Introduction to Robotics

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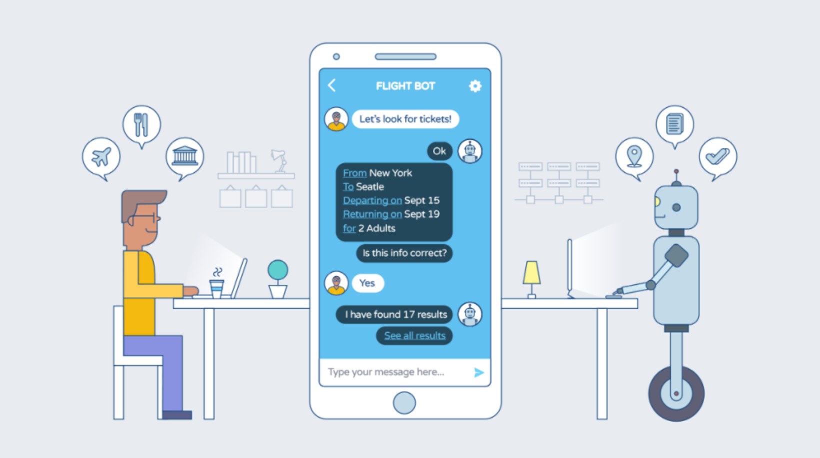
What is a robot?

- The robot is seen as a machine that, independently of its exterior, is able to modify the environment in which it operates
- This is accomplished by carrying out actions that are conditioned by certain rules of behaviour intrinsic in the machine as well as by some data the robot acquires on its status and on the environment
- In fact, robotics is commonly defined as the science studying the intelligent connection between perception and action

Robot?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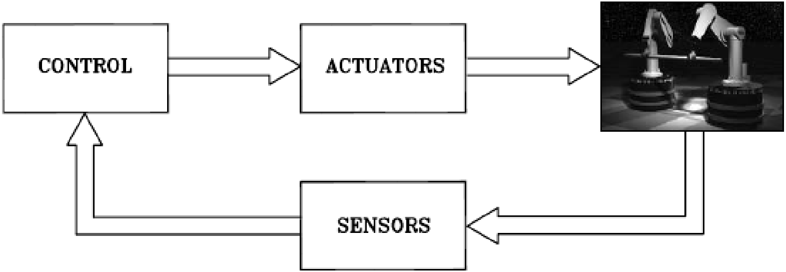
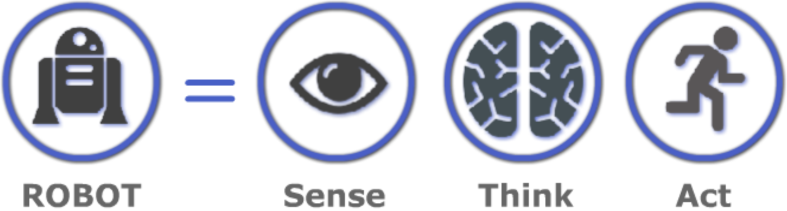
Robot?

Robot?

- A robotic system is in reality a complex system, functionally represented by multiple subsystems



Sense Think Act



Mechanical system

- The essential component of a robot is the **mechanical system** endowed, in general, with
  - a locomotion apparatus (wheels, crawlers, mechanical legs)
  - a manipulation apparatus (mechanical arms, end-effectors, artificial hands)

.

- The realization of such a system refers to the context of design of articulated mechanical systems and choice of materials

Actuation system

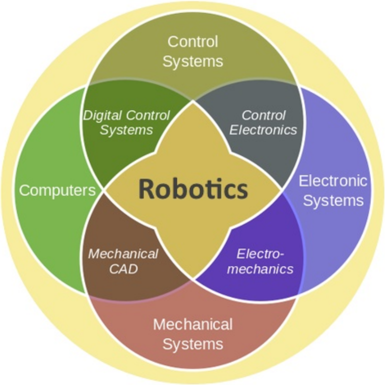
- The capability to exert an action, both locomotion and manipulation, is provided by an **actuation system** which animates the mechanical components of the robot
- The concept of such a system refers to the context of **motion control**, dealing with servomotors, drives and transmissions

- The capability for perception is entrusted to a **sensory system** which can acquire data on
  - the internal status of the mechanical system (proprioceptive sensors, such as position transducers)
  - the external status of the environment (exteroceptive sensors, such as force sensors and cameras)
- The realization of such a system refers to the context of materials properties, signal conditioning, data processing, and information retrieval

Control system

- The capability for connecting action to perception in an intelligent fashion is provided by a **control system** which can command the execution of the action in respect to the goals set by a task planning technique, as well as of the constraints imposed by the robot and the environment
- The realization of such a system follows the same feedback principle devoted to control of human body functions, possibly exploiting the description of the robotic system's components (modelling)
- The context is that of cybernetics, dealing with control and supervision of robot motions, artificial intelligence and expert systems, the computational architecture and programming environment

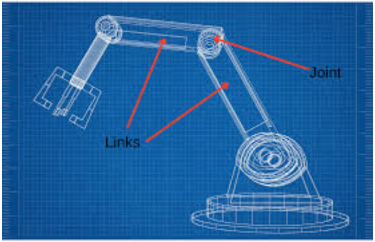
- Therefore, it can be recognized that robotics is an interdisciplinary subject concerning the cultural areas of
  - mechanics
  - control
  - computers
  - electronics



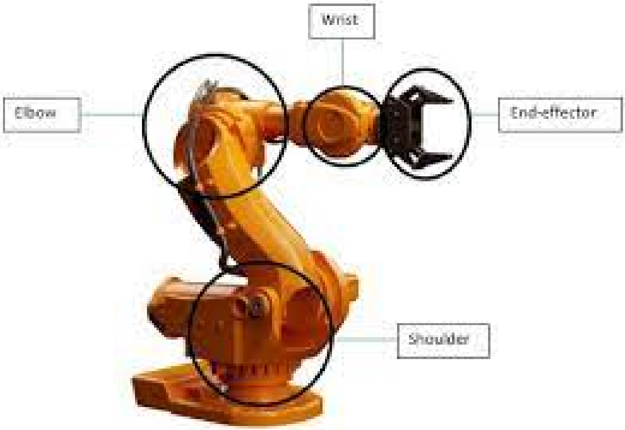
Robot Mechanical Structure

- The key feature of a robot is its mechanical structure.
- Robots can be classified as:
  - robot manipulators (with a fixed base)
  - mobile robots (with a mobile base)

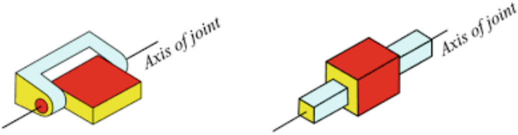
- The mechanical structure of a robot manipulator consists of a sequence of rigid bodies (**links**) interconnected by means of articulations (**joints**).
- A manipulator is characterized by:
  - an **arm** that ensures mobility;
  - a **wrist** that confers dexterity;
  - an **end-effector** that performs the task required of the robot.
- The fundamental structure of a manipulator is the serial or open **kinematic chain**: the sequence of links connecting the two ends of the chain.



Robot Manipulators: example



- A manipulator's mobility is ensured by the presence of joints.
- The articulation between two consecutive links can be realized by means of either a **prismatic** or a **revolute** joint.
- In an open kinematic chain, each prismatic or revolute joint provides the structure with a single degree of freedom (DOF).
- A prismatic joint creates a relative translational motion between the two links.
- A revolute joint creates a relative rotational motion between the two links.
- Revolute joints are usually preferred to prismatic joints in view of their compactness and reliability.



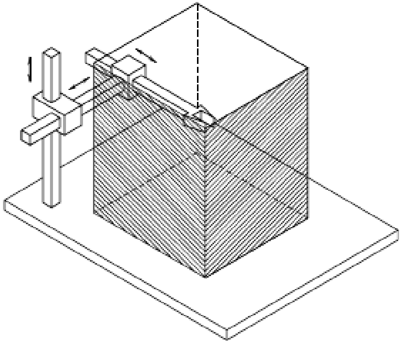
Revolute joint Prismatic joint

Degrees of freedom

- The degrees of freedom should be properly distributed along the mechanical structure in order to have a sufficient number to execute a given task.
- In the most general case of a task consisting of arbitrarily positioning and orienting an object in three-dimensional (3D) space, six DOFs are required:
  - three for positioning a point on the object
  - three for orienting the object with respect to a reference coordinate frame
- If more DOFs than task variables are available, the manipulator is said to be redundant from a kinematic viewpoint.

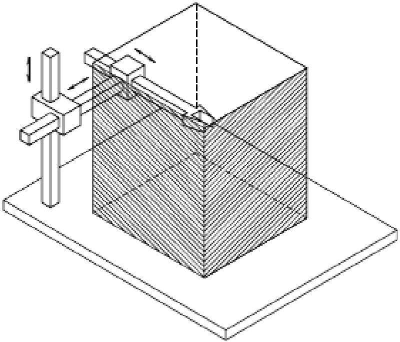
Workspace

- The workspace represents that portion of the environment the manipulator's end-effector can access.
- Its shape and volume depend on the manipulator structure as well as on the presence of mechanical joint limits.



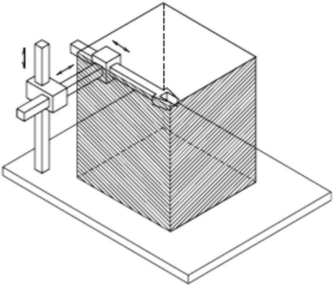
- Cartesian geometry is realized by three prismatic joints whose axes typically are mutually orthogonal.
- In view of the simple geometry, each DOF corresponds to a Cartesian space variable and thus it is natural to perform straight motions in space.

Cartesian - 2



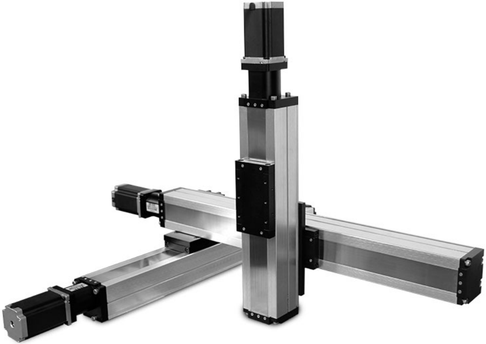
- The Cartesian structure offers very good mechanical stiffness.
- Wrist positioning accuracy is constant everywhere in the workspace.
- This is the volume enclosed by a rectangular parallel-piped.
- As opposed to high accuracy, the structure has low dexterity since all the joints are prismatic.

Cartesian - 3

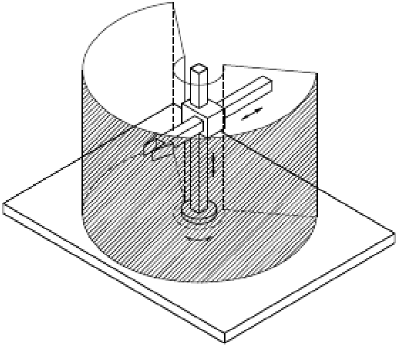


- Such a structure makes available a workspace with a large volume and enables the manipulation of objects of large dimensions and heavy weight.
- Cartesian manipulators are employed for material handling and assembly.
- The motors actuating the joints of a Cartesian manipulator are typically electric and occasionally pneumatic.

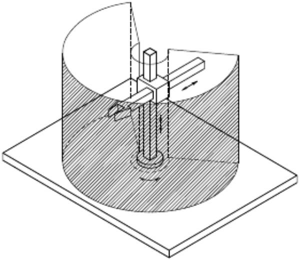
Cartesian - 4



Video

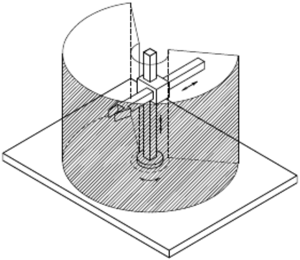


- Cylindrical geometry differs from Cartesian in that the first prismatic joint is replaced with a revolute joint.
- If the task is described in cylindrical coordinates, in this case each DOF also corresponds to a Cartesian space variable.



- The cylindrical structure offers good mechanical stiffness.
- Wrist positioning accuracy decreases as the horizontal stroke increases.
- The workspace is a portion of a hollow cylinder.
- The horizontal prismatic joint makes the wrist of a cylindrical manipulator suitable to access horizontal cavities.

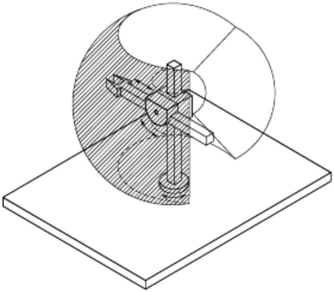
Cylindrical - 3



- Cylindrical manipulators are mainly employed for carrying objects even of large dimensions
- In such a case the use of hydraulic motors is to be preferred to that of electric motors.

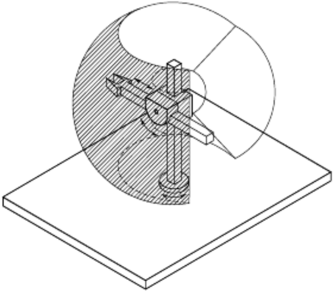
Video

Spherical - 1



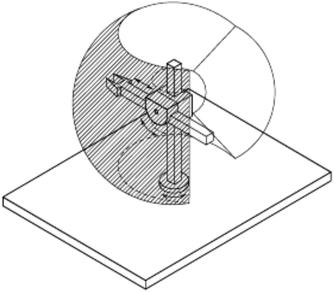
- Spherical geometry differs from cylindrical in that the second prismatic joint is replaced with a revolute joint.
- Each DOF corresponds to a Cartesian space variable provided that the task is described in spherical coordinates.

Spherical - 2



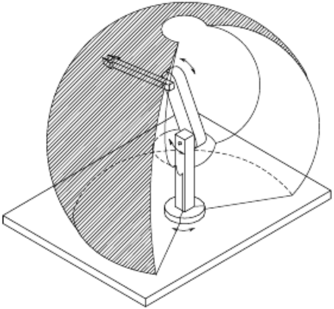
- Mechanical stiffness is lower than the above two geometries and mechanical construction is more complex.
- Wrist positioning accuracy decreases as the radial stroke increases.
- The workspace is a portion of a hollow sphere

Spherical - 3



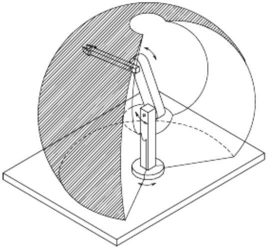
- Spherical manipulators are mainly employed for machining.
- Electric motors are typically used to actuate the joints.

Anthropomorphic - 1



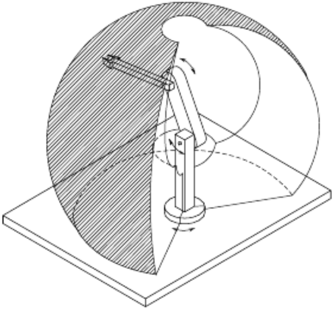
- Anthropomorphic geometry is realized by three revolute joints
- The revolute axis of the first joint is orthogonal to the axes of the other two which are parallel.
- By virtue of its similarity with the human arm, the second joint is called the shoulder joint and the third joint the elbow joint since it connects the "arm" with the "forearm."

Anthropomorphic - 2



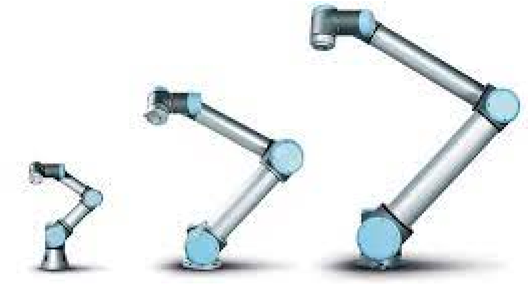
- The anthropomorphic structure is the most dexterous one, since all the joints are revolute.
- On the other hand, the correspondence between the DOFs and the Cartesian space variables is lost
- Wrist positioning accuracy varies inside the workspace.
- Workspace is approximately a portion of a sphere and its volume is large compared to manipulator encumbrance. Joints are typically actuated by electric motors. The range of industrial applications of anthropomorphic manipulators is wide.

Anthropomorphic - 3

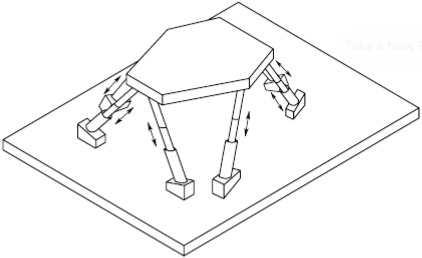


- Joints are typically actuated by electric motors.
- The range of industrial applications of anthropomorphic manipulators is wide.

Anthropomorphic - 4

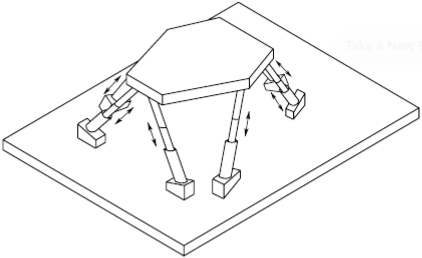


Video

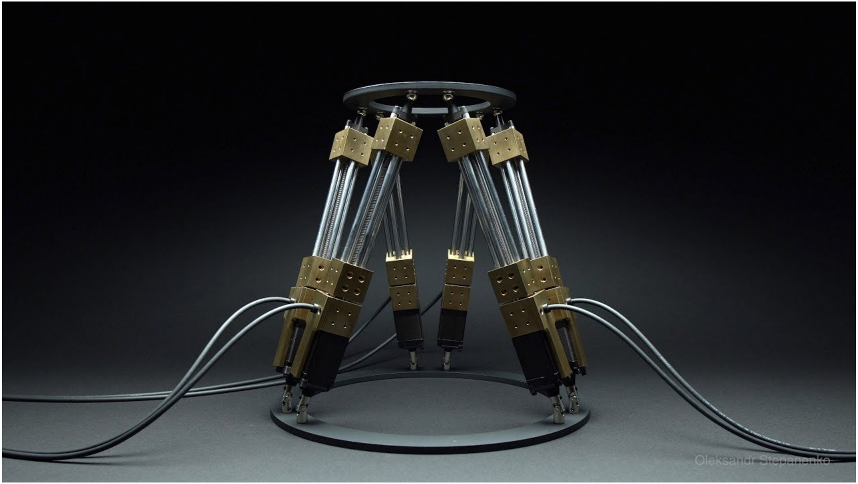


- All the previous manipulators have an open kinematic chain.
- Whenever larger payloads are required, the mechanical structure will have higher stiffness to guarantee comparable positioning accuracy.
- In such a case, resorting to a closed kinematic chain is advised.
- An interesting closed-chain geometry is parallel geometry which has multiple kinematic chains connecting the base to the end-effector.

Parallel - 2



- The fundamental advantage is seen in the high structural stiffness, with respect to open-chain manipulators, and thus the possibility to achieve high operational speeds.
- The drawback is that of having a reduced workspace.



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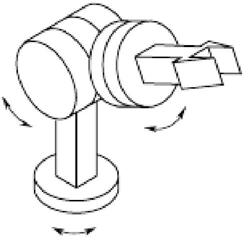
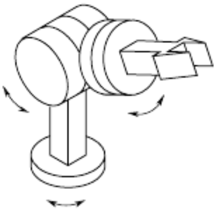


- The manipulator structures previously presented are required to position the wrist which is then required to orient the manipulator's end-effector.
- If arbitrary orientation in 3D space is desired, the wrist must possess at least three DOFs provided by revolute joints.

Wrist - 2



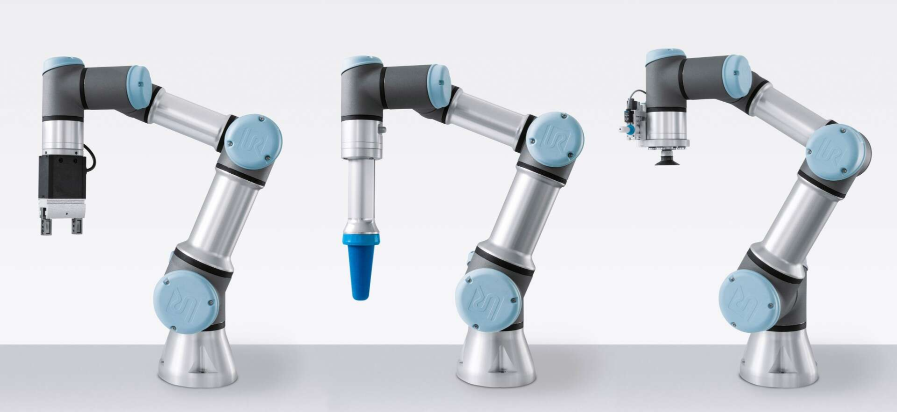
- Spherical wrist: the three revolute axes intersect at a single point.
- The key feature of a spherical wrist is the decoupling between position and orientation of the end-effector:
  - the arm is entrusted with the task of positioning the above point of intersection
  - the wrist determines the end-effector orientation
- Those realizations where the wrist is not spherical are simpler from a mechanical viewpoint, but position and orientation are coupled, and this complicates the coordination between the motion of the arm and that of the wrist to perform a given task.

Wrist - 3

End-effector - 1

- The end-effector is specified according to the task the robot should execute.
- For material handling tasks, the end-effector consists of a gripper of proper shape and dimensions determined by the object to be grasped.
- For machining and assembly tasks, the end-effector is a tool or a specialized device, e.g., a welding torch, a spray gun, a mill, a drill, or a screwdriver.

End-effector - 2



Robot Mechanical Structure
Mobile Robots

Mobile robots

- The main feature of mobile robots is the presence of a mobile base which allows the robot to move freely in the environment.
- Unlike manipulators, such robots are mostly used in service applications, where extensive, autonomous motion capabilities are required.
- From a mechanical viewpoint, a mobile robot consists of one or more rigid bodies equipped with a locomotion system.

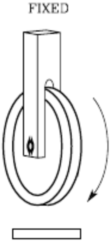
- **Wheeled** mobile robots
  - Wheeled mobile robots typically consist of a rigid body (base or chassis) and a system of wheels which provide motion with respect to the ground.
  - Other rigid bodies (trailers), also equipped with wheels, may be connected to the base by means of revolute joints.

- **Legged** mobile robots
  - Legged mobile robots are made of multiple rigid bodies, interconnected by prismatic joints or, more often, by revolute joints.
  - Some of these bodies form lower limbs, whose extremities (feet) periodically come in contact with the ground to realize locomotion.
  - There is a large variety of mechanical structures in this class, whose design is often inspired by the study of living organisms (biomimetic robotics): they range from biped humanoids to hexapod robots aimed at replicating the biomechanical efficiency of insects.

Wheeled vehicle

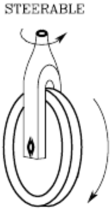
- Wheeled vehicles represent the vast majority of mobile robots actually used in applications.
- The basic mechanical element of such robots is indeed the wheel.
- Three types of conventional wheels exist.

Fixed wheel



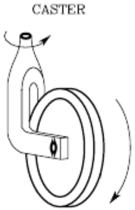
- The **fixed** wheel can rotate about an axis that goes through the center of the wheel and is orthogonal to the wheel plane.
- The wheel is rigidly attached to the chassis, whose orientation with respect to the wheel is therefore constant.

Steerable wheel



- The **steerable** wheel has two axes of rotation.
- The first is the same as a fixed wheel.
- The second is vertical and goes through the center of the wheel.
- This allows the wheel to change its orientation with respect to the chassis.

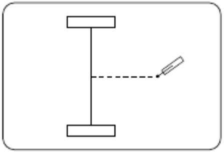
Caster wheel



- The **caster** wheel has two axes of rotation.
- The vertical axis does not pass through the center of the wheel, from which it is displaced by a constant offset.
- Such an arrangement causes the wheel to swivel automatically, rapidly aligning with the direction of motion of the chassis.
- This type of wheel is therefore introduced to provide a supporting point for static balance without affecting the mobility of the base; for instance, caster wheels are commonly used in shopping carts as well as in chairs.

- The variety of kinematic structures that can be obtained by combining the three conventional wheels is wide.
- In the following, the most relevant arrangements are briefly examined.

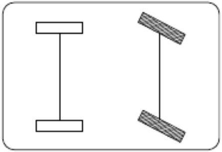
Differential-drive



- In a **differential-drive** vehicle there are two fixed wheels with a common axis of rotation, and one or more caster wheels, typically smaller, whose function is to keep the robot statically balanced.
- The two fixed wheels are separately controlled, in that different values of angular velocity may be arbitrarily imposed, while the caster wheel is passive.
- Such a robot can rotate on the spot (i.e., without moving the midpoint between the wheels), provided that the angular velocities of the two wheels are equal and opposite.

Video

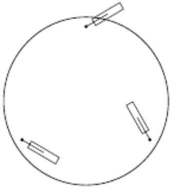
Car-like



- A **car-like** vehicle has two fixed wheels mounted on a rear axle and two steerable wheels mounted on a front axle.
- One motor provides (front or rear) traction while the other changes the orientation of the front wheels with respect to the vehicle.
- It is worth pointing out that, to avoid slippage, the two front wheels must have a different orientation when the vehicle moves along a curve; in particular, the internal wheel is slightly more steered with respect to the external one.
  $\rightarrow$ This is guaranteed by the use of a specific device called Ackermann steering.

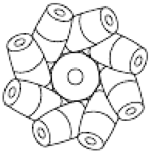
Video

Omnidirectional



- An omnidirectional robot has three caster wheels usually arranged in a symmetric pattern.
- The traction velocities of the three wheels are independently driven.
- Unlike the previous cases, this vehicle is omnidirectional: in fact, it can move instantaneously in any Cartesian direction, as well as re-orient itself on the spot.

Swedish wheel



- There exist other special types of wheels, among which is notably the Mecanum (or Swedish) wheel.
- This is a fixed wheel with passive rollers placed along the external rim; the axis of rotation of each roller is typically inclined by 45° with respect to the plane of the wheel.
- A vehicle equipped with four such wheels mounted in pairs on two parallel axles is also omnidirectional.

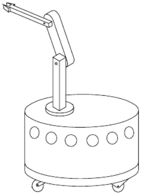
Video

Mechanical balance

- In the design of a wheeled robot, the mechanical balance of the structure does not represent a problem in general.
- In particular, a three-wheel robot is statically balanced as long as its center of mass falls inside the support triangle, which is defined by the contact points between the wheels and ground.
- Robots with more than three wheels have a support polygon, and thus it is typically easier to guarantee the above balance condition.
- It should be noted, however, that when the robot moves on uneven terrain a suspension system is needed to maintain the contact between each wheel and the ground.

Workspace

- Unlike the case of manipulators, the workspace of a mobile robot (defined as the portion of the surrounding environment that the robot can access) is potentially unlimited.
- Nevertheless, the local mobility of a non-omnidirectional mobile robot is always reduced:
  - For instance, a car-like robot cannot move instantaneously in a direction parallel to the rear wheel axle.
  - Despite this fact, it can be maneuvered so as to obtain, at the end of the motion, a net displacement in that direction.
- In other words, many mobile robots are subject to constraints on the admissible instantaneous motions, without actually preventing the possibility of attaining any position and orientation in the workspace.

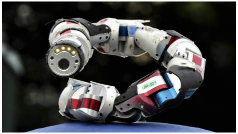


- It is obviously possible to merge the mechanical structure of a manipulator with that of a mobile vehicle by mounting the former on the latter.
- Such a robot is called a mobile manipulator and combines the dexterity of the articulated arm with the unlimited mobility of the base.
- The design of a mobile manipulator involves additional difficulties related, for instance, to the static and dynamic mechanical balance of the robot, as well as to the actuation of the two systems.

Video

Other types of mechanical locomotion systems

- **Tracked** locomotion, very effective on uneven terrain.
- **Undulatory** locomotion, inspired by snake gaits, which can be achieved with- out specific devices.
- There also exist types of locomotion that are not constrained to the ground, such as **flying** and **navigation**.



Video

Applications
Industrial Robotics

Industrial Robotics - 1

- Industrial robotics is the discipline concerning robot design, control and applications in industry
- Its products have by now reached the level of a mature technology.
- The connotation of a robot for industrial applications is that of operating in a structured environment whose geometrical or physical characteristics are mostly known a priori.
- Limited autonomy is required.

Industrial Robotics - 2

- The industrial robot is a machine with significant characteristics of versatility and flexibility.
- According to the widely accepted definition of the Robot Institute of America, a robot is:
  A reprogrammable multifunctional manipulator designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks
  Such a definition, dating back to 1980, reflects the current status of robotics technology.
- Industrial robots present three fundamental capacities that make them useful for a manufacturing process:
  - material handling
  - manipulation
  - measurement

Material handling - 1

- In a manufacturing process, each object has to be transferred from one location in the factory to another in order to be stored, manufactured, assembled, and packed.
- During transfer, the physical characteristics of the object do not undergo any alteration.
- The robot's capability to pick up an object, move it in space on predefined paths and release it makes the robot itself an ideal candidate for material handling operations.
- Typical applications include:
  - palletizing (placing objects on a pallet in an ordered way),
  - warehouse loading and unloading,
  - mill and machine tool tending,
  - part sorting,
  - packaging.

Video

Material handling - 2

- In these applications, besides robots, Automated Guided Vehicles (AGV) are utilized which ensure handling of parts and tools around the shop floor from one manufacturing cell to the next.
- As compared to the traditional fixed guide paths for vehicles (inductive guide wire, magnetic tape, or optical visible line), modern AGVs utilize high-tech systems with onboard microprocessors and sensors (laser, odometry, GPS) which allow their localization within the plant layout.

Manufacturing

- Manufacturing consists of transforming objects from raw material into finished products.
- During this process, the part either changes its own physical characteristics as a result of machining, or loses its identity as a result of an assembly of more parts.
- The robot's capability to manipulate both objects and tools make it suitable to be employed in manufacturing.
- Typical applications include:
  - arc and spot welding,
  - painting and coating,
  - gluing and sealing,
  - laser and water jet cutting,
  - milling and drilling,
  - casting and die spraying,
  - deburring and grinding,
  - screwing, wiring and fastening,
  - assembly of mechanical and electrical groups,
  - assembly of electronic boards.

Measuring

- Besides material handling and manipulation, in a manufacturing process it is necessary to perform measurements to test product quality.
- The robot's capability to explore 3D space together with the availability of measurements on the manipulator's status allow a robot to be used as a measuring device.
- Typical applications include:
  - object inspection,
  - contour finding,
  - detection of manufacturing imperfections.

Video Video2

Applications
Advanced Robotics

Advanced Robotics

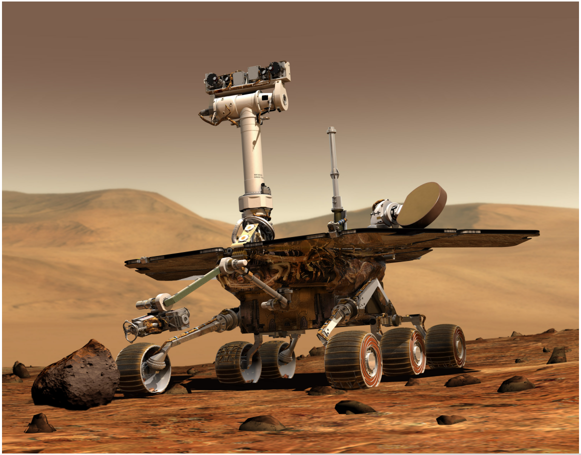
- The expression advanced robotics usually refers to the science studying robots with marked characteristics of autonomy, operating in scarcely structured or unstructured environments, whose geometrical or physical characteristics would not be known a priori.
- There are many motivations which strongly encourage advances in knowledge within this field.
- They range from the need for automata whenever human operators are not available or are not safe (**field robots**), to the opportunity of developing products for potentially wide markets which are aimed at improving quality of life (**service robots**).

Field Robots

- The context is that of deploying robots in areas where human beings could not survive or be exposed to unsustainable risks.
- Such robots should carry out exploration tasks and report useful data on the environment to a remote operator, using suitable onboard sensors.
- Typical scenarios are the exploration of a volcano, the intervention in areas contaminated by poisonous gas or radiation, or the exploration of the deep ocean or space.
- A similar scenario is that of disasters caused by fires in tunnels or earthquakes; in such occurrences, there is a danger of further explosions, escape of harmful gases or collapse, and thus human rescue teams may cooperate with robot rescue teams.

Video

- NASA succeeded in delivering some mobile robots (rovers) to Mars which navigated on the Martian soil, across rocks, hills and crevasses. Such rovers were partially teleoperated from earth and have successfully explored the environment with sufficient autonomy.



Service Robots - 1

- Autonomous vehicles are also employed for civil applications, i.e., for mass transit systems, thus contributing to the reduction of pollution levels.
- Such vehicles are part of the so-called Intelligent Transportation Systems (ITS) devoted to traffic management in urban areas.

Video

- Another feasible application where the adoption of mobile robots offers potential advantages is museum guided tours.

- Technology is ready to transform into commercial products the prototypes of robotic aids to enhance elderly and impaired people's autonomy in everyday life; autonomous wheelchairs, mobility aid lifters, feeding aids and rehabilitation robots allowing tetraplegics to perform manual labor tasks are examples of such service devices.

- Several robotic systems are employed for medical applications.
- Surgery assistance systems exploit a robot's high accuracy to position a tool, i.e., for hip prosthesis implant.
- Yet, in minimally-invasive surgery, i.e., cardiac surgery, the surgeon operates while seated comfortably at a console viewing a 3D image of the surgical field, and operating the surgical instruments remotely by means of a haptic interface.

- Agricultural robotics are used to improve productivity, specialization and environmental sustainability.
- Labor shortages, increased consumer demand and high production costs are some of the factors that have accelerated automation in this sector, with the aim of reducing costs and optimizing harvests.

Video Video2

- Another wide market segment comes from entertainment, where robots are used as toy companions for children, and life companions for the elderly, such as humanoid robots and the pet robots being developed in Japan.

Robot Modeling, Planning and Control

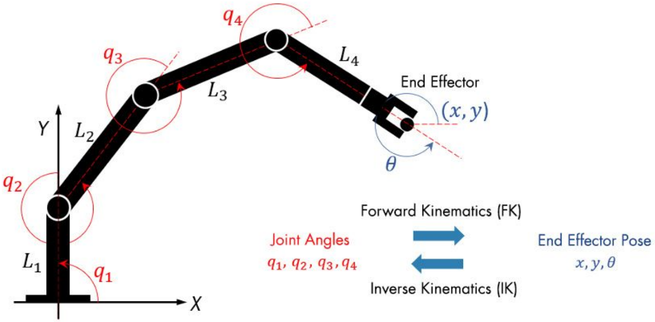
Robot Modelling, Planning and Control

- In all robot applications, completion of a generic task requires the execution of a specific motion prescribed to the robot.
- The correct execution of such motion is entrusted to the control system which should provide the robot's actuators with the commands consistent with the desired motion.
- Motion control demands an accurate analysis of the characteristics of the mechanical structure, actuators, and sensors.
- The goal of such analysis is the derivation of the mathematical models describing the input/output relationship characterizing the robot components.
- Modelling a robot manipulator is therefore a necessary premise to finding motion control strategies.

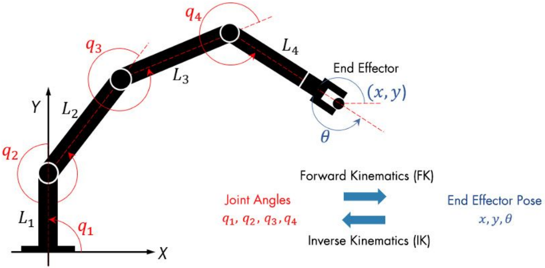
Modeling - 1

- Kinematic analysis of the mechanical structure of a robot concerns the description of the motion with respect to a fixed reference Cartesian frame by ignoring the forces and moments that cause motion of the structure.
- With reference to a robot manipulator, kinematics describes the analytical relationship between the joint positions and the end-effector position and orientation.
- Differential kinematics describes the analytical relationship between the joint motion and the end-effector motion in terms of velocities, through the manipulator Jacobiann.

- The formulation of the kinematics relationship allows the study of two key problems of robotics, namely, the **direct kinematics** problem and the **inverse kinematics** problem.
- Direct kinematics concerns the determination of a systematic, general method to describe the end-effector motion as a function of the joint motion by means of linear algebra tools.



- Inverse kinematics concerns the inverse problem; its solution is of fundamental importance to transform the desired motion, naturally prescribed to the end-effector in the workspace, into the corresponding joint motion.
- The availability of a manipulator's kinematic model is also useful to determine the relationship between the forces and torques applied to the joints and the forces and moments applied to the end-effector in static equilibrium configurations.



Modeling - 4

- Modeling of mobile robots requires a preliminary analysis of the kinematic constraints imposed by the presence of wheels.
- Depending on the mechanical structure, such constraints can be integrable or not; this has direct consequence on a robot's mobility.
- The kinematic model of a mobile robot is essentially the description of the admissible instantaneous motions in respect of the constraints.
- On the other hand, the dynamic model accounts for the reaction forces and describes the relationship between the above motions and the generalized forces acting on the robot.

Planning: robot manipulators

- With reference to the tasks assigned to a manipulator, the issue is whether to specify the motion at the joints or directly at the end-effector.
- In material handling tasks, it is sufficient to assign only the pick-up and release locations of an object (point-to-point motion)
- In machining tasks, the end-effector has to follow a desired trajectory (path motion).
- The goal of trajectory planning is to generate the timing laws for the relevant variables (joint or end-effector) starting from a concise description of the desired motion.

Video

Planning: mobile robots

- The motion planning problem for a mobile robot concerns the generation of trajectories to take the vehicle from a given initial configuration to a desired final configuration.
- Such a problem is more complex than that of robot manipulators, since trajectories have to be generated in respect of the kinematic constraints imposed by the wheels.
- Whenever obstacles are present in a mobile robot's workspace, the planned motions must be safe, so as to avoid collisions.
- Such a problem, known as motion planning, can be formulated in an effective fashion for both robot manipulators and mobile robots utilizing the configuration space concept.

Video

Control: robot manipulators

- Realization of the motion specified by the control law requires the employment of actuators and sensors.
- The trajectories generated constitute the reference inputs to the motion control system of the mechanical structure.
- The problem of robot manipulator control is to find the time behaviour of the forces and torques to be delivered by the joint actuators so as to ensure the execution of the reference trajectories.
- This problem is quite complex, since a manipulator is an articulated system and, as such, the motion of one link influences the motion of the others.

Control: mobile robots

- Control of a mobile robot substantially differs from the analogous problem for robot manipulators.
- This is due, in turn, to the availability of fewer control inputs than the robot has configuration variables.
- An important consequence is that the structure of a controller allowing a robot to follow a trajectory (tracking problem) is unavoidably different from that of a controller aimed at taking the robot to a given configuration (regulation problem).
- Further, since a mobile robot's proprioceptive sensors do not yield any data on the vehicle's configuration, it is necessary to develop localization methods for the robot in the environment.

Actuators and Sensors

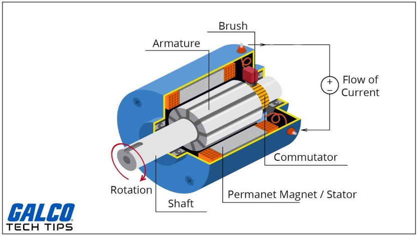
Motors

- Electric motors are used to “actuate” some parts of your robot: its wheels, legs, tracks, arms, fingers, or camera.
- There are dozens of types of electric motors but we focus on the most common types used in robotics:
  - Brushed DC motor
  - Brushless DC motor
  - Geared DC motor
  - Servo motor
  - Stepper motor
  - DC Linear Actuator
- AC (alternating current) motors are rarely used in mobile robots because most of the robots are powered with direct current (DC) coming from batteries.
- AC motors are mainly used in industrial environments where very high torque is required, or where the motors are connected to the mains / wall outlet

Brushed DC Motor

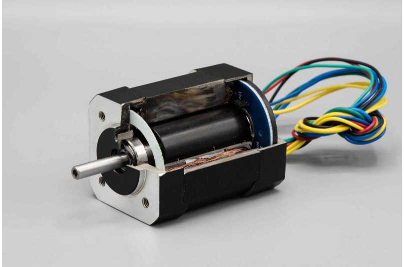
- A brushed DC electric motor is an internally commutated electric motor designed to be run from a direct current power source and utilizing an electric brush for contact.

- Advantages:
  - Inexpensive
  - Lightweight
  - Reasonably Efficient
  - Good low-speed torque
- Limitations:
  - In addition to the audible whine from the commutator brushes, these motors create a lot of electrical noise which can find its way back into other circuitry and cause problems.



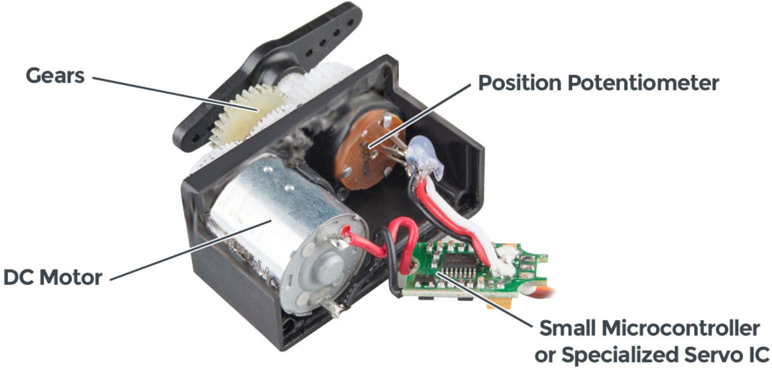
Brushless DC Motor

- A brushless DC electric motor is a synchronous motor using a direct current (DC) electric power supply.
- Advantages:
  - Higher torque to weight ratio
  - Reduced operational and mechanical noise
  - Longer lifespan (no brush and commutator erosion)
- Limitations:
  - Some types of brushless motors require a separate controller for operation.



Servo Motor

- A servomotor is an actuator that allows for precise control of position, velocity, and acceleration.
- It consists of a suitable motor coupled to a sensor for position feedback.
- It also requires a controller.

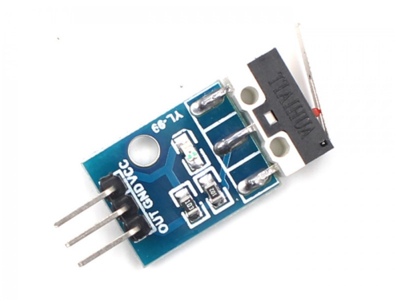


Stepper Motor

- A brushless DC electric motor is a synchronous motor using a direct current (DC) electric power supply.

- Advantages:
  - Precise repeatable positioning
  - Precise speed control
  - Excellent low-speed torque
  - Excellent 'holding torque' to maintain position
- Limitations:
  - Low efficiency
  - May need encoder or limit switch to establish a reference position
  - Subject to missed steps if overloaded

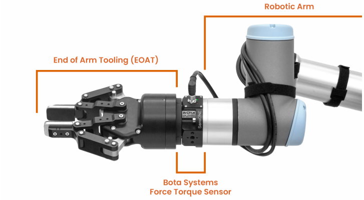
- Switch sensor
  - Very simple
  - On-Off

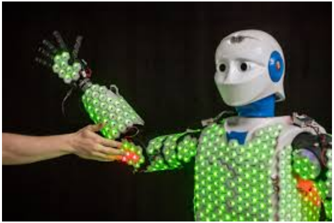


- Switch sensor
  - Very simple
  - On-Off

Interaction sensors

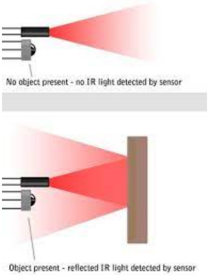
- Force/torque sensors
  - 3-axis force sensor
  - 3-axis torque sensor



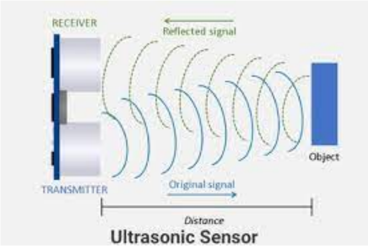


- Artificial skin
  - Temperature
  - Pressure
  - Proximity

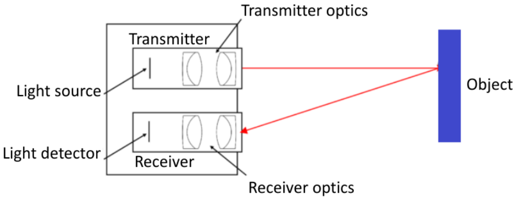
- Infrared (IR) sensor
  - Measures reflected light intensity which corresponds to distance
  - Range: 10 cm – 1 m
  - Wide detection cone
  - Can be also used to detect black vs white color (e.g., for a line detection)
  - Unaffected by material softness
  - Sensitive to object color and transparency
  - Relatively short distance



- Ultrasonic sensor
  - Measures time of reflected signal to return which corresponds to distance
  - Range: 2 cm – 3 m
  - Wide detection cone
  - Unaffected by object color and transparency
  - Sensitive to material softness
  - Relatively slow



- LIDAR sensor (laser imaging, detection, and ranging)
  - Measures time of reflected signal to return which corresponds to distance
  - Range: 5 cm – 40 m
  - Fast and long range sensing
  - One single point (no cone)
  - Relatively expensive (1D)

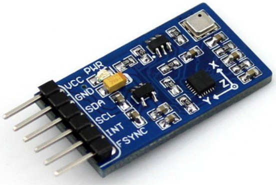


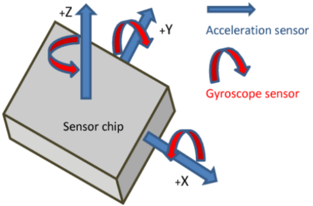
- LIDAR 2D

- LIDAR 3D

- Inertial motion unit (IMU) sensor
  - 3-axis gyroscope
  - 3-axis accelerometer
  - 3-axis magnetometer (absolute orientation)
  - Can be used for estimation of position of a mobile robot using path integration

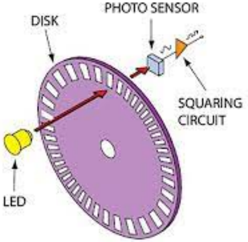
    Path reconstruction is inaccurate and gets worse with time





Position sensors

- Angular position sensor (optical encoder)
  - Measures rotary motion
  - Can be used for estimation of position of a mobile robot using path integration
  - Path reconstruction is inaccurate and gets worse with time



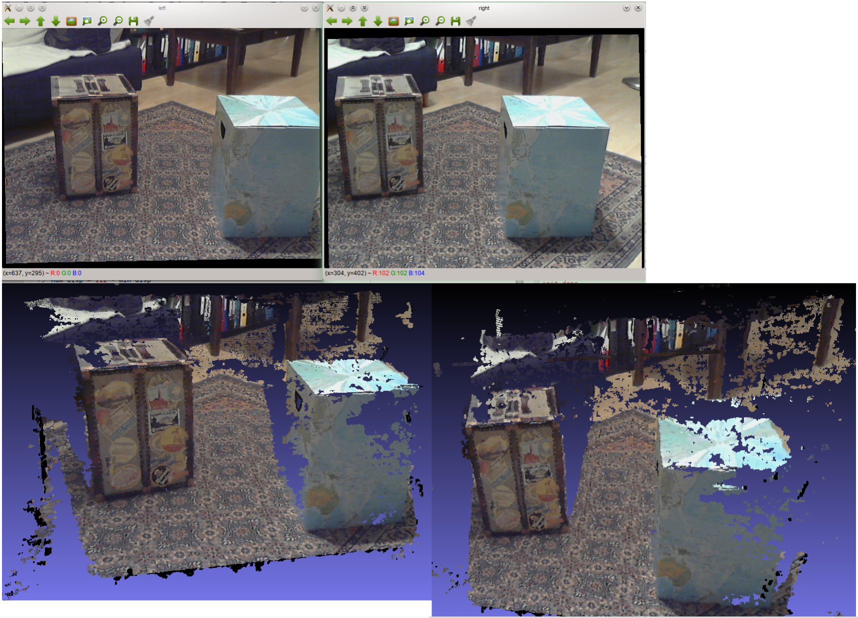
- Global positioning system (GPS) sensor
  - Global position
  - Requires satellite signal
  - Works only outdoors

- Indoor positioning system (IPS)
  - Radio frequency (RF) signals from radio sources to determine robots location

- 2D RGB cameras
  - Direct mapping of environment
  - 2D RGB image
  - Produces a lot of data: 3xWxH

- 3D RGB-D sensors
  - RGB camera
  - IR camera (depth sensor)
  - Allows 3D reconstruction
  - Sensitive to object transparency
  - Produces a lot of data: 3xWxH + 1xWxH

- 3D stereo cameras
  - Two RGB cameras
  - Allows 3D reconstruction
  - Not affected by object transparency
  - Produces a lot of data: 2x 3xWxH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Videos

- Video 3D Lidar
- Video RGBD
- Video RGBD + SLAM