

A blue industrial robotic arm is shown in a dynamic pose, reaching towards the bottom left. The background is a dark blue gradient with a network of white and yellow lines and dots, suggesting a digital or connected environment. The arm has a black gripper at the end and a coiled white cable running along its length.

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# **Industrial Robotics Control**

**Mathematical Models,  
Software Architecture,  
and Electronics Design**

**Fabrizio Frigeni**

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# ***Industrial Robotics Control: Mathematical Models, Software Architecture, and Electronics Design***

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ISBN-13 (pbk): 978-1-4842-8988-4  
<https://doi.org/10.1007/978-1-4842-8989-1>

ISBN-13 (electronic): 978-1-4842-8989-1

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*A Klara e Alice, con tanto affetto dal vostro papà.*

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# About the Author



**Fabrizio Frigeni** is a multicultural engineer, hobbyist, teacher, and entrepreneur.

Hailing from Italy, he obtained a degree in electrical engineering from the Polytechnic University of Milan; then worked on laser physics for his master's degree at the University of Illinois at Chicago, USA; and later completed a doctoral degree in microelectronics at the Technical University of Dresden, Germany.

He has gained extensive experience in the fields of automation, robotics, computer vision, and machine learning while working for several years on assignments in Austria, Brazil, India, and China. He has been based in Shanghai since 2009, where he has first managed local engineering teams, and then started his own company to teach, consult, and design control systems for automated machines and robots.

# About the Technical Reviewer

**Zbynek Uher** is a Czech developer, graduated in mathematics and computer science. Since 2005, his professional career is connected with industrial robot software development in Austria and the Czech Republic. His areas of expertise include robotic transformations, robotics control system, and its software architecture.

# Preface

Robotics is a very exciting field to be working in, and there is no better way for me to share that excitement with you than collecting and presenting all the knowledge and experience I have gained through many years of hard work with several kinds of robots and all sorts of automated machines. Also, I believe there is no better way of understanding how a device works than actually building it entirely from scratch. Therefore, the goal of this book is to provide a general overview of how a robotics control system works and how to design and build one by yourself.

Modern industrial manufacturing plans are highly automated, and a large amount of work is performed by robotic arms. They are efficient, accurate, and fast. They are often employed in tasks that are too repetitive or dangerous for humans. They increase the productivity and reliability of a production chain. However, their control is far from being easy. They require a good deal of understanding of mathematics, software algorithms, and electronic hardware.

You will be guided through the details of the robots' geometrical models, their movements in space, their driving algorithms, and their electronic control circuits. By the end of the book, you should be able to build a fully functional control system capable of driving any industrial robot.

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The original version of this book was revised. A correction to this book is available at [https://doi.org/10.1007/978-1-4842-8989-1\\_20](https://doi.org/10.1007/978-1-4842-8989-1_20)





*The author working on a large welding robot back in 2011*

## Who Is This Book For?

This book is thought for students, hobbyists, and engineers who would like to understand the theory behind a robotics control system and then put that knowledge into practice to build their own working solution.

It is not meant to be an academic textbook, and the theory is presented in a rather informal way to make it a bit lighter and friendlier. Nevertheless, university students can still find useful information to complement their more formal academic volumes.

Practicing engineers can find the solutions to several kinematic models that are rarely included in detail in robotics textbooks. Also, they will find plenty of practical suggestions on problems that are less of theoretical interest but very often faced in daily robotics activities (workspace monitoring, calibration, servo loop tuning). I tried to bring in as much information as possible from the practical side of things: tips and observations from several years of hands-on work in the industry.

Hobbyists will probably focus more on the second half of the book, where I describe how to build a complete control system for robots: from the software architecture to the electronic hardware design. Here too, I show details from real-life examples and products I built during my engineering career.

Anyone interested in technology with a basic engineering background will be able to follow along. There is indeed quite a bit of mathematics to go through, which is essential for understanding how a complex robotic arm moves in space. But as long as you are familiar with basic trigonometry and linear algebra, you will be fine. Many formulas are presented directly without formal derivation to avoid lengthy pages filled with equations.

There are also different control algorithms to digest and general software architecture to think over. However, no specific programming skill is required. I will leave the actual code implementation for you to work on, according to your background and preferences.

In general, I liked to focus on the reasoning behind certain functions more than on their direct implementation. The book is meant as a source of inspiration for creative people, not as a source of scripts to copy-paste in your system.

As for the hardware implementation, some electronics knowledge is required to put together a working circuit board. However, you could also skip that part and use third-party ready-made components. Alternatively, you could even work with a simulation environment to test out your software without using a real robot at all.

## Structure of the Book

The core of the book can be split into two distinct sections: the first half (Parts I and II) presents the mathematical models needed to describe robots' structures and their movements in space; the second half (Parts III and IV) presents the software and hardware components needed to build a complete control system for the robots.

## PREFACE

The first chapter provides an introduction to industrial robots: what different kinds there are and what applications they are used for. We also go through the various nomenclatures commonly used in the industry to make sure we all understand what we are talking about. Then we introduce a generic structure of a robotics control system to show what components you will study over the rest of the book. Finally, we briefly present a simulation environment you could use to test your controller while you build it, in case you do not have access to a real robot. Most of the images in this book are captured from that simulation environment.

Parts I and II (Robot Geometry and Robot Movements) provide the theoretical foundations for robot control. These two sections are a bit heavy on the math, but if your goal is to write a fully functional control software, you need to be patient and work through the details. We first define a generic geometrical framework for robotic arms (Chapter 2) and use it to solve the kinematic chain of a standard six-axes industrial manipulator: the forward kinematics in Chapter 3 and the inverse kinematics in Chapter 4. In other words, we learn how to define the position of a robot in space. The next step is to learn how to move the robot between different positions: we talk about path-planning (Chapter 5); we make sure the path is valid and safe using workspace monitoring functions (Chapter 6); we then describe the motion equations to generate and execute the trajectory (Chapter 7). We also give a brief overview of some advanced control techniques using static and dynamic models (Chapter 8).

Part III (Robot Software) analyzes the functions and characteristics of a typical control software package for robots. We start with the core firmware (Chapter 9) showing its internal structure and how to make it accessible via a simple interface. We describe in detail the motion control and motor commutation algorithms typically found in industrial servo drives. We also present common procedures, tips, and guidelines to calibrate the robot according to its specific application (Chapter 10) and to commission it safely to the customer's site (Chapter 11). We then show how to create a

virtual world using the game engine Unity (Chapter 12), so that you can directly test all the features of your code and receive immediate visual feedback of the resulting actions performed by the robot. This approach is useful in case you have no access to a real industrial robot or also to test your code in simulation before running it on a real machine to avoid costly and dangerous surprises. Finally, we also describe the basics of machine vision algorithms (Chapter 13), in order to augment the functionalities and range of applications of your robot.

Part IV (Robot Hardware) is all about the hardware you need to build a complete robotic arm. We start with the actuators, by describing different kinds of electric motors (Chapter 14) and positional encoders (Chapter 15). Then we delve into the electronic components and learn how to design our own inverter drives (Chapter 16), power management systems (Chapter 17), and logic controller (Chapter 18). Lastly, we take a quick look at the actual fabrication steps (Chapter 19), both for PCB implementations and for mechanical parts.

An appendix at the end of the book provides the solutions for kinematic chains other than the standard six-axes manipulator. We show how to solve a COBOT, a SCARA arm, a Palletizer manipulator, and a Delta (Tripod) parallel kinematic.

## CHAPTER 1

# Industrial Robots

The word robot is very general and normally identifies all sorts of automatically moving machines. This book focuses on robotic arms, also called manipulators, typically employed in factories for manufacturing tasks (see example shown in Figure 1-1).



**Figure 1-1.** *Industrial robots at work in a production line (with permission from EFORT)*

These industrial robots come in many shapes and sizes, depending on the applications they are going to work on. The smallest robots can only lift loads of about a kilogram or two. The largest ones can easily move loads exceeding a couple of tons.

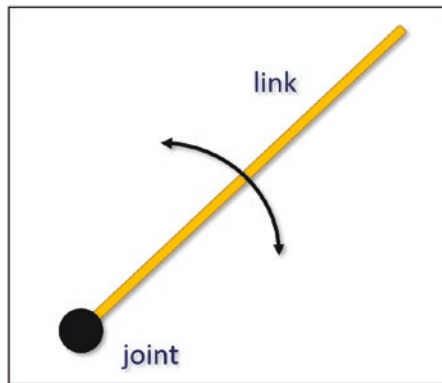
Their mechanical structures are usually very rigid in order to guarantee high accuracy and simplify the control algorithms, especially at high speed. Their movements are fast and precise, but they usually lack any intelligence. In fact, the majority of their applications are focused on simple, repetitive tasks: for instance, cutting, welding, and painting metal pieces in the automotive industry; packaging or palletizing in food or medical industries; and assembling in consumer electronics production lines.

Adding sensors and cameras to the robots makes them able to solve increasingly complex tasks and makes them more aware of their surroundings. The additional information is input in smarter algorithms and allows the control system to adapt its behavior to different situations. Typical examples are robots autonomously sorting packages in warehouses or collaborative robots (cobots) able to detect and soften collisions with human operators.

# Nomenclature

Before we start learning more details about the world of industrial robots, we need to introduce a few technical terms to make sure we all understand what their parts and features are called.

The mechanical structure of a robotic arm is essentially a chain of **links**. These links are connected together with **joints**. The joints are usually actuated by motors, so that the links can move (see Figure 1-2).

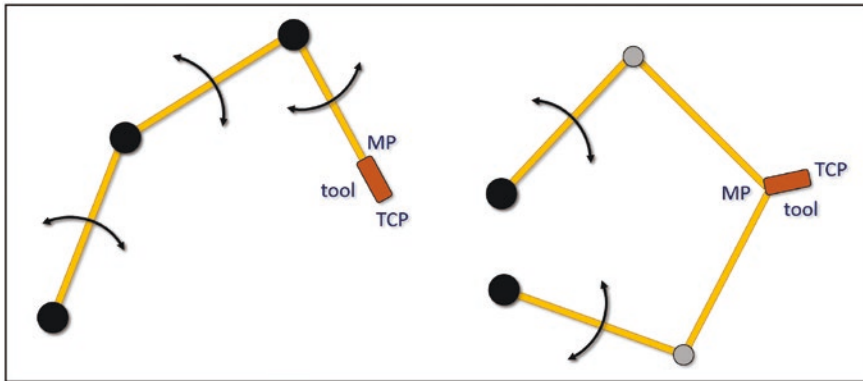


**Figure 1-2.** *Rotational joint and link*

The field of physics that describes the position of linked objects in space is called **kinematics**. This description only considers the geometrical position of the links and does not account for the forces acting on them. In Part 1 of this book, we will study how to write and solve the kinematic equations for a robotic arm.

Using a kinematic model is the most common approach of controlling a robot in the industry, by using position-based commands. However, in some cases, taking into account the forces acting on the individual links is also required: either to improve the quality of the motion control or to solve force control applications. For example, screw tightening and bottle capping are performed with force commands, not position control. The field of physics that describes the movement of objects under the action of forces is called **dynamics**. We will briefly introduce the dynamic model of industrial robots in Chapter 8.

We mentioned earlier that robotic arms can be built with different mechanical configurations. We can now make a clear distinction based on the form of their kinematic chain: serial and parallel kinematics (see Figure 1-3).



**Figure 1-3.** Serial (left) vs. parallel (right) kinematics

**Serial kinematics** consist of an open chain of links, similar to a human arm: from the shoulder, to the elbow, down to the wrist and fingers.

**Parallel kinematics**, on the other hand, are composed of links positioned parallel to each other, somewhat similar to a group of legs or to a tripod.

No matter what kind of kinematic chain we are dealing with, we call the point at the end of the structure the mounting point (**MP**) that is where a tool is normally mounted to perform certain tasks (a gripper, a drill, a welding gun). The point at the very end of the tool is called the tool center point (**TCP**). That is a fundamentally important definition because the TCP is the point where the robot interacts with the environment. *Learning how to control the position, orientation, speed, and force of the TCP is the ultimate goal of this entire book.*

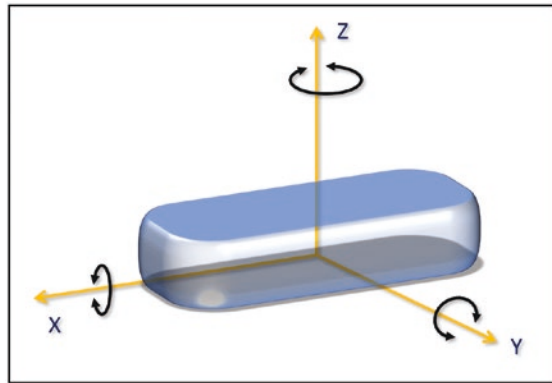
The range of all the possible positions in space that can be reached by the TCP is called the **workspace** of the robot. Serial kinematics normally offer larger workspaces when compared to parallel kinematics, which means they can reach objects farther away from their base. However, larger workspaces also increase the risk of collisions with other robots or other objects in the surrounding environment. Workspace monitoring and **collision detection** are important topics that will be covered in Chapter 6.



The TCP, even though called point, is defined not only by its position but also by its orientation, naturally derived from the tool body. As an analogy, think of how you can reach for an object with your hand from different angles. The target position is the same, but the orientation is not. In the field of robotics, the combination of position and orientation of a target point is often called a **pose**.

The ability to position and orient the TCP along and around different axes is measured by the number of **degrees of freedom** (DoFs) of the robot.

A cart travelling on a linear rail can only position its load with one degree of freedom: the position is measured with a single scalar value along the only axis of motion. However, a generic object in space can be placed with up to six degrees of freedom (see Figure 1-4): three degrees of positions (*along* the X-Y-Z axes) and three degrees of orientation (*around* the X-Y-Z axes).



**Figure 1-4.** A generic object in space has six DoFs

In practice, not all industrial robots offer six DoFs because the applications they are designed for do not require them. Think, for example, of a typical use case for industrial robots: picking cookies off a running conveyor and placing them in a box for market distribution. If the cookies

are round, then they can fit in the box at any angle. The robot is required to reach the correct target position in space, but the orientation of the cookie is irrelevant. In this case, three degrees of freedom are enough. However, if the cookies have a specific asymmetric shape, say rectangular, then they need to be oriented at a specific angle with respect to the box in order to fit inside. In that case, an additional degree of freedom is required: a rotational movement around the vertical axis.

Adding degrees of freedom to a robot means adding links, motors, weight, and control complexity to the system. You could ideally build a robot with as many joints as you wanted, but it would get harder and harder to control. Keeping the mechanics light and small usually results in faster and more accurate movements.

Serial kinematics often offer more flexibility, thanks to their high number of joints, but they lack speed and accuracy. That is because each link adds some weight and some errors to the chain, so that the total error builds up with the number of joints.

Parallel kinematics, on the other hand, are used in industrial settings for applications with low payload and with limited number of degrees of freedom. However, they move much faster and offer higher accuracy, because their mechanics are much lighter and also because errors do not add up between parallel joints.

There are, of course, parallel mechanics that can carry very high loads and have six full DoFs (e.g., hexapod platforms for motion simulators), but these are not as common in industrial settings.

## Mechanical Configurations

Now that we know how to differentiate robotic structures, we can look at some examples of kinematical configurations typically found on the market.

**SCARA:** The name stands for *Selective Compliance Assembly Robot Arm*. It is a serial kinematic that comes in two, three, or four DoFs versions, with four being the most common (see Figure 1-5). It is a compact, cheap, and fast robot, with a low payload and a small workspace. It finds application mostly in pick-and-place or assembly tasks in the electronics manufacturing lines.

This is by far the easiest and cheapest robot to manufacture, and I strongly suggest starting from here if you want to build your own working robot at home.



**Figure 1-5.** A four-axes SCARA Robot (with permission from EFORT)

**DELTA:** Also known as tripod robot. It is a parallel kinematic that, just like the SCARA, is sold in two, three, or four DoFs versions, with four-axes being the most common configuration (see Figure 1-6). In the three-axes and four-axes versions, its parallel arms are positioned at the vertex of an equilateral triangle, hence the name delta.

It is a lightweight robot that supports small payloads but can reach incredible speeds. It is typically used to speed up production lines where the size of the product is small: food, electronics, and medical industry.



**Figure 1-6.** *A four-axes Delta Robot (with permission from CODIAN)*

**ANTHROPOMORPHIC:** This is the standard six-axes robot and is by far the most common robot in manufacturing plants. It is called anthropomorphic because it resembles a human arm (see Figure 1-7), but most people refer to it simply as robotic arm or manipulator. It has six axes and six degrees of freedom, and it is offered in a large range of sizes according to the payload required by the application: from a few kilograms up to a full ton.

Six-axes robots are used in all applications where high dexterity is needed, the largest field being automotive industry: cutting, welding, polishing, painting, etc.



**Figure 1-7.** *A six-axes Anthropomorphic Robot (with permission from EFORT)*

This is the most generic type of robot, and we will study it intensively through the book. However, most of the concepts are general enough and can be quickly applied to all other kinds of robots without modifications. The main exception is the solution of the kinematic model, which is unique to each robot's structure. The equations and solutions for this robot are presented in detail in Chapter 3 and Chapter 4, while all the other models are solved in the Appendix at the end of the book.

**PALLETIZER:** This kind of robot looks similar to the anthropomorphic version, but it only has four axes and therefore two fewer degrees of freedom (see Figure 1-8). As the name suggests, it is used in palletizing applications, loading and unloading large and heavy objects, usually by means of a mechanical gripper or a vacuum suction system.

The robot picks the objects from the top and places them on a flat surface. This operation requires only four DoFs: three for the target position and one for the orientation angle around the vertical axis. No orientation around the two horizontal axes is possible nor needed. Giving up two degrees of freedom results in the advantage of removing two motors and a lot of complex mechanics, thereby saving costs and weight.

Palletizers are usually the largest industrial robots, with the furthest reach and the heaviest payload.



**Figure 1-8.** *A four-axes Palletizer Robot (with permission from EFORT)*

**COBOT:** This is a six-axes lightweight robot (see Figure 1-9), where lightweight means that its mechanical structure and its control system are engineered to make collisions soft. The main purpose of such a design is that these robots can safely work alongside human operators without causing injuries, unlike all other kinds of industrial robots, which must be protected and isolated behind metal cages. That is where the name cobot comes from (short for *collaborative robot*).

They find application in several fields where they can directly assist humans, instead of completely replacing them: assembly lines, domestic environments, and medical settings.