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# OVERVIEW OF STABILITY ANALYSIS FOR T-S FUZZY SYSTEMS

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Abstract. *T-S fuzzy control can deal with complex nonlinear systems, and has been successfully used in many industrial fields. Stability analysis of fuzzy control system is an important issue in the study of fuzzy control theory. This paper gives an overview of stability analysis for T-S fuzzy systems, including the stability of T-S fuzzy systems, the stability of T-S fuzzy time-delay systems, and the stability of interval type-2 T-S fuzzy systems. The limitations of current research methods are analyzed. Finally, several future research directions on type-2 T-S fuzzy systems are pointed out.*
**Keywords:** T-S fuzzy systems, Type-1 T-S fuzzy systems, Type-2 T-S fuzzy systems, Lyapunov stability, Time-delay system

1. **Introduction.** "Fuzzy Theory" was first proposed and created by Prof. Zadeh in a seminal article called "Fuzzy Sets" in 1965 [1]. In 1973, he published another seminal article "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes" [2], which proposed the use of fuzzy logic rules IF-THEN to quantify experts' empirical knowledge and the relevant control law was established. Since then, fuzzy control has gradually become an effective means of nonlinear system modeling and control.

T-S fuzzy system is a model-based fuzzy system, first proposed by Takagi and Sugeno in [3]. The nonlinear system had been divided into several linear subsystems by membership function, each membership function represents the weight of the corresponding linear subsystem in the entire T-S model, so that the T-S model transforms the controller design analysis of nonlinear systems into the controller design analysis of linear subsystems. Subsequently, Sugeno and Kang further studied this model and proposed the T-S-K model [4]. In [5-8], the T-S fuzzy system was selected by the membership function, and can approximate a continuous function on any closed set with arbitrary precision. However, considering the error between the nonlinear system and the T-S model, Wang used a norm-bounded uncertainty term to supplement the representation of the T-S fuzzy system in [9], which will be very close to or even completely accurate to represent the nonlinear system. A general fuzzy system is mainly composed of four parts: fuzzification, fuzzy rule base, fuzzy inference engine and defuzzification.

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Once parameter uncertainties of nonlinear plants are considered, the grades of membership may become uncertain in value. The concept of a type-2 fuzzy set was introduced by Zadeh as an extension of the concept of an ordinary fuzzy set, i.e., a type-1 fuzzy set [10]. All fuzzy sets are characterized by membership functions. Since both type-2 fuzzy logic system (T2-FLS) and type-2 fuzzy logic controller (T2-FLC) adopt T2-FS based on fuzzy membership function representation, language and data uncertainty were modeled simultaneously, so that they were directly used to deal with the uncertainty of fuzzy rules.

T-S fuzzy control can deal with complicated nonlinear systems, and has been successfully applied to a lot of industrial fields. The motivation of this work is to give relevant researchers a quick understanding of the control and stability of T-S fuzzy systems since there are few reports in recent years. The advantages and disadvantages of existing research methods have been studied and the future research direction is also prospected.

This paper is organized as follows. In Section 2, the stability of T-S fuzzy systems and T-S fuzzy time-delay systems is given. In Section 3, the stability of interval type-2 T-S fuzzy systems is given. The conclusions and future researches are drawn in Section 4.

## 2. T-S Fuzzy Systems.

### 2.1. Stability of T-S fuzzy systems.

Depending on the type of Lyapunov function, it can be roughly classified into public Lyapunov functions, piecewise Lyapunov functions, fuzzy Lyapunov functions, etc.

The public Lyapunov function method needs to find a common Lyapunov scalar function $V(x(k)) = x^T(k)Px(k)$ for each subsystem. This method was first used for the stability analysis of T-S fuzzy systems in the literature of Tanaka and Sugeno in 1990 [11], and then in 1992, the results were extended to discrete T-S fuzzy systems [12] and global asymptotically stable sufficient conditions were derived. However, for some stable T-S fuzzy systems, the public matrix $P$ that satisfies the conditions does not exist, so this analysis method may be relatively conservative. In 1995, Wang et al. proposed a method by using the principle of parallel distribution compensation (PDC) to design a fuzzy controller to make the nonlinear system globally stable, and the LMI method was first proposed in finding public matrix $P$ [13,14]. In [15], Zhao et al. have also studied this and solved these problems directly through LMI. The above Lyapunov function methods all need to solve the problem of the common matrix $P$. Although the LMI technique is an effective method to find the common matrix, when the number of rules of fuzzy inference is large, the calculation is still relatively complicated. Moreover, for many stable T-S fuzzy systems, the common matrix does not exist, which brings great conservation to the design of the system. In view of this situation, some scholars have proposed the "piecewise Lyapunov function method".

The idea of the piecewise Lyapunov function is to divide the state space into several subsets according to the properties of the membership function. On each subset, some fuzzy rules are activated and some rules are not. Then, a common Lyapunov function is found for the activated subsystems on each subset. Obviously, the Lyapunov function is a piecewise function. In addition, the derivative of this piecewise Lyapunov function is needed to be globally less than zero in the state space. In order to solve this problem, a good method for constructing continuous piecewise Lyapunov functions is presented in [16] and it is less conservative than the public Lyapunov function method. However, it is difficult to design parallel distributed controllers for T-S fuzzy systems because the same fuzzy rule will be activated in different state space sets, which leads to the bilinear matrix inequality.

A stability condition based on fuzzy Lyapunov function is proposed in [17], and the difficulties in dividing fuzzy subspaces for piecewise Lyapunov function methods are avoided. In general, the fuzzy Lyapunov function has the form $V(t) = x^T(t)\sum_{l=1}^{r}\mu_l(\theta(t))P_l x(t)$.

The membership function is included in the fuzzy Lyapunov function and it is the least conservative. However, the derivative of the membership function has to be dealt with when this method is used.

On another aspect, the stability and stabilization problems of nonlinear systems described by T-S fuzzy systems have been extensively studied in the last two decades, and several interesting results usually formulated in LMI constraints can be found in [18-24].

Other methods such as sliding mode variable structure method, small gain theory approach and circular stability criterion method are also studied [25-27].

2.2. **Stability of T-S fuzzy time-delay systems.** Generally, time-delays often occur in practical systems and in engineering problems involving rolling mills, transportation of signals, networked control systems, neural networks, and synchronization between two chaotic systems. Therefore, the issue of asymptotic stability and stabilization of T-S fuzzy systems with time-delays has been one of the hot topics in control research.

In 2000, T-S model is used as a tool to study the control problem of nonlinear time-delay systems [28].

The main research methods of T-S fuzzy time-delay systems are the Lyapunov-Krasovskii (L-K) method and the Lyapunov-Razumikhin (L-R) method. The advantages of the L-K method are as the following: (a) the method is unified, and finally it can be transformed into a solution to a class of Riccati equations or a set of linear matrix inequalities; (b) it is widely used and can be applied to parameter uncertain systems and time-varying time-delay systems.

Cao and Frank [29] applied the L-K method and the L-R method, respectively, to studying the stability conditions of continuous and discrete fuzzy time-delay systems, and gave a design method for a parallel distributed compensation fuzzy controller based on linear matrix inequalities. Some scholars extended the results of Cao and Frank, and proposed fuzzy controller design schemes such as fuzzy [30-32] and robust guaranteed cost [33-35] for fuzzy time-delay systems with uncertainty. Moreover, robust tracking of fuzzy time-delay systems was discussed in [36]. [37] studied the stability analysis and synthesis method of fuzzy time-delay correlated large-scale systems. However, the above results are all time-delay independent.

The time-delay-dependent stability analysis method is much more complicated than the time-delay-independent method. In 2004, Guan and Chen designed a guaranteed-cost state and output feedback controller by using the time-delay correlation method for T-S fuzzy systems with constant delay [38]. While Li et al. discussed the time-delay-dependent stability conditions of fuzzy systems with time-varying state delays and parameter uncertainties [39], a common feature of [38] and [39] is that they both adopt the previous method. The model transformation I described above is combined with Park's inequality. Korean scholars Jeung et al. used the model transformation III method to analyze the time-delay-dependent stability of a class of fuzzy time-delay systems [40]. Based on the idea of model transformation, Chen et al. derived the conditions for the existence of time-delay-dependent fuzzy controllers and fuzzy observer controllers by using linear matrix inequalities [41,42]. Yoneyama also proposed a generalized stability criterion for T-S fuzzy time-delay systems [43-45]. Chen et al. studied the design of guaranteed cost controllers for T-S fuzzy time-delay systems with input delays [46,47]. In addition, some literature proposed LMI conditions for the stability of interval-variable delay T-S fuzzy delay systems and the design of filters [48-52]. Wu and Li gave the stability control conditions based on the fuzzy Lyapunov function, which reduced the conservativeness of the stability conditions of the existing T-S fuzzy time-delay systems [53]. The existing time-delay correlation analysis methods for T-S fuzzy time-delay systems are all derived from the research results of linear time-delay systems, so they inevitably inherit the limitations of these results. Most of the existing literature obtains less conservative results by adding more free weight matrices to the left side of the Lyapunov functional derivative. Due to the excessive use of free weight matrices, the calculation amount of this method is too large, and the expression form of the stability condition is too complicated, especially when it involves a time-varying time-delay fuzzy system with multiple fuzzy rules, it is difficult to realize multiple linear inequalities. Therefore, it still has certain drawbacks for the application of fuzzy time-delay systems.

The recent techniques adopted in the stability analysis of T-S fuzzy systems are time-varying delay [54,55].

3. **Stability Analysis of Interval Type-2 T-S Fuzzy Systems.** It is well known that the membership functions of the T-S fuzzy model may be uncertain if the original plant contains the uncertainties [56]. A type-2 fuzzy logic system in Figure 1 is constructed by the same structure of type-1 IF-THEN rules, which is still dependent on the knowledge of experts. Three structures of type-2 T-S fuzzy model are given in Table 1. The interval type-2 T-S fuzzy control theory has been investigated widely to deal with the uncertainties [57-62]. An interval type-2 T-S fuzzy model was employed to represent the system dynamic model, and the system uncertainties were captured by the upper and lower membership functions [58].

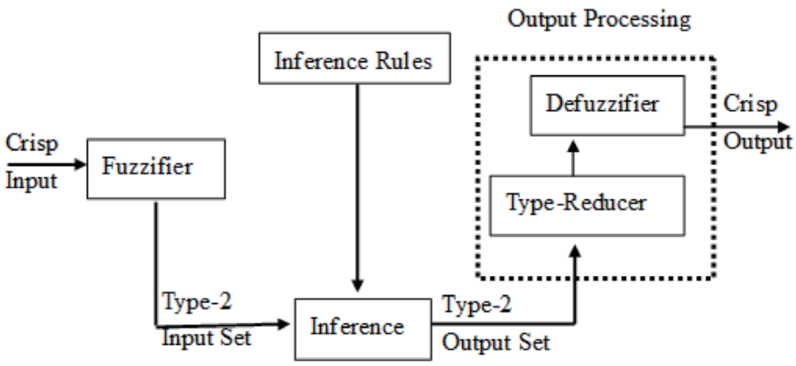


FIGURE 1. The structure of type-2 fuzzy logic system

TABLE 1. Types of interval type-2 T-S fuzzy model

| Types of interval type-2 T-S fuzzy model | | 1 | 2 | 3 |
|---|---|---|---|---|
| Structure | Antecedent | Interval type-2 T-S fuzzy sets | Interval type-2 T-S fuzzy sets | Interval type-1 T-S fuzzy sets |
| | Consequent | Interval type-1 T-S fuzzy sets | A crisp number | Interval type-1 T-S fuzzy sets |

Then a state-feedback controller was designed so that the actuator fault issue was solved [59]. In [60], the information of the membership functions for the interval type-2 T-S fuzzy model was considered so that the less conservative stability criterions are obtained. In addition, a state feedback interval type-2 T-S fuzzy controller was designed for a class of interval type-2 T-S fuzzy systems with time-varying delay to solve the parameter uncertainties [61]. Moreover, the membership functions independent stability criterions and dependent stability criterions were both presented based on the sum-of-squares approach for the interval type-2 T-S fuzzy systems to solve the uncertainties [62].

In practical industry and production, many systems are time-driven [63]. We will give a relatively conservative small sampling period when controlling the system. The system will continuously update the control signal with this fixed sampling period. Even if the system has obtained the ideal state and no longer needs any control information, the control signal will still be continuously updated. Therefore, this time-triggered control method will cause the waste of transmission resources. To settle the problem, event-triggered control [64-66] is utilized to the fuzzy systems, where an event-triggered mechanism is introduced to determine to data transmissions in the control design. [67] studied the stabilization control problem of interval type-2 fuzzy systems under network attack, and the proposed robust adaptive event-triggered control method avoids unnecessary triggering events. [68] considered discrete-time interval type-2 fuzzy control systems with nonlinear disturbances and proposed an event-driven fault detection control method. In [69], an integrated approach to model predictive control was proposed for interval type-2 fuzzy systems. Some research work on robust $H_\infty$ output feedback finite-time control for interval type-2 fuzzy systems with actuator saturation and event-triggered fuzzy output feedback fault-tolerant control for interval type-2 Takagi-Sugeno large-scale systems with time delays has been done in our previous work [70,71].

4. **Conclusions.** This paper gives an overview to the stability of fuzzy systems, including the stability of T-S fuzzy systems, the stability of T-S fuzzy time-delay systems, and the stability of interval type-2 T-S fuzzy systems. Many new fuzzy control research results on system stability are given. However, there are still no unified and complete theories to guarantee the stability of fuzzy control. Compared with deep neural networks, the structure of interval type 2 fuzzy systems has no internal features. Effective construction of deep interval type-2 fuzzy system or interval two combination of type fuzzy systems and deep neural networks may be a further feasible direction to improve its performance. With the popularity of data-driven modeling methods, there are more and more rules for fuzzy systems, and interpretability is also greatly reduced. How to balance the performance and interpretability of interval type-two fuzzy systems is a problem worth studying.

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