ARTICLE IN PRESS

ISA Transactions xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Indirect adaptive fuzzy fault-tolerant tracking control for MIMO nonlinear systems with actuator and sensor failures

Abdelhamid Bounemeur[a,*], Mohamed Chemachema[a], Najib Essounbouli[b]

[a] Dept of Electronics, Faculty of Technology, University of Constantine 1, Campus A. Hamani, route Ain El Bey, 2500 Constantine, Algéria
[b] CReSTIC Laboratory University of Reims Champagne Ardennes, France

ARTICLE INFO

Keywords:
Adaptive fault-tolerant control
Fuzzy systems
MIMO unknown nonlinear systems
Backstepping method
Sensor faults
Actuator faults

ABSTRACT

In this paper, an active fuzzy fault tolerant tracking control (AFFTTC) scheme is developed for a class of multi-input multi-output (MIMO) unknown nonlinear systems in the presence of unknown actuator faults, sensor failures and external disturbance. The developed control scheme deals with four kinds of faults for both sensors and actuators. The bias, drift, and loss of accuracy additive faults are considered along with the loss of effectiveness multiplicative fault. A fuzzy adaptive controller based on back-stepping design is developed to deal with actuator failures and unknown system dynamics. However, an additional robust control term is added to deal with sensor faults, approximation errors, and external disturbances. Lyapunov theory is used to prove the stability of the closed loop system. Numerical simulations on a quadrotor are presented to show the effectiveness of the proposed approach.

1. Introduction

In the last decade, universal approximation systems, such as fuzzy systems and neural networks, have been widely used in the area of the control theory to design suitable control schemes for uncertain nonlinear systems with no actuator and/or sensor faults [1–4]. These faults provide undesirable effects and even may drive systems to become unstable or damaged [5–7]. As control systems becomes more complex, the security remains a key point and the development of new control theory, integrating the faults that can occur on a system, is of a great interest. Faults Diagnosis [5,6], and fault tolerant control [7] have become challenging in the area of modern control theory. In fault tolerant control, the problem is to design a control law such that when a fault occurs from a sensor and/or actuator, the system keeps its own properties in terms of stability and tracking performances. The main idea to ensure these properties is to make the control law immune against these faults by canceling its bad effects.

Fault-tolerant control (FTC) techniques can be classified into passive and active techniques [8,9]. In passive fault-tolerant control (PFTC) systems, a single controller with fixed structure and parameters is utilized to deal with all possible failure scenarios assumed, a priori, to be known. Furthermore, the passive technique does not require online fault detection, diagnosis, and control reconfiguration. The implementation of this technique is easy but it is more conservative [10–12]. Many passive fault tolerant control approaches have been developed in the literature. For linear systems, a reliable H_∞ guaranteed cost control technique is proposed based on the linear matrix inequality (LMI) technique [13]. Moreover, a reliable H_∞ controller is developed in Refs. [14,15] based on LMI approach and static output feedback control. In Ref. [16], a reliable non-fragile H_∞ compensation filter is investigated. In Ref. [17–19], authors proposed fault tolerant control techniques specifically for non-linear systems. In Ref. [17] a combination of L_2/H_∞ fuzzy static output feedback control is proposed based on iterative LMI approach. A reliable H_∞ filter is designed in Ref. [18] for a class of nonlinear networked systems using Takagi-Sugeno (T-S) fuzzy model and LMI technique. A static output feedback fuzzy controller is employed in Ref. [19] for T-S fuzzy systems with sensor faults based on LMI_S.

However, if an unexpected failure occurs, the stability and the performance of the closed-loop system cannot be guaranteed. Such limitation of passive approaches provides an essential motivation for the development of new methods and control strategies for Active FTC systems [20]. Active methods consist of online reconfiguring of the controller to recover the stability and system performance as soon as a diagnostic algorithm has detected the presence of fault [21–32]. In The recent FTC literature, a steady increase of interest in developing strategies for nonlinear systems by using T-S fuzzy modelling [33–35]. Usually, T-S fuzzy models are used for fault estimation in nonlinear control systems thanks to its ability to overcome systems nonlinearities, well-developed modern linear systems and optimization and design

* Corresponding author. Tel.: +213 553632250.
E-mail addresses: hamidsie4@gmail.com (A. Bounemeur), m_chemachema@yahoo.fr (M. Chemachema), najib.essounbouli@univ-reims.fr (N. Essounbouli).

https://doi.org/10.1016/j.isatra.2018.04.014
Received 19 September 2017; Received in revised form 16 April 2018; Accepted 24 April 2018
0019-0578/

tools. However, almost all the works on this area using T-S fault estimation are based on the actuator estimation and compensation issue and do not consider simultaneous actuator and sensor faults. In Refs. [36,37], robust detection and isolation schemes for nonlinear systems subject to known nonlinear actuator faults is developed with bounded control inputs and state variables. In Ref. [38], an active FTC law is designed based on an open-loop model of the system and a function of fault parameters assumed immediately identified by a fault detection and isolation (FDI) model. In Refs. [39,40], a reconfigurable controller is developed based on FDI system represented by nonlinear observers for spacecraft under sensor bias fault. In all techniques based on faults detection (FD), there is some time-delay between faults occurrence and faults treatment. In Ref. [41], the authors designed active fault-tolerant controller using an observer for fault detection based on T-S fuzzy models and delta operator approach. Some fault-tolerant control methods based on T-S fuzzy systems are studied for networked control systems [42,43]. The fault estimation and fault-tolerant control problems for a class of fuzzy stochastic systems with sensor failures are addressed by a combination between fuzzy systems and sliding-mode approach [44]. In Ref. [45], H_∞ controller design problem is discussed for a class of nonlinear stochastic active fault-tolerant systems with Makovian parameters. In Ref. [46]**,** authors presented an integrated fault diagnosis (FD) and fault-tolerant control (FTC) design for Polytopic linear parameter varying systems (LPV) based on an adaptive Polytopic observer (APO) to estimate both states and actuator faults. In Ref. [47], a sensor active fault-tolerant control based on high-gain observers is presented for a class of nonlinear systems. In Ref. [48], a proportional derivative (PD) sliding mode observer-based fault tolerant control scheme for a class of Lipchitz nonlinear systems against sensor faults is synthesized. In Ref. [49], a T-S dynamic output feedback control is presented using two T-S fuzzy observers dedicated to provide separate estimates of actuator and sensor faults for fault compensation.

Since autonomous systems, such as unmanned aerial vehicles, have highly nonlinear unstable dynamics, fault-tolerant control of these MIMO systems is has attracted great interest to be addressed. In Ref. [50–54], authors studied the actuator faults case with only attitude measurement. In Ref. [55], authors combined adaptive disturbance observer with back-stepping method under time-varying sensor faults for a class of nonlinear systems. In Ref. [56] an active FT tracking controller to deal with sensor faults is proposed for a vehicle system based on T-S fuzzy representation. In Ref. [57], an active fault-tolerant control approach is presented for vehicle active suspension systems in finite-frequency region. In Ref. [58], an active fault-tolerant controller is developed using neural networks combined with sliding mode and the H_2 performance index for spacecraft system under the loss of effectiveness actuator fault. In Ref. [59], an active FTC based on back stepping is developed for a class of MIMO uncertain nonlinear systems. In this work, four kinds of velocity sensor faults including bias, drift, loss of accuracy and loss of effectiveness are considered. In Ref. [60], an active fault tolerant control, based on differential geometry, and a fault detection and diagnosis are presented for a class of nonlinear systems subjected to an additive fault. In Ref. [61], the authors investigated an adaptive fault tolerant control for a class of nonlinear systems based on neural networks and implicit function theorem with unknown bias and loss of effectiveness actuator faults. In Ref. [62], authors proposed an adaptive FTC scheme for a class of uncertain nonlinear multi-input single-output (MISO) discrete-time systems using radial basis function neural networks (RBFNNs) and studied only the case when actuators are failed with both bias and loss of effectiveness. In Ref. [63], authors proposed a quantization strategy to deal with the problem of nonlinear uncertain MIMO systems in the presence of only two kinds of actuator faults. Based on two observers, fault estimation (FE) and fault-tolerant control (FTC) are designed for fuzzy systems as local linear systems under only loss of accuracy for sensor and actuator faults simultaneously [64].

The emphasis of the current work is to design an active fuzzy fault-tolerant tracking control (AFFTTC) scheme for a class of second-order MIMO nonlinear systems subjected to four kinds of sensors and actuators faults and external disturbances. The dynamics of the system are assumed unknown and the controller parameters are updated according to the occurrence of the actuator and/or sensor faults. Using the fact that if we introduce the models of actuator and sensor faults into the system model, the dynamics of the system will be converted into a strict-feedback form. To deal with this class of nonlinear systems, back-stepping technique is used along with a novel fuzzy adaptive fault tolerant strategy. The proposed adaptive control law is composed of two control terms. The first control term is an adaptive fuzzy control law to cope with the unknown system dynamics and actuator failures with online adaptation of the parameters. The second is a robust control term to overcome the problem of fuzzy approximation errors, sensor faults, and external disturbances. The stability of the closed-loop system is studied using Lyapunov approach to ensure the convergence of the tracking error to zero.

Compared to the existing works in the same area (see Refs. [13–19] [38–40], [46–49] [50–54], [58,59] [61–64]]), the main contributions of this paper are the introduction of a new adaptive control strategy based on back-stepping technique mixed with Takagi-Sugeno fuzzy inference systems to cope with all types of faults which can occur on both sensors and/or actuators. The proposed work is a challenging study to deal with more general fault tolerant control problems with alleviated assumptions compared to the literature. The following points summarize the contributions of this work:

1) Unlike in Ref. [50–54], the proposed controller is less restrictive since it does not need any information about the models of velocity sensor faults. Instead, the proposed controller deals systematically with unknown sensor faults.
2) In Refs. [13–19,39,40,47–49,64], the authors proposed an FTC to deal with one or two kinds of sensor faults which limits the applicability of the controller on real systems with unexpected sensor faults. This limitation leads to performance loss and even may cause the instability. For these reasons, in the proposed work a suitable control scheme is designed with four kinds of sensor faults including bias, drift, loss of accuracy, and loss of effectiveness, to keep the desired performances even if all kinds of failures occur.
3) Unlike in Refs. [46,58,61–64] where the authors presented an **AFTC** taking into account only one or two kinds of actuator faults which considerably limits the range of applicability of these AFTC approaches, in the proposed controller, the four kinds of actuator faults including bias, drift, loss of effectiveness, and loss of accuracy are considered in the design.
4) In Refs. [55,59,64], the authors made restrictive assumptions on external disturbance. In Ref. [55], the disturbance is described as exogenous neutral stable system, and in Ref. [64] it is divided into two parts, one representing an estimated part and the second is generated by an exogenous system, while in Ref. [59] the external disturbance is modeled by time varying free-models with derivable bounds. Instead, in the proposed work, only the boundedness mild condition is assumed on external perturbations with no other information.
5) Unlike in Refs. [38–40,46] where fault detection and isolation (FDI) module is needed, in the proposed work, FDI module is not needed due to the on-line controller parameters adaptation.
6) In Refs. [58,61], the developed controllers are designed for systems with the restrictive condition on the control gain of the system to be a simple constant. To cover a larger class of dynamical systems, the latter restriction is removed in the proposed approach. Indeed, we assume the system dynamics are unknown with the control gain as an unknown nonlinear function to cover a large class of dynamical systems like inverted pendulum, induction motor drive, single-link robot arm, mass-spring-damper system, flexible spacecraft, quadrotor and many other systems.