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Multiobjective tracking control design of T–S fuzzy systems: Fuzzy Pareto optimal approach

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Abstract

In this study, a multiobjective fuzzy control design method is introduced for nonlinear dynamic systems to guarantee the optimal H_2 and H_∞ reference tracking performance simultaneously. First, the Takagi and Sugeno (T–S) fuzzy model is used to represent the nonlinear dynamic system. Then, based on the T–S fuzzy model, multiobjective H_2/H_∞ tracking control design problem is formulated as a multiobjective problem (MOP) to minimize the H_2 tracking error and H_∞ disturbance attenuation level for the fuzzy system at the same time. Since it is not easy to solve this MOP directly, an indirect method is proposed for the multiobjective H_2/H_∞ tracking control design. Finally, in order to achieve the simultaneous optimization of the MOP, linear matrix inequality (LMI)-based multiobjective evolution algorithm (LMI-based MOEA) is developed based on non-dominating sorting scheme to efficiently search the set of Pareto optimal solutions for the MOP, from which designer can select one design according to his own preference. Further, the multiobjective H_2/H_∞ fuzzy control design problem based on the weighted sum method is also solved as an alternative choice. Finally, a simulation example of a robotic system is given to illustrate the design procedure and to confirm the robust and optimal tracking performance of the proposed method.

Keywords: H_2/H_∞ tracking control design; Linear matrix inequality (LMI); Multiobjective fuzzy tracking control; Non-dominating sorting scheme; Pareto optimal solution; T–S fuzzy control

1. Introduction

In the system control design, the tasks of stabilization and tracking are two typical control design problems. Many control design techniques have been developed for the nonlinear system control designs, for example, exact feedback linearization [1,2], sliding mode control [1] and adaptive control [1]. Fuzzy control has been employed successfully to solve many nonlinear control problems [3,4]. Recently, many robust fuzzy tracking control schemes have been developed for nonlinear tracking control design problem [5–14]. In general, tracking control design problems are more difficult than fuzzy stabilization control design problem because they need to track a prescribed reference signal.

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In [5], the feedback linearization technique was proposed to design a fuzzy tracking controller for discrete time systems. As pointed out in [11,14], fuzzy controller based on feedback linearization may be not guaranteed to be stable for non-minimum phase system because of its inverse system design method. Recently, the optimal H_2 tracking control design was proposed for nonlinear stochastic systems to achieve the least mean square tracking error [11,14–17]. In general, the optimal H_2 tracking control design can be achieved only when the statistics of stochastic disturbances were available. Otherwise, its performance would be degraded if the statistics of stochastic disturbance are incorrect. For remedying the shortcomings of the H_2 tracking, a robust control design based on H_∞ tracking has received great attention for its robustness properties against uncertain disturbance without knowledge of statistics of disturbances. In [6], based on the T–S fuzzy model, a robust H_∞ tracking control design was proposed for nonlinear dynamic systems with external disturbance. An effective matrix decoupling technique was developed to derive a single-step LMI condition for the observer-based H_∞ control design [18]. In [19–23], the H_∞ fuzzy control was studied for many different systems to achieve the H_∞ control performance. Recently, the mixed H_2/H_∞ tracking designs [24–30] were proposed to minimize the H_2 tracking error with the consideration of a prescribed H_∞ attenuation level to eliminate the influence of uncertain disturbances. However, the conventional mixed H_2/H_∞ tracking control design is an optimal H_2 tracking control under a prescribed H_∞ attenuation constraint and basically is only a constrained single objective problem (SOP) for tracking control design. In this study, the proposed multiobjective tracking control design can achieve the optimal H_2 and robust H_∞ tracking performance for fuzzy systems simultaneously.

Although most existing studies capture characteristics of tracking control designs in the form of SOPs, multiple objectives arise naturally in real-life scenarios. These objectives conflict with each other normally; in other words, these objectives cannot be optimized simultaneously. In general, the optimal solution of multiple objectives is not unique and there may exist many optimal solutions for multiple objectives. In contrast to finding the global optimal solution in SOPs, the Pareto optimal solutions have been proposed for MOPs [31–33]. Classical optimization methods suggest converting a MOP to SOP by emphasizing one particular Pareto optimal solution by a weighted sum method at a time [33]. When such a method is used to find multiple solutions of a MOP, it has to be applied with different weightings in many times, hopefully finding a different solution at each simulation run. Recently, a number of multiobjective evolutionary algorithms (MOEAs) have been discussed for their ability to find multiple Pareto optimal solutions for algebraic systems in one single simulation run [31–35]. From the recent review paper about multiobjective fuzzy control [36], it is seen that the work of multiobjective control of fuzzy logical systems can be divided into two categories: (i) identification of control parameters and/or rules (e.g. tuning of membership function parameters, and rule selection as a post-processing method) and (ii) learning of controller structure (e.g. learning rule bases), i.e., at present, a MOEA is employed to learn the fuzzy controller based on fuzzy rule-based system and still cannot be applied to the multiobjective control design problems of T–S fuzzy dynamic systems [36–38]. Even MOEAs have been employed widely to solve MOPs of some algebraic or rule-based systems, it is still not easy to apply them to solve the MOP of nonlinear dynamic systems at present. More effort is still needed to apply them to multiobjective H_2/H_∞ tracking control design problem for nonlinear dynamic systems. In general, the MOP for nonlinear dynamic systems is more difficult than how to specify some variables to minimize the multiobjective functions in the conventional MOP of algebraic or rule-based systems.

Recently, T–S fuzzy systems have been used to efficiently approximate nonlinear dynamic systems [24,39–44]. In this study, the H_2 tracking control and H_∞ tracking control problems are formulated as a MOP for fuzzy systems with uncertain measurement noises and disturbances. The H_2 tracking performance needs to be minimized for the minimum tracking error. Similarly, the robust H_∞ tracking performance also needs to be minimized for the minimum worst-case effects of measurement noise and disturbance on the tracking error. Therefore, the multiobjective H_2/H_∞ tracking control design needs to minimize the H_2 tracking and robust H_∞ tracking performance simultaneously. In general, it is not easy to solve this multiobjective tracking control design problem for fuzzy systems directly. In this study, the MOP for H_2/H_∞ tracking control design of fuzzy systems is solved from the indirect perspective. Based on three LMI constraints and the proposed indirect technique, we find the H_2 tracking and robust H_∞ tracking performance have the upper bounds α and β, respectively. Therefore, the indirect method of multiobjective H_2/H_∞ tracking control design becomes how to specify the fuzzy control gains to minimize the upper bounds $(\alpha\ \beta)$ simultaneously subject to sets of LMIs. We also show that the proposed indirect MOP is equivalent to the original MOP for multiobjective H_2/H_∞ tracking control design of fuzzy systems when Pareto optimal solutions are achieved. In summary, as compared with the conventional mixed H_2/H_∞ tracking control designs, which solve the optimal H_2 tracking control problem under