

FOUNDATIONS OF ROBOTICS

Introduction

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These slides are distributed as companion material to the textbook
Foundations of Robotics by B. Siciliano, L. Villani, G. Oriolo, A. De Luca
published by Springer Nature.

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Outline

- Robotics
- Mechanical Structure
- Actuation
- Sensing
- Control Architecture

Robotics

- **Robotics** studies machines that can replace or assist humans in physical tasks and decision making
- Focus on industrial, field and service applications
- Robots combine mechanics, actuation, sensing and control intelligence
- Mechanical structures, actuators, sensors, and control architectures with examples are introduced

History

- Ancient myths and automata anticipate the robot concept
- Examples include Prometheus and Talus in Greek mythology
- Egyptian oracle statues and Babylonian clepsydra water clocks
- Automaton theater of Hero of Alexandria and Al Jazari's water powered machines
- Leonardo da Vinci designed many ingenious mechanical devices
- Eighteenth century automata in Europe and Asia such as Jacquet Droz androids
- Japanese **karakuri ningyo** mechanical dolls for serving tea or archery
- Term robot comes from Czech **robota** meaning subordinate labor and was introduced in 1920 by Czech playwright Karel Čapek in his play **Rossum's Universal Robots**

- Asimov's **three fundamental laws of robotics** introduced in his novel **Runaround**
 1. a robot may not injure a human being or, through inaction, allow a human being to come to harm
 2. a robot must obey orders given by human beings, except when such orders conflict with the first law
 3. a robot must protect its own existence, as long as this does not conflict with the first or second law

- Mid-twentieth century research linked human intelligence and machines
- Early robots emerged in the 1960s from numerical control and teleoperation technologies
- Development of integrated circuits and digital computers enabled programmable robots
- In the late 1970s **industrial robots** for automation of flexible manufacturing systems
- In the 1980s robotics defined as the science that studies the **intelligent connection of perception to action**
- In the 1990s robots to replace humans in challenging environments (**field robotics**) or to improve quality of life (**service robotics**)

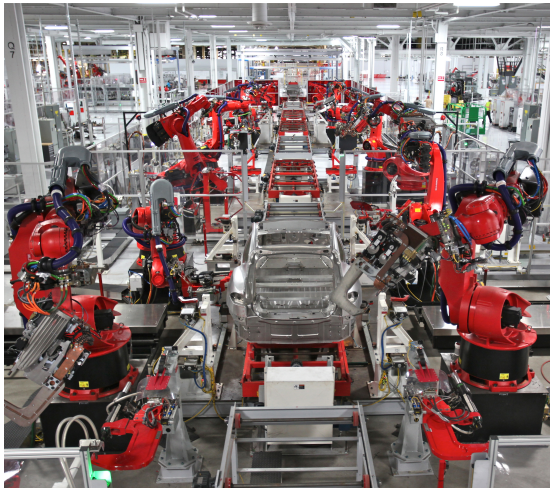
Industrial Robotics

- **Industrial robotics** studies robot design, control, and applications in industry
- Robots usually work in **structured environments** with known geometry and physics
- Goals include cost reduction, productivity increase and improved quality
- **Automation** replaces human labor in operations and information processing

- Rigid automation
 - mass production of a single product type
 - fixed sequences executed by special purpose machines
- Programmable automation
 - low to medium batches of different products
 - easily reprogrammable sequences on versatile machines
- Flexible automation
 - variable batches of different products
 - strong integration of industrial and computer technologies

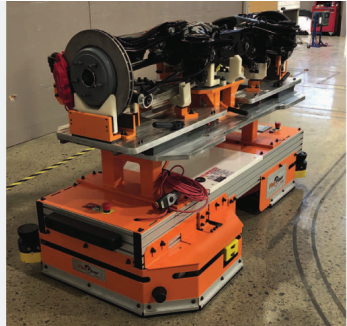
- Industrial robot is a reprogrammable multifunctional manipulator
- Moves materials parts tools or devices through programmed motions
- Three main capabilities
 - manipulation
 - material handling
 - measurement and inspection
- Widely used in automotive, chemical, electronics, and other industries

- Industrial robots in an automotive assembly line



- Manipulation tasks in manufacturing
 - 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

- Material handling tasks
 - robots move parts between storage, manufacturing, assembly and packing
 - typical tasks include palletizing, machine tending, sorting and packaging
 - **automated guided vehicles** (AGVs) move parts and tools between cells
 - modern AGVs use onboard processors and sensors for localization and workflow
- AGVs integrated in production lines



- Measurement tasks for testing product quality
 - object inspection
 - contour finding
 - detection of manufacturing imperfections
- AGVs integrated in production lines

Field and Service Robotics

- **Advanced robotics** studies robots with high autonomy in **unstructured environments**
- **Field robots** operate where humans cannot safely work
- **Service robots** operate in human environments improving quality of life
- Both require rich sensing, robust decision making and autonomy

- Perseverance rover exploring Martian environments



- Humanoid robot HUBO in a robotics challenge for hazardous environments



- Driverless car operating in complex urban scenarios



- Vacuum cleaning robot as a service device



- Robotic system for minimally invasive surgery

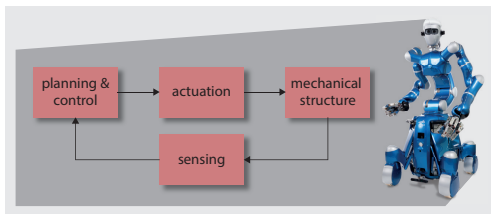


- Exoskeleton for assistance and ergonomics at work



Robotic System

- **Mechanical system**
 - locomotion apparatus such as wheels, tracks, legs
 - manipulation apparatus such as arms, hands, end-effectors
- **Actuation system** with servomotors and transmissions
- **Sensory system** with proprioceptive and exteroceptive sensors
- **Control system** for planning, decision making and feedback control
- Functional components of a **robotic system**



Mechanical Structure

- Key feature of a robot is its **mechanical structure**
- Two main classes
 - fixed-base **robot manipulators**
 - **mobile robots** with a movable base
- Mobile robots include **wheeled, legged, flying and underwater robots**
- The mechanical structure determines the reachable workspace, stiffness and payload

Robot Manipulators

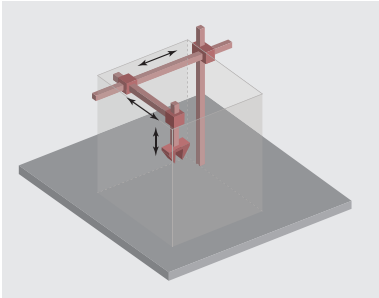
- A **robot manipulator** is a sequence of rigid **links**
- Links are interconnected by **joints** providing relative motion
- Structure is characterized by
 - **arm** for gross positioning
 - **wrist** for orientation and dexterity
 - **end-effector** for task execution
- The term arm is often used as a synonym for manipulator depending on context

- Open kinematic chain
 - single sequence of links connects base and end-effector
- Closed kinematic chain
 - at least one loop of links is present
- Industrial manipulators are mostly open chains
- Closed chains increase stiffness but reduce workspace and complicate design

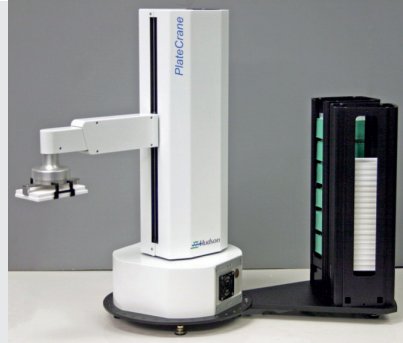
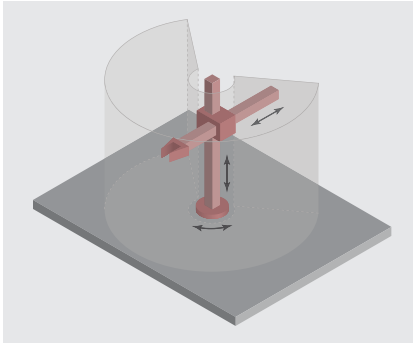
- Two basic joint types
 - **prismatic** joint for relative translation
 - **revolute** joint for relative rotation
- In an open chain each joint adds one **degree of freedom** (DoF)
- In closed chains constraints reduce the number of independent DoFs
- Revolute joints are usually preferred for compactness and reliability
- Placing and orienting an object in 3D requires **six** DoFs
 - three for position
 - three for orientation
- A manipulator with more than six DoFs is kinematically **redundant**
- Redundancy allows optimization of secondary criteria
 - examples include obstacle avoidance, joint limit avoidance and posture optimization

- **Reachable** workspace is the region accessible by the end-effector
- Workspace depends on geometry and joint limits
- Shape and volume affect feasibility of tasks and robot placement
- Different arm geometries exhibit different workspace shapes and stiffness

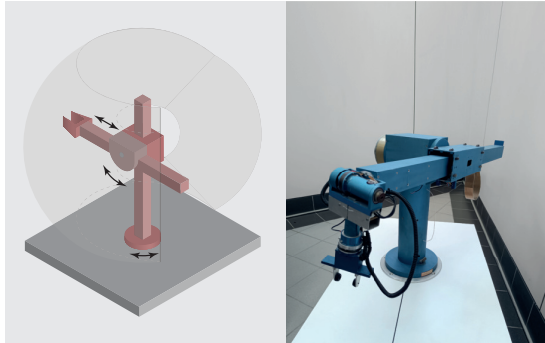
- **Cartesian** geometry
 - realized by three mutually orthogonal prismatic joints
 - simple geometry with direct correspondence between joint and Cartesian variables
 - high stiffness and uniform positioning accuracy in the workspace
 - workspace is a rectangular parallelepiped
- Cartesian arm and gantry robot with large workspace



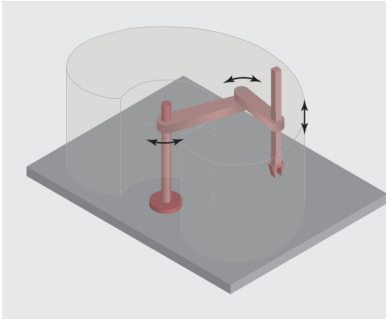
- **Cylindrical** geometry
 - first joint is revolute followed by prismatic joints
 - natural description in cylindrical coordinates
 - good stiffness and suitable for accessing horizontal cavities
 - workspace is a portion of a hollow cylinder
- Cylindrical arm and PlateCrane EX laboratory robot



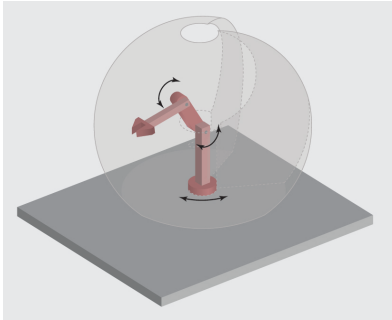
- **Spherical** geometry
 - two revolute joints followed by a prismatic joint
 - natural description in spherical coordinates
 - lower stiffness and more complex construction than Cartesian and cylindrical arms
 - workspace is a portion of a hollow sphere possibly including the base region
- Spherical arm and Stanford manipulator



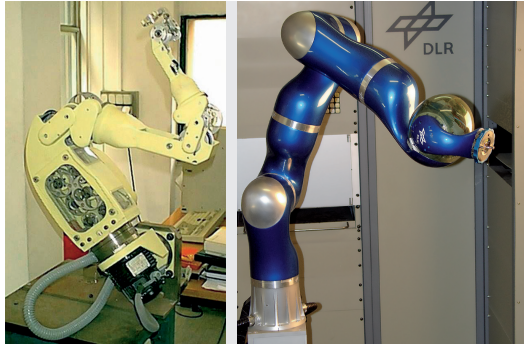
- SCARA geometry
 - two revolute joints and one vertical prismatic joint with all axes parallel
 - selective compliance assembly robot arm (SCARA)
 - high stiffness to vertical loads and compliance to horizontal loads
 - well suited for vertical assembly and high-speed pick and place
- SCARA arm and Epson Synthis T3 robot



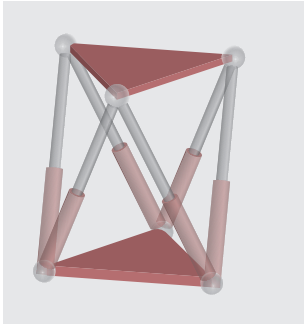
- **Anthropomorphic** geometry
 - three revolute joints analogous to human shoulder and elbow
 - highest dexterity among basic geometries
 - workspace is a large portion of a sphere relative to robot size
 - widely used in industrial applications for handling and assembly
- Anthropomorphic arm and Fanuc industrial robot



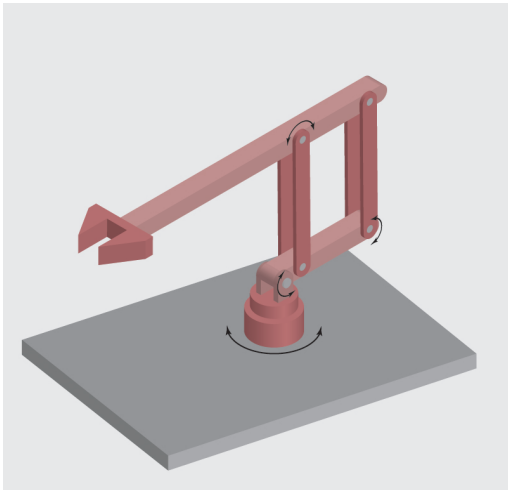
- Manipulators with **elastic elements**
 - links are usually rigid but transmissions may exhibit **elasticity**
 - elasticity arises from belts, cables, long shafts and gear reductions
 - **harmonic drives** and cycloidal gears introduce compliance with high reduction
 - joint elasticity is significant for dynamic analysis and control
- Cable-driven Dexter robot and DLR lightweight arm with harmonic drives



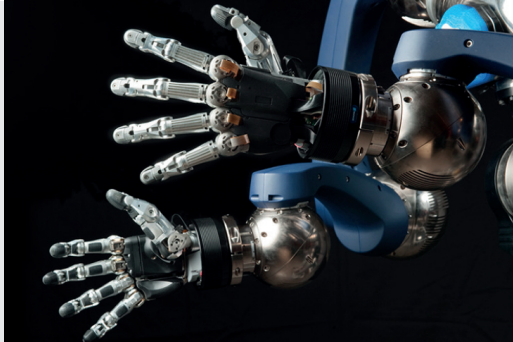
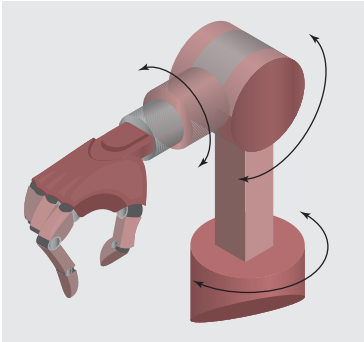
- Closed kinematic chains
 - closed chains increase stiffness for heavy payloads
 - parallelogram structures create closed chains in anthropomorphic arms
 - parallel manipulators use multiple chains between base and end-effector
 - advantages include high stiffness and high speed but reduced workspace
- Stewart platform and delta type parallel robot



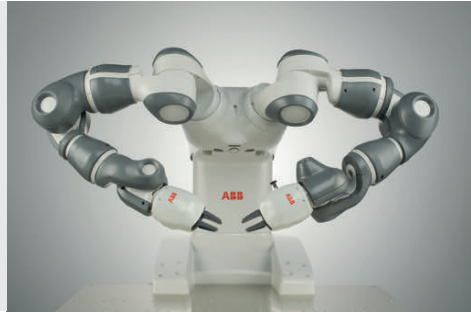
- Arm with parallelogram and palletizing robot



- End-effector orientation
 - wrist must provide at least three revolute DoFs
 - spherical wrist has three intersecting revolute axes
 - spherical wrist decouples position from orientation
 - end-effector is chosen according to task such as gripper, tool or multifingered hand
- Spherical wrist and multifingered hands on lightweight arms



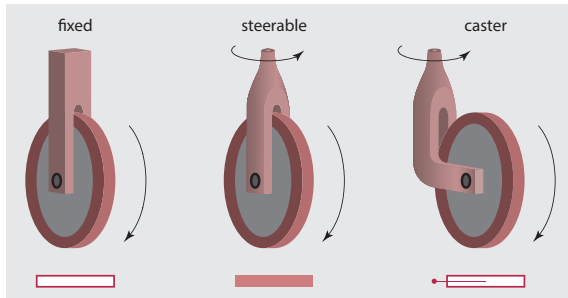
- **Redundancy** occurs when DoFs exceed task variables
 - examples include 7 DoFs or dual-arm robots
 - redundancy allows better obstacle avoidance and posture control
 - also supports human robot collaboration and shared workspaces
- KUKA LBR iiwa and ABB YuMi collaborative robots (cobots)



Wheeled Robots

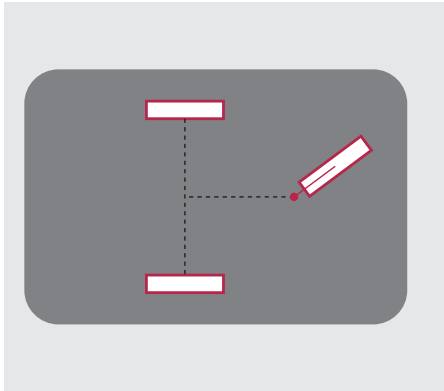
- Mobile robots displace their base using locomotion mechanisms
- Most practical mobile robots use **wheels**
- Basic element is the wheel with different mechanical realizations
- Combinations of wheels yield many kinematic structures

- **Fixed wheel**
 - rolls about a fixed axis and keeps constant orientation with respect to the base
- **Orientable wheel**
 - rolls about a horizontal axis and can rotate about a vertical axis
- **Caster wheel**
 - two non-intersecting axes provide automatic alignment with motion direction
- Fixed, orientable and caster wheels with icons

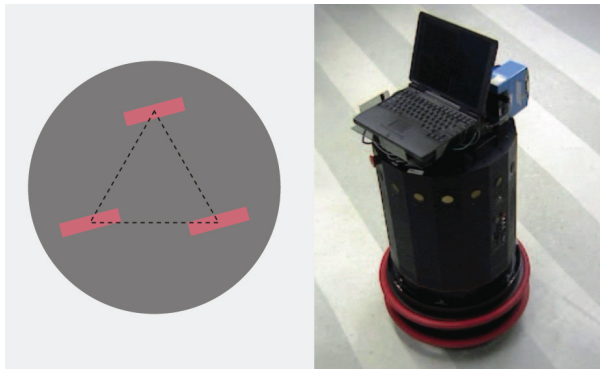


- Most wheeled robots are designed to be statically balanced on flat ground
- Center-of-mass projection must lie inside the support polygon
- Support polygon is the convex hull of wheel ground contact points
- Suspension systems maintain ground contact on uneven terrain

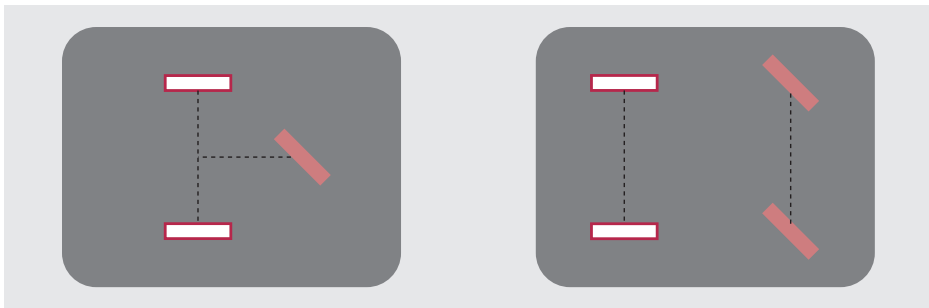
- Differential-drive kinematics
 - two independently driven fixed wheels plus passive caster
 - robot can rotate on the spot with opposite wheel speeds
- Differential-drive structure and commercial vacuum robot



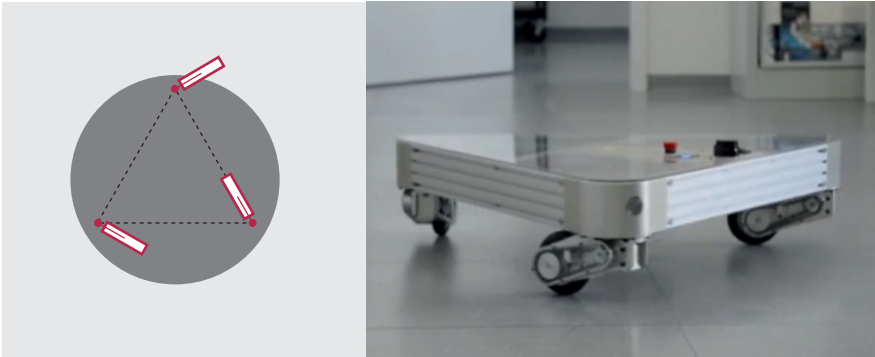
- **Synchro-drive** kinematics
 - three aligned orientable wheels driven by two motors
 - one motor for rolling, one for steering all wheels
 - turret rotation often added as a third DoF
- Synchro-drive structure and Nomad mobile robot



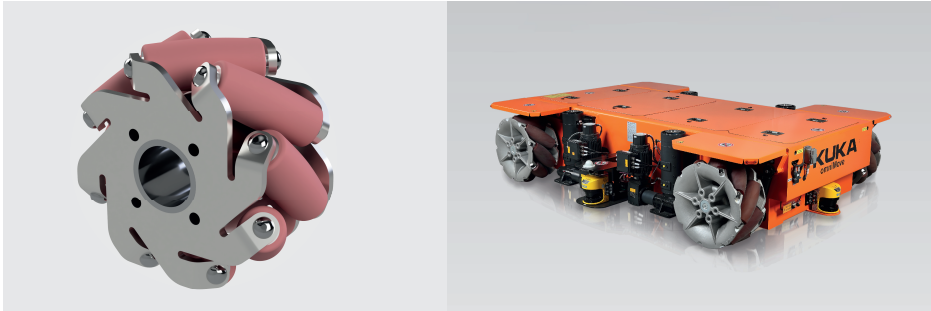
- **Tricycle** kinematics
 - most wheeled robots cannot move instantaneously sideways
 - they use maneuvers to achieve net displacement in lateral directions
- Tricycle and car-like wheeled structures



- Car-like kinematics
 - omnidirectional robots can move instantaneously in any planar direction and rotate independently
 - at least three independently driven wheels arranged appropriately are needed
- Omnidirectional robot with three driven caster wheels



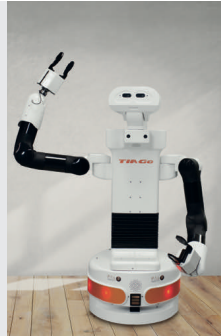
- Mecanum or Swedish wheels are fixed wheels with slanted rollers
- Passive rollers allow sideways slip while producing thrust
- Vehicles with four independently driven Mecanum wheels are omnidirectional
- Suitable for heavy loads with high maneuverability
- Mecanum wheel and omniMove modular platform



- Wheeled inverted pendulum robots have two driven wheels and no casters
- Balance is maintained by feedback control at all times
- Advantages include agility on uneven terrains and dynamic motions with payloads
- Urban delivery robot and hybrid wheel–leg robot



- Mobile manipulators
 - combine a manipulator with a mobile base
 - provide dexterity of an arm and extended workspace of a mobile platform
 - require careful control of static and dynamic balance
 - used for logistics household tasks and industrial handling
- Mobile manipulator platforms for logistics and service tasks



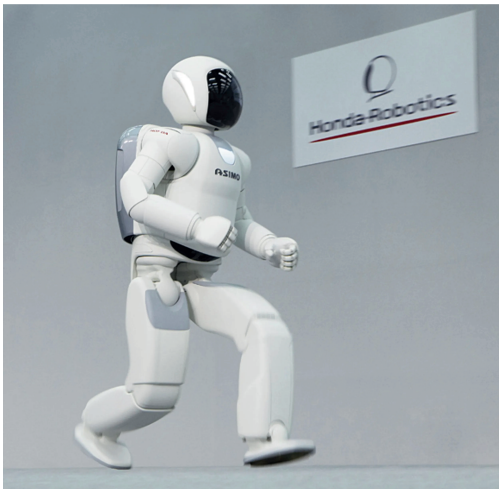
Other Robot Structures

- Legged robots use articulated limbs and feet for ground locomotion
- Designs are often **biomimetic** including bipeds, quadrupeds and hexapods
- Main advantage is higher mobility on stairs, obstacles and rough terrain
- Challenge is generating **gaits** while maintaining static or dynamic balance
- **Tracked locomotion** on uneven terrain and **undulatory locomotion** inspired by snakes

- Quadruped and hexapod robots for inspection and rough terrain



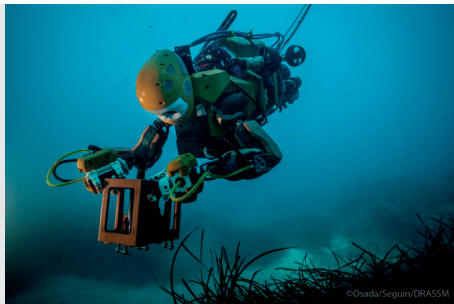
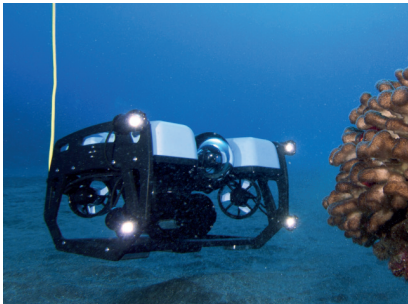
- Humanoid robots capable of dynamic walking and acrobatic motions



- **Flying** robots include rotary-wing and fixed-wing Unmanned Aerial Vehicles (UAVs) (**drones**)
- Rotary wing UAVs can hover and are suited for inspection and monitoring
- Fixed-wing UAVs are energy efficient for long range missions
- Quadrotor UAV and fixed-wing UAV for medical deliveries



- **Underwater** robots or Unmanned Underwater Vehicles (UUVs) perform inspection maintenance and exploration
- Remotely operated vehicle and bimanual underwater robot



Actuation

- Actuation provides forces and torques to move robot joints and wheels
- **Motors** are the primary actuators in most robots
 - **electric motors** use as primary supply the energy available from the electric distribution system
 - **hydraulic motors** transform the hydraulic energy stored in a reservoir into mechanical energy by means of pumps and valves
 - **pneumatic motors** use the pneumatic energy provided by an air compressor and transform it into mechanical energy by means of pistons or turbines
- Motors are integrated in servo loops for accurate control (**servomotors**)

Servomotors

- Low inertia and high power-to-weight ratio
- Ability to generate high accelerations and impulse torques
- Wide speed range from very low to thousands of rpm
- High positioning accuracy and low torque ripple
- Good performance in frequent starts, reversals and transients

- Electric servomotors
 - most common actuators in fixed base and mobile robots
 - used as permanent-magnet DC servomotors or brushless DC and AC servomotors
 - each motor is part of a servo loop with drive and sensor
 - for mobile robots DC motors are preferred for battery operation
- Permanent-magnet DC servomotor
 - stator generates magnetic flux using permanent magnets
 - armature with windings on a ferromagnetic rotor carries current
 - mechanical commutator and brushes connect rotor windings to supply
 - commutation maintains torque direction consistent with rotation
- Brushless DC servomotor
 - rotor carries permanent magnets and stator has polyphase windings
 - electronic commutator replaces mechanical brushes
 - commutation based on rotor position measured by sensors
 - advantages include higher speed, lower wear, better heat dissipation and lower inertia

- **Stepper motors**
 - operated in open loop via excitation sequences
 - achieve positioning by minimal reluctance principle
 - sensitive to load inertia and may lose steps or induce vibrations
- **Hydraulic servomotors**
 - use pressurized fluid and pistons or rotary actuators
 - provide high torques at low speeds for heavy payloads
- **Pneumatic motors**
 - are more difficult to control with precision due to the unavoidable fluid compressibility errors
 - are used mainly for typical opening and closing motion of jaws in a gripper tool

- Electric servomotors
 - widespread power supply and high efficiency
 - lower cost, easy maintenance and clean operation
 - overheating in static load conditions and special protection in flammable environments
- Hydraulic servomotors
 - require bulky supply station and maintenance
 - lower efficiency and potential oil leakage
 - no energy use in static conditions and high power-to-weight ratio

Transmissions

- Many tasks require **low speed** and **high torque** at joints
- Motors usually deliver high speed and lower torque
- **Transmission** (**gear**) introduces a reduction ratio n_r between motor and joint
- For rigid backlash-free transmission, the relationships between speed (torque) at motor shaft and speed (torque) at output axis are respectively

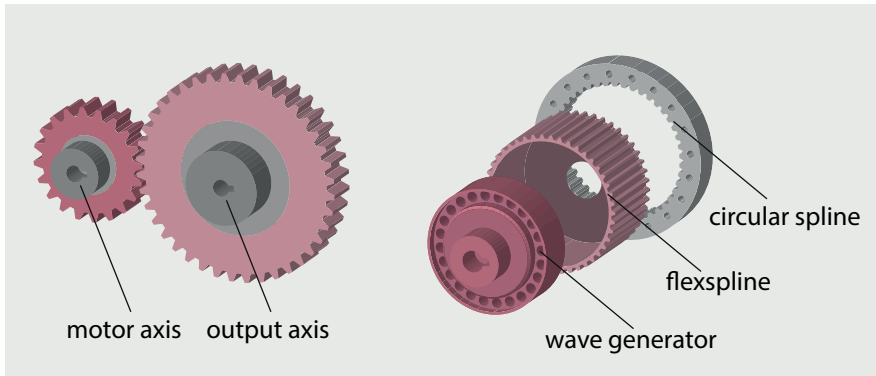
$$\dot{\theta} = \frac{1}{n_r} \dot{\theta}_m$$

$$\tau = n_r \tau_m$$

- Placing heavy motors near the base reduces moving mass
 - motion is transmitted to remote joints via shafts belts or closed chains
 - this improves dynamic performance and reduces energy consumption
 - tradeoff is increased transmission complexity and possible elasticity

- **Spur gears**
 - change direction or position of rotational axes and set reduction ratio
- **Lead screws**
 - convert motor rotation into linear motion for prismatic joints
- **Timing belts and chains**
 - displace motor axis parallel to joint axis with moderate reduction
- **Harmonic and cycloidal drives**
 - provide large reductions with compact design and low backlash

- Spur gear and harmonic drive components



- **Direct drive** connects motor shaft directly to joint without reduction
 - eliminates backlash and transmission elasticity
 - requires powerful motors and sophisticated dynamic control
- **Backdrivability** describes ability to move the motor by acting on the load
 - high backdrivability is important for force control and safe interaction
- Transmission elasticity can enhance safety during contact
- Serial elastic actuation introduces compliance on purpose
- Variable stiffness actuation modulates compliance in real time
- Compliance helps absorb impacts and reduce injury risk during collaboration

Sensing

- **Sensors** provide measurements of the robot and its environment
- **Proprioceptive** sensors measure internal state such as joint position and velocity
- **Exteroceptive** sensors measure environment such as forces, ranges and images
- Perception organizes sensor data into a coherent representation for action

- Proprioceptive measurements
 - joint position, velocity and torque in manipulators and legged robots
 - wheel angular position and speed in wheeled robots
 - body position, orientation, velocity and acceleration in mobile robots
 - used for feedback control, calibration and model identification
- Exteroceptive measurements
 - forces and moments at the interface with the environment
 - ranges and bearings to obstacles landmarks and targets
 - visual data from cameras and depth sensors
 - additional modalities such as sound, pressure, temperature and gas

Proprioceptive Sensors

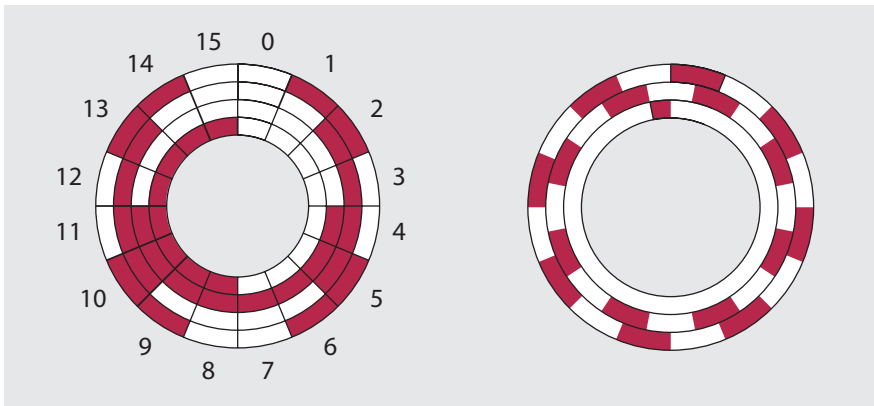
- Position transducers
- Velocity reconstruction
- Inertial measurement units
- Force sensors

Position Transducers

- Produce electrical signals proportional to displacement
- Rotary joints typically use encoders, resolvers or synchros
- **Encoders** are most common due to precision robustness and digital output
- Two encoder types are **absolute** and **incremental**

- Absolute encoders
 - use optical disks with multiple concentric tracks
 - transparent and opaque sectors encode angular position in Gray code
 - each track adds one bit increasing resolution
 - multi-turn versions count full revolutions over a limited range
- Incremental encoders
 - two tracks with transparent and opaque sectors in quadrature
 - counting signal edges yields angular displacement and direction
 - a third track marks a reference zero position
 - electronics count pulses to reconstruct absolute angle over time

- Absolute and incremental encoder disk patterns



Velocity Reconstruction

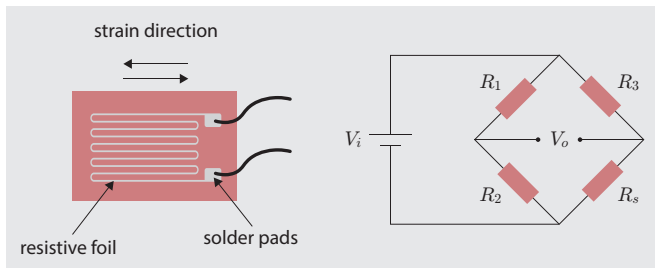
- Velocity obtained by differentiating discrete position measurements
- Simplest estimate uses backward difference on encoder counts
- More accurate estimates use multistep backward differentiation formula (BDF)
- Kinematic Kalman filter (KKF) can estimate velocity while filtering noise

Inertial Measurement Units (IMUs)

- Include accelerometers, gyroscopes and optionally magnetometers
- Measure linear accelerations and angular rates in three axes
- Onboard processing integrates signals to estimate pose and velocity
- Drift is mitigated by filtering and external corrections such as GPS
- IMU applications
 - wheeled robots moving at high speed or on uneven terrain
 - legged robots that must maintain balance during locomotion
 - aerial and underwater robots for attitude and motion estimation
 - any platform requiring robust inertial feedback

Force Sensors

- Force and torque measurements by assessing deformation on suitable extensible elements (**strain gauges**)
 - strain gauges change resistance with deformation
 - mounted on extensible elements and wired in Wheatstone bridges
 - bridge output voltage is proportional to applied strain
 - torque sensors place strain gauges on shafts between motor and joint



Exteroceptive Sensors

- Wrist force/torque sensors
- Range sensors
- Vision sensors

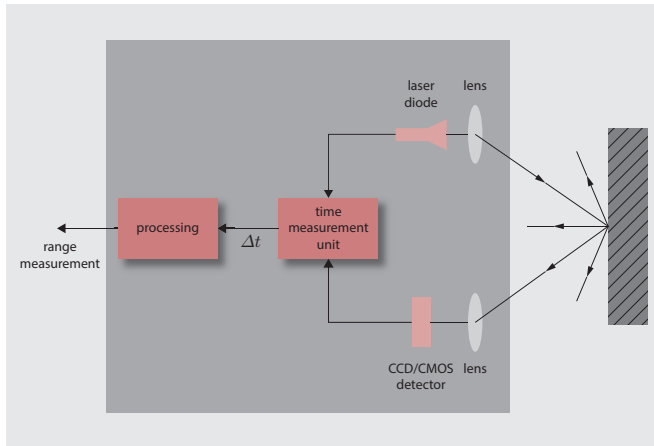
Wrist Force/Torque Sensor

- Mounted between manipulator wrist and end-effector
- Measure three force and three torque components in sensor frame
- Typically compact with high resolution and 1 kHz update rates
- Essential for force control assembly and contact tasks

Range Sensors

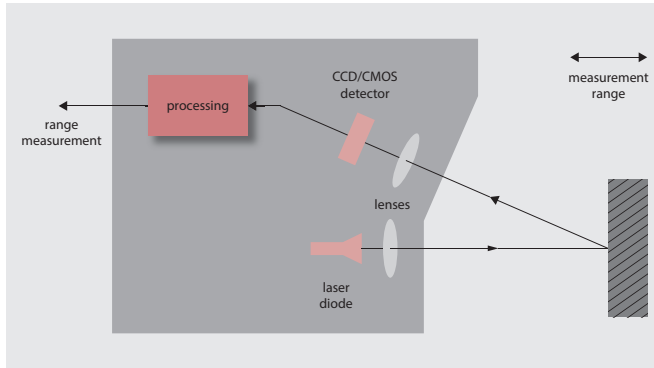
- **Proximity sensors** detect presence of objects within a sensitive range
- **Range sensors** measure distance along a direction
- Technologies include infrared, laser, ultrasonic and radio frequency
- Used for obstacle avoidance mapping and localization

- Time-of-flight laser rangefinders

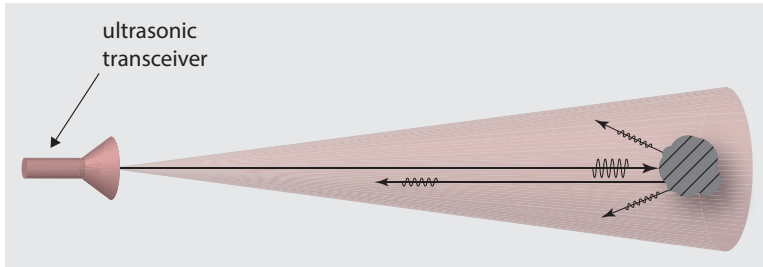


- LIDAR sensors

- emit laser pulses and measure round trip travel time
- distance computed as $r + c_l \Delta t / 2$ where c_l is speed of light, Δt is travel time and r is range measurement
- scanning mirrors produce 2D or 3D range data
- limitations include **aliasing phenomenon**, ambiguity range, and minimum distance

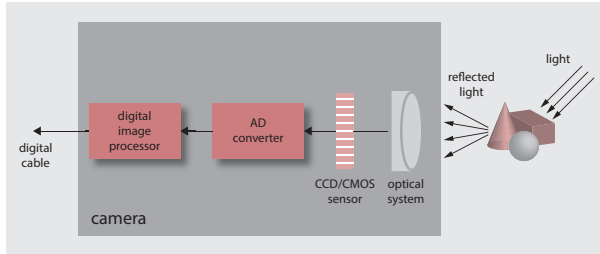


- Ultrasonic sensors
 - emit sound pulses and measure echo arrival time
 - range computed as $c_s t_v / 2$ where c_s is speed of sound and t_v is travel time
 - emission cone yields limited angular resolution
 - low cost and useful in underwater and low visibility environments



Vision Sensors

- Capture images and convert them into digital signals
- CCD and CMOS chips are common photosensitive devices
- Frames are arrays of pixels representing light intensities
- Color images obtained by RGB filters or multiple sensors
- Main components of a digital camera

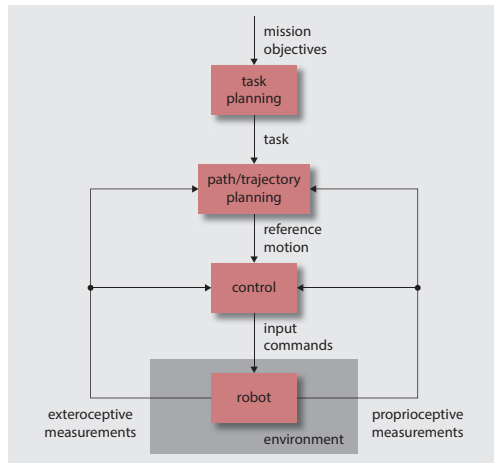


- Advanced vision systems
 - omnidirectional cameras use mirrors for wide fields of view
 - depth cameras combine RGB images with per pixel distance
 - structured light and time of flight are main depth sensing technologies
 - vision is central for localization mapping and manipulation

Control Architecture

- **Control architecture** organizes software implementing robot intelligence
- Connects perception to action through planning and control
- Must handle mission objectives, environment models and sensor feedback
- Different paradigms balance planning depth and responsiveness

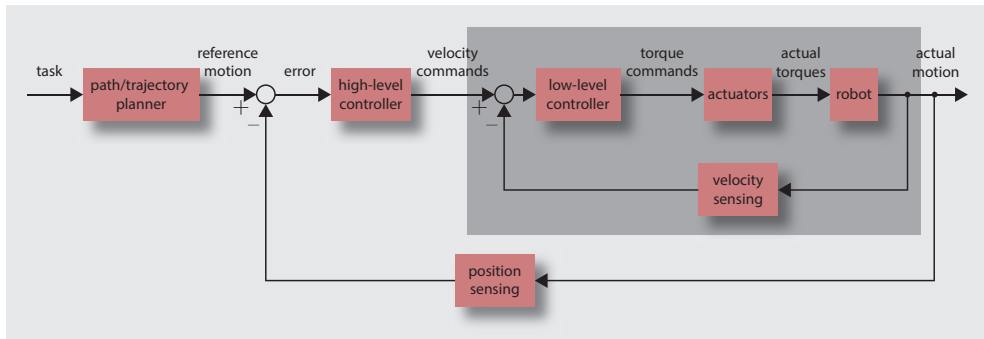
- Deliberative architecture
 - follows **first think, then act** principle
 - task planning decomposes missions into sequences of tasks
 - **path and trajectory planning** generate reference motions
 - **control** module tracks references using sensor feedback



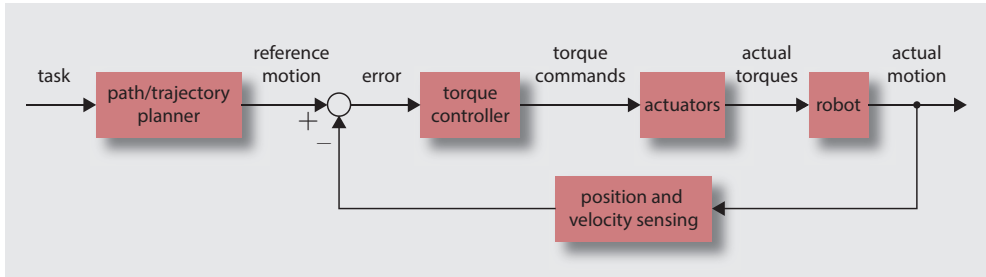
- **Reactive** architecture
 - maps sensory inputs directly to actions without explicit planning (**don't think, react**)
 - provides fast responses and simple implementations
- **Hybrid** architecture
 - combines high-level deliberation with low-level reactive behaviors
 - common in modern robots for balancing optimality and robustness

- **Kinematic control**

- low-level controllers accept joint velocity or position commands
- high-level controller views robot as a kinematic mechanism
- joint velocities generate end-effector velocities via kinematic relations
- outer loop uses task space or joint space feedback for tracking



- **Dynamic control**
 - single control module outputs torque or current commands for actuators
 - requires explicit use of full nonlinear robot dynamics
 - enables accurate tracking under high accelerations and couplings
 - particularly suitable for tasks with significant interaction forces



- Velocity control
 - easier to design and tune at high level
 - performance depends on quality of inner loops and dynamics
- Torque control
 - provides better performance for dynamic tasks and interaction
 - more complex modeling and implementation
- Typical control frequencies range from 100 Hz to 1 kHz