INTRODUCTION TO ROBOTICS

What is a robot?

The Webster defines a robot as

> *An automatic apparatus or device that performs functions ordinarily ascribed to humans or operates with what appears to be almost human intelligence.*

The Robotics Institute of America defines a robot as follows:

> *A robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks.*

Some history

The term "robot" has its origins in a Czech word "robotnik" meaning worker or serf. It was first introduced by the playwright Karel Capek in a 1920 play. The robot theme was popularized by Isaac Asimov in science fiction in the late 1940's and the early 1950's, and subsequently by Hollywood movies.

Mechanization and automation can be traced back to the industrial revolution. The first example of complete mechanization dates back to the develoment of Jacquard looms (named after the silk weaver Joseph Maria Jacquard) used in the silk industry in France and Italy in the early 19th century. These looms could be mechanically reprogrammed to produce different patterns. However, these looms were simply machines. There is no notion of "intelligence" that is built into these looms. Further, the process of programming could be very tedious, particularly for complex patterns, and had to be done manually.

The next 100-150 years saw many innovative engineering solutions to pressing problems in industry. A rotary crane equipped with a motorized gripper to remove hot ingots from a furnace was developed by Babbit in 1892. Pollard invented a mechanical arm for spray painting in 1938.

The first teleoperator, or telecheric, a device that allows an operator to perform a task at a distance, isolated from the environment that the task is performed in, was developed by Goertz[1]. It was designed to manipulate radioactive materials. The operator was separated from the radioactive task by a concrete wall with viewing ports. Two handles on the "master" side allowed the operator to manipulate a pair of tongs on the "slave" side. Both tongs and handles were

[1]Goertz, R. C., "Manipulators used for handling radioactive materials," *Human Factors in Technology*, Chapter 27, Ed. E. M. Bennet, McGraw-Hill, 1963.

coupled by multi-degree of freedom mechanisms to allow the operator dexterity in manipulating the tongs. In 1947, the first servo-controlled electric-powered teleoperator was developed. The slave side did not have to be coupled to the master side. Instead, the movements on the master side were measured by sensors and used to drive the electric actuators on the slave side.

Around this time, the first large scale electronic computer (ENIAC) was build at the University of Pennsylvania (1946), and the first multipurpose digital computer (Whirlwind) solved its first problem at MIT. The first numerically controlled machine was also the first time that the servo-system technology was combined with digital computers. This first machine was demonstrated in 1952 [KCN 89].

The robot age began with the demonstration of the first manipulator with play-back memory by George Devol in 1954. The device could exhibit repeatable "point-to-point" motions. Five years later, the first robot that eventually led to the first industrial robot was developed. The first industrial robot was developed by Unimation Inc. It combined the playback features of numerically controlled machines with the servo-control technology and the articulated mechanisms of teleoperators. In 1962, General Motors installed the first Unimate robot in a die-casting application on one of its assembly lines.

The 1960's also saw work on developing walking machines using the same technology. In 1967, Ralph Moser from General Electric developed a four-legged vehicle with funding from the Department of Defense. The vehicle was operated much like the electric teleoperators of the late 1940's. A human operator would control handles (at the master end) to coordinate the multiple joints at the legs (the slave end). The coordination task was very tedious, and the problems associated with stable walking were never quite resolved. In 1983, Odetics, Inc., a U.S. company, developed a six-legged device that could walk over obstacles while lifting loads up to 2-3 times its weight. While this vehicle was not teleoperated (in the sense of Goertz' teleoperators or the GE quadruped), it had to be controlled by a human operator.

In 1985, the first autonomous walking machine was developed at the Ohio State University. The Adaptive Suspension Vehicle (ASV) was a proof-of-concept prototype of a legged vehicle designed to operate in rough terrain that is not navigable by conventional vehicles. It was 3.3 meters (10.9 feet) high and weighed about 3200 kg (7000 lb.). It could be operated in a supervisory control mode (in the same way a human rides a horse) or in an autonomous mode. It possessed over 80 sensors, 17 onboard single board computers and a 900 c.c. motorcycle engine rated at 50 kW (70 hp). It had three actuators on each of the six legs thus providing a total of 18 degrees of freedom. The 18 degrees of freedom were hydraulically actuated through a hydrostatic configuration. The most important sensor was an optical scanning rangefinder which is a phase modulated, continuous wave ranging system with a range of approximately 30 feet and a resolution of 6 inches .It was also equipped with inertial sensor packages consisting of a vertical gyroscope, rate gyroscopes for the pitch, roll and yaw axes, and linear accelerometers to provide information to determine body velocity and position.

The ASV, unlike its predecessors, was completely computer controlled and independent except for the operator. The operator performed the functions of path selection and specifies the linear velocities of the vehicle in the fore-aft and lateral directions, and the yaw velocity. The roll and pitch rates and the velocity in the vertical direction were automatically regulated by on-line computers.

In December 1996, Honda demonstrated the Honda Humanoid, a robot with two legs and two arms that is designed for use in a typical domestic environment. The 210 kg. prototype has 30 degrees of freedom. It is equpped with cameras, gyroscopes, accelerometers, and force sensors at the wrists and feet. It is able to walk around, climb a flight of stairs, sit down on a chair, stand up from a sitting position and lift payloads of 10 lbs.

Definition of a robot revisited

The robot is a computer-controlled device that combines the technology of digital computers with the technology of servo-control of articulated chains. It should be easily reprogrammed to perform a variety of tasks, and must have sensors that enable it to react and adapt to changing conditions. Most industrial robots satisfy this definition. They basically serve to eliminate the need of high cost, specialized equipment in the manufacturing industry. However, as we will see, they may require expensive, specialized tooling.

A lay person, perhaps guided by Asimov's science fiction and Hollywood's movies, might argue that a robot must have sensing and be able to make decisions and act based on this sensory information, just as human beings do. It is this lay peron's definition of a robot that is the goal of much of the research and development in robotics. As we will see, industrial robots are very successful at simple repetitive tasks that are typical of assembly lines, but they do not meet the lay person's conception of a robot.

Anatomy of a robot

The basic components of a robot system are:

- the mechanical linkage
- actuators[2] and transmissions
- sensors
- controllers
- user interface

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[2]The book [CRA 92] calls actuators that are capable of providing continuous controlled motion drives (see page 46).

- power conversion unit

The manipulator linkage

The manipulator consists of a set of rigid *links* connected by *joints*. The joints are typically *rotary* or *sliding*. The last link or the most distal link is called the *end effector* because it is this link to which a gripper or a tool is attached. Sometimes one distinguishes between this last link and the end effector that is mounted to this link at the *tool mounting plate* or the *tool flange*.

The manipulator can generally be divided into a *regional structure* and an *orientational structure*. The regional structure generally consists of the joints (and the links between them) whose main function is the positioning of the manipulator end effector. These are generally the proximal joints. The remaining distal joints are mainly responsible for orienting the end effector. Exhibit I shows an example of an industrial robot whose regional structure produces a roughly spherical *workspace*.

The actuators are used to drive the joints of the manipulator. Note that all joints may not be powered and some may be passive. For example, if you look at Figure 6.3 [CRA 92, page 134], the elbow extension is achieved using a linear actuator (a telescoping link or a cylinder) and the elbow joint is a passive joint.

Actuators

The actuators are typically linear or rotary actuators. Also they may be electric, pneumatic or hydraulic. Typically, electric actuators or motors are better suited to high speed, low load applications while hydraulic actuators do better at low speed and high load applications. Pneumatic actuators are like hydraulic actuators except that they are generally not used for high payload. The main reason they are used in industry is because shop air is readily available. However, the maximum pressure is generally 100 psi. In contrast, hydraulic actuators may run as high as 3000 psi.

Transmissions

Transmissions are elements between the actuators and the joints of the mechanical linkage. They are generally used for three reasons.

1. Often the actuator output is not directly suitable for driving the robot linkage. The high speed DC motor (running at say 3000 rpm) may not be suitable for running a robot at lower speeds. However, with appropriate gearing or transmission, the speed may be reduced to 30 rpm (1/2 rotation per second) which is reasonably fast. In addition, the rated torque at 3000 rpm is amplified by a factor of 100 (assuming a highly efficient gearbox).

2. The output of the actuator may be kinematically different from the joint motion. For example, in Figure 1, the linear actuator is kinematically different from the elbow joint it drives. Thus the linkage consisting of the three passive joints and the linear actuator may be viewed as a transmission that converts the linear motion of the actuator to the rotary motion of the elbow joint.

3. The actuators are usually big and heavy and often it is not practical to locate the actuator at the joint. First, big actuators have large inertias and they are harder to move around in space than the links that comprise the mechanical linkage. So it is desireable to locate them at a fixed base. Second, because of their size, they can impede the motion of one or more links of the robot. Thus, it is not uncommon to find linkages or gear trains that transmit the power from the actuator over a large distance to the joint. A parallelogram drive is shown in Exhibit 2. This drive allows the joint actuators to be placed on the base (as opposed to placing them in the moving forearm or upper arm) thus reducing the inertia and weight of upper arm.

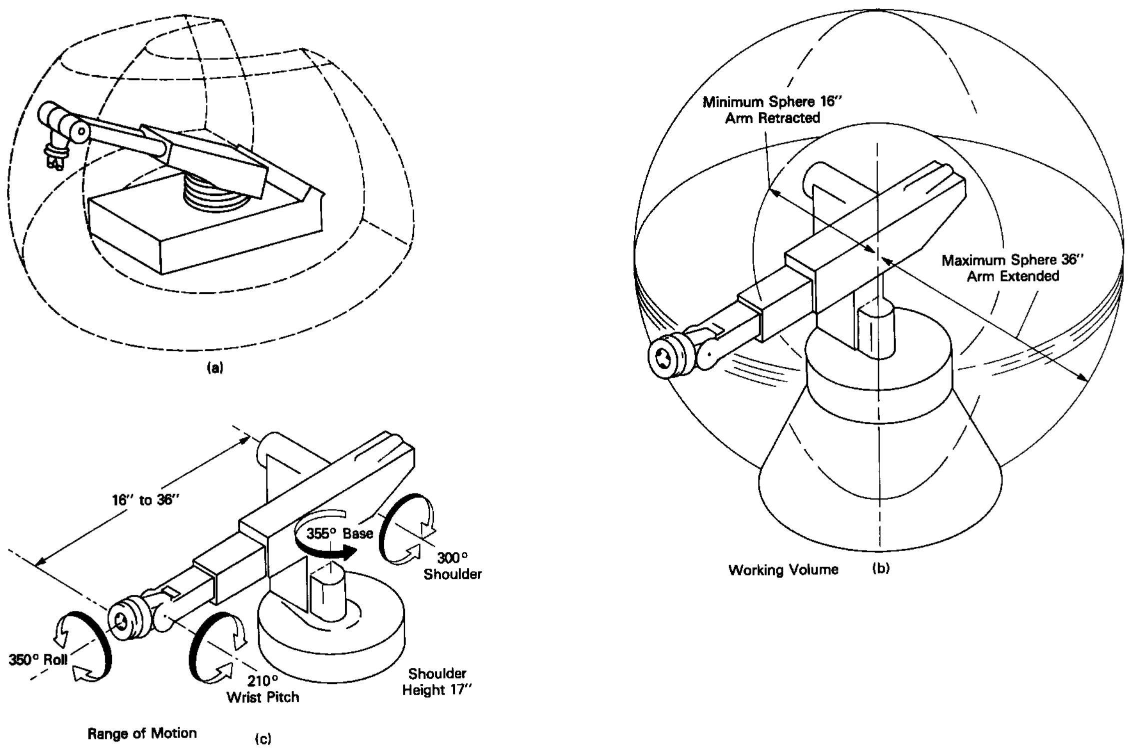


Exhibit 1 An industrial robot with a spherical workspace
(Figure 1.3.6 [KCN, page 16])

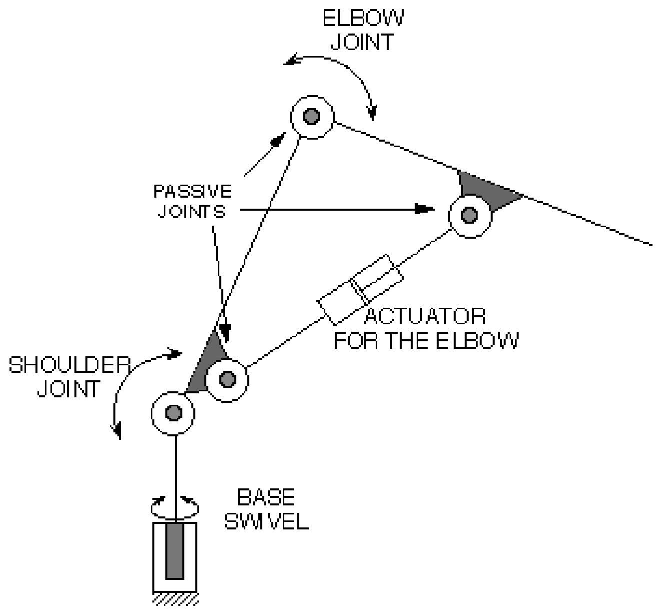


Figure 1 The regional structure for the Cincinnati Milacron T3 robot

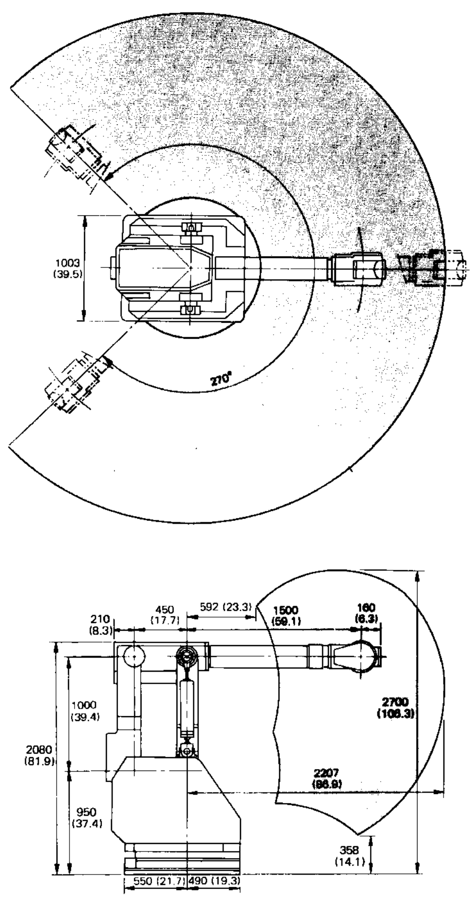


Exhibit 2 An industrial robot with a parallelogram drive arrangement

(Figure 1.3.10 [KCN, page 21])

Sensors

In order to control a robot, it is necessary to know the position of each joint in the mechanical linkage. Therefore it is necessary to instrument the joints[3] of the robot with position sensors (encoders, potentiometers, resolvers, etc.). Velocity sensors (e.g., tachometers) and acceleration sensors (accelerometers) may also be used. In addition to the position, it may be necessary to know the forces and moments exerted by the end effector or simply the torques/forces exerted by each actuator. Six axis force/torque sensors that mount between the tool and the distal link measure the forces encounted by the tool or the gripper. Pressure sensors may be used to measure the force exerted by a hydraulic or pneumatic actuator. In addition, the robot system may be commanded using sensory information from vision sensors (cameras, laser range finders), accoustic sensors (ultrasonic ranging systems) or touch sensors (optical or strain based).

Controller

The controller provides the intelligence that is necessary to control the manipulator system. It looks at the sensory information and computes the control commands that must be sent to the actuators to carry out the specified task. It generally includes:

- memory to store the control program and the state of the robot system obtained from the sensors
- a computational unit (CPU) that computes the control commands
- the appropriate hardware to interface with the external world (sensors and actuators)
- the hardware for a user interface

The user interface

This interface allows use a human operator to monitor or control the operation of the robot. It must have a display that shows the status of the system. It must also have an input device that allows the human to enter commands to the robot. The user interface may be a personal computer with the appropriate software or a teach pendant.

The power conversion unit

The power conversion unit takes the commands issued by the controller which may be low power and even digital signals and converts them into high power analog signals that can be used to drive the actuators. For example, for an electric actuator, this power conversion unit may consist of a digital to analog converter and an amplifier with a power supply. For a pneumatic actuator, this may consist of a compressor, the appropriate servovalves for regulating the flow of air, an

[3]It may not be necessary to instrument all the joints with sensors. For example, in Figure 1, the position of the linear actuator can be used to infer the joint angle of the elbow joint.

amplifier and a digital to analog converter. For a hydraulic robot, you will have a pump and a cooler instead of a compressor. See schematics in Figures 2 and 3 of controllers for an electric and a pneumatic robot. A possible implementation of a robot controller is shown in Exhibit 3.

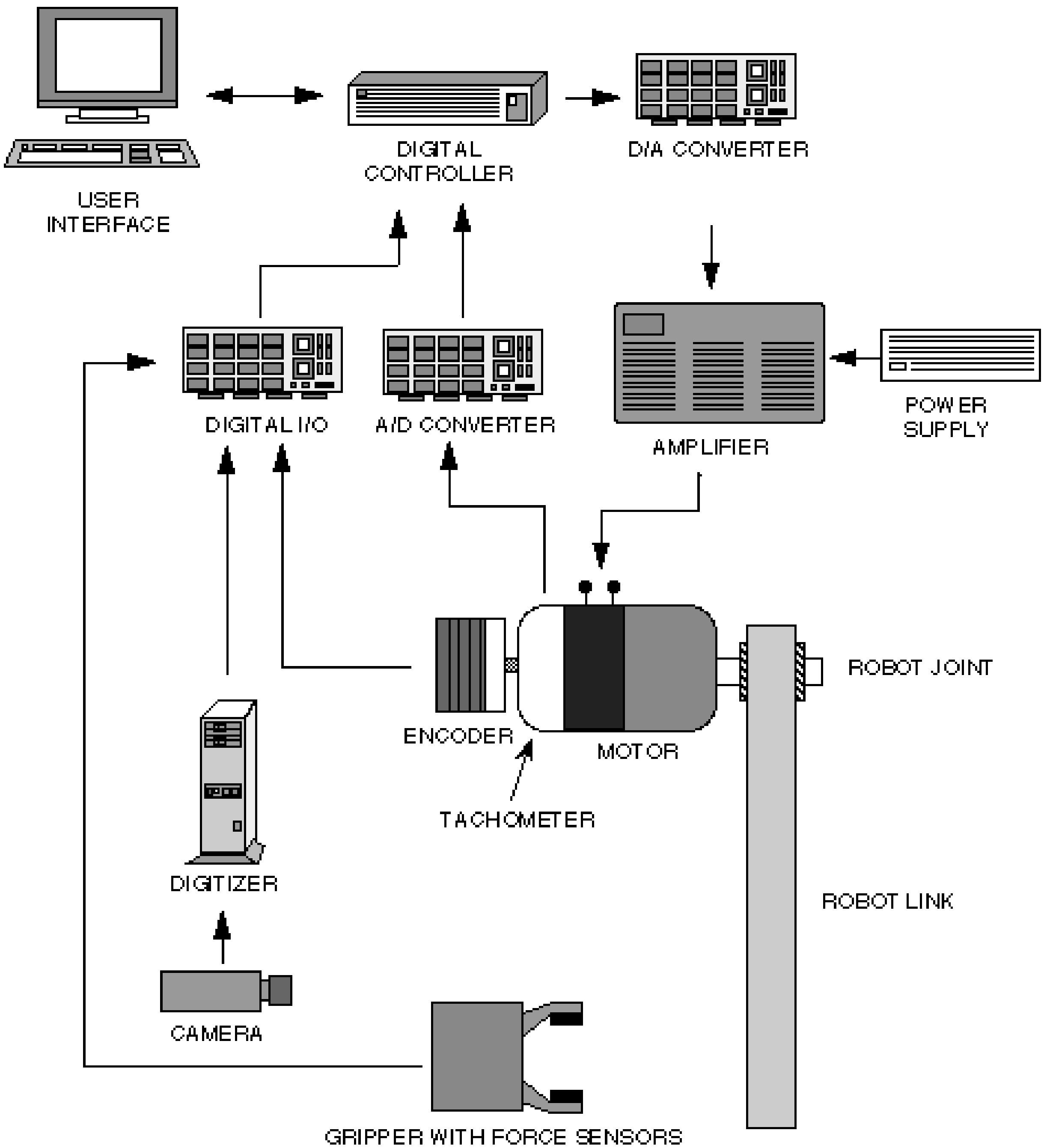


Figure 2 The basic building blocks of a rotary joint actuated by a DC motor

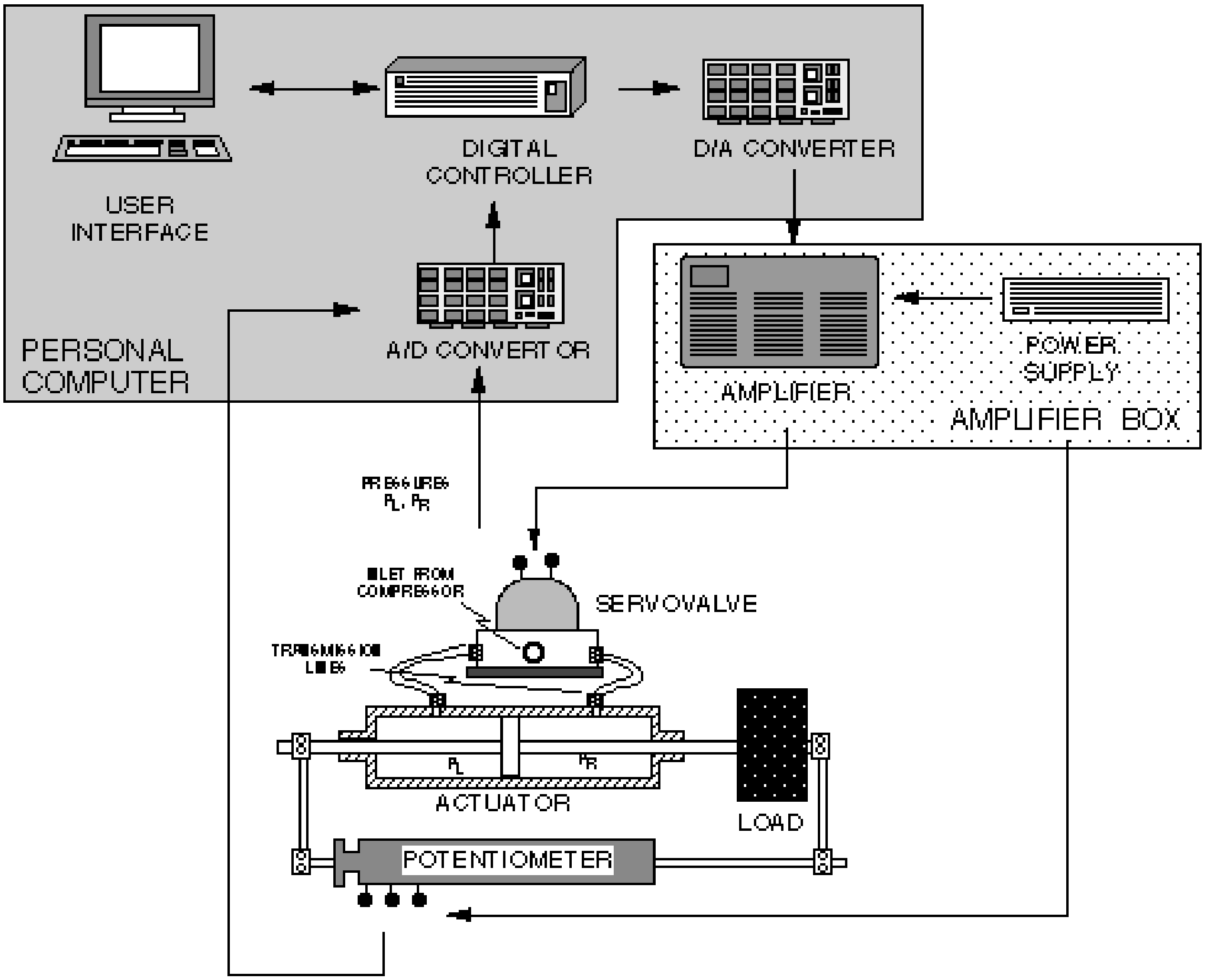
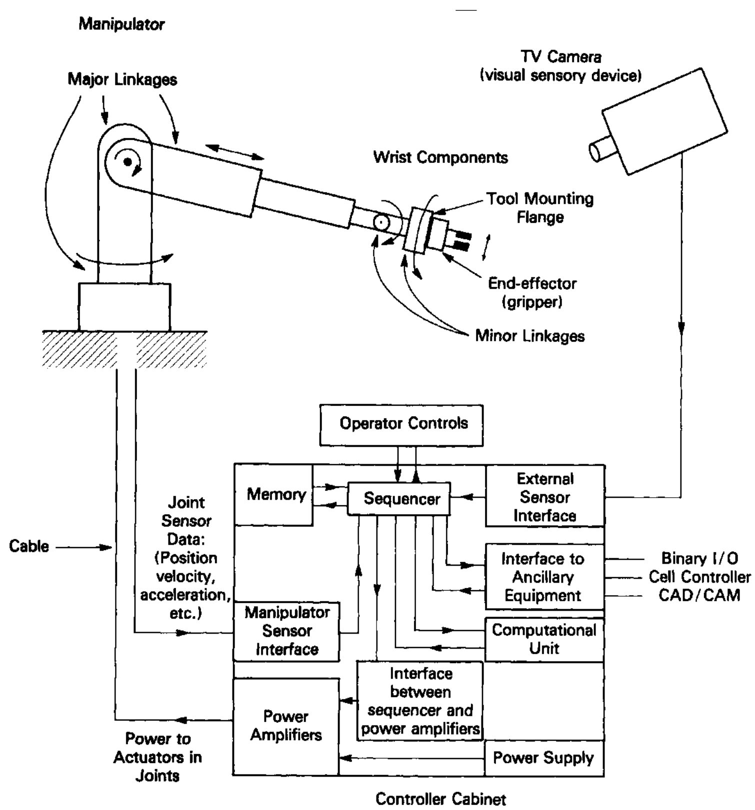


Figure 3 The basic building blocks of a sliding joint actuated by a pneumatic actuator[4]

[4]Sugar, T., *et al.*, Control of an electro-pneumatic actuator, Tech. Report, University of Pennsylvania, 1994.



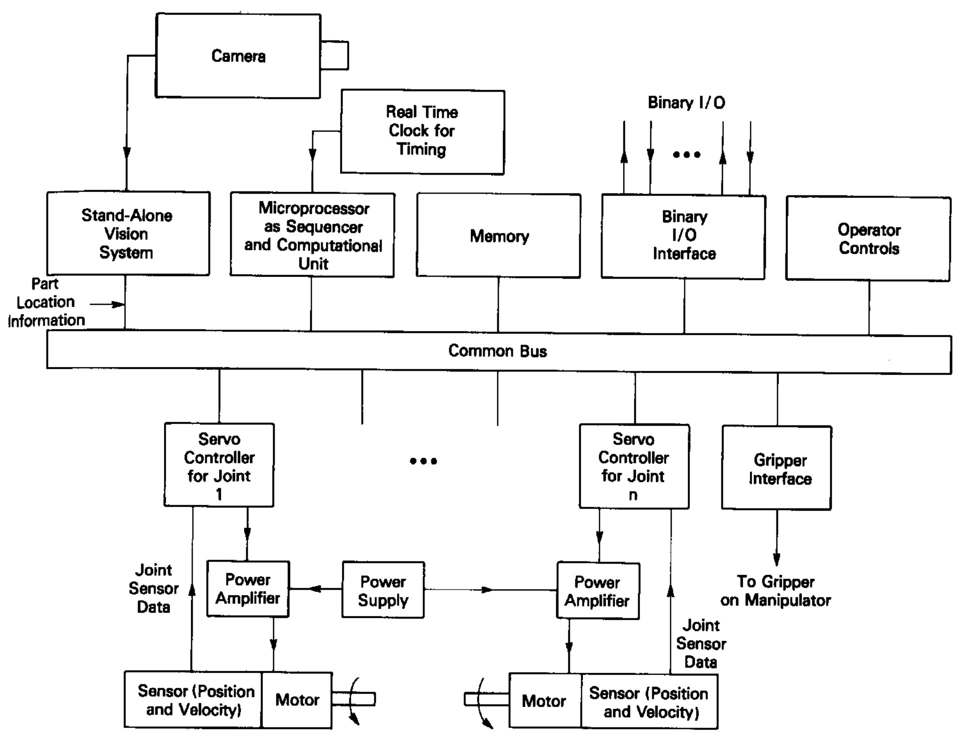


Exhibit 3 Possible implementation of a robot controller
(Figure 2.2.3, page 89, [KCN 89])

We will discuss each of the building blocks in greater detail at some point during the course. Specifically, we will cover the following subjects:

- the kinematics and geometry of mechanical linkages
  (notes, [CRA 92, pg. 133:144])
- actuators
  ([CRA 92, pg. 42:48, 144:149])
  Examples:
  Pittman dc servo motor, Compumotor stepper motor, electropneumatic actuator testbed, hydraulic actuators of the ASV, NSK megatorque direct drive motor, Kollmorgen servo disc motor)
- transmissions
  ([CRA 92, pg. 48:51])
  gear trains, spur and bevel gears, harmonic drives, cable-pulley systems, lead screws, rack and pinion systems, belt and pulley linear drives, the Roh'lix mechanism, slider crank mechanism, cam-follower systems, four-bar linkage, flexible shaft couplings, intermittent mechanisms (Geneva mechanism and walking beam)
- sensors
  potentiometers, resolvers, LVDTs, optical encoders, tachometers, accelerometers, strain gages, pressure sensors, proximity devices, ultrasonic, sensors, electromagnetic sensors, tactile sensors, computer vision systems, bar code readers, counters, timers
- controllers
  On/off control [KCN 89, pg. 176], continuous control, real-time controller

Trends in robot automation

The world's industrial robot population was estimated at 570,000 units at the end of 1992. As can be seen in Table 1, not surprisingly, Japan accounts for about 60% of the world's robots in 1992. About 48,000 robots are at work in American factories, the second largest robot user behind Japan. But Japan installs more robots each year than the total that U.S. has installed in the past 32 years.

TABLE 1. Stock of industrial robots by year-end in selected countries, 1989-1992 [DK 91]

Country	1989	1990	1991	1992
Australia	1,350	1,490	1,644	1,762
Austria	895	1,186	1,465	1,693
Benelux	1,340	1,715	1,975	2,562
Czechoslovakia	7,007	7,160	7,211	
Cyprus	3	3	3	4
Denmark	402	489	579	584
Finland	671	825	955	1,051
France	7,063	8,551	9,808	10,821
Germany	22,395	28,240	34,140	39,390
Hungary	138	199	229	237
Italy	10,000	12,500	14,700	17,097
Japan	219,700	274,210	324,895	349,458
New Zealand		70	80	90
Norway	493	527	555	576
Poland	506	532	630	627
Republic of Korea			4, 080	4,900
Singapore	1,459	1,625	1,906	2,090
Spain*	1,752	2,224	2,632	3,200
Sweden	3,463	3,791	4,099	4,550
Switzerland		1,525	1,700	2,050
Taiwan	965	1,293	1,688	2,217
Former USSR*	62,339	64,204	65,000	65,000
United Kingdom	5,717	6,227	6,974	7,598
United States	37,000	40,000	44,000	47,000
Slovakia				589
Czech Rep.				6,622
Slovenia				118
Total	384,658	458,586	530,948	571,886

The sale of industrial robots worldwide has dramatically increased in recent years[5]. After peaking at 80,000 in 1990, sales fell to 56,000 in 1993. In 1995, sales moved up by 26% to 75,000 and sales are expected to continue to grow at an average rate of 15% through the 1990's. Japan remains the largest buyer of industrial robots at 36,500 in 1995, almost half the total sales. America, Britain, France, Germany and Italy bought 23,000 robots between them. Asian

[5]*The Economist*, September 28, 1996: page 122.

countries other than Japan are likely to become major consumers of robots in 1997-1999. According to RIA (Robotic Industries Association), the U.S. sales figures for the first half of 1997 are 6,275 robots are at $548 million. The robot industry in the U.S. is around $1.5 billion per year with accessories accounting for an estimated $500,000 million every year.

Robots in the U.S.

The first industrial robot manufacturer in the world was a U.S. company, Unimation. The first industrial robot was installed by Unimation in 1961. Westinghouse, General Motors, Cincinnati Milacron and General Electric were some big names that entered the robotics business. However, now there there is only one manufacturer of industrial robots[6] in the U.S. That company is Adept[7], and it has 40% of its sales outside of the U.S. Although the U.S. is a distant second to Japan in terms of the number of installed robots, the labor shortage threatens to become as acute here as in Japan. In the U.S., in 1995, the ratio of the number of workers making social security payments to the number of retirees drawing social security checks is 3:1 and is expected[8] to go to 2:1 in 2000.

Exhibit 4 provides some information about the applications of robotics technology in the U.S. It is interesting to note that the automotive industry, which dominated robotics, now accounts only for a fourth of robot sales. Moving parts from one place to another (material transfer, tending of machines) is the most common task performed by robots. Welding and painting are also easy to automate. In the electronics industry, assembly tasks are generally automated using robots.

Growth of the robot industry in Japan

Japanese robot production in 1991 grew[9] to $3.6 billion and is estimated to grow to $11.9 billion by 2000 [DK 91]. The biggest producers of industrial robots (in 1990) were:

Manufacturer	Percentage of Japanese production
Matsushita Electric Industry (MEI)	16.5
Fuji Machine Manufacturing	8.3
Fanuc	5.4
Yasakawa Electric Manufacturing	5.3
Kawasaki Heavy Industries	3.4

[6]Note that we are excluding “service” robots here.
[7]There are very few big manufacturers of industrial robots outside Japan. Besides Adept in the U.S. Asea Brown Boveri Robotics in Sweden and REIS Robotics, Germany are prominent companies.
[8]*Wall Street Journal*, February 16, 1996. This figure was 35:1 when the social security system was first established in the 30’s.
[9]In 1978, this figure was $140 million. The growth rate was 19% in 1990.

Percentage Distribution of Robot Sales in the US, by Industry (%)

	1985	1990	1995
Agriculture	1	1	1
Mining and extractive	1	2	2
Construction	0	1	1
Electricity generation	1	1	1
Consumer non-durables	2	5	5
Non-metal primary commodities	2	4	5
Primary metals	3	4	5
Non-metal fabricated commodities	5	6	6
Fabricated metal products	10	8	8
Machinery	8	10	11
Electronics/precision equipment	8	10	16
Automotive	51	38	26
Aerospace	6	6	8
Other transport equipment	2	3	4
	100%	100%*	100%*

*Does not total 100% to rounding

Percentage Distribution of Robot Sales in the US, by Robot Application

	1985	1990	1995
Machine tending	16%	15%	15%
Material transfer (excl. machine tending)	16	15	15
Spot welding	26	15	10
Arc welding	10	10	9
Spray painting/coating	10	10	7
Processing*	5	7	7
Electronics assembly	6	12	14
Other assembly	5	8	12
Inspection	5	7	10
Other	1	1	1
	100%	100%	100%

*Includes such applications as routing, drilling, grinding etc.

Forecast of Dollar Sales of Robots in the US, by Application

	1985		1990		1995	
	Unit Sales	Total (mil.)	Unit Sales	Total (mil.)	Unit Sales	Total (mil.)
Machine tending	800	28.0	1,650	61.1	2,250	69.8
Material transfer	800	28.8	1,650	62.7	2,250	78.8
Spot welding	1,300	78.0	1,650	95.7	1,500	75.0
Arc welding	500	30.0	1,100	66.0	1,350	78.3
Spray painting	500	30.0	1,100	66.0	1,050	63.0
Processing	250	11.3	770	38.5	1,050	62.0
Electronics assembly	300	10.5	1,320	52.8	2,100	66.4
Other assembly	250	8.8	880	30.8	1,800	63.0
Inspection	250	13.0	770	38.5	1,500	75.0
Other	50	2.0	110	4.2	150	6.0
Totals	5,000	$240.4	11,000	$516.3	15,000	$637.3

Exhibit 4 Robot sales in the U.S. (SME and RIA survey, [JE 89, pages 128-129])

Others in the robotics business include Komatsu (construction), Mitsubishi, Yamaha, Seiko and Sumitomo.

The major reasons for growth in this industry are a Japanese labor shortage and strong investment by industry and the government. Labor growth in Japan is estimated to be 0.4% annually from 1994 to 2000. In 2000, 15% of the work force will be over 65. About half of Japanese manufacturing companies have invested in automated systems to cope with labor shortages. Such investments rose 20% in each of 1988 and 1989 [DK 91].

Robots are extensively used in the manufacturing of automobiles, electronic goods and semiconductors. The automotive industry "employs" 20% of all robots. Robots not only save labor costs but also allow shorter production lines[10] which means a lower capital cost per unit product and more flexibility which in turn allows customization of products[11]. Robots are also used for small volume flexible manufacturing systems for video-cameras, walkmans, and personal computers.

Other applications

The need for industrial robots (for manufacturing automation) appears to be primarily driven by the shortage of labor and the cost of labor. While only Japan has embraced robotics in a big way, it would appear that it is only a matter of time before other industrialized nations follow suit. However, there are applications in hostile environments in which it is necessary to use robots (for example, in space, nuclear plants) or it is too dangerous to use humans (for example, military operations). There are others where the physical task demands skills that humans simply do not have (for example, surgery). Some of these are briefly described here.

1. *Space robotics*

Space exploration needs human intelligence but does not need the physical presence of human bodies. In principle, human operators on earth can control partially autonomous vehicles and manipulators on the Moon, or on distant planets.

2. *Hazardous environments*

DOE uses robotics technology for automating the manufacture of explosive components and for dismantling radioactive or toxic weaponry. The U.S. Navy is trying to use robotics technology for detecting and defusing mines in shallow water. A remotely controlled underwater submersible was used when the *Titanic* was salvaged several years ago.

3. *Virtual reality*

Virtual reality systems (simulators) can be used for training and educating people. An important component of these systems is the haptic interface, that allows the user/operator to feel the virtual

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[10]Honda's Suzuka line is 2600 feet long compared to Detroit's average of 7600 feet.
[11]Nissan and Honda can produce from 4-8 models of cars on the same production line without retooling.

environment and exert forces on it. Thus a virtual reality system is a robot plus high-resolution displays.

4. Highways

Cars are being equipped with increasingly sophisticated sensors, navigation systems and controllers. The IVHS project is aimed at building an intelligent highway system in which operations such as merge, change-lane and exit can be automated so that the human driver acts only in a supervisory mode. Highway maintenance and construction are also areas where robotic systems can be used for automation.

In addition, there many areas in the service industry where robotics can be expected to play a major role and according to J. Englelberger [JE 86], “service robotics will surely outstrip industrial robotics”. Some possible application areas in the service industry are:

1. Medical Robotics

The U.S. pioneered research in this area. In robot-assisted surgery the surgeon directs the robot to make controlled, high-precision incisions with accuracy far better than a human surgeon can. The latest advance in laproscopic surgery involves inserting a micro-robot through a small incision in the body and teleoperate it to perform surgery, suturing, etc. Now Japan and Europe have active research programs in this area.

2. Personal care for disabled people

There are many assistive devices for people with disabilities. Robots can be vocational assistants by operating as arms for paraplegics. They can be used to fetch papers or pick up the phone. In a home, they can be used to push open doors, get water from a faucet, and pick up trash from the floor. Since a human user controls the personal robot, the robot need only have very limited intelligence.

3. Entertainment

Entertainment robots is a fast growing market that is fueled by growth in theme parks. In Disney’s theme parks, robots are used to create animated figures. Ford used a robot to advertise its new 1996 models. Virtual reality systems are also ready to take off.

4. Custodian robot

Cleaning public restrooms is a tedious and dirty job and best left to a robot. Since restrooms are fairly structured (most toilets, urinals and sinks look similar), the cleaning operation can be automated. In large public buildings such as airports and train stations, robot vacuum cleaners can be used to clean carpets.

5. Robot attendant at gas station

A robot system can be used to fill up the gas tank without getting out of the car. This would be a great benefit if it is very hot or cold outside or if it is very late at night.

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