

# Contact Transition Control of Nonlinear Mechanical Systems Subject to a Unilateral Constraint

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*In this paper, contact transition control of mechanical systems subject to a unilateral constraint is presented. A systematic way is proposed for designing control laws for unilaterally constrained mechanical systems. Three phases of motion (inactive, transition, active) are formulated depending on the activation/deactivation of the constraint. Our framework describes the complete behaviour of the mechanical system under the action of a unilateral constraint. We propose stable control laws for all the phases of the system. Exponential stability in each phase is shown. Of special interest is the contact transition problem. During this phase the dynamics is discontinuous. Nonsmooth Lyapunov techniques are used to show exponential stability in the transition phase. Composite Lyapunov functions are constructed for each phase and these are used to show asymptotic stability of the overall system taking into consideration switching from one phase to another. The proposed method is successfully implemented on robots interacting with an environment, and we present results of those experiments. Experimental results confirm the theoretically predicted behavior.*

## 1 Introduction

In most constrained mechanical systems, the nature of the constraint is best described by its unilateral behavior. The constraint, almost always, divides the workspace of a mechanical system into three regions. A region where the constraints are strictly satisfied and the mechanical system behaves freely, a region defining the boundary of the constraint, and a region representing the violation of the constraint. Of special significance is the transition from the free space to the boundary of the constraint set. Stability of the transition phase is essential for all applications. For example, surface following of a robot can be represented by a set of differential equations subject to a unilateral constraint. The surface represents a natural unilateral constraint for the robot, and typically divides the workspace into three regions. A typical motion for surface following is that the robot moves in free space, makes contact with the boundary of the surface, follows the surface for a prescribed time and leaves the surface. Unilateral nature of the constraint is clearly depicted in this example.

Many applications in industry involve mechanical systems interacting with the environment. Examples of such systems can be found in manufacturing automation, material handling by robots and space applications. An important task is to model the complete behavior so that the system and constraint are presented in a natural way. The formulation given in this paper systematically describes the complete behavior of mechanical systems interacting with an environment. Considerable research has been done in control of robots in constrained motion; see [36] and references therein. Much of this research has been based on the assumption that the robot is already in contact with the external environment. In many industrial applications the mechanical system is in free motion before constrained motion starts. It is known in literature that switching from constrained motion to free motion poses no problem when com-

pared to switching from free motion to constrained motion. Due to nonzero impact velocity, the transition from free motion to constrained motion leads to impulsive forces on the system.

In literature, several controllers have been designed to deal with contact transitions. In [10] and [13], environment is treated as a mechanical impedance and impedance control is used in contact transition experiments. A dimensionless representation of impact behavior was developed in [39] and integral force feedback is used to improve transient impact response. Stability and control of task transition for robots has been considered in [22] for a compliant environment, wherein the transitions are assumed to take place smoothly. Impact minimization by using redundant degrees of freedom in the robots has been considered in [35]. Force regulation and contact transition control are considered in [32]. A discontinuous control approach to general task execution of manipulators interacting with a compliant environment has been considered in [21]. Nonsmooth impact mechanics are described in detail in the monograph [4]. Recent results in the area of impact dynamical systems and dynamics and control of these systems have been expounded. Measure differential equations were used to describe impact mechanical systems, and right-continuous solutions of local bounded variations are introduced in the setting of impacting mechanical systems. The monograph [18] contains existential results for solutions of mechanical systems subject to unilateral constraints.

In this paper, we formulate a systematic way to describe the behavior of mechanical systems subject to a unilateral constraint. Some preliminary results of this problem using the Hamiltonian framework were given in [26]. Three phases, namely inactive, transition, and active, are formulated. Of special interest is the contact transition problem. Due to nonzero velocity of impact, the mechanical system exhibits a bouncing behavior during the transition phase. Hence the differential equations that describe this phase are discontinuous. Differential equations describing the dynamics in each phase are given. An impact model is chosen to describe the impact behavior. Several impact models exist in the literature; see [30, 14, 1, 2, 12, 19, 15]. Different researchers favor different models depending on the applications under consideration. Typically there are three dis-

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**Puja Mehta**

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## **Table of Contents Control Of Nonlinear Mechanical Systems**

1. Understanding the eBook Control Of Nonlinear Mechanical Systems
  - The Rise of Digital Reading Control Of Nonlinear Mechanical Systems
  - Advantages of eBooks Over Traditional Books
2. Identifying Control Of Nonlinear Mechanical Systems
  - 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 Control Of Nonlinear Mechanical Systems
  - User-Friendly Interface
4. Exploring eBook Recommendations from Control Of Nonlinear Mechanical Systems

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

- Fact-Checking eBook Content of Control Of Nonlinear Mechanical Systems
  - 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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