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Design of robust fuzzy fault detection filter for polynomial fuzzy systems with new finite frequency specifications ☆

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ABSTRACT

This paper investigates the problem of fault detection filter design for discrete-time polynomial fuzzy systems with faults and unknown disturbances. The frequency ranges of the faults and the disturbances are assumed to be known beforehand and to reside in low, middle or high frequency ranges. Thus, the proposed filter is designed in the finite frequency range to overcome the conservatism generated by those designed in the full frequency domain. Being of polynomial fuzzy structure, the proposed filter combines the H_-/H_∞ performances in order to ensure the best robustness to the disturbance and the best sensitivity to the fault. Design conditions are derived in Sum Of Squares formulations that can be easily solved via available software tools. Two illustrative examples are introduced to demonstrate the effectiveness of the proposed method and a comparative study with LMI method is also provided.

1. Introduction

Due to the increased requirements for safety as well as for reliability and higher performance in modern systems, the issues of fault detection (FD) have received more attention in the recent years (Li, Shi, Lim, & Wu, 2016; Li, Zhu, & Ding, 2011; Liu, Huang, Shi, & Xu, 2013; Wang, Shi, Lim, & Liu, 2016; Yang, Shi, & Liu, 2011). In industrial processes and engineering applications such as nuclear power stations, chemical or aerospace processes, system components like sensor, actuator etc., may be affected by several and serious failures. These problems may drastically change the system behavior, which leads to performance degradation or even system instability. Therefore, FD issues are very essential in order to enhance the system reliability and efficiency. The objective of fault detection is to detect the fault signal reliably whenever it appears. One method to do this is to generate residual signals which act as an indicator for faulty situation. In the literature, observer-based fault detection filter design is commonly used and leads to efficient results not only in theoretical developments but also in industrial applications (Chadli & Karimi, 2013; Zhang & Wang, 2016a, b). In its core, this technique consists of generating the residual signals from the difference between the system outputs and the filter outputs and then a logic algorithm to decide whether a fault has occurred (Liu, Wang, & Yang, 2005; Yang & Wang, 2010; Zhong, Ding, Lam, & Wang, 2003).

On the other hand, since most of real processes and industrial systems are in nature of nonlinear dynamics, Takagi–Sugeno (T–S) fuzzy systems are considered as very useful tool to present the dynamics of nonlinear processes (Takagi & Sugeno, 1985). The FD problem for T–S fuzzy models has been extensively investigated in last years and many solutions are formulated as optimization algorithms with LMI constraints. These optimization algorithms are dedicated to designing the fault detection filter to be as sensitive as possible to the fault (in order to detect faults in a timely way) and as robust as possible to the unknown disturbances (in order to avoid false alarms). Especially, the disturbance attenuation and the fault sensitivity requirements are expressed in terms of an H_∞ index (for example, Gao, Zhao, Lam, & Chen, 2009; Yoneyama, 2009; Zhang, Shi, & Mehr, 2012 and the references therein) or an H_- norm or a mixed H_-/H_∞ norm (see for example, Chadli, Abdo, & Ding, 2013; Wang, Shi, & Wang, 2010; Wang, Yang, & Liu, 2007).

In real processes and industrial systems, the frequency ranges of the disturbances and the faults are usually finite and known in advance. In the references previously cited, the frequency properties

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of such external signals are not considered when designing a fault detection filter. Incorporating such information into the design can definitively improve the detection performance. In this context, the fault detection problem in finite frequency domain has been addressed in a number of recent works and it has been shown that filters designed in finite frequency ranges lead to improved FD performance than those designed in the full frequency domain. These investigations are essentially motivated by the use of the so-called Generalized Kalman–Yakubovich–Popov (GKYP) lemma, which converts the various properties of dynamic systems in finite frequency domain into LMI conditions (Iwasaki & Hara, 2005). The finite frequency FD filter design for linear time invariant (LTI) systems has been first addressed in Wang and Yang (2008) and Zhang, Jiang, Shi, and Xu (2015b). The work in Yang, Xia, and Zhang (2011) proposed a multi-objective H_-/H_∞ filter in finite frequency ranges to deal with the FD problem for delta operator systems. Recently, the finite frequency H_∞ filtering is investigated for state delayed systems (Li & Yang, 2015), for switching linear parameter varying systems (Wang, Ju, & Wang, 2013; Zhong & Yang, 2015) and for uncertain linear discrete-time systems (Zhang, Wang, Ding, et al., 2015). Almost all of these papers propose to transform the FD task into optimization algorithms under LMI constraints and demonstrate that the finite frequency conditions are generally less conservative than their counter-part in the full frequency domain, and contain the standard ones as a particular case.

Turning to T–S fuzzy models, the first attempts that discussed the FD problem in finite frequency ranges for such systems appeared in Ding and Yang (2010). Indeed, three fuzzy filters, corresponding to disturbance frequency domain are designed in order to guarantee the finite-frequency l_2 gain which extends the standard l_2 gain over the whole frequency domain. The design conditions are sufficient and derived in LMI terms. Afterward, an H_-/H_∞ fault detection filter is proposed in Yang, Xia, and Liu (2011) where two finite frequency performance indices are introduced to measure fault sensitivity and disturbance robustness. In Zhang, Jiang, Shi, and Xu (2015a), the FD problem is investigated with finite frequency specification such that the proposed filter complies with pole-placement constraints. More recently, in the authors' previous work (Chibani, Chadli, Shi, & Braiek, 2016b), a multi-objective fuzzy fault detection filter is proposed in the finite frequency domain for T–S fuzzy models. The results are given in LMI formulations.

Going further, T–S fuzzy models and LMI technique have enjoyed great success and popularity due to the attractive properties of fuzzy control including robustness to disturbances, uncertainties, and sensors noise. However, there still exists a large number of design problems that either the processes cannot be exactly represented by a T–S model, either the results obtained through LMIs are too conservative.

Recently, a new type of fuzzy model, namely polynomial fuzzy system (PFS) has been developed as an extension of T–S fuzzy models where the consequent parts of the *if-then* rules are allowed to be polynomial (Tanaka, Yoshida, Ohtake, & Wang, 2009). Indeed, when the degrees of polynomial terms are all zero, the model reduces to the T–S fuzzy model and hence, this last can be regarded as a particular case. The polynomial fuzzy systems are well adopted in modeling, analysis and different design problems of nonlinear systems. Indeed, it was been proven that such models give more relaxed criteria in stability analysis or control design since, the number of local models is generally fewer than the existing T–S fuzzy systems (Chen, Tanaka, Tanaka, Ohtake, & Wang, 2014; Chen, Tanaka, Tanaka, & Wang, 2015; Lam, Liu, Wu, & Zhao, 2015; Lam, Wu, & Lam, 2015; Tanaka et al., 2009).

Note that in this case, the LMI technique can-not be applied due to the polynomial terms. Thus, design criteria in stability analysis or controller synthesis are derived in Sum Of Squares (SOS) based SDP program and lead to less conservative results than the LMI approaches (Chen et al., 2014, 2015; Lam Liu et al., 2015, Lam Wu et al., 2015; Tanaka et al., 2009). The resolution of the SOS based SDP algorithm can be efficiently performed via numerical tools such that SOSTOOLS (Parrilo, 2000; Prajna, Papachristodoulou, & Wu, 2004).

In the field of state estimation of polynomial fuzzy systems, a polynomial fuzzy observer has been proposed in Tanaka, Ohtake, Seo, Tanaka, and Wang (2012). Based on the Lyapunov method, sufficient design condition are formulated in SOS constraints. More recently, the state reconstruction problem of PFS with unknown inputs has been discussed in authors' previous work (Chibani, Chadli, & Braiek, 2016a). Indeed, a new structure of polynomial fuzzy observer has been proposed and sufficient design conditions are derived in SOS terms with equality constraints. Even if this attempts provide important innovations compared with LMI approaches for T–S fuzzy systems, the frequency properties of external signals are not incorporated in the design procedure, i.e., only full frequency domain case is investigated. Moreover, to the best of authors' knowledge, the fault detection of PFSs is not yet discussed in the literature.

The main challenge in this study is how to bring together the SOS technique and the finite frequency approach in order to establish a new criterion that permit to solve the fault detection problem for polynomial fuzzy systems. Hence, this paper investigates the problem of fault detection for discrete-time PFSs with unknown disturbances and faults in finite frequency ranges. A multi-objective H_-/H_∞ polynomial fuzzy filter will be proposed in order to guarantee the best disturbances attenuation and the best fault sensitivity. Based on the GKYP lemma, new characterizations of the H_- and the H_∞ norms are introduced with finite frequency specifications. Then, using a fuzzy Lyapunov function, sufficient design conditions are derived in SOS terms with linear equality constraints. Moreover, the case of T–S fuzzy systems will be also discussed and equivalent LMI design conditions will be presented instead of the SOS ones. In the simulation study, the effectiveness of the proposed method will be shown through two examples and a comparison study will be introduced to demonstrate the superiority of the SOS approach against the LMI one.

The main contributions of this work are as follows: (1) it is the first attempt to considers the FD problem for PFSs. (2) new characterizations, including polynomial terms, are proposed to define the finite frequency H_- and the H_∞ norms for PFSs. (3) A new form of polynomial filter is proposed to deal with the FD problem of PFSs. (4) By exploiting the SOS technique, a new SOS criterion is developed to handle the optimization algorithms with polynomial terms and less conservative conditions are further proposed. (5) Similar results for T–S fussy systems is also treated as a particular case.

The reminder of the paper is organized as follows. In Section 2, the problem is formulated and useful preliminaries are introduced. The main results are derived in Section 3. Simulation examples are presented in Section 4 to show the effectiveness and potential of the proposed design techniques. Finally, conclusion remarks are given in Section 5.

Notation. Throughout this paper, the notation is rather standard: Let $\mathbb{R}^n$ denotes the n-dimensional Euclidean space and $l_2[0, \infty)$ denotes the space of square integrable vector of discrete functions over $[0, \infty)$. $\sum_n$ denotes the subset from $\mathbb{R}^n$ that contains all SOS polynomial in n variables. $P > 0$ (Resp. $P < 0$) means that P is definite positive (Resp. definite negative) matrix. Given a matrix $\mathbf{M}$, $\mathbf{M}^T$ and $\mathbf{M}^\perp$ are used to represent the transposed and the orthogonal complement ($\mathbf{M}\mathbf{M}^\perp = 0$) of $\mathbf{M}$ respectively. $(*)$ denotes the transposed element in the symmetric position, and I is the identity matrix with appropriate dimension.