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,

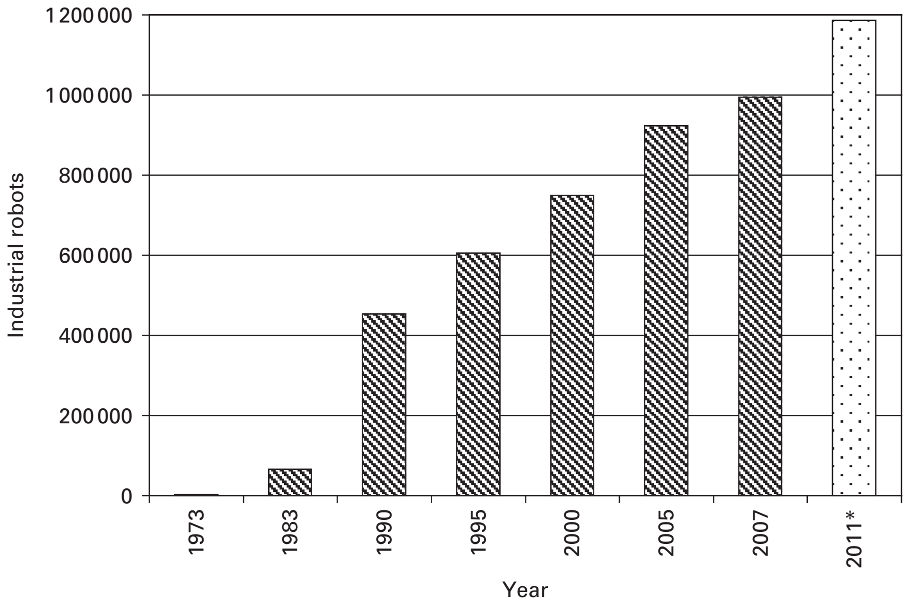

Figure 1.1 Operational stock of industrial robots 1973 to 2011 (* = estimate). Source: World Robotics 2008 (IFR, 2008a).

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

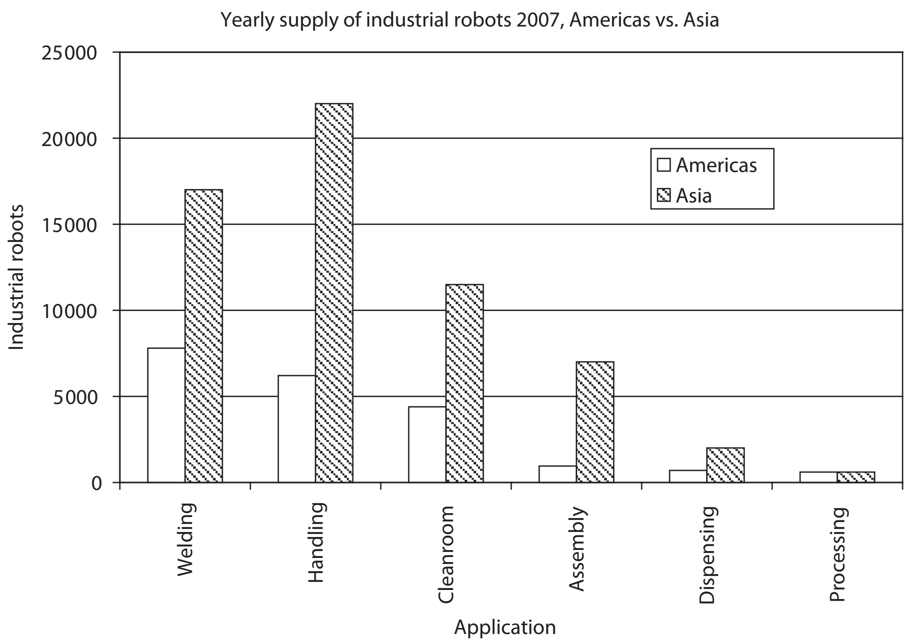

Figure 1.2 Supply of industrial robots by application, Americas versus Asia in 2007. Source: World Robotics 2008 (IFR, 2008b).

industrial robot manufacturers worldwide were Fanuc (Japan), Motoman (Japan[1]), 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.

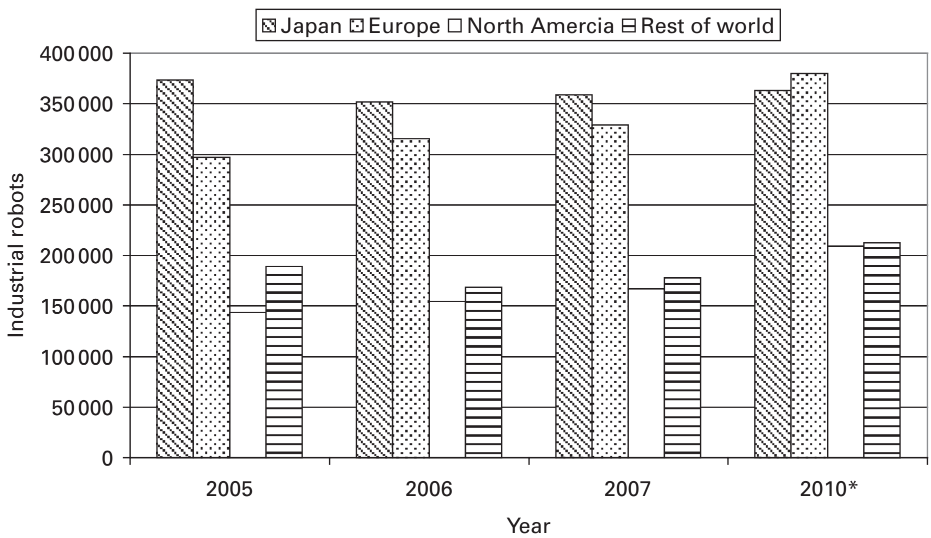

Figure 1.3 Operational stock of industrial robots 2005 to 2010 (* = estimates). Source: World Robotics 2007 (IFR, 2007).

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

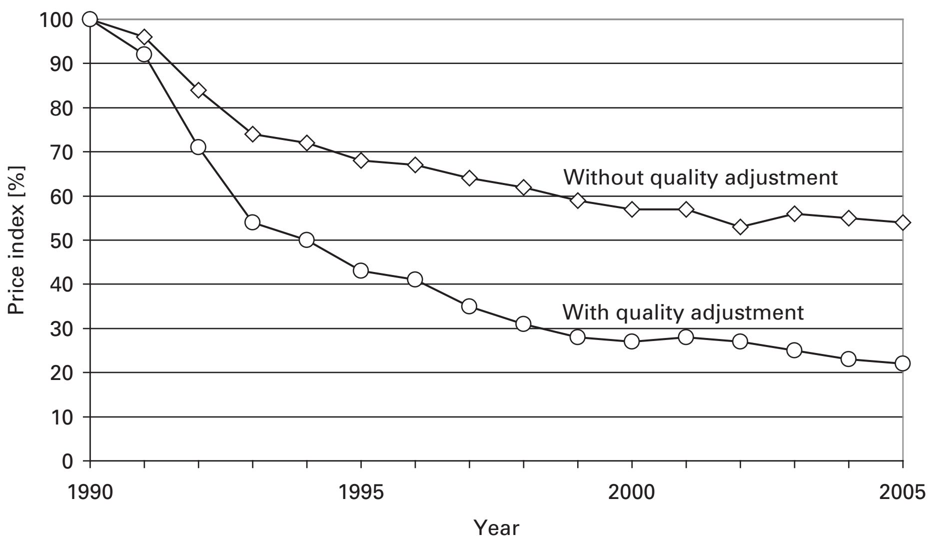

Figure 1.4 Price index for industrial robots 1990 to 2005 (IFR, 2006).

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 the broader field of industrial robotics, and is critical, for example, for automating in electronics manufacturing. It is recommended that relevant standards from international standards organizations, or applicable national standards, should be applied. Several definitions for industrial robots, robot systems, and robotics are compared below.

1.5.1 Robot definitions

Japan was the first country to identify robot production as a major strategic industry. Several policies, including standardization, were introduced to popularize robot utilization in manufacturing. The Japanese Electric Machinery Law defined 'industrial robot' in 1971, and additional terminology for industrial robots was standardized in 1979 under the Japanese Industrial Standards (JIS). Other countries followed with national standards, and in 1988 the International Organization for Standardization (ISO) established standards for manipulating industrial robots operated in a manufacturing environment (ISO standard 8373). Most standards and definitions emphasize the flexibility and versatility of 'multipurpose industrial robots.' In contrast, the JIS also included 'dedicated industrial robots' until 2000 (Aron, 1981: Sciavicco and Siciliano, 1996; Megahed, 1993).

Japanese Electric Machinery Law

The Japanese Electric Machinery Law (1971) defines an industrial robot as an all-purpose machine, equipped with a memory device and a terminal device (end-effector), capable of rotation and of replacing human labor by the automatic performance of movements (Aron, 1981).

Japan Robot Association (JARA)

JARA uses a broad classification of industrial robots based on the programming or control method used, formalizing it in the Japanese Industrial Standard JIS B0134:1979, No. 2110–2140. The classes are listed in Table 1.2 (McIntyre, 1997).

American National Standards Institute (ANSI), Robotic Industries Association (RIA)

The ANSI adopted RIA robot standards and defines an industrial robot as "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks." See, for example, ANSI standard 15.05. This definition corresponds to the JIS classes 3 to 6, but eliminates the manual manipulators and fixed sequence machines.

Association Française de Robotique (AFR)

The Association Française de Robotique (AFR) classifies industrial robots using four types, loosely corresponding to the JIS classes: Type A – telerobotic manipulator; Type B – sequencing robot; Type C – numerically controlled robot; Type D – intelligent robot.

International Organization for Standardization (ISO)

The international standard ISO 8373:1994, originally published in 1988, includes the following definitions related to industrial robots.

Table 1.2. Correspondence between robot definitions published in the Japanese Industrial Standard (JIS) and ISO standards.

Robot category per JIS B0134:1998	Robot definitions per ISO 8373:1994
Sequenced robot (No. 2110)	"Fixed sequence manipulator (No. 2.2): manipulator which performs each step of a given operation according to a predetermined motion operation pattern which cannot be changed without physical alteration."
	"Sequenced robot (No. 2.10): robot having a control system in which the state of machine movements occurs axis by axis in a desired order, the completion of one movement initiating the next."
Playback robot (No. 2120)	"Playback robot (No. 2.8): robot that can repeat a task program which is entered through teach programming."
Numerically controlled robot (No. 2130)	(ISO standard not available)
Intelligent robot, with one of three control functions (No. 2140):	"Adaptive robot (No. 2.12): robot having sensory control, adaptive control, or learning control functions."
	(ISO uses the term 'adaptive' instead of 'intelligent'.)
(a) Sensory control (No. 2141)	"Sensory control (No. 5.3.3): control scheme whereby the robot motion or force is adjusted in accordance with outputs of external sensors."
(b) Adaptive control (No. 2142)	"Adaptive control (No. 5.3.4): control scheme whereby the control system parameters are adjusted from conditions detected during the process."
(c) Learning control (No. 2143)	"Learning control (No. 5.3.5): control scheme whereby the experience obtained during previous cycles is automatically used to change control parameters and/or algorithms."
Teleoperated robot (No. 2150)	(ISO standard not available.)

Definition 1.1 (ISO 8373, No. 2.6): "A manipulating industrial robot is 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. Note: The robot includes the manipulator (including actuators) and the control system (hardware and software)."

Definition 1.2 (ISO standard 8373, No. 2.14): A robot system is a "system comprising robot, end-effector, any equipment, devices, or sensors required for the robot to perform its task, and any communication interface that is operating and monitoring the robot, equipment, or sensors, as far as these peripheral

	devices are supervised by the robot control system."
Definition 1.3 (ISO standard 8373, No. 2.15):	Robotics is the "practice of designing, building, and applying robots."

The ANSI/RIA standard R15.06 includes a similar definition for industrial robot systems. The above definitions provide the basis for the industrial cleanroom robots presented in Chapter 2.

1.5.2 National and international standards

The International Organization for Standardization (ISO) established robot definitions that correspond to definitions listed in several national standards. Table 1.2 compares the ISO definitions of robot classes with the corresponding robot classes in the Japanese Industrial Standard JIS B0134:1994. The classes also reflect the technical advancement of industrial robots over time: early sequenced robots were numerically controlled manipulators without interaction with the environment through sensors. They were (and still are) programmed off-line. Playback robots are calibrated by 'teaching' through teach pendants, where a human operator guides the manipulator to the desired position, which is recorded for operation. This method is sufficient for 'blind' pick-and-place tasks in structured environments where the locations of tools and work pieces are fixed and well-defined. Intelligent or adaptive robots are equipped with the sensory devices needed for position feedback from the environment, for example proximity sensors or vision systems. This enables feedback control for operating in a changing environment. It also allows the automatic teaching of reference positions (Megahed, 1993; Zhuang and Roth, 1996).

1.5.3 Standard robot types

The main characteristics of industrial robots are

- Number of axes of motion
- Kinematic structure
- Work envelope
- Maximum payload
- Maximum speed
- Accuracy
- Drive train (actuators, remote vs. direct-drive).

Eight robot types are defined in the ISO standard 8373:1994 based on their kinematic structure and the coordinate frame that spans the workspace: Cartesian robots, cylindrical robots, spherical (or polar) robots, pendular robots, articulated (or anthropomorphic) robots, SCARA robots, spine robots, and parallel robots. The preferred kinematic structure of industrial robots depends on the application at hand and is influenced by the required motion, payload, end-effector orientation, and other factors. A robot type