



Article

Adaptive Control Design and Stability Analysis of Robotic Manipulators

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Abstract: In this paper, the author presents the adaptive control design and stability analysis of robotic manipulators based on two main approaches, i.e., Lyapunov stability theory and hyperstability theory. For the Lyapunov approach, the author presents the adaptive control of a 2-DOF (degrees of freedom) robotic manipulator. Furthermore, the adaptive control technique and Lyapunov theory are subsequently applied to the end-effector motion control and force control, as in most cases, one only considers the motion control (e.g., position control, trajectory tracking). To make the robot interact with humans or the environment, force control must be considered as well to achieve a safe working environment. For the hyperstability approach, a control system is developed through integrating a PID (proportional–integral–derivative) control system and a model reference adaptive control (MRAC) system, and also the convergent behavior and characteristics under the situation of the PID system, model reference adaptive control system, and PID+MRAC control system are compared.

Keywords: adaptive control; stability; Lyapunov; hyperstability; robotic manipulator

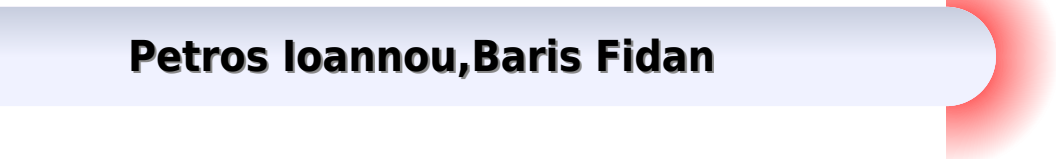
1. Introduction

Robotic mechanisms have been maturely employed in manufacturing industries [1–4]. In current robotic based manufacturing industries (e.g., in manufacturing assembly lines), robots are designed to work independently. In the situation where rapid changes in assembled products is required, traditional assembly robots are not capable to adapt to the rapid changes in assembled products. Robots working with humans is one of the effective solutions to the above situation. To make robots work with human operators, the most important issue is that robots must safely respond to contact forces while performing work. For example, a robot needs to stop or slow down when touched by a human operator, a robot must limit the amount of force it exerts while performing task, and a robot can be pushed out of the way by contact if necessary.

Furthermore, when a robot manipulator end-effector grasps an object to conduct work, it will change the dynamics of the robotic manipulator since the mass and initial properties of the grasped object may be unknown. Under this situation, traditional controls (e.g., PD (proportional–derivative) control) are not sufficient anymore. During the process of robotic mechanisms, the end-effector takes different weights of loads, usually the joint's output fluctuates along with time, and this phenomenon can deteriorate the end-effector's positioning accuracy. Rather, one approach to handle changing conditions is the adaptive control technique. In this paper, the adaptive control design and stability analysis for robotic manipulators based on two main approaches, i.e., Lyapunov stability theory and hyperstability theory, are presented. Regarding the adaptive control design and stability analysis for robotic manipulators based on Lyapunov stability theory, in most cases, one only considers the motion control. When a robot interacts with humans or the environment, force control also must be considered to achieve a safe working environment. For example, large force may damage the objects being manipulated; small force may not achieve the desired goal. The right amount of force is crucial for the human-robot interaction. Subsequently, the adaptive control technique is also applied to the

Adaptive Control Design And Analysis

Petros Ioannou, Baris Fidan



Adaptive Control Design And Analysis:

Adaptive Control Design and Analysis Gang Tao, 2003-07-09 A systematic and unified presentation of the fundamentals of adaptive control theory in both continuous time and discrete time Today adaptive control theory has grown to be a rigorous and mature discipline As the advantages of adaptive systems for developing advanced applications grow apparent adaptive control is becoming more popular in many fields of engineering and science Using a simple balanced and harmonious style this book provides a convenient introduction to the subject and improves one's understanding of adaptive control theory Adaptive Control Design and Analysis features Introduction to systems and control Stability operator norms and signal convergence Adaptive parameter estimation State feedback adaptive control designs Parametrization of state observers for adaptive control Unified continuous and discrete time adaptive control L1 a robustness theory for adaptive systems Direct and indirect adaptive control designs Benchmark comparison study of adaptive control designs Multivariate adaptive control Nonlinear adaptive control Adaptive compensation of actuator nonlinearities End of chapter discussion problems and advanced topics As either a textbook or reference this self contained tutorial of adaptive control design and analysis is ideal for practicing engineers researchers and graduate students alike

Robust and Adaptive Control Eugene Lavretsky, Kevin A. Wise, 2024-02-20 Robust and Adaptive Control second edition shows readers how to produce consistent and accurate controllers that operate in the presence of uncertainties and unforeseen events Driven by aerospace applications the focus of the book is primarily on continuous time dynamical systems The two part text begins with robust and optimal linear control methods and moves on to a self contained presentation of the design and analysis of model reference adaptive control for nonlinear uncertain dynamical systems Features of the second edition include sufficient conditions for closed loop stability under output feedback observer based loop transfer recovery OBLTR with adaptive augmentation OBLTR applications to aerospace systems case studies that demonstrate the benefits of robust and adaptive control for piloted autonomous and experimental aerial platforms realistic examples and simulation data illustrating key features of the methods described and problem solutions for instructors and MATLAB code provided electronically The theory and practical applications address real life aerospace problems being based on numerous transitions of control theoretic results into operational systems and airborne vehicles drawn from the authors extensive professional experience with The Boeing Company The systems covered are challenging often open loop unstable with uncertainties in their dynamics and thus require both persistently reliable control and the ability to track commands either from a pilot or a guidance computer Readers should have a basic understanding of root locus Bode diagrams and Nyquist plots as well as linear algebra ordinary differential equations and the use of state space methods in analysis and modeling of dynamical systems The second edition contains a background summary of linear systems and control systems and an introduction to state observers and output feedback control helping to make it self contained Robust and Adaptive Control teaches senior undergraduate and graduate

students how to construct stable and predictable control algorithms for realistic industrial applications Practicing engineers and academic researchers will also find the book of great instructional value The solutions manual can be accessed by instructors who have adopted this book for their courses at <https://sites.google.com/springernature.com/extramaterial/lecturer-material/> To find the electronic supplementary material go to the publisher's website at <https://link.springer.com/book/10.1007/978-3-031-38314-4> Please go to the Table of contents to the chapter page linked through the title Introduction for ESM related to the chapters in Part I and to the chapter page linked through the title Direct Model Reference Adaptive Control Motivation and Introduction for ESM related to Part II The download link is in the column of links to the right of the page under the book cover thumbnail [New Approaches To Fuzzy Modeling And Control: Design And Analysis](#) Gideon Langholz, Michael Margaliot, 2000-07-04 Fuzzy logic has found applications in an incredibly wide range of areas in the relatively short time since its conception It was invented by Lotfi Zadeh a leading systems expert so it is perhaps not surprising that system theory is one of the areas in which fuzzy logic has made a profound impact Fuzzy logic combined with the paradigm of computing with words allows the use and manipulation of human knowledge and reasoning in the modeling and control of dynamical systems This monograph presents new approaches to the construction of fuzzy models and to the design of fuzzy controllers The emphasis is on developing methods that allow systematic design on the one hand and mathematical analysis of the resulting system on the other In particular the methods described allow rigorous analysis of the stability and robustness of the systems which are crucial issues in control theory The first theme of the book is a new approach to the systematic design and analysis of fuzzy controllers given linguistic information concerning the plant and the control objective The new approach fuzzy Lyapunov synthesis is a computing with words version of the well known classical Lyapunov synthesis method The second theme of the book is to show that fuzzy controllers are in fact solutions of a nonlinear optimal control problem The authors formulate a novel nonlinear optimal control problem consisting of a new state space model referred to as the hyperbolic state space model and a new cost functional and show that its solution is a fuzzy controller This leads to a new framework for fuzzy modeling and control that combines the advantages of the fuzzy world such as linguistic interpretability and of classical optimal control theory such as guaranteed stability and robustness

Nonlinear and Adaptive Control Design Miroslav Krstic, Ioannis Kanellakopoulos, Petar V. Kokotovic, 1995-06-14 Using a pedagogical style along with detailed proofs and illustrative examples this book opens a view to the largely unexplored area of nonlinear systems with uncertainties The focus is on adaptive nonlinear control results introduced with the new recursive design methodology adaptive backstepping Describes basic tools for nonadaptive backstepping design with state and output feedbacks **Model Free Adaptive Control** Zhongsheng Hou, Shangtai Jin, 2013-09-24 Model Free Adaptive Control Theory and Applications summarizes theory and applications of model free adaptive control MFAC MFAC is a novel adaptive control method for the unknown discrete time nonlinear systems with time varying parameters and time varying structure and the

design and analysis of MFAC merely depend on the measured input and output

Design and Analysis of Sampled-data Adaptive Control Systems Stephen M. Phillips, 1988

Principled Controller Design: Theory, Analysis, and Practical Strategies for Robust Feedback Systems William E. Clark, 2025-09-25

Principled Controller Design: Theory, Analysis, and Practical Strategies for Robust Feedback Systems is an authoritative and comprehensive resource that equips engineers, researchers, and students with a rigorous foundation in both the theory and practice of modern control. Beginning with precise system modeling and a unified treatment of stability and performance criteria, the text develops core methodologies: PID tuning, frequency domain analysis, and state space synthesis, while seamlessly connecting classical designs to contemporary innovations. Each chapter emphasizes principled reasoning, guiding readers from mathematical fundamentals to actionable controller architectures. The book offers in-depth coverage of advanced topics essential for modern applications: digital and discrete time controllers, nonlinear and adaptive strategies, and robust techniques for managing model uncertainty. Readers will find clear expositions of Lyapunov-based methods, optimal control, H_∞ synthesis, and the design of networked and distributed systems. Special attention is given to data-driven and learning-augmented approaches, showing how AI and machine learning integrate with control theory to produce cooperative, adaptive, and resilient solutions for complex interconnected systems. Practical deployment is woven throughout the narrative, with hands-on guidance for simulation, rapid prototyping, embedded implementation, certification, and formal verification in safety-critical domains. Hardware considerations, real-world constraints, and industry case studies from aerospace to advanced manufacturing ensure the material remains grounded in engineering practice. By bridging theoretical rigor with pragmatic strategies, this book serves as an indispensable reference for those designing robust feedback systems in today's dynamic technological landscape.

Knowledge-Based Intelligent Information and Engineering Systems Ignac Lovrek, Robert J. Howlett, L. C. Jain, 2008-08-18

Annotation: The three-volume set LNAI 5177, LNAI 5178, and LNAI 5179 constitutes the refereed proceedings of the 12th International Conference on Knowledge-Based Intelligent Information and Engineering Systems (KES 2008) held in Zagreb, Croatia, in September 2008. The 316 revised papers presented were carefully reviewed and selected. The papers present a wealth of original research results from the field of intelligent information processing in the broadest sense. Topics covered in the first volume are artificial neural networks and connectionist systems, fuzzy and neuro-fuzzy systems, evolutionary computation, machine learning, and classical AI agent systems; knowledge-based and expert systems; intelligent vision and image processing; knowledge management; ontologies and data mining; Web intelligence; text and multimedia mining and retrieval; and intelligent robotics and control.

Adaptive Control Design with Guaranteed Margins for Nonlinear Plants Jinho Jang (S. M.), Massachusetts Institute of Technology, Department of Mechanical Engineering, 2009

Adaptive control is one of the technologies that improve both performance and safety as controller parameters can be redesigned autonomously in the presence of uncertainties. Considerable research has been accomplished in adaptive control theory for

several decades and a solid foundation has been laid out for stability and robustness of adaptive systems. However, a large gap between theory and practice has been an obstacle to transition theoretical results into applications and it still remains. In order to reduce the gap, this thesis presents a unified framework for design and analysis of adaptive control for general nonlinear plants. An augmented adaptive control architecture is proposed where a nominal controller is designed in the inner loop with an adaptive controller in the outer loop. The architecture is completed by addressing three separate problems. The first problem is the design of adaptive control in the presence of input constraints. With a rigorous stability analysis, an algorithm is developed to remove the adverse effects of multi input magnitude saturation. The second problem is the augmentation of adaptive control with a nominal gain scheduling controller. Though adaptive controllers have been employed with gain scheduling to various applications, no formal stability analysis has been developed. In the proposed architecture, adaptive control is combined with gain scheduling in a specific manner while stability is guaranteed. The third problem is the development of analytic stability margins of the closed loop plant with the proposed adaptive controller. A time delay margin is derived using standard Lyapunov stability analysis as an analytic stability margin. The overall adaptive control architecture, as well as the analytically derived margins, are validated by a 6 DoF nonlinear flight dynamics based on the NASA X-15 hypersonic aircraft. Simulation results show that the augmented adaptive control is able to stabilize the plant and tracks desired trajectories with uncertainties in the plant, while instability cannot be overcome only with the nominal controller. The time delay margins are validated based on a generic transport model and they are compared with margins obtained from simulations. We utilize numerical methods to find less conservative time delay margins.

AsiaSim 2012 Tianyuan Xiao, Lin Zhang, Minrui Fei, 2012-10-08. The Three Volume Set CCIS 323 324 325 *AsiaSim 2012* together with the Two Volume Set CCIS 326 327 *ICSC 2012* constitutes the refereed proceedings of the Asia Simulation Conference *AsiaSim 2012* and the International Conference on System Simulation *ICSC 2012* held in Shanghai, China, in October 2012. The 267 revised full papers presented were carefully reviewed and selected from 906 submissions. The papers are organized in topical sections on modeling theory and technology, modeling and simulation technology on synthesized environment and virtual reality environment, pervasive computing and simulation technology, embedded computing and simulation technology, verification, validation, and accreditation technology, networked modeling and simulation technology, modeling and simulation technology of continuous system, discrete system, hybrid system, and intelligent system, high performance computing and simulation technology, cloud simulation technology, modeling and simulation technology of complex system and open complex huge system, simulation based acquisition and virtual prototyping, engineering technology, simulator, simulation language and intelligent simulation system, parallel and distributed software, CAD, CAE, CAM, CIMS, VP, VM, and VR, visualization, computing and simulation applications in science and engineering, computing and simulation applications in management, society and economics, computing and simulation applications in life and biomedical engineering, computing and simulation applications

in energy and environment computing and simulation applications in education computing and simulation applications in military field computing and simulation applications in medical field *Cooperative Control Design* He Bai,Murat Arcak,John Wen,2011-06-03 Cooperative Control Design A Systematic Passivity Based Approach discusses multi agent coordination problems including formation control attitude coordination and synchronization The goal of the book is to introduce passivity as a design tool for multi agent systems to provide exemplary work using this tool and to illustrate its advantages in designing robust cooperative control algorithms The discussion begins with an introduction to passivity and demonstrates how passivity can be used as a design tool for motion coordination Followed by the case of adaptive redesigns for reference velocity recovery while describing a basic design a modified design and the parameter convergence problem Formation control is presented as it relates to relative distance control and relative position control The coverage is concluded with a comprehensive discussion of agreement and the synchronization problem with an example using attitude coordination **Modern Fuzzy Control Systems and Its Applications** S. Ramakrishnan,2017-08-30 Control systems play an important role in engineering Fuzzy logic is the natural choice for designing control applications and is the most popular and appropriate for the control of home and industrial appliances Academic and industrial experts are constantly researching and proposing innovative and effective fuzzy control systems This book is an edited volume and has 21 innovative chapters arranged into five sections covering applications of fuzzy control systems in energy and power systems navigation systems imaging and industrial engineering Overall this book provides a rich set of modern fuzzy control systems and their applications and will be a useful resource for the graduate students researchers and practicing engineers in the field of electrical engineering **Intelligent Control Design and MATLAB Simulation** Jinkun Liu,2017-09-20 This book offers a comprehensive introduction to intelligent control system design using MATLAB simulation to verify typical intelligent controller designs It also uses real world case studies that present the results of intelligent controller implementations to illustrate the successful application of the theory Addressing the need for systematic design approaches to intelligent control system design using neural network and fuzzy based techniques the book introduces the concrete design method and MATLAB simulation of intelligent control strategies offers a catalog of implementable intelligent control design methods for engineering applications provides advanced intelligent controller design methods and their stability analysis methods and presents a sample simulation and Matlab program for each intelligent control algorithm The main topics addressed are expert control fuzzy logic control adaptive fuzzy control neural network control adaptive neural control and intelligent optimization algorithms providing several engineering application examples for each method **Proceedings of the 2015 Chinese Intelligent Automation Conference** Zhidong Deng,Hongbo Li,2015-04-20 Proceedings of the 2015 Chinese Intelligent Automation Conference presents selected research papers from the CIAC 15 held in Fuzhou China The topics include adaptive control fuzzy control neural network based control knowledge based control hybrid intelligent control

learning control evolutionary mechanism based control multi sensor integration failure diagnosis reconfigurable control etc Engineers and researchers from academia industry and the government can gain valuable insights into interdisciplinary solutions in the field of intelligent automation

Fractional Modeling and Controller Design of Robotic Manipulators

Abhaya Pal Singh, Dipankar Deb, Himanshu Agrawal, Valentina E. Balas, 2020-10-15 This book at hand is an appropriate addition to the field of fractional calculus applied to control systems If an engineer or a researcher wishes to delve into fractional order systems then this book has many collections of such systems to work upon and this book also tells the reader about how one can convert an integer order system into an appropriate fractional order one through an efficient and simple algorithm If the reader further wants to explore the controller design for the fractional order systems then for them this book provides a variety of controller design strategies The use of fractional order derivatives and integrals in control theory leads to better results than integer order approaches and hence provides solid motivation for further development of control theory Fractional order models are more useful than the integer order models when accuracy is of paramount importance Real time experimental validation of controller design strategies for the fractional order plants is available This book is beneficial to the academic institutes for postgraduate and advanced research level that need a specific textbook on fractional control and its applications in robotic manipulators The book is also a valuable teaching and learning resource for undergraduate and postgraduate students

Nonrecursive Control Design for Nonlinear Systems

Chuanlin Zhang, Jun Yang, 2023-06-20 Based on the authors recent advances this book focuses on a class of nonlinear systems with mismatched uncertainties disturbances and discusses their typical control problems It aims to provide a comprehensive view of the nonrecursive control theory and application guidelines Various applications on the nonrecursive synthesis of complex nonlinear systems not only greatly simplify the control design process weaken the system assumptions and reduce the conservatism of gain selection but also realize the essential detachment of control law design and Lyapunov function based stability analysis Therefore different from the classical recursive control design methods it is of significance to study the synthesis of nonlinear systems from the perspective of a new nonrecursive control framework This book discusses the following typical control problems theoretical background homogeneous systems theory review nonrecursive robust control design nonrecursive adaptive control design nonrecursive general dynamic predictive control disturbance estimation and attenuation nonrecursive stability analysis implementation theory and real life applications to series elastic actuators DC microgrids and permanent magnet synchronous motor PMSM systems under the proposed nonrecursive synthesis framework This book will be a great reference for scholars and students in the field of automation and control It will also be a useful source for control engineers and those working on anti disturbance control nonlinear output regulation nonsmooth control and other related topics

Adaptive Control Tutorial

Petros Ioannou, Baris Fidan, 2006-01-01 Designed to meet the needs of a wide audience without sacrificing mathematical depth and rigor Adaptive Control Tutorial presents the design analysis and application of a

wide variety of algorithms that can be used to manage dynamical systems with unknown parameters Its tutorial style presentation of the fundamental techniques and algorithms in adaptive control make it suitable as a textbook Adaptive Control Tutorial is designed to serve the needs of three distinct groups of readers engineers and students interested in learning how to design simulate and implement parameter estimators and adaptive control schemes without having to fully understand the analytical and technical proofs graduate students who in addition to attaining the aforementioned objectives also want to understand the analysis of simple schemes and get an idea of the steps involved in more complex proofs and advanced students and researchers who want to study and understand the details of long and technical proofs with an eye toward pursuing research in adaptive control or related topics The authors achieve these multiple objectives by enriching the book with examples demonstrating the design procedures and basic analysis steps and by detailing their proofs in both an appendix and electronically available supplementary material online examples are also available A solution manual for instructors can be obtained by contacting SIAM or the authors Preface Acknowledgements List of Acronyms Chapter 1 Introduction Chapter 2 Parametric Models Chapter 3 Parameter Identification Continuous Time Chapter 4 Parameter Identification Discrete Time Chapter 5 Continuous Time Model Reference Adaptive Control Chapter 6 Continuous Time Adaptive Pole Placement Control Chapter 7 Adaptive Control for Discrete Time Systems Chapter 8 Adaptive Control of Nonlinear Systems Appendix Bibliography Index

Analytical Design of PID Controllers Iván D. Díaz-Rodríguez, Sangjin Han, Shankar P. Bhattacharyya, 2019-05-21 This monograph presents a new analytical approach to the design of proportional integral derivative PID controllers for linear time invariant plants The authors develop a computer aided procedure to synthesize PID controllers that satisfy multiple design specifications A geometric approach which can be used to determine such designs methodically using 2 and 3 D computer graphics is the result The text expands on the computation of the complete stabilizing set previously developed by the authors and presented here This set is then systematically exploited to achieve multiple design specifications simultaneously These specifications include classical gain and phase margins time delay tolerance settling time and H infinity norm bounds The results are developed for continuous and discrete time systems An extension to multivariable systems is also included Analytical Design of PID Controllers provides a novel method of designing PID controllers which makes it ideal for both researchers and professionals working in traditional industries as well as those connected with unmanned aerial vehicles driverless cars and autonomous robots

Fuzzy Controller Design Zdenko Kovacic, Stjepan Bogdan, 2018-10-08 Fuzzy control methods are critical for meeting the demands of complex nonlinear systems They bestow robust adaptive and self correcting character to complex systems that demand high stability and functionality beyond the capabilities of traditional methods A thorough treatise on the theory of fuzzy logic control is out of place on the design bench That is why Fuzzy Controller Design Theory and Applications offers laboratory and industry tested algorithms techniques and formulations of real world problems for immediate implementation With surgical precision

the authors carefully select the fundamental elements of fuzzy logic control theory necessary to formulate effective and efficient designs The book supplies a springboard of knowledge punctuated with examples worked out in MATLAB SIMULINK from which newcomers to the field can dive directly into applications It systematically covers the design of hybrid adaptive and self learning fuzzy control structures along with strategies for fuzzy controller design suitable for on line and off line operation Examples occupy an entire chapter with a section devoted to the simulation of an electro hydraulic servo system The final chapter explores industrial applications with emphasis on techniques for fuzzy controller implementation and different implementation platforms for various applications With proven methods based on more than a decade of experience Fuzzy Controller Design Theory and Applications is a concise guide to the methodology design steps and formulations for effective control solutions

Control of Nonlinear Systems Yongduan Song, Kai Zhao, Hefu Ye, 2024-08-14

The book Control of Nonlinear Systems Stability and Performance fills a crucial gap in the field of nonlinear control systems by providing a comprehensive yet accessible treatment of the subject Unlike many existing texts that are either too complex for beginners or omit essential topics this book strikes the right balance of mathematical rigor and practicality The main objective of the book is to simplify and unify the existing techniques for designing and analyzing control systems for nonlinear systems It aims to alleviate confusion and difficulty in understanding these methods making it an invaluable resource for students researchers and practitioners in the field By presenting the material in a tutorial manner the book enhances the reader s understanding of the design and analysis of a wide range of control methods for nonlinear systems The emphasis on stability and performance highlights the practical relevance of the concepts discussed in the book Overall Control of Nonlinear Systems Stability and Performance is a valuable contribution to the field of nonlinear control systems Its emphasis on practical applications and its accessible presentation make it an indispensable resource for engineers seeking to enhance their knowledge and skills in this important area of control theory

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Adaptive Control Design And Analysis Introduction

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