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A survey on control for Takagi-Sugeno fuzzy systems subject to engineering-oriented complexities

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ABSTRACT

Nonlinearities exist everywhere and the investigation on control problems for nonlinear systems is of both theoretical and practical significance. The Takagi-Sugeno (T-S) fuzzy techniques, as one of the powerful model-based tools for dealing with control problems for nonlinear systems, have received considerable and persistent research attention during the recent decades. Based on the T-S fuzzy model, many complicated nonlinear control problems have been addressed in the literature. In this paper, we aim to provide a survey with respect to the T-S fuzzy control problems with complexities that are frequently encountered in the engineering practice. Firstly, the backgrounds of the fuzzy control and engineering-oriented complexities are discussed. The considered complexities are divided into traditional engineering-oriented ones and the network-induced ones. The former mainly includes time-delays, parameter uncertainties, sensor/actuator faults and the latter contains network-induced phenomena, communication protocols, event-triggered schemes and cyber-attacks. Then, the recent progress on the T-S fuzzy control problems subject to these complexities has been reviewed in details. Finally, based on the literature review, the conclusions are drawn and some possible future topics are given.

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T-S fuzzy systems; T-S fuzzy control; nonlinear systems; engineering-oriented complexities; networked control systems; network-induced phenomena

1. Introduction

Since the first introduction of the concept of fuzzy sets by Zadeh in 1965 Zadeh (1965), the fuzzy set theory has been widely applied for numerous fields include but are not limited to, signal processing, decision-making, finance, and control engineering (Feng, 2006). Such success and popularity may be largely attributed to the distinct features of fuzzy sets and fuzzy logic. For example, the fuzzy sets extend the expression capability of the traditional deterministic sets by introducing the continuous grade of membership and thus provide a natural way to describe many complex phenomena in the real-world. In particular, the fuzzy set theory has been regarded as an effective tool in dealing with practical control problems as it offers a concise framework to utilize abundant human knowledge when designing and implementing control laws. A distinct superiority of the fuzzy control methods to the traditional ones is the intelligence. The first successful attempt of applying fuzzy set theory to control filed can date back to the 1970s. Specifically speaking, in 1974, the fuzzy-logic-based control algorithm was first proposed in Mamdani (1974) to control a steam engine where the heuristic control strategy has been designed based on a series of fuzzy rules. Since then, fuzzy control and fuzzy systems have become an important research topic and plenty of results have been reported in the literature (Bingiil et al., 2000; Mamdani & Assilian, 1975; Marseguerra & Zio, 2003; Marseguerra et al., 2005; Precup & Hellendoorn, 2011; Sugeno, 1999).

Generally speaking, the fuzzy control systems include model-free and model-based ones. For model-free case, the fuzzy controller is deigned only based on human and prior knowledge. For model-based case, the original nonlinear plant is firstly represented by a suitable fuzzy system and then, the desired control laws can be constructed based on the obtained fuzzy model and the given performance index. During the last decades, both of these two types of fuzzy control systems/approaches have been investigated with extensive results and wide engineering applications (Cao et al., 1996; Jiang et al., 2020; Li et al., 2015, 2013; Li & Li, 2004; Qiu et al., 2010; Wang et al., 2018). The basic structure of a fuzzy control system consists of four conceptual components: knowledge base, fuzzification interface, inference engine, and defuzzification interface. A typical fuzzy system is usually represented by an 'IF-THEN' form. The 'IF' term refers to

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the antecedent (condition) part which is used to describe the situation concerning the system dynamics. The 'THEN' term refers to the consequent (conclusion) part which is used to describe the measures that should be taken. According to the literature (Sugeno, 1999), the fuzzy control systems can be classified into type-1, type-2, and type-3 ones based on the different 'IF-THEN' forms.

It is worth mentioning that the Takagi-Sugeno (T-S) fuzzy system (which is actually the type-3 fuzzy control system), as one kind of popular fuzzy model, has attracted particular research attention since its first introduction in Sugeno and Takagi (1983); Takagi and Sugeno (1985). Under the T-S fuzzy modelling framework, any smooth nonlinear functions can be described by a set of linear submodels linked by time-varying membership functions with any desired accuracy. Due to such a concise yet accurate model, the T-S fuzzy technique serves as an effective way to handle the analysis/synthesis problem for general nonlinear systems. Thus, it is not surprising that there exists a rich body of literature concerning control problems for T-S fuzzy systems under different performance indexes, such as H_∞ control (Chiu & Chiang, 2017; Dong, Wang et al., 2009; Wang et al., 2019), security control (Chen & Wang, 2020; Ge et al., 2019), H_2 control (Li et al., 2013) and dissipative control (Tao et al., 2017; Zhang et al., 2020, june).

According to the structure of subsystems, the T-S fuzzy system can be classified into two types: the homogeneous one and affine one. In the homogeneous T-S fuzzy system, the subsystem (or the consequent part) is linear without a constant bias term, while in the affine fuzzy system, the subsystem contains a bias term. It is shown in the literature that under the same condition (fuzzy rules, fuzzy reasoning and so on), the approximation capability of the affine fuzzy model is better than that of the homogeneous one (Kim & Kim, 2001; Wang & Feng, 2004). On the other hand, the analysis for the affine fuzzy system is usually more difficult due to the relatively complex dynamics. It is indeed an interesting topic that how to utilize these fuzzy models appropriately for the practical control problems under the trade-off between approximation accuracy and design complexity. Undoubtedly, both of these two types of T-S fuzzy systems are regarded as powerful tools for dealing with nonlinear control problems and considerable research attention has been paid to the related issues (Chang & Chang, 2005; Chang et al., 2011; Feng, 2004; Hsiao et al., 2004; Qiu et al., 2011; Wei et al., 2017).

In the engineering practice, the real plants often run in a complex and mutative environment with kinds of uncertain factors which inevitably bring certain engineering complexities such as time delays, parameter uncertainties, nonlinearities and sensor/actuator faults. These complex phenomena would directly influence the system state evolution in different ways, and largely affect the system performance, and even result in instability. Once these undesired phenomena occur, the controllers designed without sufficient consideration of these factors may fail to achieve the desired control purposes. Therefore, it is crucial yet challenging to establish proper mathematical models for them and seek for effective analysis/design methods. The above-mentioned engineering-oriented complexities are usually considered as the traditional engineering complexities and have been widely investigated by communities of control engineering for decades (Hu et al., 2020; Luo et al., 2020; Shen et al., 2020; Zhao et al., 2020).

Along with the rapid development of automation and communication techniques, employing networks (especially, the wireless networks) in control systems to achieve signal transmission has become increasingly prevalent. The utilization of communication networks, on one hand, brings many advantages including improved flexibility, reduced cost, simplified installation and so forth. On the other hand, it also brings/enhances the engineering-oriented complexities such as network-induced phenomena, communication protocols and cyber-attacks. These complexities can be regarded as the newly emerged ones as the utilization of advanced communication techniques and are closely related to the network features of large scale, limited bandwidth, open and common transmission environment, wide distribution, and high internal complexity (Zhang et al., 2016, 2017).

Nowadays, the network-induced complexities constitute a main kind of factor of degrading the system performance that has attracted considerable attention from many scientific areas such as signal processing and control engineering. Generally speaking, the network-induced complexities possess complicated mechanisms and even may occur in a stochastic manner (for example, the randomly occurred transmission delays and channel fadings). Such severe facts have greatly increased the difficulties of analyzing system performance and designing control strategy that have, in turn, inspired researchers to seek new and appropriate methodology. In recent years, the analysis/synthesis problems for linear/nonlinear systems subject to network-induced complexities have been considered in much literature with many seminal results. From the perspective of a researcher of control engineering, the research focuses of these complexities-related issues mainly contain the following respects: (1) the modelling problems for network-induced engineering-oriented complexities; (2) the analysis problems of systems subject to these complexities; and (3) the controller/filter design problems.

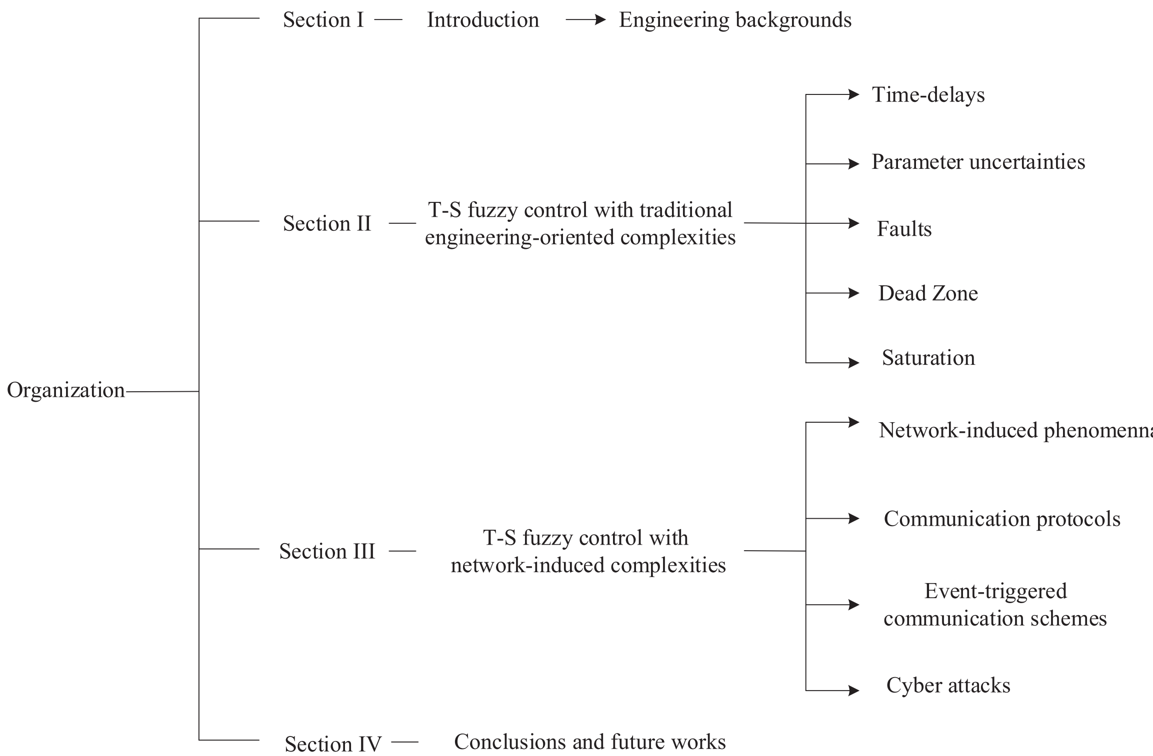

Figure 1. The organization of this survey.

Nonlinearities and engineering-oriented complexities are known to exist everywhere. Thus, the controller synthesis issues for nonlinear systems affected by engineering-oriented complexities are of great practical importance. Considering the distinct merits of nonlinear T-S fuzzy control schemes, it is a natural idea to use the T-S fuzzy theory to handle control problems for nonlinear plants subject to engineering-oriented complexities. In fact, when the engineering-oriented complexities are considered, the dynamics of the closed-loop fuzzy system would become more complex that increases the design difficulties. To be more specific, the main challenges are reflected in (1) how to establish proper models to account for these phenomena in the T-S fuzzy modelling framework; (2) how to design parallel-distributed-compensation or non-parallel-distributed-compensation T-S fuzzy controllers by sufficiently considering the effects caused by these complexities; (3) how to utilize the membership-function-dependent methods to obtain results with less conservatism; and (4) how to apply the theoretical results smoothly to the practical engineering. So far, the T-S fuzzy control issues on this topic have gained vast research interests and the superiority of such intelligent control schemes has been verified by numerous simulation/experimental results in the literature (Li et al., 2016; Qiu et al., 2016; Su et al., 2013).

In this paper, we focus our attention on the T-S fuzzy control issues subject to both traditional and newly emerged engineering-oriented complexities and provide a survey on some recent advances in this area. Some representative models accounting for engineering-oriented complexities are introduced. The theoretical framework for system analysis and controller synthesis is then systematically discussed. Finally, the conclusions and some possible future topics are given.

The organization of this paper is given in Figure 1. To be more specific, the recent advances on the T-S fuzzy control subject to the traditional engineering-oriented complexities (such as time-delays, parameter uncertainties, faults) are discussed in Section 2, where several commonly used techniques are explained. In Section 3, the network-induced complexities are introduced that mainly include network-induced phenomena, communication protocols, event-triggered transmission schemes and cyber-attacks. Then, the selective works concerning T-S fuzzy control problems with network-induced complexities are reviewed. Finally, in Section 4, the conclusions of this survey are drawn and some possible future research directions are given.

2. T-S fuzzy control with traditional engineering-oriented complexities

In this section, we will begin with the introduction of several well-known traditional engineering complexities. These complexities may appear in the engineering practice very early and the related study results are very fruitful. We will first focus our main attention on the explanations of engineering backgrounds of these complex phenomena and then, list some representative works from a T-S fuzzy control perspective.

2.1. T-S fuzzy control with time-delays

Time-delays are a kind of mostly common phenomenon which frequently occurs in many practical systems such as mechanical systems, chemical processes, hydraulic systems, and rolling mill systems (Gu et al., 2003). The existence of time-delays complicates the dynamics of systems and constitutes the main factor of deteriorating system performance. Roughly speaking, according to manners of affecting the system evolution, time-delays can be classified into discrete ones, distributed ones and mixed ones. To deal with the effects caused by time-delays, several classical methods have been developed where, the Lyapunov-Krasovskii theory combined with the linear matrix inequality technique is a mostly used one by constructing proper Lyapunov-Krasovskii functionals (LKFs). In the T-S fuzzy context, the research interests attracted by time-delays may begin with (Cao & Frank, 2000) where the synthesis problem was first discussed for continuous-time T-S fuzzy systems with a single bounded time-varying delay. Since then, the T-S fuzzy control problems with time-delays have become an increasingly popular topic and plenty of literature is available on this issue.

About 10 years ago, a hot research topic is the fuzzy control problem for continuous time-delayed T-S fuzzy system under kinds of engineering-oriented performance requirements which include, stability, H_∞, $L_2 - L_\infty$ and guaranteed cost control ones. Initially, the delay-independent approach has been adopted which shows advantages of low computational complexity and easy analysis/design (Ting & Chang, 2011; Wu, 2010). Afterward, several delay-dependent methods have been developed to reduce the possible conservatism by utilizing more delay information when constructing LKFs. In that time period, the single discrete constant/time-varying and finite-distributed delays were often considered (Liu et al., 2010; Ma et al., 2016; Zhang et al., 2011; Zhou et al., 2012).

With the development of digital computers, the application of discrete-time systems becomes wider and wider. Accordingly, for the last decade, the investigation on discrete time-delayed T-S fuzzy systems has become a popular trend with more attention transferred from the single delay to multiple and mixed delays. In addition, more complex nonlinear systems (such as large-scale systems, complex dynamic networks, switched systems) have gained folks' interests where time-delays may exist in a rather complicated way (Ali et al., 2020, july; Li et al., 2013; Senthilkumar, 2016; Tao et al., 2017). More recently, the so-called randomly occurred delays attracted special attention where the delays occur in a random way. A random sequence obeyed Bernoulli distribution has been used to represent the features of such random delays and stochastic theory has been applied for dealing with the related controller design issues (Zhang et al., 2014).

2.2. T-S fuzzy robust control with parameter uncertainties

In the process of modelling a real plant, the parameter uncertainties will inevitably occur that reflect in parameter perturbation in system matrices for a state-space model. In the practice, many factors would lead to the occurrence of uncertainties. For example, (1) when modelling, it is impossible to get an absolutely precise model due to many restrictions such as techniques; (2) a simplified model is often desired which can represent the main dynamics of a plant since a complicated model will dramatically increase the design difficulties; and (3) as the long-time run of a device, components would undergo aging. The parameter uncertainties bring technical challenges in the analysis/synthesis issues since many traditional control methods are based on the precise mathematical models and sensitive to the parameter perturbation. To overcome such a difficulty, the robust control theory has been developed with the exception of providing a unified framework to deal with uncertain systems. Since then, the controller design problems for uncertain systems have gained very much attention and a great deal of related literature is available.

In the T-S fuzzy content, the most used model accounting for uncertainties is the norm-bounded uncertainty model which provides an effective way of describing time-varying-but-bounded uncertainties. Some very early literature with respect to T-S fuzzy control problems subject to norm-bounded uncertainties can be found in Cao and Frank (2000); Wang et al. (2004). In these seminal works, to deal with the effects caused by parameter uncertainties, the well-known S-procedure lemma and some inequality techniques have been employed which have facilitated the system analysis and control design. By using the robust control design methods, the closed-loop uncertain systems can have strong robustness and display satisfactory performance for all considered uncertainties.

Based on the theoretical framework developed by these pioneering works, the past decades have witnessed a great deal of research attention devoted to T-S fuzzy control for uncertain nonlinear systems. Due to its great engineering significance, the uncertainties, even today, are still a hot research topic with more attention on more complex cases. For instance, in Wei et al. (2018), the robust controller has been designed for affine T-S fuzzy models under the coexistence of parameter uncertainties and actuator faults. To overcome the difficulties caused by the coupling term of uncertain input and output matrices, a descriptor formulation has been introduced. In Lv et al. (2019), by utilizing a special argumentation method, a kind of robust T-S fuzzy proportional-integral-derivative (PID) controller has been designed for discrete-time nonlinear uncertain systems. In Ghorbel et al. (2020), the fuzzy control problem has been addressed for uncertain and distributed systems. In Zhang et al. (2020, june), the dissipative theory has been employed to deal with the control problems for uncertain singular T-S fuzzy systems subject to time-varying delays and the actuator saturation.

Another attractive way to represent parameter uncertainties is to utilize the interval type-2 fuzzy systems (ITFSs). Different from the type-1 T-S fuzzy system whose grades of membership are fixed, the type-2 fuzzy logic system is capable of dealing with uncertain grades of membership which may vary within a certain range. Thus, in recent years, ITFSs have been employed to handle uncertainties by using interval grades of membership to describe system parameter uncertainties.

It is worth mentioning that in the remarkable paper Lam and Seneviratne (2008), the problem of stability analysis for a class of continuous-time ITFSs has been thoroughly investigated. In this work, an interval type-2 fuzzy model has been utilized to represent a uncertain nonlinear system, and the uncertainties have been captured effectively with the help of the lower and upper membership functions. Note that in the ITFSs, the traditional parallel distributed compensation scheme is no longer applicable due to the uncertain membership functions. To overcome such a difficulty in controller design, a kind of type-2 fuzzy controller has been proposed by only utilizing the average membership grades of the lower and upper membership functions. In addition, in some more recent works, the membership-function-dependent approaches have been developed for ITFSs with less conservative results obtained. Some representative work concerning the related issues can be found in Ping and Pedrycz (2020); Rong et al. (2019); Zhao et al. (2020); Zheng et al. (2020).

2.3. T-S fuzzy fault-tolerant control with faults

With the ever-increasing industrial demand and the rapid development of industrial automation, the industrial systems are characterized by severe nonlinearity, strong coupling and high complexity which give rise to the occurrence of system faults. The faults have many forms and there are some different classification principles for them. For example, according to the location faults occurred, the faults can be classified into sensor ones, actuator ones and component ones. Once the faults occur, system devices (such as sensors and actuators) will run in an abnormal condition that would degrade the performance of the closed-loop system and even result in instability. As such, to keep/improve the safety and reliability of a dynamic system, the underlying system faults should be fully taken into account when designing controllers. Accordingly, the fault-tolerant control theory has been developed aiming at providing an ideal way to solve such design problems.

Generally speaking, fault-tolerant control approaches can be mainly classified into two types: the passive and active ones. A passive fault-tolerant controller means that a same controller is applied both for the fault-free case and fault case, possessing the advantage of easy implementation. In this sense, this kind of controller can be regarded as a robust one against faults. For another case, in the active fault-tolerant systems, a new control scheme based on online accommodation is utilized to compensate faults that usually brings results with less conservatism.

Under the T-S fuzzy framework, the mostly investigated faults are the sensor faults and actuator faults. For example, in Jiang et al. (2010), the active fault-tolerant tracking control problem has been considered for near-space vehicle based on the T-S fuzzy model, where actuator faults have been modelled and analyzed. In Tian et al. (2011), the passive fault-tolerant T-S fuzzy control problem has been investigated, where the actuator and sensor faults have been both considered. From a perspective of modelling, a fault can be described by an additive or multiplicative form. It has been shown in the literature that these two forms can be transformed from each other (Chen & Patton, 1999; Ding, 2013). When modelling the multiplicative actuator/sensor faults, an extra diagonal coefficient matrix is often used to reflect the change of control inputs or measurement outputs caused by faults. In terms of the structure of the coefficient matrix, several kinds of universally used fault models have been discussed in the literature. For instance, in Nagamani et al. (2020); Shen et al. (2020), the elements of the coefficient matrix are assumed to be time-varying and vary within a given scope. The upper bounds and lower bounds of faults have been assumed to be known to obtain the desired theoretical results. In the work (Aslam et al., 2020, february; Gu et al., 2012; Peng et al., 2013; Tian et al., 2011), the elements of the coefficient matrix are assumed to be stochastic with the known expectation and variance which results in a stochastic closed-loop system. In some other works (Sun et al., 2017; Wei et al., 2017), the elements of the coefficient matrix are assumed to have different modes which are characterized by a Markov process with a known mode transition rate matrix.

2.4. T-S fuzzy control with dead zone

The dead zone is a common phenomenon which widely exists in the real systems including motion control systems, chemical process, manipulator systems and electromechanical systems. Moreover, in a system, the dead zone could occur in many system components such as sensors, valve-controlled pneumatic actuators, amplifiers and hydraulic components. If the dead zone phenomenon occurs in a device, then the device will not respond until its input amplitude exceeds a certain scope. Due to its clear engineering insights, the control problems for nonlinear systems subject to the constraints of the dead zone have attracted much research attention and plenty of literature on this issue has been reported in the recent 20 years. For example, in Ren (2008), a kind of adaptive tracking control approach has been proposed to deal with the side effects caused by the dead zone. In Li et al. (2020), the T-S fuzzy model has been utilized to represent the flexible spacecraft system with actuator dead zone, and the problems of sliding mode attitude tracking control have been addressed.

Based on the available literature, the dead zone phenomenon can be roughly divided into two categories. The first type is the symmetric dead zone where the breakpoints of the input signal and the slopes of the output signal in left-region and right-region are equal. Another type of dead zone phenomenon is called the non-symmetric one which has different breakpoints and slopes in the left-region and right-region. In fact, the non-symmetric model provides a more general description framework that is more capable of capturing the complex behaviours in the engineering practice. Thus, the investigation on the non-symmetric dead zone phenomenon, especially combined with the T-S fuzzy control framework, has attracted special attention both from engineers and theorists. For instance, in Zhang et al. (2010), an adaptive T-S fuzzy control strategy has been proposed for continuous-time nonlinear systems subject to the unknown non-symmetric actuator dead zone. In Hu et al. (2013), the authors have proposed a fuzzy integral sliding mode control method for T-S fuzzy models subject to the non-symmetric dead zone, and the theoretical results have been further applied to the flexible air-breathing hypersonic vehicles. For more literature on this topic, the readers are referred to (Chiu, 2014; Jiang, 2010; Wu et al., 2019; Yang & Tong, 2016) and the references therein.

2.5. T-S fuzzy control with actuator saturation

In industrial processes, another kind of ubiquitous phenomenon is the actuator saturation which would result in poor system performance. Because of the limited capability of a device, it often occurs that the outputs of a device no longer increase no matter how the inputs increase after the inputs exceed certain scope. Due to this, when the actuator saturation occurs, the controllers may not provide a satisfactory performance if they are designed based on the assumption that the actuator can always respond normally according to the received control signals. Thus, when designing control laws, the actuator saturation phenomenon should be taken into consideration for the possibly saturated systems.

In order to appropriately cope with the side effects caused by the saturation constraints, several desired strategies have been proposed by researchers. For example, in Cao and Lin (2003), the low-gain controller has been designed for actuator-saturated T-S fuzzy systems, where the characters of the saturation phenomenon have been fully considered. In Ting and Chang (2011), a kind of robust anti-windup controller has been proposed for fuzzy systems with delays and the actuator saturation. A specific sector condition has been employed to describe the characters of the input saturation. Furthermore, in a series of T-S-fuzzy-related works (Han et al., 2020; Yan & Tong, 2015; Zhao & Li, 2015; Zhu et al., 2019), the saturation phenomena have been represented by the polyhedral models in which the convex optimization techniques have been utilized to obtain desired results.

3. T-S fuzzy control with network-induced complexities

In this section, we will review the recent literature concerning the T-S fuzzy control problems for kinds of network-induced complexities. Particularly, we will introduce respectively, some network-induced phenomena (channel fadings, package dropouts and transmission delays), communication protocols (Try-Once-Discard, Round-Robin and stochastic protocols), event-triggered schemes and cyber-attacks. The control flow diagram for networked control systems is given in Figure 2. The models, analysis techniques and challenges are all discussed based on the selective literature.

3.1. T-S fuzzy control with network-induced phenomena

3.1.1. T-S fuzzy control with package dropouts

The package dropout (which is also called measurement missing and data loss) is a very common phenomenon

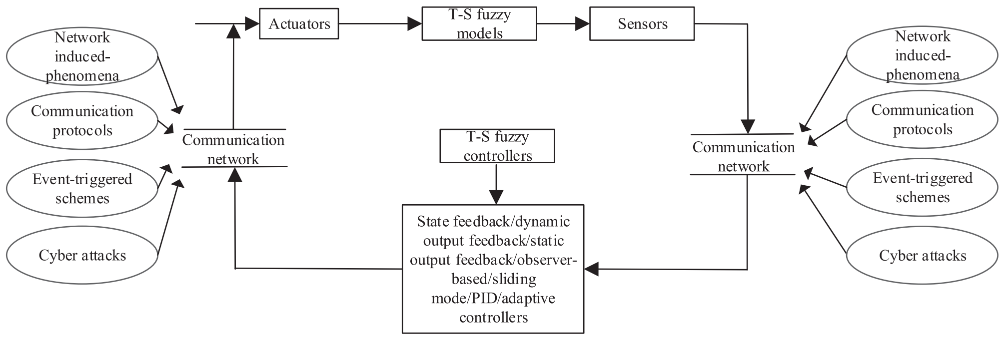

Figure 2. Fuzzy control with network-induced complexities.

in many engineering systems. The package dropout does exist in the traditional systems with a point-to-point connection mechanism, but the occurrence of this less-than-ideal situation would be enhanced in a network system due to the unreliable transmission circumstances such as data congestion. Generally speaking, once the package dropout occurs, no information will be transmitted into controllers or actuators that would dramatically degrade system performance. Thus, it is necessary yet challenging to develop effective methods to cope with the effects caused by the package dropout, especially in the controller design problems. Since the publication of a series of seminal works (Nahi, 1969; Sinopoli et al., 2004; Wang et al., 2003), tremendous research efforts have been devoted to the measurement-missing-related issues and a rich body of results has been reported.

From the perspective of the T-S fuzzy control methods, there is vast literature concerning the modelling, system analysis as well as controller design problems subject to package dropouts. In Dong et al. (2009), a sequence of Bernoulli random variables has been utilized to describe the package dropout, and the T-S fuzzy control problems have been discussed. In Dong et al. (2010), the multiple measurement missing have been considered where a more general model has been built to further reflect the specific situation of each sensor. The probability of package dropout in Gao et al. (2016); Zhang et al. (2015) has been assumed to be uncertain and robust methods have been adopted for the controller design. In Hu and Mu (2020); Song et al. (2018); Tang et al. (2019); Wang et al. (2020), the package dropout has been modelled by a Markov stochastic process with completely/partially known mode transmission probabilities. In Li et al. (2020); Zhang et al. (2019), the dropout compensation schemes have been proposed to deal with the underlying package dropout under which, the better closed-loop performance has been achieved. In Wang et al. (2016), the package dropout phenomenon has been represented by a switching model with two modes and a switching T-S fuzzy controller has been proposed.

3.1.2. *T-S fuzzy control with communication delays*

Communication delays are known to exist in the network-based transmission environment. Different from the state delay discussed in the previous section, communication delays are mainly caused by the long-instance-transmission and the data congestion. Initially, researchers have made great efforts to explore the effects caused by the communication delays for linear systems, and some remarkable works have been published. On the other hand, when it comes to the nonlinear systems, the related problems would be more complicated. As such, to facilitate the controller design process for nonlinear systems, the T-S fuzzy techniques have been adopted whose advantages have been verified in the literature.

In recent years, several modelling/analysis methods have been proposed based on different engineering perspectives, and much attention has been denoted to the continuous-time T-S fuzzy systems with communication delays. Specially speaking, in Kim (2013); Peng and Yang (2010, april), the time-varying communication delays have been considered and the delay-dependent methods have been proposed to obtain less conservative results, where the bounds of delays have been utilized sufficiently. In Zhang et al. (2013), a delay compensation strategy has been proposed to design T-S fuzzy controllers. In Ma et al. (2020); Zhang, Xie et al. (2020), the existence of communication delays both in the sensor-to-controller and controller-to-actuator channel has been modelled and discussed. In some other works, the synthesis problems of fuzzy controllers have been dealt with subject to the coexistence of communication delays and other engineering complexities, including uncertainties (Tian et al., 2011), package dropouts (Hu et al., 2013, may), and the package disordering (Zhang et al., 2018). More recently, the corresponding research results have been further applied for the real system such as the vehicle active suspension (Han et al., 2019), underactuated unmanned surface vehicle (Ma et al., 2020) and permanent-magnet synchronous motor (Kuppusamy & Joo, 2020).

3.1.3. T-S fuzzy control with channel fading

The wireless channel, as compared with the wired channel, is known to be very susceptible to the fading effects that constitutes a feature of wireless communication techniques. Generally speaking, if the signals are transmitted via a fading channel, the amplitude and phase of signals will change in a random way. In the fuzzy control content, the most used model accounting for channel fading is the Lth-order Rice fading model (Elia, 2005; Zhang et al., 2014). In this fading model, a series of stochastic variables are adopted to reflect the change situation of signal amplitude and the phase change is also considered. Compared with the single phenomenon of the package dropout or communication delay, the channel fading is more complicated to be analyzed. Actually, the Lth-order Rice fading model provides a concise way to further describe the package dropout and communication delay in a unified framework and thus, has been attracted special research attention in recent years. In the seminal literature (Zhang et al., 2014) published in 2014, the T-S fuzzy control problem subject to channel fading has been first considered, where some sufficient conditions have been obtained based on the Lyapunov stability theory and the stochastic analysis theory. Since then, some excellent works for more complicated cases have been reported, see, e.g. (Song et al., 2018; Wu et al., 2020, september; Zhang et al., 2016, 2018; Zhang, Su et al., 2020; Zhang, Zheng et al., 2020; Zheng et al., 2017).

3.2. T-S fuzzy control with communication protocols

Due to the character of the limited bandwidth and service capacity of communication networks, transmitting a large amount of information simultaneously is very likely to result in data congestion, and further cause the occurrence of the network-induced phenomena. Thus, in the engineering practice, the communication protocols are often deployed to mitigate network burden by appropriately scheduling the data transmissions. Under the effects of communication protocols, only a part of sensor/controller nodes are permitted to have access to the network at each time instant, thereby reducing the information to be transmitted (Guo et al., 2020; Zhao et al., 2018, 2020, 2018).

There are three typical communication protocols that are widely used in industrial applications, namely, the Round-Robin, Try-Once-Discard (TOD) and random access (which is also called stochastic communication) ones (Zou et al., 2017, 2019a, february, 2019b; Zou, Wen et al., 2019). The differences between these protocols are mainly reflected in the scheduling principles which are established to select nodes to send data. For the Round-Robin protocol, it gives equal opportunity to each node to access the network. On the other words, each node will access the network based on a preset circular order. Such a protocol is periodic and static, and thus, is convenient for implementation. For the TOD protocol, the scheduling principle is designed based on the real-time 'demand', and the nodes with the largest information change (in amplitude) will be selected. For the random access protocol, the access order of nodes is random, and the Markov stochastic process or other stochastic variable sequences are utilized to characterize the random behaviour of such a protocol.

The communication protocols will complicate the dynamics of the closed-loop networked system and thus bring certain challenges for the controller design tasks. In recent years, the T-S fuzzy control problems for networked system with communication protocols have attracted initial research attention and kinds of control strategies have been reported in the up-to-date literature. For instance, in Wang et al. (2019), the fuzzy PID controller has been designed to control a networked system with TOD protocol, where a switching model has been established to deal with the protocol-induced effects. In Dong et al. (2020), a kind of model predictive control scheme has been proposed under the TOD protocol, and the results have been further extended to ITFSs with RR and stochastic protocols in Dong et al. (2020a, 2020b), respectively. In Zhang et al. (2019), the sliding-control problems have been discussed for networked control systems subject to TOD protocols deployed in the controller-to-actuator channel. A kind of H_∞ fuzzy controller has been designed in Wu et al. (2020) to cope with the effects caused by the random access protocol.

3.3. T-S fuzzy control with event-triggered transmission schemes

In the engineering practice, there are mainly two kinds of communication schemes, namely, the time-driven communication and event-triggered communication. Under the scheme of the time-driven communication, the signal transmissions are conducted in a periodic manner that shows merits of good predictability and easy implementation. The time-driven communication schemes are widely employed in the traditional systems with a point-to-point connection mechanism, but when it comes to networked control systems, challenges appear. Generally speaking, since the bandwidth and other network resources in networked system are limited, the unnecessary information transmissions would increase the resource consumption and thus, is usually unfavourable if the communication resources are the major concern. As such, with the exception of reducing transmission frequency and improving the utilization of network resources, the event-triggered strategy has been developed which has been widely used in the networked control systems (Li et al., 2020; Tan et al., 2017).

In the event-triggered communication scheme, the signals are transmitted only when certain prescribed conditions are satisfied. These conditions are called event-triggering conditions which are employed to generate events and further determine the transmission instants. The triggering conditions usually contain two parts: (1) the error part designed to reflect the difference between the current information and the last transmitted information; and (2) the threshold part. According to the type of the threshold part, the event-triggered scheme can be further divided into the fixed type and the relative type. By utilizing the event-triggered communication scheme, the energy can be saved while guaranteeing the satisfactory system performance. Due to the superiority of such an engineering-oriented transmission mechanism, the investigation on the event-triggering-based control/filtering problems for networked systems have attracted much attention in the last decade, and considerable literature has been reported on these issues.

Event-triggered schemes change the traditional transmission ways, and bring more complexities for the controller design. The conventional analysis/design methods for time-driven case may fail to deal with the effects induced by the event-triggered schemes. Generally speaking, in order to design an event-based controller, more factors such as the utilization of triggering conditions, performance guarantee, avoidance of the Zeno behaviour should be fully considered. In fact, these issues become more severe when the T-S fuzzy control methods are utilized. For example, the event-triggered scheme may result in the asynchronous phenomena of the premise variables between the fuzzy plant and fuzzy controller. In this case, the well-known parallel distributed compensation approach is no longer applicable. As such, to address the event-triggering-based T-S fuzzy control problems, many efficient methods have been proposed in recent years. For example, in Chen et al. (2017); Nagamani et al. (2020); Zhang et al. (2017), the observer-based fuzzy controllers have been designed where the estimated premise variables have been used. Under the assumption of the Lipschitz membership functions, some membership-function-dependent conditions have been obtained in Shen et al. (2020) that show less conservatism. More recently, the fuzzy control problems subject to dynamical event-triggered schemes have been considered in Wang et al. (2020, october); Xu et al. (2019); Zhang, Su et al. (2020) where the utilization of resources has been further improved. Some other representative works can be founded in Chen et al. (2020); Liu et al. (2020, 2018); Liu, Zha et al. (2018); Yan et al. (2019); Zhang, Zhao et al. (2020).

3.4. T-S fuzzy security control with cyber-attacks

In the networked control systems, system components (such as sensors, controllers and actuators) are connected to the common (sometimes even public) channels to exchange their information. If no effective procedures of the security protection are deployed in such a transmission environment, it may give opportunities to attackers/opponents to steal the system information and further formulate attack signals to damage the system performance. Furthermore, if the cyber-attacks happen and no corresponding measures are adopted immediately, it will endanger the security of systems and even cause heavy casualties and property losses. Thus, the security control issues for networked systems have become a hot and important research topic, aiming at providing a satisfactory solution against cyber-attacks.

According to the literature Zhao et al. (2020), the cyber-attacks on networked control systems mainly fall into three categories, namely, denial of service (DoS) attacks, repeated attacks, and deception attacks. To be more specific, the DoS attacks can prevent the signals from reaching the destination. For example, it can prevent measurement outputs from sensors to controllers and control signals from controllers to actuators. The deception attacks can inject the fake information into the signal transmission processes, affecting the authenticity of the original signals. Under the replay attacks, the current information can be replaced by the previous one to degrade the system performance. In recent years, all of these three types of cyber-attacks have been attracted research attention and some remarkable literature has been published (Ding et al., 2018; Hou et al., 2020; Hu et al., 2018; Shen et al., 2020).

In the T-S fuzzy control content, theorists mainly focus on the investigation on the DoS attacks and deception attacks, and some initial research results are available in recent years. For example, in Liu et al. (2018), the fuzzy control problems have been considered subject to randomly occurred deception attacks whose results have been further extended to the cascade systems (Liu et al., 2019). In Ge et al. (2019); Liu, Zha et al. (2020); Zhao and Li (2020), the effects of DoS attacks and other engineering-oriented complexities such as event-triggered schemes have been analyzed in a unified framework. In Li et al. (2020); Zha et al. (2020), the deception attacks have been modelled as a delayed nonlinear functions satisfying the bounded conditions, and the related controller design problems have been handled. For more complicated cases, the DoS and deception attacks occurred both in the sensor-to-controller channel and controller-to-actuator channel have been considered respectively, in Chen and Wang (2020); Zhao et al. (2020). Furthermore, in Hu et al. (2020), the definition of the cross-layer DoS attacks has been proposed, under which the attacks occurred both in the physical area and cyber area of multi-power systems have been discussed.

4. Conclusions and future works

In this paper, we have provided an in-depth survey concerning the problems of T-S-fuzzy-model-based control for nonlinear systems subject to several engineering-oriented complexities. We have discussed in details, both traditional engineering complexities and network-induced ones which mainly include time-delays, parameter uncertainties, faults, network-induced phenomena, communication protocols and cyber-attacks. A sufficient number of representative literature is given based on which, the recent advances (such as modelling techniques, analysis methods, design procedures) on the related issues have been introduced.

Although the recent years have witnessed great progress on the T-S fuzzy control problems subject to engineering-oriented complexities, there still exist many topics that have not drawn researchers' attention due mainly to the technical restrictions. In the end, according to the literature review, we will provide some possible topics for the future research as follows.

(1) In recent years, the T-S fuzzy secure control problems subject to cyber-attacks have attracted initial attention. As we presented in the main content of this paper, until now, the DoS attacks and deception attacks have been discussed in the literature, while other types of attacks (such as replay and convert attacks) have not been considered in the T-S fuzzy content. Thus, it would be very interesting to explore effective ways to model these cyber-attacks and further deal with the T-S fuzzy control problems. Furthermore, the available results have been derived based on the assumption that only one type of attack would occur in the networks. However, in fact, the attackers can destroy the system by simultaneously injecting different kinds of attack signals. On the other hand, a system can be also influenced simultaneously by different attackers with different attack strategies. Therefore, it is of engineering significance to investigate the T-S fuzzy control issues subject to mixed (or multiple) cyber-attacks.

(2) The T-S fuzzy modelling technique provides a concise way to represent general nonlinear functions and thus facilitate the analysis for nonlinear systems. The power tools for dealing with T-S fuzzy control problems are the Lyapunov stability theory and the linear matrix inequalities. The main concerns in these techniques are (1) the computational complexities, since many subsystems are needed to be discussed; and (2) the conservatism, since the inequality operation can't be avoided in the derivation process. These issues become more severe when the T-S fuzzy control scheme meets the engineering-oriented complexities. Thus, it would be interesting to develop new methods to address these issues based on the pioneering works (Lam & Narimani, 2010; Zhang et al., 2019).

(3) Nowadays, the results concerning T-S fuzzy control problems are exceedingly vast and considerable attention has been paid to the theoretical investigation. To facilitate the analysis, some assumptions have been made with specialized purposes that would limit the application of these methods. Thus, from a perspective of application, how to remove the strong assumptions as far as possible to extend the application scope of T-S fuzzy control schemes is meaningful. In addition, the design and implementation problems of T-S fuzzy controllers for some more complicated systems are still open, such as the T-S fuzzy formation/containment control for multi-agent systems which is important.

(4) In the literature, several kinds of T-S fuzzy controllers have been proposed, including state-feedback, static output-feedback, dynamic output-feedback, observer-based, and sliding-mode controllers. It should be mentioned that the controllers presented above all fall into the proportional-type which is a special case of PID controllers. On the other hand, it is well known that the PID controllers are widely used in industrial applications that persist show the advantages of easy implementation, high robustness and clear engineering meanings. During the recent decades, the model-free fuzzy PID control problem has gained much attention, while its counterpart for fuzzy model-based case has not drawn enough attention. Although there exist some pioneering works concerning the design problems of T-S fuzzy PID controllers (Wang et al., 2020, october, 2019), the controller design for engineering-oriented complexities still needs more attention and deserves further study.

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