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How Can Robust Control of Nonlinear Systems be Achieved? Examining Optimization Techniques

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ROBUST CONTROL OF NONLINEAR SYSTEMS USING OPTIMIZATION TECHNIQUES

Abstract

Due to the inevitable nonlinearities in real systems, several nonlinear control methods (e.g., feedback linearization, sliding mode control, backstepping approach etc.) are described in detail in the literature. Due to limitations in application of well known classical methods, researchers have struggled for decades to realize robust and practical solutions for nonlinear systems by proposing different approaches or improving classical control methods.

The feedback linearization approach is a control method which employs feedback to stabilizesystems containing nonlinearities. In order to accomplish this, it assumes perfectknowledge of the system model to linearize the input-output relationship.In the absenceof perfect system knowledge, modelling errors inevitably affect the performanceof the feedback controller.Many researchers have come up with a new form of feedback linearization, called robust feedback. This method gives a linearizing control law that transforms the nonlinear system into its linear approximation around an operating point. Thus, it causes only a small transformation in the natural behavior of the system, which is desired in order to obtain robustness.

The controllers are required to provide various time domain and frequency domain performances while maintaining sufficient stability robustness. In this regard, the evolutionary optimization techniques provide better option as these are probabilistic search procedures and facilitate inclusion of wide variety of time and frequency domain performance functionals in the objective functions. A significant scope of work remains to be done which provides motivation for the research in the design of robust controllers using evolutionary optimization. Also, emerging techniques using LMI also find potential in controller design for feedback linearized systems.The thrust of the study here is to design robust controllers for nonlinear systems using Evolutionary optimization and LMI.

Furthermore, latest control methods for nonlinear system have been studied, deeply, in this thesis.Combining feedback linearization with non linear disturbance observer based control

(NDOBC) obtains promising disturbance rejection and reference tracking performance as compared to other robust control methods.

Sliding mode controller design provides a systematic approach to the problem of maintaining stability and consistent performance in the presence of modeling imprecision, for the class of systems to which it applies.Nonlinear disturbance observer (NDO) based sliding mode control (SMC) was proposed (Chen; 2004) in order to achieve better control performance by reducing chattering while maintaining the nominal performance in the presence of mismatched uncertainties. In this thesis, chattering and hitting time in NDO based SMC is reduced by obtaining the optimal controller parameters using optimization methods such as genetic algorithm (GA).

Also a novel and simple chattering free NDO based SMC methodology is proposed here for the robust tracking of nonlinear system with time varying mismatched uncertainties. The chattering alleviation is achieved by using a distance function which measures the distance between the sliding surface and trajectory of state errors as the remedial action in the control law instead of discontinuous sign function. Then Lyapunov method is used to prove the stability of the overall system.

List of Research Publications

1. Bhawna Tandon, Shiv Narayan, "Fixed Structure Robust H-infinity loop shaping of feedback linearized CSTR using PSO", International Journal of Modeling, Identification and Control, Inderscience Publications, Vol. 22, No. 1, p.p. 33-40, 2014 (SCOPUS & WEB OF SCIENCE INDEXED).

2. Bhawna Tandon, Shiv Narayan and Jagdish Kumar, "LMI based control of feedback linearized CSTR using YALMIP and CVX- a comparative analysis", International Journal of Automation and Control, Inderscience Publications, Vol. 9, No.1, 2015 (SCOPUS INDEXED).

3. Bhawna Tandon, Shiv Narayan and Jagdish Kumar, "Explicit Feedback Linearization of Magnetic Levitation System", World Academy of Science, Engineering and Technology, International Journal of Computer, Information, Systems and Control Engineering Vol:8, No:10, Dec 2014.

4. Bhawna Tandon, Shiv Narayan, Jagdish Kumar, "Structured MIMO H∞ design for feedback linearized CSTR based on non-smooth optimization", IEEE sponsored International Conference on Recent advances in Engineering and Computational Sciences (RAECS-2015) held on 21st – 22nd December 2015 at University Institute of Engineering & Technology, Punjab University, Chandigarh.

5. Bhawna Tandon, Shiv Narayan and Jagdish Kumar, "A simulation study of nonlinear disturbance observer based sliding mode control for inverted pendulum with mismatched disturbances", International Journal of System Control and Information Processing (IJSCIP), Vol. 1, No. 4, 2015, Inderscience Publications.

6. Bhawna Tandon, Shiv Narayan and Jagdish Kumar, "Stability analysis of non-smooth optimisation based controller designs for CSTR using Kharitonov theorem", International Journal of System Control and Communications, Vol. 7, No. 2, 2016, Inderscience Publications (SCOPUS INDEXED).

7. Bhawna Tandon, Shiv Narayan and Jagdish Kumar, "Design of a non-linear controller using Feedback Linearization based on back-stepping technique for Magnetic Levitation system", International Journal of Applied Nonlinear Science, Vol. 2, No. 4, 2016, Inderscience Publications (WEB OF SCIENCE INDEXED).

8. Bhawna Tandon, Shiv Narayan and Jagdish Kumar, “Sliding mode control with nonlinear disturbance observer based on genetic algorithm for inverted pendulum with mismatched disturbances”, Indian Journal of Science and Technology, Vol. 10, Issue 30, August 2017 (WEB OF SCIENCE INDEXED).

9. Bhawna Tandon, Shiv Narayan and Jagdish Kumar, “Nonlinear disturbance observer based robust control for continuous stirred tank reactor”, ICIC (Innovative Computing, Information and Control) Express letters, Vol. 12, Issue1, pp. 1-7, Jan 2018. (SCOPUS INDEXED).

10. One paper titled “A Novel chattering free Nonlinear Disturbance Observer based Sliding Mode Control for Inverted Pendulum with mismatched disturbances” has been communicated to a SCI journal.

CHAPTER 1

Introduction

1.1 Background

Researchers from various areas like robotics, biomedical engineering, mechatronics, process control and spacecraft control, have shown a great interest in developing the methodologies for nonlinear control. Most public method for nonlinear control is to use a linear controller for the nonlinear arrangement that is obtained by approximation concerning an operating point. But, this method of manipulation works merely in the tiny vicinity of the working point, as linear approximation is valid merely in this region. And, when the required operation range is large, a linear controller performs poorly because the nonlinearities in the arrangement are not compensated properly. The feedback linearization is the resolution to this setback, because the nonlinear arrangement gets transformed precisely into a linear arrangement (which is valid for the whole working region) employing feedback linearization and, hence, this combination of feedback linearization and a linear controller will work at all the points, not merely in a tiny area of the operating point. Feedback linearization is established on the cancellation of nonlinearities in the plant dynamics by the controller (Seo et al., 2007). But because of inaccurate measurements, plant uncertainties, and disturbances precise cancellation of these nonlinearities is impossible in practice. The linearized arrangement thus obtained, by using feedback linearization, has completely different dynamics and said to be in Brunovsky form (Hedrick and Girard, 2005; Isidori, 2013; Sastry, 2013), a non-robust form that is exceedingly sensitive to the uncertainties. (Franco, et al., 2006).

Thus a new idea of feedback linearization, shouted robust feedback linearization was given by researchers (Guillard & Bourles, 2000) that give a linearizing control law that transforms the nonlinear arrangement into its linear approximation concerning an operating point. The supremacy of this method is that merely a tiny makeover in the usual behavior of the system occurs, that is wanted so as to attain robustness.

It is normally vital to accept that system parameters are reasonably well recognized while designing linear controllers. But, an uncertainty in the model parameters is a large concern in many control problems (Ricardo & Patrizio, 1993; Xing & Jingping, 2004). Momentous performance degradation or even instability could be exhibited by a linear controller which established model parameters with inaccurate values. Robust controller design could find resolution to these kinds of problems. A control arrangement is said to be robust if even in the presence of probable uncertainties, it stays stable and achieves precise performance criteria (Gu et al., 2005; Zhang & Suyama, 1996). For feedback linearized systems, the H∞ optimization and its connected ways possess been shown to be competent and effectual robust design methods (Enayati & Mirzaeian, 2005; Lopez et al., 2003; Prempaina et al., 2002; Rehman et al., 2009, 2014). However, in addition to robust stability, supplementary performances of the controlled system such as steady state error, rise time, overshoot, etc. are additionally extremely vital considerations in control system design. To incorporate presentation specifications into robust control, methods such as H2/H∞ optimal control (Ali Waly, 2010), the mixed sensitivity function (Bouallegue et al., 2010), H∞ loop shaping, μ-synthesis, etc., possess proved to be extremely effective.

In this stare, the evolutionary optimization methods (Das & Suganthan, 2011; Kaji et al., 2002; Kang et al., 2002) furnish larger option as these are probabilistic search procedures and enable inclusion of expansive collection of time and frequency domain presentation useful in the objective function. A momentous scope of work stays to be completed that provides motivation for the research in the design of robust controllers for feedback linearized systems employing evolutionary optimization. Growing methods employing LMIs additionally find potential in controller design for feedback linearized systems. Solution of LMIs presents a convex optimization problem (Abdollahi & Khorasani, 2007; Aghaie & Amirifar, 2008; Boyd & Vandenberghe, 2004; Fujimori, 2004: Gussner et al., 2012; Zhang & Wu, 2003) that possesses been resolved by employing LMI Lab in Robust Control Toolbox, YALMIP Toolbox (Bakosova et al.,2011) and CVX Toolbox (Grant et al., 2007) in the MATLAB environment.

Backstepping design design is the best alternative to feedback linearization. The supremacy being that the system nonlinearities do not possess to be canceled in the control law employing backstepping and functional nonlinearity could be retained in the closed loop system managing to robustness against model errors. So, less control effort could be demanded to control the system. The term "backstepping" mentions to the recursive nature of the design procedure.

A vital feature of backstepping is that nonlinearities can be dealt alongside in countless ways. For raising the system robustness against the parameters variation the feedback linearization method is joined alongside backstepping technique. In this combination a sequence of "virtual" controls owing relative degree one is projected, next the relative degree is decreased by one by selecting a "virtual" input and the last "virtual output" is utilized to close feedback loop.

Although the methods remarked above like H2/H∞ control, back-stepping control (Alshamali & Zribi, 2012), feedback linearization based on backstepping (Wang, L., & Wang, Q.-L., 2009) possess been proved to be effectual, but their main was to deal with parametric uncertainty. Joining feedback linearization alongside Non Linear Disturbance Observer based control (NDOBC) obtains promising disturbance rejection and reference tracking performance as contrasted to other robust control methods.

The sliding mode control (SMC) possesses come to be extremely accepted because of its inherent insensitivity to external disturbances and parametric variations. But the standard SMC is merely insensitive to matched uncertainties, that way the uncertainties and the manipulation input continue in the alike channel (Li et al., 2014; Yang et al., 2013). To resolve this setback, an integral sliding mode control (I-SMC) was counseled in (Choi, 2007; Utkin & Shi, 1996). The believed behind the I-SMC is that a high-frequency switching gain is projected to power the states to accomplish the integral sliding surface, and next the integral action in the sliding surface propels the states to the wanted equilibrium in the presence of mismatched uncertainties. But integral action possesses precise disadvantages like long settling time and large overshoot. In supplement the critical portion of both the methods is the chattering problem.

Hence, the Nonlinear Disturbance Observer based sliding mode control was counseled (Chen; 2004) so as to accomplish better control performance by reducing chattering while maintaining the nominal performance in presence of mismatched uncertainties.

Traditional sliding mode control (SMC) always suffers from two vital subjects, convergence period and chattering phenomenon. Chattering and hitting period reduction in SMC should be obtained by selecting the optimal controller parameters employing intelligent optimization methods such as Genetic Algorithm (GA).

1.2 Literature Survey

The literature survey is divided into various parts:

1. **Robust controller design for feedback linearized systems**

Author	Year	Contribution
Franco Ana Lucia Driemeyer et al.	2005	In this paper, design of a robust nonlinear controller for a nonlinear system when subjected to model uncertainties is proposed. A robust linear H∞ controller is associated with “robust feedback linearization”.
Roger Fales & Atul Kelkar	2005	In this paper, an H∞ based robust controller is designed for the feedback linearized automatic bucket leveling mechanism of a wheel loader.
Iraj Hassanzadeh & Saleh Mobayen	2008	In this paper an optimum approach for the design of input output feedback linearization controller for a rotary inverted pendulum is presented employing the binary genetic algorithm by minimization of the integral absolute error of angles and velocities of the system .
Cristina Ioana Pop et al.	2011	In this paper, for a feedback linearized system a robust linear controller is projected using methods of loop shaping. In supplement a comparative analysis alongside the standard approach is done.
Michael Hansen et al.	2012	In this paper, employing feedback linearization method, control laws are projected for a marine cooling system. A robust linear H∞ controller is additionally designed for the feedback linearized system so as to cope up alongside the model uncertainties.
Ali Javadi et al.	2014	In this paper, a method for joining feedback linearization alongside linear H∞ controller is presented. Firstly, to convert a nonlinear system to a linear system a nonlinear state transformation is applied to the nonlinear state. Then, a linear H∞ controller is projected for the feedback linearized system.

2. **Structured H∞ controller design based on non-smooth optimization**

Author	Year	Contribution
Guilhem Puyou & Pierre Ezerzere	2012	This paper investigates the use of two algorithms: HIFOO and HINFSTRUCT for the non-smooth optimization that solves the issue of robust performance in a H_∞ framework.
Martin Rezac et al.	2013	In this paper structured and fixed order controllers are designed using two numerical solvers for a MIMO electromechanical system.
Pascal Gahinet & Pierre Apkarian	2014	Two new MATLAB based tools for the tuning of fixed structure linear control systems: hinfstruct and looptune are presented in this paper.

3. **Feedback linearization method is combined with backstepping technique**

Author	Year	Contribution
Wang Li et al.	2009	In this paper, process for converting pure feedback nonlinear and strictly feedback nonlinear system to linear system is presented. This technique is based on the combination of feedback linearization and backstepping technique.
E. Babaei et al.	2011	This paper presents the design of a nonlinear controller employing feedback linearization established on the back-stepping method alongside an aim of enhancing the steady-state and transient stability.
Muhammad Rizwan S. Khan & Robert N. K. Loh	2014	In this paper design of observer-based nonlinear controller is presented by combination of feedback linearization and backstepping techniques with Luenberger observers. The proposed controller is further presented for a bioprocess.
Askar Aziz et al.	2014	In this paper, combination of feedback linearization, backstepping and nonlinear disturbance observer have been presented in order to raise the performance of control methods by reducing the effects of external disturbances and system uncertainties.
Jianli Wei & Huan Chen	2015	In this paper, adaptive backstepping control method is used to design the control law for altitude system and velocity system of a hypersonic vehicle.

4. Feedback linearization with Non Linear Disturbance Observer based Control

Author	Year	Contribution
J.Yang et al.	2011	In this paper a nonlinear disturbance observer based robust control (NDOBRC) method is proposed for reducing the effects that are provoked by the mismatched disturbances and parameter variations on system output.
J.Yang et al.	2012	In this paper a method that is based on generalized nonlinear disturbance observer based control is presented that is utilized to resolve the setback of disturbance attenuation for MIMO nonlinear system having arbitrary disturbance relative degree.
Youssif Mohamed Toum Elobaid et al.	2014	In this paper, a nonlinear disturbance observer (NDO) is designed in order to deal with the nonlinearity and uncertainties of a pneumatic muscle model.
W. H. Chen et al.	2016	This paper proposes the design of a disturbance observer based control (DOBC) for uncertain nonlinear systems.
Guanghui Wu & Xiunyun Meng	2016	In this paper a robust backstepping approach in association with a nonlinear disturbance observer is designed for suppressing the effects of parameter uncertainties for a flexible air-breathing hypersonic vehicle in the longitudinal plane.

5. Nonlinear Disturbance Observer based Sliding Mode Control

Author	Year	Contribution
V. S. Deshpande & S. B. Phadke	**2011**	In this paper a novel sky hook model following scheme that is based on the sliding mode control strategy in combination with an uncertainty and disturbance estimator is presented.
Yuantao Zhang	**2013**	In this paper a novel robust sliding mode control strategy in which the optimal controller parameters are tuned by employing genetic algorithm is presented and implemented on the stabilized platform of rotary steering drilling system.

Divyesh Ginoya et al.	2014	This paper proposes a control based on extension of disturbance observer and modification of general sliding surface in order to handle a large class of uncertainties.
Divyesh Ginoya et al.	2015	A novel design of multiple-surface sliding mode control is presented in this paper that is applicable to a class of nonlinear uncertain systems alongside mismatched uncertainties and disturbances.
Junxiao Wang et al .	2015	This paper presents a nonlinear disturbance observer (NDOB) based sliding mode control (SMC) approach for PWM-based DC-DC boost converter systems that is subjected to resistance load disturbances and input voltage variation.
Saleh Mobayen	2015	This paper presents a new way of the robust tracking control of nonlinear second-order systems with time varying uncertainties that is established using the combination of fast terminal sliding mode control approach alongside the global sliding surface structure.
Samer Mohammed et al.	2016	A nonlinear observer is proposed in this study along with the terminal SMC to reduce the impact of the uncertainties in muscular torque modeling, on the system control.
Prasheel V Suryawanshi et al.	2016	This paper presents a novel method of boundary layer sliding mode control design that uses a discontinuous control outside the boundary layer and switches over to uncertainty and disturbance estimator based control inside it for chatter reduction.
Saleh Mobayen	2017	In this paper a tracking control for nonholonomic systems with external unknown disturbances is proposed. This control is based on novel recursive terminal sliding mode that guarantees the finite time convergence of the disturbance approximation error.

1.3 Motivation

The feedback linearization of a nonlinear system is a method which is based on linearizing the input-output relation of the system. But in order to cancel the nonlinearities, perfect knowledge of the state equations of the system is required. This is the most important issue of feedback linearization because in practice the perfect knowledge of a system not available. In the presence of model uncertainties, the limitations associated with feedback linearization have prompted the work done in this thesis.

The stability analysis of nonlinear systems has received considerable attention over the decades and many important advances in nonlinear design have been made. However, the challenge is to find a general methodology for the construction of stabilizing nonlinear control laws, which provides motivation for the study of various stability analysis methods for nonlinear systems.

Most of the existing controllers may provide good stability and tracking performance but usually show unsatisfactory disturbance attenuation and robustness against uncertainties. Research is continuing to develop controllers which can work successfully even in the presence of external disturbances and parametric uncertainties. This provided motivation for the work on robust control of nonlinear systems.

1.4 Objectives of the Thesis Work

Following are the objectives of the present thesis work:

- Robust control of the feedback linearized system having uncertainties in the plant using Evolutionary optimization and LMI.
- Reduced order/fixed structure Robust controller design for feedback linearized systems using Evolutionary optimization and LMI.
- Robustness analysis of the closed loop systems with designed controllers.
- Comparative study of evolutionary optimization versus LMI for the controller designs for various engineering problems.
- Design of a non-linear controller using feedback linearization based on back-stepping technique for robustness against parameter variation.
- Robust control of MIMO nonlinear system under external disturbances using feedback linearization and nonlinear disturbance observer based control (NDOBC).
- Robust control of SISO nonlinear system with mismatched disturbances using a nonlinear disturbance observer (NDO) based sliding mode control (SMC).

- Sliding mode control with nonlinear disturbance observer (NDO) based on GA.
- A novel chattering free nonlinear disturbance observer based sliding mode control for nonlinear systems with mismatched disturbances.

The control laws and design methodologies were developed for above mentioned approaches and these deisgn methodologies were implemented to various engineering systems using MATLAB and Simulink. MATLAB and Simulink were also used for the performance evaluation of the systems with designed controllers.

1.5 Thesis Outline

The Thesis is organized, in chapters, as follows:

Chapter 1 provides an overview of the work.

Chapter 2

In this chapter the concept and issues of feedback linearization are discussed along with a brief description of I/O feedback linearization for SISO and MIMO nonlinear systems. Then an overview of $H\infty$ control loop shaping is given and a fixed-structure polynomial controller based on robust $H\infty$ loop shaping control is designed for feedback linearized MIMO system.

This chapter also includes a brief introduction and advantages of LMI along with the public domain softwares/packages like YALMIP, SEDUMI, CVX that are used to solve convex optimization problems. These different toolboxes then are used for solving the LMIs for the designing of controller for a feedback linearized MIMO system.

Chapter 3

This chapter addresses structured $H\infty$ design based on non-smooth optimization. The two available numerical solvers-HIFOO and HINFSTRUCT are used for structured and fixed-order controller design, for a feedback linearized MIMO system. The Kharitonov theorem is used to analyze the stability of the designed controller for the feedback linearized MIMO system with parametric uncertainties.