Chapter 1
Introduction

1.1 Switched Systems

Switched systems provide a unified framework for mathematical modeling of many physical or man-made systems displaying switching features such as power electronics, flight control systems, and network control systems. The systems consists of a collection of indexed differential or difference equations and a switching signal governing the switching among them. The various switching signals differentiate switched systems from the general time-varying systems, because the solutions of the former are dependent on not only the system's initial conditions but also the switching signals.

In general, a switched system can be mathematically described by

$$\begin{aligned}\delta\mathbf{x}(t) &= f_{\sigma(t)}(\mathbf{x}(t), \mathbf{u}(t), \omega(t))\\ \mathbf{y}(t) &= g_{\sigma(t)}(\mathbf{x}(t), \omega(t))\\ \mathbf{x}(t_0) &= x_0\end{aligned}$$

where $\mathbf{x}(t)$, $\mathbf{u}(t)$ and $\mathbf{y}(t)$ are the system state, control input and measurement output, respectively; $\omega(t)$ represents the external disturbance signals; the symbol stands for the derivative operator in the continuous-time context ($\delta\mathbf{x}(t) = \frac{d}{dt}\mathbf{x}(t)$) and the shift forward operator in the discrete-time case ($\delta\mathbf{x}(t) = \mathbf{x}(t+1)$); $\sigma(t)$ is a piecewise constant function of time, called a switching signal, which takes its values in the finite set $S = \{1, 2, \ldots, M\}$ with M being the number of subsystems. In addition, for a series of switching instances $0 < t_1 < t_2 < \cdots < t_i < t_{i+1} < \cdots$, $\sigma(t)$ is continuous from the right everywhere. When $t \in [t_i, t_{i+1})$, we say the $\sigma(t_i)^{th}$ subsystem is active. In addition, $f_k, k \in S$ are vector fields, and $g_k, k \in S$ are vector functions.

The configuration of a general switched system is shown in Fig. 1.1. For such systems, the subsystems represent the low-level "local" dynamics governed by conventional differential and/or difference equations, whereas the supervisor is the high-

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X. Zhao et al., *Control Synthesis of Switched Systems*, Studies in Systems, Decision and Control 80, DOI 10.1007/978-3-319-44830-5_1

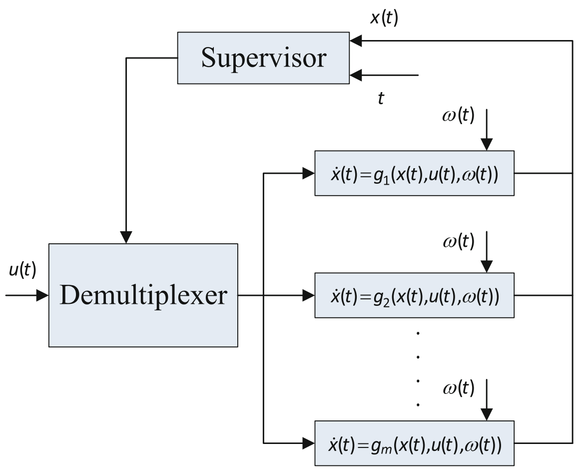


Fig. 1.1 Digram of switched system

level coordinator yielding the switchings among the subsystems [1]. The dynamics of the system is determined by both the switching signal and the subsystems.

Switching is the most important factor in a switched system, which gives the control problems of the switched systems some features and difficulties. The switching of switched systems can be classified into two categories: autonomous switching and active switching. The former is the switching law of switched systems without the influences of external switching logic, which only displays the characteristics of the system itself. Autonomous switching may be arbitrary switching, stochastic switching, time-dependent switching, and state-dependent switching, etc. The latter stands for the switching rules produced by the designers according to some control purposes. Active switching mainly comprises state-driven switching, time-driven switching, and event-driven switching, etc. In addition to the traditional control methods such as feedforward control and feedback control, the active switching design provides us another efficient control strategy for switched systems to achieve the desired state or performances.

1.2 Background and Examples

Switching among different system modes make a switched systems display very complicated dynamic behaviors such as the phenomena of chaos, Zeno, and multiple limit cycles, etc. Also, as far as the stability of a switched system is concerned, it is interesting to see that the stability cannot be ensured for a system composed of all stable subsystems, and switching among unstable subsystems may lead to stability of the whole switched system. For example,

Example 1.1 Consider the switched linear system composed of two subsystems with the following system matrices,

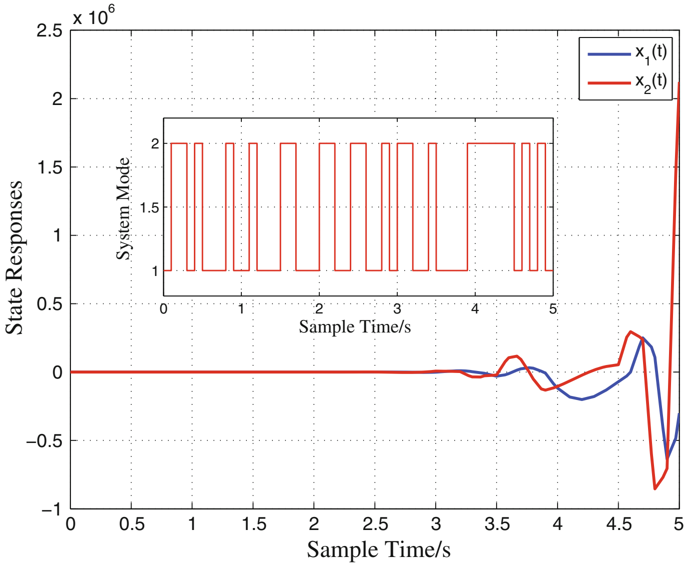


Fig. 1.2 State responses for Example 1.1

$$A_1 = \begin{bmatrix} -1.49 & 3.2 \\ -49.1 & 2.1 \end{bmatrix}, \ A_2 = \begin{bmatrix} -1.3 & 9.9 \\ -1.9 & -1.2 \end{bmatrix}$$

It is clear that both subsystems are stable. However, it can be seen in Fig. 1.2 that the system is not stable under the switching shown in the figure.

Example 1.2 Consider the switched linear system composed of two subsystems with the following system matrices:

$$A_1 = \begin{bmatrix} -1.8930 & 0.5846 \\ 0.6124 & -0.0992 \end{bmatrix}, \ A_2 = \begin{bmatrix} 0.1024 & -0.8879 \\ 0.0959 & -1.3974 \end{bmatrix}$$

It is clear that none of the subsystems is stable. However, it can be seen in Fig. 1.3 that the system is stable under the switching shown in the figure.

Switched systems clearly have attracted much attention for their wide practical applications in many areas. A few examples are listed in the following to illustrate their potential applications.

Example 1.3 Consider a simplified Pulse Width Modulation (PWM)-driven boost converter shown in Fig. 1.4.

There are two storage elements in the circuit: inductor L and capacitor C. In addition, the source voltage and load are, respectively, represented by E and R.

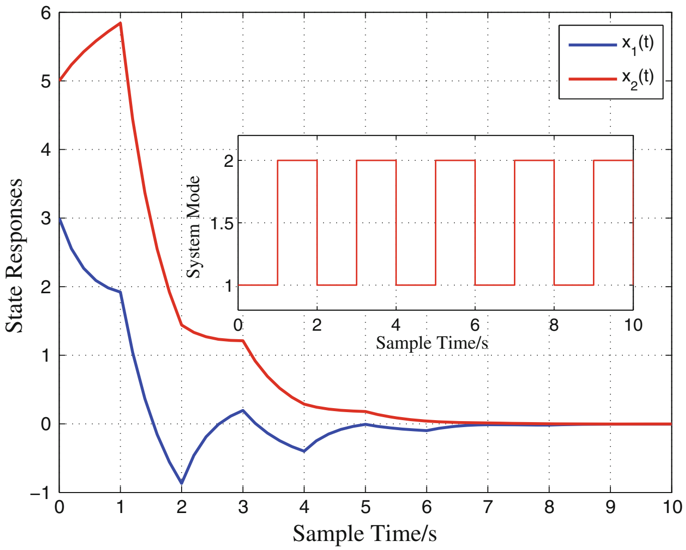
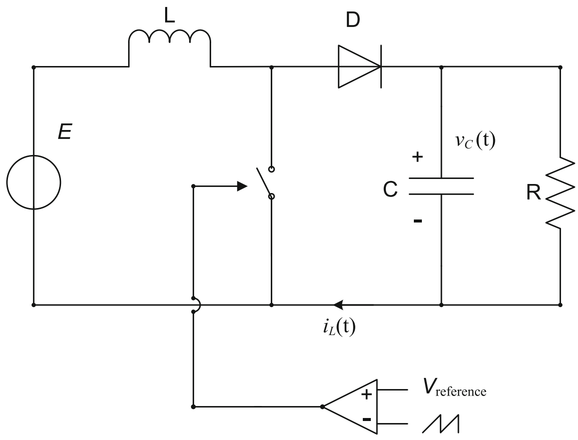


Fig. 1.3 State responses for Example 1.2

Fig. 1.4 A PWM-driven boost converter



The PWM-driven switching signal $s(t)$ that controls the on (1) and off (0) state of the switch is generated by comparing a reference signal V_{ref} and a repetitive triangular waveform. That is, $s(t) \in \{0, 1\}$. Then, the differential equations for the boost converter are given as follows.

$$\dot{v}_C(t) = -\frac{1}{RC}v_C(t) + (1 - s(t))\frac{1}{C}i_L(t)$$
$$\dot{i}_L(t) = -(1 - s(t))\frac{1}{L}v_C(t) + s(t)\frac{1}{L}E$$

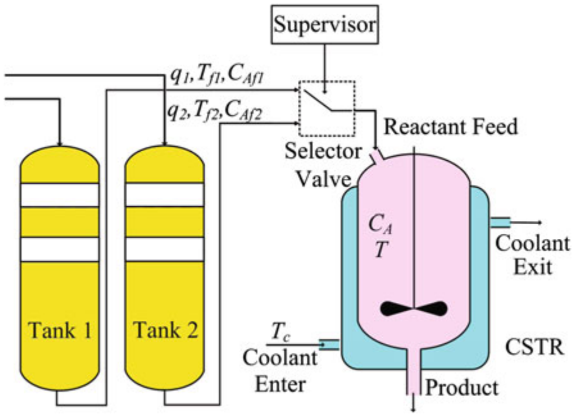


Fig. 1.5 Schematic diagram of the process

Define $\mathbf{x}_1(t) = v_C(t),\ \mathbf{x}_2(t) = i_L(t), \mathbf{u}(t) = E, \sigma(t) = s(t) + 1$, and

$$A_1 = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix}, B_1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix},$$

$$A_1 = \begin{bmatrix} -\frac{1}{RC} & 0 \\ 0 & 0 \end{bmatrix}, B_1 = \begin{bmatrix} 0 \\ L \end{bmatrix}.$$

Then the boost converter can be described by the following state-space model

$$\dot{\mathbf{x}}(t) = A_{\sigma(t)}\mathbf{x}(t) + B_{\sigma(t)}\mathbf{u}(t),\ \sigma(t) \in \{1, 2\},$$

which is exactly the switched linear system with two subsystems.

Example 1.4 Consider the continuous stirred tank reactor (CSTR) with two modes feed stream in Fig. 1.5.

In the cases of constant liquid volume, negligible heat losses, perfectly mixing and a first-order reaction in reactant A, the continuous stirred tank reactor at each operating mode can be described by the following differential equations.

$$\dot{C}_A = \frac{q_\sigma}{V}(C_{Af_\sigma} - C_A) - a_0 e^{-\frac{E}{RT}} C_A,$$

$$\dot{T} = \frac{q_\sigma}{V}(T_{f_\sigma} - T) - a_1 e^{-\frac{E}{RT}} C_A + \frac{UA}{V_\rho C_p}(T_c - T).$$

where the C_A is the reactant A concentration, T is the reactor temperature, T_c is the coolant temperature, q is the feed flow rate, V is the volume of the reactor, E is the activation energy, R is the gas constant, and $a0$, $a1$ and $a2$ are constant coefficients. Denote the nominal operating conditions corresponding to an unstable equilibrium point as T^*, T_c^* and C_A^* for both modes.

Define the states as $x_1 = C_A - C_A^*$, $x_2 = T - T^*$ and $x_2 = T_c - T_c^*$, and the control input $u = T_C - T_c^*$. Then, it is clear that the system can be represented by a switched nonlinear system model:

$$\begin{aligned}\dot{x}_1 &= f_1^i(x_1, x_2) + g_1^i(x_1, x_2)u \\ \dot{x}_2 &= f_2^i(x_1, x_2) + g_2^i(x_1, x_2)u\end{aligned}$$

where $i \in \{1, 2\}$, and

$$\begin{aligned}f_1^i &= \tfrac{q_i}{V}(C_{Afi} - C_A^* - x_1) - a_0(x_1 + C_A^*)\exp\left(-\tfrac{E/R}{x_2+T^*}\right)(x_1 + C_A^*) \\ f_2^i &= \tfrac{q_i}{V}(T_{fi} - T^* - x_2) - a_1\exp\left(-\tfrac{E/R}{x_2+T^*}\right)(x_1 + C_A^*) + a_2(T_C^* - x_2 - T^*)\end{aligned}$$

$$\begin{aligned}g_1^i &= 0 \\ g_2^i &= a_2\end{aligned}$$

Example 1.5 Consider the problem of parking the wheeled mobile robot of the unicycle type as shown in Fig. 1.6, where $\mathbf{x}_1$ and $\mathbf{x}_2$ are the coordinates of the point in the middle of the rear axle, and θ stands for the angle between the vertical axis of the vehicle and x_1 -axis. The kinematics of the robot can be modelled as below

$$\begin{aligned}\dot{\mathbf{x}}_1 &= \mathbf{u}_1\cos\theta \\ \dot{\mathbf{x}}_2 &= \mathbf{u}_1\sin\theta \\ \dot{\theta} &= \mathbf{u}_2\end{aligned}$$

where $\mathbf{u}_1$ and $\mathbf{u}_2$ are the control inputs (the forward and the angular velocity, respectively) such that $\mathbf{x}_1, \mathbf{x}_2$ and θ tend to zero. It is interesting to see that the corresponding system is nonholonomic and thus cannot be asymptotically stabilized by any time-invariant continuous state feedback law. However, the hybrid control scheme can tackle this problem. Introduce

$$\begin{aligned}y_1 &= \theta \\ y_2 &= \mathbf{x}_1\cos\theta + \mathbf{x}_2\sin\theta \\ y_3 &= \mathbf{x}_1\sin\theta - \mathbf{x}_2\cos\theta \\ D_1 &= \left\{\mathbf{x} \in \mathbb{R}^3 : |\mathbf{x}_3| > \frac{\|\mathbf{x}\|}{2}\right\} \\ D_2 &= \{\mathbf{x} \in \mathbb{R}^3 : \mathbf{x} \notin D_1\}\end{aligned}$$

Then, a feasible set of candidate controllers can be designed as

$$\begin{aligned}\mathbf{u}^1 &= \begin{bmatrix} u_1^1 \\ u_2^1 \end{bmatrix} = \begin{bmatrix} -4y_2 - 6\frac{y_3}{y_1} - y_3 y_1 \\ -y_1 \end{bmatrix} \\ \mathbf{u}^2 &= \begin{bmatrix} u_1^2 \\ u_2^2 \end{bmatrix} = \begin{bmatrix} -y_2 - sgn(y_2 y_3)y_3 \\ -sgn(y_2 y_3) \end{bmatrix}\end{aligned}$$

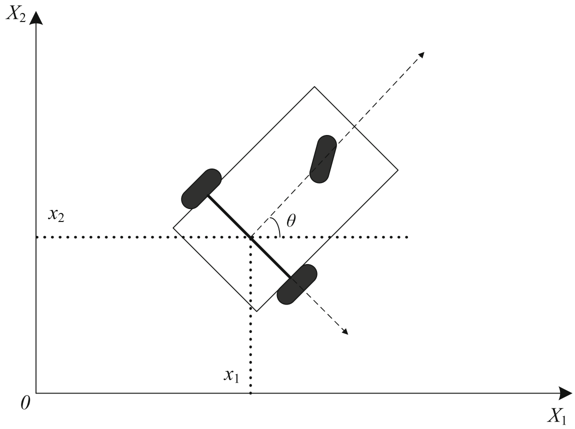


Fig. 1.6 Wheeled mobile robot of unicycle type

where function $sgn(\alpha)$ is defined as

$$sgn(\alpha) = \begin{cases} 1, \text{ if } \alpha \geq 0 \\ -1, \text{ otherwise} \end{cases}$$

Under these controllers, the system can be rewritten by an unforced switched nonlinear system

$$\dot{\mathbf{x}}(t) = f_{\sigma(t)}(\mathbf{x}(t))$$

where $\mathbf{x}(t) = [x_1, x_2, \theta]^T$, $\sigma(t) \in \{1, 2\}$, and

$$f_i(\mathbf{x}(t)) = \begin{bmatrix} u_1^i \cos\theta \\ u_1^i \sin\theta \\ u_2^i \end{bmatrix}, i = 1, 2.$$

To achieve stabilization, the switching law $\sigma(t)$ is chosen as

$$\sigma(t) = \begin{cases} 1, \text{ if } \mathbf{x}(t) \in D_1 \\ 2, \text{ if } \mathbf{x}(t) \in D_2 \end{cases}$$

Therefore, it is clear that the problem of parking the wheeled mobile robot of the unicycle type is described by a switching design problem of a switched nonlinear system.

In addition, a switched system system also finds its numerous applications in multi-controller-switching control systems, robot control systems, asynchronous switching control systems, etc. On the other hand, study on switched systems is also of great theoretical importance because it can provide additional insights and ideas to some long-standing and complicated problems, such as reset control, robust control, intelligent control, control of multi-agent systems and time-delay systems, only to list a few. In summary,a switched system deserves investigation because it is of both theoretical and practical importance.

1.3 Motivations

In recent years, research on control issues of switched systems has received great interest from both academic and engineering experts, and obtained successful achievements. In a certain sense, research on control of switched systems includes three basic issues: control problems of switched systems under arbitrary switching signals,and control problems of switched systems under certain specific switching signals,and control problems of designing certain switching signals to achieve certain performances. A brief review and discussions on the developments of these three basic problems are given in the following.

(1) Control problems of switched systems under arbitrary switching signals

A great number of works have been carried out for such problems in as much as the corresponding results are of general sense. One often resorts to the common Lyapunov function approaches to investigate control problems of switched systems under arbitrary switching. That is, a switched system is stable if there exists a common Lyapunov function for all the subsystems. To list a few Representative works, it was proved by Mosca that stable subsystems must share a common Lyapunov function if the system state matrices are exchangeable [2]. Mehmet [3] probed the existence condition of common Lyapunov functions for second- order switched systems, and proposed concrete methods for obtaining a common Lyapunov function. Stability conditions were established by Shorten for some special switched systems based on the common quadratic Lyapunov function [4]. In [5], Daafouz developed a method for constructing switched quadratic Lyapunov functions in correspondence with discrete-time switched systems, upon which, less conservative stability conditions were given. Based on such a type of Lyapunov function approach, Xie [6] proposed L_2-gain conditions in LMI formulation and controller design method for uncertain discrete-time switched systems, and Wang [7] investigated the problem of fault detection for switched systems with state delay. Liu established stability criteria in [8] for a class of delay switched positive systems with arbitrary switching, and also indicated that the stability of such a type of systems is independent of time delay. On the basis of the approximation of state transition matrices and Gronwall inequality, Sun designed state-feedback controllers for switched nonlinear systems with impulsive effects [9]. By applying the Green formula and Poincaré inequalities, Dong gave a design method of fault-tolerant controller for a class of switched delay systems with distributed parameters [10]. For switched nonlinear impulsive systems with completely unknown uncertainties, Long designed adaptive impulsive tracking controllers in [11], and found that the tracking performance can be improved by using disturbance compensation. On the other hand, the investigations on both necessary and sufficient stability conditions for switched systems under arbitrary switching have also attracted much attention by researchers [12].

It should be pointed out that although the results in the arbitrary switching case are of general sense, the conservatism to require all subsystems be stable and achieve desired control performance under arbitrary switching cannot be ignored. In reality, many switched systems own their specific switching logic, such as liquid level control system, vehicle shift system, etc., and thus there is no need to achieve the control objective with respect to arbitrary switching. It is particularly necessary to study switched systems with some specific switching rules to develop less conservative and more efficient control methods and conclusions compared with the ones in the arbitrary switching case.

(2) Control problems of switched systems under specific switching signals

For some practical switched systems, we can obtain some knowledge of the switching rules among their modes in advance, and these rules are generally described by three classes of switching signals: stochastic switching signals possessing statistical properties, state-dependent switching signals and time-dependent switching signals. Switched systems with these three types of switching signals have been widely studied in recent years. Due to successful applications in network control systems, related control theory of stochastic Markovian switching systems have received considerable attention, and developed well [13]. Meanwhile, systems with state-dependent switching and time-dependent switching have also been paid much attention for their remarkable application backgrounds. The authors in [8] established mathematical models for a Mars exploration unmanned aerial vehicle with umbrella and without umbrella, respectively, and gave the simplified switched system model for the re-entry process where the switching between the models with umbrella and without umbrella was determined by the aircraft speed. Then, an integrated control system of the Mars exploration unmanned aerial vehicle was designed via gain pre-fabricated method on the basis of the proposed switched system model. In [14], seven characteristic points were selected for the whole flight process of a BTT missile, around which, constant subsystem models were established to obtain a switched system model for the flight process. Then, the authors designed subsystem controllers and autopilot switch points under the cases that the switching instances were dependent on the system state and the switching sequence was known, such that the missile could rapidly and accurately track the guidance command, and the switching chatter was effectively suppressed. The bifurcation characteristic and chaos switching oscillation behavior were systematically investigated in [12] for the Rőssler oscillator and Chua's circuit under state-dependent switching, respectively, and the complex dynamic behavior caused by periodic switching between two Lorenz oscillators was also analyzed. In [15], the system mutation dynamics of an electro hydraulic servo actuator under different voltage supply was modelled by several subsystems of a switched system whose switching law represented the voltage supply variation, and then the authors designed a control system for an aero electro hydraulic servo actuator according to the system actual voltage supply variation to achieve good performance.

The aforementioned literatures mainly focuses on analysis and synthesis of switched systems with certain specific switching laws. On the other hand, one can also actively design switching signals to achieve some required control performances of a switched system.

(3) Control problems of switched systems via switching signal design

For switched systems, switching itself provides us a very efficient control strategy in addition to those classical control methods widely used in control theory. We can properly design switching rules to enable a switched system to achieve desired performances. It should be noted that switching control can complete some control tasks that cannot be accomplished by traditional control methods. Active switching strategies generally comprise state-driven switching control, time-driven switching control and event-driven switching control, etc. Control issues of switched systems based on these three active switching strategies have been noticed by many researchers.

In the state-driven switching control aspect, by resorting to the minimum projection strategy, the problems of quadratic stabilization and state-driven switching signal design were addressed by Pettersson in [16]. The state-driven switching design method for uncertain switched linear systems with polytopic uncertainties was proposed in [17] by the LMI technique. Allerhand discussed several control problems of switched systems with polytopic uncertainties in [18], and gave the design approach of state-driven switching signals. Sangswang systematically investigated the problems of performance analysis and state-driven switching control for power electronic converters with a pulse width modulation circuit driver [19]. Corona proposed a class of state-driven switching law via the LQ performance optimization method such that the considered systems without stable subsystems were exponentially stable [20]. For switched systems with partially unstable or all unstable subsystems, the authors in [21] developed a novel concept of multiple generalized Lyapunov-like function to solve the problems of stability, L_2-gain analysis and H_∞ control for switched nonlinear systems under state-driven switching signals. It can be seen that the investigations on state-driven switching control of switched systems have been extended from switched linear systems, systems with stable subsystems and simple systems to switched nonlinear systems, systems with unstable subsystems and complex systems, and gradually form a relatively complete theory framework. But it is noted that there are some constraints in applying state-driven switching to switched systems, such as state measurability, observability, estimation cost, and real-time ability, etc.

Due to great advantages in the aspects of applicability, reliability, real-time ability and application cost, etc., time-driven switching control of switched systems has been widely noticed by many researchers. The concepts of dwell time and average dwell time have been successively proposed and applied to the time-driven switching control of switched systems. Through a practical example, Liberzon [22] revealed the divergence phenomenon of the state trajectory of systems switched between two stable subsystems, and pointed out that the essential reason behind this phenomenon is the energy increment caused by switching was not compensated by stable subsystems. In addition, the work also indicated that for systems comprising unstable subsystems, dwelling on unstable modes or frequently switching to unstable modes would lead to the instability of a switched system. Therefore, an effective guarantee of the stability of a switched system is to activate stable modes for a long time and reduce the switching frequency (that is, slow switching). Based on this idea, the concept of dwell time was proposed and extensively used for the control of switched systems. Geromel discussed the problem of minimal dwell time stabilization for continuous-time switched systems [23]. Then, in [24], Briat extended the results in [23], and established convex stability conditions via the "Lifting Setting" technique. The obtained conditions are convenient for robust analysis and synthesis of the systems. Dwell time switching requires the dwell time on each subsystem be larger than a sufficient big constant, which greatly restricts its applications. Considering this point, Hespanha [25] creatively gave the concept of average dwell time that relaxed some restrictions on switching rules and owned more flexibilities in switching design of switched systems.Recently, on the basis of average dwell time switching, studies on control problems related to switched systems have made considerable progress. The authors in were [26] concerned with the weighted L_2-gain analysis for switched systems with time varying delay under average dwell time switching. For switched systems with polytopic uncertain parameters,a time-driven switching exponential H_∞ filter was designed in [27] by resorting to the parameter-dependent idea. Then, Zong [28] was devoted to the exponential l_2-l_∞ filtering design for discrete-time uncertain switched systems under average dwell time switching. The authors in [29] provided a time-driven switching observer scheme for delayed switched recurrent neural networks by exploring the free weighting matrix technique. In the meantime, switching control of switched nonlinear systems in the framework of average dwell time has also obtained synchronous development.

The above-mentioned literature related to time-driven switching control only considers stable open-loop or closed-loop subsystems. However, in practice, many controlled plants are unstable, and designing feedback controllers are often impractical due to an unmeasurable or unobservable state, high cost, low real-time capability, etc. On the other hand, uncontrollable subsystems, controller faults and asynchronous switching are sometimes encountered in practical switched systems. In addition, some control problems of many systems can be transformed into control problems of switching among unstable subsystems of switched systems. Causally, there have been a few reports on time-driven switching control problems of switched systems with unstable subsystems in the last decade, which are of both theoretical and practical significance. The authors in [30] studied the average dwell time switching stabilization of switched systems comprising both stable and unstable subsystems by proposing a novel class of Lyapunov-like functions, and extended the corresponding results to asynchronously switched control of switched systems. Through constructing a Lyapunov looped-function, Briat [31] solved the mode-dependent dwell time switching control and computation of the minimal dwell time for switched systems composed of stable and unstable subsystems. The problems of mode-dependent average dwell time switching control and asynchronous L_1 control of delayed switched positive systems with stable and unstable subsystems were considered in [32] based on a copositive Lyapunov–Krasovskii function approach. In [33], finite-time stability was investigated for impulsive switched systems with unstable subsystems.

As can be seen in the above illustrations, many control issues of switched systems have been noticed and developed in the past few years, some of which, however, have not been successfully solved so far. For example, time-driven switching design for switched systems composed of unstable subsystems is still an open problem in both linear and nonlinear contexts. Also, it is urgent to carry out investigations on more complicated switched system models for practical applications, such as high-order switched systems, stochastic switched systems, switched systems with completely unknown uncertainties, etc.

1.4 Structure of the Book

Structure of the book is summarized as follows.

This chapter has introduced the system description and some background knowledge, and also addressed the motivations of the book.

Chapter 2 investigates the stability and stabilization problems for a class of switched systems with mode-dependent average dwell time (MDADT) in both continuous-time and discrete-time contexts. The proposed MDADT switching law is more applicable in practice than the ADT switching. Some improved stability criteria for switched systems with our proposed switching in nonlinear settings are first derived, by which the conditions for stability and stabilization for linear systems are also presented. Finally, the results are extended to the ones for switched systems with unstable subsystems.

Chapter 3 studies the problems of switching stabilization for both switched linear systems and switched nonlinear systems with time-driven switching signals. In particular, the considered systems can be composed of all unstable subsystems. In the linear case, the switching signal is designed to exponentially stabilize the underlying system based on the invariant subspace theory. Then, some sufficient conditions are also established in the nonlinear case. Furthermore, the T-S fuzzy modeling approach is applied to represent the underlying switched nonlinear system to make the obtained conditions easily verified.

Chapter 4 is concerned with the adaptive control design for a class of switched nonlinear systems in lower triangular form with unknown functions and arbitrary switchings. First, switched strict-feedback nonlinear systems are considered. Two classes of state feedback controllers are constructed by adopting an adaptive backstepping technique, and both of them are designed by using the common Lyapunov function (CLF) method. The first controller is designed under multiple adaptive laws. Then, the second one is designed based on constructing a maximum common adaptive parameter, which can overcome the problem of over-parameterization of the first controllers. Then, controller design methods for switched nonstrict-feedback nonlinear systems are also carried out. It is shown that the designed state-feedback controllers can ensure that all the signals remain bounded and the tracking error converges to a small neighborhood of the origin.

Chapter 5 considers the problem of adaptive control for switched stochastic nonlinear systems. First, controller design approaches for stochastic switched nonstrict-feedback nonlinear systems with unknown nonsymmetric actuator dead-zone are proposed. By combining radial basis function neural networks universal approximation capability, adaptive backstepping technique with common stochastic Lyapunov function method, adaptive control algorithms are given for the considered systems.

Furthermore, under the framework of adding a power integrator technique, adaptive controllers of switched stochastic high-order uncertain nonlinear systems with SISS inverse dynamic are also designed.

Chapter 6 is focused on the output tracking control problem of constrained nonlinear switched systems in lower triangular form. First, when all the states are subjected to constraints, a Barrier Lyapunov Function (BLF) is explored, which grows to infinity whenever its arguments approach some finite limits, to prevent the states from violating the constraints. Based on the simultaneous domination assumption, we design a continuous feedback controller for the switched system, which guarantees that asymptotic output tracking is achieved without transgression of the constraints and all closed-loop signals remain bounded, provided that the initial states are feasible. Then, we further consider the case of asymmetric time-varying output constraints by constructing an appropriate BLF. In addition, we also resort to p-times differentiable unbounded functions to deal with asymmetric output constraints, which avoids the defect caused by the discontinuity of the constructed asymmetric BLF.

Chapter 7 concludes the monograph by briefly summarizing the main theoretical findings presented in our book, and proposing unsolved problems for further investigations.

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