

Robotics for
**Electronics
Manufacturing**

Principles and Applications in Cleanroom Automation

KARL MATHIA

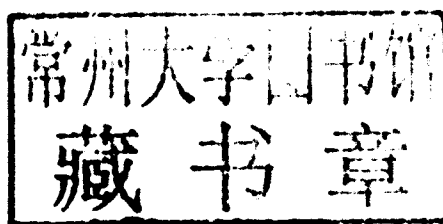
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Zitech Engineering, LLC



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Robotics for Electronics Manufacturing

Understand the design, testing, and application of cleanroom robotics and automation with this practical guide. From the history and evolution of cleanroom robots to the latest applications and industry standards, this book provides the only complete overview of the topic available. Robotics for automating the most demanding cleanroom manufacturing process, the making of semiconductor devices, is used as an example throughout the book. The principles and applications also apply to related industries, including the flat panel display, solar panels, hard disk, nanotechnology, MEMS, and pharmaceutical industries.

With over 20 years of experience in robotics and cleanroom manufacturing, Dr. Karl Mathia covers the relevant subjects for the design and testing of clean robots that operate in both atmospheric and vacuum environments. He provides numerous real-world examples so the reader can learn from professional experience, maximize the design quality, and avoid expensive design pitfalls. The book also provides guidelines and hands-on tips for reducing development time and product cost. Compliance with industry standards for the design, assembly, and handling of cleanroom robots is stressed throughout, and detailed discussions of recommended materials for atmospheric and vacuum robots are included to help shorten product development cycles and avoid expensive material testing.

This book is the perfect practical reference for engineers working with robotics for electronics manufacturing in a range of industries that rely on cleanroom manufacturing.

DR. KARL MATHIA studied in Germany and the United States and holds advanced degrees in Electrical and Computer Engineering. He has over 20 years of experience in research and development, product development engineering, and also held management positions at leading robotic firms, including Brooks Automation and Newport Corporation. Dr. Mathia has published numerous articles in the area of automation, controls, and intelligent systems, and taught short courses in industry. He currently works as Chief Engineer at Zitech Engineering, LLC.

In my 16 years of serving the robotics industry, I have never come across a single book that explains the history, design, and use of cleanroom robotics for electronics manufacturing so thoroughly. The book provides an excellent description of the environment and challenges of this industry and gives valuable insight for designing robots and equipment to meet these challenges. This is a must read for anyone designing cleanroom equipment for electronics manufacturing!

Jeff Baird, Director of Engineering, Adept Technology, Inc.

A must read for anyone working on semiconductor or flat panel robotics. This book captures theory, applications and best practices. Chapters 2, 3, 4 and 7 are a concise reference for designing, specifying and implementing robots. Chapters 5 and 6 provide the technical background to both develop and control robotic systems.

Dr. Martin P. Aalund, Director NPI Engineering, KLA-Tencor Corp.

Karl has created the definitive reference for cleanroom robotics, as well as a practical guide for anyone who wishes to go beyond theory to the economic justifications and real world commercial requirements to deploy robot technology.

Dr. Rich Mahoney, Director of Robotics, Engineering & Systems Division, SRI
International

This volume provides a comprehensive view of robot use as part of electronics manufacturing. The book gives a good overview of the different aspects to be considered in the design and deployment of robots for this sector. The text covers a sector overview, in-depth material for different applications areas and discusses also testing and deployment. It is a valuable reference both to engineers and technical managers in the field.

Dr. Henrik I. Christensen, KUKA Chair of Robotics, College of
Computing, Georgia Institute of Technology

Robotics for Electronics Manufacturing is an important new reference work for anyone involved with manufacturing robots. The book provides design guidelines for robots in both air and vacuum environments, as well as a thorough overview of robot kinematics and dynamics. The chapter on testing and measuring robot performance is especially valuable as an accessible explanation of the many ISO, ANSI and RIA standards.

Dr. Trevor Blackwell, CEO and Founder, Anybots, Inc.

Robotics for Electronics Manufacturing is a fundamental and thorough reference for engineers practicing, or preparing to practice, automation design for the semiconductor and electronics equipment manufacturing industry. No other reference covers the disparate requirements and best practices for both atmospheric and vacuum robot design, as well as including test and characterization methods which are the key to the successful manufacturing of such products.

Dr. Jeffrey C. Hudgens, Director of Robotics, Applied Materials Inc.

To Maria

Preface

This book is about the design and application of industrial cleanroom robots in electronics manufacturing. It is intended as a hands-on technical reference for engineers and factory managers involved in manufacturing electronic devices in cleanroom environments. The book provides insight into the principles and applications of industrial cleanroom robotics, in particular in semiconductor manufacturing, the most demanding process in terms of cleanliness requirements. Other examples are the hard disk, flat panel display, and solar industries, which also use high levels of cleanroom automation and robotics. In contrast to the complex manufacturing process, the typical robotic designs often utilize relatively simple robot kinematics in the highly structured environments of process and metrology tools. Some industries, for example the semiconductor front-end industry, are governed by technical standards and guidelines, which are generally helpful during the design process of robotic systems. On the other hand, robotic engineers in electronics manufacturing face challenges that are unknown in other markets, most importantly the cleanliness required in certain factories. Strict cleanliness requirements have resulted in two categories of cleanroom robots: ‘atmospheric robots’ for high-quality cleanliness at ambient atmospheric pressure, and ‘vacuum robots’ for extreme cleanliness in enclosures under various vacuum pressures. These two categories are the focus of this book.

The book is organized into seven chapters. Chapters 1 and 2 provide an overview of industrial robotics and industrial cleanroom robotics and are not prerequisites for the technical Chapters 3 to 7:

Chapter 1 provides an overview of the history and different types of industrial robots, and their socioeconomic impact.

Chapter 2 provides an overview of electronics manufacturing in cleanroom environments, cleanliness standards, and the emergence of cleanroom robots in semiconductor manufacturing.

Chapter 3 presents guidelines and best practices for the design of atmospheric robots, including the design example of a wafer-handling robot.

Chapter 4 presents guidelines and best practices for the design of vacuum robots, including the design example of a wafer-handling vacuum robot for automating a six-sided cluster tool.

Chapter 5 reviews common kinematic structures before discussing the kinematics of SCARA-type robots that are commonly used in electronics manufacturing. The forward kinematics model of a three-link robot arm is derived.

Chapter 6 discusses a general dynamic model for robot manipulators and derives the specific model for a three-link robot arm. A decentralized joint control strategy suitable for networked robot control is established.

Chapter 7 introduces several test and characterization methods and their underlying theory. Suitable test fixture designs are described.

A total of 29 examples throughout the book illustrate applications of the presented theory and concepts. All numerical examples were programmed in Matlab[®]. The International System of Units (SI units) is used whenever possible. For convenience some obsolete units that are still in use are also provided. SI base units, derived SI units, and unit conversion tables for non-SI units are listed in Appendix A. Applicable industry standards are listed at the end of each chapter. Contact information for the relevant publishing standards organizations are listed in Appendix B. Standard sets of conditions for temperature and pressure (STP) are listed in Appendix C. These are used to allow comparisons between different sets of experimental data and are relevant for applications in controlled vacuum and atmospheric environments.

Acknowledgments

This book would not have been possible without the advice and support of several engineers and scientists passionate about robotics. Special thanks go to Dr. Martin Aalund, Izya Kremerman, Ken Park, Jeff Thompson, and Enoch Wall. I also thank Andrew Ayre, Robert Bergner, Alan Campbell, Phil Danielson, Walter Henry, William Holtkamp, Dr. Jeff Hudgens, Peter Lundquist, Venu Menon, Frank Pavlik, Dr. John Tenney, and Dalton Victor. NxRev, Inc. kindly provided the Pro/ENGINEER software for creating robot drawings. The advice, guidance, and support from the editorial staff at Cambridge University Press is much appreciated. I am especially grateful to my wife Maria and our children Francisca and Dustin. Without their continuous encouragement and patience this book would have not been possible.

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1 Industrial robotics

Robotics refers to the study and use of robots (Nof, 1999). Likewise, industrial robotics refers to the study and use of robots for manufacturing where industrial robots are essential components in an automated manufacturing environment. Similarly, industrial robotics for electronics manufacturing, in particular semiconductor, hard disk, flat panel display (FPD), and solar manufacturing refers to robot technology used for automating typical cleanroom applications. This chapter reviews the evolution of industrial robots and some common robot types, and builds a foundation for Chapter 2, which introduces cleanroom robotics as an engineering discipline within the broader context of industrial robotics.

1.1 History of industrial robotics

Visions and inventions of robots can be traced back to ancient Greece. In about 322 BC the philosopher Aristotle wrote: “If every tool, when ordered, or even of its own accord, could do the work that befits it, then there would be no need either of apprentices for the master workers or of slaves for the lords.” Aristotle seems to hint at the comfort such ‘tools’ could provide to humans. In 1495 Leonardo da Vinci designed a mechanical device that resembled an armored knight, whose internal mechanisms were designed to move the device as if controlled by a real person hidden inside the structure. In medieval times machines like Leonardo’s were built for the amusement of affluent audiences. The term ‘robot’ was introduced centuries later by the Czech writer Karel Capek in his play *R. U. R. (Rossum’s Universal Robots)*, premiered in Prague in 1921. ‘Robot’ derives from the Czech ‘robota,’ meaning forced labor, and ‘robotnik,’ a slave or servant. In *R. U. R.* robots rebel against their human creators and eventually kill them, assuming control of the world. Capek seemed surprised by the enormous interest in his robots: “For myself, I confess that as the author I was much more interested in men than in robots” (Jerz, 2002). Another influential piece of art, Fritz Lang’s seminal movie *Metropolis*, was released in 1926. Maria, the female robot in the film, was the first robot to appear on screen.

Isaac Asimov, the ingenious science fiction author, is generally credited with the popularization of the term ‘robotics.’ He used it in 1941 to describe the study of robots and predicted the rise of a powerful robot industry. The term was first published in his short story ‘Runaround’ in 1942, and then in 1950 in the collection *I, Robot*, which also introduced his famous Three Laws of Robotics (Asimov, 1950). The Zeroth Law was

later added to close some ‘loopholes.’ The Laws of Robotics and their possible implications for technology attracted significant attention and are a common reference for robotics in the context of artificial intelligence. See, for example, Clarke (1993; 1994).

Denavit and Hartenberg (1955) applied homogeneous transformations for modeling the kinematics of robotic manipulators. The advent of automated flexible manufacturing systems (FMS) in the 1960s established robotics as a scientific discipline. The primary objectives for FMS are reduced labor costs, a high product mix, and a factory utilization near factory capacity. A typical FMS combines industrial robots, an automated warehouse, automated material handling, and complex software systems for simultaneously modeling, operating, and monitoring the factory. Industrial robots are a critical factor in this strategy that minimizes the role of human labor, allowing rapid changes to assembly lines, avoiding costly equipment replacements, and enabling the economical production of customized lots (Aron, 1981; Kahaner, 1991; Megahed, 1993; Sciavicco and Siciliano, 1996). *Industrial Robot*, the first international journal dedicated to robotics, began publication in 1972.

Table 1.1 lists selected milestones in the development of industrial robots, including cleanroom robots in electronics manufacturing (Isom, 2004; Kunii and Port, 2001; Spong and Vidyasagar, 1989). Some emerging areas such as service robots and intelligent robotics are not considered.

1.2 The global robotics industry

In the early 1960s the United States was virtually without competition in robot research and production and led Japan, Europe, and the Soviet Union by several years (Aron, 1981). One of the first industrial robots, the Unimate, was manufactured in the United States in 1961 by Unimation, based on a patent filed in 1954. The Unimate, also called a ‘programmable transfer machine,’ was designed for material handling. It utilized hydraulic actuators and was programmed in joint coordinates during ‘teaching’ by a human operator. The angles of the various joints were stored and played back in operation mode. Victor Scheinman’s Stanford Arm, an all-electric, six-axis articulated arm designed for tracking arbitrary paths in three-dimensional space, increased the applicability of robots to more sophisticated applications such as assembly and welding. Unimation acquired and further developed the Stanford Arm with support from General Motors, and later commercialized it as the PUMA (programmable universal machine for assembly) model.

The Japanese robot industry was ‘jump-started’ in 1967 when the Tokyo Machinery Trading Company began importing the Versatran robot from AMF Corporation. In 1968 Kawasaki Heavy Industries entered a technology license agreement with Unimation and in 1969 began to produce robots in Japan. In the late 1970s worldwide interest and investment in industrial robotics increased dramatically, resulting in a remarkable boom in global robot industries. Many start-up companies and several large US and Japanese conglomerates entered the market and began producing industrial robots, some resembling the Unimation models, whose designs were protected by patents in the United States but not in Japan (Nof, 1999).

Table 1.1. Selected milestones in industrial robotics.

Year	Milestone
1954	Devol designs a programmable factory robot (patent granted in 1961) aimed at ‘universal automation’ (patent granted in 1961). His company was named Unimation.
1956	Devol’s design prompts Joseph F. Engelberger to champion industrial robots and make Unimation Inc. the world’s robot pioneer.
1959	A prototype Unimate arm from Unimation is installed in a General Motors factory. The first commercial industrial robot is installed in 1961.
1960	AMF Corp. introduces the first industrial robot with a cylindrical coordinate frame, the Versatran by Harry Johnson and Veljko Milenkovic.
1967	Japan imports the first industrial robot, a Versatran from AMF.
1968	Unimation licenses its technology to Kawasaki Heavy Industries Ltd. of Japan. This helps to ignite an explosion of robot development in Japan.
1970	Victor Scheinman at the Stanford Research Institute (SRI) introduces the Stanford Arm, an improvement on the Unimate.
1971	Cincinnati Milacron Inc. markets T3 (The Tomorrow Tool), a computer-controlled robot designed by Richard Hohn.
1973	The Asea Group of Sweden introduces the all-electric IRb 6 and IRb 60 robots designed for automatic grinding operations.
1977	Asea Brown Boveri Ltd. (ABB) introduces microcomputer-controlled robots.
1978	Unimation and GM develop the PUMA (programmable universal machine for assembly) based on Victor Scheinman’s robot arm design.
1979	Yamanashi University designs the SCARA (selective compliance arm for robotic assembly). IBM and Sankyo Robotics jointly market this robot.
1979	The semiconductor industry publishes the first standard for 200 mm wafers* (SEMI M1.9-79).
1980	Japan becomes the world’s largest robot manufacturer. By 1990, Japan’s approximately 40 robot makers dominate the global robot market.
1981	Asada and Kanade build the first direct-drive arm at Carnegie Mellon University.
1984	The industrial robot industry consolidation begins. Most small robot companies go out of business within six years.
1994	The semiconductor industry plans to manufacture devices on 300 mm wafers. The first pilot line is targeted for 1997 and early production is planned for 1998 using a high level of automation.
1995	The second robot boom begins, enabled by the computer power now available. Robot–human interaction is addressed.
1997	Substrate-handling robotic systems begin operation at the first 200 mm wafer fabrication facility, by SGS-Thomson in Catania, Italy.
1997	First publication of standards for 300 mm wafer handling (SEMI M1.15-97).
1999	SEMICONDUCTOR300, a joint venture between Infineon Technologies and Motorola, manufactures the first 64M DRAM on a 300 mm silicon wafer, in Dresden, Germany.
2000	TSMC opens its first 300 mm wafer manufacturing line at a chip foundry in Taiwan.
2012	The semiconductor industry’s initial target date to begin manufacturing on 450 mm wafers is 2012.

*A wafer is a semiconductor substrate on which multiple die are fabricated.

During the 1980s robot boom, which automated manufacturing on a large scale, the Japanese industrial robot industry (the number one robot producer since 1980) grew at a faster pace than anyone had estimated. From 1978 to 1990 Japanese industrial robot production grew by a factor of 25. During this rapid growth period the Japan Industrial Robot Association (JIRA) repeatedly corrected its forecasts by +80% and more (Aron,

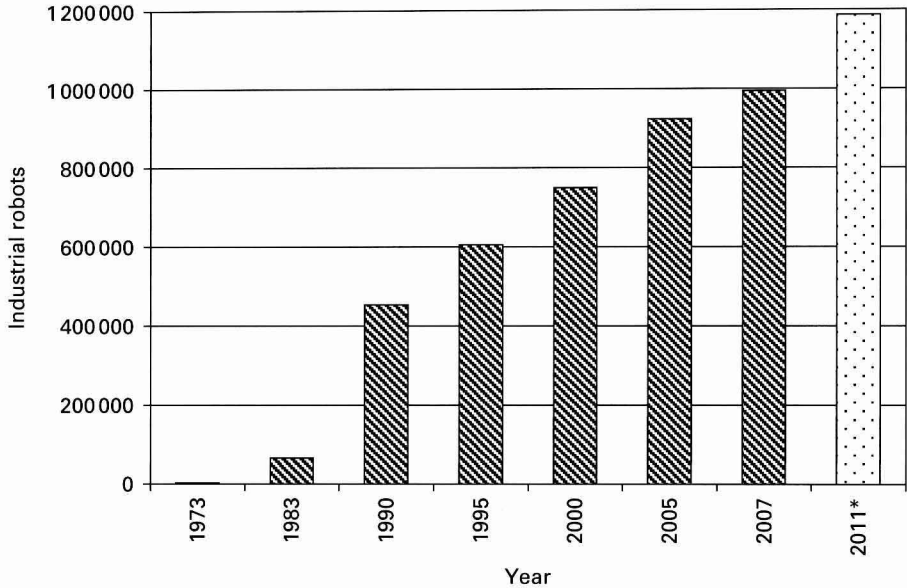


Figure 1.1 Operational stock of industrial robots 1973 to 2011 (* = estimate). Source: World Robotics 2008 (IFR, 2008a).

1981; Kahaner, 1991). (Note: until 2000 Japan used a broader definition for industrial manipulator than the USA and Europe.) The International Federation of Robotics estimates that the worldwide operational stock of industrial robots had reached almost one million in 2007 (Figure 1.1). This number is estimated to increase to almost 1.2 million by 2011. Estimates depend on the assumed average service life, typically between 12 and 15 years, and do not include about 550 000 older robots that had already been decommissioned.

JIRA (now JARA, see Appendix B) attributes this success to three characteristics of industrial robots:

- Industrial robots are programmable automation devices and are, as a consequence, flexible and versatile (unlike special-purpose automated machines).
- Industrial robots exceed the physical and mechanical abilities of humans during extended work periods and in uncomfortable or hazardous environments.
- Industrial robots perform with high fidelity and accuracy and in compliance with their programmed instructions.

Eventually the enormous Japanese robot industry, with its greater financial resources, prevailed in the global competition against its American and European rivals. The first industry consolidation lasted from about 1984, the height of the robot boom, until 1990, and only a small number of non-Japanese companies survived. In 1996, 5 of the 10 largest producers of six-axis robots were Japanese (Schubert, 2005). In 2005 the largest

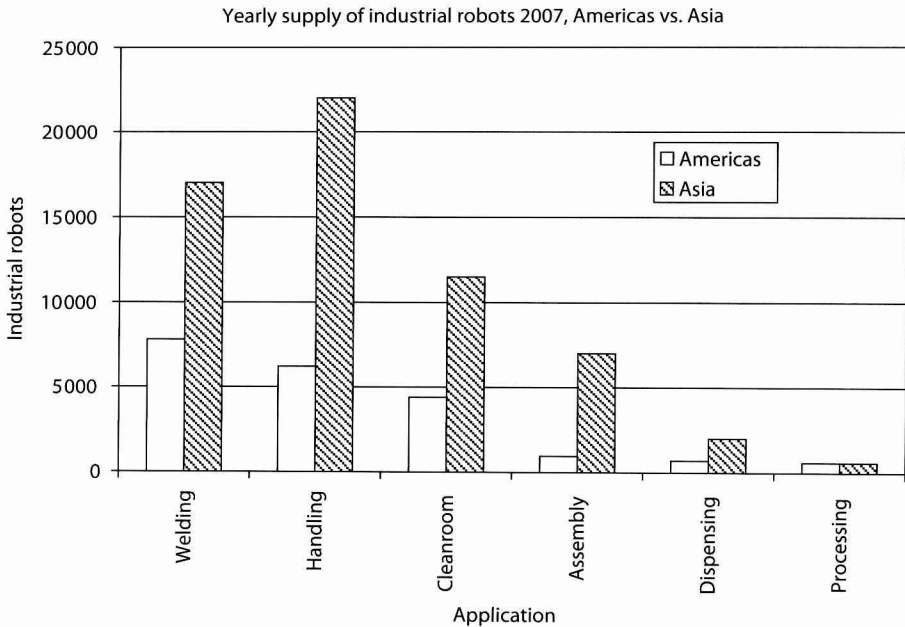


Figure 1.2 Supply of industrial robots by application, Americas versus Asia in 2007. Source: World Robotics 2008 (IFR, 2008b).

industrial robot manufacturers worldwide were Fanuc (Japan), Motoman (Japan¹), ABB (Sweden), and Kuka (Germany).

1.3 Applications and operational stock by region

The automotive industry was the first to adopt industrial robots on a large scale, primarily for welding applications, followed by the electronics industry with assembly applications. However, the distribution of industrial robot applications varies by economic regions. Figure 1.2 shows the 2007 supply of industrial robots by application for the Americas and for Asia. About 118 000 new industrial robots were supplied worldwide in 2007. The figure shows that in both regions the greatest number of robots was installed for welding and handling, followed by cleanroom applications. The shipment of cleanroom robots increased by a factor of three in the Americas from 2005 to 2007 (IFR, 2008b). In Asia that number decreased in the same time frame.

The global operational stock of multipurpose industrial robots, surveyed by the International Federation of Robotics (IFR, 2007; IFR, 2008b), suggests that Japan's lead position, which the country assumed in 1980, will gradually erode over time. See Figure 1.3. Until the early 1990s installations of multipurpose industrial robots in the European Union (20%) and the United States (7%) reached only a fraction of the number of installations in Japan. Since the mid 1990s the momentum in the industrial robot

¹ Motoman is owned by Yaskawa Electric Corporation, Japan.

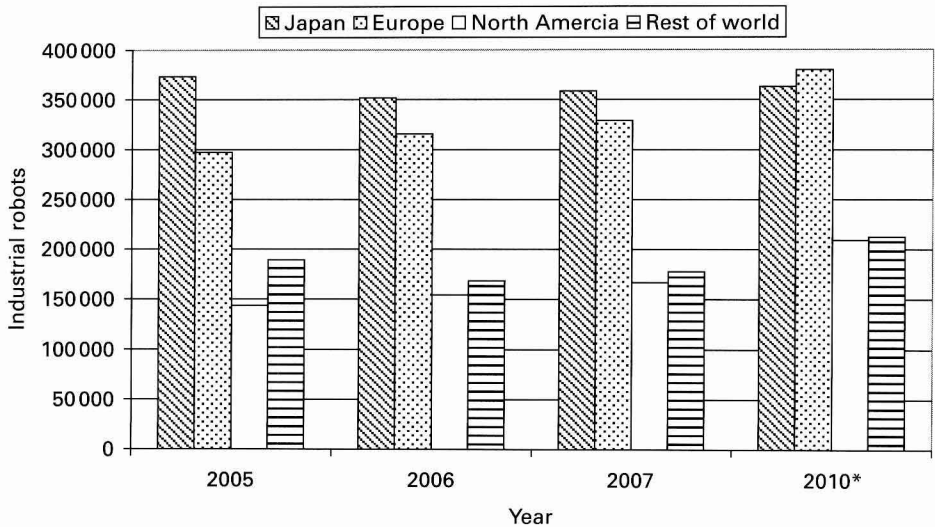


Figure 1.3 Operational stock of industrial robots 2005 to 2010 (* = estimates). Source: World Robotics 2007 (IFR, 2007).

business has shifted to Europe, North America, and other countries. This trend is reported for new installations as well as for operational stock, which has declined in Japan since 1998. Since 2001 the European Union is the leading economic region in installing multipurpose industrial robots.

1.4 Socioeconomic impact

A point of debate about the introduction of robots in America and Western Europe was the loss of jobs caused by robots. This was rarely discussed in Japan, where the positive effects of robots influenced public opinion, in particular the improvement of quality, productivity, and worker safety. It has been argued that the ‘labor problem’ in the USA and in Western Europe helped Japan to dominate the industrial robot market.

The economic advantage of the industrial robot over human labor is the most important factor in investment decisions, for several reasons (Aron, 1981):

- Reduced labor cost
- Improved productivity
- Improved and more stable product quality
- Resource conservation.

Further reasons are increased workplace safety, increased flexibility of production systems, and labor shortages. The economic advantage is accentuated by the continuously growing gap between increasing labor costs and declining robot costs. Figure 1.4 shows the global price index for industrial robots from 1990 until 2002, established by the United Nations Economic Commission for Europe (UNECE) and the International Federation of Robotics (IFR). The index is adjusted for 1990 currency conversion rates. It

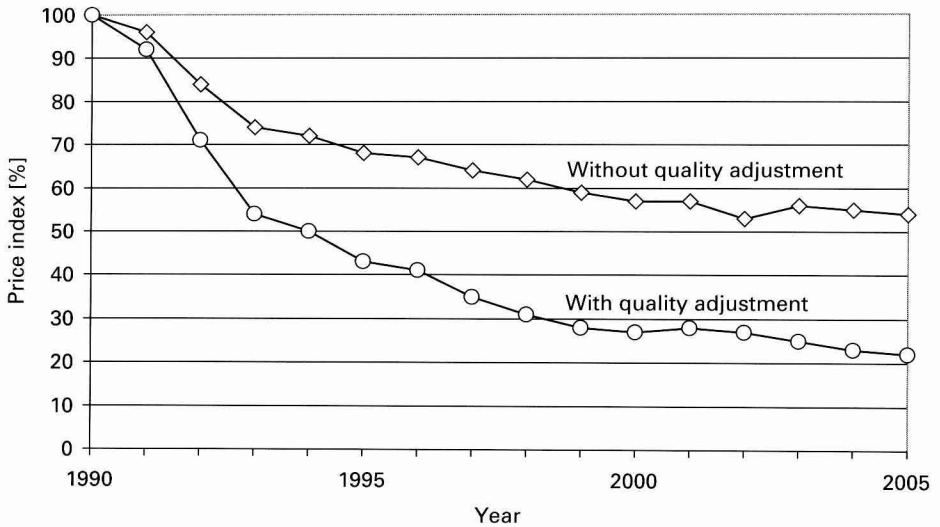


Figure 1.4 Price index for industrial robots 1990 to 2005 (IFR, 2006).

is shown with and without adjustments for quality improvements (IFR, 2006). The price indices were based on the same seven robot models supplied by four major international robot companies with large market shares in Europe and the United States. Without quality adjustment robot prices declined 46% during that time period. Taking into account the enormous performance improvement of robots, the quality-adjusted price decline was 78%.

Robots ‘compete’ with human workers in manufacturing, at least from an economics perspective, so it seems logical to include the cost of human labor in the price index for industrial robots. The relative prices of industrial robots would fall even more if the (typically increasing) cost of labor compensation is part of the equation. In fact, the IFR study (IFR, 2006) concludes that, with the index of labor compensation included in the price index for industrial robots, robot prices declined by a stunning 90% between 1990 and 2005. Decreasing robot prices, increasing labor costs, and improved robot technology are considered the key drivers for recent, massive robot investment. The amortization period for industrial robots can be as short as one to two years, although the initial cost during the first year after a robot installation can be high, due to production line changes and interest costs. Production slowdowns during robot integration also accrue cost. A case study in Japan found that production initially declined and total costs grew by up to 30%, but at the end of the second year total costs were 25% lower compared to the previous manual production.

1.5 Definitions, standards, and terminology

Standardization is essential for global industries, including not only product standards but also a common terminology and definitions. Cleanroom robotics is a discipline within