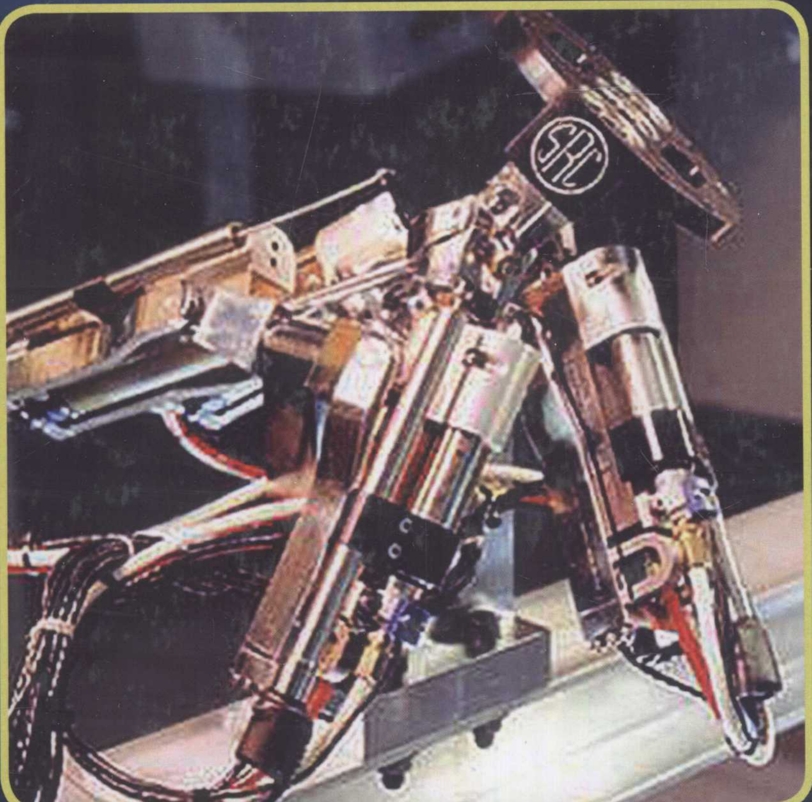
Parallel Robots

Mechanics and Control



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Preface

Robots have changed the life of human beings in the twenty-first century. In industrial automation, the use of robots is vital to preserve the quantity and quality of production by introducing flexibility to the production line. Industrial robots usually have an articulated structure in which a series of links are connected to each other to provide a large workspace. The motion of the robot is controlled through the disjointed actuators that manipulate individual motion of each link. Although, in such structures, characteristics such as a large workspace and flexibility may be obtained, the accuracy of the last manipulating element is significantly threatened by the serial structure.

For applications in which high precision and low compliance are required or a relatively high load capacity per robot weight is essential, parallel structures are the absolute alternative. A parallel robot has an inherent closed-loop kinematic structure, and its moving platform is linked to the base by several independent kinematic chains. Many industrial applications have adopted parallel structure for their design; however, only a very few textbooks have been published to introduce the analysis of such robots in terms of kinematics, dynamics, and control. This book is intended to give some analysis and design tools for the increasing number of engineers and researchers who are interested in the design and implementation of such robots in industries. In this book, a systematic approach is presented to analyze the kinematics, dynamics, and control of parallel robots.

In order to define the motion characteristics of such robots, it is necessary to represent 3D motion of the robots' moving platform with respect to a fixed-coordinate frame. This naturally leads to the need for a systematic representation of the position, orientation, and location of bodies in space. In Chapter 2, such representations are introduced with an emphasis on screw coordinates, which makes the representation of general motion of the robot much easier to follow. It should be noted that the ideas developed for position and orientation representation will form a basis for linear and angular velocity and acceleration representations, and this is also adopted to represent forces and torques applied in a robotic manipulator.

Kinematic analysis refers to the study of the geometry of motion in a robot without considering the forces and torques that cause the motion. In this analysis, the relation between the geometrical parameters of the manipulator and the final motion of the moving platform is derived and analyzed. A complete treatment of such an analysis is given in Chapter 3, and elaborative case studies are provided for three parallel robots, including a planar cable-driven parallel robot. The analysis of cable-driven parallel robots is formally treated in this book as the promising new generation of parallel structures that provide a very large workspace.

In Chapter 4, kinematic analysis of robot manipulators is further examined beyond static positioning. Differential kinematic analysis plays a vital role in the singular free design of robotic manipulators. Jacobian analysis not only reveals the relation between the joint variable velocities and the moving platform linear and angular velocities, but it also constructs the transformation needed to find the actuator forces from the task space forces and moments acting on the moving platform. A systematic approach to performing Jacobian analysis of parallel manipulators is given in this chapter and the proposed method is examined through the same case studies analyzed in Chapter 3.

The dynamic analysis of parallel manipulators presents an inherent complexity due to the closed-loop structure and kinematic constraints. Nevertheless, the dynamic modeling is quite important for the control, particularly because parallel manipulators are preferred in applications where precise positioning and suitable dynamic performance under high loads are the prime requirements. Although a great deal of research has been presented on the kinematics of parallel manipulators, works on the dynamics and control of parallel manipulators are relatively few, and almost no books cover these issues in detail. These issues are addressed well in this book in Chapter 5, in which dynamic analysis of such robots is examined by three methods, namely the Newton–Euler principle of virtual work and Lagrange formulations. Furthermore, a method is presented in this chapter to formulate the dynamic equation of parallel robots into a closed form, by which the dynamic matrices are more tractable and dynamics verification becomes possible.

The control of a parallel robot is elaborated in the last two chapters of the book, in which both motion and force control schemes are covered. Different model-free and model-based controllers are introduced and robust and adaptive control schemes are elaborated in Chapter 6. The control techniques are applied to two case studies, in which both cable-driven redundant parallel manipulator and fully parallel manipulators are examined through the proposed control schemes. Finally, Chapter 7 covers the force control of parallel robots in detail. In this chapter, stiffness control, direct force control, and impedance control schemes are elaborated and implemented on the same case studies followed in the book.

A key to verify the analysis and the controller performance is computer simulation. Computer simulations are being used for the case studies followed in all chapters throughout the text. Simulations are usually performed by commercially available packages such as MATLAB®, which provides a suitable means to simulate the robot's kinematic or dynamic characteristics and to verify the performance of the control systems. The manuscript was typeset using LaTeX, and the artworks were generated by Smart Draw and Inkscape software.

I am indebted to many people who have supported me either technically or spiritually during the writing of this book. As it involves the knowledge about many disciplines, numerous people have contributed to this work, but a list of the names could not be presented here; however, all of them are acknowledged. I would like to dedicate this book to the late Professor G. Zames and Professor P. R. Bélanger, not just for many things I have learned from them in control theory, but also for the deep influence they have induced in my soul *to make a difference*. I am also indebted to Professors J. Angeles and C. Gosselin who encouraged me to pursue this work. Many of the results presented in this book are mainly the contributions of J. Angeles, C. Gosselin, J.-P. Merlet, L-W. Tsai, and many other prominent researchers in this field. I had the pleasure to organize and further elaborate on these contributions. Any error in the presentation of their work is solely mine.

I acknowledge the enjoyable collaborations I had with Professors M. Nahon and I. Bonev and express my gratitude to them for providing me the visiting opportunities during two critical time periods and allowing me to temporarily escape my regular tight schedule and focus on the book. The content of this book was examined by many students who took the postgraduate course at McGill University and at K. N. Toosi University of Technology, and their comments and corrections have improved the quality of the materials. Among them, I would like to thank Dr. H. Sadjadian who spent a lot of time correcting the manuscript, and R. Oftadeh for his contributions in the dynamic formulation of parallel manipulators. Certainly, the current version of this book is not error-free, and I appreciate any comments

and corrections from all respected professional readers. All individuals and institutions who have contributed to graphical materials and artwork are sincerely acknowledged.

I cannot conclude without recalling the support and encouragement I received from my wife, Azam, and my daughter, Matineh, and my deepest regards go to their unlimited support and patience.

Hamid D. Taghirad
Tehran, June 23, 2012

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Introduction

Robots are very important assets for today's industry. The use of robots is vital in industrial automation to preserve the quantity and quality of production while introducing flexibility in the manufacturing line. The ever-increasing necessity to introduce new product styles, improve the product quality, and reduce the manufacturing costs has resulted in greater adoption of robotic equipment in various industries. At first, automobile manufacturing companies used robots in their production lines. However, in recent years, other industrial units that produce home appliances, food and pharmaceutical materials, and so on have adopted robotic systems in their production lines. A major reason for the growth in the use of industrial robots in different production lines is their significantly declining cost. In recent years, robot prices have significantly dropped while human labor costs are increasing. Also, robots are becoming more effective, faster, smarter, more accurate, and more flexible.

Industrial robots usually have an articulated structure. In these robotic manipulators, a series of links are connected in order to provide a large workspace. The motion of the robot is controlled through the individual actuators that manipulate the individual motion of each link. Although in such structures, design objectives such as a large workspace and flexibility can be well satisfied, the accuracy of the robot end effector is significantly threatened by its serial structure. For applications in which high precision and stiffness are required or a relatively high load capacity per robot weight is needed, parallel structures are the absolute alternative. Many books have focused on the theoretical and technological advancements of serial robots [5,31,163,168]. However, very few have covered the topics on the analysis, design, and control of parallel robots [105,133]. This book is intended to provide some analysis and design tools for the increasing number of engineers and researchers interested in the design and implementation of parallel robots in industries.

1.1 What Is a Robot?

A robot is a mechanical or virtual artificial agent, usually an electromechanical system, which, by its appearance or movements, conveys the sense that it has intent or agency of its own. While there are still controversies about which machines qualify as robots, a typical robot will have several, although not necessarily all, of the following properties:

- It is not *natural* and has been artificially created
- Can sense its environment
- Can manipulate things in its environment
- Has some degree of intelligence
- Is programmable

- Can move with one or more axes of motion
- Appears to have intent or agency

The last property, the appearance of agency, is important when people are considering whether to call a machine a robot. In general, the more a machine has the appearance of agency, the more it is considered a robot. There is no one definition of robot that satisfies everyone, and many people have written their own. For example, the international standard ISO 8373 defines a robot as

> An automatically controlled, reprogrammable, multipurpose, manipulator, programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications.

Joseph Engelberger, a pioneer of industrial robotics [44], once remarked:

> I can't define a robot, but I know it when I see one.

The *Cambridge Advanced Learner's Dictionary* defines a robot as

> A machine used to perform jobs automatically, which is controlled by a computer.

The Robotics Institute of America used the following definition for a robot:

> A *robot* is a re-programmable multi-functional manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks.

This definition includes mechanical manipulators, numerical controlled (NC) machines, walking machines, and humanoids of science fictions. Building a humanoid capable of doing what a human being can do is an ancient dream of humankind, and technologies developments to build machines and mechanisms that can perform like humans may all be seen in the field of robotics research. Hence, robotics is a multidisciplinary engineering field of research. In industry, however, a mechanical manipulator is usually recognized as a robot which resembles the human arm.

The word *robot* entered the vocabulary of English as early as in 1923. This word was first used by Karel Čapek in his book *Rossam's Universal Robots* [183]. Čapek visualized a situation where a bioprocess could create human-like machines devoid of emotions and souls. However, they were very strong and obeyed, and they could be produced quickly and cheaply. Soon, all major countries wanted to equip their armies with hundreds of thousands of slave robotic soldiers, who can fight with dedication but whose loss is not painful. Eventually, the robots decided to become superior to the humans and tried to take over the world. In this story, the word *robota* or worker was coined.

However, the emergence of industrial robots did not occur until after the 1940s. In 1946, George Devol patented a general-purpose playback device for controlling machines using magnetic recording, and in 1954, he designed the first programmable robot and coined the term *universal automation*, planting the seed for the name of his future company—Unimation. In the early 1980s, several robot-producing companies emerged or joined, and the number of industrial robots used in the industries increased significantly. In the second millennium, robotics research was focused more on the technology for building humanoid robots and robotic pets.

1.2 Robot Components

A mechanism or a robotic manipulator is usually built from a number of links connected to each other and to the ground or a movable base by different types of joints. The number of degrees-of-freedom of a robot depends on the number of links and the type of joints used for the construction of the robot. In this section, the definitions of *links, joints, kinematic chains, mechanisms,* and *machines* are given, and then the concept of degrees-of-freedom is described.

The individual rigid bodies that make up a robot are called the *links*. In industrial robots, the rigidity of the links contributes significantly to the precision and performance of the robots, and usually in the design of links, rigidity is a vital requirement. However, in applications such as space robotics or cable-driven manipulators, due to the limitations and type of applications, special designs are adopted in which the links are constructed from flexible elements. Such robots are usually called *flexible link manipulators*. In this book, links are treated as rigid bodies for most of the manipulators which are analyzed in different chapters, unless stated otherwise. The assumption of the rigid bodies makes the analysis of robot manipulators much easier to understand. For cable-driven parallel manipulators, the assumption of rigid bodies for the link is applicable only when the manipulator is operated with high stiffness, and the internal tensions in the cables are relatively high. In such cases, the sagging effect of the cables are negligible, and the assumption of a rigid body for the links gives us good insight into the development of a dynamic analysis and control of such manipulators. From a kinematic point of view, a single link can be defined as an assembly of members connected to each other, such that no relative motion can occur among them. For example, two gears connected by a rigid shaft are treated as a single link.

In robots, the links are connected in pairs, and the connective element between two links is called a *joint*. A joint provides some physical constraints on the relative motion between the two connecting members. Owing to the required relative motion in a kinematic pair, different types of joints may be distinguished.

- A *revolute joint, R*, permits rotation about an axis between two paired elements as shown in Figure 1.1. Hence, a revolute joint imposes five constraints between the connecting links and provides one-degree-of-freedom.
- A *prismatic joint, P*, permits sliding along one axis between two paired elements as shown in Figure 1.1. Hence, a prismatic joint imposes five constraints between the connecting links and provides one-degree-of-freedom.
- A *cylindrical joint, C*, permits rotation about one axis, and independent translation along another axis as shown in Figure 1.2. Hence, a cylindrical joint imposes four constraints between the connecting links and provides two-degrees-of-freedom.
- A *universal joint, U*, permits rotation about two independent axes as shown in Figure 1.2. Hence, a universal joint imposes four constraints between the connecting links and provides two-degrees-of-freedom. A universal joint can be made from two consecutive revolute joints.
- A *spherical joint, S*, permits free rotation of one element with respect to another element about the center of a sphere in all the three directions as shown in Figure 1.3. No translation between the paired element is permitted. Hence, a spherical joint imposes three translational constraints between the connecting links and provides

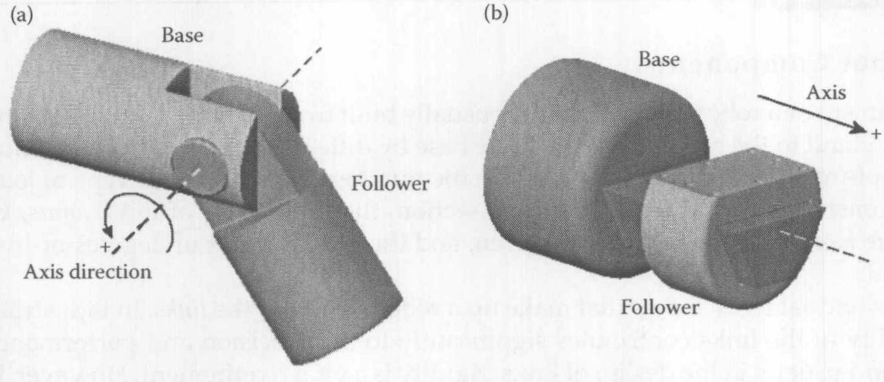

FIGURE 1.1
Schematics of a revolute joint (a) and a prismatic joint (b). (From Mathworks Inc. Schematics of a revolute joint (left) and a prismatic joint (right), 2010. Mathworks. With permission.)

three rotational degrees-of-freedom. As illustrated in Figure 1.3, a ball-and-socket joint has the kinematic structure of a spherical joint.

- A *planar joint*, *E*, permits two translational degrees-of-freedom along a plane of contact and a rotational degrees-of-freedom about an axis normal to the plane of contact, as shown in Figure 1.4. Hence, it imposes three constraints and provides three-degrees-of-freedom.

A *kinematic chain* is an assembly of links that is connected by joints. When every link in a kinematic chain is connected to other links by at least two distinct paths, then it is called a *closed-loop chain*. On the other hand, if every link is connected to its pair by only one path, the kinematic chain is called an *open-loop chain*. When a mechanism consists of both closed-loop and open-loop kinematic chains, it is called a *hybrid kinematic chain*.

As shown in Figure 1.5, a kinematic chain is called a *mechanism* when one of its links is fixed to the ground, which is called the base. A *machine* is an assembly of one or more mechanisms along with electrical and/or hydraulic components, used to transform external energy into useful work. Although in many texts the terms *mechanism* and *machine* are

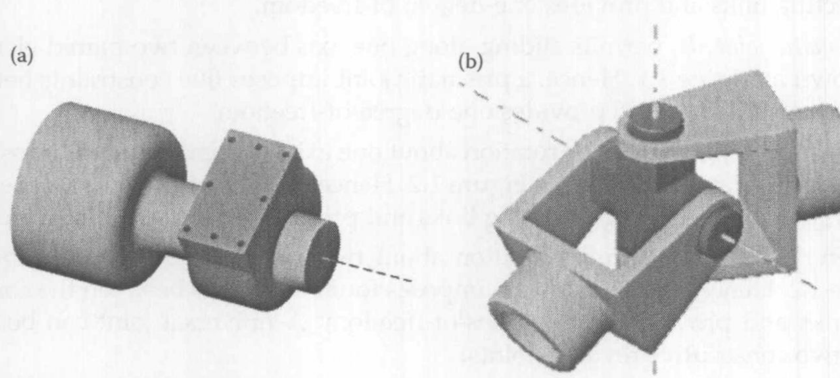

FIGURE 1.2
Schematics of a cylindrical joint (a) and a universal joint (b). (From Mathworks Inc. Schematics of a cylindrical joint (left) and a universal joint (right), 2010. Mathworks. With permission.)