Chapter 1

INTRODUCTION

1.1 PREAMBLE

This thesis investigates the imperative concerns associated with the analysis and design of nonlinear control systems. In this real world nonlinearities are exists in physical system up to certain extent. The physical system when modeled in detailed possesses nonlinearity beyond the bounds. The control aspect for nonlinear systems is a complicated task due to their complex nature.

This complexity turns out to be more sensitive when the parameters of the system are uncertain, for example: the plant, the sensor and the actuator in a control system. The uncertainty in the system due to parameter variation causes tremendous breakdown of the system's performance. This mainly happens due to information deficiency, like incomplete information or having some imprecise, fragmentary, vague data or contradictory in some other way.

Though, nonlinear control systems are frequently found in real engineering applications then also the tools for analyzing and designing purpose are still inadequate. The researcher keeps on working for innovating some of the well equipped tools for controlling and improving the performance of the nonlinear system.

The research enclosed in this thesis added theoretical consequences for the analysis and design of nonlinear control systems, and offers a variety of tools for controlling the linearized version of nonlinear system. Although, the process of linearization is of limited use but due to the wide availability of linear control tools, the controlling of linearized system gaining its popularity day by day. The thesis also incorporates the optimization of conventional control techniques for controlling various nonlinear systems.

1.2 NONLINEAR CONTROL SYSTEM

As constraints are considered to be an omnipresent likewise control systems is also ubiquitous. Control systems are being applied to a wide variety of real world engineering problems. It is expected from the control perspective that it would improve the systems performance whether it would be a linear system or a nonlinear system. However, the modeling of such nonlinearities is rather a complex task. To avoid these complexities the nonlinear system is being approximated using linearization techniques. Generally, a linear model is created, and a controller is designed on the basis of this linearized model.

Though, the controller designed for this linear model results to a bounded output and the performance of the controller degrades when is implemented to control the actual nonlinear system. The aim of this thesis is to provide an efficient controller, which improve the efficacy of the nonlinear systems [1]. The basic difference between nonlinear system and linear system is shown in Table 1.1.

Table 1.1: Comparison of Nonlinear systems versus linear systems

NONLINEAR SYSTEMS	LINEAR SYSTEMS
More realistic	Approximation to reality
Usually difficult to analyze and design	Simpler to analyze and design
Tools are under development	A lot of tools are well-developed
Can have multiple equilibrium points	Only single equilibrium point
System stability depends on initial conditions	Stability is independent of initial condition
Exhibits limit cycles	No limit cycles
Bifurcations (no. of equilibrium points and their stability nature can vary with parameter values)	No bifurcation
Chaos (very small difference in initial condition can lead to large difference in output as time increases.	No chaos
Frequency and amplitude can be coupled	Frequency and amplitude are independent

❑ WHY NONLINEAR SYSTEM?

As the controller design perspective transform from linear to nonlinear theory, the situation becomes more complicated. The principle of superposition and principle homogeneity does not hold any more. Also, the conventional tool for analyzing the stability of the system does not work for nonlinear system. To make a use of these powerful tools, the nonlinear system is generally linearized around some operating point and then these tools could be used for the analysis of resulting linear model.

However, linearization alone will not be sufficient and it desired to develop some of the tools for the analysis of nonlinear system. The nonlinear system poses various enhancements over linear systems like [2]-

- ***Enhancement of existing control systems:*** The applicability of linear control system is depends only on the basis of assumption that the range of operation is small. As this range keeps on increasing the validity and performance of the linear control system tending towards the instability, due to the fact that the nonlinearities associated with system are least vulnerable and it cannot be avoided. Whereas, nonlinear controller is capable enough to cope-up from these nonlinearities in spite of the range of operation.
- ***Hard nonlinearities:*** another assumption of linear control is that the system model is indeed linearizable. However, in control systems there are much nonlinearity whose discontinuous nature does not allow linear approximation. These so called “hard nonlinearities” include Coulomb friction, saturation, dead-zones, backlash, and hysteresis. Their effect cannot be derived from linear methods, and nonlinear analysis techniques must be developed to predict a system’s performance in the presence of these inherent nonlinearities. Because such nonlinearities frequently cause undesirable behavior of the control systems, such as instabilities or limit cycles.
- ***Strong nonlinearities:*** Higher-order terms in Taylor series expansion.
- ***Model uncertainty:*** In designing linear controllers, it is usually necessary to assume that the parameters of the system model are reasonably well known.

However, many control problems involve uncertainties in the model parameters. This may be due to slow time variation of the parameters or to an abrupt change in parameters. A linear controller based on inaccurate or obsolete values of the model parameters may exhibit significant performance degradation or even instability. Nonlinearities can be intentionally introduced into the controller part of a control system so that model uncertainties can be tolerated.

- ***Design simplicity:*** Good nonlinear control design may be simpler and more intuitive than their linear counterparts.
- ***Can lead to better Cost & Performance optimality***

The basic limitations of linearizing the nonlinear systems are:

1. Linearization is an approximation in the neighborhood of an operating point; it can only predict the “local” behavior of the nonlinear system in the vicinity of that point. It cannot predict the “nonlocal” behavior far from the operating point, and certainly not the “global” behavior throughout the state space.
2. The dynamics of a nonlinear system are much higher than the dynamics of linear system. There are “essential nonlinear phenomena” that can take place only in the presence of nonlinearity. Hence, they cannot be described or predicted by linear models.

Examples of essential nonlinear phenomena are [3]:

- ***Finite escape time:*** The state of an unstable linear system goes to infinity as time approaches infinity; a nonlinear system's state, however, can go to infinity in finite time.

- ***Multiple isolated equilibrium:*** A linear system can have only one isolated equilibrium point; hence, it can have only one steady-state operating point which attracts the state of the system irrespective of the initial state. A nonlinear system can have more than one isolated equilibrium point. The state may converge to one of several steady-state operating points, depending on the initial state of the system.
- ***Limit cycles:*** The continual oscillation of linear time-invariant system is possible only when it have a pair of Eigen-values on the imaginary axis. To maintain such oscillation in the presence of disturbance is quite impractical and also it is not a robust condition to do to so in the existence of perturbation. Still if we able to do so, the amplitude of oscillation will depends on the initial condition. In real life, stable oscillation must be produced by nonlinear systems. There are nonlinear systems which can go into an oscillation of fixed amplitude and frequency, irrespective of the initial condition. This type of oscillation is known as a limit cycle.
- ***Sub-harmonic oscillations:*** A stable linear system under a periodic input produces an output of the same frequency. A nonlinear system under periodic excitation can oscillate with frequencies which are submultiples or multiples of the input frequency. It may even generate an almost-periodic oscillation, an example of which is the sum of periodic oscillations with frequencies which are not multiples of each other.
- ***Chaos:*** A nonlinear system can have a more complicated steady-state behavior that is not equilibrium, periodic oscillation, or almost-periodic oscillation. Such behavior is usually referred to as chaos. Some of these chaotic motions exhibit randomness, despite the deterministic nature of the system.

- ***Multiple modes of behavior:*** It is usual for two or more modes of behavior to be exhibited by the same nonlinear system. An unforced system may have more than one limit cycle. A forced system with periodic excitation may exhibit harmonic, sub-harmonic, or more complicated steady-state behavior, depending upon the amplitude and frequency of the input. It may even exhibit a discontinuous jump in the mode of behavior as the amplitude or frequency of the excitation is smoothly changed.

1.3 MOTIVATION

With the increasing complexity of various industrial processes, as well as household appliances, the link among ambiguity, robustness and performance of these systems has become increasingly evident. This may explain the dominant role of emerging “intelligent systems” in recent years [5]. However, the definition of intelligent systems is a function of expectations and the status of the present knowledge: perhaps the “intelligent systems” of today are the “classical systems” of tomorrow.

The concept of intelligent control was first introduced nearly two decades ago by Fu and G. Saridis [6]. Despite its significance and applicability to various processes, the control community has not paid substantial attention to such an approach. In recent years, intelligent control has emerged as one of the most active and fruitful areas of research and development (R&D) within the spectrum of engineering disciplines with a variety of industrial applications.

During the last few decades, researchers have proposed many model-based control strategies. In general, these design approaches involve various phases such as modeling, analysis, simulation, implementation and verification. Many of these conventional and model-based methods have found their way into practice and provided satisfactory solutions to the spectrum of complex systems under various uncertainties [7]. However, as Zadeh articulated as early as 1962 [8] “often the solution of real life problems in system analysis and control has been subordinated to the development of mathematical theories that dealt with over-idealized problems bearing little relation to theory”.

This research work was mainly carried out by the rapid evolution of the intelligent control techniques. Now, a day’s intelligent control techniques playing their vital role for the advancement of the conventional control methodologies. Though, the conventional controller has its own significance as 65% of the overall contributions in the industrial fields are being handled by them only. Due to the vast growth of the digital era, the conventional controllers are being readily applied in the digital platform like digital computers.

The contribution of digital computers laid a strong foundation towards improving the efficacy of conventional controllers for satisfying each and every desired aspects required by the control engineers.

Besides this general motivation, each part of this thesis supported by its particular motivation, as presented in the following. As we move from linear to nonlinear systems, we are faced with a more difficult situation

- The principle of superposition and principle of homogeneity fails in case of nonlinear system.
- Analysis tools involve additional advanced mathematics.

The difficulties of complex nonlinear systems can be classified into the following categories [9-11]-

- Presence of nonlinearities
- Uncertainty
- Computational complexity

1.4 REALIZATION OF CONTROLLERS

Due to the speedy development in the digital technology, the controllers are implemented on the digital platform. As, we know that the conventional approach for designing a controller were losing their significance. The digital controllers are readily applicable to all the domains of control prospective. Earlier than 1950s primarily all the control systems were analog in nature, while these days, nearly all the systems consist of a digital computer as their crucial part. The controller is implemented using MATLAB/ SIMULINK environment. The analog or continuous-time system when controlled using digital controller or digital environment, an analog to digital controller (ADC) is required. The analog to digital controller forms a sampled-data system. A sampled-data control system therefore consists of an analog or continuous-time plant/process controlled on a digital environment or digital computer. Thus, a sampled-data control system is frequently referred to as computer-controlled system.

1.5 COMPLEXITIES IN CONTROL SYSTEM DESIGN

The control architecture commonly consists of various designs steps and the distinct situation is defined as follows [12]:

1. The controller is designed on the basis of the process/ plant output behavior. Therefore, the control expert has a deep insight about the system behavior and it would also have an expertise on the selection and implementation of sensors & actuators.
2. The second step is required to model the process/ plant that are to be controlled.
3. If it possible then the process/ plant needs to be simplified or the order of the system is reduced for the ease of controller design perspectives.
4. The controller design requirements are to be measured from the open-loop and closed-loop specification of the system.
5. Then the appropriate performance criterions are to be chosen for the improvement of the desired requirements.
6. On the basis of the objective function (performance indices) the suitable controller is implemented for controlling the insensitive states of the system.
7. If the system is able to track the reference input then the controller is selected else the parameters of the controller are updated.
8. The performance of the controller is then validated by performing simulation on MATLAB/ SIMULINK environment.
9. Reiterate these steps from 1 if necessary.
10. Select hardware and software and apply the controller.
11. Tune the controller on-line if required.

1.6 RESEARCH OBJECTIVES AND LITERATURE REVIEW

In this thesis, controller design techniques are broadly discussed for:

Case 1: System with actuator saturation

The physical system which pertain such a scenario is known as magnetic levitation system. The system is oscillatory in nature and it is marginally stable. The controller task is to drag these poles towards the left-half of the s-plane. The constraint associated with such type of system is the electro-magnetic coil saturation. Saturation is the most common and significant nonlinearity in a control system. The system is controlled by

- ➢ PID Control
- ➢ Teaching Learning Based Optimization

Both the control strategies try to compensate the variation between the electromagnetic force and the gravitational force. So, that the error between the reference input and the system output tends to minimized as low as possible.

❑ Literature Review Related to Case 1

A simple technique for obtaining a linearized model for a magnetic levitation system using input/output measurements was described by Galvão et.al in 2003 [13]. They had proposed a model structure that is compatible to symbolize experimental data. The nonlinear nature of the system is made apparent by identifying parameters for different equilibrium points. Actually, the parameters are estimated by varying them at 13% and 23%, correspondingly, between the extreme points considered. The dynamic behavior of the plant depends on the region of operation.

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Wenbai Chen et.al in 2010 [14] designed a new method for tuning the parameters of PID controller based on chaos optimization and applied to control the magnetic levitation system. The experimental results show that the steel ball had been successfully levitated by the use of PID controller. Comparing with the primary controller without optimization, the control performance of the optimized PID controller is improved.

M.Valluvan et.al in 2012 [15] presents a comparative analysis of conventional PID and model reference adaptive control for controlling the real time process. The model reference adaptive control is designed for controlling the magnetic levitation system and its response is compared with the conventional PID. Integral square error is calculated for the comparison of the above mentioned control schemes.

P. Šuster and A. Jadlovská [16] discussed a control algorithm design for nonlinear simulation model of the magnetic levitation system using the exact input-output feedback linearization method and pole-placement method. The proposed control algorithm together with simulation model was implemented into control structure and demonstrated in MATLAB/Simulink environment.

Salas et al. in 2015 [17] proposes a discrete-time nonlinear rational approximate model for the unstable magnetic levitation system. Based on this model and as an application of the input-output linearization technique, a discrete-time tracking control design will be derived using the corresponding classical state space representation of the model. A simulation example illustrates the efficiency of the proposed methodology.

Chen et al. [18] presents a unified theoretical framework for the identification and control of a nonlinear discrete-time dynamical system, in which the nonlinear system is represented explicitly as a sum of its linearized component and the residual nonlinear component referred to as a "higher order function." This representation substantially simplifies the procedure of applying the implicit function theorem to derive local properties of the nonlinear system, and reveals the role played by the linearized system in a more transparent form. Under the assumption that the linearized system is controllable and observable, it is shown that: 1) the nonlinear system is also controllable and observable in a local domain; 2) a feedback law exists to stabilize the nonlinear system locally; and 3) the nonlinear system can exactly track a constant or a periodic sequence locally, if its linearized system can do so. With some additional assumptions, the nonlinear system is shown to have a well-defined relative degree (delay) and zero-dynamics. If the zero-dynamics of the linearized system is asymptotically stable, so is that of the nonlinear one, and in such a case, a control law exists for the nonlinear system to asymptotically track an arbitrary reference signal exactly, in a neighborhood of the equilibrium state. The tracking can be achieved by using the state vector for feedback, or by using only the input and the output, in which case the nonlinear autoregressive moving-average (NARMA) model is established and utilized.

Case 2: When zeros of the systems are located in the unwanted region

The system which resembles such kind of uncertainty is known as nonminimum phase (NMP) system. The problem associated with NMP system is the large initial error and the system behavior is in opposite direction with respect to control action. The control methodology used here

- PID Control
- Smith Predictive Control
- Grey Wolf Optimizer

From the last few decades there has been a fascinating problem faced by the researchers for controlling the systems having zero lying in the unwanted region. The system having zeros in the right-half of the s −plane are recognized as a nonminimum phase system. The controlling of such a system becomes more critical when it mingles with the dead-time. The dead-term slack ups the system performance and it keep deteriorates with its increasing order. Several researchers/scientists have developed various methods for controlling of nonminimum phase systems.

❑ Literature Review Related to Case 2

In 1959 O. J. Smith [19] proposed a controller to overcome the dead-time of the process. This controller gains popularity due to its easier implementation and having main feature of eliminating the dead-term from the overall system. The drawback of this approach is that it is unable to work on the open-loop unstable system and for the system having integral mode. In 1980 K. J. Astrom has developed a direct method for nonminimum phase system. This method is based on identification of models with special structure and pole-zero placement design such that the residuals are bilinear in the parameters.

In 1981 Watanabe and Ito [20] modified the Smith’s controller by making changes in the predicted model to handle the systems with integrator. Mita & Yoshida [21] in 1981 investigated the undershooting phenomena of linear multivariable system. They employ a control method which suppresses the undershooting phenomena of a type $[1,1,\dots,1]$servosystem is proposed.

In 1986 Vidyasagar [22] dealt with the nonminimum phase system by deriving a necessary and sufficient condition for a stable system to exhibit an undershooting step response. He proves that undershoot occurs only if the plant has an odd number of real right-half plane zeros.

In 1992 Hagglund [23] designed a predictive PI controller for processes with long dead times. The advantage of this method it manages to predict the measurement signal even when the process has a long dead time and when the measurement signal is noisy. Gross et al. [24] in 1994 proposed a methodology based on cancellation of the unstable zeros in the linear discrete time systems with tracking control objectives. Astrom et al. [25] in 1994 proposed a modified Smith predictor for systems with an integral mode in which the controller decouples set-point response from the load response. The author as well claimed that the proposed controller provides better performance than the Watanabe et al. (1981) method. Kravaris et al. [26] in 1994 introduced Smith-type abstract operator structure for output feedback control of nonminimum phase systems. This method provides a transparent stability analysis framework and allowing the unification of existing minimum and nonminimum phase compensation structures.

Zhong et al. [27] in 2002 proposed a typical 2-degree-of-freedom PID controller in which an integral action is implemented using a delay term rather than a pure integrator while retaining the advantages of the Smith Predictor. This controller needs only two to three parameters to be tuned and has capability to eliminate the dead-time from the characteristic equation. Normey-Rico and Camacho [28] in 2002 proposes a 2 degree of freedom (2DOF) robust dead-time compensator (DTC), for both stable and integrative plants. They had shown that the 2DOF DTC is equivalent or superior to the modified Smith Predictor.

In 2008 García et al. [29] introduced a new dead-time compensator to control stable and integrating processes with long dead-time. The control goal is conveyed to control an equivalent delay-free plant, without any constraint in the controller design. Wang et al. [30] in 2014 investigates the disturbance rejection control for stable non-minimum phase systems with time delay. They employed a disturbance observer based controller to compensate the uncertain plant into a nominal one. Khalil and Braiek [31] in 2015 developed a technique of switching control based on the exact input-output linearization and the Lyapunov stability theory.

In this thesis, the authors incorporated the well defined technique of Smith's predictor to design a perfect PID controller for controlling the nonminimum phase system. As, the controller obtained by Smith's method have an extra feed-forward filter for minimizing the steady-state error of the system.

Case 3: When poles of the linearized system are lying on right-half of the s-plane

Such a scenario is a more complex one, because the system is highly unstable and requires an efficient controller to stabilize its states. The practical system which poses such a case is known as Inverted Pendulum system. It is a benchmark problem in the field of control system. The control schemes that are incorporated for the control of inverted pendulum system are

- PID Control
- Linear Quadratic Regulator
- Fuzzy Logic Control

All these control strategies are implemented to control and stabilized the inverted-pendulum system.

❑ Literature Review Related to Case 3

Recently, a lot of research on stabilization & control of inverted pendulum system has been carried out by various control methodologies. Ray et al. in 2007 [32] proposed the stabilization of an inverted pendulum system by using fuzzy control. Kar and Behera in 2009 [33] proposed a Takagi Sugeno fuzzy model for balancing a cart-pole system. Yadav et al. in 2010 [34] discussed a comparative analysis of different control techniques applied for stabilizing an inverted pendulum system.

Adrian-Vasile Duka in 2011 [35] examines the development of a genetic adaptive fuzzy control system for the Inverted Pendulum. The goal is to balance the inverted pendulum in the upright position by controlling the horizontal force applied to its cart. Fuzzy logic technique has been successfully applied to control this type of system, however most of the time the design of the fuzzy controller is done in an ad-hoc manner, and choosing certain parameters (controller gains, membership functions) proves difficult. The author examines the implementation of an adaptive control method based on genetic algorithms (GA), which can be used on-line to produce the adaptation of the fuzzy controller’s gains in order to achieve the stabilization of the pendulum. The performances of the proposed control algorithms are evaluated and shown by means of digital simulation.

Prasad et al. in 2011 [36] proposed a conventional and intelligent control schemes for stabilizing an inverted pendulum system. Apart from proposing a two loop PID controller for the stabilization of an inverted pendulum system the authors presented a PID plus linear quadratic regulator (LQR) control scheme. The authors also proposed a fuzzy logic base controller and also carried out the comparative analysis of the three control schemes.

A survey on various control techniques such as bang-bang control, PID control, fuzzy logic control, neural network are discussed by Boubaker in 2012 [37] to control an inverted pendulum system.

Ghosh et al. [38] in 2012 designed a PID controller based on pole placement technique for stabilizing the inverted pendulum system. The controller is designed by developing a two-loop robust PID controller via pole placement technique in which the position of the closed-loop poles are obtained from a linear quadratic regulator (LQR). The proposed methodology offers good robustness as compared with the LQR design method.

Kumar et al. [39] in 2013 proposed a robust LQR controller for stabilizing and tracking control of self erecting single inverted pendulum (SESIP). The proposed controller stabilizes the pendulum in the upright position keeping the cart to track the given reference signal even in the presence of disturbance.

Bettayeb et al. in 2014 [40] discussed a new pole placement fractional-PI state feedback design for the stabilization of inverted-pendulum cart system.

Lin et al. [41] proposed a method for adjusting the membership functions of a fuzzy rule base by adaptive sliding mode and applied it to the angular control of an inverted pendulum.

Lu et al. [42] used the genetic algorithm to automatically generate fuzzy rules and scaling factors for inverted pendulum control. Margaliot [43] showed a new approach to determining the structure of fuzzy controller for inverted pendulum by fuzzy Lyapunov synthesis. Mikukcic et al. [44] extracted fuzzy rules for inverted pendulum control by fuzzy clustering method. Saez et al. [45] utilized the generalized predictive controller to determine the parameters of the Takagi–Sugeno fuzzy model for controlling an inverted pendulum. Wong [46] adopted the genetic algorithm to tune all the membership functions of a fuzzy system in order to keep an inverted pendulum upright.

Yamakawa et al. [47] designed a high-speed fuzzy controller hardware system and used only seven fuzzy rules to control the angle of an inverted pendulum. Although stabilization control of an inverted pendulum system should also include the position control of the cart besides the angular control of the pendulum because of limit length of the rail, the above stated approaches only took into consideration the angular control of the pendulum.

To control both the angle of the pendulum and the position of the cart, Kandadai et al. [48] modified the structure of Berenji et al. [49] to a hierarchical controller and enabled it to generate fuzzy knowledge base automatically. It took more than 12.0 s, however, to asymptotically stabilize an inverted pendulum system with some offset besides its structure complexity.

1.6.1 OUTLINE OF THESIS

The proposed work of this thesis is divided into six chapters and their organization is outlined below.

Chapter 1 gives a general introduction to the problem and sketches an overview of the thesis.

Chapter 2 starts with the brief introduction of nonlinear system. A important survey of literature covering the various aspects of nonlinear systems. A brief introduction about the conventional controllers and intelligent controllers and also covers the literature survey about these controllers.

Chapter 3 discusses a brief introduction of magnetic levitation system. Also, describes the mathematical modeling and controlling aspects of magnetic levitation system. Optimization of conventional controller is also described in detail and simulation results were produced to validate the efficacy of the optimization techniques for providing the optimum solution for the conventional controllers.

Chapter 4 discusses the implication of right half zero. A brief introduction about the nonminimum phase system and also describes the stability issues associated with the nonminimum phase system. The controllers are designed for the approximation of the delay term and results are validated by comparing the conventional controllers with the intelligent controllers.

Chapter 5 discusses the modeling of nonlinear system. The nonlinear system incorporated here is SIMO (single-input multi-output) system. The practical system which represents such a case is known as inverted pendulum system. The controlling aspects for inverted pendulum system are discussed in detail. Optimal & intelligent controllers are designed for stabilizing the cart's position and pendulum's angle. Linear quadratic regulator is designed as an optimal controller and fuzzy logic control is implemented as an intelligent controller. The validations of both the control techniques are checked on MATLAB-SIMULINK environment by comparing it with the conventional control techniques.

Chapter 6 summarizes the main conclusions of the thesis and suggests methods on which further investigation may be carried out.