



Semnan University  
Faculty of Mechanical Engineering

دانشکده مهندسی مکانیک



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درس رباتیک پیشرفته

ADVANCED ROBOTICS

*Chapter 5 – Actuators and Sensors*

*Class Lecture*

❑ CONTENTS:

- ❖ Chapter 1: Introduction
- ❖ Chapter 2: Kinematics
- ❖ Chapter 3: Differential Kinematics and Statics
- ❖ Chapter 4: Trajectory Planning
- ➔ ❖ Chapter 5: **Actuators and Sensors**
- ❖ Chapter 6: Control Architecture

## 5. ACTUATORS AND SENSORS

### □ Actuating System

- ❖ Power supply
- ❖ Power amplifier
- ❖ Servomotor
  - ✓ Electric Servomotors
  - ✓ Hydraulic Servomotors
- ❖ Transmission

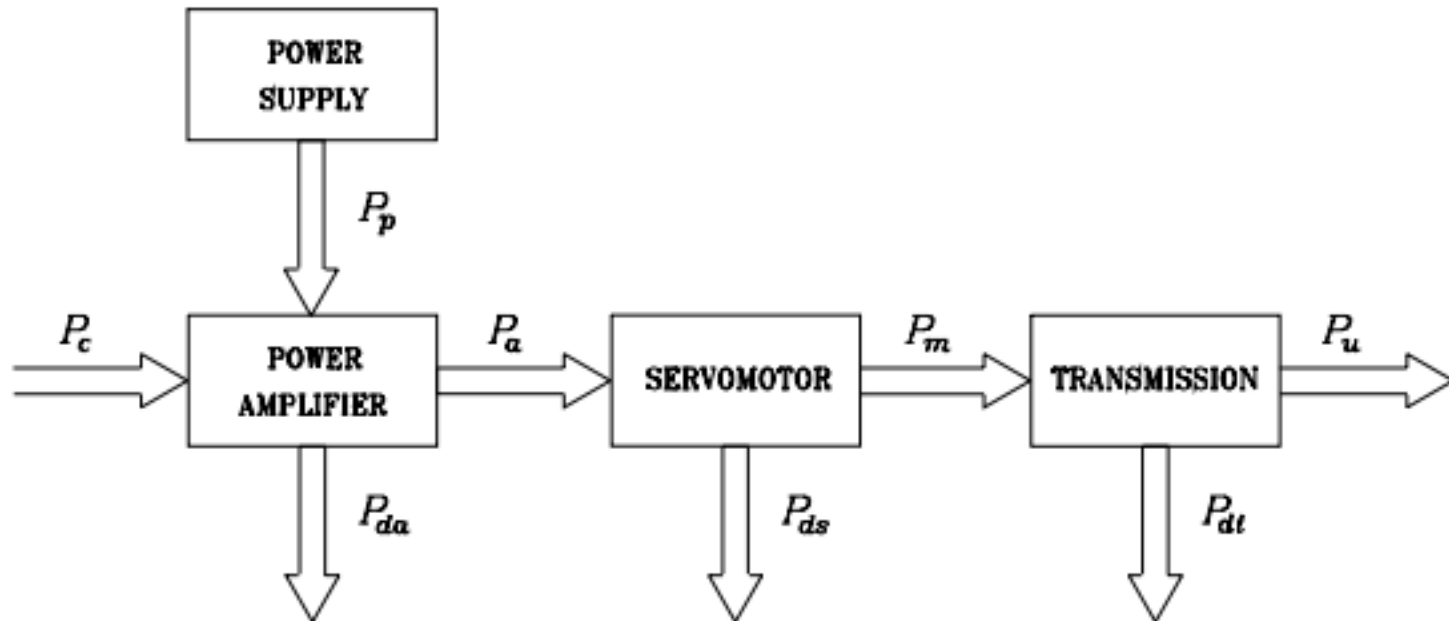
### □ *Sensors*

- ❖ 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



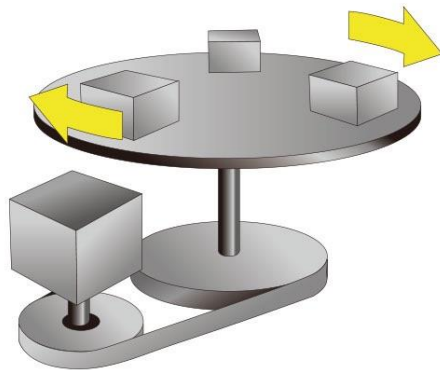
## 5.1 JOINT ACTUATING SYSTEM

### □ 5.1.1 Transmissions

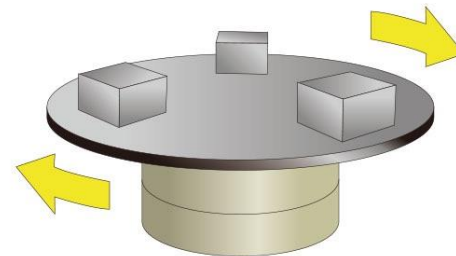
#### ❖ Direct Drive:

- ✓ 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

Servo motor + Reduction gear



Direct Drive Motor





## 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



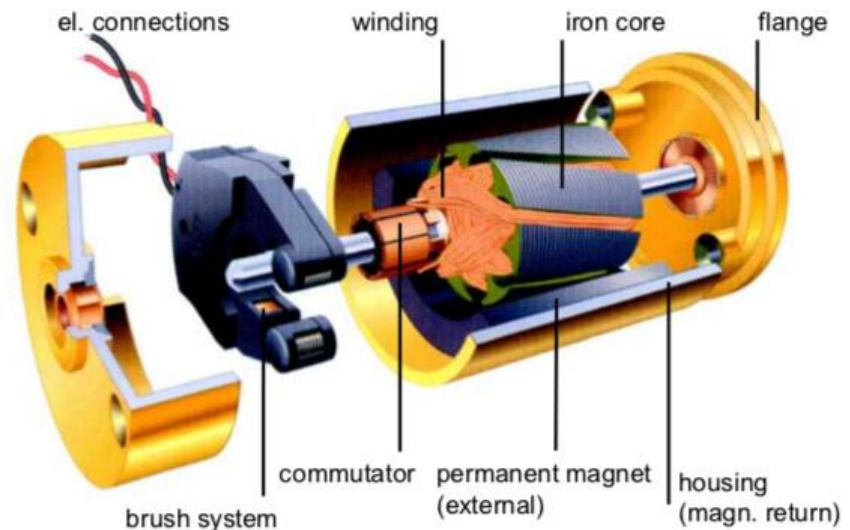
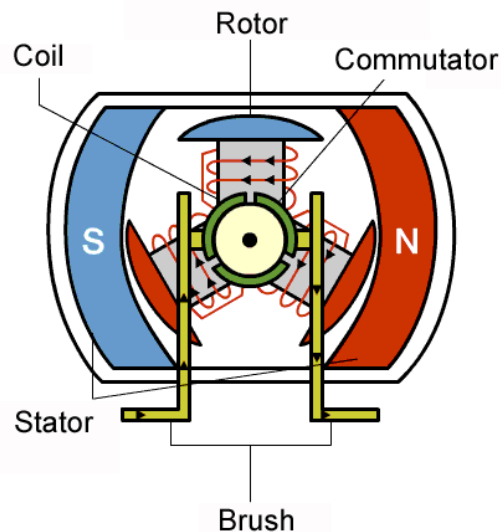
## 5.1 JOINT ACTUATING SYSTEM

### □ 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



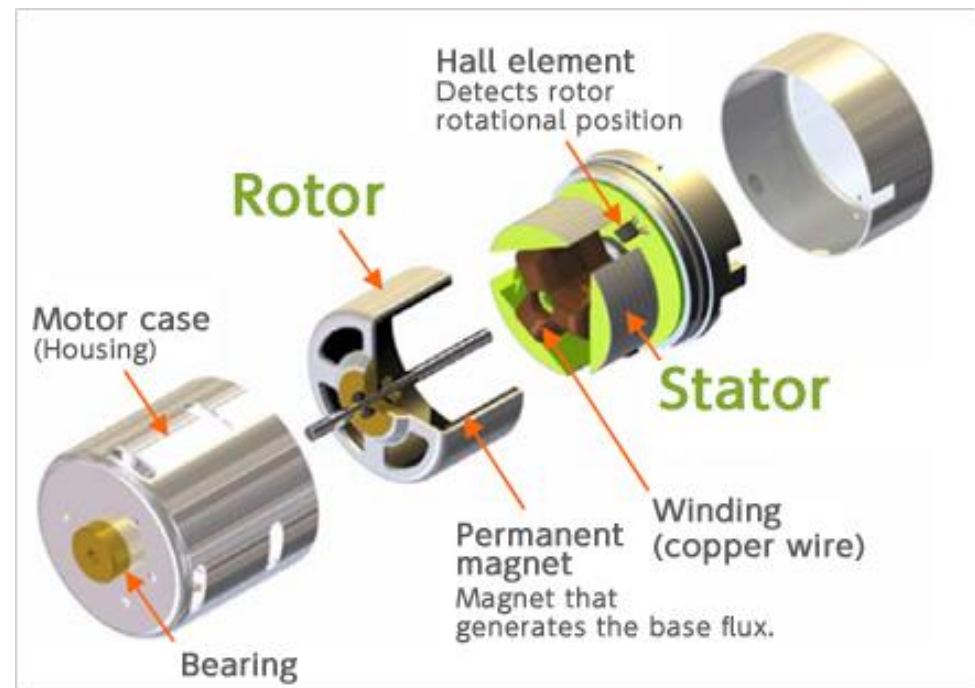
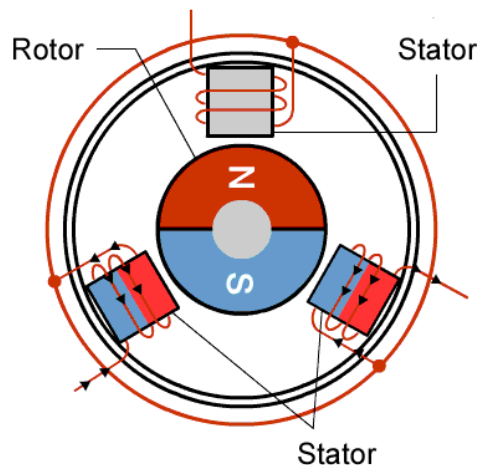
## 5.1 JOINT ACTUATING SYSTEM

### □ 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.

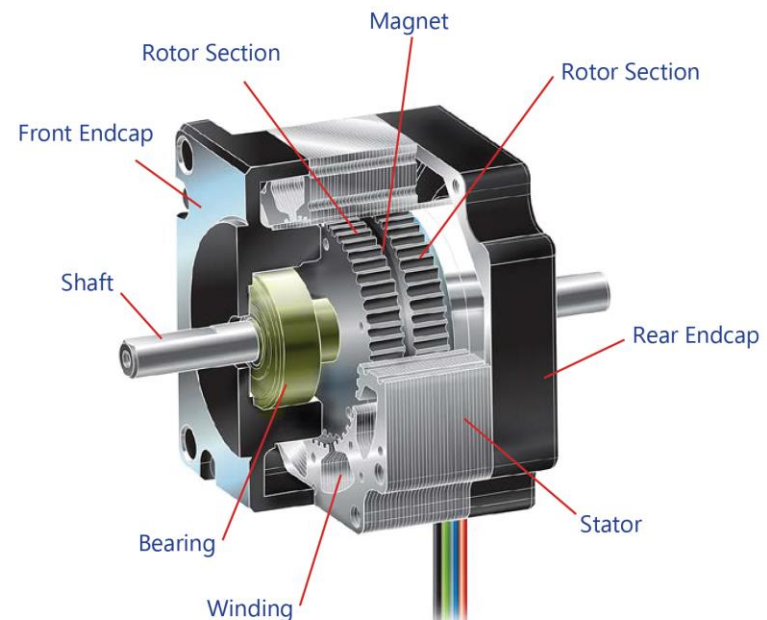
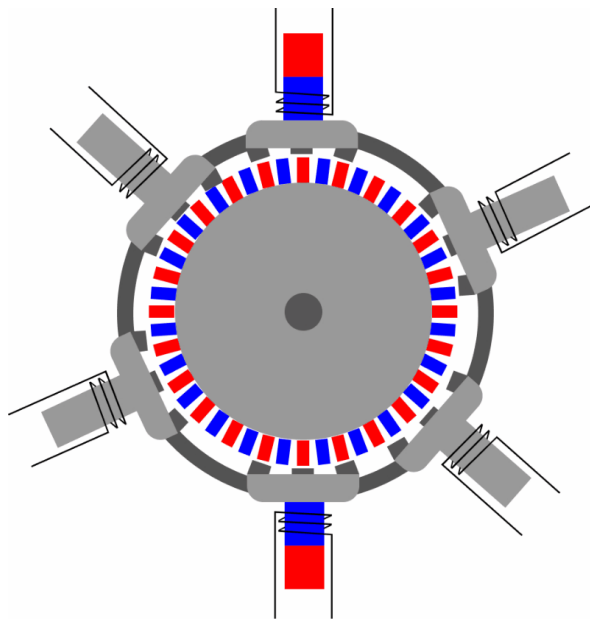


## 5.1 JOINT ACTUATING SYSTEM

### □ 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 ( $P_p$ )
  - ✓ Power from the control signal ( $P_c$ )
  
- ❖ Outputs:
  - ✓ Useful actuator power ( $P_a$ )
  - ✓ Dissipated power losses ( $P_{da}$ )





## 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

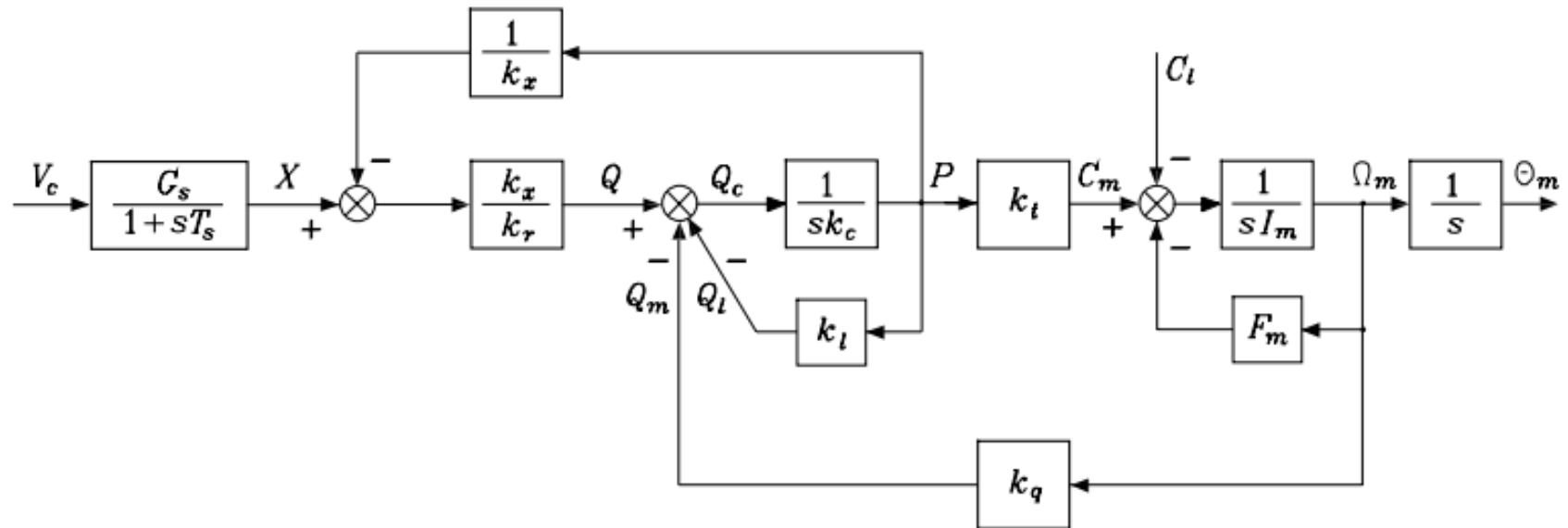
### ❑ Electric and hydraulic drives used for actuating robot joints

- ❖ 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



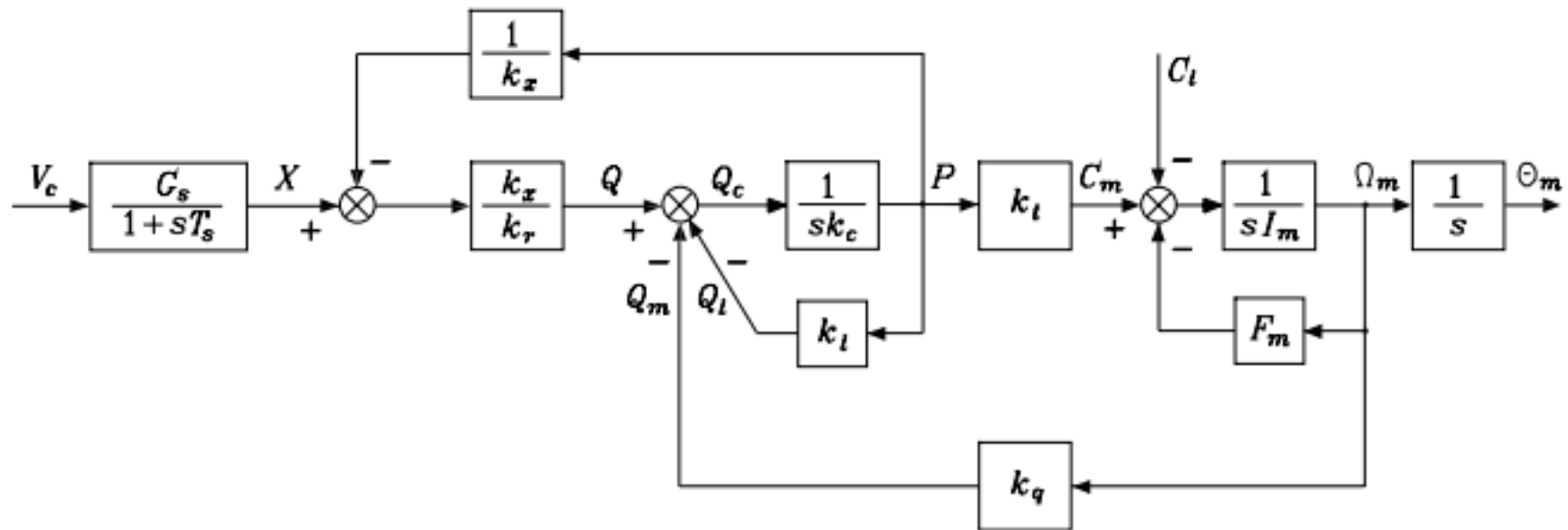
## 5.2 DRIVES

### □ Block scheme of an electric drive



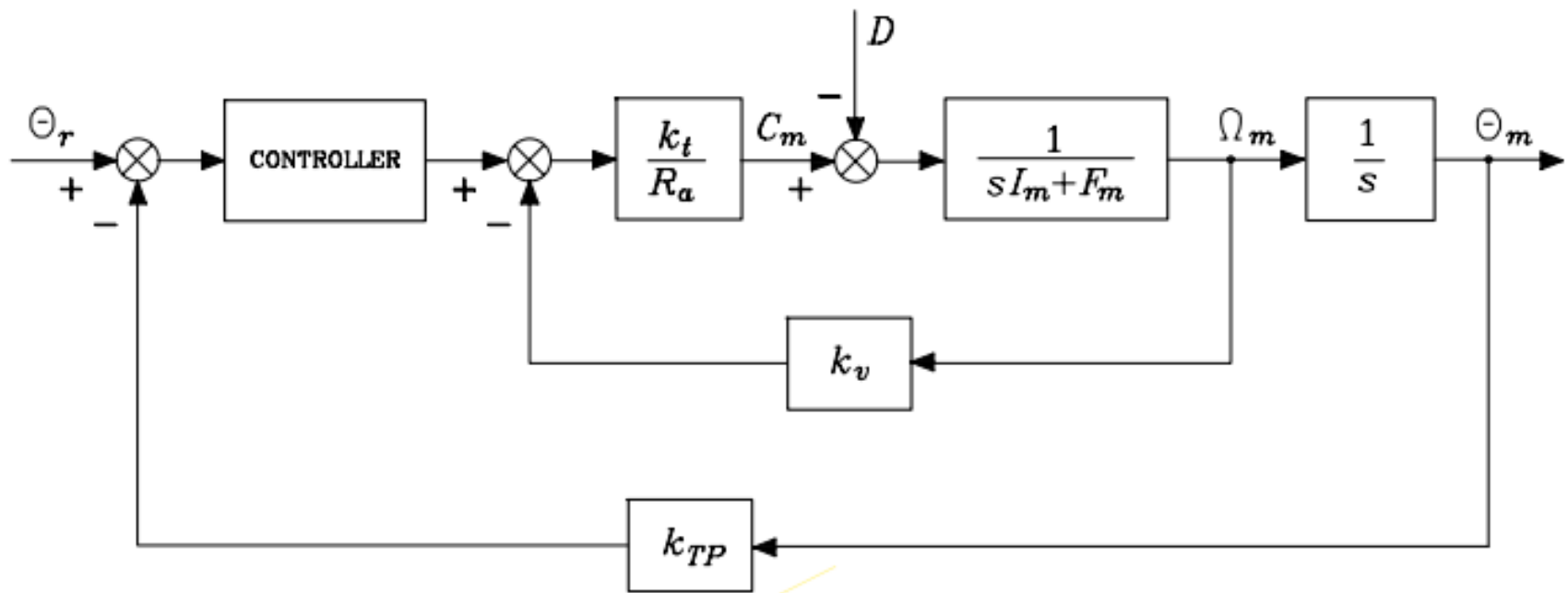
## 5.2 DRIVES

### □ 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.

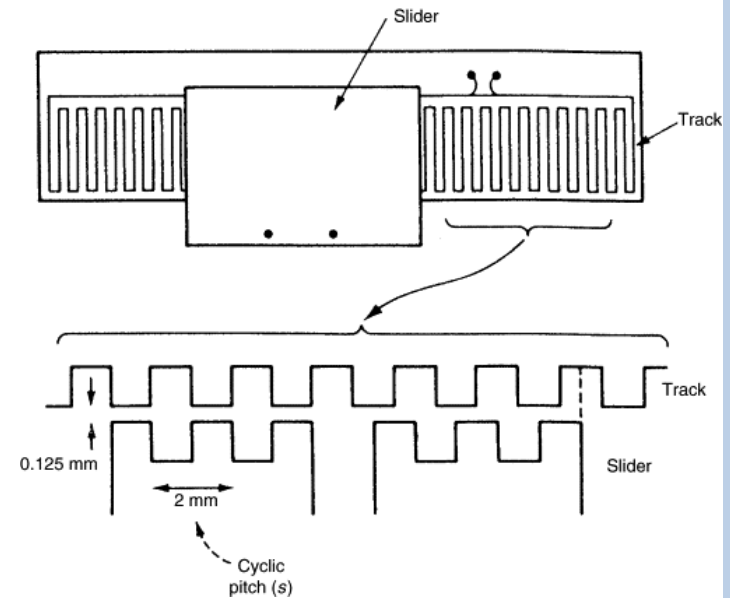
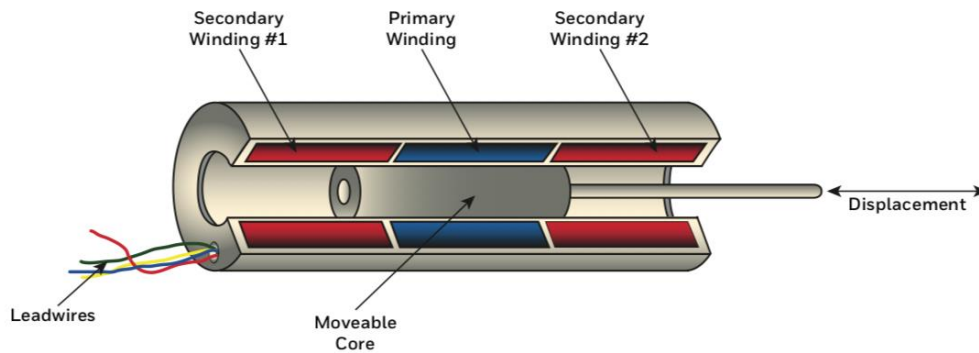


## 5.3 PROPRIOCEPTIVE SENSORS

### 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

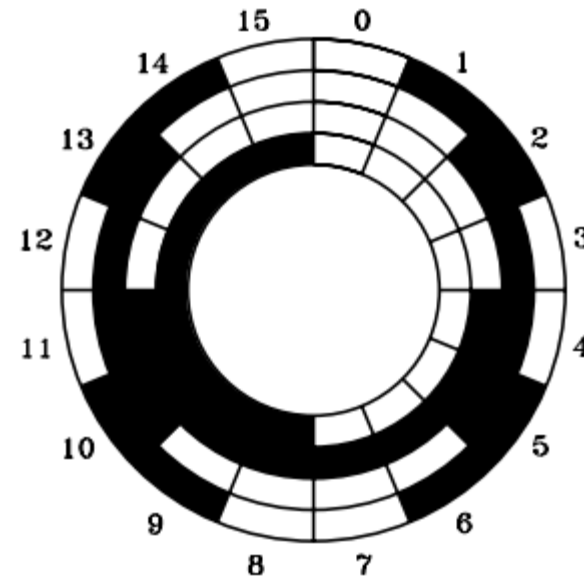
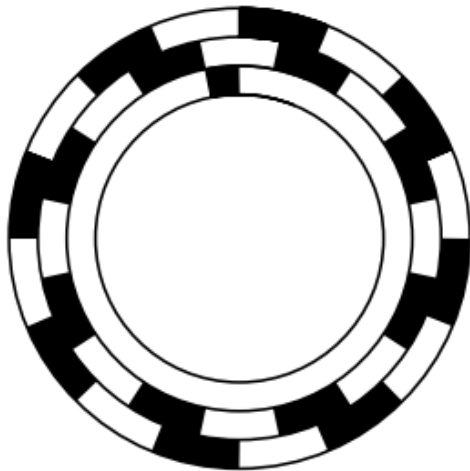


## 5.3 PROPRIOCEPTIVE SENSORS

### 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

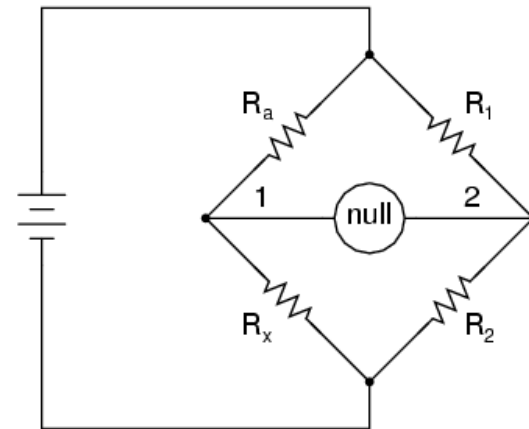


## 5.4 EXTEROCEPTIVE SENSORS

### □ 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

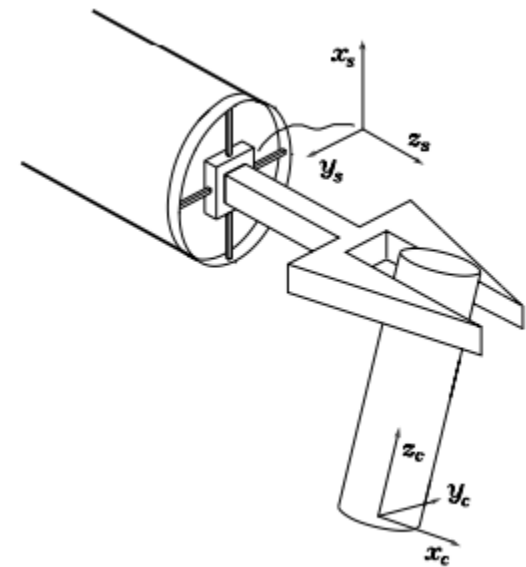
- ✓ Used for direct torque measurement when current-based indirect estimates are insufficient
- ✓ Strain gauges placed on hollow shafts with:
  - Low torsional stiffness
  - High bending stiffness
- ✓ Gauges connected to a Wheatstone bridge and signal transmitted via slip rings and graphite brushes
- ✓ 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

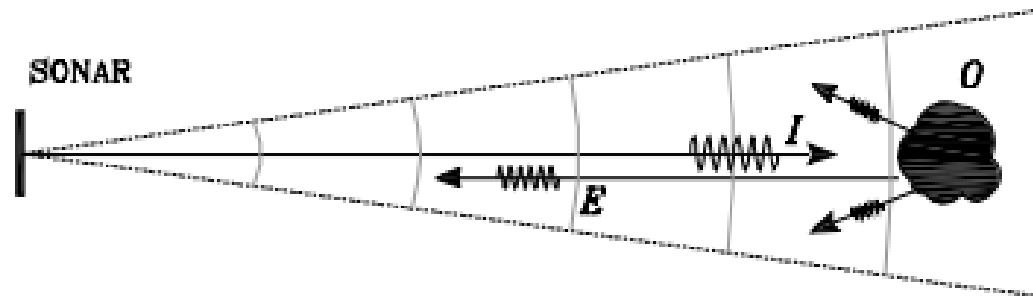


## 5.4 EXTEROCEPTIVE SENSORS

### □ 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

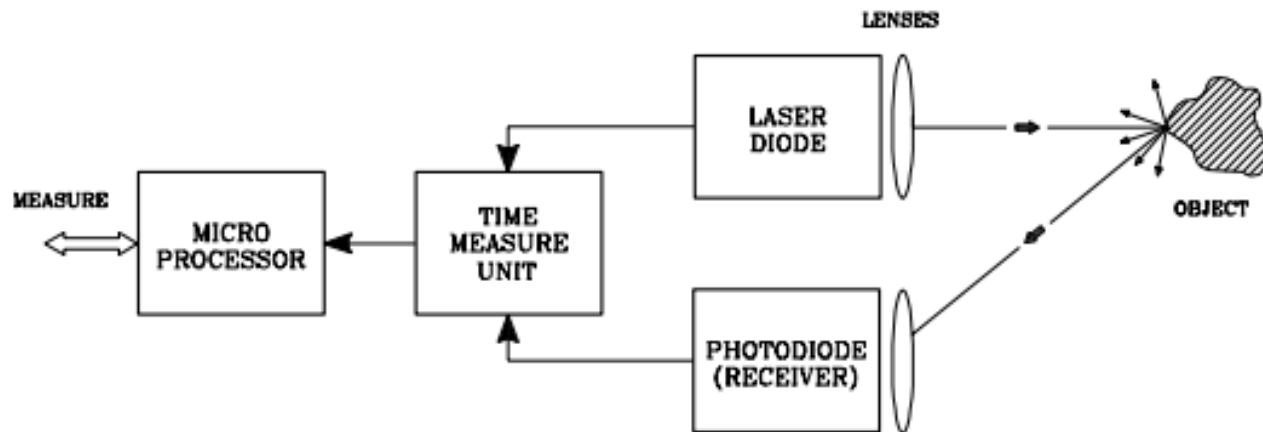


## 5.4 EXTEROCEPTIVE SENSORS

### □ 5.4.2 Range Sensors

#### ❖ Laser (LIDAR)

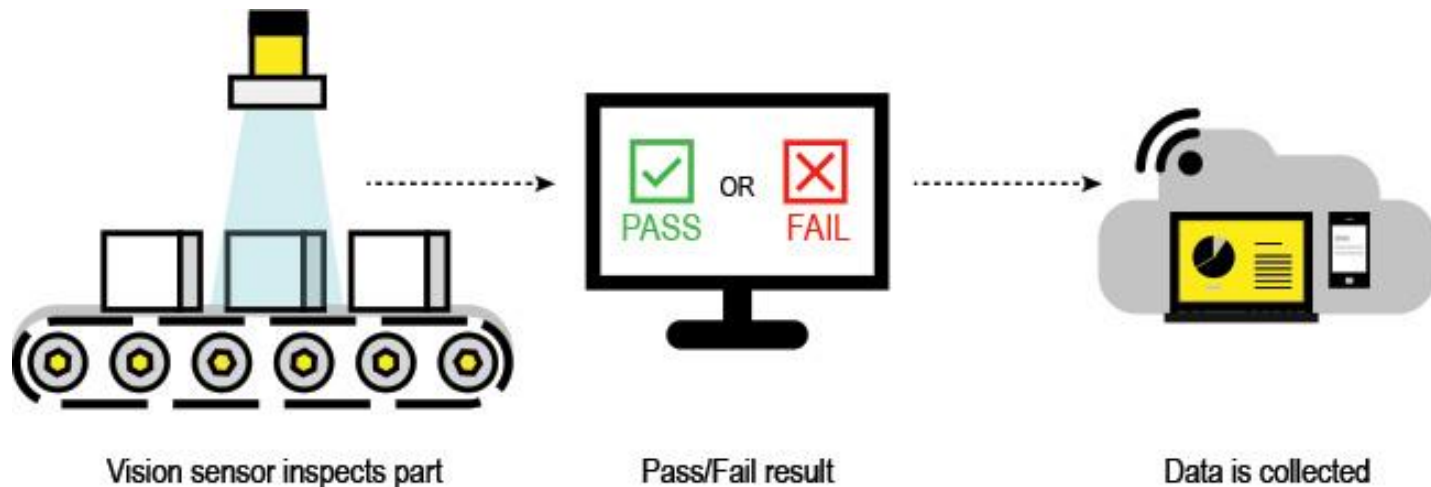
- ✓ Based on light wave propagation (laser beams).
- ✓ Provide high-resolution, accurate distance measurements.
- ✓ Widely used for:
  - SLAM (Simultaneous Localization and Mapping)
  - Navigation in autonomous vehicles and robots



## 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