Chapter 1

Introduction

1.1 Introduction

All the physical systems are inherently nonlinear and uncertain in nature. The nonlinear systems can have much richer and more complex behavior. The nonlinearities may be inherent or intentional. The uncertainty (deviation from true value) can arise both in static and dynamic system qualities. The uncertainty can be classified into two categories: disturbance signals and dynamic perturbations. The design of control system for dynamic systems with nonlinearities and uncertainties due to mathematical modelling error is an important and challenging task. The imperfect knowledge of the system degrades the performance of control system.

Many nonlinear control techniques can be found in the literature. Among them are feedback linearisation, backstepping, adaptive backstepping, and sliding mode control (SMC) [1]. The variable structure system's (VSS) based SMC [2,3] is one of the most effective nonlinear robust control method, as it provides invariance property to uncertainties once the system dynamics is in the sliding mode. Even after years of sustained active research on SMC, the key problems like chattering, the removal of unmodeled dynamics effect, susceptibility to disturbances and uncertainties during the reaching phase and improvement of robustness are still remains. The chattering can be eliminated by replacing the signum function with a boundary layer technique [4], [5] and integral sliding control [6]. The boundary layer approach eliminates the control discontinuity and chattering around the switching surface within this thin boundary layer. However, the large system uncertainties results in higher chattering. A high switching gain with a thicker boundary layer used to eliminate chattering. Further, increase in boundary layer thickness results in a feedback system without sliding mode. To tackle these difficulties, fuzzy logic controller (FLC) are often used to deal with the discontinuous signum function in the reaching phase of SMC [7–10].
The FLC is applicable to plants that are ill-modelled, but qualitative knowledge of an experienced operator is available. It is particularly suitable for those systems with uncertain or nonlinear dynamics. When precise model of system under control is not available or expensive to prepare, this algorithm proves to be very effective. But, they are poor in stability. The stability of the FLC is guaranteed by introducing the principle of SMC in fuzzy logic controllers. This fusion is called as fuzzy sliding mode control (FSMC), provides the mechanism for designing robust controller for nonlinear systems with uncertainty. The FSMC preserves robustness characteristics of SMC, as the rule base of FLC is designed based on conventional SMC.

Hence, from an implementation perspective, FSMC is used for systems or plants having uncertainty and nonlinearities. Due to fast computing facilities, implementation of FSMC has motivated the research in the area of nonlinear control systems. Among the developed control strategies for robust nonlinear control, FSMC plays an important role because it not only stabilizes nonlinear uncertain system but also provides the capability of disturbance rejection and insensitivity to parameter variations.

The FSMC is successful in minimizing the chattering problem but the other problems like system susceptibility to parameter variation during reaching phase and need of precise mathematical model for the design of controller are still remains. These problems can be minimized by using the controller design methods like exponential function based sliding mode control (ExFSMC) and neural fuzzy sliding mode control (NFSMC).

In ExFSMC design approach, the gain or normalization factor of output membership is defined by considering an exponential function. An exponential function will adapt dynamically, the variation of the controlled system, which reduces the reaching time and makes the system less vulnerable to parameter perturbation and external disturbances during the reaching phase. The design of controller for ill-modelled systems having complex dynamics is difficult and complex. This problem can be overcome by exploiting the approximation ability of neural network (NN) and FLC by an hybrid control design approach called NFSMC. In this approach, NNC and FSMC methods are used to approximate either continuous control or discontinuous control term of SMC, to make it mathematical computation free controller design method [11–13], and to enforce ideal sliding mode without chattering under uncertainty and nonlinearities.

1.2 Review of Related Literature

This section contains a brief review of FSMC for uncertain and nonlinear systems. The literature review is not intended to be exhaustive but includes most of the sources which motivated or directly pertains to the new results presented in the thesis.

Hwang et.al. [7] proposed a FSMC design method for nonlinear systems to achieve
asymptotic stability of the systems and also highlighted the attractive features of the controller such as robustness against model uncertainties and external disturbances. These features are demonstrated using an example of inverted pendulum system. Wu et.al. [9] have shown that, the FLC can be formulated to become a class of variable structure system (VSS) control. In this approach, sliding modes are used to determine best values for parameters in FLC rules, thereby robustness in FLC can be improved. Choi et.al. [14] designed a fuzzy sliding-mode controller by fuzzifying a sliding surface in order to attenuate the chattering. Yu et.al. [10] have suggested the design of FLCs according to the SMC law. The reduced chattering can be achieved by FSMC without sacrificing its robust performance. Many researchers proposed different adaptive laws and techniques to improve the performance of the FSMC. Abdelhameed et. al. [15] proposed a technique for incorporating a FLC system as adaptation mechanism of the SMC called as fuzzy logic adaptive SMC. The proposed controller has been applied to a motion trajectory tracking of a two-degree of freedom polar manipulator. Noroozi and Wu et.al. [16,17] proposed an adaptive law to tune the parameters of FSMC to control a class of nonlinear systems in the presence of uncertainties and external disturbance. An adaptive fuzzy terminal SMC was proposed by Nekoukar et.al. [18] to overcome the singular problem with terminal sliding mode control (TSM) by combining a continuous non-singular TSM with an adaptive learning algorithm. In this approach, the fuzzy logic system is used to estimate the dynamics of the controlled plant. The adaptive laws are formulated based on the assumption that the system states are available for measurement. The lack of accurate information and upper bounds of uncertain nonlinear system, makes it difficult to have an analytical description of the system dynamics. Thus, the adaptive systems encounter problems like algorithm convergence and stability conditions to satisfy. Alouia and Delavari et.al. [19–22] have proposed different control structures like two-input single-output (TISO) and fractional order based FSMC design methods to improve the performance of the FSMC. The FSMC is able to approximate the discontinuous control of SMC and successfully minimizes the chattering effect, and fulfills the invariance property once the system dynamics is on sliding surface. However, the problem of reaching phase vulnerable to parametric uncertainty and disturbances remains. One way to minimize the sensitivity during reaching phase is by accelerating the reaching time to sliding surface using larger gains, but this involves excessive control effort and may increase chattering effects. To overcome this problem, Ha, Choi et.al. and others [23–27], proposed moving sliding surface for fast tracking with rotating or shifting surfaces obtained by fuzzy tuning. These methods have complex algorithm and take longer execution time. Recently, Fallaha et.al. [28] proposed an exponential function based reaching law for multi-input multi-output (MIMO) nonlinear systems to have faster reaching phase. The exponential
function dynamically adapts the variation of the controlled system to change the gain of the discontinuous control law to reduce reaching time and minimize the chattering by generating larger control gain simultaneously.

Many systems are modelled with higher order dynamics and stiffness. The difficulties in the design of such systems is avoided by modelling the system as singularly perturbed system. A small singular perturbation parameter $\epsilon$, is exploited to determine the degree of separation between slow and fast subsystem of dynamical systems. In singularly perturbed systems, the degeneration of the full order system not only eliminates the stiffness difficulties, but also make the boundary layer subsystems asymptotically stable, so that, the deviation rapidly decays. Controlling such systems is a difficult task, as control has to react decomposed reduced order slow and fast dynamic states simultaneously. The stability of the full order system can be achieved by design of separate controllers for subsystems and the combined composite control is applied to govern the full order system [1,29–32]. Several researches have made attempts to apply SMC strategy to singularly perturbed system and are reported in [33–36]. Heck, [33] proposed a design of SMC for singular perturbation system with parameter uncertainties and external disturbances. Gallegos et.al. [34], proposed a two-time scale SMC for nonlinear singularly perturbed system. The full order system is stabilized by combining separately designed SMC controllers for slow and fast subsystems. Innocenti et.al. [35] proposed a controller in which global stability of linear time invariant systems was achieved by means of singular perturbation technique and by synthesizing SMC for each subsystem. Recently, Nguyen et.al. [36] proposed a SMC for linear singularly perturbed system in presence of matched bounded external disturbances. However, these methods suffer from SMC related problems like chattering in control input and state variable and these are also weak in robustness against parameter variation and disturbances during reaching phase.

Elshabrawy et.al. [37] proposed the FSMC for singularly perturbed systems. This was the only literature found on FSMC for linear singularly perturbed systems. In this approach, the FLC was used as supervisory system to connect two different SMC controllers designed based on conventional SMC method. The obtained controller was used to stabilize only the slow subsystem by neglecting dynamics of the fast subsystem. However, chattering in the control input remains as FLC acts like a supervisory system or adaptive system to the controller.

When system models are complex and precise model of the system under control are unavailable, the approximation ability of artificial NNs was exploited to overcome the computational problem of SMC. The continuous term or in some works both terms of SMC are approximated by NNC, such controllers are called as the neuro-sliding mode control [38–42]. Gokhan, Boubakir and Shiferaw et.al. [11–13] proposed NFSMC to ap-
proximate both terms of SMC by combining NNC and FSMC methods. Gokhan et.al. used Radial Basis Function Network (RBFN) to approximate the equivalent control $u_{eq}$ and gain of the discontinuous control $u$, was adjusted with fuzzy logic. Whereas, Boubakir et.al. proposed NFSMC for linearized model using nonlinear sliding surface. The weights are adjusted to minimize the cost function selected as the difference between the desired equivalent control value and the approximated equivalent control. Shiferaw et.al. [11] designed NFSMC by using fuzzy logic system to approximate equivalent control and the feed-forward NN was employed to design discontinuous control term.

The design method of FSMC was further extended to higher order nonlinear systems and MIMO systems via a two-level decoupling strategy. Lo et.al. [43] proposed decoupled FSMC (DFSMC) for higher order nonlinear systems. The decoupled control strategy provides a simple way to decouple a class of fourth-order nonlinear systems into two second-order subsystems by a separate control objective expressed in terms of a sliding surface for each subsystems. Using the DFSMC method, the second subsystem was successfully incorporated into the first one via a two-level decoupling strategy. Many researchers proposed alternative controller design methods using decoupled control strategy, such as Chen et.al. [44] proposed a signed distance to the sliding surface based DFSMC, and Ghanbari et.al. [45] suggested decentralized neuro-fuzzy controller for two dimensional inverted pendulum system. A self tuned signed distance method was proposed by Hung et.al. [46]. Further, Hung et.al. [42], in their work designed a decoupled NNC to approximate both terms of SMC, the equivalent control and discontinuous control, and the weights of the NN are changed according to some adaptive algorithm. Recently, a decoupled fuzzy NNC was proposed by Hung et.al. [42], in which the NN approximates continuous fuzzy valued functions using four-layer feedforward fuzzy neural network.

1.3 Motivation

The conventional controllers are well suited when the process are precisely modelled. Whenever quantitative study of physical systems is undertaken, it is necessary to describe the system in mathematical terms. The accurate modelling of the system is difficult due to complexity and lack of information about system parameters. However, the effort of realistic representation of few physical systems are associated with high order dynamics and stiffness. For such systems, one of the robust control method called variable structure system based SMC is suitable to compensate the modelling errors, nonlinearities, etc. The recent literature witnesses the importance of SMC in
the field of nonlinear control system applications. The SMC results in superb system performance which includes insensitivity to parameter variations, and complete disturbance rejection. Even after sustained active research on SMC, the key problems like chattering, the removal of unmodeled dynamics effects, disturbances and uncertainties during the reaching phase, need of precise mathematical model of systems and improvement of robustness still remains. FLC are one of useful control schemes for plants having difficulties in deriving mathematical models or having performance limitations with conventional linear control schemes. FLC is designed on the basis of human experience which means a mathematical model is not required for controlling a system. Due to this advantage FLC has been implemented for many industrial applications [47]. The reduced chattering can be achieved by combining the attractive features of SMC and FLC called as FSMC, without sacrificing robust performance of the SMC. The integration of SMC and FLC methods overcomes the weakness of one method over the other so that, the guaranteed stability and robust control performance can be achieved. Considering the increase in demand of robust controllers for modern nonlinear control systems, this thesis aims to develop simple and effective FSMC schemes for uncertain and nonlinear control systems. We also aim to verify the developed FSMC strategies on some real life applications. Furthermore, we aim to develop and investigate composite FSMC (CFSMC) for handling dynamics of large scale interacting systems like nonlinear singularly perturbed systems. To approximate continuous control term of SMC, neural FSMC (NFSMC) is investigated. The above related literature review has motivated us to focus on the design of robust and stable control systems using FSMC.

1.4 Contributions

The contributions of this work are summarized as follows.

1. A fuzzy sliding mode control design for uncertain and nonlinear system is proposed. The proposed controller is designed by considering sliding surface as input, defining the output membership functions on universe of discourse of control with system gain. The rule base of the controller is designed based on sliding mode control law. The effectiveness of proposed controller is proved by simulation results using uncertain and nonlinear systems.

2. An exponential function based fuzzy sliding mode control design for uncertain and nonlinear system is proposed. The system susceptibility to parameter variation and disturbances during reaching phase are overcome by an ExFSMC. The proposed controller is designed by considering sliding surface as input, defining the output membership functions on universe of discourse of control with expo-
ential function based gain. The rule base of the controller is designed based on sliding mode control law. The exponential function dynamically adapts the variation of the controlled system such that, reduction in reaching time to the sliding surface and chattering in the control input and system dynamics is minimized. The effectiveness of proposed controller is proved by simulation results using a nonlinear systems and validated on real time experimentation.

3. A Neural-Fuzzy Sliding Mode control is proposed for robust asymptotic stabilization of a nonlinear system. The sliding mode control has two terms as continuous mode and discontinuous mode, are approximated using direct neural network control method based on neural sliding mode control and fuzzy sliding mode control method respectively. The combined control is termed as neural-fuzzy sliding mode control. The weights of the neural network are updated online to minimize the cost function. The cost function is the difference between reference value and plant output. The performance of the proposed controller is tested on examples of nonlinear systems and results are compared with conventional SMC, FSMC, and ExFSMC methods to demonstrate its superiority in terms of parameter variations and disturbance rejection.

4. A CFSMC law is proposed for nonlinear singularly perturbed systems. In the proposed approach the original system is decomposed into two subsystems as slow and fast models by singularly perturbed method. The composite fuzzy sliding mode controller is designed for stabilizing the full order system by combining a separately designed slow and fast fuzzy sliding mode controllers. The two-time scale design approach minimizes the effect of boundary layer system on the full order system. A stability analysis allows us to provide sufficient conditions for the asymptotic stability of the full order closed-loop system. The simulation results show improved system performance of proposed controller as compared to existing methods. The experimentation results validate the effectiveness of the proposed controller.

5. A CNFSMC law is proposed for a class of nonlinear singularly perturbed system. The slow and fast controllers are designed based on NFSMC method. A stability analysis allows us to provide sufficient conditions for the asymptotic stability of the full order closed-loop system. An example of nonlinear singularly perturbed type DC motor system is used to illustrate the design procedure and performance of the proposed control scheme. The simulation results are compared with composite SMC (CSMC) and CFSMC.

6. The ExFSMC and NFSMC are extended to higher order nonlinear systems us-
ing decoupled control strategy. In decoupled control strategy, the fourth order nonlinear system is decoupled into two second-order subsystems by a separate control objective expressed in terms of a sliding surface for each subsystems. The second subsystem is successfully incorporated into the first one via a two-level decoupling strategy. Based on these strategy, the exponential function based decoupled FSMC is proposed (EDFSMC) and decoupled NFSMC (DNFSMC) methods. The simulation results are carried out on two systems. The performance of the proposed controller is compared with the DFSMC method.

### 1.5 Organization of the Thesis

The thesis is organized as follows:

A brief introduction to the FSMC for uncertain nonlinear systems is presented in Chapter 2. The basic design of SMC and FLC are discussed. The motivation and the challenges in applying the FSMC for uncertain nonlinear system are discussed. The design steps of FSMC for uncertain nonlinear systems are presented. The FSMC method is verified on some benchmark models of uncertain nonlinear systems. In Chapter 3, ExFSMC is designed based on exponential function. The parameter selection of exponential function and design method for nonlinear systems are discussed. The proposed method is verified on some benchmark models and experimental setup for position control of DC motor. In Chapter 4, NFSMC scheme is presented for improved performance of nonlinear systems. The basic NNC design method and design of NFSMC method are discussed in details. The obtained controller is tested on nonlinear systems. In Chapter 5, a CFSMC scheme is investigated using two-time scale approach for nonlinear singularly perturbed system. The singular perturbation technique and design of CSMC is discussed. The closed loop robust stability analysis is proved by checking its interconnection properties of the CFSMC. The proposed CFSMC applicability is tested for real time experimentation on position control of DC motor system. The proposed CFSMC is also applied for spatial control of advanced heavy water reactor (AHWR) modelled as a singularly perturbed system. It is shown that, the proposed CFSMC is able to suppress spatial oscillations due to xenon developed in AHWR. In Chapter 6, a CNFSMC for nonlinear singularly perturbed system is presented. The stability and robustness properties of proposed method are analysed. The EDFSMC and DNFSMC design methods are investigated on higher order nonlinear systems using decoupled control strategy in Chapter 7. Finally, in Chapter 8, the concluding remarks and future scope is discussed.