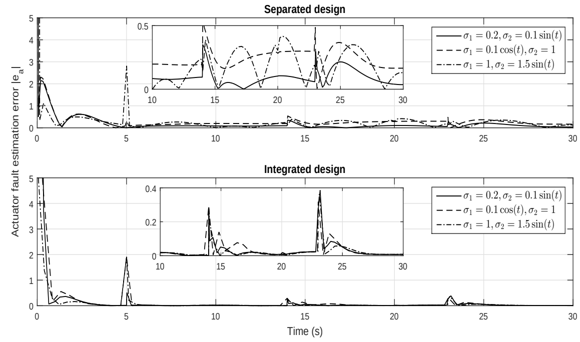

Fig. 15. Actuator fault estimation with different uncertainties: *Case 3*

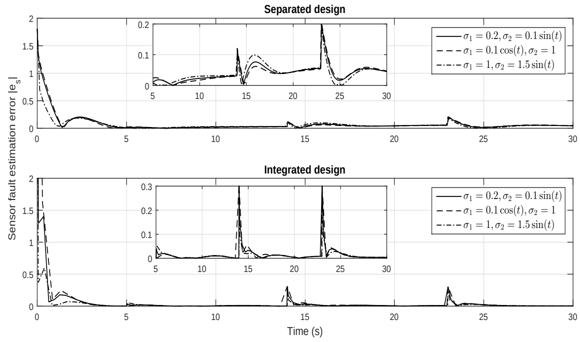

Fig. 16. Sensor fault estimation with different uncertainties: *Case 3*

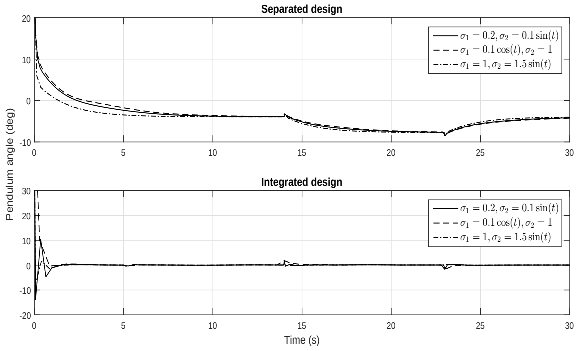

Fig. 17. Angle response with different uncertainties: *Case 3*

VII. CONCLUSION

Although the idea of integration of control and fault diagnosis was suggested three decades ago by [19], no existing works have attempted the true integrated design of FTC systems (rather than just control/diagnosis) with FDI/FE for nonlinear system. In this paper, a new integrated FE/FTC design strategy is proposed for nonlinear systems subject to actuator and sensor faults along with uncertainty and disturbance using T-S fuzzy modelling.

An ASUIO is proposed to estimate the system states and faults simultaneously, and then the estimates obtained are used to construct a reconfigurable fuzzy FTC controller. Compared to the FDI based FTC system design which requires an optimal residual threshold setting and a robust stable reconfigurable mechanism, the direct use of the observer-based FE within the FTC system design framework is proposed to enable the integrated design to be an observer-based robust control problem with a single-step LMI formulation. The simulation example corresponds to a physical system illustrating the effectiveness of the proposed integrated FTC design and its practical potential. By considering in advance the bi-directional robustness interactions between the FE and FTC, the proposed integrated design can achieve better overall FTC system performance than the separated design.

It should be noted that the robustness interaction leads to increased design complexity, which makes the integrated FE/FTC design necessarily a challenging problem (BMI problem). Thus, a simpler way to solve the BMI problem or a strategy to reduce the design complexity, e.g., by decoupling the FE observer from the FTC controller can help to achieve the integrated FTC system design. In addition, pole placement can be combined together with H_∞ optimization to ensure acceptable time response of the overall system.

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