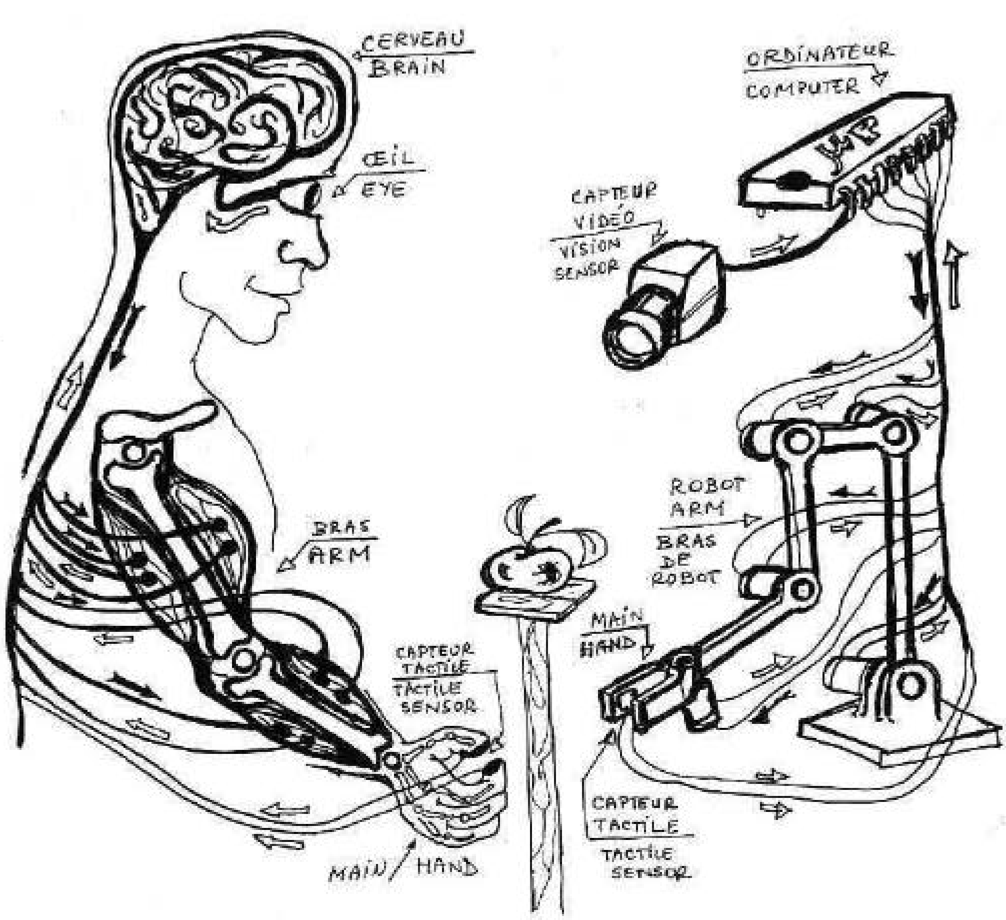
❑ ROBOTICS THE INTELLIGENT CONNECTION OF THE PERCEPTION TO ACTION.

A robot is defined in many ways: "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" (Robot Institute of America definition, 1979), "An automatic device that performs functions normally ascribed to humans or a machine in the form of a human." (Webster Dictionary).

The first definition is restricted to what a robot manipulator is doing in a mechanical sense. The second definition is more general but still limited to what robots are supposed to do.

The definition given by M. Bradley, "**Robotics is the intelligent connection of the perception to action**" considers robotics from a system integration perspective, indicating how robots are doing things. Programmable robots (manipulators, vehicles) provide the *action* function. A variety of sensors provide the *perception* capability. Computers provide the framework for *integration/connection* as well as the *intelligence* needed to coordinate in a meaningful way the perception and action capabilities.

Bradle'y definition recognizes a new step in the evolution of robotics. In the early stages, computers were seen as mere convenient programmable controllers for the sequence of motions to be performed by the articulated mechanical structure that was the robot. Today robots are more and more seen from an artificial intelligence perspective as providing arms, legs and wheels which, together with sensors, allow computer-based intelligent agents to interact with the physical reality.



The robot as a cybernetic alter ego of the human.

Highlights in the History of Robotics

1400s The first android clocks are developed in Germany and Switzerland.

1770 Pierre and Henri Jacquet-Droz construct lifelike automata that can write, draw, and play musical instruments and are controlled by cams and driven by springs.

1818 Eli Whitney invents a milling machine.

1830s Charles Babbage devises his analytical engine, the forerunner of the modern digital computer.

1870s Herman Hollerith perfects the first automatic calculator.

1921 Karel Capek’s play Rossum’s Universal Robots introduces the term **robot**, derived from the Czech word "robota" which means “forced labor”.

1930s The first spray-painting machines with recorded paths are developed.

1940s Isaac Asimov and John Campbell devise the concept of the intelligent robot that follows instructions, and together they write numerous science fiction stories about robots. Asimov coins the phrase **robotics** to denote the study of robots.

1942 The first automatic sequence controller is developed at Harvard University.
1944 R. Goertz introduces the first master-salve (teleoperator) manipulator.
1946 George Devol develops the magnetic controller playback device.
1948 J.P. Eckert and John Mauchley complete construction of the ENIAC computer at the University of Pennsylvania.
1949 EDSAC, the first computer with a stored program, is developed at Cambridge University.

- A Canadian Contribution [J.J. Brown, "The inventors - great ideas in Canadian enterprise", McClelland & Stewart Ltd., 1967]: Eric Leaver - AMCRO (automatic machine control by recorded operation):
  "During the rest of 1945 and early 1946, Leaver …. worked out not only the basic design of a hand-arm machine that could function as either a remotely controlled or a programmed manipulator, but in addition carried his thinking much farther into the general field of making products without using the labour of men. After a characteristically thorough and critical study of all the ways of controlling machine tools automatically, he settled o the system which he called AMCRO. By mid-1946 these ideas were well enough developed to enable me to write a long article for Fortune called "The Automatic Factory". In the meantime, at this company's small Toronto plant, Leaver, with the help of G.R. Mounce ....built the first production tool capable of memorizing a skilled workman's operations and then playing them back to make a product. This basic invention, one of the first contributions to what is today the great field of automation, was operating in their Toronto plant by 1947 .... Canadian, U.S. and foreign patents were granted Leaver and Mounce in 1949."

1952 The first numerically controlled machine tool is built at MIT.
1954 George Devol designs the first programmable robot.
1955 Denavit and Hartenberg develop their method for determining and specifying the configuration of the various links in a manipulator.
1956 Joseph Engelberger, a Columbia University physics student, buys the rights to Devol's robot and soon after starts the Unimation Company.
1961 The first Unimate robot is installed in a Trenton, New Jersey, plant of general Motors (to tend a die-casting machine).
1965 A major program in robotics is initiated at the Stanford University Artificial Intelligence Laboratory (SAIL) by John McCarthy.
1968 Kawasaki Heavy Industries in Japan obtains a licensing agreement from Unimation.
1974 Cincinnati Milacron introduces the T3, the first industrial robot to employ a completely revolute configuration.
1975 Unimation Inc. registers its first financial profit.
1978 The first PUMA (whose design is based on Victor Sheinman's Stanford manipulator) is shipped to GM by Unimation.
1980 Fujitsu Fanuc Company of Japan develops the first totally automated factory.

SPACE ROBOTICS:

- NASA Telerobotics Program addresses the three specific mission and application areas: on-orbit assembly and servicing, science payload tending, and planetary surface robotics. => **Mars Rover**
- Canadian Space Agency:

  In 1981, Canada confirmed its position as a world leader in space technology with the development of the Remote Manipulator System, or **Canadarm**. The RMS can be used: to deploy and retrieve satellites, to hold targets, to explore samples, and to manipulate hardware for the Space Shuttle.

  In 1988, Canada agreed to join the international partners to build a permanently inhabited Space Station. Canada's contribution is to design, manufacture, and operate a robotic system, the **Mobile Servicing System** (MSS), for assembly, maintenance, and servicing tasks on the Space Station.

Asimov's laws of the robotics, *[I. Asimov, Robots and Empire, Doubleday & Co., New York 1985, p. 291]*

0^{th} law: "A robot may not injure humanity or, through inaction, allow humanity to come to harm."

1^{st} law- updated: "A robot must not harm a human being or, through inaction allow one to come to harm, unless this would violate the 0^{th} law."

2^{nd} law: "A robot must always obey human beings unless that is in conflict with the 1^{st} law".

3^{rd} law: "A robot must protect itself from harm unless that is in conflict with the 1^{st} and 2^{nd} law".

❑ ROBOT COMPONENTS AND SUBSYTEMS

NB: Most of this *Robot Components and Systems* section represents a summary of chapter *Components and Subsystems* of the reference *P.J. McKerrow, "Introduction to Robotics*," *Addison-Wesley, 1991*.

A robot system is an integrated system providing an intelligent connection of the perception to action. From a mechanical point of view a robot appears, as illustrated in Fig. 2.1, as an articulated structure consisting of a series of links interconnected by joints. Each joint is driven by a motor which can change the relative position of the two links connected by that joint.

The **functional subsystems of a robot** are process, planning, sensor, control, electrical, and mechanical.

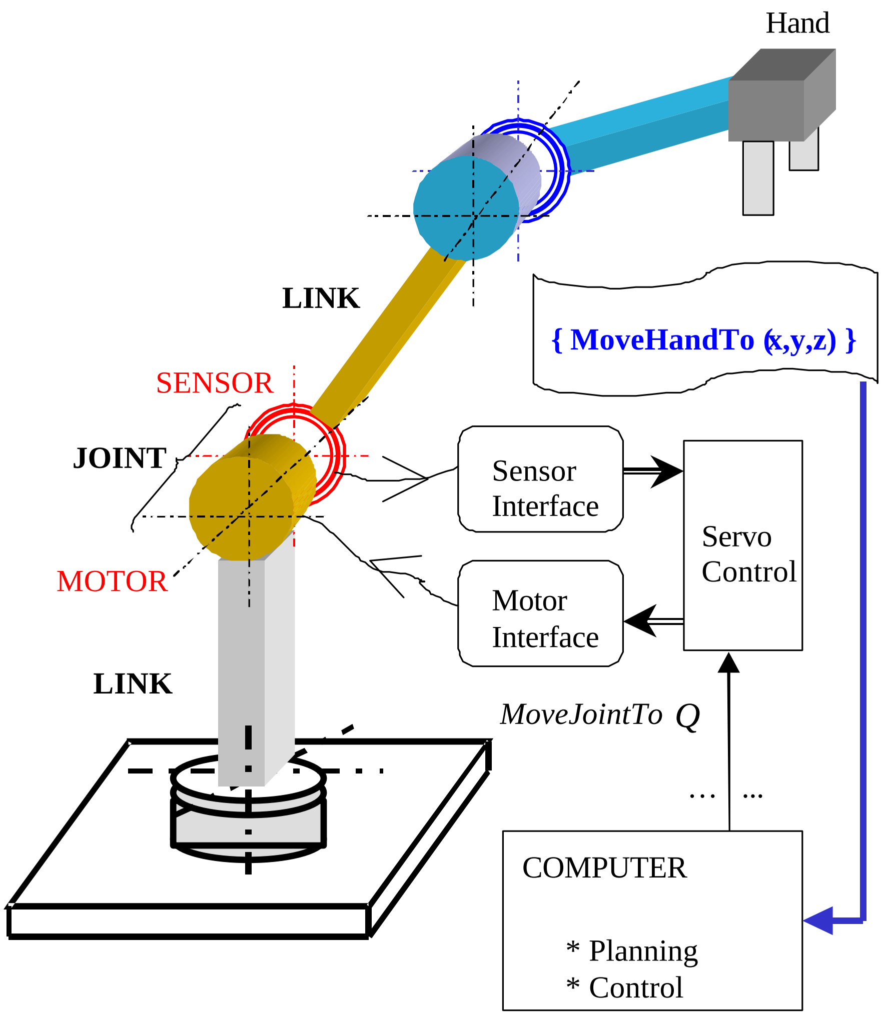
The **process subsystem** includes the task the robot performs, the environment in which it is placed and the interaction between it and the environment. The task the robot is expected to perform must be formulated a sequence of steps that the robot can execute. Task formulation includes the « intelligent » processes of environment perception, task and world modelling and **planning** the actions. Two types of sensors are used: (i) *proprioperceptors* for the measurement/moitoring of the robot's internal state parameters, and (ii) *exteroceptors* for the measurement of the environment's state parameters.

Data from a variety of sensors is fused with mathematical models of the task to form a model of the world. At the perception level, this world model is used to infer the system and environment satte, and to assess the consequences of the planned course of the robot's actions. Task execution startegies are converted into robot control programs during the action planning phase.

The task execution programs are executed by the **control subsystem**. This subsystems converts, if needed, high-level robot programming instructions into robot joint-level commands. It also provides the servo-control of the physical actuators driving the robot joints.

The **electrical subsystem** comprises of computers, sensors, motors, electronic interfaces, data transmission/communication links, and power supplies.

The **mechanical subsystem** comprises of all the mechanical components of the *robot manipulators, robot vehicles*: links, joints, hands, end effectors, gears, tendons, brakes, frames, wheels, tracks, legs, propellers, etc.



Subsystems of a robotic manipulator

♦ Manipulator Arms

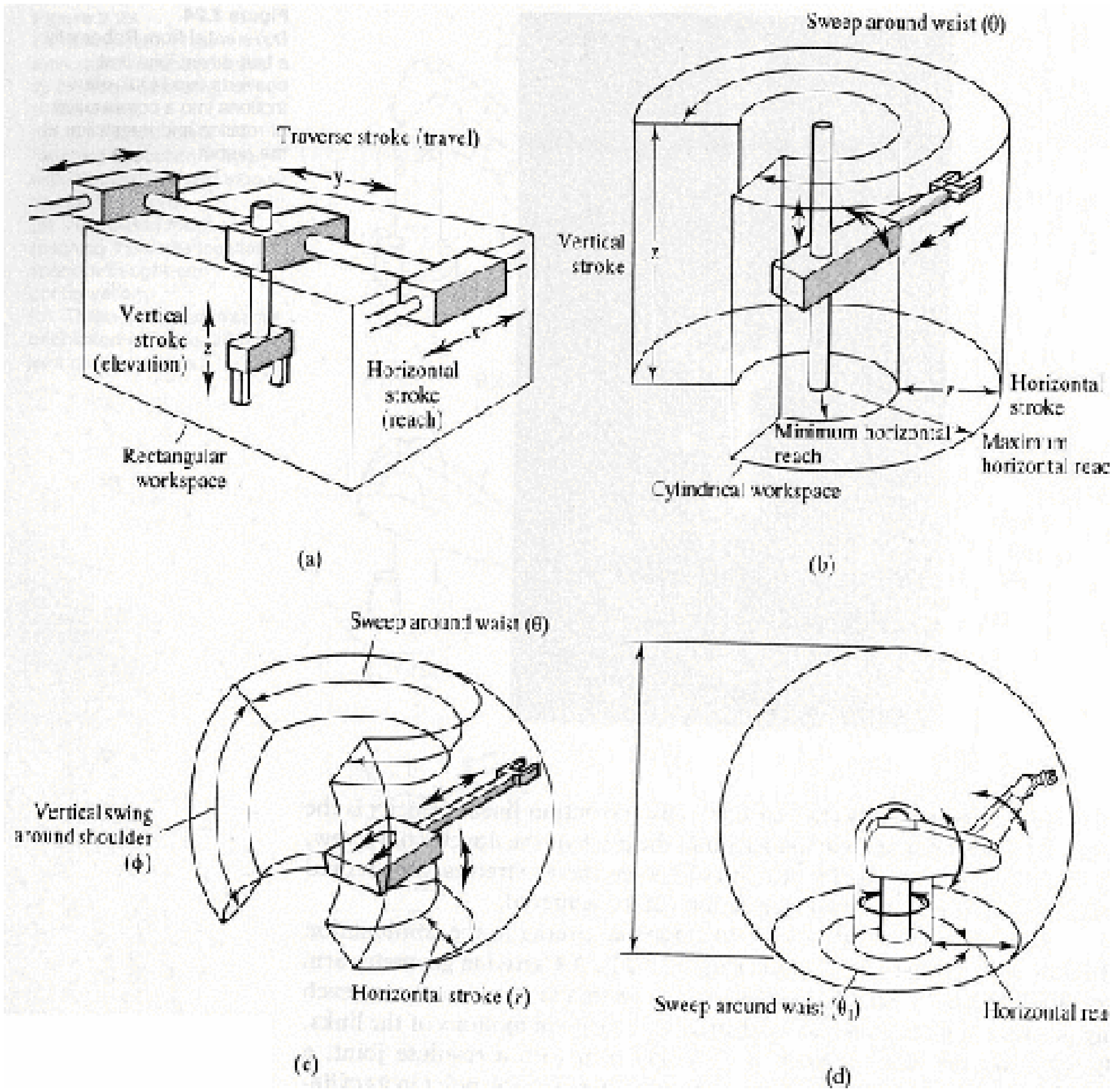
The common industrial manipulator is often referred to as a robot arm, with links and joints described in similar terms. Manipulators which emulate the characteristics of a human arm are called articulated arms. All their joints are rotary (or revolute).

The motion of articulated robot arms differs from the motion of the human arm. While robot joints have fewer degrees of freedom, they can move through greater angles. For example, the elbow of an articulated robot can bend up or down whereas a person can only bend their elbow in one direction with respect to the straight arm position.

Motions of an articulated robot arm.

Many applications do not require arms with articulated (or revolute) geometries. Simpler geometries involving prismatic or sliding joints are often adequate. Prismatic and revolute joints represent the opposite extremes of a universal screw. In a revolute joint, the screw pitch is zero, constraining the joint to pure rotation. In a prismatic joint, the pitch is infinite, constraining the joint to pure sliding motion. Revolute joints are often preferred because of the strength, low friction and reliability of ball bearings. Joints that allow a combination of translation and rotation (such as lead screws) are not normally used to join the links of robot arms.

Manipulators are grouped into classes according to the combination of joints used in their construction. A **Cartesian geometry arm** (sometimes called a gantry crane) uses only prismatic joints, and can reach any position in its rectangular workspace by Cartesian motions of the links. By replacing the waist joint of a Cartesian arm with a revolute joint, a **cylindrical geometry arm** is formed. This arm can reach any point in its cylindrical workspace (a thick-shelled cylinder) by a combination of rotation and translation. If the shoulder joint is also replaced by a revolute joint, an **arm with a polar geometry** is formed. The workspace of this arm is half a thick spherical shell, and end effector positions are best described with polar coordinates. Finally, replacing the elbow joint with a revolute joint results in a **revolute geometry, or articulated arm**. The workspace of an articulated arm is a rather complex thick walled spherical shell. The outside of the shell is a single sphere, but the inside is a set of intersecting spheres.



Workspaces for different robot geometries:
(a) Cartesian geometry; (b) cylindrical geometry ; (c) polar/spherical geometry;
(d) revolute geometry/articulated arm, (from [McKerrow]).

Comparison of robot configuration (from [*McKerrow*]).

Robot	*Joints*	*Coordinates*
		Advantages
Cartesian	prismatic waist prismatic shoulder prismatic elbow	. linear motion in three dimension . simple kinematic model . rigid structure . easy to visualize . can use inexpensive pneumatic drives for pick and place operation. *Disadvantages* . requires a large volume to operate in . work space is smaller than robot volume . unable to reach areas under objects . guiding surfaces of prismatic joints . must be covered to prevent ingress of dust
		Advantages
Cylindrical	revolute waist prismatic shoulder primatic elbow	. simple kinematic model . easy to visualize . good access into cavities and machine openings . very powerful when hydraulic drives used *Disadvantages* . restricted work space . prismatic guides difficult to seal from dust and liquids . back of robot can overlap work volume
		Advantages
Spherical	revolute waist revolute shoulder prismatic elbow	. covers a large volume from a central support . can bend down to pick objects up off the floor *Disadvantages* .complex kinematic model . difficult to visualize
		Advantages
Articulated	revolute waist revolute shoulder revolute elbow	. maximum flexibility . covers a large work space relative to volume of robots . revolute joints are easy to seal . suits electric motors . can reach over and under objects *Disadvantages* . complex kinematics . difficult to visualize . control of linear motion is difficult . structure not very rigid at full reach

Workspace considerations, particularly reach and collision avoidance, play an important part in the selection of a robot for an application. All manufacturers give detailed specifications of the work space of their robots and associated equipment.

Consideration of the motions involved in assembly has led to the development of a simpler arm geometry for use in assembly applications, known as the **SCARA** (*Selective Compliance Automatic Robot Arm*) geometry. While all SCARA robots have the same geometry the name SCARA does not have a geometric basis. Most assembly operations involve building up the assembly by placing parts on top of a partially complete assembly. A SCARA arm has two revolute joints in the horizontal plane, allowing it to reach any point within a horizontal planar workspace defined by two concentric circles. At the end of the arm is a vertical link which can translate in the vertical direction, allowing parts to be raised from a tray and placed on to the assembly. A gripper placed at the end of this link may be able to rotate about the vertical axis of this link, facilitating control of part orientation in a horizontal plane.

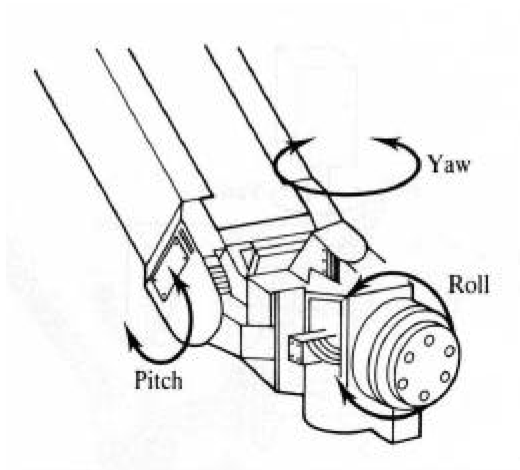
♦ *Wrists*

The kinematic structure of the robot arm allows to postion its end point at any (x,y,z) location in the 3D space (…. within the robot's working space)

In order to provide for the proper orientation of the hand/end-effector the robot arm should have *a wrist*. Typically a robot wrist provides the same 3D rotations as a human hand: roll, pitch, and yaw. A wrist where the three axes of rotation intersect is called a *spherical wrist*. These have the advantage that the mathematical model used to calculate the wrist joint angles from their position and orientation in space is soluble.

One problem in achieving spherical wrist design is the physical difficulty of fitting all the components into the available space. The size of the human wrist is small because the muscles which power it are located in the forearm, not in the wrist. Wrist design is a complex task, involving conflicting goals. Desirable features of a wrist include :

- small size
- axes close together to increase mechanical efficiency
- tool plate close to the axes to increase strength and precision
- soluble mathematical model
- no singularities in the work volume
- back-driving to allow programming by teach and playback
- decoupling between motions around the three axes
- actuators mounted away from the wrist to allow size reduction
- paths for end effector control and power through the wrist
- power proportionate to the proposed task
- rugged housing.



Robot wrist

♦ Robotic Vehicles

Most mobile robots use either wheels, tracks or legs to move around. The most versatile robots are serpentine (snake-like) robots. These may be used in confined spaces where people cannot fit and where the environment is often unhealthy, such as in mines, tunnels, sewers, and cable ducts.

A major problem faced by all mobile robot designers is the generation and storage of power: umbilical cords restrict motion while providing unlimited power. In contrast free roaming robots are restricted by the amount of energy they can carry and require wireless communication links.

Mars rover, a wheeled vehicle for rough terrain.

Most mobile robots roll on wheels, which are simpler to control, pose fewer stability problems, use less energy per unit distance of motion, and can go faster than legs. Stability is maintained by ensuring that the centre of gravity of the vehicle is always within a triangle formed by three points touching the ground. Wheeled vehicles are reasonably manoeuvrable, some are able to turn in their own length, and some can move sideways. However, wheels are only usable on relatively smooth, solid terrain; on soft ground they can slip and get bogged down. In order to scale rough terrain, wheels have to be larger than the obstacles they encounter.

The most familiar wheel layout for a vehicle uses four wheels placed at the corners of a rectangle. Most four-wheeled vehicles have limited manoeuvrability because they have to move in a forward direction in order to turn. Also, a wheel suspension system is required to ensure that the wheels are in contact with the ground at all times.

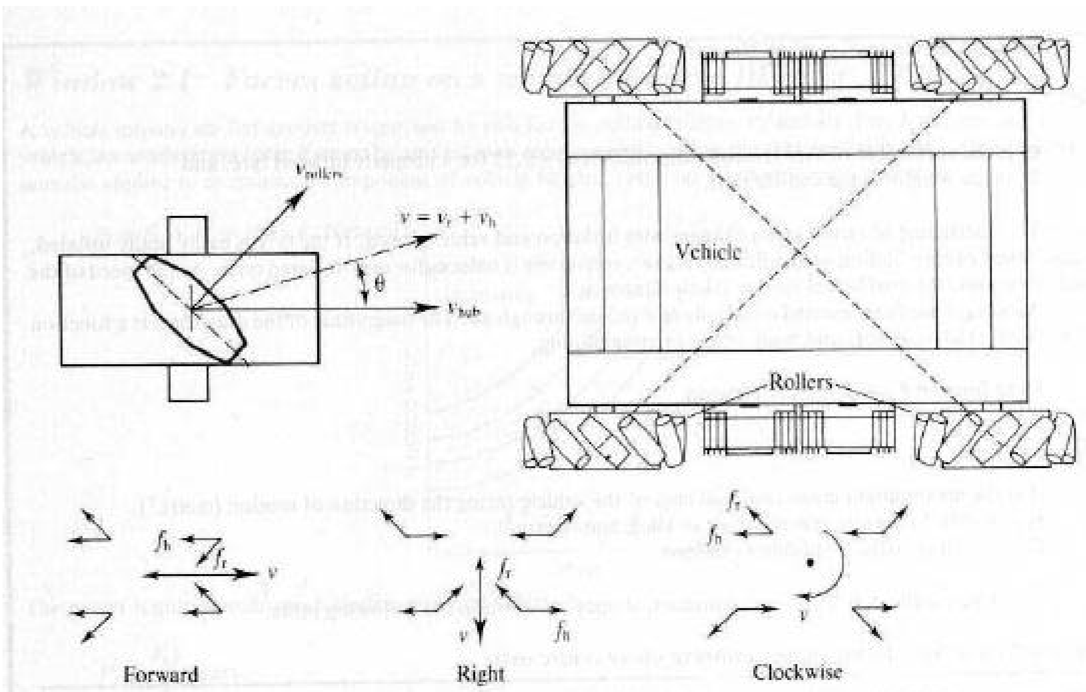
Three-wheeled vehicles have the advantage that wheel-to-ground contact can be maintained on all wheels without a suspension system. The centre of a three-wheeled vehicle is the centre of the circle defined by the ground contact points of the three wheels. Other variants of the three-wheeled vehicle configuration are found in practice. In one, the single wheel is the drive wheel as well as the steering wheel, enabling the other wheels to idle. Combining drive and steering mechanisms in one wheel results in a more complex mechanical design, and small tolerances can result in noticeable steering errors over a distance of a few meters.

Some wheeled vehicles are capable of sideways motion. They use wheels which consist of a circular hub surrounded by rollers. On the Stanford wheel, the rollers are perpendicular to the axis of the hub and on the *Illanator* wheel, the rollers are at 45 degrees to the axis of the hub. In both cases, the hub is driven, and the rollers idle.

An Illanator wheel as used on the Carnegie-Mellon robot *Uranus*, can rotate about the hub with the rollers still, or move at 45 degree with the hub still and the roller in contact with the ground spinning. Left-handed and right-handed arrangements of the wheel are possible, where left or right is the direction the wheel will move with only the rollers spinning. Motion in other directions involves rotation of both the rollers and the hub. The velocity of the wheel can be resolved into two components one perpendicular to the axis of the wheel (0 = 0), and one perpendicular to the axis of the rollers (0 = 45). Similarly, the force applied to the ground by the wheels can also be resolved into components.

Uranus uses four wheels, two left-handed and two right-handed, and requires a suspension system. The wheels are arranged so that the diagonal lines through the wheel contact points intersect at the centre of the vehicle. Thus, the wheel contact points form a square. With these wheels, the vehicle can still move forwards or backwards if a roller jams. A disadvantage of Illanator wheels is that drive efficiency is poor when moving in a lateral direction, because vehicle movement is at 90 to the direction of rotation of the hubs.

Uranus moves forward and backward in the conventional manner, with the hubs rotating and the rollers still. To move laterally, diagonal pairs of wheels are driven in opposite directions. The robot can move at 45 to the forward direction, by driving one pair of diagonal wheels and holding the other pair still. The vehicle is omni-directional and can translate in any direction. If the magnitudes of the wheel velocities are equal and the pair of wheels on the right side of the robot rotate in the opposite direction to the pair on the left side then the robot spins around its centre. Other combinations of wheel speeds result in circular trajectories – the natural trajectory for this platform. Many trajections rely on friction to cause the rollers to rotate, otherwise the rollers would have to slide laterally on the ground. Again, the forces applied to the ground by the wheels sum to produce a force vector which determines the motion of the robot. As the platform has three degrees of freedom, only three of the four wheel velocities can be assigned independently.



Uranus robot built at Carnegie-Mellon University using Illanator wheels

Several designs are used for robots that traverse rough terrain. Tracked vehicles, like bulldozers, handle rough terrain very well, but can damage the environment, particularly when turning. There are many places on the surface of the earth where wheeled and tracked vehicles cannot go, but people and animals can. While more difficult to build and control than the wheeled vehicles, **legged robots** have a number of advantages :

- can step over obstacles
- can walk up and down stairs.
- can give a smooth ride over rough ground by varying the effective length of their legs to match the surface undulations.

Legged robots are grouped into two classes : dynamically and statically stable systems. For static stability, at least three feet must be firmly placed on the ground and the centre of gravity of the vehicle must be within the triangle formed by the feet contact points. Dynamic stability is essential for vehicles with less than three feet, and useful for multi-legged vehicles. It is achieved by moving either the body or the feet to maintain the centre of gravity within the area described by the contact points between the feet and the ground.

Hexaped legged robots

In some industrial flexible manufacturing systems (FMSs) parts are carried from one work cell to another by conveyors or by **automated guided vehicles** (AGVs).

Automated Guided Vehicle (AGV) developed
In the SMRLab at the University of Ottawa

♦ *User interfaces*

Manually, the motion of a robot is controlled with a tech box containing a display and an array of push buttons. With these buttons, the operator controls the position and orientation of the end effector in Cartesian or joint corrdinates while the display indicates the current coordinate frame, and the instataneous value of the variable being controlled. Only one variable is controlled at a time. The operator uses the teach box to move the end effector along a desired trajectory, and at the push of a button, request the controlling computer to record positions along that trajectory. Some robots can be taught by a human operator physically pushing the robot through the desired motions. This is the method used in spray painting.

Most robots can be propgrammed using a *programming language*. Usually, programs are emtered from a video display terminal. Some researchers are experimenting with automatic generation of programs from models of the processes.

♦ **Controllers**

Computer-based robot controllers perform the following tasks :

- maintain a model of relationships between the references to the actuators and their consequential movements using measurements made by the internal sensors;
- maintain a model of the environment using the exteroceptor sensor data;
- plan the sequence of steps required to execute a task;
- control the sequence of robot actions in response to perform the task;
- adapt robot’s actions in response to changes in the external environment;

The power of a controller and the case with which it can be programmed are determined by the operating system, the programming language, and the programming environment.

Robot classificiation

The Japanese robot association (JIRA) has classified robots into six classes on the basis of their **level of intelligence** :

1. **Manual handling devices** controlled by a person
2. **Fixed sequence robots**.
3. **Variable sequence robots** where an operator can modify the sequence easily.
4. **Playback robots** where the human operator leads the robot through the task.
5. **Numerically controlled robots** where the operator supplies a motion program.
6. **Intelligent robots** which can understand and interact with changes in environment.

Robot controller can have a multi-level hierarchical architrcture:

1. **Artificial intelligence level**, where the program will accept a command such as, 'Pick up the bearing ' and decompose it into a sequence of lower level commands based on a strategic model of the task.
2. **Control mode level** where the motions of the system are modelled, including the dynamic interactions between the different mechanisms, trajectories planned, and grasp points selected. From this model a control strategy is formulated, and control commands issued to the next lower level.
3. **Servo system level** where actuators control the mechanism parameters using feedback of internal sensory data, and paths are modified on the basis of external sensory data. Also failure detection and correction mechanisms are implemented at this level.

There also are different levels of abtraction for the robot **programming languages**:

1. **Guiding systems**, in which the user leads the robot through the motions to be performed.
2. **Robot-level programming** in which the user writes a computer program to specify motion and sensing.
3. **Task-level programming** in which thed user specifies operations by their actions on the objects the robots is to manipulate.