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Introduction

In the past decade, networked control systems (NCSs) have attracted much attention owing to their successful applications in a wide range of areas for the advantage of decreasing the hardwiring, the installation cost, and implementation difficulties. Nevertheless, network-related challenging problems inevitably arise due to the physical equipment constraints, the complexity, and uncertainty of the external environment in the process of modeling or information transmission, which would drastically degrade the system performance. Such network-induced problems include, but are not limited to, missing measurements, communication delays, sensor and actuator saturations, signal quantization, and randomly varying nonlinearities. These phenomena may occur in a probabilistic way that is customarily referred to as randomly occurring incomplete information.

For several decades, nonlinear analysis and stochastic analysis have arguably been two of the most active research areas in systems and control. This is simply because (1) nonlinear control problems are of interest to engineers, physicists, and mathematicians as most physical systems are inherently nonlinear in nature, and (2) stochastic modeling has come to play an important role in many branches of science and industry as many real-world system and natural processes may be subject to stochastic disturbances. There has been a rich literature on the general nonlinear stochastic control problems. A great number of techniques have been developed on filtering, control, and fault detection problems for nonlinear stochastic systems in order to meet the needs of practical engineering. Recently, with the development of NCSs, the analysis and synthesis problems for nonlinear stochastic systems with the aforementioned network-induced phenomena have become interesting and imperative, yet challenging, topics. Therefore, the aim of this book is to deal with the filtering, control, and fault detection problems for nonlinear stochastic systems with randomly occurring incomplete information.

The focus of this chapter is to provide a timely review on the recent advances of the analysis and synthesis issues for complex systems with randomly occurring incomplete information. Most commonly used methods for modeling randomly occurring incomplete information are summarized. Based on the models established, various filtering, control, and fault detection problems with randomly occurring incomplete information are discussed in great detail. Subsequently, some challenging issues for future research are pointed out. Finally, we give the outline of this book.

Filtering, Control and Fault Detection with Randomly Occurring Incomplete Information, First Edition.
Hongli Dong, Zidong Wang, and Huijun Gao.
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1.1 Background, Motivations, and Research Problems

1.1.1 Randomly Occurring Incomplete Information

Accompanied by the rapid development of communication and computer technology, NCSs have become more and more popular for their successful applications in modern complicated industry processes, e.g., aircraft and space shuttle, nuclear power stations, high-performance automobiles, etc. However, the insertion of network makes the analysis and synthesis problems much more complex due to the randomly occurring incomplete information that is mainly caused by the limited bandwidth of the digital communication channel. The randomly occurring incomplete information under consideration mainly includes randomly missing measurements (RMMs), randomly occurring communication delays, sensor and actuator saturations (SASs), randomly occurring quantization and randomly varying nonlinearities (RVNs).

Missing Measurements

In practical systems within a networked environment, measurement signals are usually subject to missing probabilistic information (data dropouts or packet losses). This may be caused for a variety of reasons, such as the high maneuverability of the tracked target, a fault in the measurement, intermittent sensor failures, network congestion, accidental loss of some collected data, or some of the data may be jammed or coming from a very noisy environment, and so on. Such a missing measurement phenomenon that typically occurs in NCSs has attracted considerable attention during the past few years; see Refs [1–24] and the references cited therein. Various approaches have been presented in the literature to model the packet dropout phenomenon. For example, the data packet dropout phenomenon has been described as a binary switching sequence that is specified by a conditional probability distribution taking on values of 0 or 1 [25, 26]. A discrete-time linear system with Markovian jumping parameters was employed by Shu *et al.* [27] and Xiong and Lam [28] to construct the random packet dropout model. A model that comprises former measurement information of the process output was introduced by Sahebsara *et al.* [29] to account for the successive packet dropout phenomenon. A model of multiple missing measurements was proposed by Wei *et al.* [18] using a diagonal matrix to describe the different missing probability for individual sensors.

Communication Delays

Owing to the fact that time delays commonly reside in practical systems and constitute a main source for system performance degradation or even instability, the past decade has witnessed significant progress on analysis and synthesis for systems with various types of delays, and a large amount of literature has appeared on the general topic of time-delay systems. For example, the stability of NCSs under a network-induced delay was studied by Zhao *et al.* [30] using a hybrid system technique. The optimal stochastic control method was proposed by Nilsson [31] to control the communication delays in NCSs. A networked controller was designed in the frequency domain using robust control theory by Gokas [32] in which the network delays were considered as an uncertainty. However, most of the relevant literature mentioned above has focused on the *constant time-delays*. Delays resulting from network transmissions are inherently *random* and *time varying* [33–41]. This is particularly true when signals are transmitted over the internet and, therefore, existing control methods for constant time-delay cannot be utilized directly [42]. Recently, some researchers have started to model the network-induced time delays in multi-form probabilistic ways and, accordingly, some initial results have been reported. For example, the random communication delays have been modeled as Markov chains and the resulting closed-loop systems have been represented as Markovian jump linear systems with two jumping parameters [43, 44]. Two kinds of random delays, which happen in the channels from the controller to the plant and from the sensor to the controller, were simultaneously considered by Yang *et al.* [45]. The random delays were modeled by Yang *et al.* [45] as a linear function of the stochastic variable satisfying a Bernoulli random binary distribution. Different from Yang *et al.* [45], the problem of stability analysis and stabilization control design was studied by Yue *et al.* [46] for Takagi–Sugeno (T–S) fuzzy systems with probabilistic interval delay, and the Bernoulli distributed sequence was utilized to describe the probability distribution of the time-varying delay taking values in an interval. It should be mentioned that, among others, the binary representation of the random delays has been fairly popular because of its practicality and simplicity in describing communication delays.

However, most research attention has been centered on the *single* random delay having a *fixed* value if it occurs. This would lead to conservative results or even degradation of the system performance since, at a certain time, the NCSs could give rise to multiple time-varying delays but with different occurrence probabilities. Therefore, a more advanced methodology is needed to handle time-varying network-induced time delays in a closed-loop control system.

Signal Quantization

As is well known, quantization always exists in computer-based control systems employing finite-precision arithmetic. Moreover, the performance of NCSs will be inevitably subject to the effect of quantization error owing to the limited network bandwidth caused possibly by strong signal attenuation and perturbation in the operational environment. Hence, the quantization problem of NCSs has long been studied and many important results have been reported; see Refs [47–64] and references cited therein. For example, in Brockett and Liberzon [65], the time-varying quantization strategy was first proposed where the number of quantization levels is fixed and finite while at the same time the quantization resolution can be manipulated over time. The problem of input-to-state stable with respect to the quantization error for nonlinear continuous-time systems has been studied by Liberzon [66]. In this framework, the effect of quantization is treated as an additional disturbance whose effect is overcome by a Lyapunov redesign of the control law. A switching control strategy with dwell time was proposed by Ishii and Francis [67] to use as a quantizer for single-input systems. The quantizer employed in this framework is in fact an extension of the static logarithmic quantizer in [68] to the continuous case. So far, there have been mainly two different types of quantized communication models adopted in the literature: uniform quantization [62–64] and logarithmic quantization [56–59, 61]. It has been proved that, compared with a uniform quantizer, logarithmic quantization is more preferable since fewer bits need to be communicated. A sector bound scheme to handle the logarithmic quantization effects in feedback control systems was proposed by Fu and Xie [69], and such an elegant scheme was then extensively employed later on; for example, see Refs [58, 70, 71] and references cited therein. However, we note that the methods in most of the references cited above could not be directly applied to NCSs, because in NCSs the effects of network-included delay and packet dropout should also be considered.

Sensor and Actuator Saturations

In practical control systems, sensors and actuators cannot provide unlimited amplitude signal due primarily to the physical, safety, or technological constraints. In fact, actuator/sensor saturation is probably the most common nonlinearity encountered in practical control systems, which can degrade the system performance or even cause instability if such a nonlinearity is ignored in the controller/filter design. Because of their theoretical significance and practical importance, considerable attention has been focused on the filtering and control problems for systems with *actuator saturation* [72–82]. As for *sensor saturation*, the associated results have been relatively few due probably to the technical difficulty [83–88]. Nevertheless, in the scattered literature regarding sensor saturation, it has been implicitly assumed that the occurrence of sensor saturations is deterministic; that is, the sensor always undergoes saturation. Such an assumption, however, does have its limitations, especially in a sensor network. The sensor saturations may occur in a probabilistic way and are randomly changeable in terms of their types and/or levels due to the random occurrence of networked-induced phenomena such as random sensor failures, sensor aging, or sudden environment changes. To reflect the reality in networked sensors, it would make practical sense to consider the randomly occurring sensor saturations (ROSSs) where the occurrence probability can be estimated via statistical tests. Also, it should be mentioned that very few results have dealt with the systems with simultaneous presence of actuator and sensor saturations [89], although such a presence is quite typical in engineering practice.

Randomly Varying Nonlinearities

It is well known that nonlinearities exist universally in practice, and it is quite common to describe them as additive nonlinear disturbances that are caused by environmental circumstances. In a networked system such as the internet-based three-tank system for leakage fault diagnosis, such nonlinear disturbances may occur in a probabilistic way due to the random occurrence of a networked-induced phenomenon. For example, in a particular moment, the transmission channel for a large amount of packets may encounter severe network-induced congestions due to the bandwidth limitations, and the resulting phenomenon could be reflected by certain randomly occurring nonlinearities where the occurrence probability can be estimated via statistical tests. As discussed in Refs [90–93], in the NCSs that are prevalent nowadays, the nonlinear disturbances themselves may experience random abrupt changes due to random changes and failures arising from networked-induced phenomena, which give rise to the so-called RVNs. In other words, the type and intensity of the so-called RVNs could be changeable in a probabilistic way.

1.1.2 The Analysis and Synthesis of Nonlinear Stochastic Systems

For several decades now, stochastic systems have received considerable research attention in which stochastic differential equations are the most useful stochastic models with broad applications in aircraft, chemical, or process control systems and distributed networks. Generally speaking, stochastic systems can be categorized into two types, namely internal stochastic systems and external stochastic systems [94].

As a class of internal stochastic systems with finite operation modes, Markovian jump systems (MJSs) have received particular research interest in the past two decades because of their practical applications in a variety of areas, such as power systems, control systems of a solar thermal central receiver, NCSs, manufacturing systems, and financial markets. So far, the existing results for MJSs have covered a wide range of research problems, including those for stability analysis [95–97], filter design [98–104], and controller design [105, 106]. Nevertheless, compared with the fruitful results for MJSs for filtering and control problems, MJS use for the corresponding fault detection problem has received much less attention [107, 108], due primarily to the difficulty in accommodating the multiple fault detection performances. In the literature concerning MJSs, most results have been reported by supposing that the transition probabilities (TPs) in the jumping process are completely accessible. However, this is not always true for many practical systems. For example, in NCSs, it would be extremely difficult to obtain precisely all the TPs via time-consuming yet expensive statistical tests. In other words, some of TPs are very likely to be incomplete (i.e., uncertain or even unknown). So far, some initial efforts have been made to address the incomplete probability issue for MJSs. For example, the problems of uncertain TPs and partially unknown TPs have been addressed by Xiong and coworkers [95, 98] and Zhang and coworkers [100, 109], respectively. Furthermore, the concept of deficient statistics for modes transitions has been put forward [110] to reflect different levels of the limitations in acquiring accurate TPs. Unfortunately, the filtering/control/fault detection problem for discrete-time MJSs with RVNs has yet to be fully investigated.

For external stochastic systems, stochasticity is always caused by an external stochastic noise signal, and can be modeled by stochastic differential equations with stochastic processes [94, 111]. Furthermore, recognizing that nonlinearities exist universally in practice and both nonlinearity and stochasticity are commonly encountered in engineering practice, the robust H_∞ filtering, H_∞ control, and fault detection problems for nonlinear stochastic systems have stirred a great deal of research interest. For the fault detection problems, we refer the readers to [82, 112–114] and references cited therein. With respect to the H_∞ control and filtering problems, we mention the following representative work. The stochastic H_∞ filtering problem for time-delay systems subject to sensor nonlinearities has been dealt with by Wang and coworkers [115, 116]. The robust stability and controller design problems for NCSs with uncertain parameters have been studied by Zhang *et al.* [44] and Jiang and Han [117], respectively. The stability issue was addressed by Wang *et al.* [118] for a class of T–S fuzzy dynamical systems with time delays and uncertain parameters. In Zhang *et al.* [119], the robust H_∞ filtering problem for affine nonlinear stochastic systems with state and external disturbance-dependent noise was studied, where the filter can be designed by solving second-order nonlinear Hamilton–Jacobi inequalities. So far, in comparison with the fruitful literature available for continuous-time systems, the corresponding H_∞ filtering results for discrete-time systems has been relatively sparse. Also, to the best of our knowledge, the analysis and design problems for *nonlinear discrete-time stochastic systems with randomly occurring incomplete information* have not been properly investigated yet, and constitutes the main motivation for this book.

1.1.3 Distributed Filtering over Sensor Networks

In the past decade, sensor networks have attracted increasing attention from many researchers in different disciplines owing to the extensive applications of sensor networks in many areas, including in surveillance, environment monitoring, information collection, industrial automation, and wireless networks [120–127]. A sensor network typically consists of a large number of sensor nodes and also a few control nodes, all of which are distributed over a spatial region. The distributed filtering or estimation, as an important issue for sensor networks, has been an area of active research for many years. Different from the traditional filtering for a single sensor [111, 103, 128, 129], the information available for the filter algorithm on an individual node of a sensor network is not only from its own measurement, but also from its neighboring sensors' measurements according to the given topology. As such, the objective of filtering based on a sensor network can be achieved in a distributed yet collaborative way. It is noted that one of the main challenges for distributed filtering lies in how to handle the complicated coupling issues between one sensor and its neighboring sensors.

In recent years, the distributed filtering problem for sensor networks has received considerable research interest and a lot of research results have been available in the literature; for example, see Refs [122–124, 126, 130–142]. The distributed diffusion filtering strategy was established by Cattivelli and Sayed [140, 122] for the design of distributed Kalman filters and smoothers, where the information is diffused across the network through a sequence of Kalman iterations and data aggregation. A distributed Kalman filtering (DKF) algorithm was introduced by Olfati-Saber and Shamma [142], through which a crucial part of the solution is used to estimate the average of n signals in a distributed way. Furthermore, three novel DKF algorithms were introduced by Olfati-Saber [141], with the first one being a modification of the previous DKF algorithm [142]. Olfati-Saber also rigorously derived and analyzed a continuous-time DKF algorithm [141] and the corresponding extension to the discrete-time setting [124], which included an optimality and stability analysis.

It should be pointed out that, so far, most reported distributed filter algorithms for sensor networks have been mainly based on the traditional Kalman filtering theory that requires exact information about the plant model. In the presence of unavoidable parameter drifts and external disturbances, a desired distributed filtering scheme should be made as robust as possible. However, the robust performance of the available distributed filters has not yet been thoroughly studied, and this would inevitably restrict the application potential in practical engineering. Therefore, it is of great significance to introduce the H_∞ performance requirement with the hope to enhance the disturbance rejection attenuation level of designed distributed filters. Note that some initial efforts have been made to address the robustness issue. Very recently, a new distributed H_∞-consensus performance was proposed by Shen *et al.* [143] to quantify the consensus degree over a finite-horizon and the distributed filtering problem has been addressed for a class of linear time-varying systems in the sensor network, and the filter parameters were designed recursively by resorting to the difference linear matrix inequalities (LMIs). Ugrinovskii [144] included an H_∞-type performance measure of disagreement between adjacent nodes of the network and a robust filtering approach was proposed to design the distributed filters for uncertain plants. On the other hand, since nonlinearities are ubiquitous in practice, it is necessary to consider the distributed filtering problem for target plants described by nonlinear systems.

Unfortunately, up to now, the distributed nonlinear H_∞ filtering problem for sensor networks has gained very little research attention despite its practical importance, and it remains as a challenging research topic.

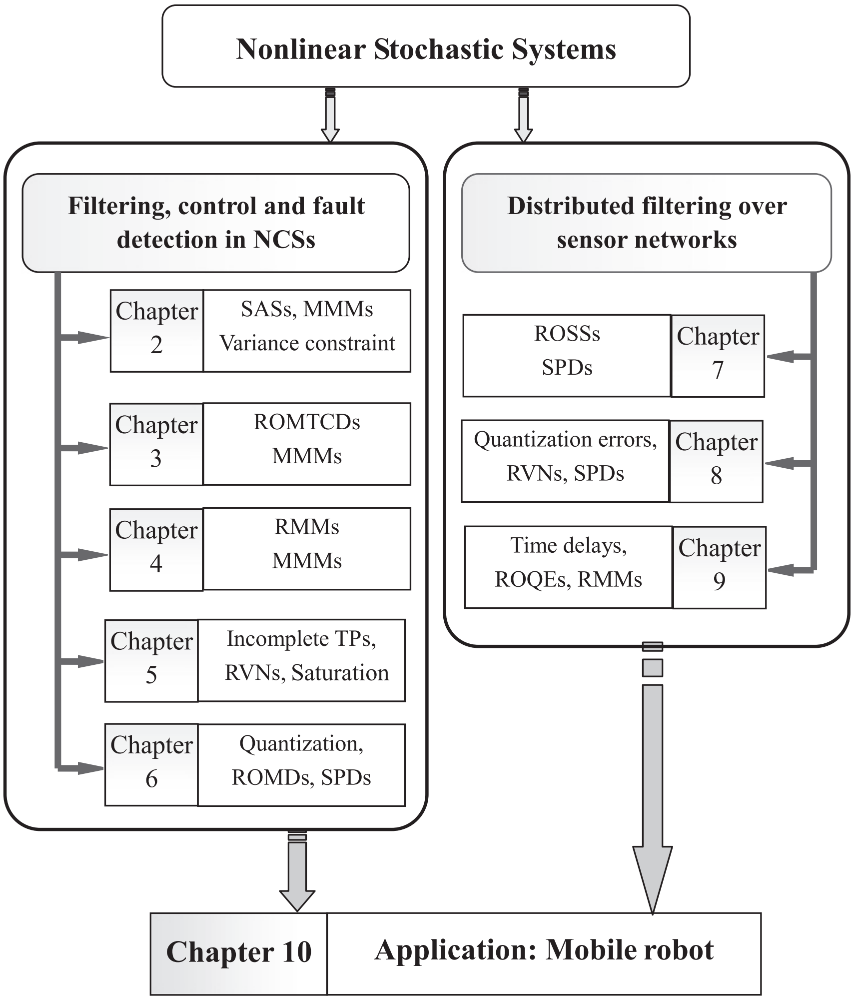

Figure 1.1 Organizational structure of the book (see List of Abbreviations for the meanings of the abbreviations)

1.2 Outline

The organization of this book is shown in Figure 1.1 and the outline of the book is as follows:

1. Chapter 1 has introduced the research background, motivations, and research problems (mainly involving incomplete information, nonlinear stochastic systems, and sensor networks), and concludes by presenting the outline of the book.
2. Chapter 2 addresses the robust H_∞ finite-horizon filtering and output feedback control problems for a class of uncertain discrete stochastic nonlinear time-varying systems with

sensor and actuator saturations, error variance constraints, and multiple missing measurements. In the system under investigation, all the system parameters are allowed to be time varying, and the stochastic nonlinearities are described by statistical means which can cover several classes of well-studied nonlinearities. First, we develop a new robust H_∞ filtering technique for the nonlinear discrete time-varying stochastic systems with norm-bounded uncertainties, multiple missing measurements, and error variance constraints. Sufficient conditions are derived for a finite-horizon filter to satisfy both the estimation error variance constraints and the prescribed H_∞ performance requirement. Such a technique relies on the forward solution to a set of recursive linear matrix inequalities (RLMIs) and, therefore, is suitable for online computation. Second, the corresponding robust H_∞ finite-horizon output feedback control problem is investigated for nonlinear system with both sensor and actuator saturations. An RLMI approach is employed to design the desired output feedback controller achieving the prescribed H_∞ disturbance rejection level.

3. In Chapter 3, the robust H_∞ filtering and control problems are studied for two classes of uncertain nonlinear systems with both multiple stochastic time-varying communication delays and multiple packet dropouts. A sequence of random variables, all of which are mutually independent but obey a Bernoulli distribution, are first introduced to account for the randomly occurring communication delays. The packet dropout phenomenon occurs in a random way and the occurrence probability for each sensor is governed by an individual random variable satisfying a certain probabilistic distribution on the interval [0, 1]. First, the robust H_∞ filtering problem is investigated for the discrete-time system with parameter uncertainties, state-dependent stochastic disturbances, and sector-bounded nonlinearities. Intensive stochastic analysis is carried out to obtain sufficient conditions for ensuring the exponential stability, as well as prescribed H_∞ performance. Furthermore, the phenomena of multiple probabilistic delays and multiple missing measurements are extended, in a parallel way, to fuzzy systems, and a set of parallel results is derived.
4. In Chapter 4, the H_∞ filtering and control problems are investigated for systems with repeated scalar nonlinearities and missing measurements. The nonlinear system is described by a discrete-time state equation involving a repeated scalar nonlinearity which typically appears in recurrent neural networks. The communication links, existing between the plant and filter, are assumed to be imperfect and a stochastic variable satisfying the Bernoulli random binary distribution is utilized to model the phenomenon of the missing measurements. The stable full- and reduced-order filters are designed such that the filtering process is stochastically stable and the filtering error satisfies the H_∞ performance constraint. Moreover, the multiple missing measurements are included to model the randomly intermittent behaviors of the individual sensors, where the missing probability for each sensor/actuator is governed by a random variable satisfying a certain probabilistic distribution on the interval [0, 1]. By employing the cone complementarity linearization procedure, the observer-based H_∞ control problem is also studied for systems with repeated scalar nonlinearities and multiple packet losses, and a set of parallel results is derived.
5. Chapter 5 addresses the filtering and fault detection problems for discrete-time MJSs with incomplete knowledge of TPs, RVNs, and sensor saturations. The issue of RVNs is first addressed to reflect the limited capacity of the communication networks resulting from the noisy environment. Two kinds of TP matrices for the Markovian process are considered: those with polytopic uncertainties and those with partially unknown entries.

Sufficient conditions are established for the existence of the desired filter satisfying the H_∞ performance constraint in terms of a set of RLMIs. The other research focus of this chapter is to investigate the fault detection problem for discrete-time MJSs with incomplete knowledge of TPs, RVNs, and sensor saturations. Two energy norm indices are used for the fault detection problem: one to account for the restraint of disturbance and the other to account for sensitivity of faults. The characterization of the gains of the desired fault detection filters is derived in terms of the solution to a convex optimization problem that can be easily solved by using the semi-definite program method.

6. Chapter 6 is concerned with the quantized fault detection problem for two classes of discrete-time nonlinear systems with stochastic mixed time-delays and successive packet dropouts. The mixed time-delays comprise both the multiple discrete time-delays and the infinite distributed delays that occur in a random way. The fault detection problem is first considered for a class of discrete-time systems with randomly occurring nonlinearities, mixed stochastic time-delays, and measurement quantizations. A sequence of stochastic variables is introduced to govern the random occurrences of the nonlinearities, discrete time-delays, and distributed time-delays, where all the stochastic variables are mutually independent but obey the Bernoulli distribution. In addition, by using similar analysis techniques, the network-based robust fault detection problem is also investigated for a class of uncertain discrete-time T–S fuzzy systems with stochastic mixed time-delays and successive packet dropouts.
7. Chapter 7 is concerned with the distributed H_∞ filtering problem for a class of nonlinear systems with ROSSs and successive packet dropouts over sensor networks. The issue of ROSSs is brought up to account for the random nature of sensor saturations in a networked environment of sensors and, accordingly, a novel sensor model is proposed to describe both the ROSSs and successive packet dropouts within a unified framework. Two sets of Bernoulli-distributed white sequences are introduced to govern the random occurrences of the sensor saturations and successive packet dropouts. Through available output measurements from not only the individual sensor but also its neighboring sensors, a sufficient condition is established for the desired distributed filter to ensure that the filtering dynamics is exponentially mean-square stable and the prescribed H_∞ performance constraint is satisfied. The solution of the distributed filter gains is characterized by solving an auxiliary convex optimization problem.
8. Chapter 8 is concerned with the distributed finite-horizon filtering problem for a class of time-varying systems over lossy sensor networks. The time-varying system (target plant) is subject to RVNs caused by environmental circumstances. The lossy sensor network suffers from quantization errors and successive packet dropouts that are described in a unified framework. Two mutually independent sets of Bernoulli-distributed white sequences are introduced to govern the random occurrences of the RVNs and successive packet dropouts. Through available output measurements from both the individual sensor and its neighboring sensors according to the given topology, a sufficient condition is established for the desired distributed finite-horizon filter to ensure that the prescribed average filtering performance constraint is satisfied. The solution of the distributed filter gains is characterized by solving a set of RLMIs.
9. Chapter 9 is concerned with the distributed H_∞ filtering problem for a class of discrete-time Markovian jump nonlinear time-delay systems with deficient statistics of modes transitions. The system measurements are collected through a lossy sensor network

subject to randomly occurring quantization errors (ROQEs) and randomly occurring packet dropouts (ROPDs). The system model (dynamical plant) includes the mode-dependent Lipschitz-like nonlinearities. The description of deficient statistics of modes transitions is comprehensive, accounting for known, unknown, and uncertain TPs. Two sets of Bernoulli-distributed white sequences are introduced to govern the phenomena of ROQEs and ROPDs in the lossy sensor network. We aim to design the distributed H_∞ filters through available system measurements from both the individual sensor and its neighboring sensors according to a given topology. The stability analysis is first carried out to obtain sufficient conditions for ensuring stochastic stability, as well as the prescribed average H_∞ performance constraint for the dynamics of the estimation errors, and then a filter design scheme is outlined by explicitly characterizing the filter gains in terms of some matrix inequalities.

10. In Chapter 10, a new stochastic H_∞ filtering approach is proposed to deal with the localization problem of the mobile robots modeled by a class of discrete nonlinear time-varying systems subject to missing measurements and quantization effects. The missing measurements are modeled via a diagonal matrix consisting of a series of mutually independent random variables satisfying certain probabilistic distributions on the interval [0, 1]. The measured output is quantized by a logarithmic quantizer. Attention is focused on the design of a stochastic H_∞ filter such that the H_∞ estimation performance is guaranteed over a given finite horizon in the simultaneous presence of plant nonlinearities (in the robot kinematic model and the distance measurements), probabilistic missing measurements, quantization effects, linearization error, and external non-Gaussian disturbances. A *necessary and sufficient* condition is first established for the existence of the desired time-varying filters in virtue of the solvability of certain coupled recursive Riccati difference equations (RDEs). Both theoretical analysis and simulation results are provided to demonstrate the effectiveness of the proposed localization approach.
11. In Chapter 11, we sum up the results of the book and discuss some related topics for future research work.