

# Nonlinear stabilizing control for a class of underactuated mechanical systems with multi degree of freedoms

Ancai Zhang · Xuzhi Lai · Min Wu · Jinhua She

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**Abstract** An underactuated mechanical system with  $n$  ( $n \geq 3$ ) degree of freedoms (DOFs) is a complicated nonlinear system. This paper develops a new strategy to solve the nonlinear stabilizing control problem for this kind of mechanical systems. First, we introduce a coupled relationship between control torques. It changes the  $n$ -DOF underactuated system into a cascade-connected system, which has a 2-DOF driven subsystem and a  $(n-2)$ -DOF stable driving subsystem. And then, we analyze the passivity of the driven subsystem and discuss how to design an passivity-based

controller that stabilizes the driven subsystem at the origin. Finally, the stabilization of the  $n$ -DOF underactuated system is achieved by the triangle lemma. Our proposed strategy transforms the stabilization of the  $n$ -DOF underactuated system into that of the 2-DOF driven subsystem. This makes the structure of the control system simple and also makes the problem of stabilizing a multi-DOF underactuated system easy to handle. As an application of the strategy, we give detailed statements of using it to achieve the global stabilization of a 3-DOF underactuated mechanical system called spring-coupled horizontal three-link underactuated manipulator. Simulation results demonstrate its validity.

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**Keywords** Nonlinear control · Underactuated mechanical system · Torque-coupled relationship · Passivity · Cascade-connected system

## 1 Introduction

An underactuated mechanical system (UMS) has more degree of freedoms (DOFs) than installed actuators. One or more DOFs of this type systems are unactuated. This makes a UMS lighter, less energy-consuming and more flexible than a fully actuated one. However, the existence of unactuated DOFs simultaneously makes such systems possess second-order non-holonomic constraints [1], also makes them not full-state feedback linearizable [2] and not even small-time

# Nonlinear Control For Underactuated Mechanical Systems

**Alexander M. Formalskii**



## **Nonlinear Control For Underactuated Mechanical Systems:**

Non-linear Control for Underactuated Mechanical Systems Isabelle Fantoni, Rogelio Lozano, 2002 This book deals with the application of modern control theory to some important underactuated mechanical systems It presents modelling and control of the following systems the inverted pendulum a convey crane system the pendubot system the Furuta pendulum the inertia wheel pendulum the planar flexible joint robot the planar manipulator with two prismatic and one revolute joints the ball the hovercraft model the planar vertical and take off landing PVTOL aircraft the helicopter model on a platform the helicopter model In every case the model is obtained in detail using either the Euler Lagrange formulation or the Newton s second law The text develops control algorithms for every particular system using techniques such as passivity energy based Lyapunov functions forwarding backstepping or feedback linearization techniques This book is designed for PhD students and researchers in the areas of non linear control systems mechanical systems robotics and control of helicopters It will help the reader gain experience in the modelling of mechanical systems and familiarize with new control methods for non linear systems

**Nonlinear Control of Underactuated Mechanical Systems with Application to Robotics and Aerospace Vehicles** Reza Olfati-Saber, 2001

Non-linear Control for Underactuated Mechanical Systems Isabelle Fantoni, Rogelio Lozano, 2012-12-06 This book deals with the application of modern control theory to some important underactuated mechanical systems from the inverted pendulum to the helicopter model It will help readers gain experience in the modelling of mechanical systems and familiarize with new control methods for non linear systems

Control of Underactuated Mechanical Systems Afef Hfaiedh, Ahmed Chemori, 2025-04-01 Control of Underactuated Mechanical Systems Stabilization and Limit Cycle Generation clearly explains stabilization and limit cycle generation in underactuated mechanical systems UMS addressing control design challenges and demonstrating concepts through real time experiments The book begins with advancements in UMS introducing key concepts such as stabilization and limit cycle generation supported by literature examples It then focuses on the inertia wheel inverted pendulum presenting a detailed discussion The second part tackles stabilization offering various control solutions validated through numerical simulations and real time experiments The final part addresses stable limit cycle generation detailing three proposed control solutions and their validation through different case studies This book is a valuable resource for PhD and Master students engineers researchers and educators It provides guidance in robotics and automatic control utilizing a simplified methodology for controlling underactuated mechanical systems Addresses stabilization and stable limit cycle generation in underactuated mechanical systems amid perturbations Explores the design development and validation of robust control solutions Illustrates concepts through case studies Validates control solutions with numerical simulations and real time experiments

**Analysis and Control of Underactuated Mechanical Systems** Amal Choukchou-Braham, Brahim Cherki, Mohamed Djemaï, Krishna Busawon, 2013-11-18 This monograph provides readers with tools for the analysis and control of systems with fewer control

inputs than degrees of freedom to be controlled i.e. underactuated systems. The text deals with the consequences of a lack of a general theory that would allow methodical treatment of such systems and the ad hoc approach to control design that often results in imposing a level of organization whenever the latter is lacking. The authors take as their starting point the construction of a graphical characterization or control flow diagram reflecting the transmission of generalized forces through the degrees of freedom. Underactuated systems are classified according to the three main structures by which this is found to happen: chain, tree, and isolated vertex, and control design procedures are proposed. The procedure is applied to several well-known examples of underactuated systems: acrobot, pendubot, Tora system, ball and beam, inertia wheel, and robotic arm with elastic joint. The text is illustrated with MATLAB/Simulink simulations that demonstrate the effectiveness of the methods detailed. Readers interested in aircraft vehicle control or various forms of walking robot will be able to learn from it.

**Underactuated Mechanical Systems**      **Motion Control of Underactuated Mechanical Systems** Javier

Moreno-Valenzuela, Carlos Aguilar-Avelar, 2017-07-11 This volume is the first to present a unified perspective on the control of underactuated mechanical systems. Based on real-time implementation of parameter identification, this book provides a variety of algorithms for the Furuta pendulum and the inertia wheel pendulum, which are two degrees of freedom mechanical systems. Specifically, this work addresses and solves the problem of motion control via trajectory tracking in one joint coordinate while another joint is regulated. Besides discussions on extensions to higher degrees of freedom systems, are given. The book aimed at control engineers as well as graduate students ranges from the problem of parameter identification of the studied systems to the practical implementation of sophisticated motion control algorithms. Offering real-world solutions to manage the control of underactuated systems, this book provides a concise tutorial on recent breakthroughs in the field: original procedures to achieve bounding of the error trajectories, convergence, and gain tuning guidelines.

*Nonlinear Control Systems* Alberto Isidori, 2013-04-17 The purpose of this book is to present a self-contained description of the fundamentals of the theory of nonlinear control systems with special emphasis on the differential geometric approach. The book is intended as a graduate text as well as a reference to scientists and engineers involved in the analysis and design of feedback systems. The first version of this book was written in 1983 while I was teaching at the Department of Systems Science and Mathematics at Washington University in St. Louis. This new edition integrates my subsequent teaching experience gained at the University of Illinois in Urbana-Champaign in 1987, at the Carl Cranz Gesellschaft in Oberpfaffenhofen in 1987, at the University of California in Berkeley in 1988. In addition to a major rearrangement of the last two chapters of the first version, this new edition incorporates two additional chapters at a more elementary level and an exposition of some relevant research findings which have occurred since 1985.

Advances and Applications in Nonlinear Control Systems Sundarapandian Vaidyanathan, Christos Volos, 2016-03-17 The book reports on the latest advances and applications of nonlinear control systems. It consists of 30 contributed chapters by subject experts who are specialized in the

various topics addressed in this book The special chapters have been brought out in the broad areas of nonlinear control systems such as robotics nonlinear circuits power systems memristors underwater vehicles chemical processes observer design output regulation backstepping control sliding mode control time delayed control variables structure control robust adaptive control fuzzy logic control chaos hyperchaos jerk systems hyperjerk systems chaos control chaos synchronization etc Special importance was given to chapters offering practical solutions modeling and novel control methods for the recent research problems in nonlinear control systems This book will serve as a reference book for graduate students and researchers with a basic knowledge of electrical and control systems engineering The resulting design procedures on the nonlinear control systems are emphasized using MATLAB software      *Algebraic Methods for Nonlinear Control Systems* Giuseppe Conte, Claude H. Moog, Anna Maria Perdon, 2007-01-19 A self contained introduction to algebraic control for nonlinear systems suitable for researchers and graduate students Algebraic Methods for Nonlinear Control Systems develops a linear algebraic alternative to the usual differential geometric approach to nonlinear control using vector spaces over suitable fields of nonlinear functions It describes a range of results some of which can be derived using differential geometry but many of which cannot They include classical and generalized realization in the nonlinear context accessibility and observability recast for the linear algebraic setting discussion and solution of basic feedback problems results for dynamic and static state and output feedback Dynamic feedback and realization are shown to be dealt with and solved much more easily in the algebraic framework The second edition has been completely revised with new text examples and exercises it is divided into two parts necessary methodology and applications to control problems      **Control of Underactuated Manipulators** Jundong Wu, Pan Zhang, Qingxin Meng, Yawu Wang, 2023-05-13 This book investigates in detail cutting edge technologies of underactuated manipulator control which is a frontier topic in robotics that possesses great significance in energy conservation as well as fault tolerance for industrial applications It is also the crucial technology associated with systems in special environments including underwater or aerospace environments So far the topic of underactuated manipulator control has attracted engineers and scientists from various disciplines such as applied physics material automation and robotics Pursuing a holistic approach the book establishes a fundamental framework for this topic while emphasizing the importance of design and optimization in the control of underactuated manipulators Chapters of the book cover a wide variety of manipulator systems including vertical underactuated manipulator planar underactuated manipulator with first order nonholonomic constraint planar underactuated manipulator with second order nonholonomic constraint and flexible underactuated manipulator The book is intended for undergraduate and graduate students that are interested in underactuated manipulators researchers that investigate the design and optimization for controllers of underactuated manipulators and engineers working with underactuated systems      *Block Backstepping Design of Nonlinear State Feedback Control Law for Underactuated Mechanical Systems* Shubhobrata Rudra, Ranjit Kumar Barai, Madhubanti

Maitra,2016-09-08 This book presents a novel generalized approach to the design of nonlinear state feedback control laws for a large class of underactuated mechanical systems based on application of the block backstepping method The control law proposed here is robust against the effects of model uncertainty in dynamic and steady state performance and addresses the issue of asymptotic stabilization for the class of underactuated mechanical systems An underactuated system is defined as one for which the dimension of space spanned by the configuration vector is greater than that of the space spanned by the control variables Control problems concerning underactuated systems currently represent an active field of research due to their broad range of applications in robotics aerospace and marine contexts The book derives a generalized theory of block backstepping control design for underactuated mechanical systems and examines several case studies that cover interesting examples of underactuated mechanical systems The mathematical derivations are described using well known notations and simple algebra without the need for any special previous background in higher mathematics The chapters are lucidly described in a systematic manner starting with control system preliminaries and moving on to a generalized description of the block backstepping method before turning to several case studies Simulation and experimental results are also provided to aid in reader comprehension

#### **Adaptive and Fault-Tolerant Control of Underactuated Nonlinear Systems**

Jiangshuai Huang,Yong-Duan Song,2017-12-22 The purpose of the book is to provide an exposition of recently developed adaptive and fault tolerant control of underactuated nonlinear systems Underactuated systems are abundant in real life ranging from landing vehicles to surface ships and underwater vehicles to spacecrafts For the tracking and stabilization control of underactuated mechanical systems many methodologies have been proposed However a number of important issues deserve further investigation In response to these issues four important problems are solved in this book including control of underactuated nonlinear systems with input saturation output feedback control in the presence of parametric uncertainties fault tolerant control of underactuated ships with or without actuator redundancy and adaptive control of multiple underactuated nonlinear systems including formation control and flocking control of multiple underactuated systems

*Control Design and Analysis for Underactuated Robotic Systems* Xin Xin,Yannian Liu,2014-01-03 The last two decades have witnessed considerable progress in the study of underactuated robotic systems URSs Control Design and Analysis for Underactuated Robotic Systems presents a unified treatment of control design and analysis for a class of URSs which include systems with multiple degree of freedom and or with underactuation degree two It presents novel notions features design techniques and strictly global motion analysis results for these systems These new materials are shown to be vital in studying the control design and stability analysis of URSs Control Design and Analysis for Underactuated Robotic Systems includes the modelling control design and analysis presented in a systematic way particularly for the following examples 1 directly and remotely driven Acrobots 1 Pendubot 1 rotational pendulum 1 counter weighted Acrobot 2 link underactuated robot with flexible elbow joint 1 variable length pendulum 1 3 link gymnastic robot with passive first joint 1 n link planar robot with

passive first joint 1 n link planar robot with passive single joint double or two parallel pendulums on a cart 1 3 link planar robots with underactuation degree two 2 link free flying robot The theoretical developments are validated by experimental results for the remotely driven Acrobot and the rotational pendulum Control Design and Analysis for Underactuated Robotic Systems is intended for advanced undergraduate and graduate students and researchers in the area of control systems mechanical and robotics systems nonlinear systems and oscillation This text will not only enable the reader to gain a better understanding of the power and fundamental limitations of linear and nonlinear control theory for the control design and analysis for these URSs but also inspire the reader to address the challenges of more complex URSs **Nonlinear and**

**Adaptive Control** Alessandro Astolfi, 2006 This book summarizes the main results achieved in a four year European Project on nonlinear and adaptive control The project involves leading researchers from top notch institutions Imperial College London Prof A Astolfi Lund University Prof A Rantzer Supélec Paris Prof R Ortega University of Technology of Compiègne Prof R Lozano Grenoble Polytechnic Prof C Canudas de Wit University of Twente Prof A van der Schaft Politecnico di Milano Prof S Bittanti and Polytechnic University of Valencia Prof P Albertos The book also provides an introduction to theoretical advances in nonlinear and adaptive control and an overview of novel applications of advanced control theory particularly topics on the control of partially known systems under actuated systems and bioreactors Control of Nonlinear Dynamical Systems Felix L. Chernous'ko, I. M. Ananievski, S. A. Reshmin, 2008-09-26 This book is devoted to new methods of control for complex dynamical systems and deals with nonlinear control systems having several degrees of freedom subjected to unknown disturbances and containing uncertain parameters Various constraints are imposed on control inputs and state variables or their combinations The book contains an introduction to the theory of optimal control and the theory of stability of motion and also a description of some known methods based on these theories Major attention is given to new methods of control developed by the authors over the last 15 years Mechanical and electromechanical systems described by nonlinear Lagrange's equations are considered General methods are proposed for an effective construction of the required control often in an explicit form The book contains various techniques including the decomposition of nonlinear control systems with many degrees of freedom piecewise linear feedback control based on Lyapunov's functions methods which elaborate and extend the approaches of the conventional control theory optimal control differential games and the theory of stability The distinctive feature of the methods developed in the book is that the controls obtained satisfy the imposed constraints and steer the dynamical system to a prescribed terminal state in finite time Explicit upper estimates for the time of the process are given In all cases the control algorithms and the estimates obtained are strictly proven **Passivity-based Control of**

**Euler-Lagrange Systems** Romeo Ortega, Julio Antonio Loria Perez, Per Johan Nicklasson, Hebertt Sira-Ramirez, 1998-09-16 The essence of this work is the control of electromechanical systems such as manipulators electric machines and power converters The common thread that links together the results presented here is the passivity property which is at present in

numerous electrical and mechanical systems and which has great relevance in control engineering at this time Amongst other topics the authors cover Euler Lagrange Systems Mechanical Systems Generalised AC Motors Induction Motor Control Robots with AC Drives and Perspectives and Open Problems The authors have extensive experience of research and application in the field of control of electromechanical systems which they have summarised here in this self contained volume While written in a strictly mathematical way it is also elementary and will be accessible to a wide ranging audience including graduate students as well as practitioners and researchers in this field

**Advances in the Theory of Control, Signals and Systems with Physical Modeling** Jean Levine, Philippe Müllhaupt, 2010-09-30 In the 60 s control signals and systems had a common linear algebraic background and according to their evolution their respective backgrounds have now dramatically differed Recovering such a common background especially in the nonlinear context is currently a fully open question The role played by physical models finite or infinite dimensional in this hypothetical convergence is extensively discussed in this book The discussion does not only take place on a theoretical basis but also in the light of two wide classes of applications among the most active in the current industrially oriented researches Electrical and Mechatronical systems Chemical Processes and systems appearing in Life Sciences In this perspective this book is a contribution to the enhancement of the dialogue between theoretical laboratories and more practically oriented ones and industries This book is a collection of articles that have been presented by leading international experts at a series of three workshops of a Bernoulli program entitled Advances in the Theory of Control Signals and Systems with Physical Modeling hosted by the Bernoulli Centre of EPFL during the first semester of 2009 It provides researchers engineers and graduate students with an unprecedented collection of topics and internationally acknowledged top quality works and surveys

Discontinuous Systems Yury V. Orlov, 2008-10-28 Discontinuous Systems develops nonsmooth stability analysis and discontinuous control synthesis based on novel modeling of discontinuous dynamic systems operating under uncertain conditions While being primarily a research monograph devoted to the theory of discontinuous dynamic systems no background in discontinuous systems is required such systems are introduced in the book at the appropriate conceptual level Being developed for discontinuous systems the theory is successfully applied to their subclasses variable structure and impulsive systems as well as to finite and infinite dimensional systems such as distributed parameter and time delay systems The presentation concentrates on algorithms rather than on technical implementation although theoretical results are illustrated by electromechanical applications These specific applications complete the book and together with the introductory theoretical constituents bring some elements of the tutorial to the text

**Stabilisation and Motion Control of Unstable Objects** Alexander M. Formal'skii, 2015-11-13 Systems with mechanical degrees of freedom containing unstable objects are analysed in this monograph and algorithms for their control are developed discussed and numerically tested This is achieved by identifying unstable modes of motion and using all available resources to suppress them By using this approach the region of



states from which a stable regime can be reached is maximised The systems discussed in this book are models for pendula and vehicles and find applications in mechatronics robotics as well as in mechanical and automotive engineering

**Stability Theory of Switched Dynamical Systems** Zhendong Sun, Shuzhi Sam Ge, 2011-01-06 There are plenty of challenging and interesting problems open for investigation in the field of switched systems Stability issues help to generate many complex nonlinear dynamic behaviors within switched systems The authors present a thorough investigation of stability effects on three broad classes of switching mechanism arbitrary switching where stability represents robustness to unpredictable and undesirable perturbation constrained switching including random within a known stochastic distribution dwell time with a known minimum duration for each subsystem and autonomously generated with a pre assigned mechanism switching and designed switching in which a measurable and freely assigned switching mechanism contributes to stability by acting as a control input For each of these classes this book propounds detailed stability analysis and or design related robustness and performance issues connections to other control problems and many motivating and illustrative examples

## **Nonlinear Control For Underactuated Mechanical Systems** Book Review: Unveiling the Magic of Language

In an electronic era where connections and knowledge reign supreme, the enchanting power of language has become much more apparent than ever. Its power to stir emotions, provoke thought, and instigate transformation is actually remarkable. This extraordinary book, aptly titled "**Nonlinear Control For Underactuated Mechanical Systems**," written by a highly acclaimed author, immerses readers in a captivating exploration of the significance of language and its profound effect on our existence. Throughout this critique, we will delve into the book's central themes, evaluate its unique writing style, and assess its overall influence on its readership.

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