

# Optimal Control of Nonlinear Systems Using the Homotopy Perturbation Method

Amin Jajarmi

Department of Electrical Engineering  
Ferdowsi University of Mashhad  
Mashhad, Iran  
jajarmi@stu-mail.um.ac.ir

Hamidreza Ramezanzpour

Department of Nuclear Engineering and Physics  
Amirkabir University of Technology  
Tehran, Iran  
h.ramezanzpour@aut.ac.ir

Arman Sargolzaei, Pouyan Shafaei

Department of Electrical Engineering  
Sadqad Institute of Higher Education  
Mashhad, Iran

a.sargolzaei@icee.org, pouyan.shafaei@gmail.com

**Abstract**—This paper presents a new method for solving a class of nonlinear optimal control problems with a quadratic performance index. In this method, first the original optimal control problem is transformed into a nonlinear two-point boundary value problem (TPBVP) via the Pontryagin's maximum principle. Then, using the Homotopy Perturbation Method (HPM) and introducing a convex homotopy in topologic space, the nonlinear TPBVP is transformed into a sequence of linear time-invariant TPBVP's. By solving the presented linear TPBVP sequence in a recursive manner, the optimal control law and the optimal trajectory are determined in the form of infinite series. Finally, in order to obtain an accurate enough suboptimal control law, an iterative algorithm with low computational complexity is introduced. An illustrative example demonstrates the simplicity and efficiency of proposed method.

**Index Terms**—nonlinear optimal control problem, Pontryagin's maximum principle, two-point boundary value problem, Homotopy Perturbation Method

## I. INTRODUCTION

Theory and application of optimal control has been widely used in different fields such as biomedicine [1], aircraft systems [2], robotic [3], etc. However, optimal control of nonlinear systems is a challenging task which has been studied extensively for decades.

Methods of solving nonlinear optimal control problems (NOCVP's) can be divided into two categories. The first category, which contains direct methods, converts the problem into a nonlinear programming by using the discretization or parameterization techniques [4-5]. The second category contains indirect methods and leads to the Hamilton-Jacobi-Bellman (HJB) equation, based on dynamic programming [6], or nonlinear two-point boundary value problem (TPBVP), based on the Pontryagin's maximum principle [7]. In general, the HJB equation is a nonlinear partial differential equation that is hard to solve in most cases. An excellent literature review on the methods for approximating the solution of HJB

equation is provided in [8]. Besides, nonlinear TPBVP has no analytical solution except for a few simple cases. Thus, many researches have been devoted to find an approximate solution for the nonlinear TPBVP's. Recently, successive approximation approach (SAA) and sensitivity approach have been introduced in [9] and [10], respectively. In those, a sequence of nonhomogeneous linear time-varying TPBVP's is solved instead of directly solving the nonlinear TPBVP derived from the Pontryagin's maximum principle. However, solving time-varying equations is much more difficult than solving time-invariant ones.

The Homotopy Perturbation Method (HPM) was initially proposed by the Chinese mathematician J. H. He [11-12]. This method has been widely used to solve nonlinear problems in different fields [13-15]. In contrast to the perturbation method [16], the HPM is independent upon small/large physical parameters in system model. However, like the other traditional non-perturbation methods such as the Lyapunov's artificial small parameter method [17] and Adomian's decomposition method [18], uniform convergence of the solution series obtained via the HPM can not be ensured.

In this paper, based on the HPM, a new method is proposed to solve a class of nonlinear OCP's. In this method, first the original nonlinear OCP is transformed into a nonlinear TPBVP by using the maximum principle. Applying the HPM transforms the nonlinear TPBVP into a sequence of linear time-invariant TPBVP's. Solving the proposed linear TPBVP sequence in a recursive manner leads to the optimal control law and the optimal trajectory in the form of infinite series. The proposed method avoids the trouble of directly solving the nonlinear TPBVP or the HJB equation. In addition, it avoids solving a sequence of linear time-varying TPBVP's. It only requires solving a sequence of linear time-invariant TPBVP's. Hence, it reduces the computational complexity, effectively. The rest of paper is organized as follows. In section 2 the statement of problem is discussed. Section 3 elaborates the

# Optimal Control Of Nonlinear Systems Using The Homotopy

**Judd E. Hollander**



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**Deep Reinforcement Learning with Guaranteed Performance** Yinyan Zhang, Shuai Li, Xuefeng Zhou, 2019-11-09 This book discusses methods and algorithms for the near optimal adaptive control of nonlinear systems including the corresponding theoretical analysis and simulative examples and presents two innovative methods for the redundancy resolution of redundant manipulators with consideration of parameter uncertainty and periodic disturbances It also reports on a series of systematic investigations on a near optimal adaptive control method based on the Taylor expansion neural networks estimator design approaches and the idea of sliding mode control focusing on the tracking control problem of nonlinear systems under different scenarios The book culminates with a presentation of two new redundancy resolution methods one addresses adaptive kinematic control of redundant manipulators and the other centers on the effect of periodic input disturbance on redundancy resolution Each self contained chapter is clearly written making the book accessible to graduate students as well as academic and industrial researchers in the fields of adaptive and optimal control robotics and dynamic neural networks Computational Optimal Control Dr Subchan Subchan, Dr Rafal Zbikowski, 2009-08-19 Computational Optimal Control Tools and Practice provides a detailed guide to informed use of computational optimal control in advanced engineering practice addressing the need for a better understanding of the practical application of optimal control using computational techniques Throughout the text the authors employ an advanced aeronautical case study to provide a practical real life setting for optimal control theory This case study focuses on an advanced real world problem known as the terminal bunt manoeuvre or special trajectory shaping of a cruise missile Representing the many problems involved in flight dynamics practical control and flight path constraints this case study offers an excellent illustration of advanced engineering practice using optimal solutions The book describes in practical detail the real and tested optimal control software examining the advantages and limitations of the technology Featuring tutorial insights into computational optimal formulations and an advanced case study approach to the topic Computational Optimal Control Tools and Practice provides an essential handbook for practising engineers and academics interested in practical optimal solutions in engineering Focuses on an advanced real world aeronautical case study examining optimisation of the bunt manoeuvre Covers DIRCOL NUOCCCS PROMIS and SOCS under the GESOP environment and BNDSCO Explains how to configure and optimize software to solve complex real world computational optimal control problems Presents a tutorial three stage hybrid approach to solving optimal control problem formulations **Analysis and Control of Nonlinear Systems** Christopher I. Byrnes, Clyde Martin, Richard Saeks, 1988 *Applied Mechanics Reviews*, 1994 **Proceedings of the 1993 American Control Conference**, 1993 **Scientific and Technical Aerospace Reports**, 1994 **Proceedings of the ... American Control Conference**, 1992 **Role of Nutrients in Neurological Disorders** Senthilkumar Rajagopal, Saravanan Ramachandran, Geethalakshmi Sundararaman, Swarnalatha Gadde Venkata, 2022-03-12 This book provides the latest research

on the role of nutrients in the prevention and treatment of neurological disorders It discusses dietary supplements and dietary restrictions for combating neurological disorders including Alzheimer s disease Parkinson s disease stroke and epilepsy The book also explains the impact of different nutrients such as herbal products algae micronutrients in stimulating the brain and central nervous system during abnormal functions It covers the effect of the nutrients on the function of neurotransmitters their stimulatory effect in autism dementia Alzheimer s and other neuropathological states The book also defines the mechanistic effects of neuroprotective and psycho protective effects of natural food in repairing brain damage This book is essential reading for neuroscientists and neurologists and healthcare professionals **International**

**Aerospace Abstracts** ,1999 Nonlinear and Optimal Control Systems Thomas L. Vincent,Walter J. Grantham,1997-06-23 Designed for one semester introductory senior or graduate level course the authors provide the student with an introduction of analysis techniques used in the design of nonlinear and optimal feedback control systems There is special emphasis on the fundamental topics of stability controllability and optimality and on the corresponding geometry associated with these topics Each chapter contains several examples and a variety of exercises Nonlinear Controllability and Optimal Control H.J. Sussmann,2017-11-22 This outstanding reference presents current state of the art research on important problems of finite dimensional nonlinear optimal control and controllability theory It presents an overview of a broad variety of new techniques useful in solving classical control theory problems Written and edited by renowned mathematicians at the forefront of research in this evolving field Nonlinear Controllability and Optimal Control provides detailed coverage of the construction of solutions of differential inclusions by means of directionally continuous sections Lie algebraic conditions for local controllability the use of the Campbell Hausdorff series to derive properties of optimal trajectories the Fuller phenomenon the theory of orbits and more Containing more than 1 300 display equations this exemplary instructive reference is an invaluable source for mathematical researchers and applied mathematicians electrical and electronics aerospace mechanical control systems and computer engineers and graduate students in these disciplines *Proceedings, 1995 International Symposium on Nonlinear Theory and Its Applications* ,1995 **On the Necessary Condition for Optimal Control of Nonlinear Systems** H. Halkin,1963 **Mathematical Reviews** ,2007 *Dissertation Abstracts International* ,2006 **Technology for Large Space Systems: A Bibliography with Indexes (supplement 22)** ,1990 **Journal of Guidance, Control, and Dynamics** ,2008 *Applied Science & Technology Index* ,1997 *Documentation Abstracts* ,1996 **SIAM Journal on Control and Optimization** Society for Industrial and Applied Mathematics,1999 Contains research articles on the mathematics and applications of control theory and on those parts of optimization theory concerned with the dynamics of deterministic or stochastic systems in continuous or discrete time or otherwise dealing with differential equations dynamics infinite dimensional spaces or fundamental issues in variational analysis and geometry

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## **Table of Contents Optimal Control Of Nonlinear Systems Using The Homotopy**

1. Understanding the eBook Optimal Control Of Nonlinear Systems Using The Homotopy
  - The Rise of Digital Reading Optimal Control Of Nonlinear Systems Using The Homotopy
  - Advantages of eBooks Over Traditional Books
2. Identifying Optimal Control Of Nonlinear Systems Using The Homotopy
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Optimal Control Of Nonlinear Systems Using The Homotopy
  - User-Friendly Interface
4. Exploring eBook Recommendations from Optimal Control Of Nonlinear Systems Using The Homotopy

- Personalized Recommendations
  - Optimal Control Of Nonlinear Systems Using The Homotopy User Reviews and Ratings
  - Optimal Control Of Nonlinear Systems Using The Homotopy and Bestseller Lists
5. Accessing Optimal Control Of Nonlinear Systems Using The Homotopy Free and Paid eBooks
    - Optimal Control Of Nonlinear Systems Using The Homotopy Public Domain eBooks
    - Optimal Control Of Nonlinear Systems Using The Homotopy eBook Subscription Services
    - Optimal Control Of Nonlinear Systems Using The Homotopy Budget-Friendly Options
  6. Navigating Optimal Control Of Nonlinear Systems Using The Homotopy eBook Formats
    - ePub, PDF, MOBI, and More
    - Optimal Control Of Nonlinear Systems Using The Homotopy Compatibility with Devices
    - Optimal Control Of Nonlinear Systems Using The Homotopy Enhanced eBook Features
  7. Enhancing Your Reading Experience
    - Adjustable Fonts and Text Sizes of Optimal Control Of Nonlinear Systems Using The Homotopy
    - Highlighting and Note-Taking Optimal Control Of Nonlinear Systems Using The Homotopy
    - Interactive Elements Optimal Control Of Nonlinear Systems Using The Homotopy
  8. Staying Engaged with Optimal Control Of Nonlinear Systems Using The Homotopy
    - Joining Online Reading Communities
    - Participating in Virtual Book Clubs
    - Following Authors and Publishers Optimal Control Of Nonlinear Systems Using The Homotopy
  9. Balancing eBooks and Physical Books Optimal Control Of Nonlinear Systems Using The Homotopy
    - Benefits of a Digital Library
    - Creating a Diverse Reading Collection Optimal Control Of Nonlinear Systems Using The Homotopy
  10. Overcoming Reading Challenges
    - Dealing with Digital Eye Strain
    - Minimizing Distractions
    - Managing Screen Time
  11. Cultivating a Reading Routine Optimal Control Of Nonlinear Systems Using The Homotopy
    - Setting Reading Goals Optimal Control Of Nonlinear Systems Using The Homotopy
    - Carving Out Dedicated Reading Time
  12. Sourcing Reliable Information of Optimal Control Of Nonlinear Systems Using The Homotopy

- Fact-Checking eBook Content of Optimal Control Of Nonlinear Systems Using The Homotopy
  - Distinguishing Credible Sources
13. Promoting Lifelong Learning
- Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
- Integration of Multimedia Elements
  - Interactive and Gamified eBooks

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