1 Introduction and Overview

1.1 Motivation and Background

Robots are already widely used in manufacturing, where they assemble products, handle machining operations, transfer parts on factory floors or package orders for shipping. Robots are now being assigned to assist humans in a much broader range of tasks, such as medical procedures, elderly care, agricultural work, disaster response, remediation of toxic waste and, somewhat unfortunately, battlefield operations. In all of these current and future applications, robots must *grasp and manipulate* objects in their environment in order to realize their assigned task goals. These robotic operations rely upon the use of *multi-finger robot hands* to securely grasp the task-related objects and realize the task goals.

This book is devoted to the kinematics and mechanics principles that govern the behavior of multi-finger robot hands. Robot hands typically make multiple contacts with physical objects during grasping and manipulation tasks. However, the principles described in this book are relevant to a much wider range of robotic applications. To see the common issues in these seemingly different applications, let us briefly describe each one of these areas.

Multi-finger robot grasping: Figure 1.1 shows an example of a multi-finger robot hand that can grasp and manipulate a wide variety of objects. This hand was designed by Salisbury at Stanford University in the 1980s. As seen in Figure 1.1, a *grasp* is used to fix the object position securely within the robot hand, which itself is typically attached to a robot arm. Properly designed robot hands can implement a wide variety of grasps – from *precision grasps*, where only the fingertips touch the grasped object (Figure 1.1), to *power grasps*, where the robot hand makes additional midfinger and palm contacts with the grasped object in order to provide highly secure grasps (Figure 1.2). Once grasped, the object can be securely transported or manipulated as part of a more complex robotic task.

In the context of robot grasping, the finger joints serve two purposes. First, the mechanical torques or forces generated at each finger joint control the contact forces between the fingers and the grasped object to maintain a secure grasp in the presence of external disturbances. Second, they allow the finger mechanisms to be positioned so that the robot hand can grasp a wide variety of objects with a range of contact arrangements. Beyond basic grasping, the finger joints allow manipulation of a grasped object within the robot hand.

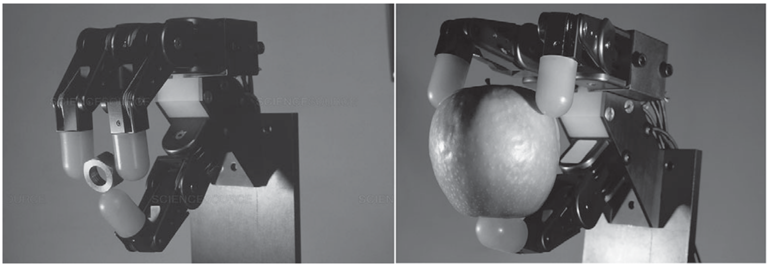


Figure 1.1 A three-finger robot hand demonstrating *precision grasps.* Original image ©Hank Morgan/Science Source, (Left). Original image ©RGB Ventures / SuperStock / Alamy Stock Photo, (Right).

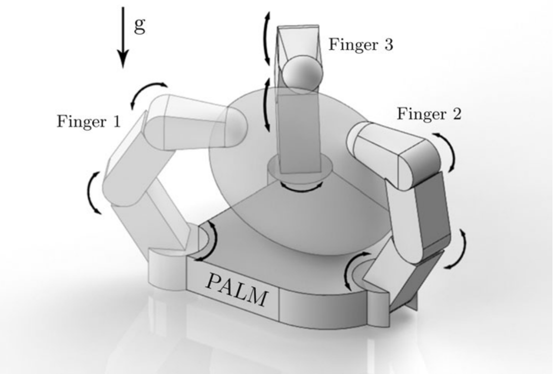


Figure 1.2 A three-finger robot hand demonstrating a *power grasp.*

The quality of a grasp is largely dictated by the location of the finger contacts on the grasped object surface. While the finger joints can actively change the contact forces applied on the grasped object, for purposes of grasp analysis, one can conceptually replace the finger mechanisms by *finger bodies* that apply equivalent forces at the contacts. Alternatively, one can take the conceptual viewpoint that the fingertips, if held rigidly by the robot hand, provide constraints on the grasped object's motion. Thus, as depicted in Figure 1.3, the analysis of a multi-finger grasp can be simplified to the study of a central *grasped object*, $\mathcal{B}$, in contact with surrounding *finger bodies*, $\mathcal{O}_1, \mathcal{O}_2, \ldots, \mathcal{O}_k$. Parts I, II and III of the book focus on this simplified grasp system. Building on these foundations, Part IV considers the kinematics and mechanics principles that govern the full robot hand during grasping.

Workpiece fixturing: Similar situations that involve multiple contacts arise in workpiece fixturing. Figure 1.4(a) shows a *modular fixture* that consists of fixuring elements, or *fixels,* that restrain a workpiece object. Fixtures are commonly used to securely hold workpieces during manufacturing and assembly processes. While some fixturing systems include actuation to actively control some of the clamping forces, most fixturing

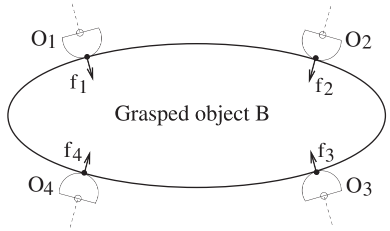
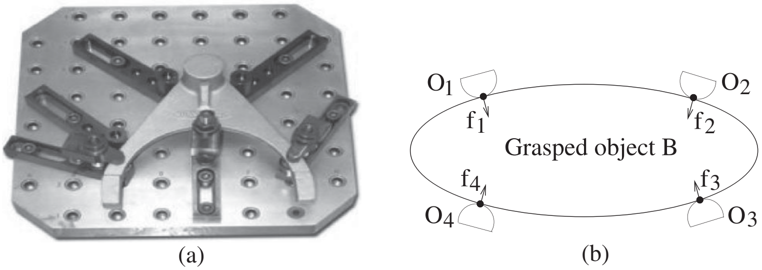


Figure 1.3 A multi-finger grasp can be abstracted as a system of finger bodies $\mathcal{O}_1, \mathcal{O}_2, \ldots, \mathcal{O}_k$ interacting with a grasped object $\mathcal{B}$.



(a) (b)

Figure 1.4 (a) A modular fixture in which a curved workpiece is held by multiple fixels. (b) Abstraction of the fixture system as a central workpiece in contact with multiple rigid bodies. Credit: Advanced Machine & Engineering (www.ame.com)

systems are unactuated. The contact forces between the fixels and the workpiece are typically generated during preloading of the fixtures, or arise from reactions of the fixels and workpiece materials as they are stressed and strained by machining or assembly operations. As depicted in Figure 1.4(b), the analysis of fixtures can also be idealized as a central workpiece in contact with multiple fixel bodies.

Quasistatic legged robot locomotion: The physical arrangements seen in robot grasps can also be applied to the study of some key issues in quasistatic legged robot locomotion. Figure 1.5(a) shows the Adaptive Suspension Vehicle, a 7,000-pound (about 3,000-kilogram) six-legged walking machine built at Ohio State University in the 1980s. This amazing vehicle could walk over uneven and muddy terrain while towing a load of 2,000 pounds (about 1,000 kilograms). A smaller four-legged robot developed at NASA JPL for disaster recovery missions is shown in Figure 1.5(b). Legged robot postures are analogous to robot grasps in the following ways. The terrain supporting the legged robot is analogous to the terrain formed by a robot hand supporting an object against gravity via multiple contacts. Legged robots are said to walk with *quasistatic gait* when the mechanism's center of mass lies within the *support region* of the leg contacts on the terrain.[1] If all the leg joints were to be instantaneously fixed, the robot's rigidified posture must be *statically stable* to ensure stable gait. Thus, as suggested in

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[1] When walking on a flat horizontal terrain, the support region is the convex hull of the contact points. On uneven terrain, the support region assumes a more complex shape fully described in this book.

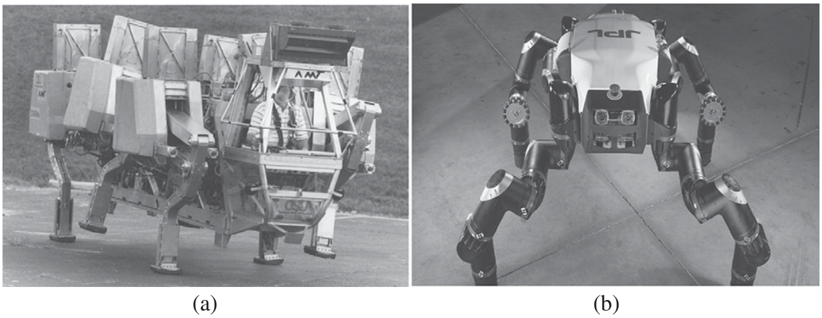
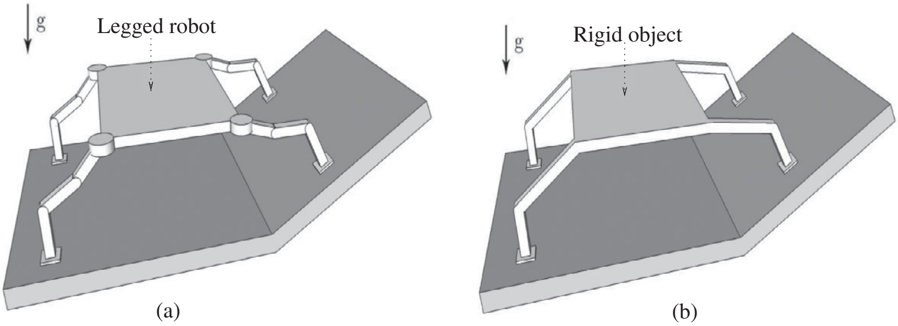

(a) (b)

Figure 1.5 (a) The six-legged Adaptive Suspension Vehicle built in the 1980s. (b) A four-legged robot developed in the 2010s for disaster recovery missions. Picture of Ohio State University's Adaptive Suspension Vehicle, obtained from www.theoldrobots.com.



(a) (b)

Figure 1.6 (a) A conceptual four-legged robot posture. (b) An abstraction of the legged robot posture as a rigidified body supported by multiple contacts on uneven terrain.

Figure 1.6, the question of legged robot posture stability can be reduced to the stability of a rigid object supported against gravity by a robot hand.

Multi agent transport systems: A team of ground-based mobile robots is tasked with transporting a heavy object to a new location. Each robot may only push against the object on its periphery and therefore can be thought of as a fingertip body that can apply transport forces to the object through contact or provide motion constraints for the object while it is pushed by other team members. A team of such robots is analogous to multiple finger bodies performing a manipulation task. Large objects can also be transported by a team of flying robots. In such transport schemes, a large object is suspended from cables attached to each agent. The cables provide *unidirectional* force constraints. That is, each flying robot can only *pull* on its cable to provide needed transport and maneuvering forces. In an analogous manner, the fingers of a robot hand provide *unidirectional* force constraints, as they can only *push* against the grasped object surface.

These examples show that the category of robot grasping includes diverse problems that can all be reduced to the study of multiple contacting bodies. While the principles described in this book apply equally well to all of these areas, the book describes these principles in the context of *robot grasping*.

1.2 Purpose of This Book

The first goal of this book is to assemble historical and recent results on robot grasping into one volume. There are many compelling reasons to do so. While several issues in robot grasping clearly merit further research, the basic kinematics and mechanics principles underlying the processes of grasping, fixturing and quasistatic legged locomotion have become well understood. Since the publication of the first book dedicated to grasp mechanics, *Robot Hands and the Mechanics of Manipulation* [1] published in 1985, real progress has been made on basic geometric modeling of these processes. Many robotics texts – such as [2–5] – discuss some important aspects of robot grasping. However, they do not provide a complete survey of the topics that we feel should be collected into one comprehensive volume, which can serve both as an educational and as a reference text.

A second goal of this book is to formulate the diversity of issues in robot grasping into a common language. We focus on the *configuration space* (c-space) formulation of multi-finger robotic grasps, as it provides an intuitively appealing viewpoint on many issues in grasp mechanics in a manner which is consistent with mainstream robot motion planning theory. This synergy of kinematics, mechanics and c-space should simplify future efforts in the development of algorithms for robot grasping systems. A third goal of this book is to highlight the impact of higher-order kinematics and mechanics effects such as surface curvature on robot grasping performance. Such effects, which were often ignored in the early robot grasping literature, can be significant in many practical circumstances.

We have purposefully limited the scope of this book to the kinematics and mechanics principles underlying robot grasping. We do not present or analyze grasp planning algorithms. While such algorithms are essential to maximize the utility of robot grasping systems, we purposely choose to avoid a survey of such algorithms. However, because grasping mechanisms must incorporate the basic principles of grasp mechanics, successful planning algorithms, even one based on machine learning, will be based on the theories presented in this book. Other than an advanced chapter on robot hand *manipulability,* the book does not study the mechanics of manipulation (the process of repositioning parts using a robot hand and possibly a robot arm). While the book touches upon a small set of issues concerning legged robots, it does not survey the field of legged robot locomotion. Instead, three chapters discuss the *static stability* of objects supported against gravity by a robot hand. This material appeared only as research papers and can be directly applied to legged robot locomotion on uneven terrains.

Thus, the goal of this book is to present material in the context of robot grasping, with the belief that this material can serve as a foundation for students, researchers and practitioners interested in developing new algorithms for all related robotics tasks.

1.3 How to Use This Book

The book is organized so that it can serve different purposes. First, it could serve as a textbook for those portions of an introductory graduate robotics course that touch upon robot grasping. Consequently, we have added exercises and some worked-out examples to help students master the key material through the problem-solving process. Note that exercises marked with an asterisk (*) are advanced problems, often bordering upon basic research questions. Second, the book can serve as a useful reference for researchers and practitioners. Bibliographical notes at the end of each chapter serve as a jumping-off point for further investigation. Moreover, we have included detailed proofs of some of the more critical and foundational results. To develop these analyses, we rely upon a few mathematical tools, such as *non-smooth analysis* and *stratified Morse theory,* which are not standard in the robotics literature. We therefore provide self-contained reviews of these methods in the book appendices so that their use can be readily followed in the main body of the text and so that their effectiveness can be appreciated.

The book is organized into *four parts,* whose content and purpose are summarized as follows.

- **Part I – Basic Geometry of Robot Grasping:** Chapters 2, 3, 4 and 5 review the essential geometric and kinematic concepts behind the *configuration space* of multiple contacting rigid bodies. For students who are newly starting their study of grasp mechanics, Part I is *essential background reading.* Practitioners already familiar with the field can skim most of these chapters to take note of the notational and kinematic conventions used in this book. However, it should be noted that Chapter 2 presents a novel formulation of the geometry of *c-space obstacles* using non-smooth distance functions. This approach provides a more coherent and straightforward framework for the analysis of multiple contacting bodies. Chapter 3 introduces a graphical representation of the tangent space to a c-space obstacle. This representation, which is not standard in the robotics literature, plays an important role in subsequent chapters. Chapter 4 describes *equilibrium grasps,* where the grasped object is held stationary within the robot hand. Equilibrium grasps are necessary for maintaining *secure grasps,* whose study forms the bulk of Parts II and III of the book. Chapter 5 subsequently describes a comprehensive catalog of the equilibrium grasps in terms of *line geometry.* This line geometry formulation has not previously appeared in a textbook, and some equilibrium grasps in the catalog have not appeared previously in any publication. Thus, even experienced readers may want to devote some attention to these portions of Part I.
- **Part II – Frictionless Rigid-Body Grasps and Stances:** Chapters 6–11 focus on multi-finger grasps under *frictionless* contact conditions. While no grasp contacts are truly frictionless, nor are any physical objects truly rigid, such models constitute useful idealizations. First, they serve as a conservative approximation to many real robot grasping applications. Second, friction has no bearing on the notion of *immobilizing grasps* considered in Chapters 7–9, nor does it play any role in the synthesis of *caging grasps* considered in Chapter 10.

For students, Part II introduces alternative notions of *secure grasps*. Individual chapters are devoted to the different types of secure grasps associated with frictionless contacts: *first-order* immobilization in Chapter 7, *second-order* immobilization in Chapter 8 and then *caging grasps* in Chapter 10. This part of the book stresses how the geometric and kinematic ideas of Part I can be used to analyze these types of grasps and serves as a useful bridge between the purely geometric ideas of Part I and the mechanics-oriented methods of Part III. In particular, the notion of *second-order immobilization* has only appeared in the research literature. Similarly, no text has previously organized the material on caging grasps into a coherent whole.

Chapter 9 considers *minimalistic robot grasps*. The chapter shows how to use mobility analysis to bound the number of fingers that are necessary to grasp different classes of objects in a secure immobilizing grasp. This material is not essential reading for a first introduction to the subject of robot grasping. Practitioners should note that this material collects together results which appeared only in the research literature. The final chapter of Part II considers the gravitational stability of objects supported by a robot hand via frictionless contacts. This chapter is not essential for beginning students. Experienced practitioners should note that this subject relies upon second-order mobility analysis and the use of *stratified Morse theory*, which is a unique and powerful tool for the analysis of multi-contact grasps. Neither of these analyses has previously appeared in a textbook.

- **Part III – Frictional Rigid-Body Grasps and Stances:** Chapters 12–15 study multi-finger grasps under *frictional* contact conditions. Chapter 12 introduces the notion of secure *wrench resistant* grasps. Both students and practitioners may be interested in the portions of Chapter 12 that formulate the wrench resistance property as a linear matrix inequality and relate this same property to the notion of small-time local controllability. Chapters 14 and 15 consider the gravitational stability of hand-supported stances when friction is present at the contacts. These chapters are not essential reading for beginning students. However, experienced practitioners should note that these chapters are highly relevant for legged robot locomotion on uneven terrains.

  Chapter 13 describes *grasp quality functions* that assess the value of alternative grasps. This chapter summarizes the key concepts behind most grasp quality functions that appeared in the literature. One of these key concepts concerns the behavior a grasp quality function under different choices of reference frames. The analysis of *frame invariance* that appears in Chapter 13 should interest both students and practitioners.
- **Part IV – Robot Hand Mechanisms:** The previous chapters abstracted the finger mechanisms to *finger bodies* that can generate fingertip motions and contact forces as necessary. Chapters 16, 17, and 18 consider the full robot hand during grasping processes. Chapter 16 considers how the kinematic structure of a robot hand affects key properties of the entire grasp system. The chapter studies the division of forces within a grasping hand into distinct linear subspaces and

considers how these different subspaces manifest as different types of wrench resistant grasps at the fingertips. Practitioners should note that these include *active* wrench resistant grasps, which correspond to precision grasps, and *structurally dependent* wrench resistant grasps, which correspond to power grasps.

Chapter 17 studies the property of *grasp manipulability,* defined as the ability of a robot hand to impart arbitrary local motions to the grasped object. This chapter forms an important link between basic grasp mechanics principles and the ability of a robot hand to locally manipulate objects while maintaining the grasp. Chapter 18 looks at the influence of compliance in grasping mechanisms. The chapter introduces the *grasp stiffness matrix*, which describes how the grasped object reacts to disturbances – assuming that the hand's joints behave in a compliant manner. The grasp stiffness matrix determines the stability of compliant grasps and provides information on the basin of attraction surrounding the grasp. Practitioners should note that robot hand control algorithms often implement proportional–integral–derivative (PID) control of the hand mechanism joints during grasping. Hence, this chapter describes the behavior and stability properties of objects that are grasped in controlled hand mechanisms.

- **Appendices:** Appendix A summarizes some useful tools of *non-smooth analysis.* These tools are central in modeling the *c-space obstacles* induced by grasping fingers and are used to explain the theory of immobilizing grasps. Appendix B summarizes the subject of *stratified Morse theory.* This theory offers analytical tools that characterize extremum points on *stratified sets.* One finds these sets in the configuration space formed by a robot hand that interacts with the grasped object. Stratified sets also appear as the sets of wrenches that can be affected on a grasped object by multiple fingers. Hence, all readers may wish to read these short appendices in order to appreciate the elegant and effective tools offered by these theories.

We hope that this organizational approach provides a text that is relatively self-contained for readers who are new to this field and that this format allows experienced practitioners to quickly pinpoint topics of interest.

1.4 Suggested Reading

As part of an introductory robotics course, Part I, Chapters 6 and 7 and Chapter 12 of Part III would give students a working knowledge of key issues in robot grasp modeling and analysis. Armed with this knowledge, students could pursue a self-study of this book's other chapters. A longer introduction would additionally include Chapter 8, on contact curvature effects, and possibly Chapter 10, on caging grasps. For courses that also include some study of legged robot locomotion, Chapters 14 and 15 of Part III would give students thorough insight into the stability of legged robot postures on uneven terrains. The remaining chapters primarily serve as advanced topics or reference material. The portions of the text that are more apt to be used as part of a course also have an increased number of exercises and worked-out examples.

Prerequisites: Obviously, it is difficult to write a book that can be both accessible and engaging to readers with a vast range of backgrounds. In writing this book, we have assumed that the reader has a basic understanding of matrix analysis and advanced calculus, which are reviewed when needed. We also assume working knowledge of rigid-body kinematics and the kinematics of serial chain robotic linkages. Both topics are covered in robotics texts such as [4] and [6].

1.5 A Brief History of Robot Grasp Mechanics

What follows is an abbreviated and incomplete history of the relevant developments in robot grasp mechanics, including connections to the contents of this book. Rather than give a detailed list of references, this review emphasizes some of the main trends and their influence on the organization of this book. This section can be skipped upon a first reading of the book.

1.5.1 The Early Influences

The theory underlying all robot grasping processes is built upon three classical foundations: kinematics, mechanics and mechanism theory. Before summarizing more modern developments, let us review some of the classical developments that underlie the principles and techniques described in this book.

All practical grasping systems involve multiple contacting bodies. To a very good approximation, in many practical situations, one can analyze multi-finger grasps using quasistatic rigid-body approach. The subject of *statics* has been around for centuries. However, Louis Poinsot's 1803 book *Théorie Nouvelle de la Rotation des Corps* can be identified as one of the first to geometrize rigid-body statics and mechanics principles. Poinsot observed that any system of forces acting on a rigid body can be resolved into a single force and a couple acting about the force axis. In the context of robot grasping, a system of contact forces applied to a grasped object can be replaced by an equivalent *net wrench.*[2] Coupled with the use of *line geometry,* these ideas are the basis of the equilibrium grasps described in Chapters 4 and 5.

The detailed mechanics of the contact between each finger and the grasped object can have significant influence upon the properties of the grasp. A *contact model* describes the types of forces that can be transmitted through a finger–object contact. Throughout the modern history of grasp analysis, contact models have included the effects of surface friction. Charles Augustin de Coulomb introduced the concept that friction and cohesion can have an influence on problems of statics. In his *Théorie des Machines Simples* (1781), Coulomb developed what we now call the *Coulomb friction model.* The

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[2] The term *wrench* was introduced later by Ball [7] in his treatise on screw theory.

Coulomb friction model may be criticized as too simplistic and inaccurate, since it does not capture many tribological effects. However, experience has shown that it provides a surprisingly effective approximation for grasp analysis, and consequently it has been widely used in the study of robot grasping. The rigid-body contact models are reviewed in Chapter 4. Moreover, the influence of mechanics on the analysis of grasps drives the partition of the book into multiple parts.

In many ways, the theory of grasp mechanics starts with Reuleaux's 1875 book, *The Kinematics of Machinery* [8]. This book introduced a systematic theory for categorizing and analyzing mechanisms as well as multi-contact systems. In this work, Reuleaux established the basic concept of *force closure,* which is introduced in Chapter 6 and fully analyzed in Chapter 12. Intuitively, a grasp is said to be *force closure* if any force and torque applied to the grasped object can be resisted by feasible finger forces at the contacts. The force closure concept has been a central issue in robot grasping. This book will use the term *wrench resistant grasp,* as it encompasses a broader notion of a grasp's ability to resist forces and torques applied to the grasped object.

A grasp is said to be in *form closure* if the contacting fingers provide sufficient rigid-body constraints on the grasped object motion so that the object is fully restrained by the grasping fingers. This book will use the term *immobilizing grasp* rather than form closure, as it more accurately describes the notion of complete restraint based on rigid-body constraints. In 1900, Somoff provided the first systematic analysis of immobilization [9]. This book provides a thorough analysis of rigid-body immobilization in Chapters 7 and 8. A key contribution of this book is the extension of classical form closure concepts to include surface curvature effects, leading to *second-order immobilization.* Chapter 9 shows that by including curvature effects at the finger contacts, a robot hand can immobilize objects with fewer contacts than is predicted by these classical models.

The next historical developments concern techniques to represent and analyze grasp kinematics. Two different schools of analysis emerged independently in the late nineteenth and early twentieth centuries. In the mid-1870s, Lie developed his notion of infinitesimal groups, which we know today as Lie algebra. In 1900, Ball published *A Treatise on the Theory of Screws* [7], while in 1924 von Mises introduced the related concept of *motors* [10]. These techniques became what we now call *line geometry.* The engineering kinematics community largely relied upon line geometry until the 1980s, when Lie group approaches were introduced by control theory researchers working in the newly energized field of robotics. Because of the prevalence of line geometry notions in the robot grasping literature, we review the relevant aspects of line geometry where needed. More generally, this book uses standard notions of *differential geometry,* such as tangent and cotangent vectors to the grasped object configuration space manifold, to formulate all topics of grasp analysis.

In the late 1970s Lozano-Perez, Mason and Taylor introduced the *configuration space* (c-space) approach for robot motion planning. All of the analyses in this book are developed under the influential c-space framework in a manner that is compatible with robot grasp planning concepts [11–13]. This formulation comes with a rich body of analytical methods from differential geometry that can be leveraged to the analysis of robot grasps. This book reviews all concepts associated with the c-space framework in a self-contained manner.

1.5.2 The Autonomous Robot Hands Era

Significant research of immediate relevance to robot grasping did not emerge until the 1970s. The nascent research in the 1970s was driven by three different lines of practical activity in the 1950s and 1960s: industrial robotics, telerobotics and human prosthetics. When the first industrial robots were installed in a General Motors factory in 1961, these early factory robots relied upon special-purpose grippers to accomplish their grasping and part manipulation tasks. It was an obvious next step for robot engineers and researchers to imagine general-purpose dextrous hands modeled after the human hand. The hope was that anthropomorphic robot hands could eliminate the need to develop special-purpose tooling and robot grippers, thereby enabling robots to be easily reprogrammed for different assembly operations. An example of such an early investigation is the Waseda arm of the late 1960s, which included a four-degrees-of-freedom gripper. Similarly, the rise of nuclear power generators in the 1950s motivated significant work in teleoperated robot arms. Telerobots acted as mechanical proxies, thereby removing humans from highly radioactive environments. While simple parallel jaw grippers sufficed for most teleoperation tasks, some tasks demanded dextrous end effectors that could mimic human hand motions. Additionally, electronic and battery technology had sufficiently advanced to the point where dextrous prosthetic hands were worthy of serious research endeavors. A notable early work in this area is the Tomovic prosthetic hand of 1965.

Early robotics researchers were challenged by these practical demands to develop more comprehensive approaches to the analysis and synthesis of multi-finger robot grasps. In the late 1970s, Lakshminarayana [14] updated Somoff's classical form closure theory, or *first-order immobilization.* Subsequent work during the 1980s and early 1990s was dominated by the force closure, or *wrench resistance,* approach to grasp analysis, instead of the form closure approach. This book tries to present a balanced view between the force closure and form closure approaches to grasp analysis. From the viewpoint of geometric analysis, form closure is actually a more natural framework for rigid-body grasp analysis and certainly provides the highest level of grasp security.

In the late 1970s and through the 1980s, Roth and his students at Stanford University systematically analyzed many fundamental issues in robot grasping and dextrous manipulation. Much of their work was based on classical *line geometry* [15]. In his PhD thesis [16], Salisbury formalized the common rigid-body *contact models* which are reviewed in Chapter 4. He also gave one of the first general formulations of *grasp stiffness* in multi-finger robot hands [17], which underpins Chapter 18. Cai [18] subsequently determined how the point of contact between two bodies moves as a function of the bodies' relative motions and their surface curvatures. Simultaneously, Montana, in his PhD work at Harvard [19], developed what we now call the *Montana contact equations* to describe this same effect. Montana relied upon differential geometry to obtain results analogous to those of Cai. The influence of surface curvature on the mechanics of grasping is a common theme in many chapters of this book. Our presentation tends more toward Montana's geometric formulation, as this approach is more consistent with the configuration space framework.

The early 1980s also saw the first fully functional robot hand prototypes. Salisbury completed the JPL/Stanford hand in 1982 (see Figure 1.1), while Jacobsen, Hollerbach and coworkers completed the Utah/MIT hand in 1985. These hands represented a new level of technical sophistication and performance. While these devices were still somewhat impractical, their successful demonstration of basic grasping operations motivated a new generation of researchers to tackle grasping and dextrous manipulation issues. A recurrent theme of this book is how to transfer the theory of robot grasping into insights that can lead to successful robot hand designs. We will see in Chapter 9 and the bulk of Part IV that three-finger robot hands are *minimalistic,* provided that the hand's palm (or alternatively, an additional supporting finger) is used occasionally to achieve highly secure grasps.

The field of robot grasping is continuously expanding with new applications and designs. For example, *cable grasps* can hold and manipulate objects just like multi-finger robot hands. In a similar manner, *suction devices* used in manufacturing as well as *adhesives* can be integrated into heterogeneous robot hands. *Jamming grippers* use a phase transition in granular materials (caused by the withdrawal of air between the granules when a vacuum is applied to the granular material) to lock an object within a conformal envelope, thereby securing the object within the grasp. Advances in 3-D printing technology allows *flexure joints* to be rapidly assembled into compliant robot hands. Moreover, advances in soft materials have enabled a new generation of *soft hands* that can safely interact with biological materials that are themselves soft and easily damaged. While the physical actuation or grasping procedure is different in each of these novel grasping devices, the kinematics and mechanics principles underlying the grasping process in these diverse devices have many commonalities. We believe that the principles described in this book should be relevant to all future innovations in the broad and ever expanding field of robot grasping and manipulation.

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