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Near Optimal Event-Triggered Control of Nonlinear Discrete-Time Systems Using Neurodynamic Programming

Avimanyu Sahoo, Hao Xu, *Member, IEEE*, and Sarangapani Jagannathan, *Senior Member, IEEE*

***Abstract*—This paper presents an event-triggered near optimal control of uncertain nonlinear discrete-time systems. Event-driven neurodynamic programming (NDP) is utilized to design the control policy. A neural network (NN)-based identifier, with event-based state and input vectors, is utilized to learn the system dynamics. An actor–critic framework is used to learn the cost function and the optimal control input. The NN weights of the identifier, the critic, and the actor NNs are tuned aperiodically once every triggered instant. An adaptive event-trigger condition to decide the trigger instants is derived. Thus, a suitable number of events are generated to ensure a desired accuracy of approximation. A near optimal performance is achieved without using value and/or policy iterations. A detailed analysis of nontrivial inter-event times with an explicit formula to show the reduction in computation is also derived. The Lyapunov technique is used in conjunction with the event-trigger condition to guarantee the ultimate boundedness of the closed-loop system. The simulation results are included to verify the performance of the controller. The net result is the development of event-driven NDP.**

***Index Terms*—Event-triggered control (ETC), Hamilton–Jacobi–Bellman equation, neural networks (NNs), neurodynamic programming (NDP), optimal control.**

I. Introduction

EVENT-TRIGGERED control (ETC) [1]–[6], which is evolved as an alternate control paradigm in the recent times, is found to be effective in terms of resource utilization. The ETC scheme uses events to sample the system state and execute the controller in an aperiodic manner. The aperiodic sampling and execution reduces the computational costs for the closed-loop system. In the case of a networked control system (NCS) [7], the ETC scheme saves network bandwidth due to the event-based aperiodic transmissions. The sampling and transmission instants, referred to as event-trigger instants, are decided using a state-dependent criterion. The threshold in the criterion is designed analytically via the Lyapunov stability technique. Thus, the event-triggered paradigm saves resources, and maintains both stability and closed-loop performance.

Recently, various ETC schemes [1]–[6] have been introduced in the literature for linear [3], [4] and nonlinear systems [1], [2]. Typically, in the ETC schemes, the system dynamics are considered either completely known [1], [2], or with a small uncertainty [3].

In contrast, in [5] and [6], an attempt has been made to design the event-based controllers for systems with uncertain dynamics. In [5], the knowledge of the system dynamics is partially relaxed using an event-based neural network (NN) approximator. The NN-based design is extended to the case of completely unknown dynamics in [6]. In both the cases, the state-dependent criteria, referred to as event-trigger conditions, are made adaptive. This is in contrast with the traditional nonadaptive event-trigger conditions [1], [2]. These adaptive criteria generated a required number of events during the initial online learning phase of NN. This facilitated the event-based approximation of the unknown dynamics with aperiodic weight update. A tradeoff is observed between the accuracy of NN approximation and the reduction in computation. However, these controller designs [5], [6] render only stability without optimizing any performance index.

Imer and Basar [9] studied the optimal ETC in a constrained communication scenario using the certainty equivalence principle. Furthermore, Molin and Hirche [10] extended the linear quadratic Gaussian approach to an event-triggered context using a separation principle. However, these methods [9], [10] use backward-in-time Riccati equation-based solution with completely known system dynamics.

Traditionally, adaptive dynamic programming [11]–[14] or neurodynamic programming (NDP) [15] techniques are used to design the optimal control policy in a forward-in-time and online manner. These techniques use the policy and/or value iterations to solve the Hamilton–Jacobi–Bellman (HJB) equation online. However, a significant number of iterations within a sampling interval are needed to maintain the system stability resulting in a high computational cost. Furthermore, the knowledge of the control coefficient function is also necessary to compute the optimal control policy.

For a finite-time [16] optimal control, the solution to the HJB equation (i.e., the cost function) becomes explicitly time varying. The terminal cost constraint must also be satisfied at the same time. The event-based sampling of the state

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A. Sahoo and S. Jagannathan are with the Department of Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, MO 65409 USA (e-mail: asvw6@mst.edu; sarangap@mst.edu).

H. Xu is with the Department of Electrical Engineering, College of Science and Engineering, Texas A&M University–Corpus Christi, Corpus Christi, TX 78412 USA (e-mail: hao.xu@tamucc.edu).

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Neurodynamic Programming

Olfa Boubaker,Quanmin Zhu,Magdi S. Mahmoud,Jose Ragot,Hamid Reza Karimi,Jorge Dávila

Neurodynamic Programming:

Neuro-Dynamic Programming Dimitri Bertsekas,John N. Tsitsiklis,1996-11-01 This is historically the first book that fully explained the neuro dynamic programming reinforcement learning methodology a breakthrough in the practical application of neural networks and dynamic programming to complex problems of planning optimal decision making and intelligent control Neuro dynamic programming uses neural network approximations to overcome the curse of dimensionality and the curse of modeling that have been the bottlenecks to the practical application of dynamic programming and stochastic control to complex problems The methodology allows systems to learn about their behavior through simulation and to improve their performance through iterative reinforcement This book provides the first systematic presentation of the science and the art behind this exciting and far reaching methodology It develops a comprehensive analysis of reinforcement learning algorithms and guides the reader to their successful application through case studies from complex problem areas It contains material that is not available elsewhere in book form such as a comprehensive and rigorous analysis of temporal difference methods Q learning and error bounds associated with various methods **Adaptive Learning Methods for Nonlinear System Modeling** Danilo Comminiello,Jose C. Principe,2018-06-11 Adaptive Learning Methods for Nonlinear System Modeling presents some of the recent advances on adaptive algorithms and machine learning methods designed for nonlinear system modeling and identification Real life problems always entail a certain degree of nonlinearity which makes linear models a non optimal choice This book mainly focuses on those methodologies for nonlinear modeling that involve any adaptive learning approaches to process data coming from an unknown nonlinear system By learning from available data such methods aim at estimating the nonlinearity introduced by the unknown system In particular the methods presented in this book are based on online learning approaches which process the data example by example and allow to model even complex nonlinearities e g showing time varying and dynamic behaviors Possible fields of applications of such algorithms includes distributed sensor networks wireless communications channel identification predictive maintenance wind prediction network security vehicular networks active noise control information forensics and security tracking control in mobile robots power systems and nonlinear modeling in big data among many others This book serves as a crucial resource for researchers PhD and post graduate students working in the areas of machine learning signal processing adaptive filtering nonlinear control system identification cooperative systems computational intelligence This book may be also of interest to the industry market and practitioners working with a wide variety of nonlinear systems Presents the key trends and future perspectives in the field of nonlinear signal processing and adaptive learning Introduces novel solutions and improvements over the state of the art methods in the very exciting area of online and adaptive nonlinear identification Helps readers understand important methods that are effective in nonlinear system modelling suggesting the right methodology to address particular issues

Adaptive Dynamic Programming with Applications in Optimal Control Derong Liu,Qinglai Wei,Ding Wang,Xiong

Yang,Hongliang Li,2017-01-04 This book covers the most recent developments in adaptive dynamic programming ADP The text begins with a thorough background review of ADP making sure that readers are sufficiently familiar with the fundamentals In the core of the book the authors address first discrete and then continuous time systems Coverage of discrete time systems starts with a more general form of value iteration to demonstrate its convergence optimality and stability with complete and thorough theoretical analysis A more realistic form of value iteration is studied where value function approximations are assumed to have finite errors Adaptive Dynamic Programming also details another avenue of the ADP approach policy iteration Both basic and generalized forms of policy iteration based ADP are studied with complete and thorough theoretical analysis in terms of convergence optimality stability and error bounds Among continuous time systems the control of affine and nonaffine nonlinear systems is studied using the ADP approach which is then extended to other branches of control theory including decentralized control robust and guaranteed cost control and game theory In the last part of the book the real world significance of ADP theory is presented focusing on three application examples developed from the authors work renewable energy scheduling for smart power grids coal gasification processes and water gas shift reactions Researchers studying intelligent control methods and practitioners looking to apply them in the chemical process and power supply industries will find much to interest them in this thorough treatment of an advanced approach to control

Soft Computing and Intelligent Systems Madan M. Gupta,1999-10-28 The field of soft computing is emerging from the cutting edge research over the last ten years devoted to fuzzy engineering and genetic algorithms The subject is being called soft computing and computational intelligence With acceptance of the research fundamentals in these important areas the field is expanding into direct applications through engineering and systems science This book cover the fundamentals of this emerging filed as well as direct applications and case studies There is a need for practicing engineers computer scientists and system scientists to directly apply fuzzy engineering into a wide array of devices and systems

Neural Information Processing Long Cheng,Andrew Chi Sing Leung,Seiichi Ozawa,2018-12-03 The seven volume set of LNCS 11301 11307 constitutes the proceedings of the 25th International Conference on Neural Information Processing ICONIP 2018 held in Siem Reap Cambodia in December 2018 The 401 full papers presented were carefully reviewed and selected from 575 submissions The papers address the emerging topics of theoretical research empirical studies and applications of neural information processing techniques across different domains The 7th and final volume LNCS 11307 is organized in topical sections on robotics and control biomedical applications and hardware

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convergence analysis kernel methods large margin methods and SVM optimization algorithms varational methods control robotics bioinformatics and biomedical engineering brain like systems and brain computer interfaces data mining and knowledge discovery and other applications of neural networks Artificial Neural Networks in Finance and Manufacturing Kamruzzaman, Joarder,Begg, Rezaul,Sarker, Ruhul,2006-03-31 This book presents a variety of practical applications of neural networks in two important domains of economic activity finance and manufacturing Provided by publisher *New Trends in Observer-based Control* Olfa Boubaker,Quanmin Zhu,Magdi S. Mahmoud,Jose Ragot,Hamid Reza Karimi,Jorge Dávila,2019-08-23 New Trends in Observer Based Control A Practical Guide to Process and Engineering Applications presents a concise introduction to the latest advances in observer based control design The book gives a comprehensive tutorial on new trends in the design of observer based controllers for which the separation principle is well established It covers a wide range of applications also including worked examples that make it ideal for both advanced courses and researchers starting work in the field This book is also particularly suitable for engineers who want to quickly and efficiently enter the field Presents a clear and concise introduction to the latest advances in observer based control design Offers content on many facets of observer based control design Discusses key applications in the fields of power systems robotics and mechatronics flight and automotive systems *The 1997 IEEE International Conference on Neural Networks, June 9-12, 1997, Westin Galleria Hotel, Houston, Texas, USA.* ,1997 **IEEE ... International Conference on Neural Networks** Shun'ichi Amari,1997 NTC ... National Telesystems Conference Proceedings ,1991 **1997 IEEE International Conference on Acoustics, Speech, and Signal Processing** ,1997 *IEEE International Symposium on Intelligent Control, 1999* IEEE Control Systems Society Staff,IEEE Robotics & Automation Society,IEEE Neural Networks Council,1999-09 This volume contains the proceedings of the 1999 IEEE International Symposium on Intelligent Control The wide variety of topics covered include timed discrete event systems learning genetic and fuzzy systems emotions in psychology and neural networks and a panel discussion on autonomy *Holonic and Multi-agent Systems for Manufacturing* ,2003 **Naval Research Logistics** ,1987 *Applications and Science of Neural Networks, Fuzzy Systems, and Evolutionary Computation II* Bruno Bosacchi,David B. Fogel,James C. Bezdek,1999 Neural Computation ,2006 *The Cross-entropy Method for Combinatorial Optimization, Rare Event Simulation and Neural Computation* ,2005

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Table of Contents Neurodynamic Programming

1. Understanding the eBook Neurodynamic Programming
    - The Rise of Digital Reading Neurodynamic Programming
    - Advantages of eBooks Over Traditional Books
2. Identifying Neurodynamic Programming
    - 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 Neurodynamic Programming
    - User-Friendly Interface

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

12. Sourcing Reliable Information of Neurodynamic Programming
    - Fact-Checking eBook Content of Neurodynamic Programming
    - 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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