UNIVERSITY OF TORONTO

INSTITUTE FOR AEROSPACE STUDIES

AER 525F

ROBOTICS

Course Notes

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Chapter 1

Introduction

1.1 Definitions

1.1.1 Robotics:

Longman Dictionary of Contemporary English, 3rd Edition, 1995:

The study of how *robots* are made and used.

Ro.bot a machine that can move and do some of the work of a person, and is usually controlled by a computer.

Meriam-Webster Dictionary On-line:

Technology dealing with the design, construction, and operation of robots in automation.

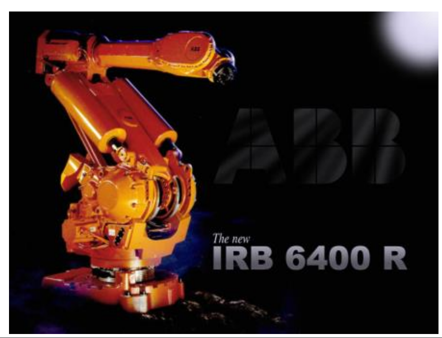
Ro.bot **1:** a machine that looks like a human being and performs various complex acts (as walking or talking) of a human being; **2:** a device that automatically performs complicated often repetitive tasks; **3:** a mechanism guided by automatic controls.

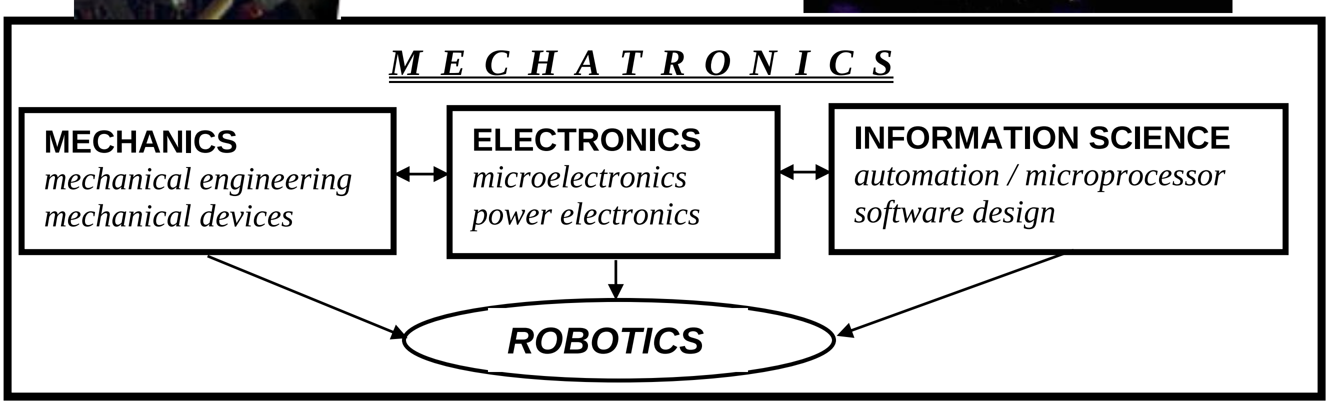
Robotics Institute of America, 1979:

A collection of science and knowledge that is useful for design, analysis and control of (industrial) robots, i.e., ***automatic*** (servo-controlled), ***reprogrammable***, ***multifunctional*** manipulators designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks.

Hollywood Perception

Industrial Perception

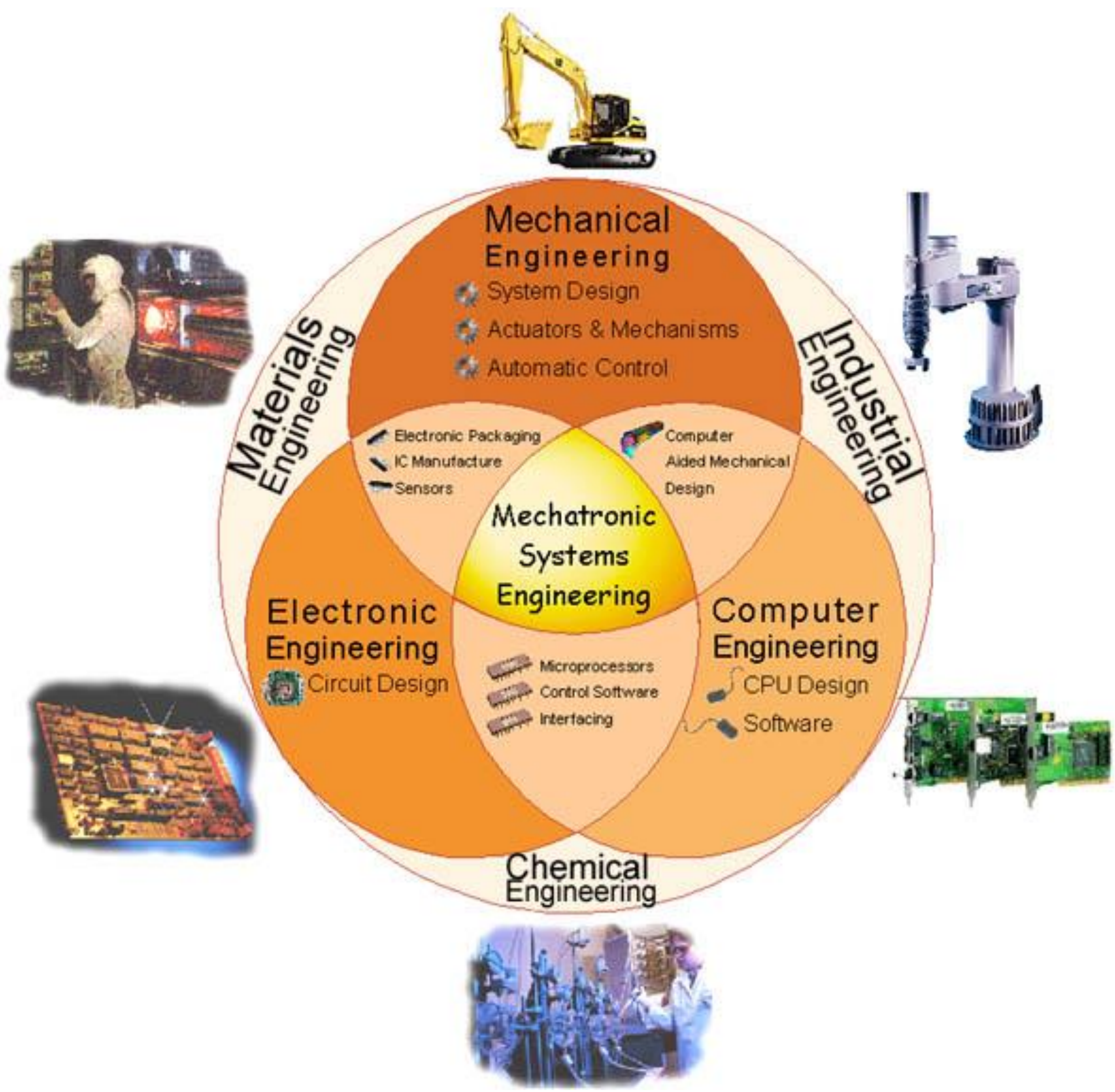




1.1.2 Mechatronics:

An integrative discipline utilizing the technologies of *mechanics*, *electronics* and *information/microprocessor technology* to provide enhanced products, processes and systems. It integrates the classical fields of mechanical engineering, electronic engineering and computer science/information technology at the design stage of a product or a system.

Mechatronics is the synergetic combination of precision mechanical engineering, electronic control and system thinking in the concurrent design of products and processes.



1.1.3 Essential Characteristics of A Robot

1. A robot must be produced by manufacturing rather by biology. (This does not rule out the eventual use of artificial biochemically-produced structures such as muscles.
2. It must be able to move/manipulate physical objects and/or be mobile itself (mimic some human actions.)
3. It must be a power or force source or amplifier, or displacement resolver.
4. It must be capable of some sustained action without intervention by an external agent, i.e., make decisions based on available information or ask for additional information.
5. It must be able to modify its behavior in response to sensed properties of its environment, and therefore must be equipped with sensors.
6. It must interact with humans in a "friendly" manner.
7. It must operate "safely."

1.1.4 Asimov's Laws of Robotics (1950)

Law Zero: A robot may not injure humanity, or, through inaction, allow humanity to come to harm.

Law One: A robot may not injure a human being, or, through inaction, allow a human being to come to harm, unless this would violate a higher order law.

Law Two: A robot must obey orders given it by human beings, except where such orders would conflict with a higher order law.

Law Three: A robot must protect its own existence as long as such protection does not conflict with a higher order law.

1.2 Objectives

1.2.1 Why Robotics?

The key benefit of Robotics is automation in manufacturing and services. Motives for automation are:

Shortage of labour

- The ratio of the number of workers to the number of retirees in the U.S. was close to 2 to 1 in 2000.

High cost of labour

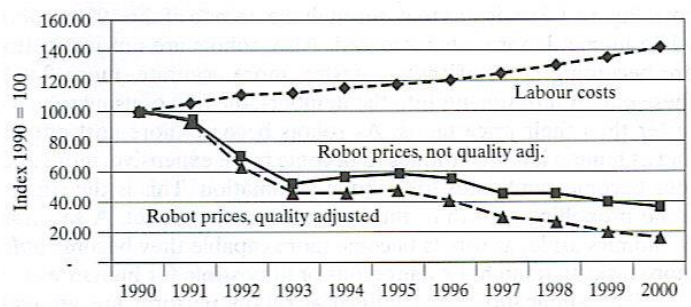
- Labour costs are rising. According to a U.N. study comparing wages in different countries, the average hourly labour cost (in US Dollars) has increased from 1985 to 1995 according to the table. At the same time, robot prices have been declining as illustrated in the graph (U.N. report).

Country	1985	1995
Germany	9.6	31.88
Japan	6.34	23.66
France	7.52	19.34
USA	13.01	17.20
UK	6.27	13.17
Malaysia	1.08	1.59
South Korea	1.23	7.40
China	0.19	0.25
India	0.35	0.25

- Low wages are also accompanied by lower productivity.

Increased productivity

- The value of output per person per hour increases through automation.



Lower costs

- Reduced scrap rate
- Lower in-process inventory
- Superior quality
- Shorter (compact) lines

Reducing manufacturing lead time

- Respond quickly to the consumers' needs
- Rapid response to changes in design

Competition

- Lower prices, better products
- Better image
- Better labour relations

Safety

- Operation in dangerous environments

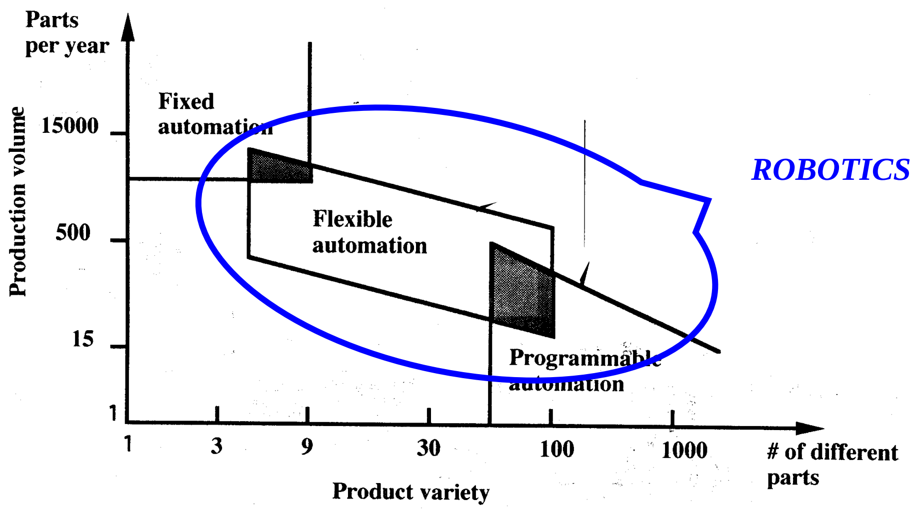
1.2.2 Types of Automation

Fixed Automation: Fixed automation refers to the use of custom-engineered (special purpose) equipment to automate a fixed sequence of processing or assembly operations. It is typically associated with high production rates and it is relatively difficult to accommodate changes in the product design. This is also called *hard automatio*n. Fixed automation is reasonable only when the product designs are stable and product life cycles are long.

Programmable Automation: In programmable automation, the equipment is designed to accommodate a specific class of product changes and the processing or assembly operations can be changed by modifying the control program. It is particularly suited to “batch production,” or the manufacture of a product in medium lot sizes (generally at regular intervals). In programmable automation, reconfiguring the system for a new product is time consuming because it involves reprogramming and set up for the machines, and new fixtures and tools.

Flexible Automation: In flexible automation, the equipment is designed to manufacture a variety of products or parts and very little time is spent on changing from one product to another. Thus, a flexible manufacturing system can be used to manufacture various combinations of products according to any specified schedule. With a flexible automation system, it is possible to quickly incorporate changes in the product (which may be redesigned in reaction to changing market conditions and to consumer feedback) or to quickly introduce a new product line.

Automation	When to consider	Advantages	Disadvantages
Fixed	high demand volume, long product life cycles	maximum efficiency, low unit cost	large initial investment, inflexibility
Programmable	batch production, products with different options	flexibility to deal with changes in product, low unit cost for large batches	new product requires long set up time, high unit cost relative to fixed automation
Flexible	low production rates, varying demand, short product life cycles	flexibility to deal with design variations, customized products	large initial investment, high unit cost relative to fixed or programmable automation



1.2.3 Reasons for Not Automating

Labour resistance

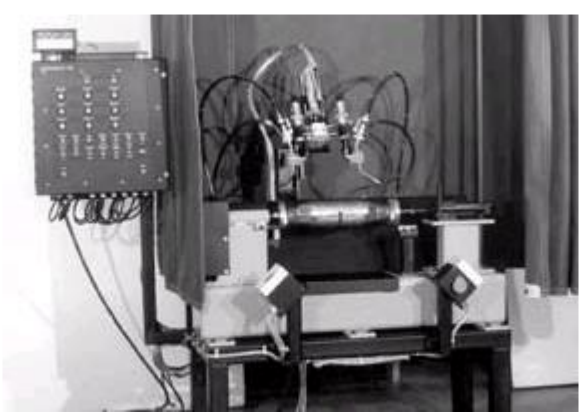
Cost of upgraded labour

- Chrysler Detroit plant - 1 million hours of retraining
- GM Wilmington assembly plant - $250 hours/person/year

Initial investment

Management of process improvements

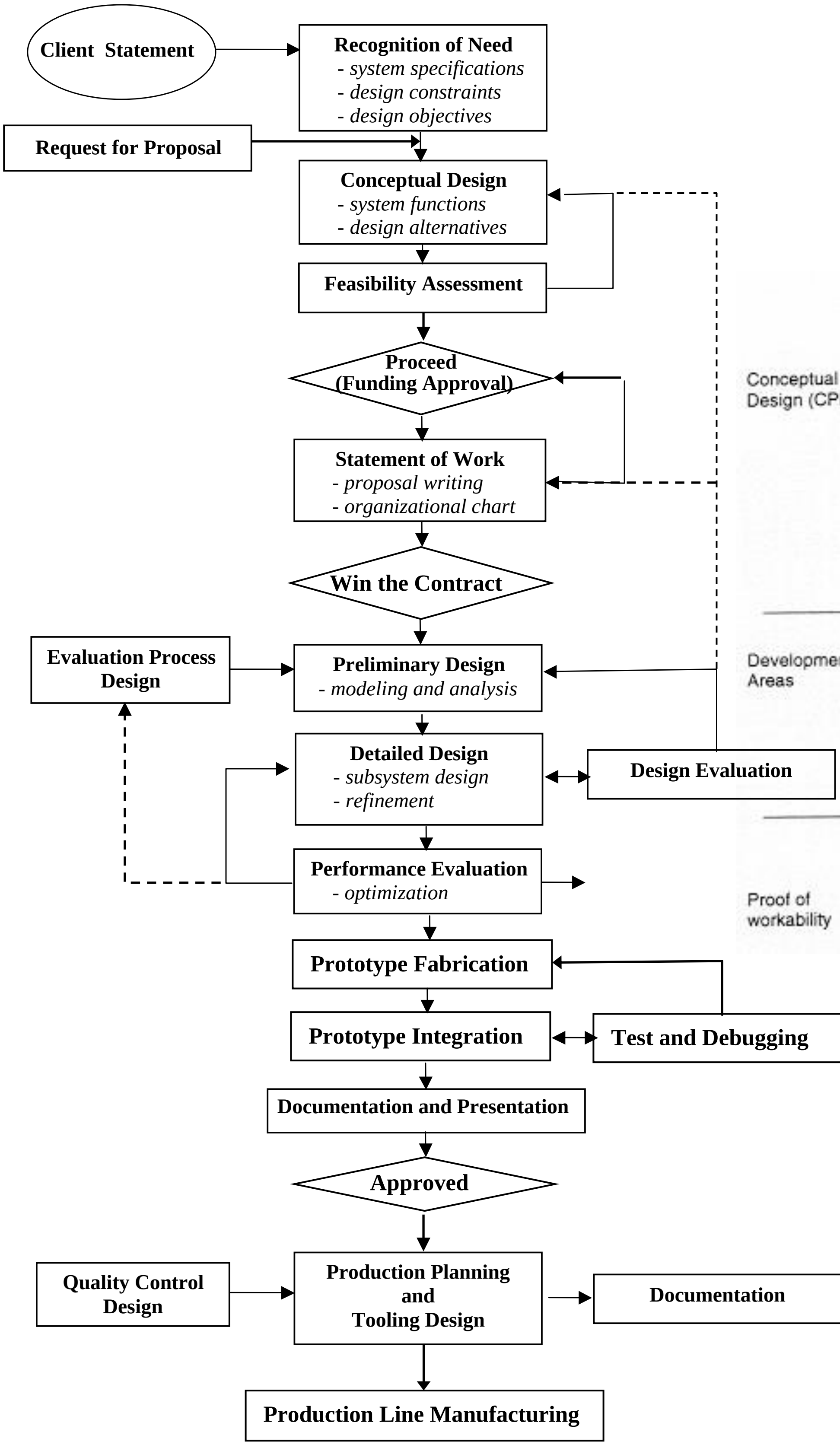
- Intellectual assets versus technological assets
- Appropriate use of technology
- A systems approach to automation is important
- Equipment incompatibilities

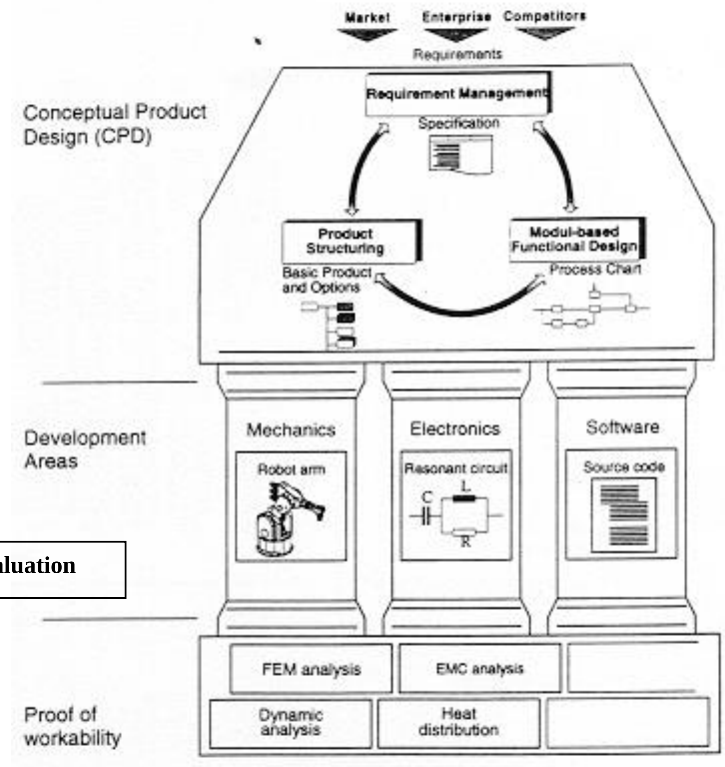


Fixed Automation dual torch welding lathe cell simultaneously welding two flanges onto an automotive catalytic converter

Flexible Automation robotic cell welding automotive engine cradle assembly

1.3 Design Process:





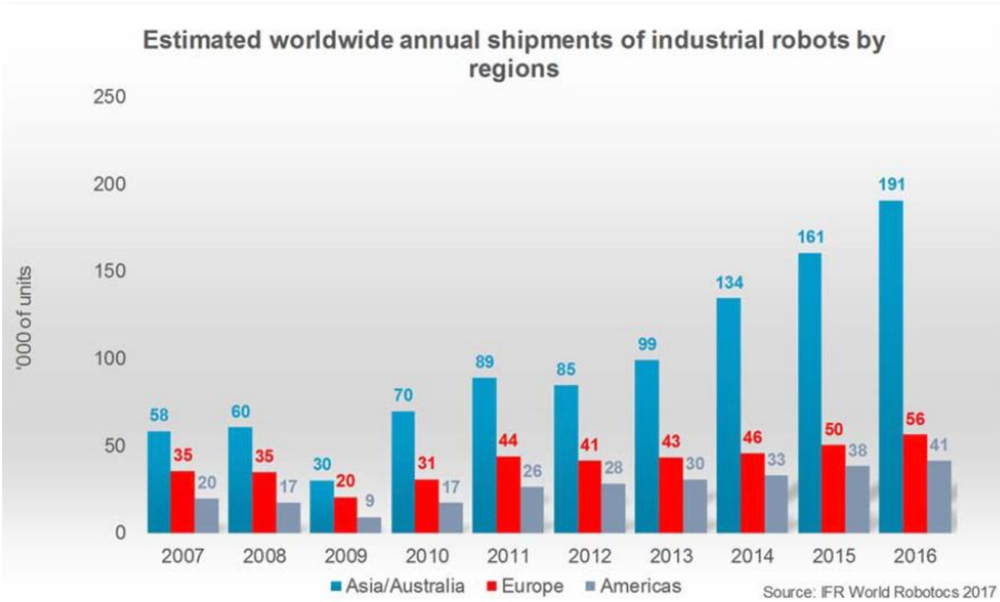
1.4 Robotics: A Brief History

- Early History, An ancient legend in India speaks of mechanical elephants. Also, the Greek myth of Jason and the Argonauts tells an encounter with Talos, a giant bronze sentinel “programmed” by gods to defend the island of Crete against intruders.
- ~ 800 B.C., In the Iliad, Book IX, walking tripods are referenced.
- ~ 350 B.C, The Greek mathematician, Archytas ('ahr 'ky tuhs') of Tarentum built a mechanical bird dubbed "the Pigeon" that was propelled by steam.
- ~ 322 B.C., The Greek 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.” .hinting how nice it would be to have a few robots around.
- ~ 300 B.C., The Greek inventor Ctesibus ('ti sib ee uhs') of Alexandria designed water clocks that had movable figures on them. Up until then the Greeks used hour glasses that had to be turned over after all the sand ran through. Ctesibus' invention changed this because it measured time as a result of the force of water falling through it at a constant rate. In general, the Greeks were fascinated with automata of all kinds often using them in theater productions and religious ceremonies.
- 1495, Leonardo DaVinci designed a mechanical device that looked like an armored knight. The mechanisms inside "Leonardo's robot" were designed to make the knight move as if there was a real person inside.
- 1738, Jacques de Vaucanson began building automata in Grenoble, France. He built three in all. His first was the flute player that could play twelve songs. This was closely followed by his second automaton that played a flute and a drum or tambourine, but by far his third was the most famous of them all. The duck was an example of Vaucanson's attempt at what he called "moving anatomy," or modeling human or animal anatomy with mechanics. The duck moved, quacked, flapped its wings and even ate and digested food.
- 1921, Karel Capek, the Czech writer coined the word “robot” from the Czech word “robotnik” for forced labour in his play “*Rossum’s Universal Robots*.”
- 1950, Issac Asimov introduced the notion of “robotics” in his science fiction book “*I Robot*.”

- 1954, George C. Devol filed a U.S. patent for a programmable method for transferring articles between different parts of a factory.
- 1958, Joseph F. Engelberger and George C. Devol set up the world's first robot company, Unimation, Inc.
- 1961, General Motors (GM), New Jersey ran the first industrial service robot in a car factory.
- 1962, The MIT Lincoln Laboratory and later, the Standford Artificial Intelligence Laboratory, 1968, began their development of robot manipulators with tactile sensors and computer vision.
- 1968, Unimation Inc. handed over its robot technology to Kawasaki Heavy Industries, Japan.
- 1982, GM signed a pact with Fanuc Ltd. For a joint robotics venture to make and market robots in the U.S.
- As of 1987, only the U.S. robotics market was valued at more than $170 billion.
- By 1990, there were more than 40 Japanese robotic companies, 10 in U.S., 10 in Europe, 2 in Canada.
- 1997, NASA sent a robotic rover called *Pathfinder* to Mars. Honda Laboratory invested nearly $80 million in the development of ASIMO, a 200 kg humanoid that is capable of walking up and down stairs.
- 1998, Tiger Electronics introduced the Furby into the Christmas toy market. Using a variety of sensors this "animatronic pet" could react to its environment and communicate using over 800 phrases in English and their own language "Furbish." Also, LEGO released their first toy of their product line MINDSTORMS, namely Robotics Invention System™ 1.0.
- 2003, NASA launched the MER-A "Spirit" and MER-B "Opportunity" rovers destined for Mars.
- 2004, both NASA’s rovers landed on Mars safely.

Current Status

Robotics is considered as a major industry in i) Manufacturing, ii) Military & Space Technology, iii) Services and Appliances, and iv) Entertainment.



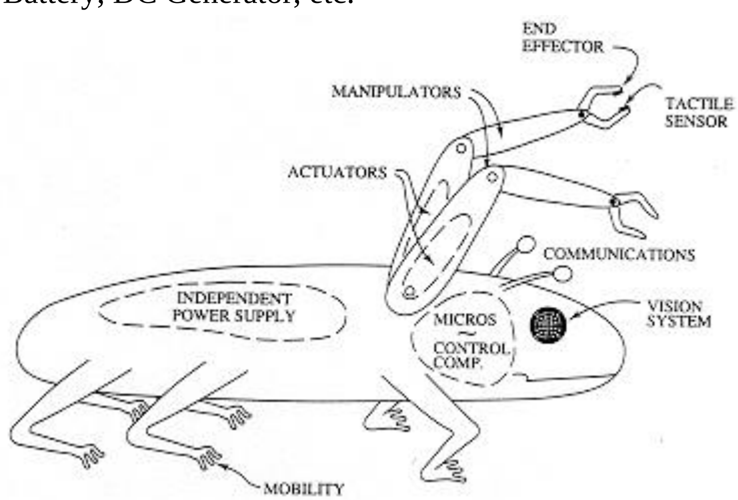
Estimated annual shipments of multipurpose industrial robots in selected countries.
Number of units

Country	2015	2016	2017*	2018*	2019*	2020*	2017/ 2016	CAGR 2018 - 2020
America	**38,134**	**41,295**	**48,000**	**50,900**	**58,200**	**73,300**	**16%**	**15%**
North America	36,444	39,671	46,000	48,500	55,000	69,000	16%	14%
- United States	27,504	31,404	36,000	38,000	45,000	55,000	15%	15%
- Canada	3,474	2,334	3,500	4,500	3,000	5,000	50%	13%
- Mexico	5,466	5,933	6,500	6,000	7,000	9,000	10%	11%
Brazil	1,407	1,207	1,500	1,800	2,500	3,500	24%	33%
Rest of South America	283	417	500	600	700	800	20%	17%
Asia/Australia	**160,558**	**190,542**	**230,300**	**256,550**	**296,000**	**354,400**	**21%**	**15%**
China	68,556	87,000	115,000	140,000	170,000	210,000	32%	22%
India	2,065	2,627	3,000	3,500	5,000	6,000	14%	26%
Japan	35,023	38,586	42,000	44,000	45,000	48,000	9%	5%
Republic of Korea	38,285	41,373	43,500	42,000	44,000	50,000	5%	5%
Taiwan	7,200	7,569	9,000	9,500	12,000	14,000	19%	16%
Thailand	2,556	2,646	3,000	3,500	4,000	5,000	13%	19%
other Asia/Australia	6,873	10,741	14,800	14,050	16,000	21,400	38%	13%
Europe	**50,073**	**56,043**	**61,200**	**63,950**	**70,750**	**82,600**	**9%**	**11%**
Central/Eastern Europe	6,136	7,758	9,900	11,750	13,900	17,500	28%	21%
France	3,045	4,232	4,700	4,500	5,000	6,000	11%	8%
Germany	19,945	20,039	21,000	21,500	23,500	25,000	5%	6%
Italy	6,657	6,465	7,100	7,000	7,500	8,500	10%	6%
Spain	3,766	3,919	4,300	4,600	5,100	6,500	10%	15%
United Kingdom	1,645	1,787	1,900	2,000	2,300	2,500	6%	10%
other Europe	8,879	11,843	12,300	12,600	13,450	16,600	4%	11%
Africa	**348**	**879**	**800**	**850**	**950**	**1,200**	**-9%**	**14%**
not specified by countries**	4,635	5,553	6,500	7,000	8,000	9,400	17%	13%
TOTAL	253,748	294,312	346,800	379,250	433,900	520,900	18%	15%

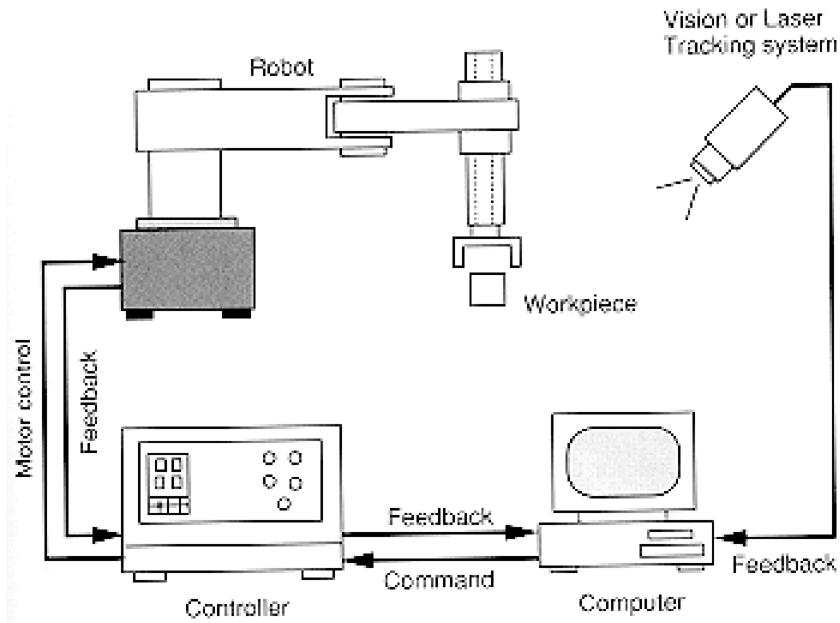
Sources: IFR, national associations
*forecast
** reported and estimated sales which could not be specified by countries

1.5 Robotic System Components:

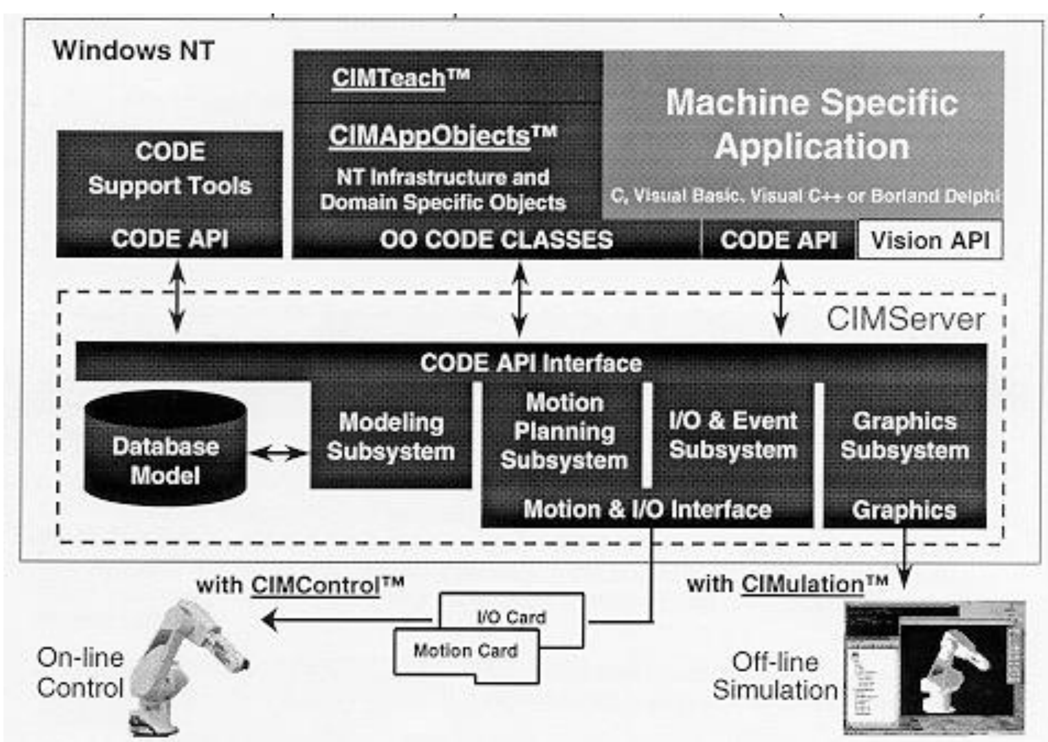
- **Mechanical Parts**
  - *Manipulator*: Several links connected by passive and active joints.
  - *End-Effector*: Attached at the output link to grasp, lift, and manipulate workpieces (from a simple gripper to a dexterous hand).
  - *Locomotion Mechanism*: Wheeled or legged platform to move the manipulator base.
- **Actuators**
  - *Rotary*: rotational displacement (mostly DC motors)
  - *Prismatic*: linear displacement (DC motors and Hydraulic/Pneumatic actuators)
- **Sensors**
  - *Displacement*: Optical Encoders, LVDT's, etc.
  - *Velocity*: Tachometers
  - *Torque*: (strain gauges)
  - *Tactile Sensors*
  - *Vision System*
- **Control Computer**: A microprocessor chip, a personal computer, or a mainframe computer capable of high-speed real-time computation, reasoning, and issuing intelligent control commands.
- **Communicator**: A/D and D/A interface, Filters and Amplifiers, Drivers, etc.
- **Power Supply**: Battery, DC Generator, etc.



Typical Structure:



Advanced Architecture:



1.6 <u>Examples</u>:

1.6.1 Industrial Applications

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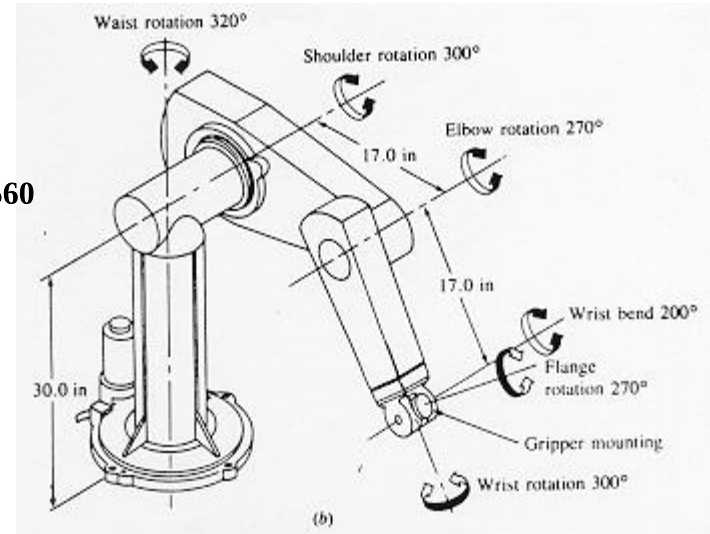
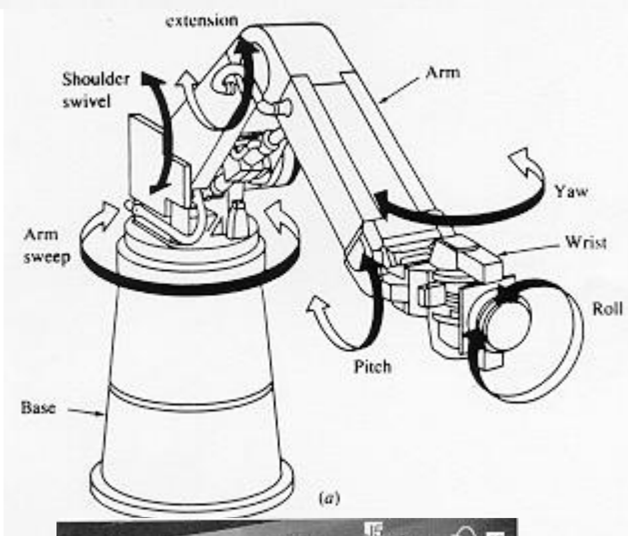
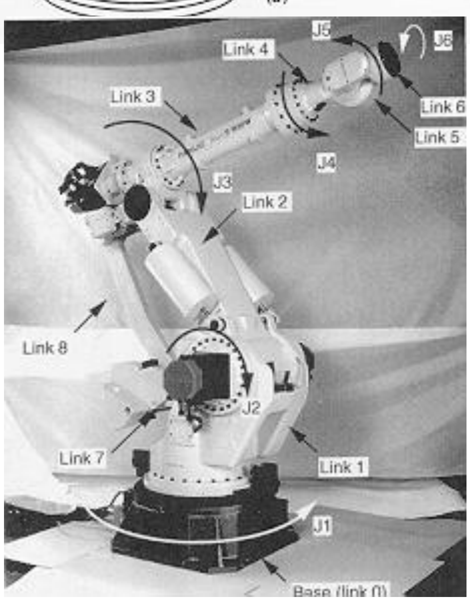
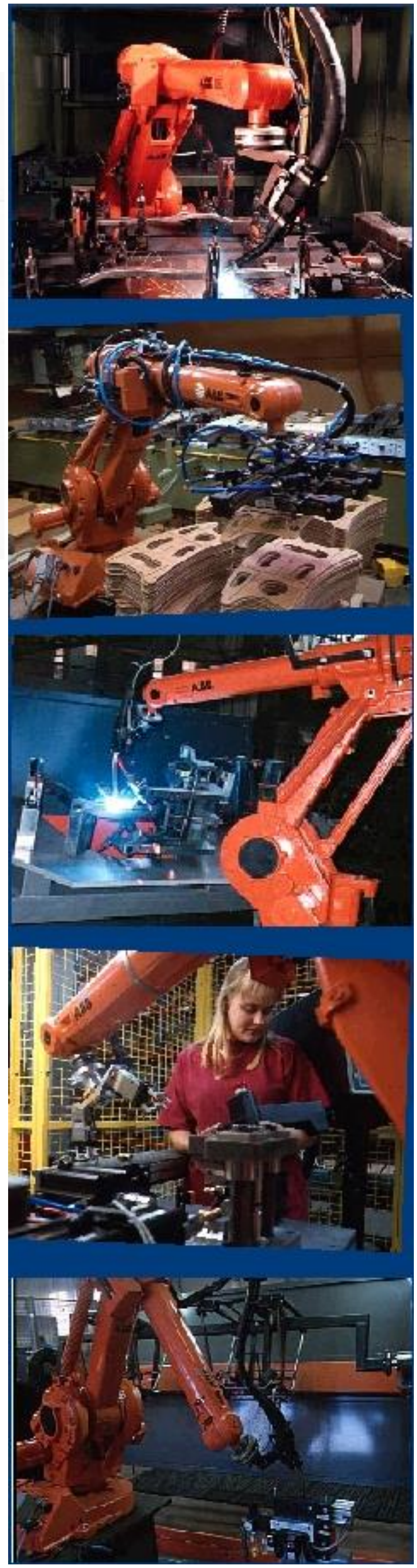


Cincinnati Milacron T3



Fanuc S-900W

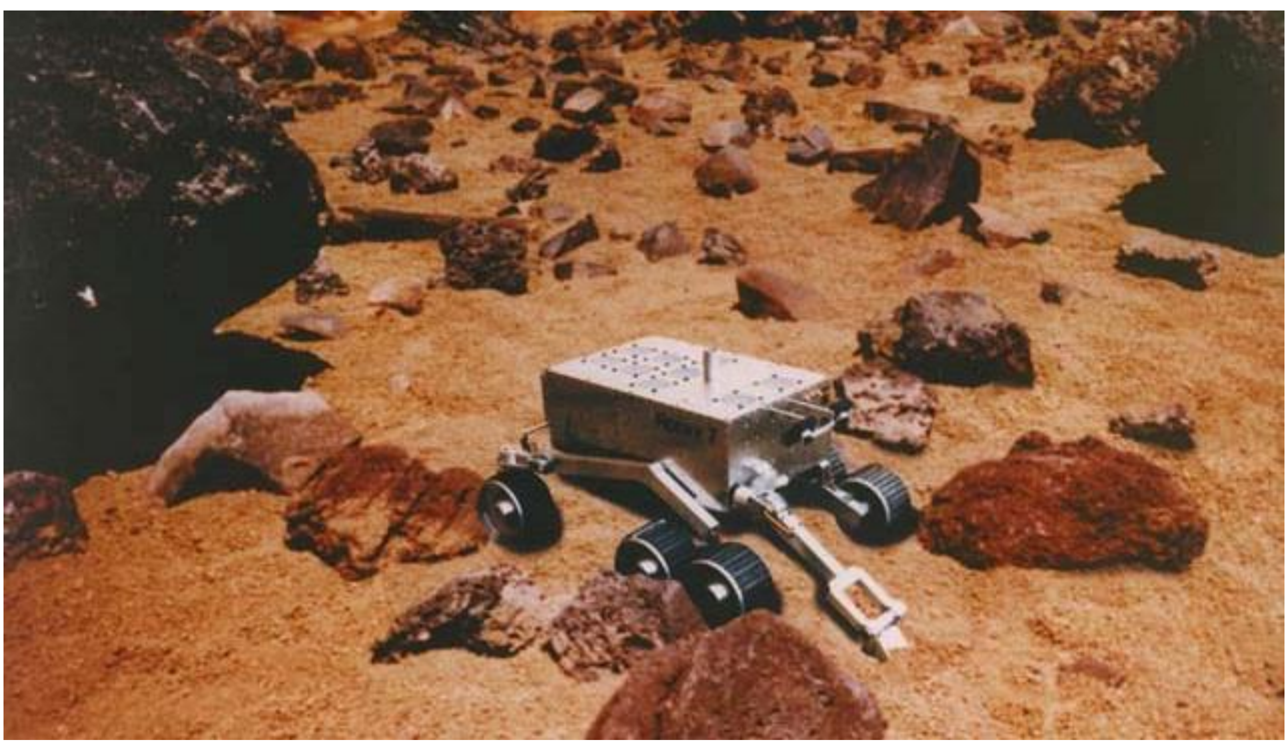




1.6.2 Military Applications

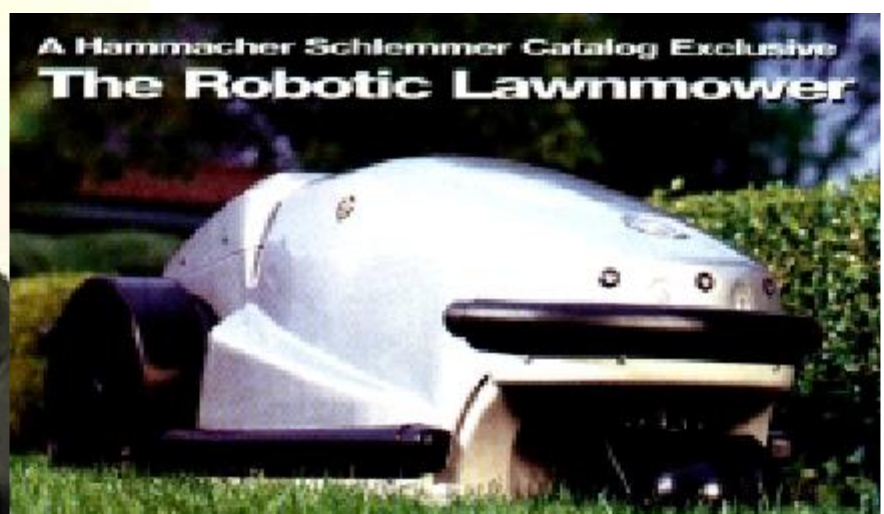
1.6.3 Fire Fighting, Search & Rescue Applications

1.6.4 Space Applications



1.6.5 Service Robots

Types of robots	Stock at end 1998	Installations 1999-2002
Cleaning robots	300	500
- Floor cleaning		
- Tank cleaning		
- Window cleaning; wall cleaning		
- Other (Aircraft cleaning)		
Sewer robots (cleaning, inspection))		
Wall-climbing robots (cleaning, inspection))	200	200
Inspection robots, general (power plants, nuclear sites, bridges, etc.)		
Underwater robots	400	200
- Inspection		
- Work class robots		
Domestic robots	2,000	12,500
- Vacuum cleaning		
- Lawn mowing		
- Other		
Medical robots	800	7,000
- Surgical robots		
- Robot-assisted surgery		
- Other		
Robots for disabled persons; Assistive robots; Wheelchair robots	200	200
Courier robots; Mail delivery robots	100	200
Mobile robot platforms (multiple use)	400	200
Surveillance robots; Security robots	50	300
Guide robots (e.g. in museums)		100
Refuelling robots	50	800
Fire and bomb fighting robots	150	400
Robots in the construction industry)		
Robots in agriculture and forestry)		
Hotel and restaurant robots)		
Clean-room robots)	350	1,000
Laboratory robots)		
Space robots)		
Entertainment robots)		
Other types)		
Total number of units, excluding vacuum cleaning robots	**5,000**	**23,600**
Vacuum cleaning robots		**450,000**
Estimated value in $ millions	**600**	**3,300**

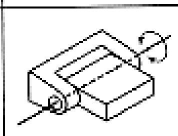
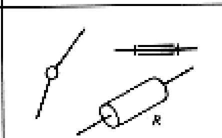
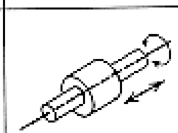
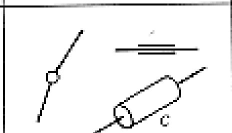
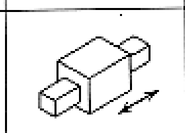
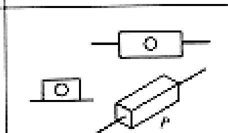
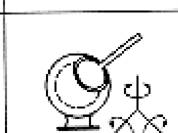
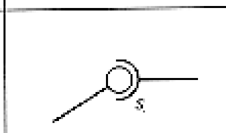
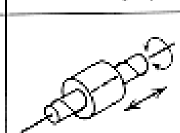
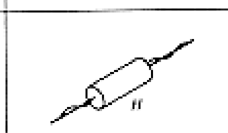
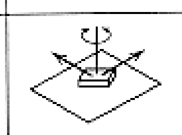
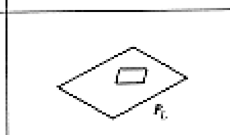


1.7 Robot Joint and Arm Structure

***Link*:** Individual (rigid) bodies that make up a mechanism are called *links*. In this course all links are treated as rigid bodies. However, for high-speed or highly loaded mechanisms , the elastic effects of a material body become significant and should be taken into consideration. From the kinematic and dynamic point of view, two or more members connected together with no relative motion will be considered as a single link.

***Joint*:** The connection between two links is called a *joint*. A joint provides some physical restriction on the relative motion between the two links. Six basic types of joint used in mechanisms and robot manipulators are shown in the table.

***Kinematic Chain*:** An assemblage of links that are connected by joints is called a *Kinematic Chain*.

Name of Pair	Geometric Form	Schematic Representations	Degrees of Freedom
Revolute			1
Cylinder			2
Prismatic			1
Sphere			3
Helix			1
Plane			3

- If every link in a kinematic chain is connected to every other link by at least two distinct paths, the chain forms one or more closed loops, and is *called closed-loop chain*. If every link is connected to every other link by one and only one path, the chain is called an *open-loop chain*.
- A kinematic chain that is made up of both closed- and open-loop chains is called *hybrid chain*.

***Mechanism*:** A kinematic chain is called mechanism when one of its links is fixed to the ground. It is a device that transforms motion or torque from one or more input links to the others.

***Machine*:** A machine is an assemblage of one or more mechanisms along with other electrical, hydraulic or pneumatic components, used to transform external energy into useful work or other forms of energy.

EXAMPLE: The mechanical manipulator of a robotic system is a mechanism. For the mechanism to become a machine, a micro-processor-based controller, encoders, motors, etc. must be incorporated to transform an external source of energy (e.x. electricity) into useful work.

***Degree of Freedom (d.o.f)*:** Total number of independent variables that can completely identify the configuration of the system, e.x., manipulator mechanism, in the space. The number of degrees of freedom for a general mechanism can be calculated as:

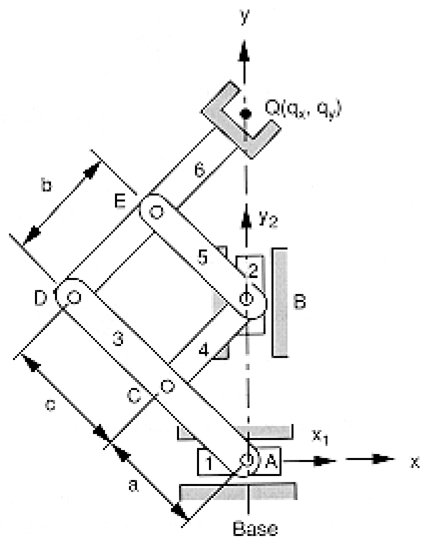
$$d.o.f. = \lambda\left(l-1\right) - \sum_{i=1}^{n}\left(\lambda - f_i\right)$$

where l is the number of links, n is the number of joints, and f_i is the number of degrees of freedom for joint i. For planar mechanisms $\lambda = 3$ and for spatial mechanisms $\lambda = 6$.

EXAMPLE: *Pantograph Mechanism:*

$\lambda = 3$, $l = 7$ (including the ground link), $n = 8$, $f_i = 1$ ($i=1,\ldots,8$); hence, $d.o.f. = 2$.

NOTE: The above formulation is valid if the joint constraints are independent of one another, which is the case in most serial manipulators. Few complex mechanisms do not obey the above criterion.



Pantograph Mechanism

1.8 Classification of Robots

1.8.1 Classification by Motion Characteristics

- **Planar Manipulator:** All the moving links in the mechanism perform planar motions that are parallel to one another. (λ = *3*)
- **Spherical Manipulator:** All the moving links perform spherical motions about a common stationary point. A spherical manipulator can be used as a pointing device.
- **Spatial manipulator:** At least one of the moving links possesses a general spatial motion. (λ = *6*)

1.8.2 Classification by Number of Degrees of Freedom

- **General-Purpose Robot:** It possesses λ degrees of freedom (3 for planar ad 6 for spatial). It can handle an object freely in a plane (for planar) or in space (spatial).
- **Redundant Robot:** It possesses more than λ degrees of freedom. It provides more freedom to move around obstacles and operate in a tightly confined workspace.
- **Deficient Robot:** It possesses less than λ degrees of freedom.

1.8.3 Classification by Kinematic structure

- **Serial (open-loop) Manipulator:** Every link is connected to every other link by one and only one path, hence, the kinematic structure takes the form of an open-loop chain.
- **Parallel Manipulator:** Every link in a kinematic chain is connected to every other link by at least two distinct paths. In general, a parallel manipulator has the advantages of higher stifness, higher payload capacity, and lower inertia, at the price of a smaller workspace and more complex mechanism.
- **Hybrid Manipulator:** A kinematic chain that is made up of both closed- and open-loop chains. In some industrial manipulators, such as Fanuc S-900W, is four-bar (push-rod) linkage is used to drive the intermediate joints, in order to be able to mount the intermediate joints on the robot base or waist and therefore reduce the inertia of the manipulator.

1.8.4 Classification by Drive Power

- **Electric Robot:** Mostly DC servo motors or stepper motors. Clean and relatively easy to control.
- **Hydraulic Robot:** Preferred for high load carrying capacity. Leak and fluid compressibility problems.
- **Pneumatic Robot:** Preferred for high-speed applications. Clean but hard to control due to air compressibility.

1.8.5 Classification by Drive Technology

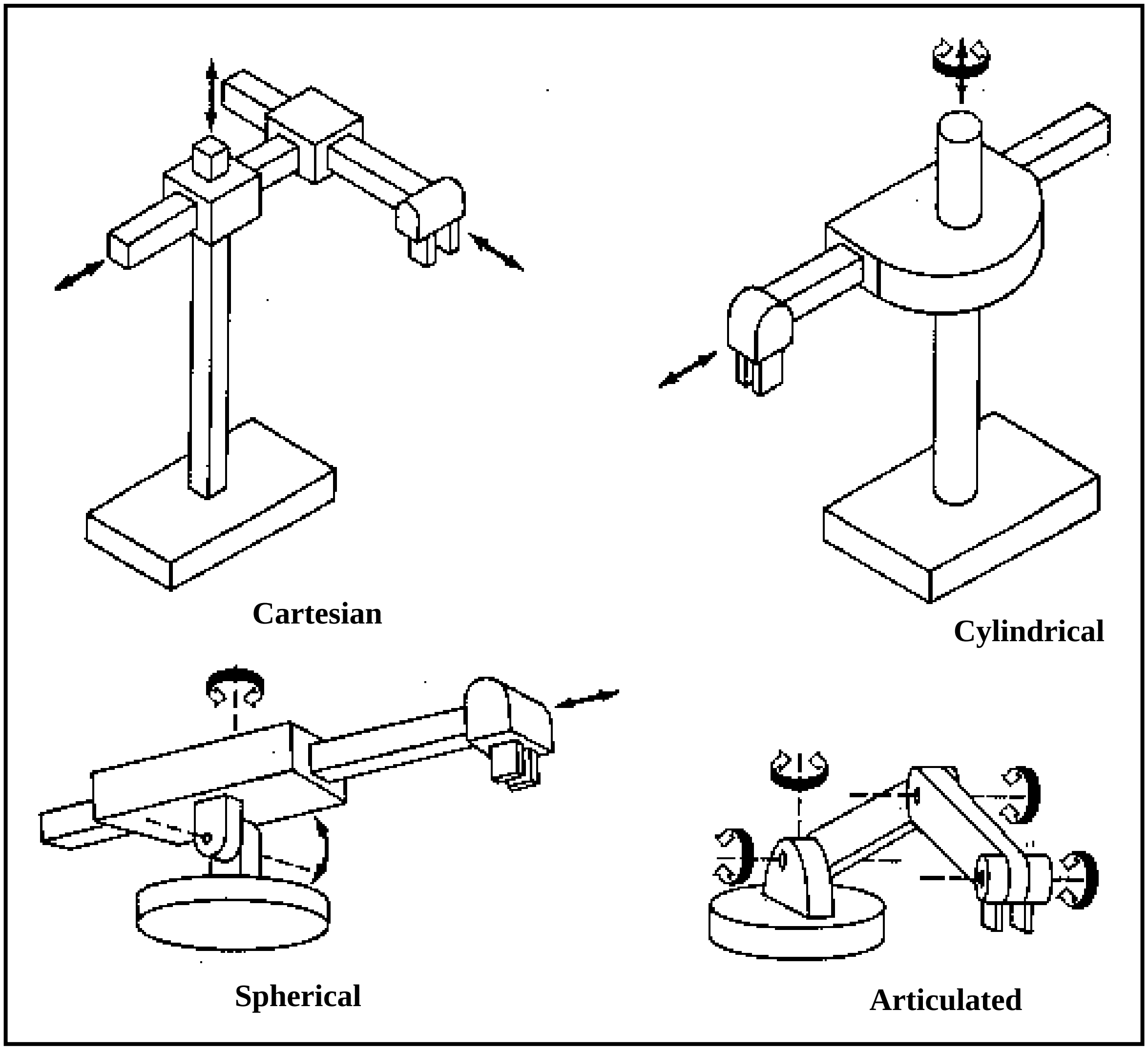
- **Direct-Drive Manipulator:** Each joint is driven directly by an actuator without any torque transmission mechanism. They are bulky and heavy, but do not possess backlash or drive flexibility.
- **Conventional Manipulator:** The driver torque is magnified by the transmission mechanism (usually gear reduction or harmonic drive unit), hence allowing to use smaller actuators. However, gear mechanisms suffer from backlash and harmonic drives possess flexibility inherently.

1.8.6 Classification by Workspace Geometry

Manipulator Workspace: The volume of Space that the end-effector can reach. The envelope within which every point can be reached by the end-effector in at least one orientation is called ***reachable workspace***. The envelope within which every point can be reached by the end-effector in all possible orientations is called ***dexterous workspace***.

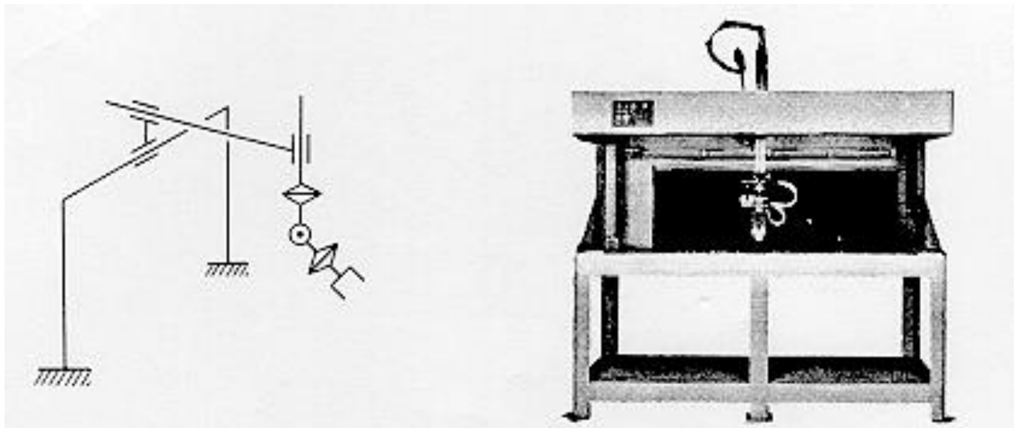
Four major robot types and their primary motion capabilities are illustrated in the Figure below.

NOTE: Most of industrial serial manipulators are designed with their first three moving links longer than the remaining links, being used primarily for manipulating the end-effector position, and the remaining links are used for controlling the end-effector orientation. The sub-assembly associated with the first three links is called *arm*, and that associated with the remaining links is called *wrist*.

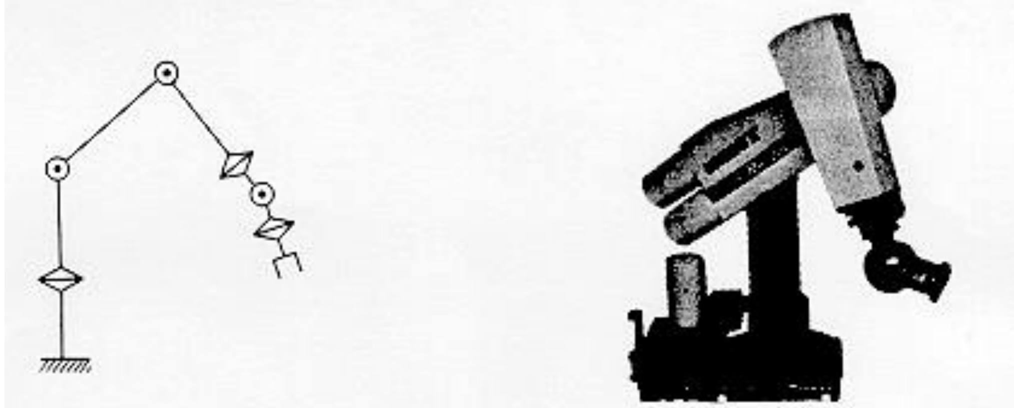


1.9 Manipulator Diagrams

Schematic diagrams show the configuration of the robot manipulator, and are convenient for assignment of links, joints and coordinate frames (Figure below).



IBM 7565 Robotic System (1984)



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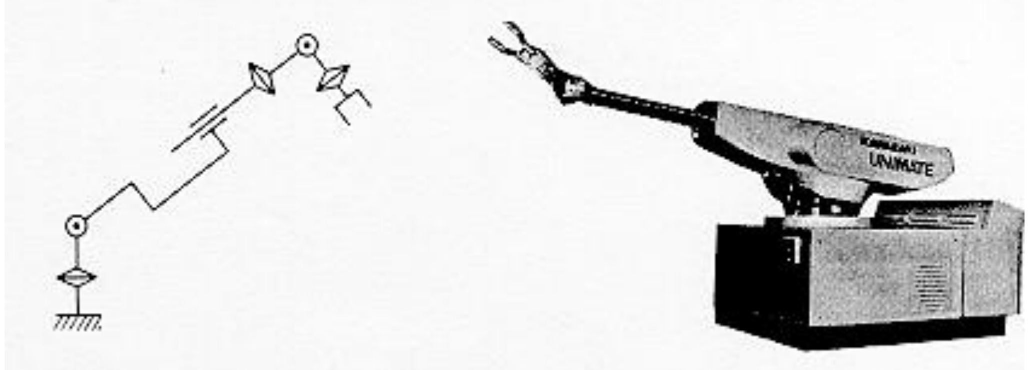
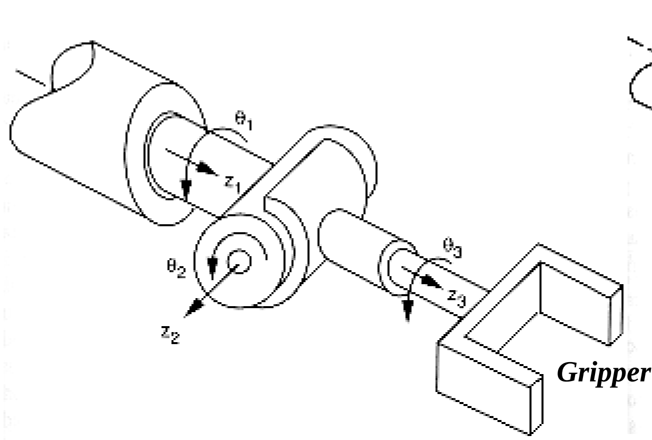
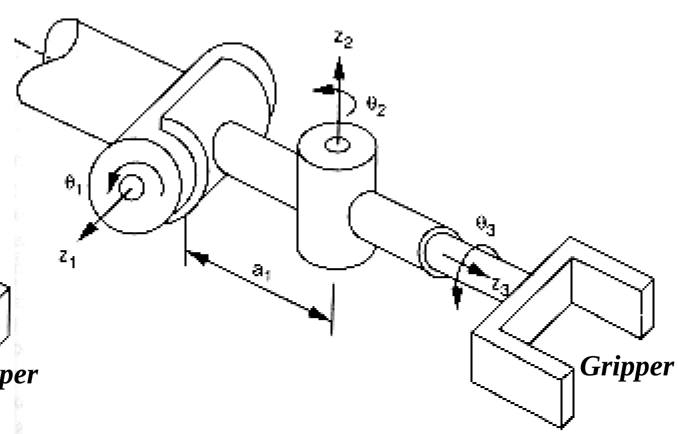


1.10 Manipulator Wrist Mechanisms

A robot manipulator needs at least 6 degrees of freedom to manipulate an object freely in the space. Typically, the lengths of the first three moving links are much longer than those of the last three links. Thus, the first three moving links, called *arm*, are used primarily for manipulating the position of the end-effector, while the last three moving links, called *wrist*, are used for controlling the orientation of the end-effector. Two types of wrist mechanisms are shown in figures below. As it will be discussed in Chapter 4 (Inverse Kinematics), it is beneficiary to design the last three joints to intersect at a common point called wrist point, in order to decouple the translation and orientation of the end-effector. Hence, spherical wrist mechanism is more common in industrial manipulators.



Spherical Wrist



Non-spherical Wrist