دانشگاه سمنان

Semnan University
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دانشکده مهندسی مکانیک

دانشکده مهندسی مکانیک

درس رباتیک

ROBOTICS

Chapter 5 – Actuators and Sensors

Class Lecture

- **CONTENTS:**

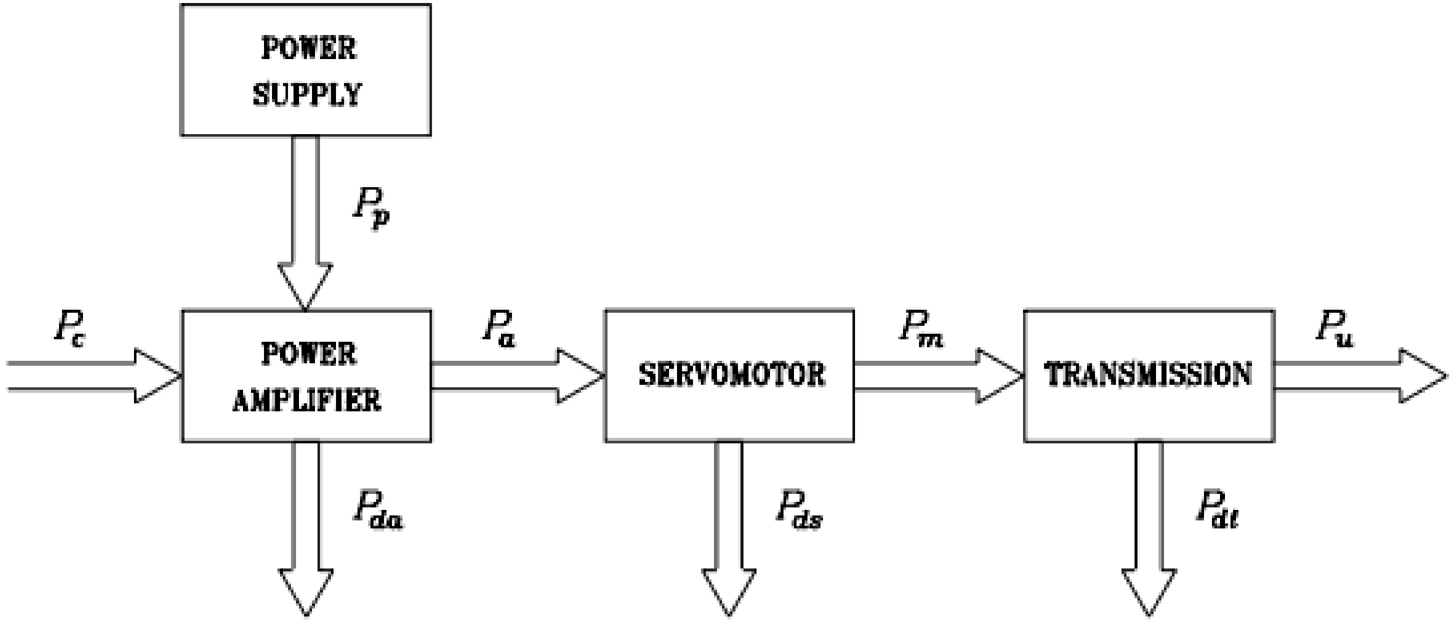
5. Actuators and Sensors

- Actuating System
  - Power supply
  - Power amplifier
  - Servomotor
    - Electric Servomotors
    - Hydraulic Servomotors
  - Transmission

- ***Sensors***
  - Proprioceptive Sensors (internal state of the manipulator – encoders, resolvers& tachometers)
  - Exteroceptive Sensors (force sensors, distance sensors & vision sensors)

5.1 Joint Actuating System

- Components of a joint actuating system



- Power can always be expressed as the product of a flow and a force quantity.

5.1 Joint Actuating System

- 5.1.1 Transmissions
  - Manipulator joints need low speed, high torque
  - Servomotors give high speed, low torque → not ideal alone
  - Transmissions convert motor output in both magnitude (speed/torque) and type (rotational to translational)
  - Some power is lost to friction
  - Gear choice depends on motion type, power, and motor placement
  - Transmissions improve performance and reduce load
  - Mounting motors at the base reduces weight and boosts efficiency

5.1 Joint Actuating System

- 5.1.1 Transmissions
  - Transmissions used for industrial robots:
    - ✓ Spur Gears
    - ✓ Lead Screws
    - ✓ Timing Belts & Chains

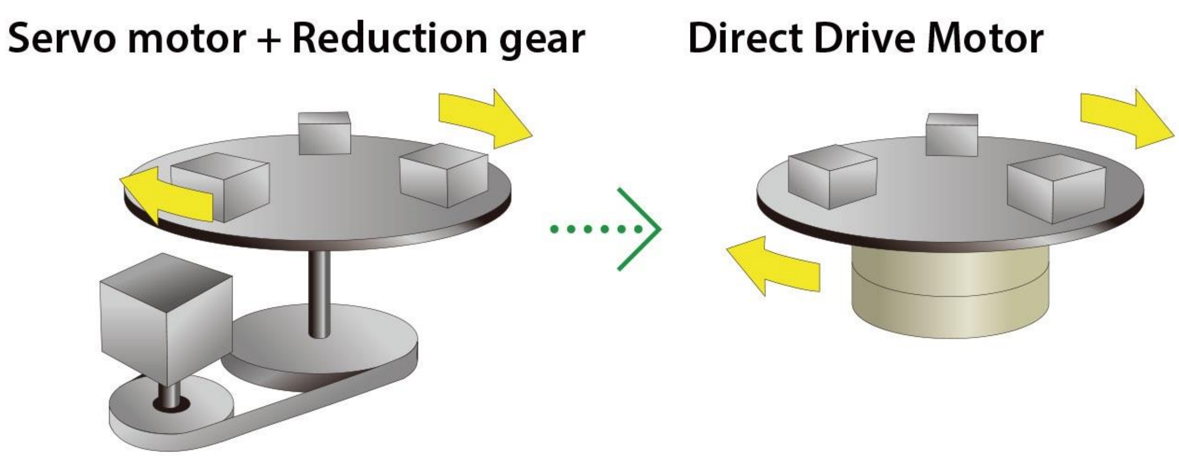
5.1 Joint Actuating System

5.1.1 Transmissions

- Transmissions used for industrial robots:
  - ✓ Spur Gears:
    - Modify motor rotation (axis or position).
    - Built with thick teeth and short shafts for strength.
  - ✓ Lead Screws:
    - Convert rotation to translation (for prismatic joints).
    - Ball screws used to reduce friction, increase stiffness, and minimize backlash.
  - ✓ Timing Belts & Chains:
    - Allow motor placement away from joint.
    - Belts: Good for high speed, low force (can stretch under stress)
    - Chains: Suitable for low speed due to heavy mass and potential vibration

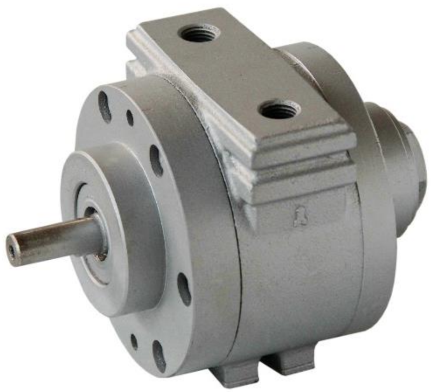
5.1 Joint Actuating System

- 5.1.1 Transmissions
  - Direct Drive:
    - ✓ Sometimes, motors can be connected directly to joints without a transmission (direct drive)
    - ✓ This setup eliminates issues like transmission elasticity and backlash
    - ✓ However, it requires more advanced control algorithms



5.1 Joint Actuating System

- 5.1.2 Servomotors
  - Motors which allow the realization of a desired motion
  - Based on the type of input power
    - ✓ Pneumatic motors
    - ✓ Hydraulic motors
    - ✓ Electric motors



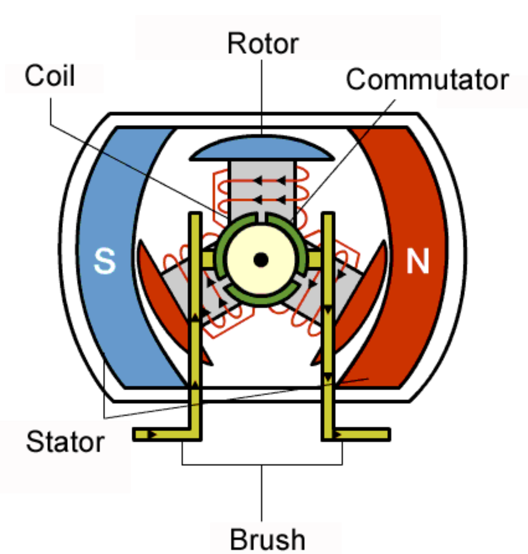
5.1 Joint Actuating System

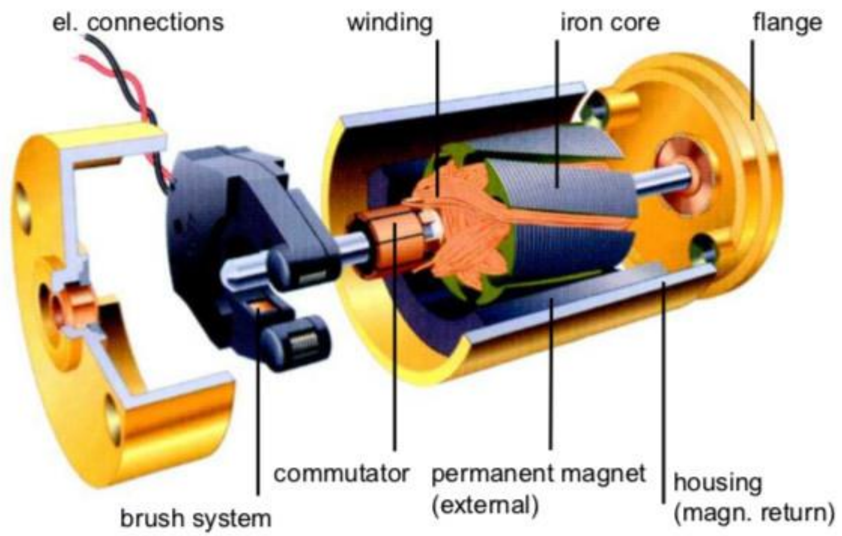
- 5.1.2 Servomotors
  - Powers ranging from about 10W to about 10 kW
  - Requirements:
    - ✓ Good trajectory tracking and positioning accuracy
    - ✓ Low inertia and high power-to-weight ratio
    - ✓ Possibility of overload and delivery of impulse torques
    - ✓ Capability to develop high accelerations
    - ✓ Wide velocity range (from 1 to 1000 revolutes/min)
    - ✓ High positioning accuracy (at least 1/1000 of a circle)
    - ✓ Low torque ripple so as to guarantee continuous rotation even at low speed

5.1 Joint Actuating System

5.1.2 Servomotors

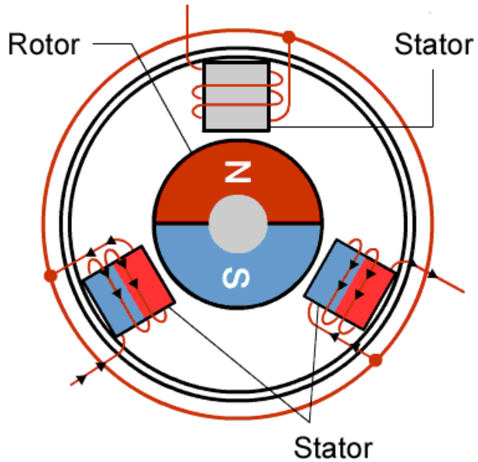
- The most employed motors in robotics applications are electric servomotors
  - ✓ Permanent-Magnet Direct-Current (DC) servomotors
    - A stator coil
    - An armature (rotor)
    - A commutator

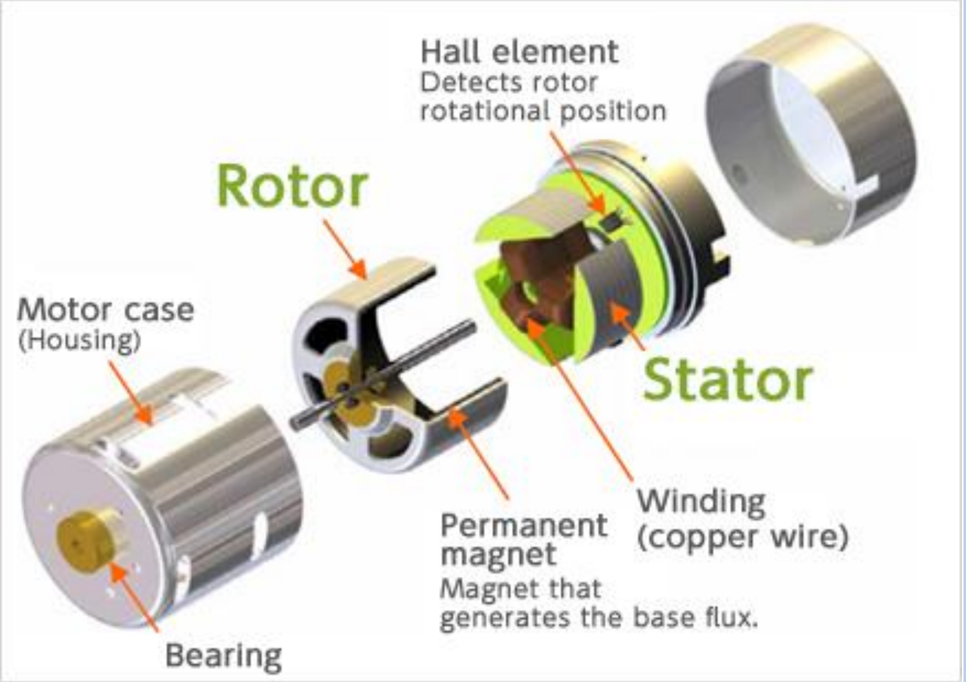




5.1 Joint Actuating System

- 5.1.2 Servomotors
  - The most employed motors in robotics applications are electric servomotors
    - ✓ Brushless DC servomotors
      - A rotating coil (rotor)
      - A stationary armature (stator)
      - A static commutator





5.1 Joint Actuating System

- 5.1.2 Servomotors
  - Brushed vs. Brushless Motor

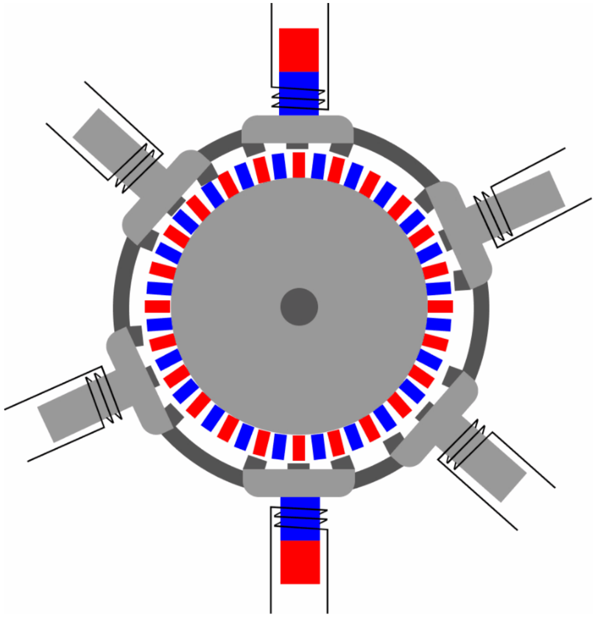
Feature	Brushed Motor	Brushless Motor
Lifetime	Shorter	Longer
Maintenance Requirements	Regular brush replacement	Minimal
Speed & Acceleration	Lower	Higher
Efficiency Lower	Lower	Higher
Noise & Vibration Levels	Higher	Lower
Torque	Moderate	Higher
Weight & Size	Lighter	Heavier
Cost	Lower	Higher

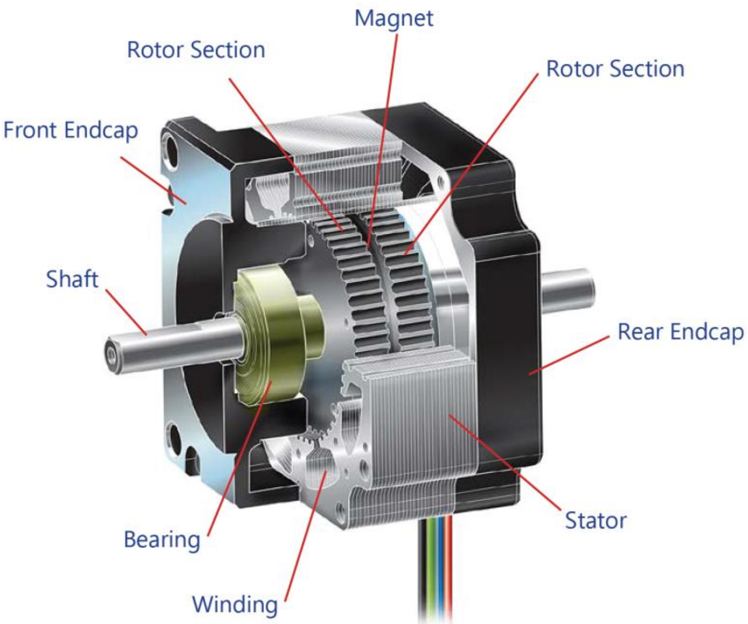
5.1 Joint Actuating System

- 5.1.2 Servomotors
  - Brushed vs. Brushless Motor
    - ✓ DC motors use rotor position sensors and electronic control to maintain orthogonal field alignment for rotation
    - ✓ Permanent-magnet DC motors use mechanical commutation via brushes and commutator plates to achieve the same effect
    - ✓ Functional similarity:
      - Brush/commutator in PMDC = Sensor/controller in brushless DC
  - Brushless DC motors offer superior performance but come at higher cost.

5.1 Joint Actuating System

- 5.1.2 Servomotors
  - Stepper Motors
    - Controlled by excitation sequences; no position feedback needed
    - Sensitive to payload changes; can cause vibrations
    - Best suited for low-cost, low-dynamic applications like micromanipulators





5.1 Joint Actuating System

- 5.1.3 Power Amplifiers
  - Modulates power from the primary supply based on the control signal
  - Delivers power to actuators in forms suitable for executing desired motion

  - Inputs:
    - Power from the source (Pp)
    - Power from the control signal (Pc)

  - Outputs:
    - Useful actuator power (Pa)
    - Dissipated power losses (Pda)

5.1 Joint Actuating System

- 5.1.4 Power Supply
  - Supplies primary power to the amplifier for operating the actuating system

  - Electric Servomotors
    - ✓ Transformer: Adjusts voltage level
    - ✓ Uncontrolled bridge rectifier: Converts AC from the grid into DC
    - ✓ Provides suitable direct voltage to feed the amplifier

  - Hydraulic Servomotors
    - ✓ Uses gear or piston pump to compress fluid
    - ✓ Pump driven by a primary motor (usually a 3-phase nonsynchronous motor)
    - ✓ A hydraulic reservoir stores energy and reduces pressure oscillations (analogous to a filter capacitor in electric systems)

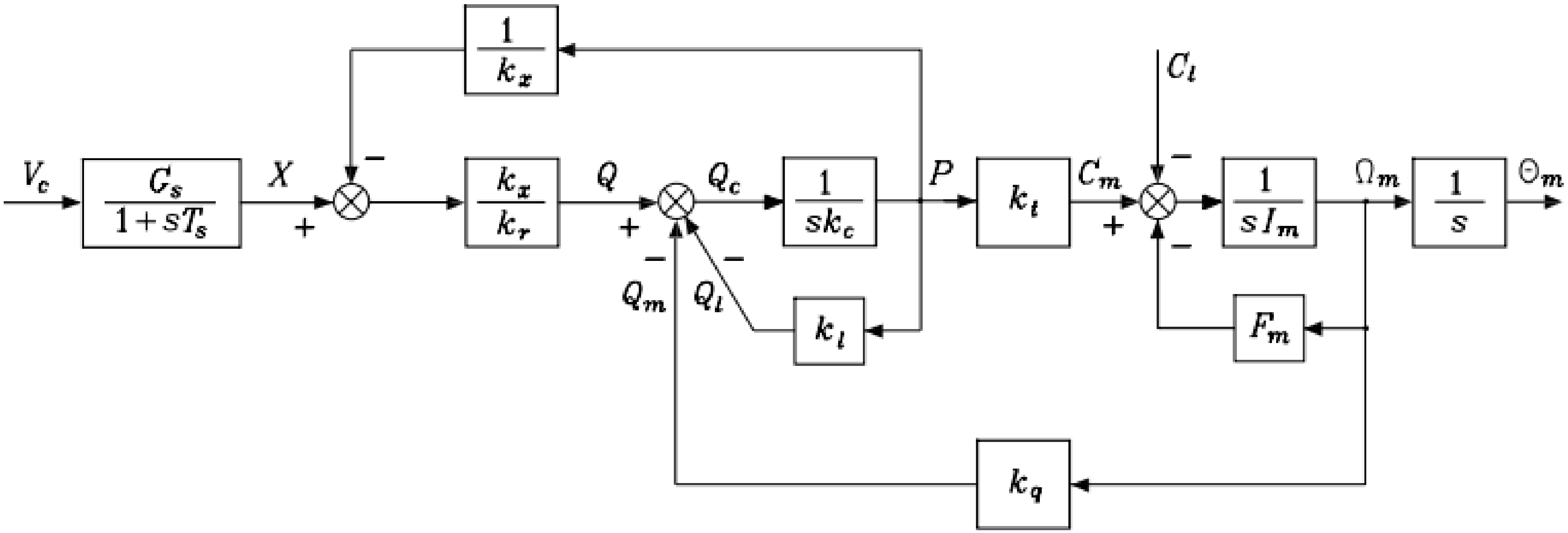
5.2 Drives

- **Servomotor Drive:**
  - A system that controls the motion of a servomotor by regulating power input based on feedback
  - Enable precise positioning, speed, and torque control in automated mechanisms

- Electric and hydraulic drives used for actuating robot joints
  - Begins with mathematical models that describe their dynamic behavior
  - Block diagrams are derived to highlight:
    - ✓ Control system characteristics
    - ✓ Impact of mechanical transmission on system performance

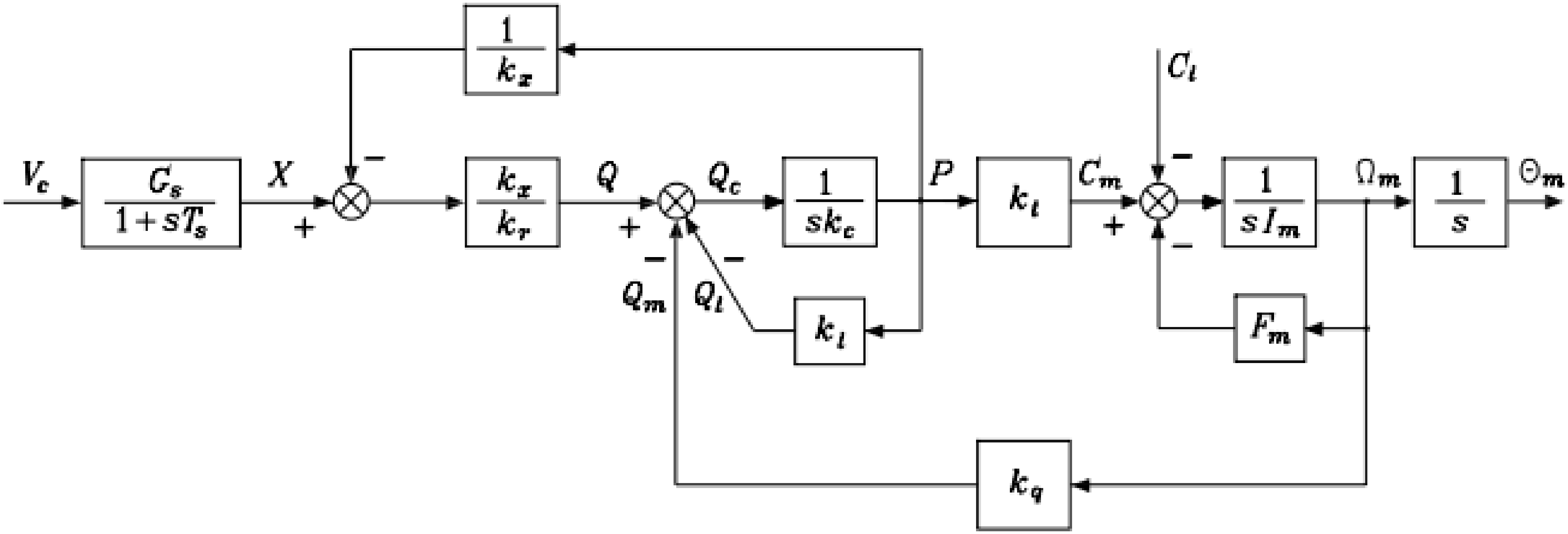
5.2 DRIVES

- Block scheme of an electric drive



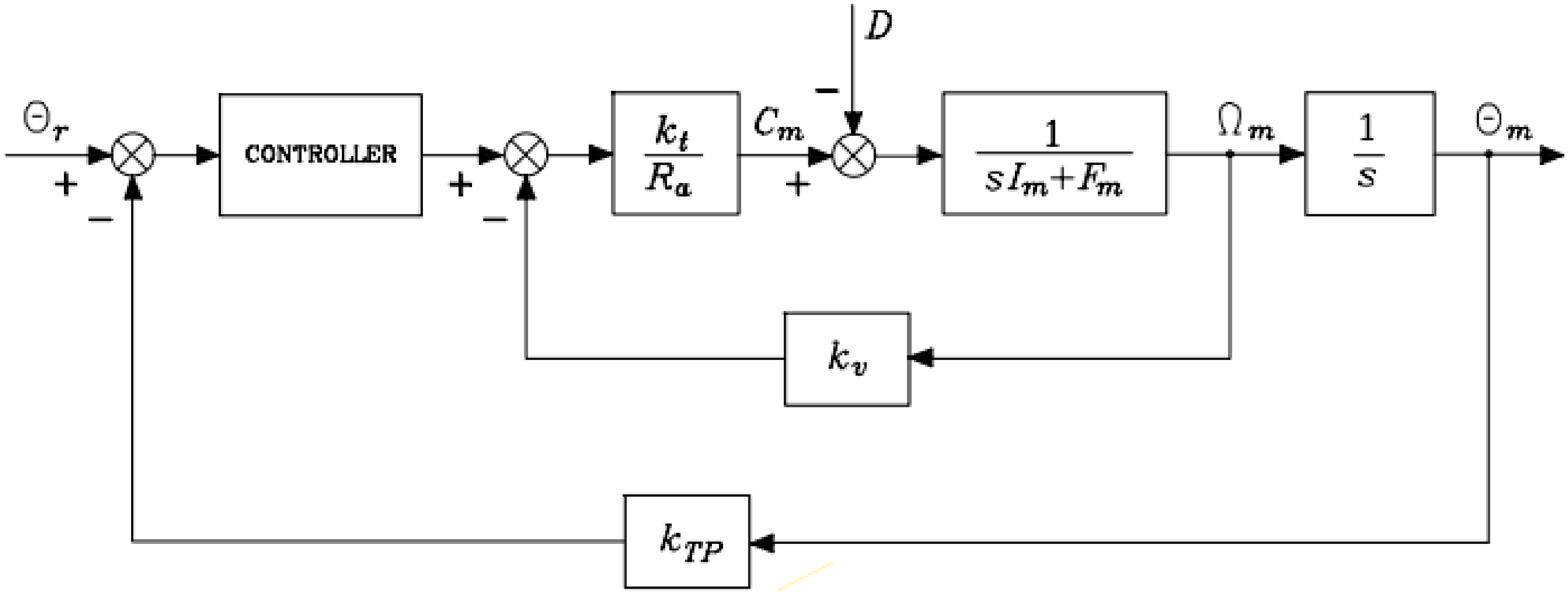
5.2 DRIVES

- Block scheme of a hydraulic drive



5.2 DRIVES

- General block scheme of electric drive control



5.3 Proprioceptive Sensors

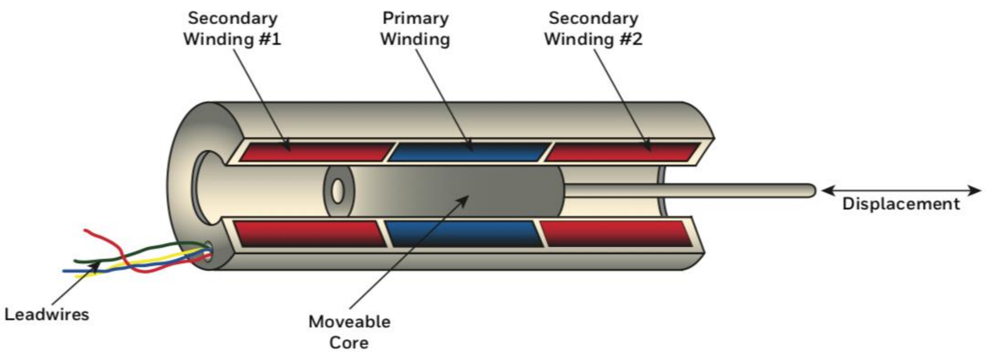
- Sensors
  - Proprioceptive sensors that measure the internal state of the manipulator
    - ✓ Joint positions
    - ✓ Joint velocities
    - ✓ Joint torques
  - Exteroceptive sensors that provide the robot with knowledge of the surrounding environment
    - ✓ Force sensors
    - ✓ Tactile sensors
    - ✓ Proximity sensors
    - ✓ Range sensors
    - ✓ Vision sensors
    - ✓ Sound, humidity, smoke, pressure, temperature sensors, …

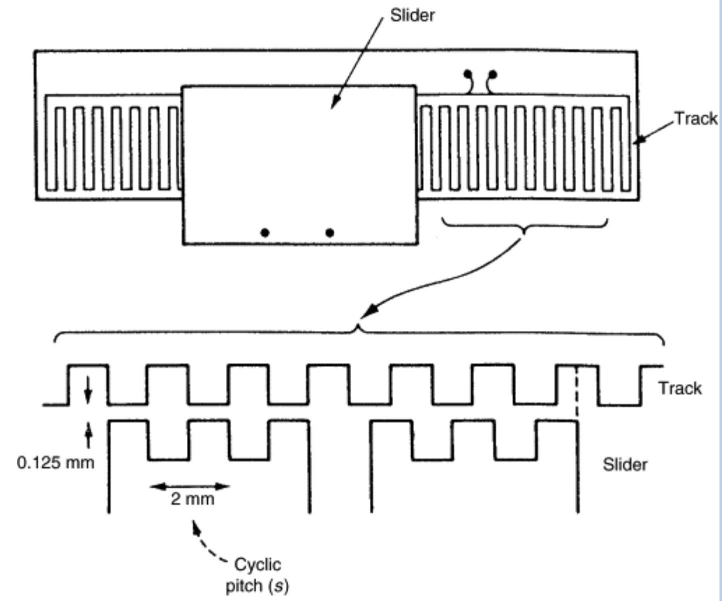
5.3 Proprioceptive Sensors

- 5.3.1 Position Transducers
  - Position transducers generate an electrical signal proportional to a system's linear or angular displacement from a reference point
  - Widely used in machine tool control, so they cover a broad measurement range
  - In **robotics**, angular transducers are commonly used, even for prismatic joints, because servomotors are typically rotary.

5.3 Proprioceptive Sensors

- 5.3.1 Position Transducers
  - Linear displacement transducers
    - ✓ Potentiometers
    - ✓ LVDTs (Linear Variable Differential Transformers)
    - ✓ Inductosyns



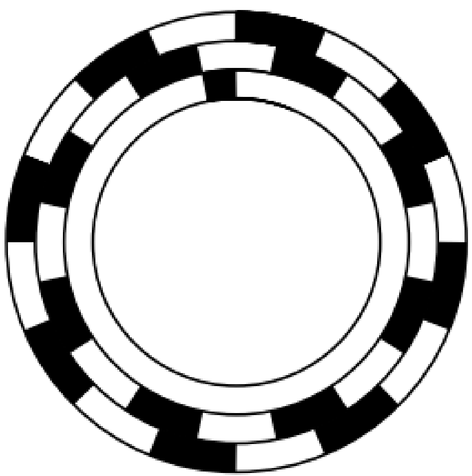


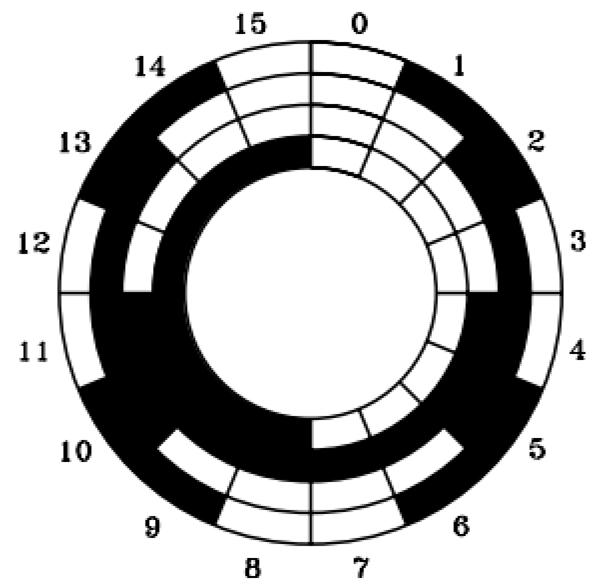
5.3 Proprioceptive Sensors

- 5.3.1 Position Transducers
  - Angular displacement transducers
    - ✓ Potentiometers
    - ✓ Encoders
    - ✓ Resolvers
    - ✓ Synchros

5.3 Proprioceptive Sensors

- 5.3.1 Position Transducers
  - Encoders
    - ✓ Absolute (Gray-code)
    - ✓ Incremental





#	Code	#	Code
0	0000	8	1100
1	0001	9	1101
2	0011	10	1111
3	0010	11	1110
4	0110	12	1010
5	0111	13	1011
6	0101	14	1001
7	0100	15	1000

5.3 Proprioceptive Sensors

- 5.3.2 Velocity Transducers
  - Tachometers
    - ✓ Although velocity can be estimated from position data, direct measurement is preferred for accuracy
    - ✓ Devices for direct velocity measurement are called tachometers
    - ✓ Most tachometers operate on electric machine principles
    - ✓ Two main types:
      - DC Tachometers
      - AC Tachometers

5.3 Proprioceptive Sensors

- 5.3.2 Velocity Transducers
  - DC Tachometer
    - Most commonly used type
    - Functions as a small DC generator with a permanent magnet field
    - Output voltage is proportional to angular speed
    - Design aims to ensure:
      - Linearity of output
      - Minimal hysteresis and temperature effects
    - Drawbacks:
      - Output has a residual ripple that varies with speed and can't be fully filtered
      - Ripple coefficient: 2–5% of mean output
      - Linearity: within 0.1–1%.

5.3 PROPRIOCEPTIVE SENSORS

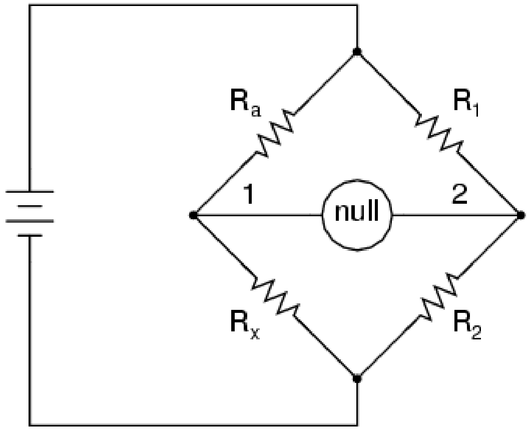
- 5.3.2 Velocity Transducers
  - AC Tachometer
    - ✓ Avoids DC ripple problems
    - ✓ Not a true generator; designed for specific speed-proportional output
    - ✓ Structure includes:
      - Two quadrature stator windings, A lightweight rotor (low inertia, no brushes)
      - One winding is excited with a 400 Hz sinusoidal voltage.
      - Other winding produces an output voltage:
        - Same frequency as input, Magnitude proportional to speed, Phase indicates rotation direction
    - ✓ Advantages:
      - No mechanical contacts (more durable), Smoother output, better suited for precision

5.4 Exteroceptive Sensors

5.4.1 Force Sensors

- Force/torque measurement is typically based on detecting strain in an element
- Strain gauges convert small mechanical deformations into changes in electrical resistance, enabling indirect force measurement
- Strain Gauge
  - ✓ Consists of a wire on an insulated support, glued to a deformable element
  - ✓ Wire's **resistance (Rs)** changes with deformation
  - ✓ Incorporated into a **Wheatstone bridge** to convert resistance changes into measurable voltage:

$$V_o = \left(\frac{R_2}{R_1 + R_2} - \frac{R_s}{R_3 + R_s} \right) V_i$$

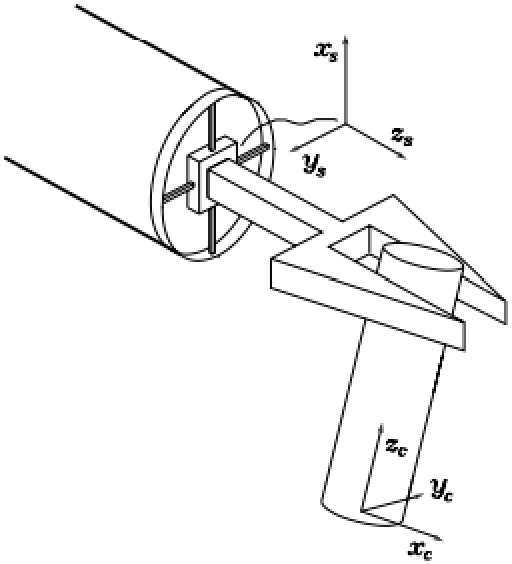


5.4 Exteroceptive Sensors

- 5.4.1 Force Sensors
  - Shaft Torque Sensor
    - Used for direct torque measurement when current-based indirect estimates are insufficient
    - Strain gauges placed on hollow shafts with:
      - Low torsional stiffness
      - High bending stiffness
    - Gauges connected to a Wheatstone bridge and signal transmitted via slip rings and graphite brushes
    - Measures output torque to the joint, not the internal motor torque

5.4 Exteroceptive Sensors

- 5.4.1 Force Sensors
  - Wrist Force Sensor
    - ✓ Measures 3D force and 3D moment vectors at the manipulator's end-effector
    - ✓ Typically placed between the manipulator’s outer link and the end-effector
    - ✓ Contains multiple extensible elements with strain gauges
    - ✓ Geometry ensures:
      - At least one element deforms for any force/moment direction.
      - Minimal cross-sensitivity between components



5.4 Exteroceptive Sensors

- 5.4.2 Range Sensors
  - Provide external environmental data to enable autonomous, intelligent behavior.
  - Primary Purposes:
    - ✓ Object detection
    - ✓ Distance measurement
    - ✓ Obstacle avoidance
    - ✓ Environment mapping
    - ✓ Object recognition

5.4 Exteroceptive Sensors

- 5.4.2 Range Sensors
  - Proximity Sensors
    - ✓ Detect presence of nearby objects without contact.
    - ✓ Output: Binary (object detected or not).
    - ✓ Operate within a limited "sensitive range".
    - ✓ Simplified version of range sensors.

Photoelectric Sensor

Proximity Sensor

Inductive Sensor

Capacitive Sensor

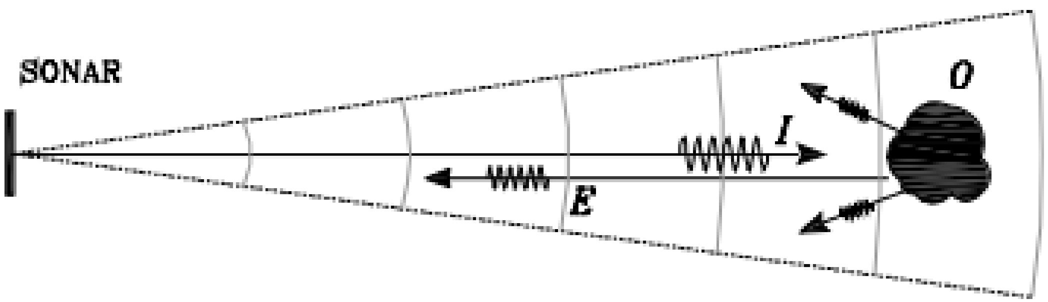
Ultrasonic Sensor

5.4 Exteroceptive Sensors

- 5.4.2 Range Sensors
  - Range Sensors
    - ✓ Provide distance and direction to objects → allow spatial localization.
    - ✓ Output: Structured data (e.g., coordinates in sensor's reference frame).
    - ✓ Enable:
      - Mapping
      - Navigation
      - Object tracking

5.4 Exteroceptive Sensors

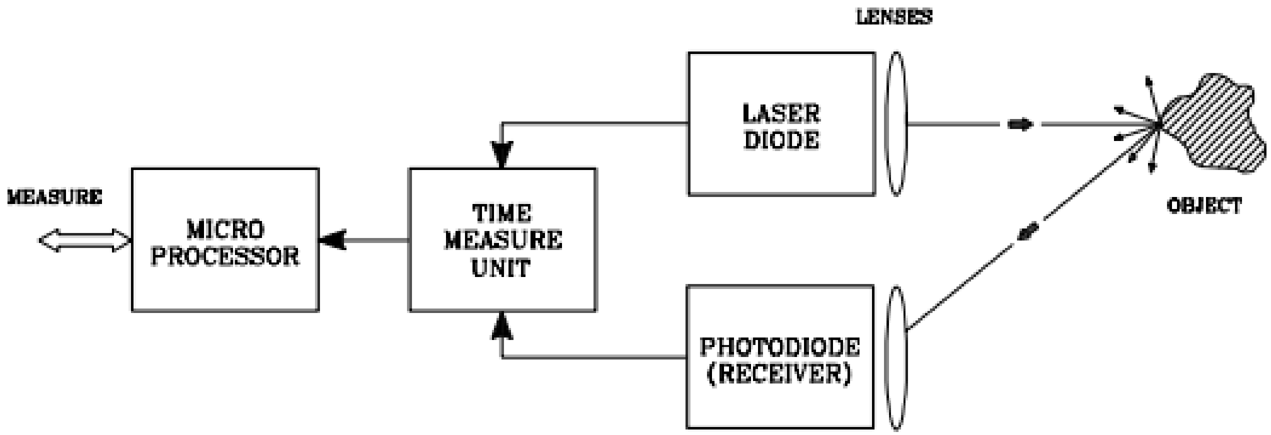
- 5.4.2 Range Sensors
  - Sonar (Ultrasonic Sensors)
    - ✓ Based on sound wave propagation
    - ✓ Advantages:
      - Low cost, Lightweight, Low power consumption, Low processing needs, Works in low-visibility (e.g., underwater, dark) environments
    - ✓ Limitations:
      - Low angular and radial resolution, Minimum/maximum range constraints, Broad beam (less precise localization), Accuracy and resolution decrease in complex or reflective environments



5.4 Exteroceptive Sensors

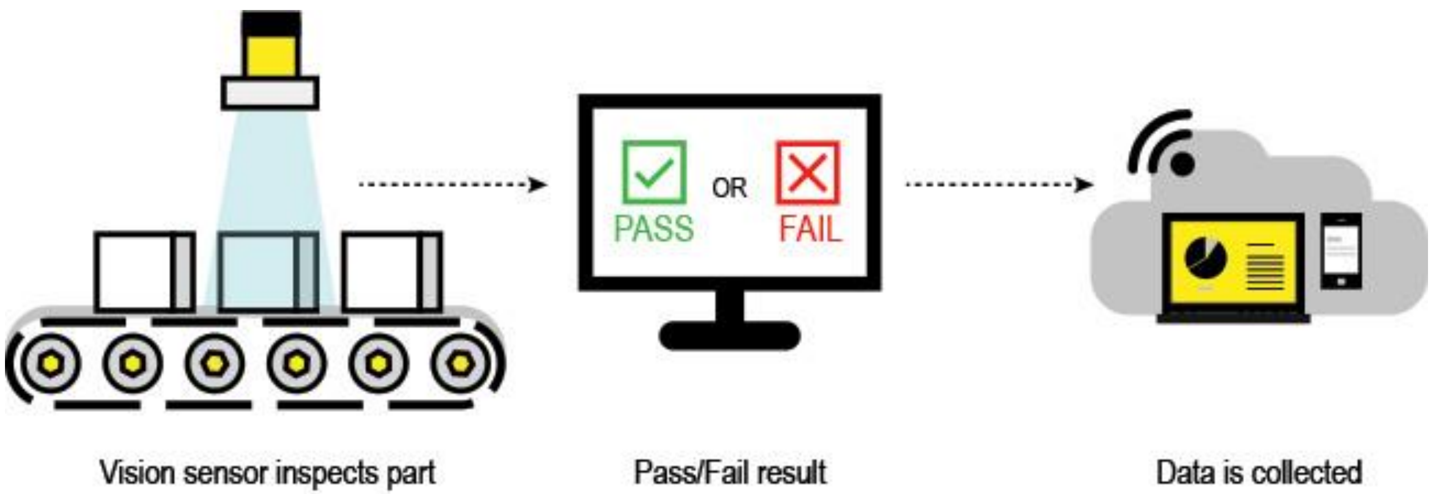
5.4.2 Range Sensors

- Laser (LIDAR)
  - ✓ Based on light wave propagation (laser beams).
  - ✓ Provide high-resolution, accurate distance measurements.
  - ✓ Widely used for:
    - SLAM (Simultaneous Localization and Mapping)
    - Navigation in autonomous vehicles and robots



5.4 Exteroceptive Sensors

- 5.4.3 Vision Sensors
  - Pixel (Photosite): Converts light to electrical energy
  - Lens: Focuses light onto the image plane
  - Shutter: Controls light exposure time
  - Preprocessing Electronics: Prepare the signal for further processing



5.4 Exteroceptive Sensors

- 5.4.3 Vision Sensors
  - Sensor Technologies:
    - ✓ CCD (Charge Coupled Device)
    - ✓ CMOS (Complementary Metal Oxide Semiconductor)

Feature	CCD	CMOS
Power efficiency	Lower	Higher
Cost	Higher	Lower
Speed	Slower	Faster
Image quality	Higher (traditionally)	Improving steadily